Chapter 12
Virtual Archaeoastronomy: Stellarium for Research and Outreach

Georg Zotti, Bernard Frischer, Florian Schaukowitsch, Michael Wimmer, and Wolfgang Neubauer

Abstract In the last few years, the open-source desktop planetarium program Stellarium has become ever more popular for research and dissemination of results in Cultural Astronomy.

In this time we (LBI ArchPro and TU Wien) have added significant capabilities for applications in Cultural Astronomy to the program, in particular a way to allow virtual 3D exploration of architecture from any period. The major part of this chapter describes our recent accomplishments for allowing its use in a multi-screen installation running both completely automated and manually controlled setups in an exhibition about Stonehenge. During the development time, also the accuracy of astronomical simulation has been greatly improved. The final part of this chapter (authored by B. Frischer) presents the latest application examples, in particular of these 3D capabilities, for Cultural Astronomy research in the Roman world.

Introduction

Communicating scientific topics in state-of-the-art exhibitions and science centres frequently involves the creation of impressive visual installations. In the 2016–2017 exhibition "STONEHENGE. A Hidden Landscape." at the MAMUZ Museum in Mistelbach, Lower Austria (MAMUZ, n.d.), LBI ArchPro presented its recent research results from the Stonehenge Hidden Landscape Project (e.g. Gaffney et al. 2012; Löcker et al. 2013). A central element of the exhibition which extended over two floors in a former machine factory hall connected with open staircases was

G. Zotti (✉) · W. Neubauer
Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology (LBI ArchPro), Vienna, Austria
e-mail: Georg.Zotti@univie.ac.at; Wolfgang.Neubauer@archpro.lbg.ac.at

B. Frischer
Department of Informatics, Indiana University, Bloomington, IN, USA

F. Schaukowitsch · M. Wimmer
Institute of Visual Computing and Human-Centered Technology, TU Wien, Vienna, Austria
e-mail: florian.schaukowitsch@alumni.tuwien.ac.at; wimmer@cg.tuwien.ac.at

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an assembly of original-sized CNC-milled replicas of most of the central trilithon horseshoe which is seen from both floors.

In the upper floor, visitors were at eye level with the lintels and could study, for example, the connections between the stones made with mortise and tenon joints, made visible by lifting one lintel. On a huge curved projection screen of 25 × 4 m size which extended along the long wall of the hall the exhibition team aimed to create an experience where the visitors could look out over the Sarsen circle into the surrounding landscape. Two possibilities were discussed:

1. A pre-rendered panoramic movie could take the visitors around the landscape. This required a storyboard quite early in the planning phase, detailed 3D modelling that might allow for animation of virtual characters or animals, weather phenomena etc. but needed lots of computing power to create about 15–20 min footage of approximately 4 FullHD frames side-by-side, and required a specialized movie player for synchronized replay over several projectors. The scenes could include everything available from the movie industry, like animations, inserts, fly-overs of the 3D landscape, and in the context of Stonehenge also the changing aspects of celestial objects, sunrise and sunset at the solstices (if properly modelled), the course of the seasons etc. However, the production effort seemed very high.
2. A programmable (scriptable) panorama viewer could be used to present artificial horizon renderings. Unfortunately, most panorama viewers were only able to display a section of a panorama in perspective projection on a regular flat screen (4:3, 16:9 etc.), and not the full width on a very wide screen (25:4 in our case) in cylindrical projection. Also, static panoramas limited the possibilities of explanations around the astronomical connections of Stonehenge to the solstices.

Given the clear astronomical peculiarities of Stonehenge and its sibling monuments, we found that the open-source desktop planetarium program Stellarium (then at version 0.13.2) could be used for our purposes, if some features for automated shows could be added and some improvements in the long-time accuracy of the program could be implemented to allow presentation of celestial motion in prehistory. Stellarium already provided various projections including cylindrical (equirectangular and Mercator) which seemed the natural choice for such a panorama wall, and scripting capabilities which allow automated shows.

Both manufacturers of dedicated high-power graphics hardware, AMD and Nvidia, offered graphics cards which could drive multi-screen setups, and an early test showed that Stellarium could work with a viewport of at least 8192 pixels width.

Over the following months, we would therefore develop Stellarium a few steps further, both in astronomical accuracy and usability as a carrier for media-rich presentations.

An Open-Source System for Virtual Archaeoastronomy

Virtual Archaeology allows the 3D visualisation of reconstructed building structures in a reconstruction of the past landscape with the help of computer graphics technologies. If the system is capable of presenting such models together with celestial objects at astronomically correct simulated positions, we can use such a system for accurate visual simulation of astronomical circumstances potentially connected to those buildings. This enables researchers to find and/or better understand astronomical orientation patterns or, if the system allows, light and shadow phenomena caused by sunlight or moonlight around such sites (Zotti 2015).

A typical sky simulation program can simulate stars and planets as they are located in the sky on any date and time and any location on Earth. For a better feeling of 'being outside in the field', a panorama photograph or artificial rendering of the landscape horizon can be added to the simulation. However, the observer usually cannot move inside the surrounding landscape, whereas archaeoastronomy often deals with extended monuments in and above the ground, and a combination of sky simulation and 3D foreground renderer had been a desire for a long time (Zotti et al. 2006).

The open-source movement has brought forth a number of high-quality programs. A highly realistic sky simulation program called Stellarium had been developed by a small group of developers around Fabien Chéreau and had already become quite mature by around 2007 (Stellarium n.d.). Over the following years it has been used by many laypeople and researchers because of its free availability, ease of use and high visual quality, although on closer investigation it was evident that it was not accurate enough for simulations in very remote times like Roman antiquity or even prehistory because some long-time effects had not been fully implemented. However, an open-source project allows own improvements and extensions, so this project seemed almost perfect to continue and extend when, during the ASTROSIM project (2008–12), we were looking for a good visualisation engine to investigate the potential astronomical orientation of Neolithic circular ditch systems in Lower Austria (Zotti and Neubauer 2015).

The Scenery3D Plugin

A first prototype of a plugin (program extension) for 3D landscape models in Stellarium had been developed in collaboration with students of the Institute of Visual Computing and Human-Centered Technology and used during the ASTROSIM project (Zotti and Neubauer 2012). At that time changes in the project structure of Stellarium did not allow the publication of this plugin. However, further large changes of the Stellarium project which now required the Qt5 framework allowed one of us (FS) to update, extend and complete the integration of the

Scenery3D plugin into a mature and efficient polygonal real-time 3D renderer that was released with Stellarium 0.13.3 in April 2015 (Zotti 2016).

This plugin allows loading a 3D model in the well-known Wavefront OBJ format (complete with MTL material and texture definition) in a way that the user is placed at eye height (configurable) over the surface of the model terrain. This model is currently rendered in a 'flat earth' approximation, i.e., on a plane tangential to the Earth's globe at the location coordinates configured in Stellarium. Actually two OBJ files can be loaded: one includes the full scene with architecture, walls, pillars etc., while a 'ground' layer without walls and pillars defines the plane where the virtual camera (i.e., the visitor's eye) will be located. Like in a computer game, the user can explore the model by moving the view over this ground layer of the model, which means that we can simply enter rooms or walk through walls without jumping onto roofs or stepping onto those walls. The plugin does not attempt to act as a complete game engine with animations, wind-moved vegetation, sound, etc. On the other hand, fine detail in the model (e.g. inscriptions on the walls of a temple) can be modelled by normal mapping, and the shadow of the Sun and Moon can be rendered diffuse by the PCSS algorithm (Fernando 2005), which should help simulating the reduced saliency of shadows cast by slim columns (see discussion of the Montecitorio Obelisk and Ara Pacis below).

The models can be presented with eyepoint (camera) coordinate values representing real-world survey coordinates e.g. in the UTM coordinate system, which allows proper investigation and reproducible results to be gained for scientific applications. We had to overcome a problem though: real-time computer graphics applications usually only work with single-precision (32-bit) floating point numbers, providing only about 7 significant decimal digits. Coordinates in metre-based UTM can easily grow to millions of metres, which means that vertex (corner) coordinates for model elements could be specified only to the nearest decimetre or even metre, which is clearly not enough. We can however split off a large 'offset' from the coordinate values of our location (either the centre coordinates of our virtual terrain or some full-metre offset for easier maintenance by humans) and work in a local coordinate system for rendering. The numerical coordinate text display simply reconstructs the original coordinates by adding the offset to the local coordinates used for rendering.

Another problem when modelling in a Cartesian survey grid like UTM: unless the location is located on the UTM zone meridian, the direction called 'Northing' does not point strictly northward, but slightly deviates because of the meridian convergence towards the poles. For a limited area typical for an archaeological site, this deviation can be compensated by a simple rotation of the model around the vertical axis.

Currently (as of version 0.15.2) the model does not deal with curvature of the Earth or terrestrial refraction, and also does not take into account that walking in the model should modify the geographic location coordinates in an order of arcseconds. Usually the modelled landscapes are small enough that these effects can be neglected. Mountains in tens of kilometres distance on the far horizon should be included as classical Stellarium ‘landscape’, a 2D panorama accurately rendered along the mathematical horizon.

We are convinced that such a machinery for virtual archaeoastronomy is the best tool to recreate observers’ views of past landscapes, buildings and monuments under the day and night sky of corresponding past times, i.e. the ‘skyscape’ (Silva and Campion 2015). For best possible results, accurate data should necessarily be used. Especially for the landscape surrounding a monument of interest, LIDAR-based digital terrain models provide critically more detail than data previously available from official survey authorities. Possible users should take note that terrain models based on the freely available 90 m SRTM data are generally too coarse to achieve reliable results. As a first preview of local horizon conditions in not too steep or rough terrain, their use seems acceptable though.

Likewise, another plugin called ArchaeoLines, particularly aimed at archaeoastronomical simulations, was introduced in late 2014 (Zotti 2016). It can show diurnal arcs for the most prominent declinations (solstices, solar cross quarters, lunistices, zenith passages etc.) and azimuth indicator lines (either arbitrary azimuth or azimuth towards geographical targets like sacred mountains or places). Such simple lines can be helpful in explanations and presentations of astronomical concepts also in the context of the forthcoming exhibition. Also the landscape panoramas have been enhanced by an option to label features like mountain peaks.

Meanwhile, several deficiencies of Stellarium for celestial simulations in remote times were identified, and it was now time to improve computational accuracy for this application which should extend Stellarium’s applicability if possible back into the Mesolithic. The largest impact was the replacement of the simple first-order approximation of the precessional motion of Earth’s axis by a modern long-time model compatible with IAU2006 precession but applicable for ±200,000 years around the year 2000 (Vondrák et al. 2011, 2012). This model has been explicitly developed for applications like archaeoastronomy. In addition, nutation (IAU2000B from McCarthy and Luzum 2003) has been added, a small faster ‘wobble’ of Earth’s axis in the order of several arcseconds that is however only applied ±500 years from J2000.

Stellarium’s planetary positions were based on the widely used VSOP87 analytic model which has been created as fit over the numerical solution DE200 from NASA/JPL and is recommended for use in the year range −4000 to +8000. With the accurate precession model mentioned above added, we can observe in Stellarium what happens outside this time: between 8000 and 8100 the Sun moves from the ‘ecliptic of date’ to the ecliptic of J2000 that is VSOP’s XY plane. Likewise, before −4100 the Sun (or rather Earth) is mathematically ‘forced’ into this plane, likely to achieve at least approximate positions outside the recommended range of dates (Fig. 12.1). This clearly indicates that for dates before −4000, VSOP87 should not be relied upon (as specified by its authors). Fortunately NASA/JPL recently has released DE431, results of a numerical simulation for the years −13,000 to +17,000 (Folkner et al. 2014). ESA has sponsored another student in the ‘Summer of code in space’ project 2015 so that Stellarium can now access both DE430 (high accuracy) and DE431 (long-time simulation) files to retrieve accurate planetary and lunar positions for a far longer period than before (Fig. 12.2).

Fig. 12.1 Spring equinox, −4200, simulated in Stellarium 0.15.2 with positions from VSOP87 (outside its recommended date range). The Sun is forced to be on the J2000 ecliptical plane (lower line)

Fig. 12.2 Spring equinox, −4200, simulated in Stellarium 0.15.2 with positions from DE431. The Sun is on the ecliptic given by the new precession model from Vondrák et al. (2011, 2012). Note also the different positions of Mercury and Venus

Improvements for Astronomical Demonstrations

Stellarium has provided scripting capabilities for automatic shows since its early years. However, scripts had to be started manually. Also, Stellarium's earlier transition to the Qt5 framework had caused a temporary reduction of its multimedia capabilities. In preparation for the exhibition we have restored and extended Stellarium's multimedia capabilities so that still images and movie clips can be inserted into the screen to add visual detail to the audio narration.

The largest change for automatic shows and remote accessibility was however the development of the RemoteControl plugin. This required a 're-wiring' of the internal program modules so that their 'properties' (state variables) could be exposed and changes forwarded to other interested program modules. We developed a dedicated plugin that provides a web server interface which allows operation of Stellarium via webbrowser, where the user can switch almost every setting available in the regular program menu without showing this interface menu on the big screen of the exhibition. An alternative page layout has been added for small screens typically found on tablets. In addition, a web API allows triggering of show scripts. In the context of our exhibition, a little Raspberry Pi computer with touch screen interface has been configured to act both as master switch for the PC and 5-projector system and to send such script calls every 25 min via cronjob.

Outreach Result: The Skyscape Planetarium

Several years ago, one of the authors found that the classical immersive astronomical simulation environment of the twentieth century, the optomechanical projection planetarium, was actually not well suited when it came to the simulation of archaeoastronomical concepts and case studies of horizon astronomy: although the sky was visualized on an all-enclosing hemispherical dome, the projection included only the area above the mathematical horizon, so that the sub-horizontal context of archaeologically documented or reconstructed monuments which should have been presented in the foreground was missing. Advances in computer graphics and virtual realities promised a more applicable solution (Zotti et al. 2006).

The setup which we have now developed can best be described as 'Skyscape Planetarium' (Zotti et al. 2017), where 'skyscape' describes the inseparable combination of landscape and the sky behind, observed and experienced by human observers (Silva and Campion 2015). The projection, configured with five overlapping projectors, is limited to presenting the horizon area, but the system allows shifting the horizon up or down as required to show more sky or more of the ground, and therefore allows displaying celestial objects in a maximum altitude of about 30°, which is enough for simulating many typical views in both prehistoric and contemporary skyscapes (see Fig. 12.3).

Fig. 12.3 A Fisheye photograph of the Skyscape Planetarium in the MAMUZ Museum, combining panoramas from virtual reconstruction, astronomical simulation and explanatory inserts. On the right side, the screen is partially hidden by one of the horseshoe trilithon replicas, but the continuation of the screen adds to the immersive quality of the installation

In the context of the exhibition, we present artificial renderings of panoramic views of the landscape evolving over several millennia from the time of Mesolithic hunters to the artisans of the Bronze Age, highlighting important phases in the history of, and visiting important sites in the landscape around, Stonehenge in an automated narrated tour of about 20 min.

Most of the panoramic vistas are not related to astronomical events and Stellarium is only used to show the panoramas, often in slow pans over the landscape. We do not use the Scenery3D plugin in this exhibition, but the changing colours of simulated daylight and landscape brightness depending on solar altitude changing over time both help to create an almost 3D feeling of the landscape and standing Sarsen and Bluestone circles. Currently, Stellarium's sky does not include meteorological phenomena like clouds, but some have been included as static renderings in some panoramas when they only serve decorative purpose and are not required to move with the winds. Of course, views like the iconic summer solstice sunrise over the Heel Stone can be presented in all its glory, using high-quality panorama renderings of virtual reconstructions of Stonehenge and related sites in several phases of construction in their reconstructed landscapes.

In contrast to presenting only a pre-produced panoramic movie, using Stellarium offers the benefit of providing a complete and flexible astronomical simulation environment. This allows us, for example, to experience and demonstrate the slow shift of the solstice rising points due to changes in ecliptic obliquity. On special occasions, the regular show can be switched off, and an operator can control the application using a web browser interface on a tablet computer provided by the new RemoteControl plugin which has been developed in the context of our exhibition project.

Fig. 12.4 A scene from a 'flashlight tour' for children with the Skyscape Planetarium providing the nocturnal atmosphere

The experience of a starry virtual nightscape that fills the field of view on a big wall, first seen a few days before opening the exhibition on 20 March 2016, was stunning. Unfortunately only a few visitors are given this experience. The 20-min narration shown during daytime opening hours only shows brief moments of sunrise, sunset or twilight but does not include a nightly setting. In fact, showcase illumination during the day would brighten up any night scene to a point where the visual atmosphere would be severely degraded. However, on a few evenings, the museum offers 'flashlight tours' especially targeting primary school children. With all regular lighting switched off, the children's flashlights dancing around the replica Sarsens of the horseshoe, the projected view out of Stonehenge with the stars twinkling through the Sarsen circle panorama created from the virtual reconstruction that shows Stonehenge shortly after completion provide a stunning night atmosphere (Fig. 12.4). Seen from the centre of the room, the rightmost part of the screen is partially hidden by a trilithon replica, which means we cannot present important detail on this part of the wall. But the fact that there *is* a screen surface behind this stone definitely helps to increase the immersive experience. More sites of archaeoastronomical interest would deserve a presentation in such an installation.

Two Applications of Stellarium to Roman Archaeoastronomy

The utility of Stellarium in the field of Roman archaeoastronomy can be exemplified by two recent projects: the identification of the sanctuary at Hadrian's Villa conventionally called the Antinoeion; and an assessment of the validity of an influential theory about the relationship of the Montecitorio Obelisk and the Ara Pacis Augustae in Rome. Detailed reports about both projects have been written (see Frischer 2017–2018; Frischer et al. 2016, 2017), so we can be brief here.

The Antinoeion

Antinous was a young man from Bithynia who became Hadrian's lover in the 120s AD (Galimberti 2012). In October of 130, he drowned in the Nile while on a trip to Egypt with the Emperor. Hadrian was devastated by this loss and bestowed cult honors on his friend, founding the city of Antinoopolis in Egypt and building temples all over the Empire (Galli 2012).

A feature conventionally called the Antinoeion is located at Hadrian's Villa in Tivoli. Discovered in 1998, the site was excavated from 2002 to 2004 under the direction of Zaccaria Mari (Mari 2012; Mari and Sgalambro 2007). The area measures ca. 63 × 50 m located adjacent to the double road leading to the so-called Vestibule. The perimeter was surrounded by a wall, within which were discovered two identical temples, ca. 15 × 9 m in size: one to the northwest, the other to the southeast. They faced each other across a plaza into which were cut water channels and planters. Springing off the western side of the plaza is a large colonnaded exedra, in the middle of which was another temple. For the sake of convenience, we refer to the three shrines as Temples 1, 2, and 3 (Fig. 12.5).

Archaeological investigation of the site was motivated from the first to prove the theory that somewhere at Hadrian's Villa there must have been a sanctuary dedicated to Antinous. The first to propose the theory was Kähler (1975: 42), who argued that the likely spot was the Canopus, but, despite various efforts (e.g. see Hannestad 1982), no evidence was ever found there to support Kähler's theory.

In the early 2000s, Mari's excavations of the site now conventionally called the Antinoeion turned up dating material placing it securely in the period after Antinous' death in AD 130. They also uncovered many fragments of Egyptianizing sculpture (Mari 2012), decorative elements clearly appropriate for the cult of a young man who drowned in the Nile and who was sometimes assimilated into his new cult to Osiris. Mari also argued that the obelisk now in the Villa Borghese on the Pincian Hill in Rome came from the Antinoeion. Furthermore, Mari produced documentary evidence that the Egyptianizing statues in the Gregorian Egyptian collection of the Vatican Museums were also found on land adjacent to the Antinoeion and thus, according to Mari, must have originally been erected in the sanctuary.

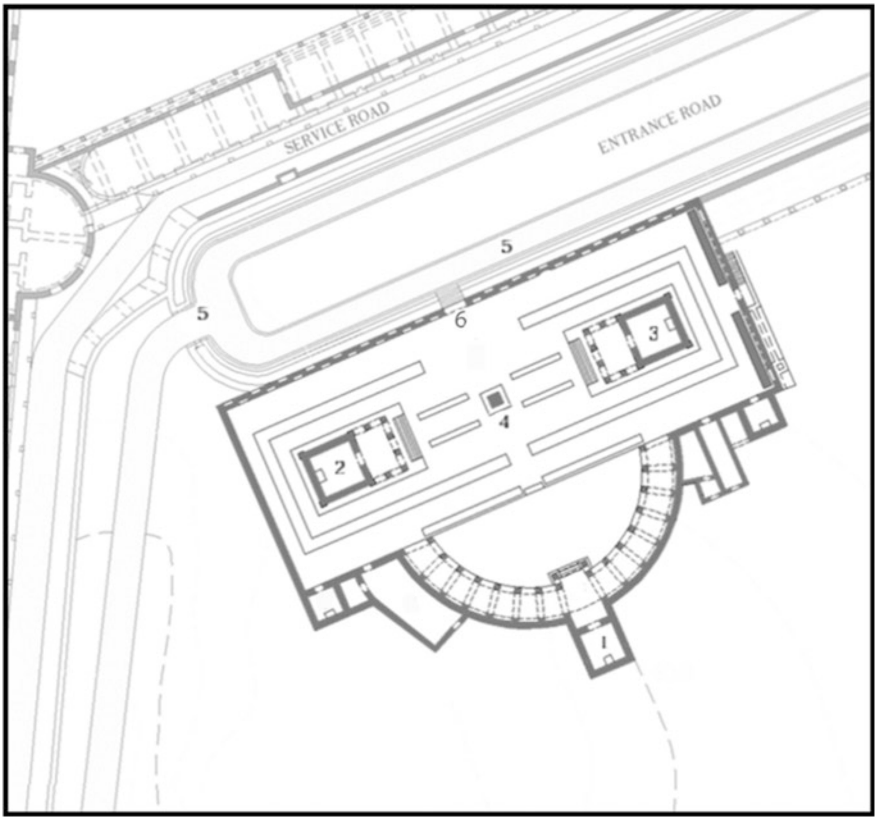

Fig. 12.5 The Antinoeion at Hadrian's Villa. Within the sanctuary are three temples (1, 2, 3), a platform which may have supported an obelisk (4), the main entrance road to the Villa (5), and the East Portal (6), leading from the road into the sanctuary. East is at top (courtesy: Matthew R. Brennan, Virtual World Heritage Laboratory, Indiana University)

Mari's work in bringing to light the Antinoeion appeared to have brought the search for Antinous' monument at the Villa, initiated by Kähler, to a successful conclusion. But in the 10 year period after Mari concluded his fieldwork, skepticism about some of his conclusions was expressed, notably in Grenier (2008). Our virtual archaeoastronomical project had the goal of trying to see if there were any alignments between celestial features and the built features of the sanctuary and, if so, to gauge their impact on the validity of Mari's interpretation of the site as an Antinoeion.

We took as our point of departure the fact that the sanctuary was clearly Egyptian in inspiration, décor, and cult. We therefore used as our working assumption the conclusions about the astronomical orientation of Egyptian temples reached by Magli (2013) and by the Egyptian-Spanish Mission on Egyptian Archaeoastronomy (henceforth ESMEA; see Belmonte et al. 2009).

Magli showed the importance of the concept of the 'sacred landscape' in the layout and design of Egyptian monuments such as pyramids and temples. ESMEA investigated whether Egyptian temples tended to be oriented to the Nile, as is commonly believed, or to appropriate astronomical phenomena. ESMEA surveyed a remarkable 98% of existing shrines and temples in Egypt from all periods found at nearly 400 sites around the country. The mission found that temples near the Nile were oriented to it but in such a way that astronomical orientations were also common. Both determinants of temple orientation could operate in tandem because it was possible to choose a site near the Nile, which does not run perfectly straight, such that the siting would point the temple to the correct orientation in the sky.

Applying these findings to the Antinoeion, we might equate to the Nile (in purely functional—not symbolic—terms) the double road, along which the sanctuary is located (no. 5 on Fig. 12.5). It was an obvious determinant of the orientation of the complex, though nothing required siting the sanctuary here—there was ample available land elsewhere at Hadrian's Villa. In this connection, we should also note that within the perimeter walls of the sanctuary the built features could be positioned and oriented with complete freedom. So, it makes sense to consider whether we find the same complementary terrestrial and astronomical factors dictating the orientation of the Antinoeion as ESMEA discovered in its Egyptian study.

There were three temples within the complex, each with its own orientation (nos. 1, 2, and 3 on Fig. 12.5). The possible astronomical orientation of each of these needs to be considered separately. Owing to space limitations, we concentrate here on Temple 1. The overall orientation of the sanctuary, from the point of view of the ancient visitor entering from the access road, runs from the East Portal (no. 6 on Fig. 12.5) to Temple 1. This was clearly the important axis for the ancient visitor to the site.

We created a 3D digital model to reflect the Mari-Sgalambro reconstruction of the sanctuary (Mari and Sgalambro 2007: 85, Fig. 3) set into the landscape reconstructed using data from the survey of Hadrian's Villa by the Scuola degli Ingegneri di Roma in Lanciani 1906 as augmented by the terrain map of the Tivoli area published at a scale of 1:25,000 by the Istituto Geografico Militare. The accuracy of the latter for the cardinal points was graciously confirmed for us by Valerio Baiocchi, an expert on the cartography of central Italy. Putting the digital model into Stellarium and setting the time for the years in the 130s AD after the death of Antinous, we were able to take observations of the day and night-time sky throughout the year, looking for possible celestial alignments of interest. We discovered that from the vantage point of someone looking east and standing anywhere along the axis running from the East Portal to Temple 1, the Sun would have been visible rising behind the mountains to the east on the summer solstice in the 130s (Fig. 12.6). Because of the narrowness of the East Portal, the view of sunrise would have been blocked most of the other days of the year.

Once we had discovered the sanctuary's orientation toward sunrise on the summer solstice, we interpreted it by noting that there was a major Roman holiday on the summer solstice, the festival of Fors Fortuna (Degrassi 1963: 472–473). This festival was relevant to an Egyptianizing sanctuary because we know that the Romans assimilated Fors Fortuna to Isis (Champeaux 1982: 210).

Temple 1 is located at the end of the axis of entrance opposite the East Portal. We know that when Antinous died, the grief-stricken Emperor carved out a new constellation in his memory. As Ptolemy (Almagest VII.5) reports, it was located in what had formerly been the lower part of Aquila. The idea was that Antinous is a

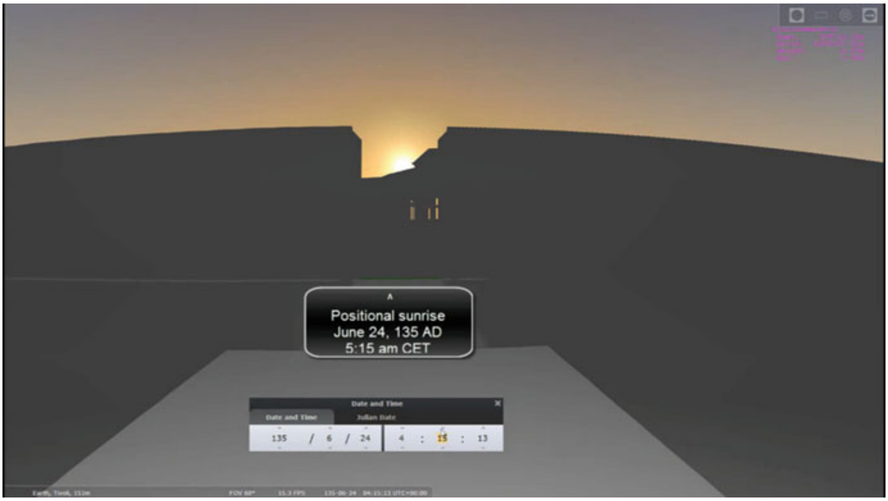

Fig. 12.6 A Stellarium simulation showing the Sun rising at 5: 15 am CET on the summer solstice (24 June) in the year AD 135 as seen by someone looking eastward toward the East Portal of the Antinoeion while standing on the axial line running from the East Portal to Temple 1

Ganymede figure, snatched to the heavens by Zeus, symbolized by the eagle. When we stood along the axis of entry and looked west in the direction of Temple 1 all year during the mid-130s AD, we discovered that the stars making up Antinous set on axis behind Temple 1 and that their heliacal settings occurred during a two-week period around 27 November, the date of Antinous' birthday (Fig. 12.7). Mari had already associated Temple 1 with Antinous on the level of iconography: he had noted that the Osirantinous telamones, originally known to be from Tivoli and presently in the Sala Greca of the Vatican Museum, would fit onto the porch of the temple. Mari also suggested that one of the several Osirantinous statues found out of context at the Villa might have been the cult statue. Our finding that Antinous' constellation started to set on axis with Temple 1 and had its heliacal setting around the time of Antinous' birthday added a new reason to support Mari's identification of the shrine as an Antinoeion.

The Relationship Between the Ara Pacis Augustae and the Montecitorio Obelisk

The second project in which Stellarium was used involved one of the first obelisks brought to Rome—the Montecitorio obelisk brought by Augustus from Heliopolis—and one of the best-preserved Augustan monuments, the Ara Pacis Augustae. The so-called Monte Citorio obelisk was brought by Augustus to Rome in 10 BC and set up in the Campus Martius about 90 m west of the Ara Pacis, which had been under construction since 13 BC and was completed in 9 BC. Explicitly dedicated by Augustus to the Sun

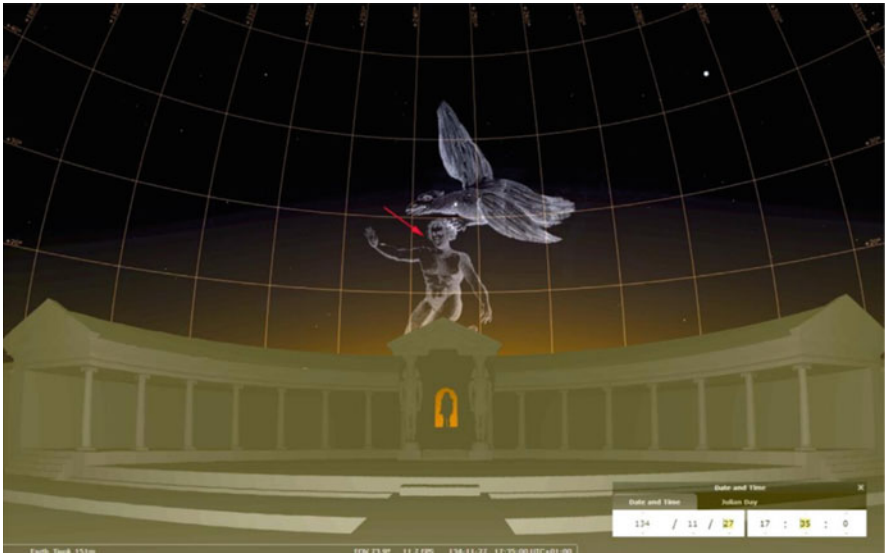

Fig. 12.7 A Stellarium simulation showing the constellation Antinous (red arrow) seen by someone standing on the axial line from the East Portal to Temple 1 of the Antinoeion at Hadrian's Villa. The constellation (taken from J.E. Bode's *Uranographia* (1801) appears just before its heliacal setting on axis behind Temple 1 at 6:35 pm CET on AD 27 November 134. 27 November was Antinous' birthday

god, as the still extant inscription attests, this obelisk was used to support a sphere that served as the gnomon for a monumental timekeeping device, something we know from a famous chapter in book 36 of Pliny's *Natural History*.

Since the sixteenth century, scholars have debated the nature of the timepiece, alternating between a meridian and a huge horizontal sundial. Buchner (1976) made a case in favor of the sundial theory. Buchner worked out a detailed reconstruction of its design and dimensions as part of a more general theory to explain the spatial and ideological relationship between the obelisk and the Ara Pacis. The theory had three parts: first, the set-up of the monuments, that is, exactly where they were sited in the ancient city. This is not obvious since, although we do know where the Ara Pacis stood, we do not know precisely where the obelisk was erected. All we know is that it was somewhere under the modern building at Piazza del Parlamento 3. Moreover, Buchner speculated that there was a vast pavement, 70 × 160 m, on which was inscribed a horizontal sundial. He thought the sphere we know from Pliny that stood atop the obelisk was the gnomon for the sundial. As noted, other scholars since the eighteenth century thought that there was no such pavement and no sundial but just a meridian line, that is, a single line running due north of the obelisk. This matter is still under debate and recently opinion has shifted back to the idea that the timepiece was simply a meridian, but clearly only new fieldwork (presently underway by a team led by Bernard Frischer) will resolve this issue.

The second element concerns the environmental effect caused by the set-up. Buchner thought that the effect concerned the shadow cast by the obelisk on

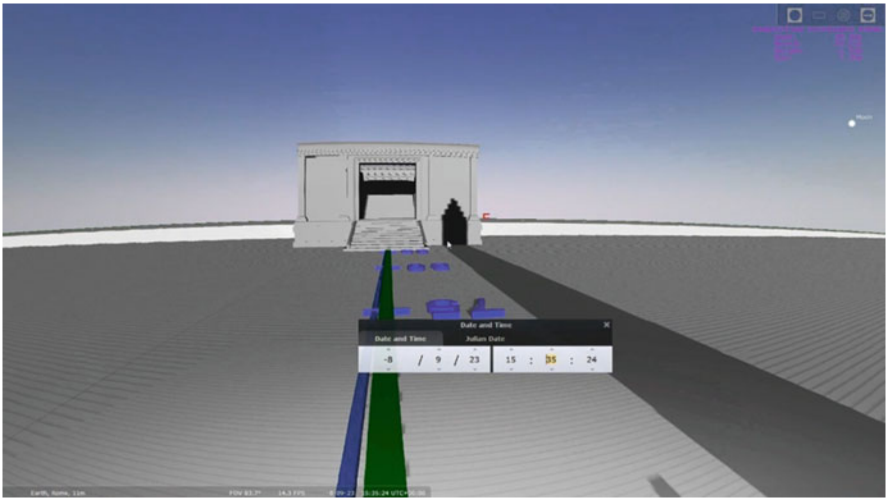

Fig. 12.8 A Stellarium simulation showing the shadow of the Montecitorio Obelisk seen by someone standing on the axial line running from the Ara Pacis Augustae to the Montecitorio Obelisk. The shadow misses entering into the entrance into the altar, which it strikes at 4:35 pm CET on 23 September 9 BC (Augustus' birthday)

Augustus' birthday, 23 September. In particular, he speculated that the shadow went down the equinoctial line inscribed on the pavement right into the middle of the Ara Pacis. Finally, the third element was the message implicitly transmitted by the effect. Buchner thought it was that Augustus was *natus ad pacem*, or 'born to bring peace'.

The purpose of our study was to test the validity of Buchner's theory about the relationship between the obelisk and Ara Pacis (for details, see Frischer et al. 2017). In assessing the validity of the theory, we started by commissioning two independent surveys of all the monuments in question, and these determined that Buchner had made a major error in siting the obelisk: he had it 4 m too far east and 2 m too far north. Once this error was corrected, we made a computer simulation of the area and used Stellarium for the year 9 BC to see whether the obelisk's shadow really proceeded along the equinoctial line into the middle of the altar on Augustus' birthday. The theory turned out to be wrong: the shadow did not enter into the western doorway of the altar but hit the west façade off axis to the south (Fig. 12.8).

Once Buchner's theory had been critiqued, Stellarium was used to support new empirical observations of the virtual Campus Martius. We found that on 48 days of the year, the shadow of the obelisk did enter into the Ara Pacis Augustae (Fig. 12.9), so Buchner may well have been on the right track but erred about the specific date(s). Moreover, virtual observations gradually produced a new insight: while the shadow cast by the obelisk toward the Ara Pacis Augustae was certainly one environmental effect created by the spatial relationship between the obelisk and altar, two other effects were equally relevant: the appearance of the solar disk seemingly centered on the top of the obelisk, as seen by an ancient observer standing along the axial line linking the altar and the obelisk (Fig. 12.10); and the rising Sun seen on axis with the altar by an observer standing on the axial line with the obelisk to his back (Fig. 12.11).

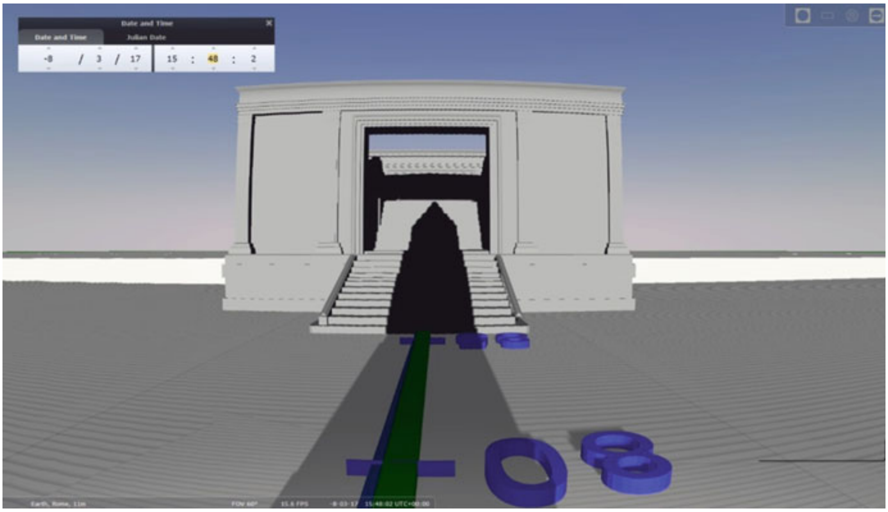

Fig. 12.9 A Stellarium simulation showing the shadow of the Montecitorio Obelisk entering into the middle of the Ara Pacis Augustae at 4:48 pm CET on 17 March 9 BC. Using Stellarium, a total of 48 days of the year were found when the shadow entered the interior of the monument. Contrary to what Buchner's theory required, Augustus' birthday (23 September) was not one of those dates

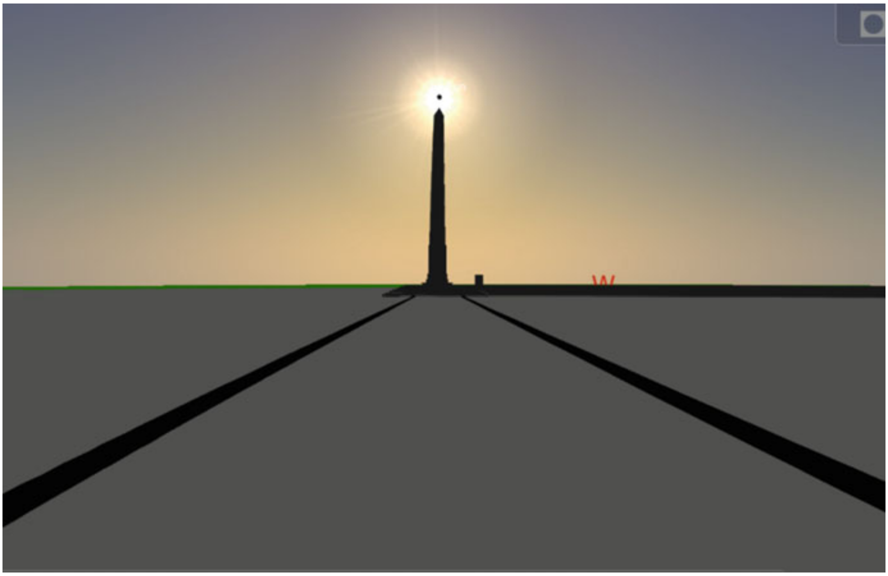

Fig. 12.10 A Stellarium simulation showing the solar disk centered on the top of the Montecitorio Obelisk as seen by someone looking west while standing on the axial line between the Ara Pacis Augustae and the obelisk at 4:33 pm CET on 23 March 9 BC. Such alignments were found on a total of 224 days of the year

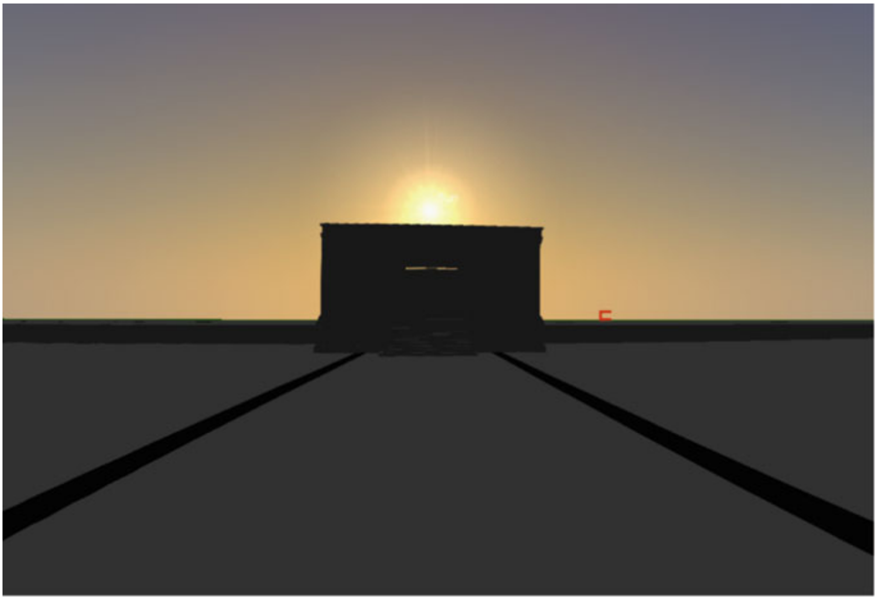

Fig. 12.11 A Stellarium simulation showing the Sun rising on axis behind the Ara Pacis Augustae as seen by someone standing on the axial line running from the Montecitorio Obelisk to the altar at 4:48 am on 22 May 9 BC. Such alignments were found on a total of 111 days of the year

Frischer et al. (2017) presents the evidence as well as a series of interpretations linking these solar effects to Augustus' dedication of the obelisk to the Sun god (*CIL* 6.702 = *ILS* 91).

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The 3D models and renderings of the Stonehenge landscape were created by LBI ArchPro's partner 7reasons.

In the weeks before the opening, we were supported also by Stellarium maintainer Alexander Wolf (Barnaul, Russia) who even created a new customized installer package with some critical corrections built overnight just in time to set up at the Museum 2 days before the opening.

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