Astronomical Simulation of UNESCO World Heritage Sites with Stellarium

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Abstract

An accurate desktop planetarium program can be of great importance for research and explanations in cultural astronomy. The author has developed virtual archaeoastronomy in the free and open-source desktop planetarium “Stellarium”. This paper summarizes 15 years of development and highlights applications where the sky and architecture over UNESCO world heritage had to be simulated.

Keywords: *Desktop planetarium, Stellarium, astronomical phenomenology, virtual archaeoastronomy*

1 Introduction

Astronomy is often seen as the oldest science, and it has certainly driven development of other sciences and mathematical methods. Archaeoastronomy deals with the oldest traces of humans’ engagement with celestial phenomena, much of which has been expressed in form of structural orientation of built monuments like tombs or temples (Ruggles, 2015).

Some of these monuments and also other landscape features or human cultural achievements have gained importance and acknowledgement from cultural heritage protectors, with UNESCO the most prominent example, for their respective unique values. Ruggles & Cotte (2010, 2017) have collected information about heritage sites of astronomical interest, either of archaeoastronomical value or of value in context of the development of modern astronomy.

As part of research and outreach activity, an accurate and visually appealing simulation engine for astronomical phenomenology is important. This author is part of the Stellarium development team and has improved it over the last 15 years to become a versatile desktop planetarium application for cultural astronomy research and outreach. This paper highlights a few of the developments and applications to UNESCO World Heritage sites.

2 Celestial simulation

Astronomy is a discipline where computation has a long tradition. A tedious but important work of earlier times was the computation and release of an annual almanac for astronomical observation, and especially astronomical navigation purposes. The introduction of mechanized and later electronic computers has greatly eased this task, and the wide availability of programmable pocket calculators and later desktop computers has made the creation of astronomy programs possible (e.g., Zotti, 1996).

For public explanations of planetary phenomena, a century ago the optomechanical planetarium was developed. A dedicated auditorium room with hemispherical dome projection surface and a specialized projector in its center which projects thousands of stars visible to the unaided eye, the Milky Way, Sun, Moon and the major planets. While these have meanwhile seen numerous upgrades to become full-dome electronic cinemas, computer programs have been developed which allow the same explanatory demonstrations on the average desktop computer system (Zotti, 2015).

In summer of 2000, Fabien Chèreau started developing such a desktop planetarium: Stellarium. He decided to create it as free and open-source community project with a handful of co-developers distributed

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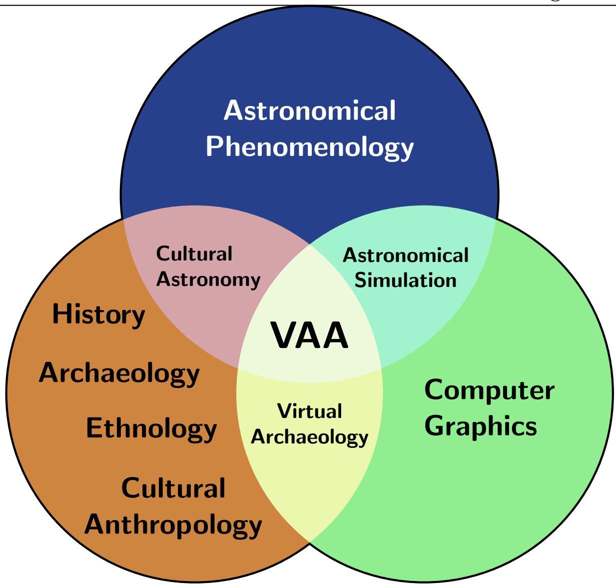

Figure 1: The multidisciplinary nature of Virtual Archaeoastronomy (VAA)

around the globe. Its numerous features which span from driving GOTO telescopes to showing constellation patterns of various cultures gained much attraction among amateurs and astronomy popularizers.

For a research project around potential astronomical orientation in Neolithical circular ditch systems ((Pásztor et al., 2015, Zotti & Neubauer, 2015), ASTROSIM 2008-12) this author needed a good visualisation system. Unfortunately Stellarium at that time was not accurate for historical research, but its open-source nature allowed inspection, corrections, and ultimately the addition of many features which have made Stellarium an almost perfect system for research and dissemination of historical sky views (Zotti & Wolf, 2022, Zotti et al., 2021).

During these years, the present author was involved in several archaeological and archaeoastronomical research projects, some of which also involved sites on the UNESCO world heritage list.

2.1 Scenery3D: Virtual Archaeoastronomy in Stellarium

During ASTROSIM, Zotti & Neubauer (2012) and Zotti (2016) introduced the first round of relevant changes towards virtual archaeoastronomy in Stellarium. This combines three very different research fields: archaeology, astronomical phenomenology and computer graphics (Fig. 1). An important part of virtual archaeology is the creation of virtual 3D models to test hypotheses on the appearance of long-lost buildings. The investigation of potential astronomical components like main axes, view corridors or light-and-shadow phenomena requires adding accurate astronomical models, which are, apart from solar position, generally absent from architectural visualisation systems.

2.2 Why simulate?

It might seem desirable to study the astronomy or sky views from a site of archaeological or historical significance on the actual site. However, this might not provide the relevant observations due to several reasons.

1. Many sites are fragile and should not be visited too frequently to perform the observations necessary to ascertain the postulated importance of astronomical observations.

2. The sky has changed over time. Precession changed rising/setting points (azimuths) of stars, and changes in the obliquity of Earth's axis changed those points for Sun and Moon.

3. Moreover, in urban or near-urban environments, the horizon line may have been changed by modern buildings, and especially the overall impression of the sky has largely been altered by adverse effects of excessive artificial light at night, i.e., light pollution, removing almost all stars and especially the Milky Way from urban skies. A new danger is already threatening even scientific ground-based professional astronomy in the form of uncontrolled growth of "satellite constellations" which also for visual observers have destroyed the solemnity of a natural starry sky.

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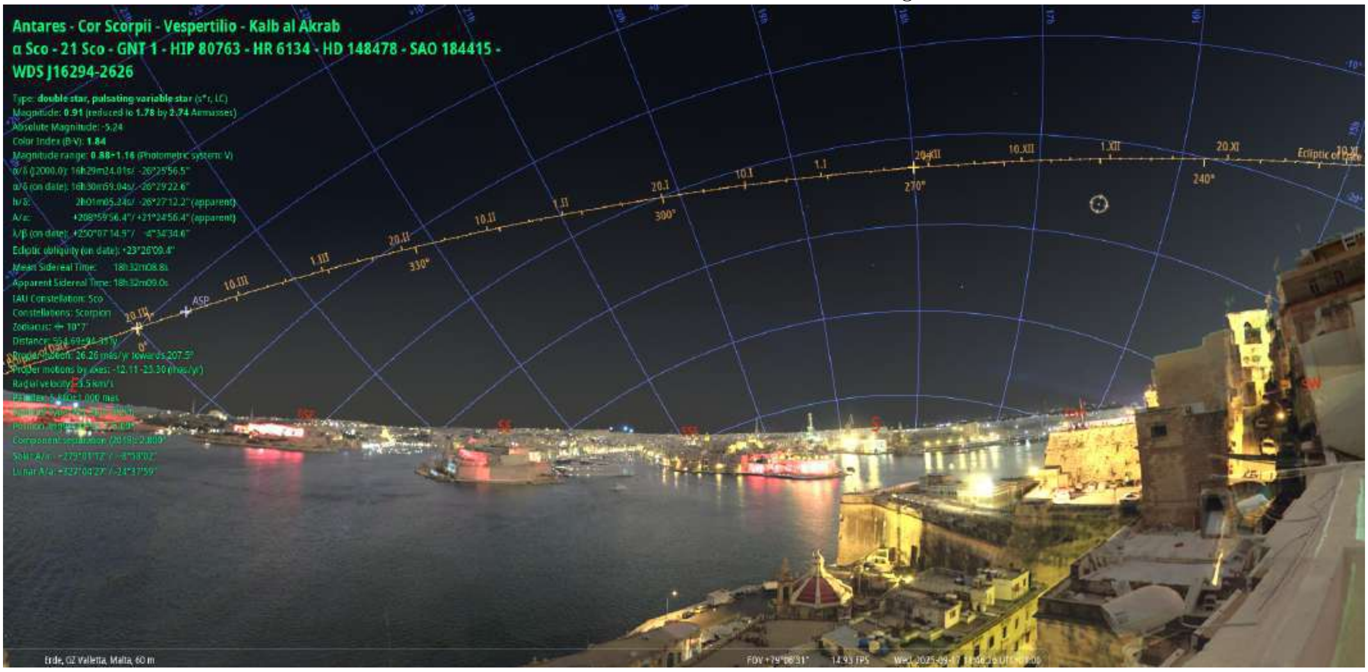

Figure 2: Nocturnal sky over the UNESCO world heritage site of Valletta, Malta. Light pollution diminishes stellar visibility. A dedicated night light layer in Stellarium simulates detailed artificial light at night.

In addition, some celestial cycles, e.g., the Meton Cycle or similar nodal cycle of the Moon, or the orbital motion of Saturn, require decades of observational activity. This can be tremendously sped up by simulation using current high-quality ephemeris models.

3 Stellarium and Astronomical World Heritage

Desktop planetarium programs nowadays allow the inclusion of a panorama photograph or artificial panorama which, when correctly created, allows to accurately discern features along the horizon like mountains or conspicuous rock formations which may relate to important horizon events like solstitial sunrises, sunsets, minor or major standstill moonrises/moonsets (the extreme points in the Lunar orbit repeating in a 18.6 year pattern) or stellar events in the period the observation would have taken place. Obviously, in urban areas, modern buildings would have to be removed from the image, or an artificial panorama can be rendered which depends only on a digital terrain model without buildings. Some websites[1] even allow downloading of landscape files particularly for Stellarium. However, those are usually created from SRTM data and cannot model small details in the nearby environment.

3.1 Light pollution

The sky over many historical sites close to current human settlements has been greatly changed by artificial outdoor lighting. Stellarium can be used to illustrate the effect by globally reducing stellar visibility. Zotti & Wuchterl (2016) introduced the addition of a night light layer to Stellarium's horizon panoramas, with UNESCO heritage site Valletta, Malta, as example (Fig. 2).

3.2 Analyzing astronomical orientation of human-made structures

Frischer et al. (2016) investigated the orientation of a temple in the Villa of Roman emperor Hadrian, the UNESCO WH site Tivoli. An architectural model of a building tentatively named the Antinoeion of which only traces remain today, embedded in a digital terrain model that includes the nearby mountains to the east, was configured as Stellarium 3D scenery. We could identify corroborating evidence for setting this temple into an egyptianizing context that involves the Sun: the entrance axis of the building is in line with

[1]HeyWhatsThat: https://heywhatsthat.com, Peakfinder: https://www.peakfinder.com, Skyliner: https://archaeoastronomyireland.github.io/skyliner. The author has developed a Google Earth-based workflow at https://homepage.univie.ac.at/georg.zotti/php/panoCam.php

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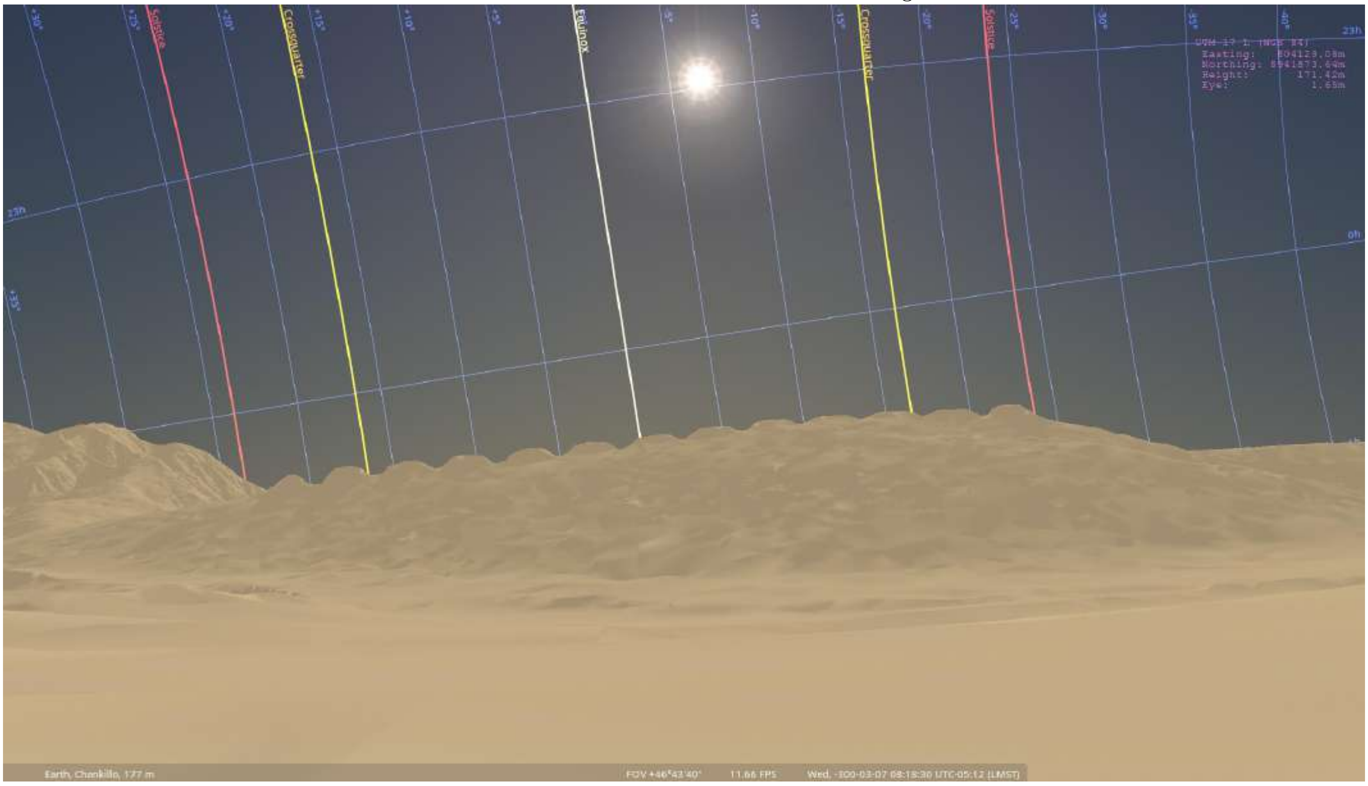

Figure 3: The 13 towers of Chankillo, Peru, cover the range of sunrises when observed from the end of a corridor in a temple. The lines indicate diurnal tracks of the sun at the solstices (red), equator (white) and intermediate dates called "cross-quarter days".

the point of sunrise on summer solstice behind the mountains, so that the statue in the central niche would have been illuminated by the first rays of the rising sun in the days around solstice.

Another very fine example was a 3D model gained from a laser scan of the prehistoric temple of Mnajdra, Malta, courtesy of Heritage Malta. During the SEAC 2014 conference, attendants visited this temple to experience equinoctial sunrise, where the first rays of the sun as it climbed over the nearby terrain ridge falls inside along the entrance axis. Putting the 3D temple model on a piece of Lidar-based digital terrain model, the geometrical light and shadow effects recorded in photographs taken on that date could be accurately replayed, finally indicating that Scenery3D held its promises (Zotti et al., 2021, Figs. 4&5).

Lidar based landscape models have been a game changer for archaeology since the 2000s. The ability to digitally remove vegetation has allowed the discovery of structures hidden in forested areas for centuries, or to create highly detailed 3D models of extended terrain. The principal workflow for model creation for Stellarium was described by Zotti (2019).

A large structure of archaeoastronomical relevance is the UNESCO Astronomical World Heritage site of Chankillo near the coast of northern Peru (Ghezzi & Ruggles, 2015). 13 towers, dated to the 3rd century BC, have been erected along the crest of a ridge. Observed from the end of a corridor in a temple to the west, the sun always rises along the horizon area covered by the towers (Fig. 3).

The extent of this model is huge, however. The Lidar-based terrain is surrounded by SRTM-based terrain of the Andes where the mountains can still be seen tens of kilometres away. And here a limitation of most 3D landscape modelling must be conceded: buildings are placed onto 2D coordinates in the Cartesian UTM (or other) survey grid. Earth curvature is happily ignored, and faraway mountains in the 3D model appear definitely too high when attempting to accurately recreate observations along the horizon. In such cases, use of a classical panorama is recommended, either from photographs (which may however miss mountains on hazy days; see Fig. 6) or from dedicated programs like Horizon (Smith, 2020) – or see section 4.1 for another approach.

Stonehenge is likely the most iconic example of a prehistoric built structure connected to astronomy, and it is on the list of UNESCO world heritage. The latest discoveries from an ongoing project (Gaffney et al., 2018) were presented in an exhibition in Austria, which included full-size replica of the stone circle's central Sarsen "horseshoe" combined with a 25 × 4 m screen on which Stellarium was used as "Skyscape Planetarium" to present a narrated automated show lasting over 20 minutes (Zotti et al., 2017). On special

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Figure 4: Stellarium used on a big screen in an exhibition about Stonehenge. While in daily use a scripted 20-minute story about the Stonehenge landscape was told, during special “flashlight tours” for children, a manual operation mode allowed using it for nocturnal ambience and the iconic summer solstice sunrise.

occasions the museum provided “flashlight tours” for school children who were guided through the dark museum where the starry sky was shining through the stones, and where they found a sleeping “man from the past”, an actor who first acted grumpy, but later helped explaining exhibit pieces in his own (unknown) language enhanced with pantomime. The tour ended after twilight was setting in (initiated by the author with Stellarium’s then-new RemoteControl plugin on a small tablet) and the group welcomed the iconic summer solstice sunrise within the horseshoe with a little music and dance guided by the “man from the past” (Fig. 4).

Another problem was also solved for a landscape like Stonehenge for which a temporal sequence or “phases” have been identified. When exploring a 3D model in Stellarium, loading a large model representing a different phase disrupts the immersive experience. Zotti et al. (2018) introduced “phased models” which include several versions of the model, and Stellarium’s own time control governs the appearance of the appropriate components, to avoid showing, e.g., the early Neolithic timber circle phase under a much later Bronze-age sky.

Archaeological reconstructions can be found as 3D models in some online repositories, which can be configured to be shown in Stellarium following instructions in Stellarium’s User Guide. A major problem with most of them is a lack of proven georeferencing (ground coordinates) in many such models, so care is advised before trusting any unverified download and drawing wrong conclusions.

4 Advanced Virtual Archaeoastronomy

The 3D sceneries in Stellarium were developed with geometrical analysis of architectural monuments and nearby landscape features in mind. They do not attempt to provide photorealistic simulation of landscapes with vegetation, wind, moving (terrestrial) objects, flowing water or animals enriching the scene. For such tasks, modern game engines provide building blocks for the development of “game realistic” environments. The most popular game engines include Unity and the Unreal Engine. *Serious Gaming* utilizes computer gaming technology for non-recreational purposes. Users typically explore their environment in the first person perspective. In an outdoor landscape environment, the sky often plays a background role only, and in the simplest scenarios is formed by six tiles of a cube, forming a static *skybox*, which are quickly rendered ahead of, and later partially overpainted by the actual scene. More advanced environment modules may provide atmospheric effects like moving clouds or even rain, or a “Sun” light source that can be arbitrarily

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Figure 5: The Virtual Park demo application which shows the combination of Stellarium and the Unity game engine (Zotti, 2021). The user can operate virtual reconstructions of Ghazan Khan's 14th century instruments re-used from Mozaffari & Zotti (2012). In the background a virtual reconstruction of Ulugh Beg's Samarqand observatory (15th century) which users can also explore (Zotti & Muzaffari, 2020). Ambient effects like seasonal vegetation or bird sounds enhance the simulation atmosphere. The sky background is provided by Stellarium.

positioned in the sky as the developer finds useful. "Night sky" modules are commercially available, but even if some are based on real star positions, they often lack sufficient astronomical accuracy (or just don't provide relevant information in the accompanying documentation).

Zotti (2014) and, more exhaustive, Zotti & Neubauer (2019) presented results of their research on Neolithic circular ditch systems in a Unity-based environment with a self-made sky module which included the Sun and the about 9000 stars from the Yale Bright Star Catalog, and which was sufficient to illustrate the final results which were astronomically much less spectacular than originally anticipated (Zotti & Neubauer, 2015, 2023). Unfortunately Unity's proprietary web player browser plugin which allowed guided user visits was removed soon after the project was finished, limiting further project outreach to a few screenhots or pre-recorded animations. This also shows the importance of using open systems for long-time use in the rapidly developing computer game industry.

In the context of astronomical simulation, this author has further experimented with Unity and co-developed a module which combines it with Stellarium in multiple technical modes of operation (Zotti et al., 2020). The simplest mode 1 only creates predefined skyboxes and provides data for the three shadow casting natural luminaries, Sun, Moon and the planet Venus. These can then be mixed appropriately to provide scene illumination similar to what is available in Stellarium/Scenery3D, while the simulation designer may include whatever interaction with scene objects or ambience elements (seasonally changing vegetation, birds singing in the trees, . . .) is required. This mode is also appropriate for providing Unity-based simulations on websites[2].

The other modes require running an instance of Stellarium on the same Windows PC as the Unity-based simulation application. Mode 2 connects the simulation via Stellarium's RemoteControl plugin and sends commands that influence settings in Stellarium, and then triggers the generation of six new skybox

[2]The author has made the Instrument Park available at https://homepages.univie.ac.at/Georg.Zotti/

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tiles which get loaded to update the current skybox, and a text file with data on Sun, Moon, and Venus. Other settings can still be changed with a quick task switch to Stellarium. The advantage of this mode is the availability of all graphical features and improved capabilities that Stellarium provides at the time of simulation, so that future updates in Stellarium not necessarily require updates in the simulation program (as long as the communication protocol is not changed). A disadvantage of all skybox-based methods however is the limited angular resolution of the skybox tiles which are usually created with 2048^2 or at best 8192^2 pixels resolution. Zooming into the terrain, e.g. to observe a sunrise or sunset, will show this limitation. For the Sun, an actual 3D sphere has been placed into the simulation which enhances observability.

The most immediate mode 3 uses a camera-mounted virtual canvas in the scene on which the output of Stellarium is first displayed before overpainting it with simulation output. The view direction is transferred to Stellarium, which renders a new output to be displayed on the virtual canvas. When the camera (viewer, virtual character) in the Unity based simulation is not moving in the scene, this provides an almost "live view" into Stellarium, and zooming in will also enlarge details in the Stellarium-generated canvas content, which enables the user to observe celestial motions in connection with the simulation scene. Moving around in the scene will however cause a notable frame delay of the sky background. On a PC screen this may be acceptable for research in virtual archaeology, however, this frame delay will make application in setups with VR headsets very problematic.

Zotti (2021) presents this in a demo application, the "Virtual Instrument Park", where visitors can experience the Vienna "Sterngarten" (a modern public observing installation designed to learn about horizon astronomy; the model was originally created by the author for and is available as demo scenery in Stellarium), several virtual reconstructions of observational instruments which had been used in Maragha in the early 14th century re-used from earlier work (Mozaffari & Zotti, 2012, Zotti & Mozaffari, 2010), and devices related to and including Ulugh Beg's 15th century observatory in Samarqand (UNESCO World Heritage) reused from Zotti & Muzaffari (2020).

The user can walk around in a "game-realistic" virtual landscape, observe the sky being reflected in a wavy moving water surface, and can take actual observations with the old instruments, guided by on-screen instructions (Fig. 5). Some instruments have constructive elements linked to their geographical latitude, so when approaching them, the user is secretly transported to Rayy (Iran) or Samarqand (Usbekistan) as necessary. To decorate the game-like environment, the ground is covered in grass which can change according to the season (solar longitude) to show frost, fresh green or dried summer grass, the visual perimeter is decorated with trees, and bird voices have been planted into the trees. Also the user creates a stomping sound while walking.

4.1 Mitigating the Earth Curvature problem

The scene setup in Scenery3D and most Unity-based applications consists of buildings and landscape features on an otherwise flat surface in Cartesian coordinates. The user can at best read UTM grid coordinates of the current view position. However, any two-dimensional map suffers from its principal simplification of flattening out a piece of Earth's near-spherical surface. For large scenes and far-away horizons, it would be desirable to take earth curvature into account. NAOJ (2022) have developed a system which first utilizes a QGIS plugin to preprocess 300×300 km of a digital terrain model in curved shape which is then used as game terrain in Unity. When moving in the central part of the game terrain the mountains on the outer area therefore appear properly shifted downward by earth curvature (Fig. 6 left). Unfortunately the reprojecting makes accurate placement of otherwise properly georecerenced scene objects difficult because their UTM coordinates do no longer fit. The simulation connects to Stellarium with a method derived from the one by Zotti et al. (2020). A complete solution might have to involve geocentric Cartesian coordinates and dynamic computation of the local vertical, and developing a complete workflow around these tasks.

4.2 Point Clouds

The natural file format after a laser survey are point clouds, and the creation of meshes is often a challenge. If mesh generation is not part of the processing and no more than a quick check regarding astronomical orientation is possible within some project, you can utilize an extension of the free web based point renderer Potree (Schütz et al., 2020). This program can render large georeferenced point clouds in a web browser window. Again, a skybox can be utilized to enclose the scene with a static background that may include sky and enclosing panorama. If a sky view from a small part of the model is enough, you

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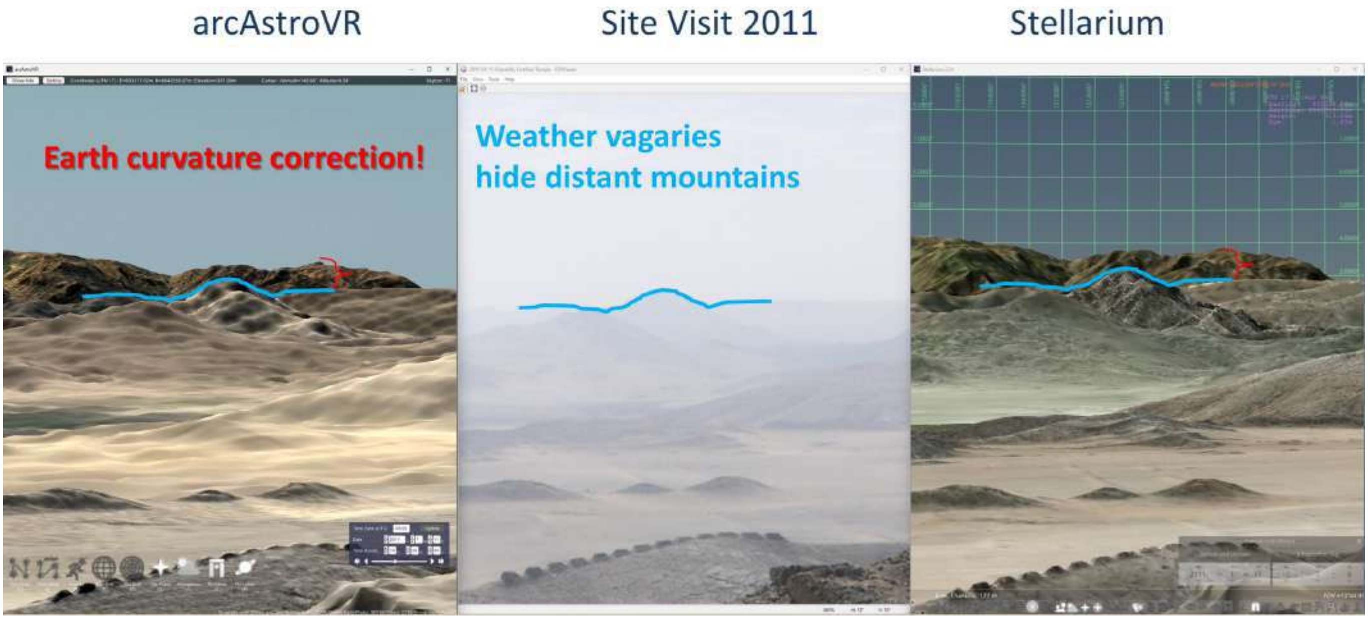

Figure 6: Chankillo, Peru. View over the fortified temple (lower right) and the ridge with 13 towers towards the east. Comparing photo from a site visit (center) with views in Stellarium/Scenery3D (right) and arcAstroVR (left), which itself uses a Skybox from Stellarium. Both simulations show mountains which are no longer visible in the photograph due to atmospheric haze. While the model in Stellarium cannot cope with earth curvature, the terrain in arcAstroVR is processed into a curved shape. The red indicators are of the same size and show the difference in horizon elevation of a few tenths of a degree. It depends on the use case whether this matters, but users ahould be aware of the principal issue.

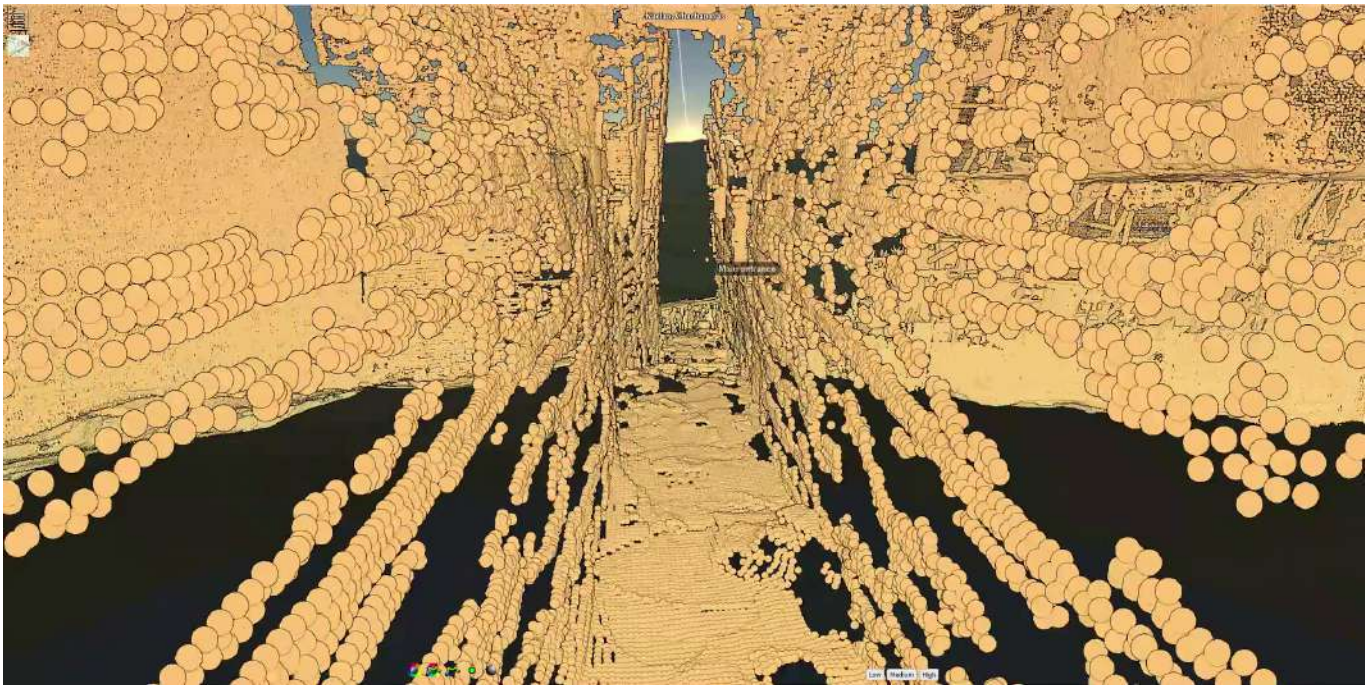

Figure 7: Visualisation of a Laser scan of Kuelap, Peru, in Potree with a skybox created in Stellarium (Zotti et al., subm). The narrow main (southerly eastern) entrance corridor points towards the sunrise azimuth on the day of zenith passage, which also announces the rainy season. Through the entrance you can see the diurnal path of the sun on this day rising above the mountain in the skybox view created in Stellarium. According to 17th century literature, stars and sky observations were important to the Chachapoya, although most details have been lost.

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can create a static panorama with Horizon (Smith, 2020) for this viewpoint and use this in Stellarium to create relevant skyboxes with a built-in script. The author's fork of the official repository[3] allows re-loading skyboxes on the fly, and enables Potree users to analyze their data for possible connections to astronomical observations.

Zotti et al. (subm) describe this application for investigations around the Chachapoya fortified settlement of Kuelap, now another UNESCO world heritage site in Peru (Fig. 7). A tower-like building with an opening in the roof had previously been interpreted as zenith observatory. Our new finding of entrance orientation towards sunrise on the day of zenith passage further corroborates interest of the Chachapoya in celestial observation.

5 Discussion

Virtual archaeology has numerous applications in archaeology and historical research for analyzing, understanding and explaining human-made buildings and their natural environment. While architects are often interested in interaction with sunlight and many architectural simulation systems can simulate the sun, the other celestial objects are often neglected and require dedicated software. Most workflows and software presented in this paper are free and open-source and run on most desktop computers, and thus are accessible to all. While technology has been greatly improved in the past 20 years, it requires interdisciplinary interest to bring these systems to good use.

Both astronomy and archaeology often raise public interest and can attract many visitors to exhibitions or public events. Archaeoastronomy is a topic of considerable interest. The astronomy is accessible to typical amateur astronomers and, if well explained, to most exhibition visitors or attendants of public presentations who are interested in the value astronomical phenomena had in the lives of earlier human cultures. However, claims about the astronomy of prehistoric cultures and dating of archaeological structures so that they appear relevant in astronomical context should be reverified in accordance with archaeological dating methods.

While technology for virtual archaeoastronomy is now available, archaeological data are rarely released to the public in a format complete enough for integration to Stellarium or for other use by the interested public. It has been observed that some official authorities' archives store files in proprietary vendor formats which become obsolete within a few years. Those are advised to use well-documented open formats, else digital data which has been collected to help preserving and protecting ancient structures are useless well before significant changes can be seen around the recorded sites.

To allow others experience at least some aspects of the interesting landscape around Chankillo without travelling, Ghezzi and Ruggles agreed to let this author release the 3D scenery created for them as seen in Figure 3 to the public. It can be downloaded from the 3D sceneries repository on the Stellarium website[4], and it is to be hoped that more datasets usable for explaining sites of archaeoastronomical interest can be collected in the future (e.g., Zotti et al., 2024).

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[3] https://github.com/gzotti/potree/tree/gz_skyboxExtension

[4] https://stellarium.org/en/scenery3d-collection.html

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