OPEN-SOURCE VIRTUAL ARCHAEOASTRONOMY

Georg Zotti

Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology

ABSTRACT

A large fraction of archaeoastronomical surveys is concerned with the evaluation of azimuth orientations of artificial, or sometimes natural, structures to find a correlation with potential astronomical targets, like sunrise/sunset, or the interplay of light and shadow at particular dates like the solstices. Given the difficulties of observing such a structure during months or even years, it seems very desirable to record or reconstruct the structure in question and bring a virtual 3D model into a computer system capable of accurately rendering the sky, the model, and light and shadow effects depending on proper astronomical simulation, also including the situation at other times.

Applications for such a system can be manifold. Horizon panoramas in various desktop planetarium programs have already previously allowed assessment of single-viewpoint observations with proper horizon altitudes. But the ability to load a properly georeferenced and accurate 3D model into virtual space and identify and observe sight lines combined with a recreation of past skies, or to observe light and shadow effects that would change over weeks and months within just minutes of simulation, should allow much better understanding of the potential use of such structures, and can clearly illustrate and demonstrate these phenomena also for a wider audience. Likewise, an archaeologically sound virtual reconstruction beyond today's often deteriorated state can be used to recreate the likely appearance of the site in past times.

A few such installations can be seen in museums, but none of them are widely available. The author has initiated development of a plugin for the popular open-source desktop planetarium Stellarium to allow research on 3D virtual reconstructions which has recently been greatly refurbished and integrated into the regular distribution of Stellarium. The paper also describes other contributions made by the author towards application of Stellarium for research and communication of cultural astronomy.

1. INTRODUCTION

A considerable part of archaeoastronomy research and literature deals with the orientation of built monuments, their enclosing landscape, and celestial objects on the sky of times often long ago (Ruggles, 2015). Astronomical computations appear difficult to adherents of the related disciplines (esp. Archaeology), so they welcome tools which alleviate computations and provide immediate feedback about how some site may have looked ages ago. *Virtual Archaeology* has been introduced as valuable tool to provide computer-aided recording, visualisation and analysis of archaeological finds. One important part in this field is *Virtual Reconstruction*, the creation of plausible virtual architectural models of structures of which usually at best ruins have survived. In recent years, no longer only single buildings are being visualized, but the architectural models are presented embedded in a reconstruction of their surrounding landscapes. The popular *game engines* often used for such projects allow virtual walkthroughs, interaction with game objects, artificial characters, or avatars of other players connected over a network, interesting light-and-shadow effects or 3D sound, but there is usually no particular interest in creating an accurate model of the sky and accurate placement and motion of celestial objects in it. It is however at least possible with moderate effort to place an accurately positioned sun into the sky either by implementing the relevant positioning code (Zotti 2014; this also includes a properly rotating sphere of stars) or by using external resources like NASA's Horizons service (Frischer and Fillwalk 2012). However, the addition of an astronomically accurate high-quality night sky simulation including planets and other computationally expensive objects to such a game engine has not been presented yet.

For astronomically correct sky simulation, the class of programs which can be described as *desktop planetarium* provides information about the placements and diurnal movements of the celestial bodies. While several programs have been developed in the past few years which cater mostly the observational needs of contemporary amateur astronomers, it is often not easy to find information about the limitations in and applicability of algorithms which are used in such programs also for research in prehistoric times. Also, they can only simulate the sky for one particular (configurable) viewpoint on earth, and only a few of them can present realistic simulation of the daylight sky, twilight, or decorate the horizon with a panorama photograph which can, if accurately adjusted to the natural environment, act as a proxy for the real horizon in orientation studies. When researching architectural sight lines along building axes (or similarly, rows of upright stones,

etc.), each viewpoint requires the creation of such a panorama either from photographs taken on site or from renderings of 3D models, which may become cumbersome for more than just a few known points, or if a structure should be investigated only in virtual space. This requirement motivated search of a desktop planetarium which either can load a 3D landscape, or can be enhanced to do so.

2. OPEN-SOURCE SOFTWARE: STELLARIUM

Software development requires programming skills and familiarity with the field the application will be aimed at. Apart from commercial software, the development of the Internet and World-wide web allowed collaborative efforts of developers working on a community project even if they are located on different continents. Most of such community projects distribute their programs free of charge and under the Free Software Foundation's GNU Public License, which requires that the source code for a program must be made available, and derived work must again be published under the same license (to prevent commercial closed-source spin-offs). This openness allows and invites modifications and additions by the members of respective peer groups and also allows public code reviews and verification.

One of these community projects is the open-source desktop planetarium Stellarium. It was started by Fabien Chéreau in 2000 and by 2006 had developed into a community project hosted at one of the open source community repositories, SourceForge.net. In a way this repository can be interesting for "software archaeology": most of the older versions are still available for download on the project website. By 2006 it already had reached high visual quality with physically based sky brightness and colour models which are still in use today, and came with original high quality artwork for the constellations which have become quite popular in the last years. It was even possible to exchange the usual constellations by those of other "sky cultures", which made this program very promising for application in cultural astronomy. The project was featured as "Sourceforge Project of the Month" in May 2006. The handful of developers continued to expand the functionalities and features, and by 2009 it was possible to add some extra functionality with the plug-in concept. Plugins meanwhile come for such diverse extras like additional object catalogues, satellite visibility, or "goto" telescope control. It was also in widespread outreach use during IYA2009 (e.g., Berglund and Spearman 2010), and a plugin was developed to access ESO's archives (Chéreau 2012). In effect, the team had created an excellent project infrastructure, and the availability as open-

source project invited extension by others. The only difficulty for newcomers was an admitted lack of complete source code documentation, which necessitates long explorations into the code to understand how parts fit together.

In 2009 I had started in the ASTROSIM project (2008-12), analysing potential astronomical orientation of Neolithic Circular Enclosures (*Kreisgrabenanlagen*, KGA) in Lower Austria. While a commercial product also provided a way to configure photorealistic horizons and Stellarium at that time was explicitly not recommended for historical work due to some astronomical simplifications traded in for efficiency and beautiful graphics, the long-time vision of a combination of a high-quality sky simulation where the code can be read, verified and possibly improved and the possibility to develop a 3D foreground renderer seemed very attractive.

A minimal system useful for archaeoastronomical orientation studies can be described as a simulation that combines astronomically correct views of the sky for the time in question with an accurately adjusted panorama photograph or rendering of the site in question. Stellarium at that time already used planetary positions from the VSOP87 which is recommended for use in the years-4000…+8000, but the precession model implemented was only very approximate, and ecliptic obliquity was assumed constant. Also, the effect of the slowing down of Earth's rotation known as ΔT was not included at that time, but this mostly affected eclipse simulation. Stellarium's sky brightness simulation had been implemented already following physical models (Schaefer 1998), and the daylight colours follow a widespread standard model from computer graphics (Preetham et al. 1999). However, other important aspects of astronomical phenomenology include atmospheric refraction and extinction, which were not included at that time.

3. FIRST AMENDMENTS FOR ORIENTATION STUDIES

It turned out that a small correction was required to really bring a correctly created panorama "landscape" into the correct position. The bugfix was welcome. This accurate simulation of being embedded in the landscape is one key value for simulations of the historical skyscape (see e.g. the discussion by Brown 2015).

Another early change was implementation of refraction and extinction. Both were done in collaboration with Fabien who was able to patch the rotation matrices wherever refraction is needed, which was essential for an efficient solution of this feature (V0.11). While extinction for point sources came quite soon, extinction for the largest element, the Milky Way, came only much later.

Later, the problem of ΔT was solved mostly by Alexander Wolf and Victor Reijs in a way that now even allows selecting from a multitude of models (V0.12).

4. THE SCENERY 3D PLUGIN

The first idea for a 3D plugin came during ASTROSIM in late 2009. This should allow loading of a 3D model under Stellarium's sky and walking around to find possible astronomical orientation of the KGA. The estimated amount of work was enough to have it implemented as student project with the Institute of Computer Graphics and Algorithms at the Technical University of Vienna. At that time, Stellarium already used the Qt4 GUI framework and OpenGL 2 graphics, but adding more complex graphics required a high-end computer and additional software libraries, so the plugin saw first light in late 2010 in a special branch of the project only and was not easily portable to other platforms (Zotti and Neubauer 2012). A second student project introduced better shadow options. Unfortunately, shortly before integration into the main line of Stellarium could have been attempted in late 2012, an important part of Stellarium was changed, which impeded this integration into the V0.12 line.

5. TESTS AND FIRST APPLICATIONS

To test various features of Stellarium and the anticipated plugin, I developed a virtual model of the Vienna *Sterngarten* ("star garden"). This public sky observing installation consists of a stepped pyramid platform which provides an artificial horizon, solstice poles, north and south pillars with altitude marks, a meridian line with date marks where the shadow end of the north pillar indicates calendar dates, and many other observable elements of fundamental astronomy (Mucke 2002). This model has also been accepted for the (meanwhile "legacy") 3D building layer of Google Earth. The *Sterngarten* was an optimal model because it includes many phenomenologically valuable elements which all can be used to test Stellarium's geometrical accuracy (Figure 1).
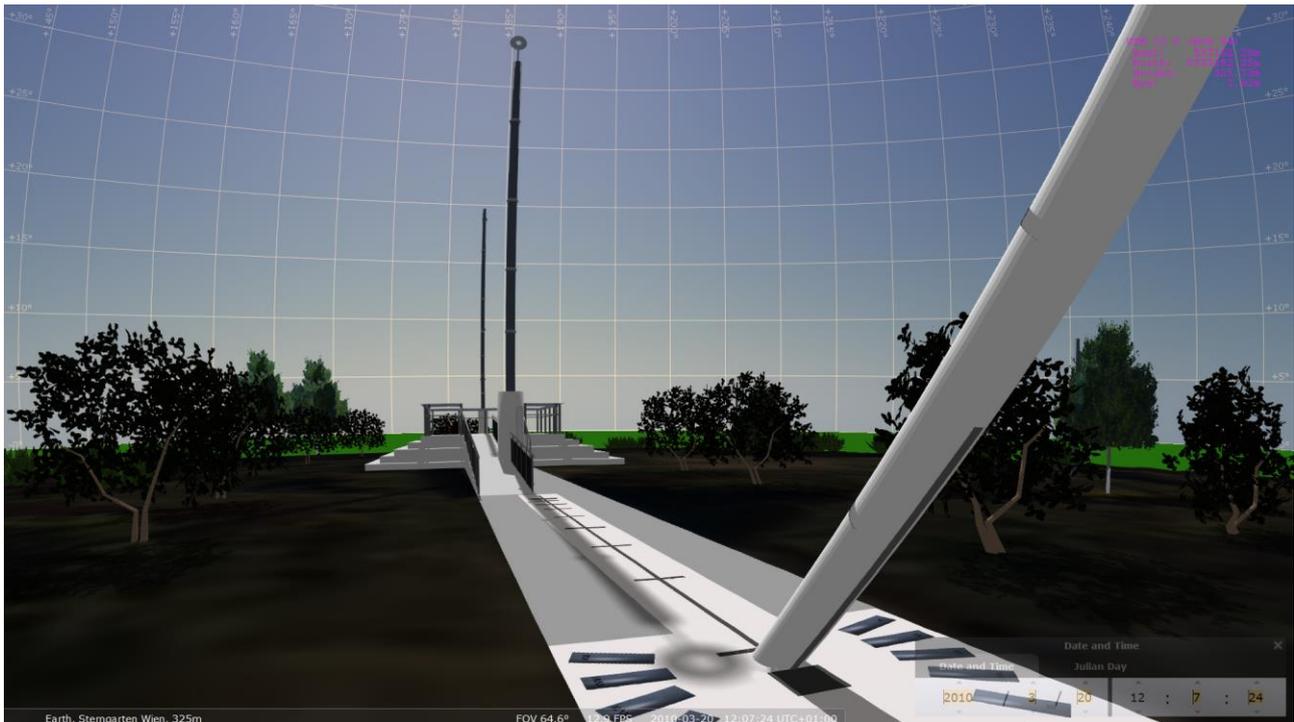
Figure 1. The Sterngarten model was used to test accuracy of Stellarium's Scenery3D plugin and other important phenomenological effects. The meridian passage of the North Pillar's Shadow (actually the bright spot caused by the hole in the disk on top) indicates calendar date on the meridian line. In this scene, the shadow has passed the foot of the inclined pillar, indicating equinox. Observed from the platform, the disk indicates the north celestial pole. Six outlying pillars indicate sunrise and sunset at equinoxes and solstices, with indications which show the effect of refraction. All these elements can be simulated in Stellarium.
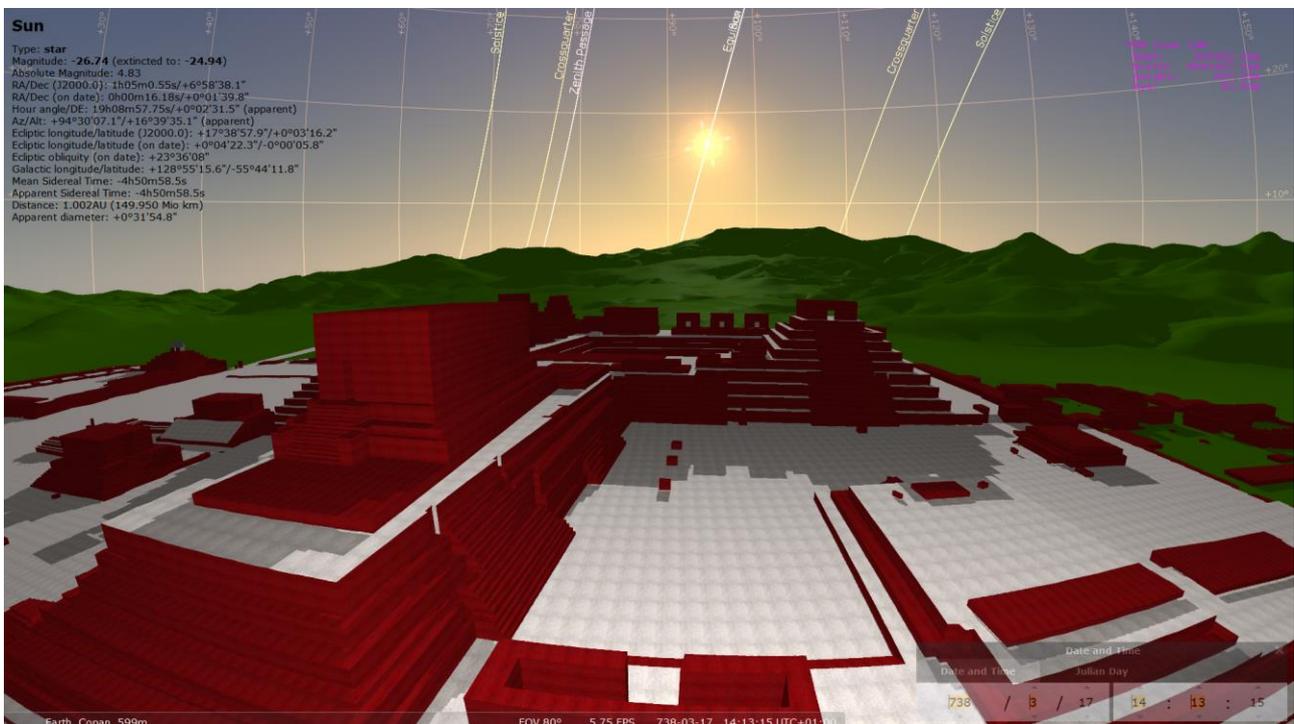
Figure 2. A 3D model of the Maya city of Copan, fl. ca. 738, visualized with the Scenery3D plugin for Stellarium. Courtesy the MayaArch3D project.

Figure 3. A corridor in Temple 11 in Copan is oriented exactly to equinox sunrise over the mountains.

Its first application in an archaeoastronomical context was obviously during the ASTROSIM project on Neolithic Circular Ditch Systems. Here, despite earlier assumptions, modelling the prehistoric monuments in the 3D terrain mostly dispelled assumptions about astronomical orientation of entrances (Zotti and Neubauer, 2015).

Other research groups also showed interest. I was asked to test a virtual model of the Maya metropolis of Copan built by the MayaArch3D project (Schwerin et al., 2011). Focus of this project was on new ways of using computer-based explanations for online visitors. The model (Figure 2) had originally not been specifically made for astronomical investigations, but it was based on the best available survey data collected in a GIS, which should guarantee proper georeferencing information. I found that a corridor running along the long axis of the virtual reconstruction, and with it of course the long axis of the massive Temple 11, seems to be accurately oriented towards equinoctial sunrise behind the mountains (Figure 3). Even if this relation may have been found earlier, the immediate visual effect of viewing and walking through the corridor and seeing the celestial equator line rising from the mountains on the other end is quite impressive. Replacing the coarse landscape data by LiDAR data should provide clarity whether the horizon really is correct.

Other models done mostly for testing new methods and applications included a cup-marked stone and a multi-faceted sundial, both modelled using Autodesk 1-2-3-catch, a cloud-based service which can deliver a 3D model created from matching common feature points in a collection of photographs. The returned model must be georeferenced by external means, e.g. by including features with available coordinates in the photographs.

A repository with a large number of georeferenced models is the Trimble/Google 3D warehouse. It is easy to take a model from there, add a piece of surrounding terrain in Sketchup, and export the model for Stellarium. However, the quality and exactness of the orientation of the models can hardly be assessed, and Trimble's license practically forbids a reuse of "Google Geolocated Models" in a geolocated context (Trimble, n.d.).

6. FURTHER DEVELOPMENT

The Stellarium project had a big technical issue to solve by adaptations to the Qt5 GUI framework. Fortunately members of the original developer group were still available to deal with most of the issues, so that starting with V0.13 (which appeared in July 2014) Stellarium requires more modern hardware to start with, but runs on more platforms than ever, including some tiny ARM-based single-board computers running Linux. In this version I have also introduced several landscape functionality improvements (see e.g. Zotti and Wuchterl, 2016). Now it is possible to accompany a photo panorama with a measured horizon line, and (using some scripting trickery) the actual landscape horizon can be used to programmatically set the sun or other celestial object on the visible landscape horizon.

Only these changes also allowed me to implement proper extinction for the Milky Way and other extended objects, and invited the addition of that feeble glow of the zodiacal light which can be impressive only in dark sites (modelled after Kwon et al. 2004, introduced with V0.13.2), and proper extinction and mix with twilight for comet tails. Also, the removal of some changes from 0.12 made it possible now to finally integrate the Scenery3D plugin which appeared with version 0.13.3 after additional improvements, with the *Sterngarten* model as example, and is included with the regular download of Stellarium.

The first application after release concerned research around a structure proposed as "Antinoeion" in the complex of Hadrian's Villa in Tivoli, Italy (Frischer et al., 2016). A 3D model with terrain data representing the mountains which define the landscape horizon towards the East was loaded into Stellarium, and we discovered that the main axis of the building is oriented very accurately towards summer solstice sunrise over the mountains (Figure 4).

The available simulation of the night sky allowed us to explore and propose other interesting observations mostly in context with Sirius and with the Antinous constellation introduced in memory of Hadrian's fellow, which, together with Egyptianizing statues which have been found in this area, all supports the association of this complex with Antinous.
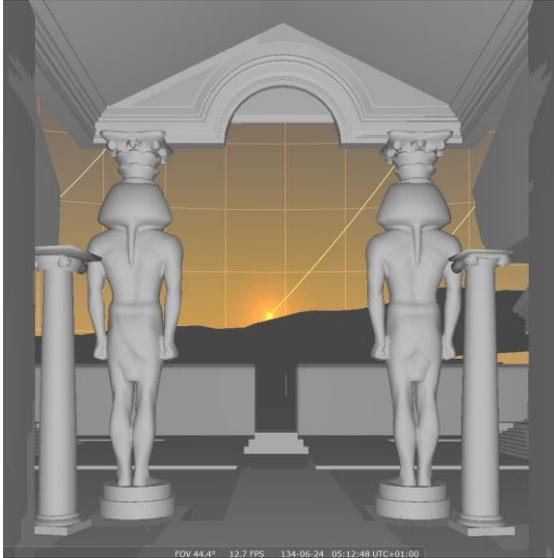

Figure 4. Virtual reconstruction of the "Antinoeion" in Hadrian' Villa, Tivoli. The main axis was discovered to be oriented to summer solstice sunrise with the Scenery3D plugin. Model by Matthew R. Brennan, courtesy B. Frischer.

7. OTHER RECENT CHANGES USEFUL FOR CULTURAL ASTRONOMY

In orientation studies we frequently come across a handful of "typical" astronomically defined directions. I have added a plugin "ArchaeoLines" for version 0.13.1. This is able to present diurnal lines of equinoxes, solstices, crossquarters, lunistices, planets, current sun and moon, zenith and nadir passages, and the currently selected object. Concepts often regarded as very difficult, like the swing of the Moon between minor and major standstills, can now be demonstrated almost directly by running a fast-paced simulation through time with a line showing the diurnal track of the moon swinging between the monthly extremes, and observing the slow changes of those growing and shrinking between the major and minor standstill marks.

While 3D visualisation of architecture is a feature currently unique to Stellarium when compared to other planetarium programs, Stellarium was originally developed with some unfortunate simplifications which – by the fact that it is open-source software– can however be repaired. Of course what we need most for historical sky simulation is more accurate long-time simulation. For version 0.14 I have implemented a long-time model for ecliptic obliquity and precession (Vondrák et al., 2011), which finally also fixed the long-standing problem with the solstice directions which were farther apart in antiquity due to a larger value of ecliptic obliquity.

ESA has funded a "Summer of Code in Space" student project in 2015 to make the NASA/JPL DE430 and DE431 ephemerides available to Stellarium. I have finished the task for version 0.15. DE431 provides planetary positions for the years -13000 to +17000, i.e., 30.000 years of data. The data files are almost 3GB and are not required for most users, so those who critically need these data have to download and install them separately. Even then of course, some questions like eclipse computation cannot be accurately answered when they depend on unknown changes in the Earth's rotation (ΔT).

8. CONCLUSION AND FUTURE WORK

Stellarium has still not reached "Version 1", and a few milestones towards reliable historical application of this software have still to be taken until I can wholeheartedly recommend it for all applications which it has already been used for. Capable software developers are invited to contribute with useful program code, but many researchers from other disciplines related to cultural astronomy can provide input: ethnoastronomers can collect and edit more celestial mythology, constellation "stick figures" and artwork for new and better "sky cultures"; astrophotographers can add better deep-sky images; and linguists can still improve the translations in an easy to use online translation system. The Stellarium team would welcome not only these "traditional" contributions, but would also be happy to host your correctly configured 3D models of the sites you have explored in order to better understand the motivation of members of past cultures to orientate their buildings in alignment with celestial phenomena.

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