Archaeoastronomical simulations in a desktop planetarium

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Abstract: Many prehistorical and historical cultures have created buildings which were often orientated with respect to naturally given directions. The astronomical orientation of architecture is well-established and likewise well-popularized. However, research requires on-site surveys and computation, and usually relevant directions are only published as simple arrows in ground plans. A plugin recently integrated in the Stellarium open-source desktop planetarium allows loading of 3D models and interactive investigation of orientations under a good sky simulation.

Keywords: Archaeoastronomy, virtual reconstructions, interactive exploration, Stellarium.

Introduction

It is well-known that many prehistorical and historical building structures (e.g. the Pyramids of Giza and several temples in Egypt, Stonehenge, Newgrange, India, or Mesoamerica) have been erected following astronomical orientation patterns. Some buildings have been erected following the cardinal directions with surprising accuracy, while in other cases definite links to the brightest of all celestial bodies can be seen by following directions where the sun could have been seen to rise or set on solstice days. For other locations, complex light and shadow interaction with sunlight on either natural rock-art sites or in built architecture has been discussed. Countless examples are available in the literature (e.g. RUGGLES 2015). However, in many publications the interested reader can only see a simple arrow in a ground plan, so that the larger context of this built structure in its surrounding landscape can hardly be fully understood.

Frequently, sites of interest are in remote locations, making the continuous observation of astronomical phenomena which may only occur at certain times of the year difficult. Furthermore, links to the starry sky of past centuries may no longer be experienced in their previous context: changes to the sky itself by the precessional drift of the stars may have invalidated previous stellar alignments, or, if the sites are close to today's civilization, the light pollution of nearby cities may have destroyed much of the visual experience of the pristine sky of past times.

3D reconstructions

A powerful way to identify and analyze, and also to demonstrate and disseminate astronomical orientation patterns in archaeological structures to a wider audience is the use of accurately georeferenced virtual reconstructions of past architecture in a virtual environment capable of accurate astronomical simulation (ZOTTI 2015). In principle there are two kinds of software which have been utilized for this task in the past. There are architectural simulations which include simple sun positioning models and real-time shadows or even physically-based light diffusion solutions to simulate the appearance of buildings during daytime hours in

the present era. However, many such systems are limited to post-1900 or even post-1970 dates (the “UNIX era”), which means that the slight difference in ecliptic obliquity centuries ago, which leads to a shift in solstitial rising or setting directions, is usually not covered, and the night sky usually is not properly represented at all. Accurately computed solar positions usually require expensive custom developments.
Usually it is not enough to visualize a single building for such studies: all orientations towards rising or setting positions of celestial objects necessarily involve the horizon formed by the surrounding landscape, which can either be surveyed from the relevant viewpoint of the site in question, or created from a digital elevation model. In the latter case, it is necessary to take as much of the landscape into account as can be seen from the site in question – the *viewshed* in terms of GIS.

Related Work

Early attempts at using such visualization in virtual reality, combining architecture and a triangulated surface as landscape, have been presented long ago also at this conference. At CAA03/CHNT8 Beex and Peterson discussed the visualization of solstice orientation of a Bronze-Age henge in Britain (BEEX and PETERSON 2004), and at CHNT9 Frischer presented research on the orientation of an Inca temple at Lake Titicaca (FRISCHER et al. 2004). Both cases used interpolation of solar positions found by external means.
A contemporary solution for presenting 3D models in their surrounding landscape in more vivid simulation environments has become possible by the development of game engines like Unity3D (UNITY n.d.), the Cry Engine (CRY ENGINE n.d.) or the Unreal Engine (UNREAL ENGINE n.d.). Those provide many basic building blocks for the creation of first-person experience inside a vivid virtual world, including, e.g., 3D sound, animated vegetation, smoke and steam simulation including light beams, other game characters (computer-driven or even avatars of other players), and the possibility to interact with them. Especially Unity3D has seen wide application towards visualization in archaeology and cultural heritage. Even the free version allows real-time shadows by a single light-source, which has been used to study light-and-shadow interaction in a building of Hadrian’s Villa near Rome (FRISCHER and FILLWALK 2012) with solar positions again gained from external resources. A larger landscape containing Neolithic circular ditch systems (*Kreisgrabenanlagen*) with one highly possible astronomical orientation has been presented by the author (ZOTTI 2014). But also in game engines, the sky is just a module usually without much preconfigured attention for astronomical details – whatever the developer wants to show has to be programmed, which can easily become too expensive or too complicated for non-astronomers, especially if the modelling is done only for research purposes.
On the other hand, visually convincing and astronomically accurate desktop planetarium programs so far could at best load a photographic (or artificially rendered) horizon panorama of a single viewpoint to be used as foreground in visual analysis of possibly important sightlines, so that analysis of structures of archaeoastronomical interest like temple axes can require lots of such panoramas to be prepared with other programs.

Astronomical Simulation with Stellarium

Desktop planetarium programs which can simulate the night sky with stars, constellations, deep-sky objects etc. as they can be seen from any place on earth and for any time (at least reasonably close to the present

time) have been popular since the 1980s. Development of Stellarium (STELLARIUM n.d.) has been started in the early 2000s. It was created by a small team of developers with much care for visual quality and by 2008 was stable enough for public use. It has become highly popular in the amateur astronomical community, suiting beginners and advanced observers who even can point their automated telescopes with it. Its free availability for the most relevant desktop operating systems (Windows, Mac OS X, and Linux) and multilingual interface made it suitable as educational tool for astronomy, and exchangeable constellations make it well suitable for ethnoastronomical research and presentations. Its functionality can be further enhanced with plugins. However, it was developed with a focus on simulation of the sky of today, and so several simplifications and omissions in the astronomical routines had been applied which made it at that time not yet perfectly suitable for simulations of the skies of past millennia. With open-source software, however, we can look behind the scenes and fix and improve what seems insufficient, so I have joined the development team for further improvements.

The Scenery3D plugin for Stellarium

Aim of the ASTROSIM project (2008-12) was research and simulation of the possible solar and maybe even stellar astronomical orientation of Neolithic *Kreisgrabenanlagen* (KGA) in Lower Austria, so that more than just solar positions in a simple VR system were required. These monumental buildings, consisting of large circular ditches surrounding wooden palisade rings, have been erected in a short period of about 4800 to 4500 BC by several culture groups in Central Europe (MELICHAR and NEUBAUER 2010). Much has been speculated about the orientation of their usually two or four opposing entrances. Therefore we initiated development of a plugin prototype for Stellarium to simulate the potential astronomical use of those prehistoric monumental buildings on a high-end graphics PC (ZOTTI and NEUBAUER 2012).

This plugin enables researchers to load a properly oriented virtual environment (e.g. a georeferenced model of a temple with surrounding landscape) in the widely used OBJ format into an astronomical simulation environment and explore it in a virtual walkthrough fashion to combine architectural and celestial simulation, including real-time shadows cast by the sun, moon and even the planet Venus. (Indeed Venus, which was very important for Mesoamerican cultures, can cast shadows when the sky else is dark enough!) The observer’s eye is kept a fixed (settable) distance from the ground plane which may not necessarily be identical to the model, in order to enter buildings and study views in a field full of statues or pillars without colliding or jumping on top of them.

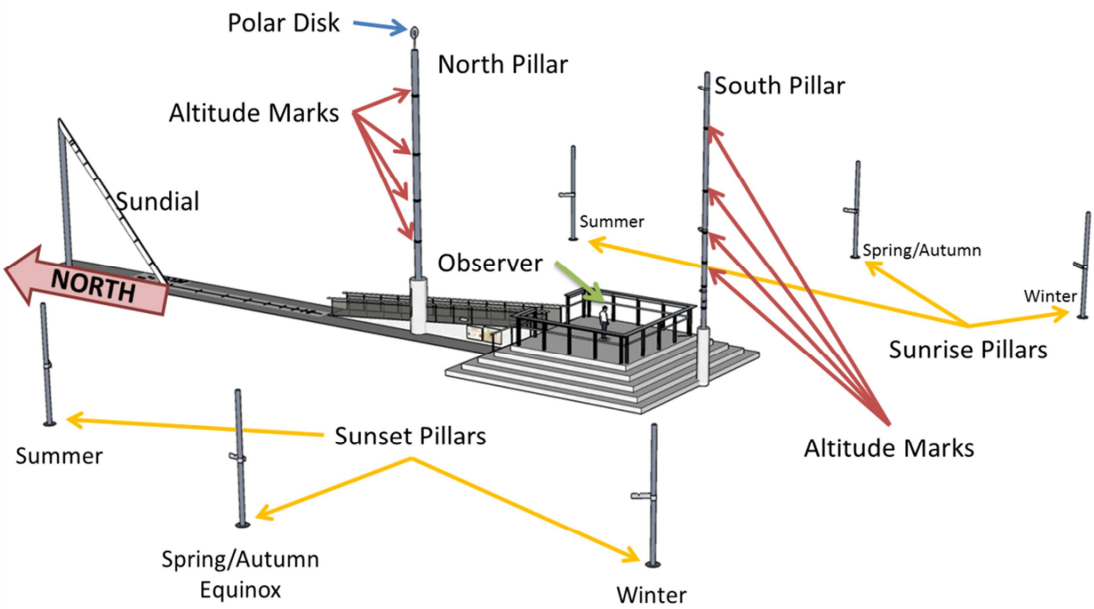

Fig. 1 – Vienna Sterngarten, a place to demonstrate basic astronomical concepts to the public, was used as test case for developing the Scenery3D plugin for Stellarium.

The configuration file also allows specification of real-world survey grid coordinates (e.g., UTM) for the origin of the OBJ model which allows identification and documentation of important viewpoints in such real-world coordinates. A description file (with options for multilingual translation) should accompany the model and explain to other users what can be seen on the site. It is also possible to save interesting viewpoints, optionally including date and time, for later retrieval.

A critical test case

While most of the actual programming was implemented by students of computer graphics, to make sure that the application accurately follows astronomically motivated geometries, I created a model of the Vienna *Sterngarten* (MUCKE 2002)[1], a public sky observing platform on the south-western outskirts of Vienna with a large number of elements which accurately depict and explain the basic astronomical phenomena which are also frequently discussed with the possible astronomical orientation of prehistoric monuments (Fig. 1): With the observer standing in the center of the platform, we have North and South pillars with altitude marks when the observer's eye is vertically aligned with the surrounding railing. The South pillar in addition has marks for solar meridian altitude at solstices and equinoxes, while the North pillar carries a disk with a hole which shows the North Celestial Pole. Outlying pillars indicate solstice and equinox risings and settings, and arms attached to them indicate how far the observable sun is shifted north by atmospheric refraction. Towards the north a meridian line with date marks is crossed by the (unsharp) light patch surrounded by the shadow of the North pillar's pierced disk to indicate the calendar date, while an inclined pole acts as gnomon for a sundial. The idea

[1] I thank Prof. Mucke for providing accurate dimensions from the original plans.

behind the model creation was that if the geometries of the model and the coordinate marks that can be displayed in the sky by Stellarium fit together, they provide an accurately working solution.

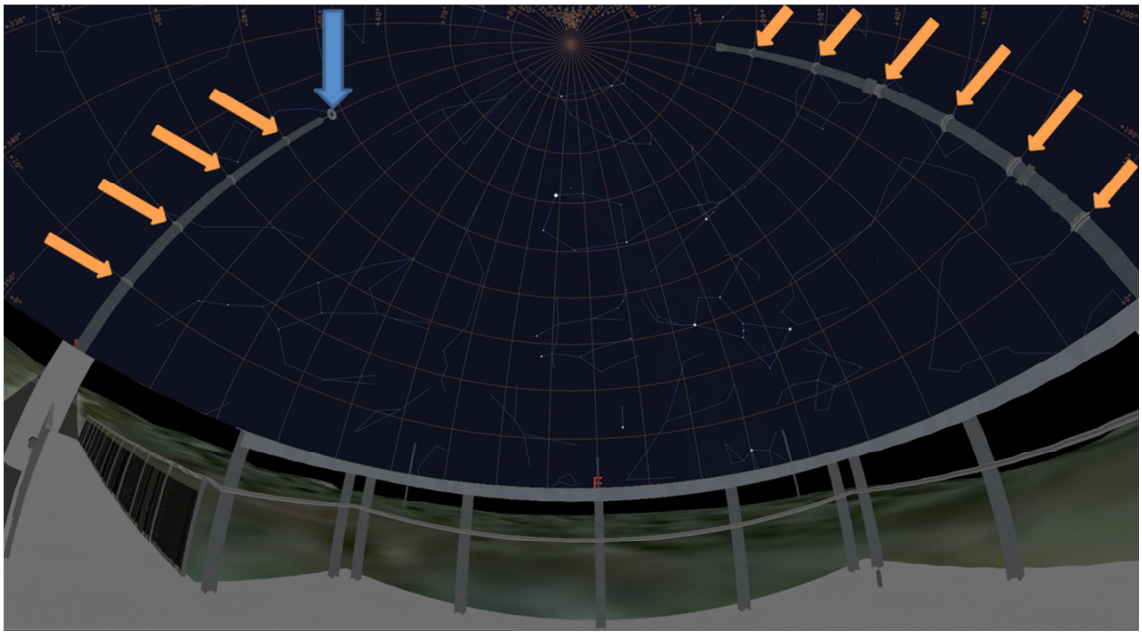

Fig. 2 –Testing the geometrical accuracy: Altitude marks on the modelled pillars exactly match the celestial altitude lines in Stellarium. The pole disk on the North Pillar (left) exactly indicates the north celestial pole.

Several tests were performed with the Sterngarten model. First, horizon and altitude marks on the North and South pillars had to fit the altitude lines on the sky displayed in Stellarium. This works flawlessly (Fig. 2). Further, while the outlying pillars indicate where the sun would cross the mathematical horizon on solstice or equinox days without taking Earth's atmosphere into account, the notches in the arms which extend from them indicate where the sun, lifted by atmospheric refraction, would indeed become visible – if there was no obstruction by the real-world landscape. In the simulation, we can switch away the surrounding far-field landscape panorama and can indeed observe both scenarios: sunrise behind the pillars with atmosphere switched off, and upper sun rim appearing in the notch when atmosphere is switched on. This combination of the didactical concept of the *Sterngarten* and Stellarium as visualization system for astronomical phenomenology is in itself also a resource of high didactic value.

The most ambitious test is likely the shadow simulation. The solar shadow is not sharp, but PCSS sampling (FERNANDO n.d.) can be switched on to provide an estimate of the saliency of solar shadows for large shadow casters like monumental gnomons or obelisks. In the Sterngarten, the North pillar acts as gnomon for the meridian passage date scale. The geometric construction of the *Sterngarten* required that the equinox shadow of the disk with hole on top of the North Pillar touches the foot of the inclined pillar when it crosses the meridian line. Fig. 3 shows indeed the softened shadow in the right location just after transit. So, all conceivable and useful component tests required for an accurate simulation have been passed, and the plugin appears to fulfill its goals.

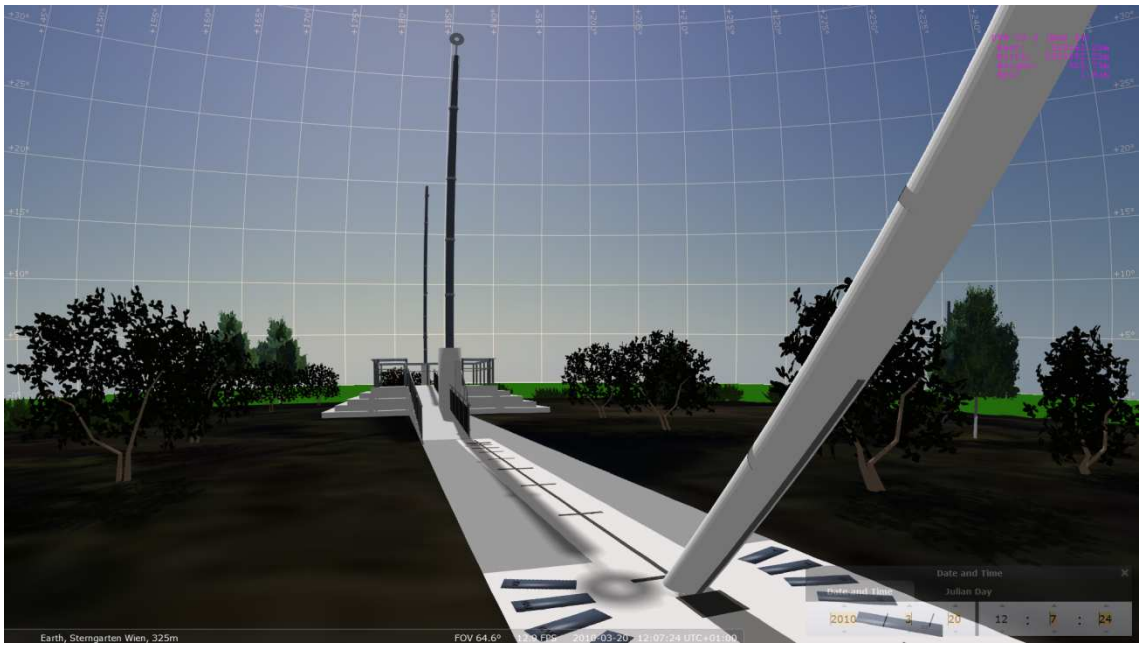

Fig. 3 – Testing shadows. The light patch in the shadow of the Polar Disk on the North Pillar crosses the meridian line (also equipped with date marks) just at the foot of the inclined mast (left in Fig.1). The simulation in Stellarium provides an almost identical view to the scene observed in nature on that day.

Final Integration

Stellarium was subject to several technical changes just when the plugin prototype had been completed, preventing the immediate integration of the plugin. When the most important issues had been settled, it was finally time to take up work again on this plugin. The prototype plugin was further improved in functionality and massively improved in rendering performance. Walking around in a virtual landscape of several hundred thousand triangles is no problem. It now should run on most average PC systems which run Stellarium – small models (up to 64k triangles) even can be shown on small ARM single-board computers! The plugin has finally been integrated in the regular distribution V0.13.3 of Stellarium, accompanied by the Sterngarten model as one of two examples.

Examples of Usage

Neolithic Kreisgrabenanlagen

Given that traces of the ditches can only be seen in magnetograms and nothing is visible on the ground, the only way to create virtual models of KGA was by building 3D models on top of a piece of digital elevation model. Many such models were required for the project, but we did not aim for polished photorealism. The geometry was adequately modelled in SketchUp on top of the DTM exported from ArcGIS. The far horizon (which defines sunrise or sunset) had been measured with a total station from the respective KGA centre, and a small shift caused by moving a few metres in the KGA does not cause a significant change in the horizon line. To get a better feeling for the environmental view on-site, the horizon has in addition been documented with a panorama photograph which was aligned with the measured horizon. Even these simple looking models helped, because of their accurate construction and care for the surrounding landscape, to better understand

the placement of the KGA in their landscapes and the impossibility of astronomical motivation behind several of the sight lines proposed earlier on flat maps, and ultimately led to the conclusion that simply the orientation (*aspect)* of the local slope motivated the entrance directions in most KGA. However, for a single KGA, Pranhartsberg 2, which also has a slightly different architecture, the direction of the north-western entrance is unrelated to the slope (i.e., does not point up or down the local slope), but accurately points towards summer solstice sunset (Fig. 4; more in ZOTTI and NEUBAUER 2015).

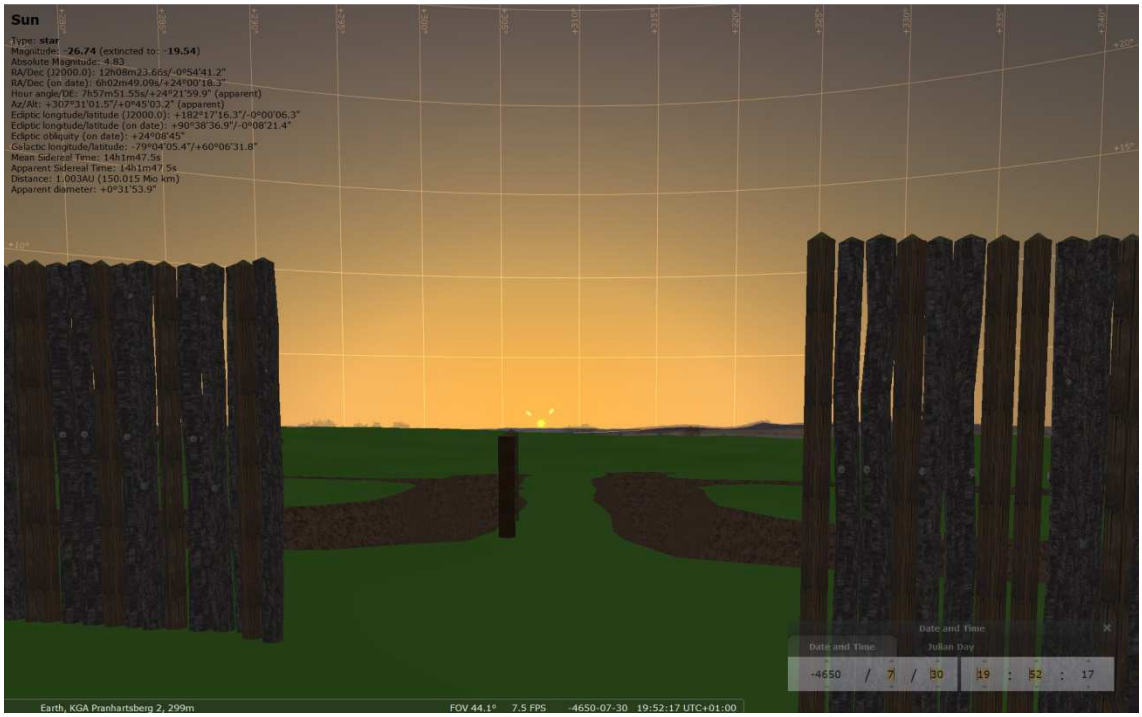

Fig. 4 – Sunset in the Neolithic Circular Ditch System of Pranhartsberg 2.We are looking out of the north-western entrance of the inner palisade ring towards summer solstice sunset, which is visible just in line with the earth bridge which forms the entrance between a double ring of deep ditches.

Structure from Motion models

In contrast to model building, existing structures can be captured by laser scanning or the photogrammetric processing known as *structure-from-motion*. Processing a large number of overlapping photographs taken from different viewpoints allows the creation of a textured 3d mesh. From a series of photographs of a multifaceted sundial from the 18th century found by chance in a public park in Weimar, Germany, I created such a model by the AutoDesk 123D Catch cloud-based service. A base was added to the model in SketchUp, and the model exported to OBJ. The sundial had been recorded without coordinate or even orientation information, but setting up a sundial with square edges in this astronomical context is rather straightforward. Given that it has been obviously removed from its original location, it is permissible to also add a different decorative horizon to the scenery. The original has been placed next to a big tree which actually prevents proper use nowadays, so only in the Stellarium simulation we can observe the proper functioning of the dozen (or so) different sundial faces which have been created on this stone (Fig. 5).

Orientation of other models of this kind has been done with a trick: If the photographic record contains shadows, putting a high-quality model under the simulated sun of the date and time of the photograph should

accurately recreate the same shadow in the virtual model. It is advisable to check several places where the shadow has been captured in the texture to increase certainty that the orientation has been successfully achieved, and also to check the quality of geometric reconstruction of critical shadow casting edges in the model vs. reality.

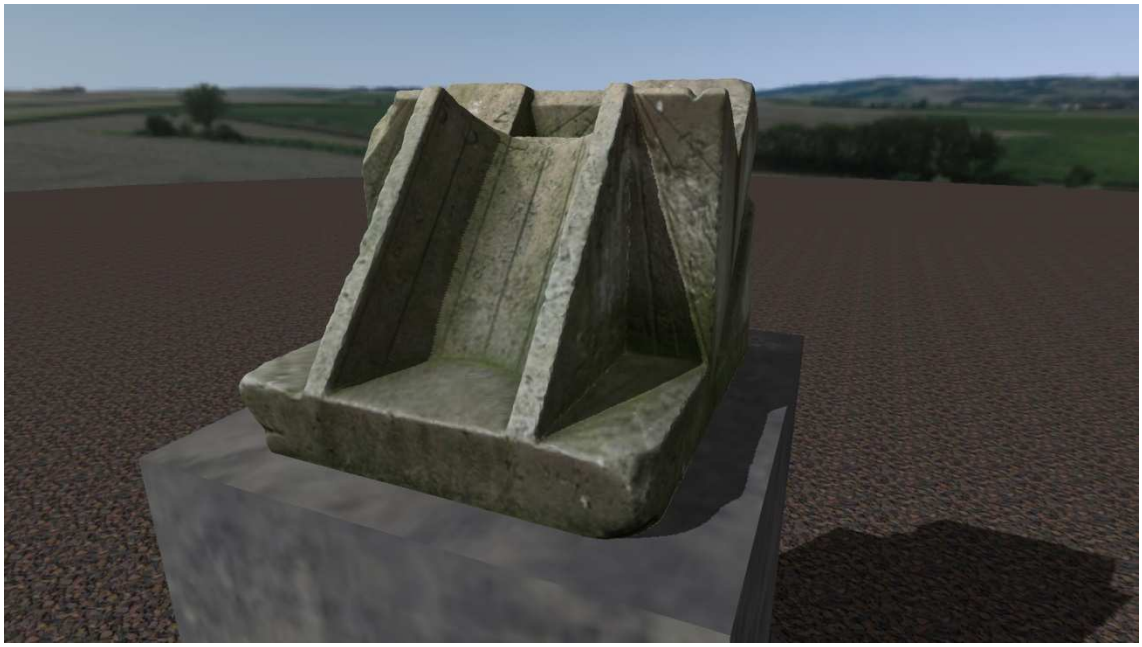

Fig. 5 – A historical sundial in Tiefurt Castle, Weimar, Germany. Modelled using the structure from motion approach and illuminated with Stellarium, it is possible to study light-and-shadow interactions.

Conclusions and future work

The immediate visualization of 3D models under the simulated sky seems to have great potential. Apart from a modelling program and high-quality digital terrain model data, no other software is required, which made the process of model building just for the purpose of interactive investigation affordable also for a larger number of models.

Some more words of advice shall be given for potential future users: When a 3D model of a site has originally been created for other purposes and is now re-used for addressing questions where astronomical objects are involved, creators of such models are well-advised to re-consider all far objects which may change the apparent landscape horizon (buildings or simply the terrain also outside the vicinity). For simple cases, a quick check with e.g. Google Earth can help getting an idea of the horizon. However, the SRTM data provided there may not suffice when the site horizon is close or the terrain has steep mountains which are not properly modelled by SRTM. For such a possibly close horizon, a Digital Terrain Model based on a LiDAR survey would be the optimal source for a critical investigation. Also, most obviously, it is an essential requirement to know the North orientation not just from a published map with a “north arrow”, but make sure this “North” really points to geographical/astronomical North, and is not just parallel to some local survey grid or – Heaven forbid! – magnetically determined North.

I developed an additional plugin, “ArchaeoLines”, available in Stellarium since V0.13.1, which shows the most relevant diurnal paths of sun and moon (solstices, lunistices, solar crossquarter paths), planets and any

currently selected object. The intersection of these lines with either landscape features like mountain peaks, or with built architecture in the 3D model as seen from a particular place, can immediately identify those directions which are most relevant in many works of cultural astronomy.

To further increase the applicability of Stellarium for simulation in earlier historic and prehistoric times, for the current version V0.14 I could finally implement a long-term solution to more accurately model the slow precessional motion of Earth's axis (VONDRÁK et al. 2011), which clearly also helps to identify the limits of the currently used planetary theory VSOP87 (although as an analytical solution you can feed any date, it is recommended to limit its application to the years between -4000 and +8000). Future development should allow us also to use other solutions for the planetary positions, e.g. NASA's JPL DE430 and DE431 series would increase the range of useable dates to the years -13000 to +17000.

I hope this plugin will enable also other researchers to much easier than ever before visualize models of their buildings whose alleged astronomical orientation they want to either investigate, or visualize for others. The Stellarium team welcomes user-contributed royalty-free models to host for download from the project website.

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