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BEYOND THE LANDSCAPE: ANALYSIS OF NEOLITHIC CIRCULAR DITCH SYSTEMS OF LOWER AUSTRIA WITH ADVANCED VIRTUAL ARCHAEOASTRONOMY

MÁS ALLÁ DEL PAISAJE: ANÁLISIS DE LOS SISTEMAS DE FOSAS CIRCULARES NEOLÍTICAS DE LA BAJA AUSTRIA CON ARQUEOASTRONOMÍA VIRTUAL AVANZADA

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Highlights:

- Virtual archaeology can help to better understand archaeological remains embedded in the landscape. Occasionally, the “landscape” concept must be extended to include the celestial landscape.
- Open-source development allowed the combination of a desktop planetarium with 3D landscape and architecture visualisation. Also, datable changes in the landscape can meanwhile be simulated.
- Astronomical elements added to a game engine can also be used to faithfully provide important insights while providing the most appealing visualisation environments so far, but with considerably more effort.

Abstract:

This paper describes developments in virtual archaeology that started in a research project about the possible astronomical entrance orientation of Neolithic circular ditch systems (German *Kreisgrabenanlagen,* KGA) of Lower Austria. Starting from data analysis in a Geographical Information System (GIS), we will cover a simple way of modelling, and discuss three ways of visualisation for the combination of landscape and human-made buildings together with celestial objects. The first way involves extensions to the modelling program SketchUp to bring in just enough astronomical data for scientific evaluation. The second introduces a set of extensions to the open-source desktop planetarium program Stellarium, which can meanwhile be used to load a standard 3D model format to allow detailed research in astronomical orientation patterns, and light-and-shadow interaction over many millennia, even for researchers less familiar with astronomical programming. The third presents a “serious gaming” approach, which can provide the most natural view of the landscape, but requires at least some, if not deep, familiarity with astronomical and 3D computer graphics programming and, therefore, due to this considerably larger effort, appears to be mostly useful for outreach of high-profile results to the public. The entrances to the KGA of Lower Austria turned out to be mostly oriented following a purely terrestrial pattern of up- and downward sloping terrain, but with one noteworthy exception.

Keywords: virtual archaeology; landscape archaeology; digital archaeology; serious game; 3D reconstruction

Resumen:

Este artículo describe los desarrollos en el campo de la arqueología virtual que se iniciaron en un proyecto de investigación sobre la posible orientación astronómica de la entrada de los sistemas de fosas circulares neolíticas (*Kreisgrabenanlagen* en alemán, KGA) de Baja Austria. Partiendo del análisis de los datos en un Sistema de Información Geográfica (SIG), cubriremos una forma sencilla de modelización, y discutiremos tres formas de visualización para la combinación de los paisajes y los edificios construidos por el hombre junto con objetos celestes. La primera forma implica extensiones del programa de modelado SketchUp que aporta sólo los datos astronómicos necesarios para la evaluación científica. El segundo introduce un conjunto de extensiones al programa de sobremesa, de código abierto y de planetario denominado Stellarium, que pueden utilizarse para cargar un formato de modelo 3D estándar que permita la investigación detallada de patrones de orientación astronómica y la interacción luz-sombra a lo largo de muchos milenios, incluso a investigadores menos familiarizados con la programación astronómica. El tercero presenta un enfoque de "juego serio", que puede proporcionar la visión más natural del paisaje, pero que requiere al menos cierta, si no profunda, familiaridad con la programación astronómica y de gráficos por ordenador en 3D y, por lo tanto, debido a este esfuerzo considerablemente mayor, parece ser mayormente útil para la divulgación de resultados destacados al público. Las entradas a la KGA de Baja Austria resultaron estar orientadas en su mayor parte siguiendo un patrón terrestre puro de terreno inclinado hacia arriba y hacia abajo, pero con una excepción digna de mención.

Palabras clave: arqueología virtual; arqueología del paisaje; arqueología digital; juego serio; reconstrucción 3D

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1. Introduction

The classical computer tools to study archaeological sites in their surrounding landscapes are Geographic Information Systems (GIS) like ESRI ArcGIS or the open-source systems Geographic Resources Analysis Support System (GRASS) and QGIS. However, most of the time these analyses provide a top-down view like on classical printed maps. Several interesting technologies have been developed for automatic visualisation of some location and terrain characteristics, such as viewshed computation which finds the region of visibility, least-cost paths finding optimal roads, orientation and slope visualisation, and more advanced image processing methods which also can reveal characteristic spots that either stand out or hide in the landscape (Kokalj, Zakšek, & Oštir, 2011). Usually, however, such analyses are lacking the first-person view of an observer located in the 3D landscape.

Over the last few decades, virtual archaeology has become a widespread tool to visualize reconstructions of historical buildings of which only ruins or even just foundations remain. Increases in computing power also allowed embedding such remains into a reconstruction of the environment in form of a larger landscape. Most 3D modelling programs allow the use of at least some limited terrain model surrounding the main 3D structure of interest.

The demands to navigate in this landscape to gain better insights into the use, views or visibility of buildings also led to the widespread use of game engines, i.e., frameworks for computer games which already provide basic navigation, rendering of plausible real-time visualisation of vegetation, sound effects, moving water, or interaction with game objects and even other characters in the scene. The application of computer graphics and game technology for non-recreational purposes (e.g. various applications of real-world simulation, emergency training, also flight and military training…) is termed *serious gaming* (Vaz de Carvalho, Latorre Andrés, & Serón Arbeloa, 2013). On the other hand, too much of this "eye candy" evoked negative criticism about unscientific "Hollywood toys" which allow too much unproven fantasy construction, and guidelines had to be worked out which scientifically acceptable models should adhere to, the London Charter (Denard, 2009) and Seville Principles (Carrillo Gea, Toval, Fernández Alemán, Nicolás, & Flores, 2013; Principles of Seville, 2011).

1.1. Virtual archaeoastronomy

There can hardly be any doubt that celestial phenomena have been observed already by the earliest humans. The daily rhythm of sunrise and sunset, the phases of the Moon with dark and illuminated nights, and daily and seasonal changes in the starry night sky have left their traces in the material record of most cultures. Some of the cave paintings in Lascaux and other Palaeolithic sites have been interpreted with respect to the Lunar year, the Pleiades star cluster and seasonal appearance of animals (Rappenglück, 2001). Celestial phenomena are also deeply connected to ritual orientation patterns (Frothingham, 1917) which have found their way in the built orientation of countless sacred buildings in ancient history. We, therefore, can frequently observe that the main axis of such building points towards the point on the horizon where the sun rises or sets on a particular day of the year, for example, winter or summer solstice, or some festival day fixed in a solar calendar. Examples include temples of Egypt (Belmonte, 2011), early Christian churches (McCluskey, 2015) or Mesoamerican architecture (Šprajc, 2015). The most famous prehistoric site with astronomical orientation is surely Stonehenge. The solstitial orientation of its main axis and also probable but highly disputed lunar connections have been under discussion for centuries or at least decades (Atkinson, 1966; Hawkins, 1963; Lockyer, 1906; Ruggles, 1999; Sims & Fisher, 2017). Many other Megalithic sites in Britain and the Mediterranean have been investigated with respect to their orientation (Hoskin, 2001; Ruggles, 1999). A recent overview of the growing field of archaeoastronomy and ethnoastronomy has been given by Ruggles (2015), and a modern introduction into the field has been given by Magli (2016).

While most sites of archaeological interest still are best experienced during a physical site visit, there is one aspect which cannot be properly experienced today: the night sky and the course of celestial objects as they had been observable in earlier times. Over centuries and millennia earth's axis has shifted its orientation in space, causing a slight change in the points where the sun rises or sets at the solstices, and –frequently to an even greater extent– also stars change their place, both by their proper motion, and by the Earth's precessional movement, so that stellar visibility changes over seasons and geographical latitudes. In addition, most culturally important sites of past times are still close to inhabited places, and modern civilisation has destroyed most of the night sky's beauty by its ever-increasing light pollution caused by excessive outdoor lighting and, in many cases of monument buildings, by changing the nocturnal appearance of such monuments by deliberate bright illumination. A starry sky for Antiquity or even prehistory is, therefore, best simulated with computer graphics.

Demonstrating archaeological sites featuring astronomically orientated architecture to a wider audience requires a combination of methods from virtual archaeology with astronomical simulation. Given the early time frame of most such monuments, we cannot simply apply the built-in illumination and shadow support found in current rendering systems which often only can simulate solar positions and shadows for the present time, and not long-time developments mentioned above. An environment that provides an astronomically valid day and night skylight simulation is however also highly desirable not only for outreach and final illustrations but as a research tool, where simple, self-made georeferenced 3D models of architectural reconstructions can easily be investigated with respect to astronomical orientation patterns.

1.2. Neolithic Kreisgrabenanlagen (KGA)

An enigmatic monument class which appeared for a rather short timespan in the Neolithic, but over a large area spanning several archaeologically distinct cultures, were the Neolithic Circular Ditch Systems (German *Kreisgrabenanlagen*, further abbreviated as KGA). They are characterized by one to three concentric, near-circular ditches of up to 6 m depth and several metres width with V-shaped cross-section and usually two opposing entrances, or four entrances in a cross-shape, with some exceptions like the KGA

Glaubendorf 2 which at first seemed to have a layout for 6 entrances 60° apart, of which one entrance is however missing. The overall diameter can span tens of metres to over 150 m. The entrances are simply formed by leaving earth bridges intact. The central part was further enclosed by one or several palisade rings, with gaps (entrances) which are aligned with the earth bridges. The central area is usually free from archaeological finds, although a few very uncommon burials have been found occasionally, which can be interpreted as human sacrifice or execution. Recent publications include (Bertemes & Meller, 2012; Daim & Neubauer, 2005; Melichar & Neubauer, 2010), and an extensive overview of the Early and Middle Neolithic of Lower Austria has recently been published by (Lenneis, 2017).

The concept of KGA seems to have spread to Central Europe from the south-east, from today's Hungary, Slovakia, Austria, Czech Republic (the area of the Lengyel Culture) further to Bavaria (*Oberlauterbacher Gruppe* SOB), Western and Northern Germany (*Stichbandkeramik* SBK and *Rössener Kultur*) (Trnka, 2005). KGA in Austria are uniformly dated to 4850/4750 to 4650/4500 BC (Neubauer, 2017).

Nothing remains in today's topography of these monuments which had consisted of earthworks and wood. Most of them have been discovered from the air where they appear as circular structures in arable land, and, given their size, only a few KGAs have been excavated in total. Since the 1990s geophysical prospection, especially the magnetometer survey, has been applied to survey and document KGA (Melichar & Neubauer, 2010).

The significance of KGA for their builders is still under discussion (Neubauer, 2017). Their location and architecture practically exclude their use as fortification, and also use as cattle corral has been excluded. They usually have been built on sloped terrain and close to a freshwater spring. They belonged to a settlement, but no houses are to be found inside. The Lengyel population built their settlements generally on slightly higher sites than the older *Linearbandkeramik* (LBK, linear pottery) who preferred settlements close to rivers (Neubauer, 2017). Archaeologists have observed a sharp increase of hunting activity in the Lengyel culture compared to LBK, especially of red deer and aurochs. Lengyel people kept domesticated cattle and pigs, while goats and especially sheep had almost vanished (Pucher, 2017).

The enormous size of KGA and the estimated effort it must have taken to construct them signifies their high importance to the builders and invited the idea of a multi-functional cult or gathering place which may also be related to the ritual observation of celestial events like sunrise or sunset at the solstices for celebrations. Helmut Becker had described several KGA in Bavaria as "Solar Temples" (Becker, 1996), while KGA from the Lengyel culture in Slovakia and Austria had both been described as connected to extreme Lunar standstill events (Pavúk & Karlovský, 2004), and for other Lengyel KGA in Hungary and Austria a solar connection had been proposed (Pásztor, 2008). The discovery, excavation and analysis of KGA Goseck near Halle, Germany (Schlosser, 2002) further supported a solar connection with the orientation of an entrance towards winter solstice sunrise.

In 2005 a county exhibition on the KGA of Lower Austria allowed a preliminary analysis of the orientation of almost 30 KGA in Lower Austria, which provided a tentative interpretation that included a few solar orientations (solstices and "cross-quarter days"), suggesting a partition of the solar year into 8 roughly equal parts which can be found in other cultures. While Lunar interpretations could not be corroborated, it even suggested a few stellar targets, but recommended that these preliminary results must undergo further research, especially regarding the local horizon, because the exact apparent altitude of the surrounding hills are a decisive ingredient in the computation of rising and setting points (Kastowski, Löcker, Neubauer, & Zotti, 2005; Zotti, 2005, 2006, 2008, 2012; Zotti & Neubauer, 2010).

In 2009-12, a dedicated research project, ASTROSIM, allowed the detailed survey and analysis of horizons of 32 KGAs in Lower Austria to solve the questions which had to be left open. Given that nothing remains visible in today's landscape, working with virtual reconstructions quickly turned out to be the only meaningful way of analysis. This paper describes the various steps applied in the process. First, we give a brief view of our data, methods and applications available. After describing relevant functionality of the 3D modelling program SketchUp, a section introduces the astronomy simulation program Stellarium and extensions developed which can now also be applied for studies similar to this. The application of a game engine for an even stronger immersion into the landscape is then focused in the following section, followed by a discussion of some insights and the current state of available tools that we have developed further.

2. The GIS and virtual reconstruction in SketchUp for archaeoastronomical insights

Data from previous surveys had already been collected and prepared in a GIS. These consisted of results from geomagnetic surveys, aerial views for some places and a digital terrain model (DTM) of today's landscape. The latter had a raster width of 25 m from which artificial horizon lines had been computed for the preliminary study, but which was too coarse for a purely digital approach. Only at the end of the project LiDAR DTM data with 1 m resolution became available which meanwhile have become *de facto* standard.

Of course, the use of DTMs that represent today's terrain may in some cases be problematic because these do not necessarily represent the terrain as it has been 6800 years ago. Natural developments like erosion or processes of alluvial or aeolian depositing, and human-made changes like terracing or road building should be taken into account if possible when building a landscape model of the past. The fields with KGA have typically lost 1-2 m of topsoil by ploughing since the time of KGA (Neubauer, 2017). The images from magnetic prospection allow some further estimate of localized erosion when the usually very regular shape of a circular ditch, which is assumed to have reached equal depth and width at completion, still appears regular, or when the image of the filled ditch is markedly weakened on one side, which indicates that the respective side of the KGA was subject to stronger erosion and may also indicate that the local slope orientation was slightly different at the time when the KGA was visible. Only few sites showed such inhomogeneous erosion that would have changed the overall result of our investigation, therefore we worked with DTM of today.

Starting in ArcGIS/ArcScene 9.3, a piece of DTM was prepared for each KGA with a texture from the geomagnetic prospection which clearly shows the outlines of the KGA, and a shapefile which defined the cut lines of ditches and palisades. This was exported to Google SketchUp v. 8 (meanwhile sold to Trimble), where the V-shaped ditches and simple palisade reconstructions were added. The focus of this phase of model building was not to provide the most photorealistic models of KGA possible but to quickly create geometrically accurate models, which allowed a visual analysis of what could have been seen in the landscape. Uncertainties with the height of the palisade were indicated with timbers of different height, which however caused some irritation with archaeologists who insisted on a more regular appearance of the palisade's top edge. The models allowed navigation and walking around inside SketchUp to see how an inhabitant would have experienced the seclusion and separation from the outside discussed as important factors in the literature (Gibson, 2005).

2.1. The astronomical analysis in SketchUp

Despite its limitations of model complexity and a rather simple rendering style, SketchUp as modelling program has several advantages over other programs. It is very simple to use also for untrained or beginning model builders, and users familiar to programming can develop program extensions (plugins) in the Ruby programming language, which can extend functionalities at least to some degree. Models can be georeferenced so that SketchUp was used at that time to create the 3D buildings in Google Earth. This georeferencing property allows simple solar shadow simulation at least for the present epoch. However, the range of calendar dates that can be set in SketchUp's shadow module is limited to the UNIX epoch, i.e. allows only dates between 1970 and 2038. In the epoch of the KGA more than 6500 years ago, Earth's equator was tilted to its orbital plane (ecliptic, also the sun's apparent annual path) slightly more (ca. 24.2°) than today's 23.4° (Meeus, 1998; Vondrák, Capitaine, & Wallace, 2011, 2012). The resulting slightly different maximum declinations of the Sun from the celestial equator at the solstices (which influence the maximum/minimum noon altitudes and northernmost or southernmost rising and setting points) caused by this larger tilt, and therefore the slightly different directions of sunrise or sunset shadows therefore cannot be simulated properly with SketchUp's integrated solar shadow module.

SketchUp has no possibility to display a skybox or other geometrical representation of background at an infinite distance. For a visibility estimation of celestial objects, a diagram was developed in the Encapsulated PostScript (EPS) language (a vector graphics format which allows computation of diagrams and arbitrary scaling) which showed a grid with azimuths and altitudes, solar tracks for the solstices, equinoxes, and cross-quarters, extreme lunar paths, declination lines and diurnal paths of the stars for the beginning of the KGA epoch (year -4800). Slight differences in geographic latitude required the creation of one such panorama diagram per KGA. A plugin developed for SketchUp in the Ruby language allowed reading the relevant data from the "Georeferencing Dictionary" (model metadata which contains the geographical location data), and a chain of external commands was then called from inside SketchUp that created the diagram and customized it for the current model's location, converted it from EPS to the PNG raster image format, created the spherical ring geometry and applied the PNG panorama as texture. The horizon elevation polygon and calibrated panorama photograph from the KGA's respective centre point taken during each site survey were later added once they had been visited and surveyed (Fig. 1).

The Georeferencing Dictionary also contains a "North Angle" entry. The beginning modeller may expect to find the north direction along one of the model axes, however, there is usually a slight deviation caused by the UTM projection used for placing the model into the geographic location. Only at the "UTM Zone Meridian" the direction to the North Pole coincides with the "Grid North". For locations east of the zone meridian, "Grid North" deviates slightly to the east, or True North is slightly west of Grid North. This is caused by the convergence of the meridians towards the poles, and can be one source of errors when reading orientation azimuths from published maps, where the north arrow can mean either one of true (geographic) north, magnetic north (which even depends on the time of measurement) or grid north (which depends on the projection and site location). The "North Angle" entry in SketchUp is used to adjust the solar position in SketchUp's built-in shadow simulations.

The panorama/diagram combination was therefore used as a texture on a spherical ring along the horizon in the SketchUp model which for analysis was programmatically linked (with another plugin) to the eye point of the current camera to avoid the parallax shift caused by the limited distance to the spherical ring. Although the panorama/diagram was strictly valid only for the point where the horizon altitude survey had been performed with a total station, moving by a few steps inside the palisaded enclosure does not noticeably change a far horizon with visible distant mountains, while shifts in the near horizon were already apparent in the piece of terrain included in the model. The position of the camera inside the model plus the georeferencing information in the model metadata allowed computing the survey grid coordinates for each point of observation in case particular viewpoints would have been of interest.

Already inside these models it soon became clear that some previous assumptions did not hold. Previous top-down analysis of the entrance orientations on flat maps had suggested a flat terrain surrounded by the usual slightly elevated horizon formed by the low hills of that area. In contrast, most KGAs were seen to have been built on sloped terrain, which was sometimes so steep that it should even have been possible to look over the palisade while standing in the KGA centre unless the palisade was exceptionally high. This notably contradicts the description of a "secluded place for ceremonies" where unauthorized persons should not be able to look inside. Also, it seemed to make no more sense to link entrances which were found to be directed towards such directions and which looked onto the opposite side of the valley, to a celestial object which was previously assumed to be the only thing visible from the centre just over the entrance in the palisade gap.

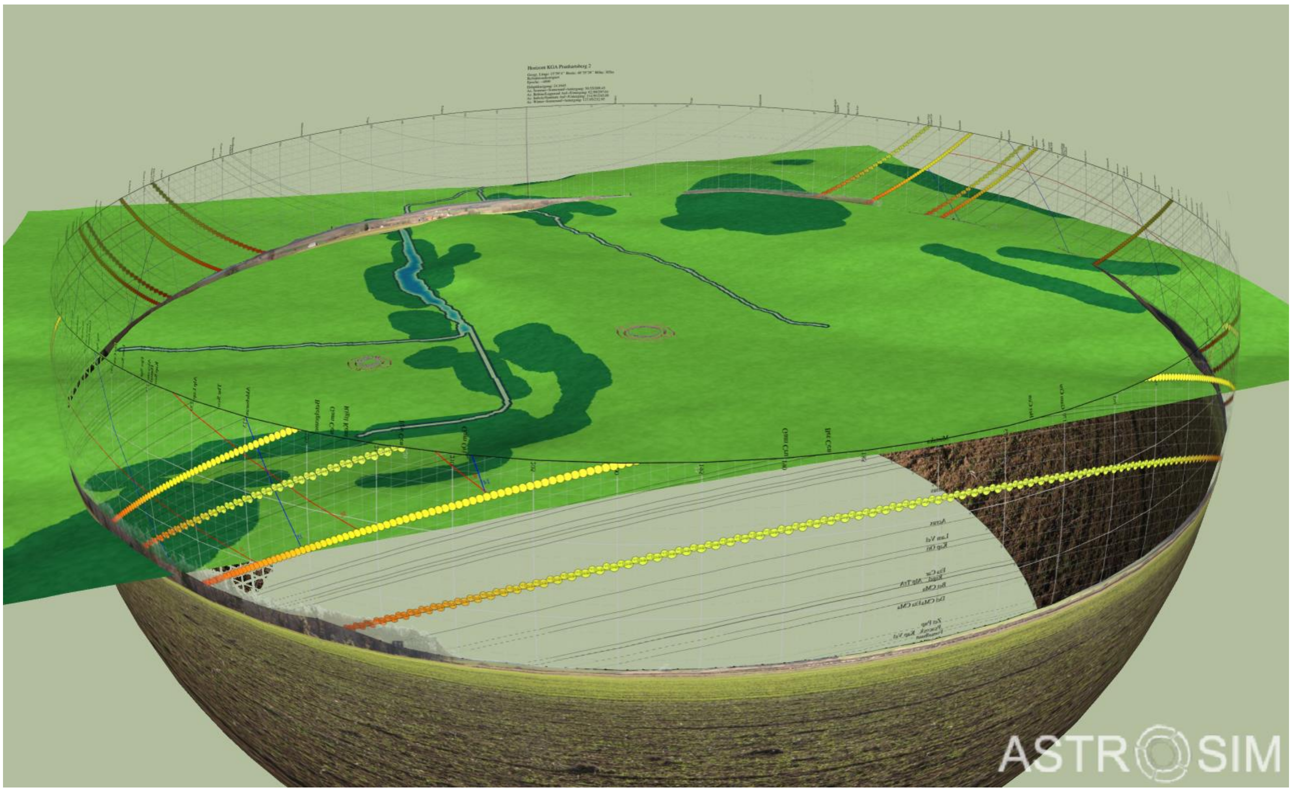

Figure 1: A piece of DTM textured to show hints of forest and water currents. North is towards the top left. The object of our interest, KGA Pranhartsberg 2, is surrounded by a combined astronomical diagram/panorama photo mapped to a spherical ring centred on the position of the survey camera which, seen from the inside, allows estimates of the possible astronomical significance of archaeological features when they correlate with architectural and/or landscape features. The panorama photo includes mountains too far away to be included in the local piece of DTM but of course important because only they define the visible horizon line. The panorama diagram is used as a texture on a spherical shell which always is placed to enclose the viewer.

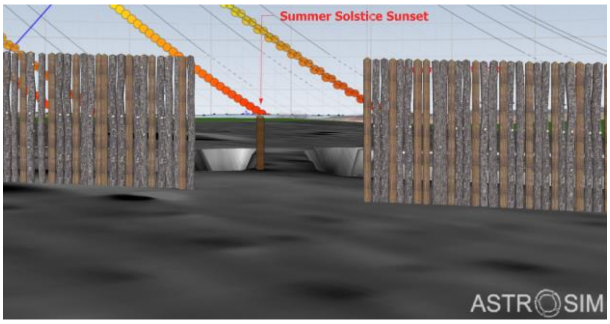

Figure 2: The first-person view in a SketchUp model looking out of the north-western entrance of KGA Pranhartsberg 2. The ground is textured by the magnetogram which revealed the archaeological features. In the background, the summer solstice sun path (the chain of circles coloured from yellow to red as the sun sinks) is seen to set just behind the aligned double-posts. The right chain of circles would relate to the moon, and other inclined lines to bright stars, which both turned out to be irrelevant. The photographed landscape horizon is also visible beyond the edge of the DTM.

There was however one KGA with a slightly different overall ground plan as visible from the magnetometer survey (Melichar & Neubauer, 2010). Its north-western entrance coincides perfectly with the summer solstice sunrise, and the entrances have been further accentuated by extending the earth bridge towards the outside with parallel side ditches. In addition, the magnetogram showed two point-like anomalies in the earth bridge. When reconstructed as postholes with vertical posts, these could have been used as a sighting device. This may corroborate that this orientation was intentional; however, the site has not been excavated yet to secure further evidence. Figure 2 shows a first-person view along this entrance from SketchUp.

3. Astronomical simulation

A crucially important part of the project also was the development of better ways for astronomical simulation. The simulation of archaeoastronomical landscapes in a classical planetarium with optomechanical projection and projected horizon panorama performed during another preliminary study had shown to be insufficient: it can only show a simulation of the sky above the mathematical horizon, while in the context of “horizon astronomy” employed in archaeoastronomical orientation studies at least several degrees of horizon view towards the ground should be provided by any simulation environment, to achieve a better contextualisation with the landscape and potentially visible archaeological remains (Zotti, Wilkie, & Purgathofer, 2006). Therefore some computer graphics solution seemed more applicable. Several approaches of this kind also have been applied in a context similar to ours, e.g. on Arminghall Henge (Beex & Peterson, 2004) or the Thornborough Henges (Harding, Johnston, & Goodrick, 2006).

Desktop planetarium programs have been available since the 1980s. These allow the simulation of the sky as seen from any location on Earth for (in principle) any point in time. Around 2008, the most advanced of these programs allowed also the inclusion of a panorama photo to get a better immersive feeling of an observation location. Of course, the astronomical accuracy of the simulation depends on the selection of implemented astronomical-mathematical models. While one commercial product available at that time seemed to have high visual appeal, some astronomical phenomena like atmospheric refraction were modelled noticeably unsatisfactorily, and the source code of commercial products is in general not available for verification. But there was an even better alternative.

The Internet and especially development of the World Wide Web and growing accessibility of online resources has allowed the development of open-source software where many developers can collaborate despite living in very different locations on Earth. One such project is the desktop planetarium Stellarium[1], started in 2001, which by 2008 was already quite popular and could be used to control computerized telescopes or even run small planetarium shows because its small but dedicated group of developers brought in expertise and interest from various fields of astronomy. Open-source means the source code is freely accessible so that it can be downloaded, studied and improved where necessary. Contributions like improved program code can be sent to the maintainers who decide upon acceptance for the next release. Therefore, although in 2009 this program was far from accurate enough for archaeoastronomically sufficient simulation, it was quickly identified as a perfect starting point for future development.

3.1. 2D simulation

Stellarium allowed the display of a panorama photo or rendering to gain a good representation of the landscape surrounding the observer. After a first little correction contributed to Stellarium 0.10.5, any mountain or other obstacle recorded in our surveys and panorama photographs was faithfully represented in the astronomical visualisation of the land- and skyscape at the point of observation. This invited the creation of another SketchUp plugin which helped to export artificial panorama renderings of particular viewpoints inside the KGA models which were shown in front of the panorama photographs in Stellarium. Given that SketchUp itself can only render perspective views, such views were simply combined with panorama software into the required spherical panoramas. The static panorama diagram in SketchUp significantly helped in the identification of possibly relevant viewpoints because it showed the diurnal tracks of objects which could then be shown animated in Stellarium. However, for many KGA models, it was necessary to export several such panoramas to test and investigate possible viewpoints. At some locations it became also clear that a single point of observation (where our total station and photographic registration of the horizon line had been performed) was not enough to gain a complete understanding of the landscape and observer situation, because some landscape features were close enough to influence the visible horizon line when the observer walked around in the virtual terrain.

3.2. 3D simulation

While surveys and modelling were well underway, a student project was initiated at the Institute of Computer Graphics and Algorithms (ICGA) at TU Wien. The aim of this sub-project which could be finalized and ultimately integrated into the regular Stellarium distribution only after our research project (Zotti, 2016; Zotti, Schaukowitsch, & Wimmer, 2018) was the development of a 3D rendering module (plugin) for Stellarium which should allow a virtual observer to move freely in a 3D model of an archaeologically relevant landscape and under the Neolithic sky.

For testing purposes of both the astronomical and rendering accuracy of Stellarium and test model for the plugin developers an accurate model of a definitely astronomically motivated building was created from its original plans. The "Sterngarten Vienna" is a public sky viewing platform created in the late 1990s in the outskirts of Vienna which consists of a pyramid platform, which raises the observer over the bushes, several pillars north and south of it and several outlying pillars which mark points on the horizon where the sun rises and sets at equinoxes and solstices. One pillar's shadow indicates the date when it transits the meridian line, and another pillar acts as a sundial. The construction also includes indicators which explain the azimuth difference between geometric and apparent rising/setting points, the latter adding the refractive lifting of the Sun caused by Earth's atmosphere.

A panorama created from the designated viewpoint in the centre of the platform thus could be used to test and later demonstrate the simulation of atmospheric refraction which was also developed by us for and added to Stellarium, along with atmospheric extinction of starlight, during our project. Refraction causes a lifting of celestial objects along the horizon. For example, when the geometrical sun's upper limb touches the mathematical horizon (i.e. its geometrical position computed without effects of the terrestrial atmosphere), the apparent (visible) sun is already completely visible above the horizon under average conditions. This also causes a lateral (azimuthal) shift of the apparent rising points against the geometrically derived points by more than a solar diameter in mid-northern latitudes. This effect, modelled for standard conditions (Meeus, 1998), can meanwhile be properly simulated, demonstrated or observed in Stellarium.

A first working prototype of the 3D plugin was finished at the end of the project, but saw significant improvements in a later student project again at TU Wien. The current version (as of Stellarium 0.18) can load a model in the Alias Wavefront OBJ format including textures and normal mapping, load a separate "walking ground" layer which controls the eye position (Zotti, 2016), and even has the ability to show parts of the model only when they fit to the time currently simulated in the sky (Zotti et al., 2018), so that the evolution of a multi-phase site like Stonehenge can be experienced without having to interrupt the simulation to load separate models for the various phases described in the literature (Darvill, Marshall, Parker Pearson, & Wainwright, 2012). This open-source 3D rendering system therefore allows virtual walks through landscapes and buildings combined with a high quality astronomical simulation that provides application possibilities from orientation studies to analysis of light-and-shadow interaction like the particular solar illumination of a statue or painting by a spot of sunlight cast through a window on an associated festival day (Frischer, Zotti, Mari, & Vittozzi, 2016). Our largest model so far consisted of 14 million triangles created from a laser scan, which is still shown

[1] https://www.stellarium.org

at interactive frame rates with shadows on a middle-class notebook PC (with NVidia Geforce 960M). While moving through the scene, the actual eyepoint coordinates are always available in the grid coordinate system of the DTM, and interesting points of observation can be stored as bookmarks. Figure 3 shows the same scene as Figure 2, but from the visualisation in Stellarium. The sky includes all astronomical data to be expected from a desktop planetarium, and yet another plugin has been developed which provides lines important for archaeoastronomical studies, for example, the particular diurnal track curves for solstices, equinoxes (equator) and the "cross-quarter days", dates which lie just between equinoxes and solstices, similar lines for the Moon, or indicators of the direction towards "sacred" locations.

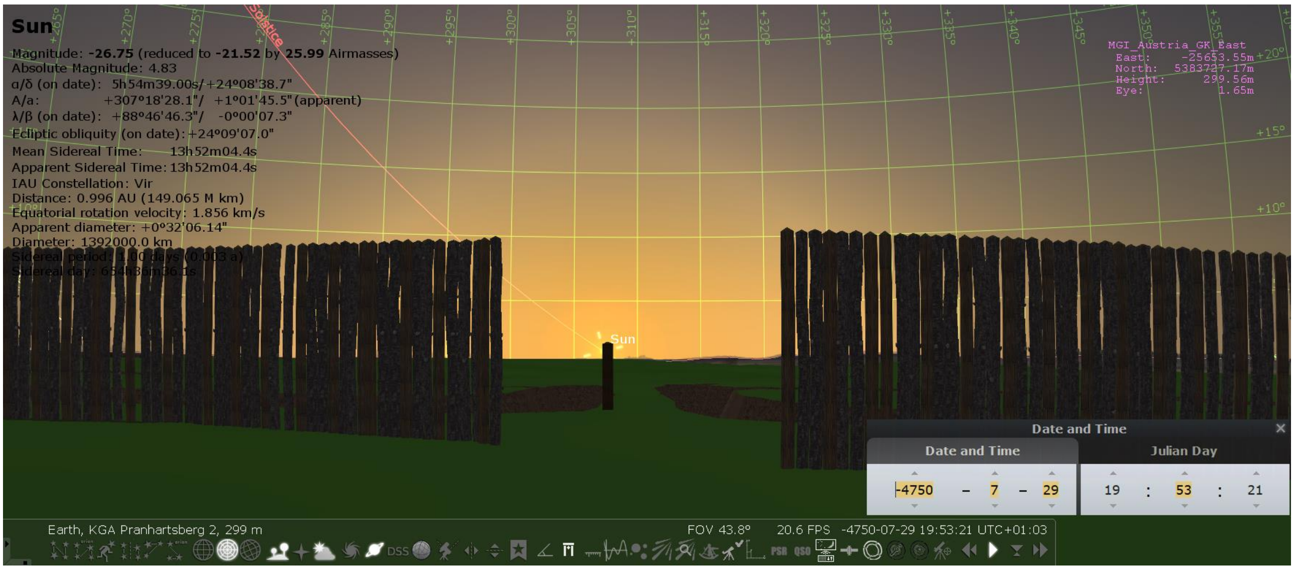

Figure 3: The same scene as in Fig. 2, simulated in Stellarium's Scenery3D plugin developed for this project. Stellarium provides astronomical data for celestial objects, and the Scenery3D plugin allows moving in a virtual landscape to explore possible astronomical orientation. The red curve in the sky again indicates the path of the Sun at the summer solstice.

4. Serious gaming in virtual archaeoastronomy

The archaeoastronomical result of our KGA project was rather sobering (Zotti, 2017; Zotti & Neubauer, 2015). Most KGA had been built on sloping terrain, and the orientation of entrances in most cases followed the terrain slope so that two opposing entrances were placed either on the steepest path or on a contour line through the KGA centre. In the few cases where the KGA traces in the magnetograms indicated localized erosion, reconstructing the original slope usually improved consistency with the typical result of slope orientation for the entrances. Occasionally these directions coincided with solstices, but all but one possible stellar orientation that had previously caught our attention clearly could be excluded when the surveyed horizon and panorama photograph were evaluated. The remaining single "working" stellar orientation in over 30 KGAs must be classified as chance alignment. All those directions could be explained away by the terrain slope, with the exception of the KGA site at Pranhartsberg 2.

As the final reconstruction of our project, also to be used in outreach, we, therefore, have created a landscape model only of this site and its surroundings with the Unity game engine (Zotti, 2014). Although it takes considerably more effort than creating a static 3D landscape and probably is beyond the modelling capabilities of the average archaeologist and therefore requires additional funding and external contractors, it has become quite popular in archaeological outreach due to its capabilities in providing attractive graphics and the creation of game-like interactive scenes.

A much larger piece of surrounding terrain than we had in SketchUp was imported from the DTM, and virtual reconstructions of the two KGA of Pranhartsberg were accurately placed. The previous vegetation, water currents and a little pond with beaver dam which has almost dried out nowadays were reconstructed under consideration of archaeobotanical results (Neubauer, 2017). A few Neolithic houses were placed where a settlement has been suggested; however their real location is still unknown.

The sky in most Unity-based games does not appear to receive much attention from the developers. Even if the sky is not simply rendered as static skybox and may include a sun model which allows showing a sunset, there is no astronomically useful sky component available, therefore we had to create our own. A sky model based on Preetham's classic model (Preetham, Shirley, & Smit, 1999) which also showed simple moving clouds was available from a previous project. Only a few simple astronomical models have been added.

Our modern calendar, or the Julian calendar commonly used in software for dates before 1582, is not suited for dates in the Neolithic, because events like seasons beginnings would fall on unexpected dates. For example, summer solstice around the year -4700 would be displayed to be on July 30th (in the Julian calendar), while a user knowing today's date might be tempted to set June 21st and would, therefore, set a wrong date. Therefore, we were free to develop a simpler interface which directly moves the sun along the ecliptic.

For the sun, a directional light source (with glare effect) and a luminous sphere of the right size were linked to the camera so that its direction is always correct.

A custom shader allows putting this Sun ball into the moderate distance, nearer than the far camera clipping plane, but rendered ahead of the scene, so that the landscape would cover it as applicable. The sunlight colour is reddened by atmospheric extinction and the sun is lifted by refraction when it is close to the horizon. Likewise, for at least a simple representation of the night sky, a particle system was created which surrounds the scene, with over 9000 particles representing the naked-eye stars from the Yale Bright Star Catalog (Hoffleit, 1991). These stars, affixed on a spherical shell again surrounding the view camera, provide accurate seasonal behaviour in relation to the solar positions. These "star" particles are again modelled close in 3D space but rendered before the landscape. Their brightness is of course modulated with the sky brightness so that the stars vanish in the twilight. The user can move the sun along the ecliptic to influence the seasons, and can rotate the whole sky (consisting of sun and star sphere) around the celestial poles. Given the negative results of stellar connection and KGA, further refinement like detailed twilight visibility or the Milky Way was not required. Also, no model of the moon or the planets has been implemented. The difference of the DTM's Grid North to geographic True North can be adjusted in Unity by rotating the celestial model around the vertical axis.

Some additional astronomical data was still brought into the sky using a transparent skybox (Fig. 4) where a variant of the original sky path diagram already used in SketchUp was used in form of six optional and independently switchable diagram layers. Three diagrams could be packed into the RGB channels of one texture and made visible by dedicated shaders. These diagrams added astronomically relevant information like azimuth/altitude grid, declination lines, diurnal tracks of the stars for the KGA period and solstice tracks and other relevant data for the Sun and, similarly, for the Moon. It also included the horizon polygon line measured with the total station in the centre of the KGA to be able to compare the artificial landscape and the natural horizon that may lie beyond the far clipping plane or beyond the end of the terrain extent in Unity (Zotti, 2014).

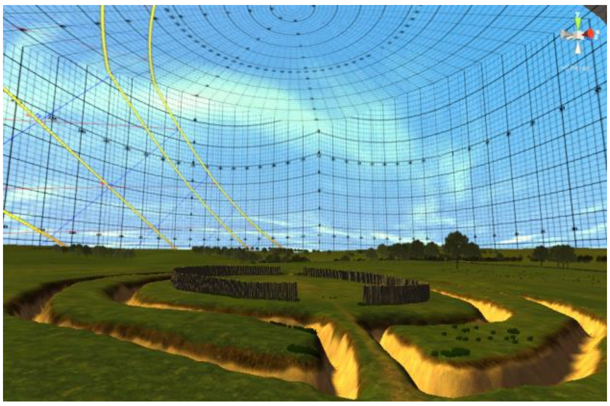

Figure 4: Editor View from Unity, showing the virtual reconstruction of KGA Pranhartsberg 2 and the diagram skybox which adds astronomical information to a natural looking sky with moving clouds. During regular gameplay, it is centred on the viewer and therefore hides the cube faces seen here (Zotti, 2014).

The application allowed free ground-based movement in the first-person perspective (Fig. 5), alternatively switching to a bird's eye mode (Fig. 6), change of the sky in terms of diagram layers, and change of time of day and date in the solar year. The observer's real-world (survey grid) coordinates can be read from the GUI, so that coordinates for a potential place of observation can be faithfully reproduced. These were the relevant features for archaeoastronomical simulation in the context of our moderate findings. To make the scene more lively and "natural", Unity offers an extensive set of "game" effects, therefore we added particle systems for burning fires or splashes of water running over rocks, moving and reflecting water surfaces, vegetation shaking in the wind, the sky model includes moving clouds, etc. However, we did not attempt to make a complete game out of it, with virtual characters to talk to, collecting items or carrying game objects around.

Apart from a PC version for our own demonstrations, the model was also released on the project website as an application for the "Unity Webplayer". Unfortunately, several popular web browsers have eliminated most plugins including the Unity Web player in 2017, but (as of late 2018) it still works with Internet Explorer 11 (Windows) and Safari (Mac OS X). Later similar applications can use WebGL builds from Unity.

5. Discussion and future work

This paper gave an overview of three ways of archaeoastronomical visualisation and simulation developed in a research project about the possible astronomical orientation of Neolithic circular ditch systems (KGA) in Lower Austria. The project involved previous data from geophysical prospection, field surveys, GIS-based analysis, virtual reconstruction, important improvements in astronomical simulation, and development of, and visualisation in, a dedicated plugin for a desktop planetarium as well as game-level visualisation mostly for outreach developed using the Unity game engine. Even if the question of astronomical orientation had to be answered largely negatively for the Lengyel KGA of Lower Austria (see Section 4), we should not apply this result to KGA of the almost contemporary cultures in Bavaria and northern Germany. In any case, the technologies developed during the project should be useful for future similar projects.

The simulation of –and walking inside– a 3D scenery under the artificial sky of past times inside Stellarium with all its astronomical features and details opens up new ways of interactive investigation in archaeoastronomy and –in the same application– creation of accurate illustrations for dissemination of valid results (Frischer et al., 2016). The approach of loading a 3D model in a well-known 3D model format (Wavefront OBJ) in Stellarium, and free availability of Stellarium, should be easy enough to be applied more frequently also just for research purposes. On the other hand, the creation of a Unity landscape and application usually is a larger project and may require more expertise from graphics developers and probably additional funding, so that such projects seem better suited for the presentation of final results in museums or other outreach channels.

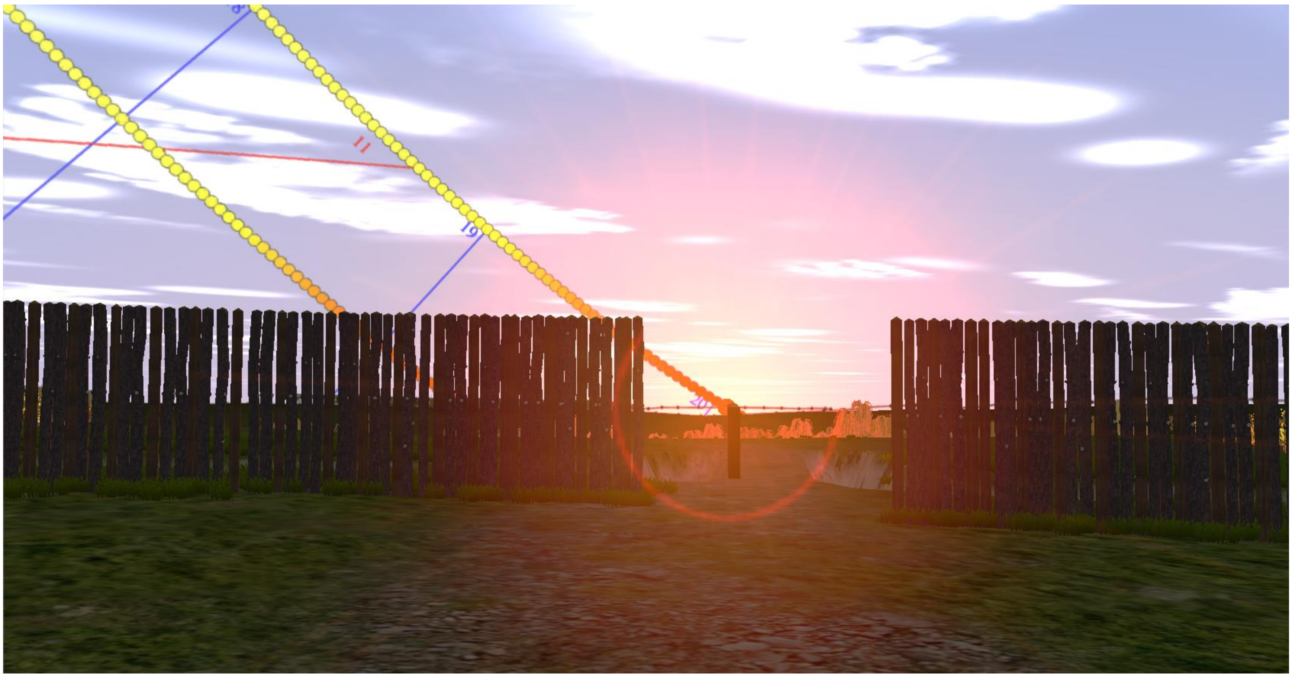

Figure 5: The sunset scene in Figures 2 and 3 in Unity (Zotti, 2014). The sky shows the combination of natural blue sky with moving clouds and the Solar diagram component activated in the otherwise transparent diagram skybox. We can see that the measured far horizon (horizontal line connecting measured altitude points just above the terrain horizon) is somewhat higher than the one formed by the Unity DTM, caused by the limited DTM. Compare with the panorama photo visible in the SketchUp version, Figure 1, where the photograph is visible above the DTM surface. The setting sun causes a "nice" glare effect while keeping the sun visible. This application may provide the most attractive view. However, adding more sky elements than just the Sun involves considerable development effort.

Figure 6: Aerial view from the east of the Pranhartsberg site in our Unity application. In the right foreground is KGA Pranhartsberg 2, in the central background is the neighbouring KGA Pranhartsberg 1 (cf. to Fig. 1). A freshwater stream is flowing in the little valley between them. In this view, the GUI has been switched off to show only landscape. It usually provides a few buttons to switch the sky diagram, show online help or the current eyepoint coordinates.

Moving in the first person view through a prehistoric landscape, be that in Stellarium or in the more natural looking environment of a game engine like Unity, allows much more immersive views than top-down views in a GIS, and promises new insights into visibility studies for landscape archaeology, also apart from archaeoastronomy.

Some limitations remain currently. Most notably, the 3D landscape models both in Stellarium and Unity use a "flat earth" approximation, and the difference between astronomical north and the "grid north" used in the DTM which defines the project coordinate system which is caused by meridian convergence towards the poles is compensated by a rotation of the 3D model around the vertical axis in Stellarium, or by rotating the celestial simulation in Unity, respectively. This is no problem with a typical site model consisting of buildings and a piece of DTM usually not exceeding a few hundred metres. However, for the study of larger landscapes with high mountains visible in tens of kilometres distance, altitude and also azimuth errors have to be taken into account. It is recommended to enclose any 3D model with a classical panorama horizon ("landscape" in Stellarium's parlance) that should include horizon features so far away that they do not move appreciably when the core region of the 3D model is explored. Similarly, a panorama attached to a Skybox in Unity also can help to overcome problems with mountains beyond Unity's far camera clipping plane. Stellarium's nature as open-source project invites improvements by other voluntary contributors, so that hopefully also large-scale curved-earth landscapes could ultimately be studied.

Another limitation is the fact that Stellarium's 3D scenery plugin does not provide features found in more complete game engines. The OBJ model is static (apart from the parts which are switched invisible depending on simulated date). Therefore no interaction with scene objects is possible, and any water surface, trees or other natural object appear rock-solid. As a deliberate feature, the eyepoint is moved in relation to a "walking surface", which is usually generated by leaving away most vertical walls, columns and other architecture apart from temple bases, staircases or other ground layer objects. This allows walking through walls or putting the eyepoint onto a column or inside a statue head when this wall or statue is not included in that walking surface. On the other hand, multi-storey buildings or staircases cannot be explored with the "walking surface" paradigm in this approach. In any case, the vertical distance to the walking surface can be adjusted interactively, so that aerial views can be created, or multi-storey buildings explored at least to some degree.

The astronomical engine of Stellarium has also seen numerous improvements in long-time accuracy of object coordinates in recent years. In addition to the analytic standard model for planetary positions, VSOP87 (Bretagnon & Francou, 1988), which is recommended for use in the years -4000 to +8000, the user can now access position data from the JPL DE431 long-time ephemeris, providing planetary positions for the years -13000 to +17000 (Folkner, Williams, Boggs, Park, & Kuchynka, 2014), and the latest model for ecliptic obliquity should provide dependable results for many more millennia (Vondrák et al., 2011, 2012). However, some final corrections still have to be done, the star catalogue needs further attention (De Lorenzis & Orofino, 2018), and some astronomical problems like the irregular slowdown of Earth's rotation cannot be properly simulated by current astronomical models, so that esp. Solar eclipses elude any accurate simulation in earlier prehistory. Known other limitations are described in the Stellarium User Guide (Zotti & Wolf, 2018).

The application of a game engine for such simulations seems necessary when we must interact with game objects, or when the natural appearance of the scene is of high importance, e.g. for outreach purposes. It is a pity that solutions built during research projects to be presented to the public on the project websites may be quickly outdated and obsoleted by browser developments.

For a game engine based context where some limited simple sky model as described above is not enough, we are currently developing a method to connect Stellarium and Unity so that the former's astronomically solid sky simulation can be used in the latter's lively environment.

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