Session 4: Astronomy in other disciplines to promote science vocations

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Education and Heritage in the era of Big Data in Astronomy
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Introduction

This section begins with the invited talk "Stellarium: Simulation for Research and Outreach" by Georg Zotti. In his presentation Georg describes the history of Stellarium's development and the value that it provides. Here you will see him discuss capabilities of the open-source program and he provides good example. He talks about its planetarium-like utility and work for the future.

Following the presentation John Briggs asked:

The latest versions of Stellarium seem to have more demanding requirements for graphics and will not run, for example, on some older laptops. Can you explain about the advantages of the newer graphics requirements, as I am sure exist? (Stellarium is one of our very most wonderful current tools for astronomy education!)

Georg responded:

Stellarium is currently based on Qt5 which requires OpenGL 2.1. Some graphics simply requires support for OpenGL shading language. If you want a nice and modern simulation, old computers are just that, sorry: too old. But the current Stellarium runs on a tiny Raspberry Pi, so I think the requirements are not high. Any computer with Intel Core-i 2xxx or later should work well, or any earlier with a Geforce 8000 and later (2008?). For older laptops, you can still run version 0.12.9 or so. It is based on Qt4. However, the latest developments in historical accuracy are not included. But I used such an Atom netbook (built 2010) to track my telescope in a stay in Namibia

Anahí Caldú asked:

Georg, thank you very much for the nice talk and to all the Stellarium team for such a great work! I imagine everything is done in a voluntary way? Is it possible to raise funds somehow to hire more developers?

Georg answered:

Unfortunately... I could use full time work hours while developing this exhibition to advance precession/nutation and some other details. But most hours are our weekends and evenings. My observing time suffers...

Stellarium can be supported via OpenCollective donations (link on stellarium.org). But it's not enough to make a living from that. We use that for e.g. hardware replacements, Apple publishing licenses (!), open-access fees for publishing in qualified journals or as incentive for students working on some future additions.

I would like to be involved in a R & D program that would allow some months of concentrated development to bring this program further. We are still on version 0. until we have fixed aberration and the Lunar axis orientation I mentioned. And then the Qt framework on which Stellarium is based just has moved on to their next decade with Qt6 (released this week), which will require considerable effort adapting, maybe until 2022, esp. w.r.t. scripting support and maybe even graphics.*

Cristian Goez Theran asked:

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Is there any way to indicate the vernal points (without having to indicate the ecliptic and celestial equator), as well as indicate the galactic center in Stellarium?

and Georg answered:

Equinox and solstice points: yes: Sky & Viewing options (F4), Markings tab, find Equinoxes/Solstices.

Galactic center: Not yet, but you are the first to ask for it. Should not be hard to do. :-)

Next is Chris Impey's invited "Online Resources for Astronomy Education and Outreach" where he talks about the many astronomy education resources now available on the internet. Chris describes the global role that the IAU plays in astronomy education with initiatives such as the International Schools for Young Astronomers (ISYA). He describes how access to resources such as outreach, textbooks, and videos has been digitally enhanced and expresses the value added to their utility through internet availability. Chris cites examples such as Stellarium and other platforms as well.

"Galaxy Forum South America-Argentina" by Steve Durst, Margarita Safonova, Santiago Paolantonio, Marcelo Colazo, and Geng Li. The authors outline activity of the Galaxy Forum South America 2020 that was held on December 8th, 2020 and offered by the International Lunar Observatory Association (ILOA) with support from the Instituto de Tecnologías en Detección y Astropartículas and the IAU. Forum topics presented here regard astronomy from the Moon, the history of constellations, UV observations from the Moon, CONAE deep space station activity, and the skies of ancient China.

Johanna Casado, Gonzalo de la Vega, Wanda Díaz-Merced, Poshak Gandhi, & Beatriz García contributed "SonoUno: a user-centred approach to sonification." The authors describe sonoUno for human-computer interface for astrophysical data access, collection, sonification, and analysis. A strongpoint of this software is that it was developed from the start to be centered on the user.

After the talk Tim Spuck asked:

SonoUno question: I'm PI on Innovators Developing Accessible Tools for Astronomy where we have developed the Afterglow Access software making image analysis accessible to BVI. SonoUno sounds very interesting. Are you doing any work with whole image sonification, or is it limited to sonification of data plots? When will SonoUno be available? Is it Web-based software or does it require an install on a computer? Would love to talk more sometime.

Johanna Casado answered:

SonoUno is available at github and it is not sonorixe images but data...I will send a more detailed answer this nigh, sorry...

The last paper in this section is called "SciAccess: Making Space for All" and was written by Anna Voelker, Caitlin O'Brien, and Michaela Deming. Anna tells about the SciAccess Initiative regarding the need for greater diversity and inclusion in STEM for scientists with disabilities. She gives an overview of the initiative's projects and outlines some of the inclusive practices that can help. She concludes by stressing the importance of engaging more of those who previously had been excluded from STEM.

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Stellarium: Simulation for Research and Outreach

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Abstract. Over the past decade the free and open-source cross-platform desktop planetarium program Stellarium has gained not only most of the computational accuracy requirements for today's amateur astronomers, but also unique capabilities for specialized applications in cultural astronomy research and astronomical outreach. A 3D rendering module can put virtual reconstructions of human-made monuments in their surrounding landscape under the day and night skies of their respective epochs, so that the user can investigate and experience the potential connection of architecture, landscape, light and shadow, and the sky. It also played a key role in an exhibition about Stonehenge in Austria.

Exchangeable "skycultures" allow the presentation of constellation patterns and mythological figures of non-Western cultures. Stellarium's multi-language support allows community-driven translation of the whole program, which predestines its use in education also in minority languages.

Stellarium is developed by a very small core team, but is open to external contributions.

Keywords. Stellarium, virtual observatory, desktop planetarium, historical astronomy simulation, virtual archaeoastronomy, cultural astronomy, outreach

1. Introduction

In summer of the year 2000, Fabien Chéreau created a student project. His aim was to use modern 3D computer graphics to create a fast and realistic realtime simulation of the night sky. He decided to make this project and its source code available on the Internet, thereby attracting a handful of collaborators. By around 2006 they had raised the attention of a growing user community which earned them the title of "project of the month May 2006" on the SourceForge open-source code repository. Shortly after, Stellarium was used by ESO to easily access and browse VLT images (Kapadia et al. 2008).

The open-source nature of Stellarium also attracted the present author to use Stellarium for research and simulation in historical and archaeoastronomy Zotti & Neubauer 2011, 2015. However, the program at that time was not well suited for historical simulation, given some trade-offs in implementing simplified astronomical models in favour of high execution speed. Over the recent years, several of these issues have been solved, and several features unique to Stellarium now invite users and also researchers in the fields of cultural astronomy (archaeo- and ethnoastronomy) and history of astronomy to use it as tool for research and outreach activities.

2. Motivations for simulating past skies

There is countless evidence that the sky and its phenomena have inspired humans since earliest times (Ruggles 2015). Many earlier cultures have left traces in form of built monuments, and frequently those buildings have been erected with axes or other viewports aligned with simple but impressive celestial phenomena, like solstice sunrises or sunsets. Where those monuments are still at least partially preserved in ruins, we could visit those sites and aim at recreating the observations which caused the orientation or illumination effect in question, when sunlight may fall into a natural or artificial (or reshaped) cavity on particular dates of the year. However, there are several reasons why such observations nowadays are not really possible.

First, many archaeological sites are too fragile to be visited extensively, and well-known sites actually are in danger of destruction by overtourism. In many cases the best way to preserve an archaeological site from the elements after excavation is to carefully fill up the site again after all relevant data have been retrieved. Nowadays, documentation should include repeated 3D recording by laser scanning or photogrammetric modelling to allow recreating the excavation process (Filzwieser et al. 2016). In other cases, surface features have even vanished, and only subsoil features have been detected by aerial imaging and geophysical archaeological prospection methods like magnetometer or ground-penetrating radar surveys (Trinks et al. 2018).

The more relevant factor are secular changes in the sky. The slow changes in earth's axis tilt slightly change the solstice sunrise and sunset positions along the horizon, and precessional movement shifts the starry sky along the ecliptic, likewise changing rising and setting points of bright stars suspected to have been the target of some orientations.

Therefore, and also to make research results more accessible to a wider audience, a contemporary approach should involve computer graphics simulation which must combine an accurate astronomical simulation engine with some elements that represent the foreground, be it a simple panoramic photograph or rendering of one particular observing location, or a full three-dimensional simulation of a landscape with accurate virtual reconstructions of buildings through which the user can walk in virtual space, similar to the experience in first-person computer adventure games.

Since the 1990s desktop planetarium programs have become popular, and with advances in computer graphics, a few titles have allowed adding landscape panoramas to provide a better feeling of immersion into the observing location. Given their visual appeal and practical use, the programs are highly popular in the amateur astronomy community, and they are also frequently used for research in topics of cultural astronomy.

3. Stellarium milestones for simulation of historical sky vistas

The first group of Stellarium's developers have created a very realistically looking sky simulation based on several relevant studies from astronomical and computer graphics literature (Schaefer 1993; Preetham et al. 1999; Jensen et al. 2001; Tumblin & Rushmeier 1993; Devlin et al. 2002; Jensen et al. 2000; Larson et al. 1997). The program soon covered a wide spectrum of applications. One of the early developers added the functionality to show constellations of other cultures. He later forked off a branch (spinoff project) from which he developed a digital planetarium project from which further spinoff planetarium projects grew worldwide. Unfortunately such forks usually prevent changes made to one subproject finding their way back to the original project. The desktop version of Stellarium can be used in a planetarium dome either with fisheye projector or built-in predistortion for projecting onto a curved mirror, and it can run automated presentations programmed in JavaScript, however it has no further planetarium show-oriented infrastructure like a dome video player. Other developers concentrated on the application

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Figure 1. Comet C/1858 L1 Donati (left) in a contemporary illustration (Weiß (1892), Fig. XX) and (right) simulated in Stellarium 0.20.4. Further tweaking could improve the match of tail curvature.

for observation support by creating program extensions (plugins) for simulated ocular and sensor views, and even for driving GOTO telescopes. Stellarium was then based on the Qt4 C++ toolkit, allowing the development of the program with an unconventional user interface which is however easy to operate and works on all three major desktop platforms (MS Windows, Linux/X11, Apple MacOS X). It also allows translation of the program into dozens of user languages, which is performed by several hundred voluntary collaborators utilizing a simple web interface. These factors, and obviously the free availability, have attracted the attention of a large community of users. Currently Stellarium is regularly released around equinoxes and solstices, and each version has seen several hundred thousand downloads.

Around 2010 I have joined the team of developers and since then added a few elements which improved its applicability for research in historical sky simulation. I have first participated in including atmospheric refraction and extinction, and while we started to develop a 3D foreground renderer (Zotti & Neubauer 2012a,b), others implemented the important correction for ΔT, the irregular slowdown of Earth's rotation, which had been missing from the program so far, but is essential especially for accurate eclipse simulation. Stellarium can meanwhile apply over 30 models for ΔT correction. However, users interested in historical eclipses must be aware that to our knowledge it is not useful to attempt eclipse simulation in the remote past and expect to derive solid conclusions, given that reliable observation reports only date back to about the 8th century BC (Stephenson et al. 2016), and simply extrapolating ΔT's parabolic trend may soon lead to many hours of error, which for Solar eclipses means that while the geographic latitude of the shadow's central axis may be correctly determined, the longitude can be wrong by tens of degrees. This is not a problem of Stellarium in particular, but an open question about Earth's rotation in general.

A major challenge was then posed by an upgrade in the underlying Qt C++ toolkit in 2013/14 after which Stellarium (version 0.13 and later) had to drop support for hardware not capable of providing a sufficient level of OpenGL or DirectX graphics functionality. Unfortunately, also most developers from the first group left the project shortly after these works, which has been maintained since around that time by Alexander Wolf.

This version also saw integration of a simple comet tail model mostly taken from previous work ((Zotti 2001; Zotti & Traxler 2003)) and based on own observations of C/1996 B2 Hyakutake and C/1995 O1 Hale-Bopp, consisting of two textured slim parabolas which model ion (straight, pointing away from the sun) and dust tails (curved, depending on solar distance and velocity), and the addition of an optional data file for more than 1000 historical comets (see Fig. 1) from several sources (Frommert 2014;

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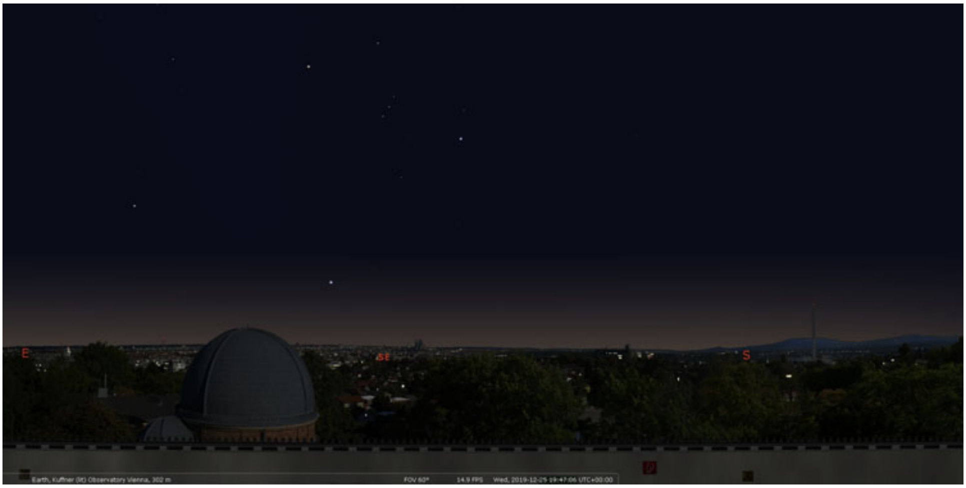

Figure 2. An illustrative simulation of artificial light at night in Stellarium 0.20.4. The landscape panorama from Vienna's historical Kuffner observatory (late 19th century) was created by M. Prokosch and made available on the Stellarium repository of publicly available landscapes. It was modified by the author by adding a simple hand-painted layer of nocturnal illumination: street lights, bright windows and the light glow of the city of Vienna towards the east.

Yeomans & Kiang 1981; Mucke 1985). A week under the pristine skies of Namibia convinced me to implement a visualisation of the Zodiacal light for version 0.13.2 (Kwon et al. 2004).

In addition to the already existing simulation of global light pollution following the Bortle scale (Bortle 2001), an optional *localized light pollution layer* (see Fig. 2) was then added to the landscape foregrounds (Zotti & Wuchterl 2016).

The higher minimum level of graphics hardware required to run the program finally allowed us to integrate the Scenery3D landscape rendering plugin (Zotti 2015, 2016) and a further plugin which shows diurnal track (declination arc) visualisations for solstices, the "cross-quarter" days (between solstices and equinoxes), and the "lunistice" declinations relevant to many archaeoastronomical studies. Also azimuths to configurable locations like sacred mountains can be displayed.

A major leap forward in creating a reliable tool for historical simulation was the implementation of an accurate long-time model of precession (Vondrák et al. 2011, 2012) and IAU 2000B nutation (McCarthy & Luzum 2003) in version 0.14.0. (Unfortunately a sign error in the original formulation of the nutation matrix Hilton et al. 2006, eq.21) went undetected until reported by a user and finally fixed in version 0.20.2.)

Shortly after, the 3D visualisation found its first real applications by other researchers (Frischer et al. 2016, 2017), where we could identify the summer solstice sunrise orientation of the entrance axis in the so-called Antinoeion in Hadrian's villa in Tivoli near Rome.

Supported by ESA's *Summer of Code in Space* (SOCIS) programme, we could develop code to access the JPL DE430 and DE431 ephemerides (Folkner et al. 2014), the latter of which provides planetary positions into times as early as −13.000, which significantly extends the applicability over the time range recommended for the classic VSOP87 analytical solution (Bretagnon & Francou 1988) used by default.

In preparation for a major exhibition (below), we could put considerable effort into the program for some time. The scenery 3D plugin was made more efficient and meanwhile

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allows us to use Stellarium's time control to also make parts of the 3D foreground semi-transparent or invisible when they do not fit to the time currently set in Stellarium. This allows the simulation of evolving monuments, like phases of building and destruction (Zotti et al. 2018).

Many users appeared to have problems understanding the seasons beginnings and how calendar dates relate to them. The application of the Julian calendar for all dates before October of 1582 leads to a known drift of the dates for season beginnings against the "canonical" dates engraved in most people's minds (and in the Christian rules for Easter computation) of March 21st, June 21st etc. Of course, for dates in the 5th millennium BC, this calendar error pushes summer solstice deeply into "July", a named date that does not really make sense in the historical context. Other cultures also have developed their own calendars and have left observational reports recorded with them. The latest release (0.20.4) introduced the Calendars plugin which allows display and handling of various calendar systems in parallel. This plugin will be extended in future versions.

Two problems identified in the original implementation have then still persisted for a long time. The rotation and orientation of planet axes, best seen in the Moon showing part of its back face in early prehistory, will finally follow more accurate procedures (e.g. Urban & Seidelmann 2013) with release of version 0.21.0 in early 2021.

A final known accuracy issue that remains to be solved is the aberration of starlight, most noticeable in lunar occultation simulation. Only after solving this we will be able to assess overall acuracy of the simulation, and may have to find remaining errors.

Astronomical improvements not primarily aimed at historical applications included the optional rendering on non-spherical planetary bodies and the addition of planetary feature nomenclature labels, both of which were implemented by students again sponsored by ESA's SOCIS programme. Over the last years, Stellarium's maintainer Alexander Wolf has added a module named AstroCalc which provides a wide variety of ephemeris tabulation and visualisation options. We have also resurrected and extended the User Guide which meanwhile contains almost 400 pages (Zotti & Wolf 2020b).

A data set which has not been significantly changed over the last decade is the use of the HIPPARCOS (ESA 1997), Tycho 2 (Høg et al. 2000) and NOMAD (Zacharias et al. 2004) star data. While cross-identification with a few other catalogs was added and some data errors removed, Stellarium does still not compute stellar proper motion in 3 dimensions (only working with the linear proper motion components) and does also not simulate motion of binary star components around their common center of gravity. A handful of bright stars therefore deviate from applications which include those corrections (De Lorenzis & Orofino 2018). A future complete remodelling of the star catalog should of course be based on results from GAIA.

4. Application of 3D foregrounds

The visualisation of 3D models under the simulated sky allows an almost natural game-like experience while studying building axes, view corridors, or also the appearance of shadows (Fig. 3). A workflow involving GIS (Geographical Information System) software, a self-made data converter and the open-source Blender 3D modelling program has been presented (Zotti 2019; Zotti et al. 2019) which allows the creation of larger landscapes. The capabilities of the Scenery3D plugin have been tested with two datasets: a 3D laser scan from the Neolithic temple of Mnajdra in Malta (Hoskin 2001), and a LiDAR (airborne laser scan) based model of the Chankillo landscape in Peru (Ghezzi & Ruggles 2015). Both models are discussed in detail elsewhere (Zotti et al. 2020b).

The immobile rigid foreground rendered by the Stellarium Scenery3D plugin may not be enough in some situations when interaction with the scene is required, for example to study the operation of historical observational instruments. Therefore a connection

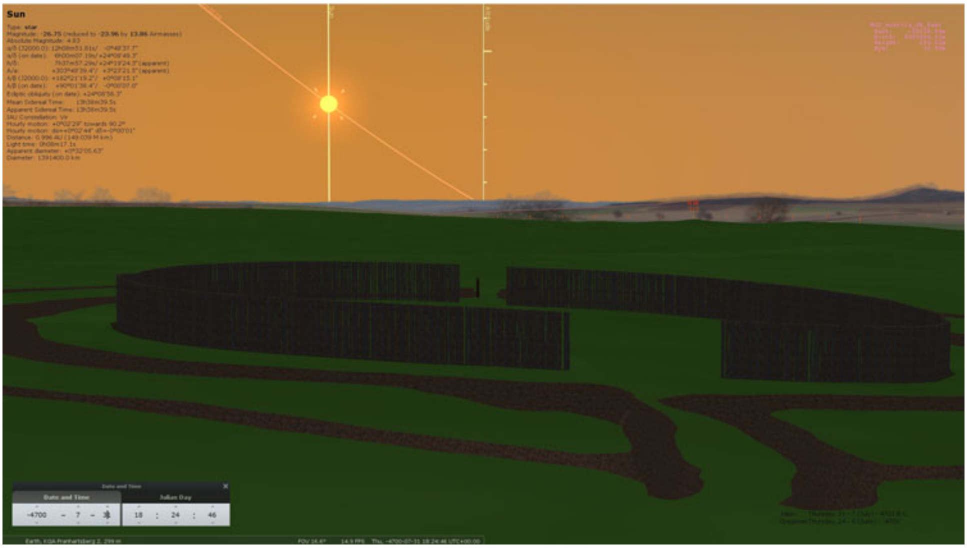

Figure 3. A simple virtual reconstruction of the Neolithic enclosure (*Kreisgrabenanlage*) Pranhartsberg 2 in Lower Austria shown with the Scenery3D plugin in Stellarium. Dozens of these monuments, consisting of circular deep ditches and palisade walls with usually 2 or 4 entrances, were erected in Neolithic Europe (ca. 4800-4500 BC), and archaeologists still discuss their purpose and use. Their traces can be usually detected only in aerial images and magnetometry surveys. One frequently discussed idea is the orientation of entrances towards solstices and other astronomically determined directions. The entrance on the far side shows a passage oriented towards summer solstice sunset, probably also visually augmented by an aligned pair of posts. The ArchaeoLines plugin indicates summer solstice declination and the Solar vertical. A vertical line indicates altitudes, and the Calendars plugin provides dates in proleptic Julian and Gregorian calendars, the latter giving a more intuitive date with respect to the seasons. However, this is the only such monument in over 30 studied in Lower Austria to show such orientation – the rest most commonly shows orientation following the terrain slope (Zotti & Neubauer 2015).

kit to the Unity game engine has been developed (Zotti et al. 2020a) which allows use of Stellarium as sky background renderer and provider of astronomical information for interactive, vivid and game-like applications.

The Stellarium team is willing to host interesting 3D models of astronomically relevant sites released under a permissive license, similar to the many conventional photographic landscapes contributed by users worldwide. However, while astronomical data usually can be freely accessed shortly after observation, keepers of accurate data of cultural heritage sites interesting to archaeoastronomical simulation unfortunately appear to generally not allow the release of such data to the public, even if that would certainly raise interest and awareness around such sites. We sincerely hope this statement can be disproved as soon as possible and robust, well-made, accurately georeferenced 3D sceneries made available.

5. Outreach: The skyscape planetarium

An exhibition project on Stonehenge in the MAMUZ museum for prehistory in Mistelbach, Austria, opened in 2016, provided developing time for some improvements. The exhibition showed replica of parts of Stonehenge's central "horseshoe" stones in original size. The surrounding circle of stones and the outer landscape was to be provided as seamless projection by 5 projectors on a 25m wide and 4m high canvas. For this screen form factor, Stellarium's capabilities of presenting a rendered sky view not only with the

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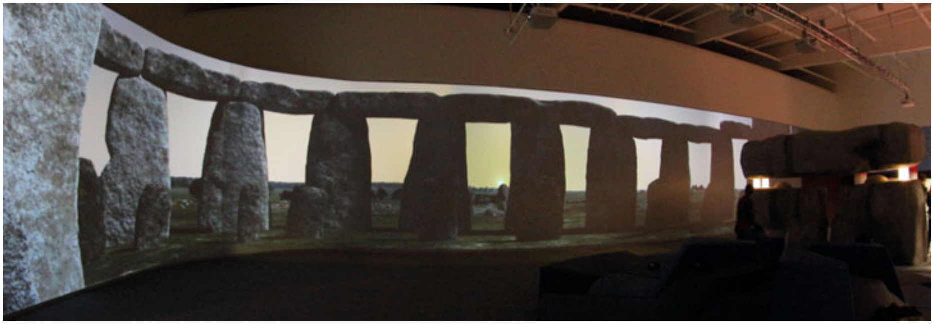

Figure 4. The skyscape planetarium, a 25×4 m screen with 5 overlapping projectors providing the landscape backdrop for the central replica horseshoe of Stonehenge in an archaeological exhibition. The scripting functions of Stellarium were used for the narration in daylight hours, and a human operator could operate the program during special tours.

perspective or stereographic projections found elsewhere, but with several others, and especially cylindrical (or Mercator and Miller variants), proved essential.

An automated show should present relevant pieces of information and take visitors on a narrated tour through the history of Stonehenge and related sites. We did not use Stellarium's 3D capabilities but limited ourselves to pre-rendered artificial panoramas, with the sky background always provided by Stellarium. The changing hues of the sky behind seen through the stones still gave an almost three-dimensional impression. When fitting to the narration, solstice sunrises or diurnal tracks could be shown. Stellarium provides a scripting engine based on JavaScript for such shows, which can also play audio files or insert images onto the screen (Fig. 4).

The big advantage of using a "live" computer program over a pre-recorded movie however lies in the possibilities the program can provide for special occasions. On a few evenings, the museum offered flashlight tours for children who entered a dimly lit museum with a tour guide. At some point they woke up a "man from the past" who then joined the group and explained some exhibits in his own language, augmented by acting, music and dancing, all this while the stars of the unpolluted night sky twinkled through the Stonehenge panorama. At some point, twilight had to set in, and the group welcomed the famous summer solstice sunrise seen from within the central stones of Stonehenge with a little ceremony. The highly successful exhibition was extended for the 2017 season.

Operating Stellarium's user interface on the big canvas would have been distracting. We therefore developed the RemoteControl plugin which allows the control of the program with an HTTP control interface (Zotti et al. 2017). This means Stellarium can be controlled from a web browser, and enables a museum operator to control the program on a portable device like a simple tablet computer or even smartphone. Meanwhile several other projects are using this RemoteControl API for their own purposes to communicate with Stellarium.

6. Skycultures

Since early in its development Stellarium has allowed displaying various collections of non-Western constellations (termed "skycultures") and a text panel of background information. Constellations can be shown just as bordered regions in the sky (IAU borders), constellation stick figures, artistic renditions, or any combination. In addition, asterisms in the modern sense of non-official stick figures and "ray helpers", longer orientation lines, can be displayed.

Over the past years several users from non-Western cultures contributed new or improved existing skycultures, but it became clear that we will also need to extend the available functionalities, because several concepts like Lunar stations (highly important in many Asian cultures) or Dark Constellations (formed by dark clouds in the Milky Way) are currently not available. A more advanced solution for the skycultures which also must involve considerations about multilingual transliteration and translation is still an important area of future research and development (Zotti & Wolf submitted).

7. Other contemporary and scientific uses

Stellarium has a plugin for the display of meteor showers with data retrieved from the International Meteor Organisation (IMO). Another plugin can display artificial satellites. A temporary popular pastime was the observation of "Iridium flares", bright reflections of sunlight by flat antennas on the first generation of Iridium communication satellites, which could be predicted and impressively visualized until the satellites were taken down. Stellarium is capable of simulating lunar and solar eclipses with meanwhile pretty good accuracy, although a few more timestamped videos (from known sites) should be investigated before we can give a final assessment. Alexander Wolf has created several further plugins to show historical supernovae and novae, pulsars, quasars and exoplanet systems, and Guillaume Chéreau made the HiPS surveys (Fernique 2017) accessible for Stellarium. He also added an extension to show multi-resolution texture maps for the planets. A few examples for the simulation of transient astronomical phenomena were given earlier (Zotti & Wolf 2020a), and the benefits of showing historical (super)novae in the context of the reporters' skycultures is discussed in detail elsewhere (Zotti et al. 2020b).

8. Conclusion and further work

Stellarium provides several unique capabilities useful for astronomical teaching, research and outreach in the domains of astronomy basics, historical astronomy, archaeoastronomy and ethnoastronomy. Likewise it is widely appreciated in the amateur astronomy community as simple and accurate tool for presentations and preparation of own observations, and it can be used during observation for telescope control and ocular/sensor view simulation. It is used by many authors as de-facto standard tool for astronomical illustrations. The constellation artwork created by Johan Meuris for Stellarium has been seen in other places outside the program, just like a multitude of screenshots, unfortunately often without giving proper credits.

As open-source tool Stellarium grows mostly by the personal ambition, motivation and interests of its authors and contributors. Over the past decade, its accuracy has been significantly improved in some most relevant parts, but it is always advisable to compare critical results to those from other sources. Authors of scientific work are still advised to keep existing accuracy limitations in mind which we give in the User Guide.

The team accepts suggestions and code contributions on the project's Github website (Stellarium 2021), but pace of development depends on available resources. The team will soon have to face the next major upgrade of the Qt framework (Qt6) to keep Stellarium available for the next decade.

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