5
Visualization of Archaeological Structure Data with Astronomical Objects

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We aim to build a light, flexible, and interactive system designed to visualize extensive three-dimensional (3D) archeological structure data combined with the positional data of astronomical objects. Visualizing astronomical objects in the sky and their positions with respect to archeological structures will provide insights into the spatial concepts employed by the builders of such structures. It will also allow us to compare the conceptual developments of civilizations. Visualization allows us to understand how people of ancient civilizations saw the astronomical objects and to explore their conceptual developments of space and the world. We will first examine the tools and technology available today, and then consider what improvements and/or modifications are needed for our purposes.

Nuestra meta es construir un sistema ligero, flexible e interactivo diseñado para visualizar datos extensos de estructuras arqueológicas tridimensionales (3D) combinados con los datos de posición de objetos astronómicos. La visualización de objetos astronómicos en el cielo y sus posiciones con respecto a las estructuras arqueológicas proporcionará información sobre los conceptos espaciales empleados por los constructores de las estructuras. También nos permitirá comparar los desarrollos conceptuales de las civilizaciones. La visualización nos permite comprender cómo la gente de civilizaciones antiguas veía los objetos astronómicos y explorar sus desarrollos conceptuales del espacio y el mundo. Primero examinaremos las herramientas y la tecnología disponibles en la actualidad y luego consideraremos qué mejoras y / o modificaciones son necesarias para nuestros propósitos.

All ancient societies throughout the world have watched the sky. Celestial events and processes were perceived by our ancestors to develop concepts of times and seasons. In antiquity the sky was a part of everyday life and it must have played an important role in developing beliefs about nature and human existence. There are many archaeological studies concerned with possible correlations between the orientations of archaeological structures and astronomical objects and events, such as sunrise/sunset, moonrise/moonset, positions of planets and stars, spatial patterns of stars, and even light and shadow cast by the Sun during the solstices and other particular times. Ample evidence of the orientation of archaeological structures with astronomical objects has been presented in earlier studies (for example, [Belmonte, 2015)], [González-García, 2015], and [Ruggles, 2015b] for the solar, lunar, and stellar alignments, respectively). By analyzing the alignment and orientation of prehistoric monuments, we can interpret the spatial perception of the people, and thereby the society, who built them.

How do we recreate the sky and landscape alignment at a specific time and visualize it? This requires accurate reconstruction of the archaeological structures, the surrounding landscape, and the positions of the celestial objects at that time. Visualization would help us to palpably understand how the people of early civilizations comprehended their environments and how they might have developed their concepts of the "World". There are several commercial software packages which can be used for visualization and analysis of archaeological structures using landscape geographic information system (GIS) data. However, they also need to display the accurate position and motion of celestial objects. On the other hand, there are desktop planetarium programs that can simulate an astronomically correct view of the sky. Most of these allow users to be at any place on Earth at any given time, though they usually use simplified astronomical calculations not suitable for testing the alignments of the distant past (Ruggles, 2015a).

Our aim is to build an accurate and interactive system designed to visualize extensive three-dimensional (3D) archaeological structures with the surrounding landscape and sky. With the help of computer graphics technology, virtual reality (VR) would allow us to walk through the reconstructed archaeological structures and to consider their alignments with the surrounding landscape and the positions of the celestial objects. Since we do not intend to reproduce a software program and/or subroutine already available to us, we began by examining three popular stellar projection software, *StellaNavigator, Mitaka*, and *Stellarium*, to determine their capabilities and accuracy in recreating scenes of the archaeological past. This allows us to ascertain what features need to be added, modified, or improved to best suit our purposes.

Sky Simulation Programs

Sky simulation programs able to simulate the accurate placement and motion of celestial objects in the sky have long been popular among astronomy enthusiasts. Many of these programs are focused on simulation of the sky in relatively recent times and are therefore not suitably useful for simulations of the skies during the archaeological past. Additionally, often it is not easy to obtain information about the algorithms used in such programs, making it difficult to assess their applicability for our purposes. In this study, we chose three popular sky simulation programs for which we have information on the astronomical data used. These are *StellaNavigator*, *Mitaka*, and *Stellarium*, which are readily available in Japan. We compared these programs to determine their applicability and limitations for archaeological use and to assess what further developments and modifications may be needed to make them more suitable for archaeological studies.

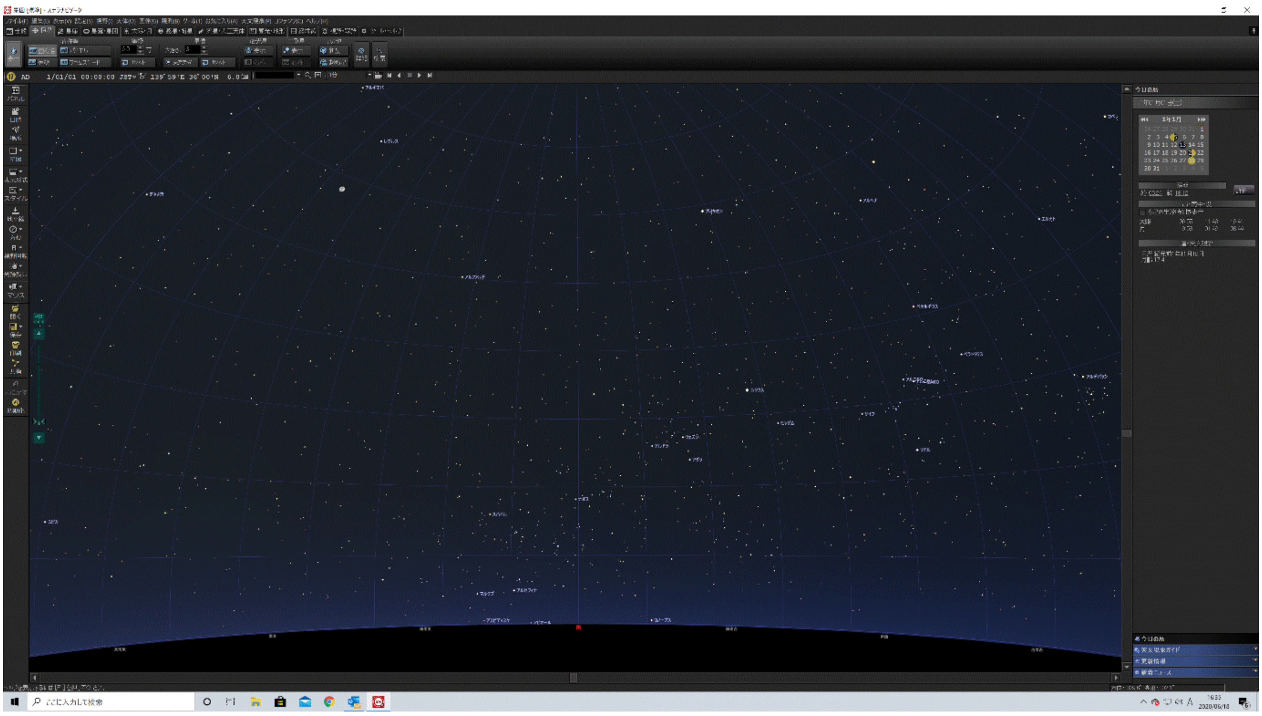
StellaNavigator

StellaNavigator (Figure 5.1) is a popular commercial software sold in Japan since 1992. The current version (Ver. 11) of this fully featured astronomy simulation software allows users to enjoy multimedia planetarium shows, fly through space, and control a telescope. A joystick or gamepad can also be used to control the system. With the use of the PC's GPS receiver, the system can obtain the correct time and current position of the user (i.e., the position of the system in use). It can also simulate the sky for any chosen viewpoint on Earth. For the simulation of celestial objects, *StellaNavigator* claims to be able to calculate star position to 0.1-arcsecond and the Moon and planets to 1.0-arcsecond accuracy in the range of 3000 BC to AD 3000.

For precession correction, *StellaNavigator* uses Newcomb's century-old values of the precession constants (Newcomb, 1895). Astronomers have suspected that there are significant errors in these values and the International Astronomical Union (IAU) adopted new precession quantities at epoch J2000.0 (JED 2451545.0) (Lieske et al., 1977). For proper motion corrections, it uses the latest Hipparcos space astrometry mission data (Damljanovic & Taris, 2019). However, there is no polar motion nor nutation correction. On the other hand, it makes rather precise Delta time (ΔT is the time difference between Universal Time and Terrestrial Time) corrections from the year 1972 to the present time using the United States Naval Observatory

Figure 5.1.

Screenshot of StellaNavigator.



Note. *StellaNavigator* screen view of the sky at the latitude +36 degrees and the longitude 136 degrees at 0 hour on January 1, AD 1. Copyright © 2019 *StellaNavigator* 11, AstroArts Inc.

(USNO) Delta T determinations, and for earlier than 1972 and for future days, it uses NASA's Five Millennium Catalog of Solar Eclipses (Espenak & Meeus, 2006). The position of the Moon and the planets was calculated with perturbations for the period between 3000 BC and AD 3000 (Kudryavtsev, 2007). The estimated error of the position coordinates compared with astronomical calendar DE406 of NASA/JPL (Standish, 1998) is less than one arcsecond.

For landscape simulations, *StellaNavigator* can generate and display a topographic image around the observation point automatically. Topographical data includes 50 m grid domestic elevation data and 1:25,000 scale topographic maps with 50 m altitude grid mesh from the Geospatial Information Authority of Japan (GSI), in addition to global 1 km digital raster data derived from a variety of sources. While this is more or less sufficient to create horizon panoramas, it may not be good enough for the testing of detailed astronomical alignments of archaeological architecture. Additionally, it does not have the option to display reconstructed 3D features.

Mitaka

Mitaka (Figure 5.2) is a free downloadable software that allows users to visualize the universe based on real astronomical data and theoretical studies, and can interactively display various celestial bodies and the hierarchical structure of the universe. It was developed by Tsunehiko Kato of the National Astronomical Observatory of Japan (NAOJ)'s Four-Dimensional Digital Universe (4D2U) Project. The latest version (1.6.0b; currently in Japanese only) was released on May 1, 2020 (Kato, 2020). Mitaka navigates across space from Earth to the edges of the known universe. It is optimized for 3D visualizations on multiple screens, but it can also be used on a single Windows PC. There is a virtual reality (VR) version which is compatible with a head-mounted display. The VR version works as a plug-in for the regular versions (currently works with Japanese version 1.5.1 and English version 1.4.1a). Users can navigate in *Mitaka*'s VR space with a game controller, such as the DualShock for Sony PlayStation, with the JC-PS201USV USB adapter by ELECOM or the SMART JOY PAD 3 PlusN by SKnet.

Mitaka employs the IAU 2000/2006 precession-nutation procedures (Capitaine & Wallace, 2007) to correct Earth's precession and nutation for the period between AD 1800 and AD 2200. Outside of this period, it uses the precession expressions by (Vondrák et al., 2011), which are valid for long time intervals with an accuracy comparable to IAU 2006 around the central epoch J2000.0, a few arcseconds throughout the historical period, and a few tenths of a degree at the ends of the ± 200,000 year time span. The Earth's axial tilt is taken from (Capitaine et al., 2000). The ΔT is corrected using (Stephenson et al., 2016) for 720 BC to AD 2015, with years outside this range corrected using polynomial expressions for delta T (ΔT) from (NASA, 2004). The positions of the Earth in the range of 13,000 BC to AD 17,000 and the Moon in the range of 3000 BC to AD 3000 are adapted from (Kudryavtsev, 2016) and (Kudryavtsev, 2007), respectively. For the planets, ephemerides of planets between AD 1900 and AD 2100 by (Chapront & Francou, 1996) are used.

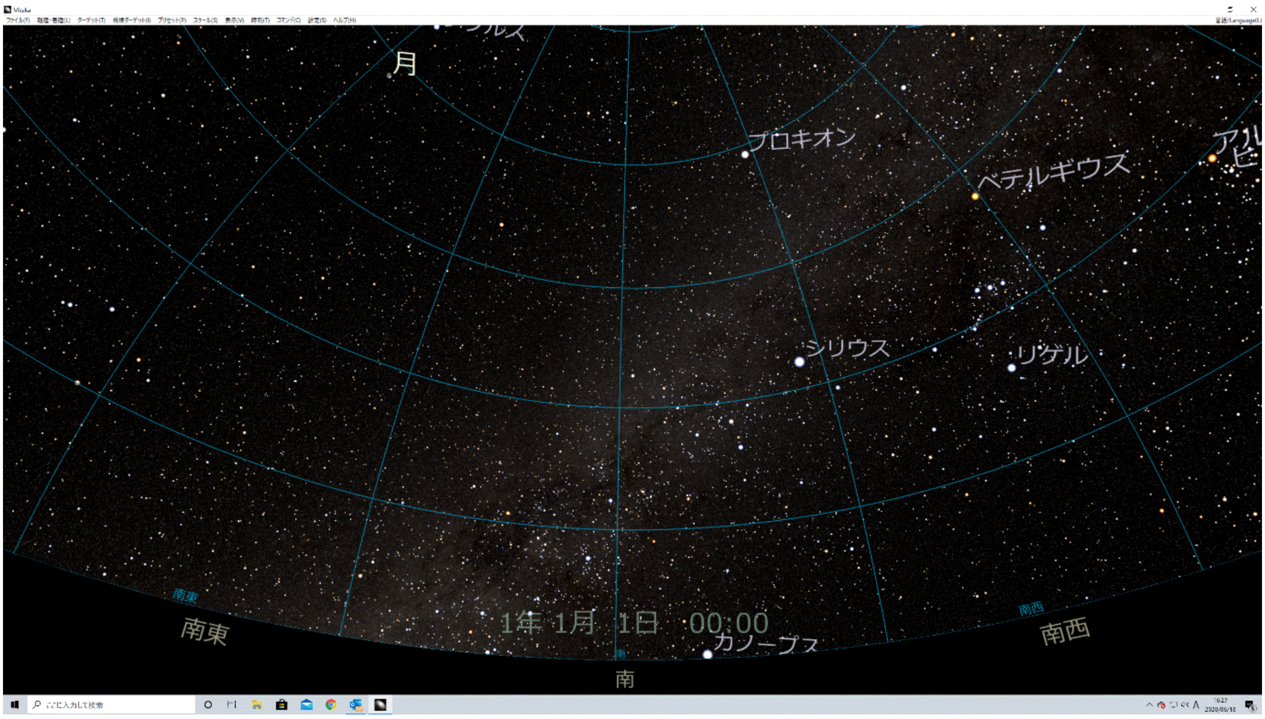
For the Earth's landscape information, GTOPO30 from the U.S. Geological Survey (USGS; U.S. Geological Survey, 1997) is used. Because *Mitaka* focuses on maneuvering in outer space, not much attention was given to the virtual reconstruction of landscape or features on Earth.

Stellarium

Stellarium (Figure 5.3) is a popular open-source desktop planetarium software package originally developed by Fabien Chéreau and others in 2000. *Stellarium* has been

Figure 5.2.

Screenshot of Mitaka.



Note. Mitaka screen view of the sky at the latitude +36 degrees and the longitude 136 degrees at 0 hour on January 1, 1 AD. Copyright © 2020 *Mitaka* Version 1.6.0b. NAOJ

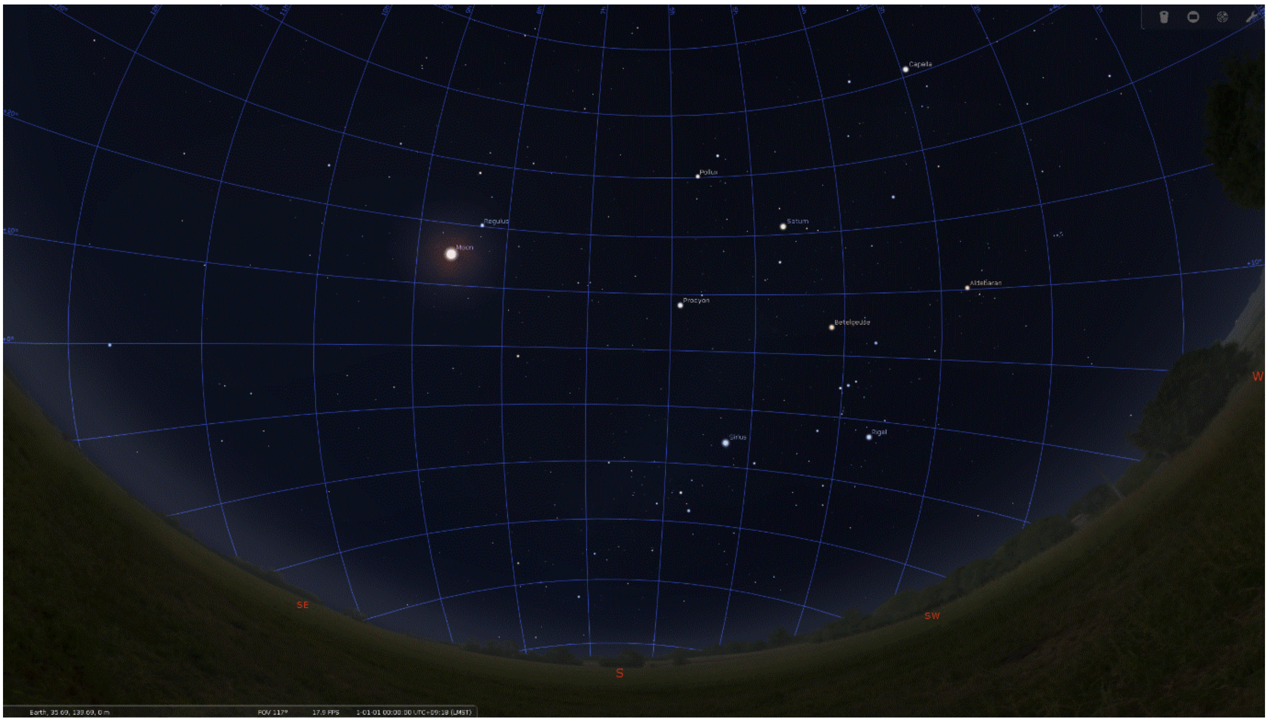
further developed and used extensively for archaeological applications by Georg Zotti (Zotti, 2016a; Zotti & Wolf, 2018). With various plugins, *Stellarium* can project celestial objects, visualize reconstructed 3D architecture, and recreate the past landscape anywhere and at any given time. It can simulate shadows cast by the Sun and Moon on the reconstructed archaeological features.

The latest version, *Stellarium* 0.20.1 (Zotti, 2020), uses precession corrections by (Vondrák et al., 2011) and IAU2000B nutation (McCarthy & Luzum, 2003), though nutation is only computed for ± 500 years around J2000.0. Positions of the planets are calculated using analytic model VSOP87 (Bretagnon & Francou, 1988) and its use is recommended for 4000 BC to AD 8000. However, as an option, for the range between 13,000 BC and AD 17,000, JPL DE431 (Folkner et al., 2014) can be used for much more accurate planet positions. The ΔT is corrected using, by default, (Espenak & Meeus, 2006). Additionally, *Stellarium* offers several ΔT models which the user can choose from.

The Scenery 3d plugin was released with *Stellarium* 0.13.3 in 2015 (Zotti, 2016b). The current Version 0.20.1 (Zotti, 2020) allows architectural 3D models to be embedded into the landscape. It allows users to walk through reconstructed structures and confirm the astronomical alignment of the structures. This plugin also simulates the shadows of the scene's structures cast by the Sun, Moon, and even Venus. Furthermore, it has a plugin called ArchaeoLines which displays any combination of declination (δ) arcs, such as the declinations of equinoxes,

Figure 5.3.

Screenshot of Stellarium.



Note. Stellarium screen view of the sky at the latitude +36 degrees and the longitude 136 degrees at 0 hour on January 1, 1 AD. Copyright © 2020- *Stellarium* 0.20.1.

declinations of the cross-quarter days, declination of the Zenith passage, current declination of the Sun, current declination of the Moon, etc.

Discussion

The tools of archaeology continue to change and evolve as new questions arise, bringing with those changes many technological challenges. In response to those challenges, the toolkit of archaeology is also changing. Whether or not archaeological structures were built in connection with astronomical orientation patterns can be tested visually, using accurate virtual recreations of the archaeological site with astronomically correct simulated positions of the celestial objects. With the help of computer graphics technology, such 3D visualization can be achieved.

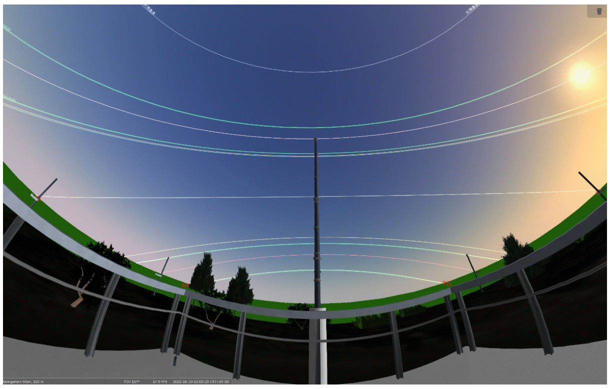
There are two possible ways forward in developing a system for the testing of possible correlations between the orientation patterns of archaeological structures and celestial objects. One is to add an accurate background astronomical simulation to the landscape visualization programs; the other is to add landscape and archeological structures to astronomical simulation programs. In this study we took the latter approach, because there are many astronomical simulation packages that allow calculations of the accurate position and movement of celestial objects and the ability to project them on monitors and screens. We compared three popular astronomy simulation software.

Each of the three programs examined was developed for slightly different applications. *StellaNavigator* is for an individual user on a desktop PC and mobile terminal. *Mitaka* is mainly for a dome theater focused on visual rendering performances and has versions for 3D and virtual reality (VR). *Stellarium* was originally developed for the desktop PC and now has a mobile and Web version. All three programs apply various corrections achieving accurate views of the sky in past centuries. Though it depends on the degree of accuracy required, for at least a rough approximation, these are adequate to test the astronomical circumstances surrounding the archaeological structures.

To combine the landscape and the sky view, *StellaNavigator* allows users to project a skyline, which was created using the topographical data, or a 360-degree panoramic picture taken from a fixed viewpoint. *Mitaka* uses the global 1-km digital raster data (USGS) to draw the horizon. Only *Stellarium* is equipped with a sophisticated 3D landscape plugin, called Scenery3d (Zotti, 2015, 2016b, 2019; Zotti et al., 2019), which allows us to incorporate 3D structure and landscape models into the sky view (Figure 5.4).

Figure 5.4.

Screenshot of a sample Stellarium simulation.



Note. Stellarium simulation showing *Sterngarten* (Star Garden) of Vienna with ArchaeoLines plugin, which shows declinations of equinoxes, declinations of the cross-quarter days, declination of the Zenith passage, declination of the Nadir passage, declination (δ) of the currently selected object, etc. Copyright © 2020 *Stellarium* 0.20.1.

Over the last decade, Zotti and his collaborators have developed and improved *Stellarium* for use in archaeological studies (Zotti et al., 2019). They successfully applied *Stellarium* to archaeoastronomical simulations of Middle Neolithic Circular Ditch Systems (Zotti, 2016a; Zotti & Neubauer, 2012), the MayaArch3D project (Zotti, 2016b), and Hadrian's Villa (Frischer et al., 2016). Because *Stellarium* is an open-source software, it allows modifying and/or adding new plugins without any license agreement. Additionally, while *StellaNavigator* and *Mitaka* are good for astronomical displays, they require more development to display architectural 3D models. We therefore chose *Stellarium* for further investigation in developing our customized system.

The Scenery3d plugin for *Stellarium* enables users to load 3D models of architecture with the surrounding landscape into an astronomical background simulation. It also allows users to walk through the simulated architectural 3D models and investigate the potential astronomical orientation of the structures. Scenery3d uses Wavefront Technologies' OBJ file format, which stores geometric objects and 3D data. For the 3D archaeological structure data, the actual measurement data can be used (for example, in the CAD format). For the GIS-based landscape modeling, we could use GTOPO 30 or NASA's Shuttle Radar Topography Mission (SRTM) data for a coarse landscape. If available, LiDAR data would provide a finer and better landscape model.

Conclusions

We examined three popular astronomy simulation software, *StellaNavigator, Stellarium*, and *Mitaka*, for their suitability in investigating the possible alignment of archaeological structures and celestial objects and events. While all three software can accurately model the sky from centuries past, *Stellarium* offers a better option for modeling 3D architecture within the surrounding landscape. Furthermore, as *Stellarium* is an open-source software, it can be freely modified to suit our specific needs. While *Stellarium* is currently offered for PC, mobile phones, and the Web, no VR versions are available. The next stage of our project is to construct an OBJ file for a sample archaeological site in Japan and develop a VR version which can be used on-site. Visualizing 3D models with the simulated sky has the great potential to allow researchers to address questions about the possible alignment of archaeological structures and celestial objects.

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