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Visualization on the Day Night Year Globe

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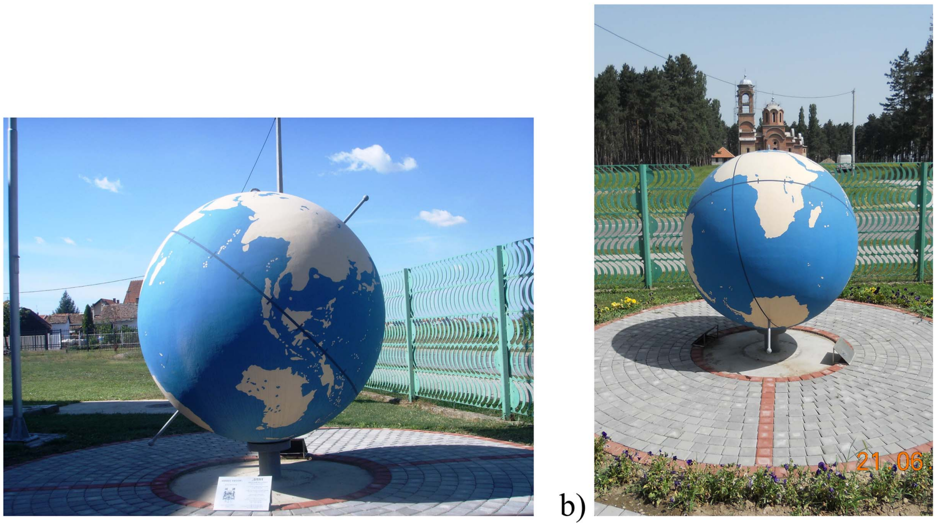
Abstract
The story about a properly oriented outdoor globe in the hands and minds of Eratosthenes, Jefferson, Milanković and science educators is presented. Having the same orientation in space as the Earth, the Day Night Year Globe (DING) shows in real time the pattern of illumination of the Earth's surface and its diurnal and seasonal variations. It is an ideal object for the visualization of knowledge and increase in knowledge about: the form of the Earth, Earth's rotation, Earth's revolution around the Sun, the length of seasons, solstices, equinoxes, the longitude problem, the distribution of the Sun's radiation over the Earth, the impact of this radiation on Earth's climate, and how to use it efficiently. By attaching a movable vane to the poles, or adding pins around the equator to read time, DING becomes a spherical/globe-shaped sundial. So, the DING is simultaneously useful for teaching physics, geophysics, astronomy, use of solar energy and promoting an inquiry-based learning environment for students and the public.

Keywords: globe, spherical sundial, Eratosthenes, Jefferson, Milanković, insolation of Earth, scientific visualization

(Some figures may appear in colour only in the online journal)

1. Introduction

The terrestrial globe, which has been widely used in education, is mounted on a support in such a way that its axis of rotation makes a fixed angle with the plane of the horizon. Such a globe is useful in teaching geography and in representing political and other kinds of maps. But such a globe cannot be useful in teaching the effects on Earth which depend on Earth's



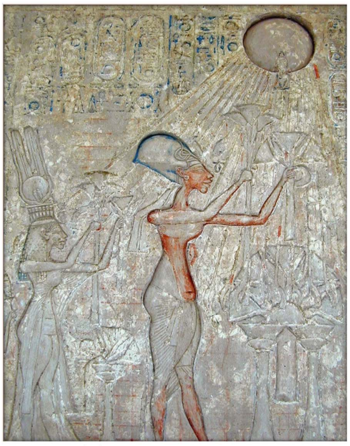
a) b)

Figure. 1 DING in Šabac, Serbia. The day–night line (a) lies along the meridian during the spring equinox and (b) makes an angle of 23.5° with the meridian during the summer solstice. Figures 1(a) and (b) are reproduced with the kind permission of Europhysics News from Božić (2013).

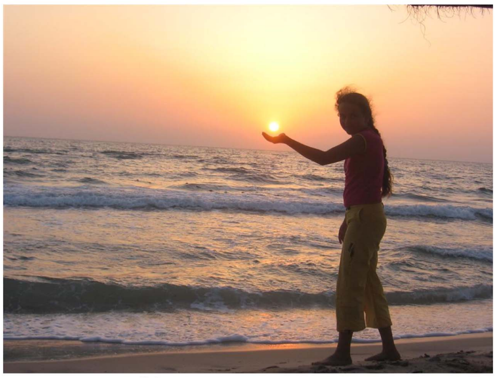
(a) (b)

Figure 2. (a) Wonder globe created by Replogle (Replogle Globe 2013). It offers smooth rotation around two different axes; (b) The OmniGlobe (Old Dominion University 2011) located in the foyer of the Physical Science Building of Old Dominion University in Norfolk, VA, displaying a spherical projection of sea surface temperature (with kind permission of Charles I Sukenik who took the photo).

orientation in space, i.e. on its orientation with respect to the Sun. For these purposes an outdoor static globe that has the same orientation in space as the Earth is necessary. We shall name it the Day Night Year Globe (DING), by slightly modifying earlier proposed names and abbreviations Day Night Globe—DNG (Geva 2002) and Dan I Noć na Globusu—DING



(a)



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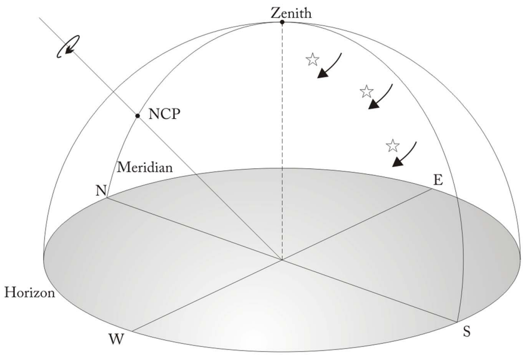

(c)

Figure 3. (a) Pharaoh Akhenaten and his family adoring the ancient Egyptian solar deity Aten—disk of the Sun. This Pharaoh Akhenaten image has been obtained by the author(s) from the Wikimedia website (Wikipedia 2016) where it was made available by Magnus Manske under a CC BY-SA 2.0 licence. It is included within this article on that basis. It is attributed to Jean-Pierre Dalbéra. (b) The Sun in the hands of Jelena Banjac, the winner of the Physics Talent Search Competition in 2005 in Serbia and of the Kodak Photo Competition in 2006 (with kind permission of the Serbian Physical Society, the publisher of *Mladi Fizičar*). (c) The celestial sphere above the observer's local horizon.

(Topalović and Božić 2011). Since the beginning of this century, static globes positioned in this way were erected in the Clore Garden of Science in the Wiezmann Institute in Israel (Geva 2002, Sharon 2005, Božić and Ducloy 2008), near the Max Valier Observatory in Italy, in the courtyard of the Tre University in Rome (Altamore *et al* 2010), in the Center for Advanced Education of Teachers in Šabac, Serbia (Božić 2013) (figure 1), in the Science park in Zurich (Garoon Gateway to Science 2010) and other locations. In the same period producers of globes created globes which offer exceptionally smooth two-axis rotation. The globe with two-axis of rotation produced by Replogle Globes was named Wonder Globe (Replogle Globes 2013). Such a globe may be positioned at any place on Earth so to have the same orientation with respect to the Sun as the Earth itself (figure 2(a)). In this way, as long as it stands in open space without being moved or rotated, Wonder Globe functions as Day Night Year Globe—DING.

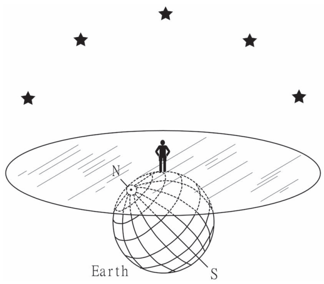

Figure 4. An observer stands on the Earth looking at the sky. The *local horizon plane* is tangent to the Earth beneath an observer (Kemble 1966).

OmniGlobe (Old Dominion University 2011, ARC Science Simulations 2015) uses artificial light sources, instead of the Sun, for demonstration and simulation of various phenomena on Earth. It is equipped with two projectors and a hemispheric mirror inside the five-foot translucent globe, and a library of digital imagery provided by the instrument's computer component housed in a nearby kiosk. The OmniGlobe (figure 2(b)) can project a range of geospatial data from the wide field of Earth and planetary sciences.

The need, advantages, and usefulness of using a DING in education and public understanding of science will be exposed and explained here following the historical development of concepts and human knowledge related to the form of the Earth, Earth's rotation about its axis, Earth's revolution around the Sun, longitude problem, time keeping and the distribution of sunlight and radiation over the Earth.

In section 2 we explain the rule for setting a globe in a position so that it has the same orientation in space as the Earth. This rule is discussed by comparing the relevant concepts associated with the idea of the Earth as a plate with the concepts associated with a spherical Earth. Section 3 is devoted to the invention of the scaphe and Eratosthenes' measurement of Earth's size in the antiquity and in the schools of today. In section 4 we describe the mapping of Earth's daily rotation onto a DING and the use of this mapping in the construction of a spherical and globe sundial, as well as in the explanation of solar time, standard time and equation of time. The mapping of Earth's revolution around the Sun onto a DING, in particular the variation of the angle between th DING's axis and circle of illumination during one orbital year, is studied in section 5. In section 6 we argue that a DING might be useful in teaching about the insolation of Earth in the context of the efficient use of solar energy, as well as about secular changes of climate on Earth. In section 7 we conclude that a DING is simultaneously useful for promoting an inquiry-based learning environment for students, teachers and public and in teaching the nature of science (NOS).

2. From the idea of Earth as a plate to the spherical Earth

Although man has observed the Sun and Moon since pre-history (figures 3(a) and (b)) and could note their spherical shape, the idea of the spherical Earth appeared only around the third century BC (Gore 1891). Previously, the idea of the Earth as a plate prevailed, because the Earth appeared to an observer on its surface as a vast plain, with the horizon (figure 3(b)) supporting the sky as a dome-shaped ceiling (figure 3(c)). The line perpendicular to the horizon plane pierces the celestial sphere at the point called the zenith (figure 3(c)). The line from the observer pointing towards the North Celestial Pole (NCP) is the next important line.

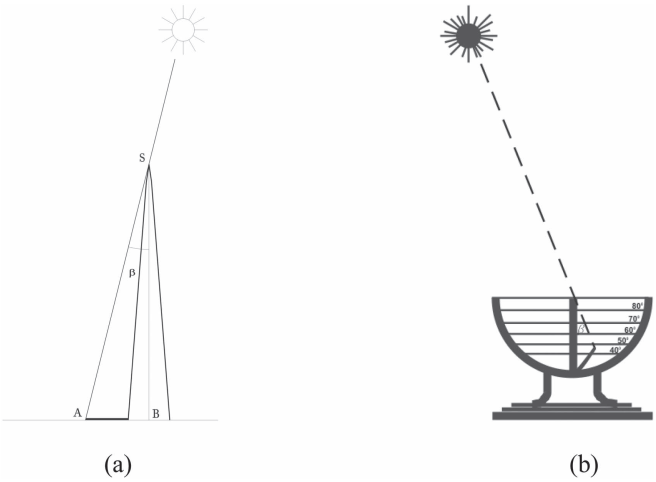

Figure 5. Measurement of the Sun's altitude using: (a) obelisk (vertical gnomon) and (b) gnomon in a hemispherical bowl with scale.

The plane defined by the normal to the horizon plane and the line from the observer's position towards the NCP defines the local meridian plane. The intersection of this plane with the celestial sphere defines the local celestial meridian. The intersection of the local meridian plane and horizon plane defines the local geographic meridian. This line is at the same time the projection onto the horizon plane of the line from the observer's position to the NCP.

All these concepts, formed in the period when the idea of the Earth as a plate dominated, remained important and useful during the development of the idea and knowledge of the Earth as a sphere. The horizon plane remained an important concept because the horizon plane coincides with the tangent plane of a spherical Earth at the observer's position (figure 4).

The line perpendicular to the horizon plane leads to the zenith. Its prolongation towards the center of the spherical Earth lies along the radius connecting Earth's center and observer's position. The line from the observer's position to the NCP to a very good approximation coincides with the line connectingthe Earth's center and NCP, i.e. the Earth's south–north axis. This is in fact the Earth's axis of rotation.

These concepts are necessary and sufficient to set a globe in such a position that it has the same orientation in space as the Earth, i.e. to become a DING. The tangent plane of the DING at the point on the globe representing the DING's position has to be parallel to the horizon plane at this position (see figure 4(b) in Božić *et al* 2005). This means that the point on the DING that represents its position on Earth should be on the top. For example, Rehovot is at the top of the DING erected at the Weizmann Institute (Geva 2002, Sharon 2005) and Rome is at the top of the DING erected at the Tre University in Rome (Altamore *et al* 2010).

The south–north axis of the DING has to be parallel to the Earth's south–north axis. Therefore, it is inclined with respect to the horizontal plane at an angle equal to the latitude of the site. Its projection on the horizontal plane lies along the local geographic meridian. This provides a practical method for properly orienting the DING's axis.

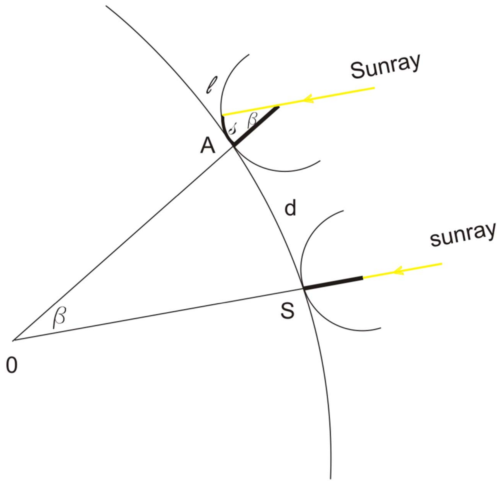

Figure 6. Illustration of Eratosthenes' procedure, similar to the illustration in Weir's translation (1931) from the Greek of Cleomedes' account of Eratosthenes' measurement.

3. Invention of scaphe and the measurement of Earth's size

From the above description it is clear that a DING is very useful to teach concepts associated with the idea of the Earth as a plate developed to concepts associated with the spherical Earth. In addition, a DING is very useful to visualize these concepts and to use them in teaching how the advent in the speculations about the size of the Earth were made in the third century BC. Thanks to Aristarchus' improvements of the instrument gnomon-shadow measurer, Eratosthenes not only put forward the idea of a spherical Earth, but devised a method to determine its circumference (Gore 1891, Weir 1931, Decamp and Hosson 2012).

The gnomon was unquestionably known to Chadleans and ancient Egyptians as well as by Anaximander (611–546 BC) and/or his pupil Anaximenes. A gnomon consisted of a pin standing perpendicularly upon a horizontal plane on which it casts its shadow (figure 5(a)). The length and the direction of the shadow change during the day and they used these phenomena to measure time.

Aristarchus of Samos (~310–230 BC) improved the gnomon instrument by substituting for the plane a hemispherical bowl—scaphe (figure 5(b))—and placed in its lowest interior point a peg equal in length to the radius and perpendicular to the plane to which the bowl was attached. Concentric equidistant circles, drawn about this peg on the inner surface of the bowl, formed the scale by which the Sun's altitude was directly read from its shadow. This invention is of great importance, since it was the forerunner of all angle-measuring devices where a graduated circle is employed (Gore 1891).

The scaphe was also used to determine the latitude of the place. On the equinoctial day, the noon Sun casts no shadow at the equator, hence the angular length of the Sun's shadow at any other point on this day when it is on the zenith will give the angular distance of that point from the equator or its geographical latitude.

From Cleomedes' account (first century AD) of the measurement of the Earth's circumference as performed by Eratosthenes about 200 BC, it is now known (Gore 1891, Weir 1931, Decamp and Hosson 2012) that Eratosthenes used a scaphe in his measurement. Eratosthenes (~284–194 BC), director of the famous Library of Alexandria, learned from books that in Syene, at the time of the summer solstice and at noon local solar time, the Sun illuminates the bottom of the well, meaning that the Sun will cast no shadow of an erect object. Eratosthenes knew that the latitude of Syene (now Aswan) in South Egypt, was a little less than the latitude of the Tropic of Cancer. Considering that Alexandria and Syene lay on the same meridian (Weir 1931) he observed the shadows of the columns in Alexandria during the next summer solstice and measured the angle β at that day using a scaphe (figures 5(b) and 6). According to Cleomedes (Weir 1931), Eratosthenes found that the angle β is one-fiftieth of the whole circle ($\beta = 7°12' = 7.2°$, as we write today). So: 'Whatever proportion then the arc in the scaphe holds to its complete circle, the arc from Syene to Alexandria holds the same. But the arc in the scaphe is found to be the one-fiftieth part of the whole circle. Necessarily, therefore, the interval from Syene to Alexandria is the fiftieth part of the great circle of the Earth. And this is five thousand stadia. Hence, the whole circle becomes 25 myriad (250 000) stadia' (Weir 1931).

Using mathematical symbols (figure 6) and relations this reasoning is written as follows: $s/2l = d/O$, where O is Earth's circumference. Eratosthenes found that the arc in the scaphe was one-fiftieth of the whole circle, i.e. $s/2l = 1/50$. Therefore, $d/O = 1/50$. Taking that $d = 5000$ stadia, the whole circle becomes $O = 250\,000$ stadia.

Today, we do not know exactly what distance a stadium meant to Eratosthenes. Based on actual sizes of Greek stadia, it must have been about $1/6$ km (Bennett *et al* 2004). Thus, the quantities are $d = (5000/6)$ km $= 833.3$ km and $O = 50 \cdot d = 41665$ km. This value for O is quite close to the modern value of just over 40 000 km.

On the basis of a rather simple model of the Earth's insolation, Babović and Babović (2014) generalized Eratosthenes' method and derived a new formula for determining the length of the year for all planets with sufficiently small eccentricity.

Eratosthenes' measurement and the historical scientific process which led to it are an ideal example that shows 'that historic process often promotes a dynamic view of science that is useful for the implementation of inquiry-based teaching learning sequences' (Hosson 2008). Many collaborative educational projects and activities have been realized since 1996, when four students proposed to their science teacher Karen Nishimoto, at Punahou School in Honolulu, Hawaii, to do 'something like Eratosthenes's experiment' as their annual science project (Nishimoto 1996). Melanie, Alex, Elise and Kawika performed a true inquiry-based experiment because they had to perform the experiment during winter, and none of the seven schools they contacted were directly north or south of Hawaii. To find answers to their questions, a student consulted Arno Penzias, Nobel prize winner and head of research at Bell Laboratories at that time. The internet was not yet so accessible, so students collected data from companion schools by e-mail.

Starting September 2000, thousands of students from 8 to 14 measured the Earth's circumference by observing the shadow of a vertical stick at solar noon during lectures at school. They exchanged their results with companion schools through the internet and deposited the results at the web site of the project 'Following the footsteps of Eratosthenes' (Sur le pas d'Eratosthene 2000, Folco *et al* 2002).

2180 students from 89 schools in five different countries (Finland, Poland, Serbia, Greece, Egypt) completed Eratosthenes' experiment on the same day in the framework of the multinational European Science Education Initiative (acronym: OSR). Working groups of up to four students collected the measurement scores within their school sites, which by selection covered about 30 degrees of latitude (Sotiriou and Bogner 2015). The analyses clearly show more accuracy in the scores as the measurement sites become more distantly located (within Greece: 17.6% error; Greece–Finland: 1.3% error). The results of Eratosthenes-like

Figure 7. Inflated globe sundial with pins attached around its equator is a hands-on version of the spherical sundial erected that is made of marble near the Max Valier Observatory in Italy (Peer S.r.l. 2016).

measurements with observers located in Australia and New Zealand were published by Longhorn and Hughes (2015).

For future inquiry-based projects based on Eratosthenes' measurement we have three proposals.

a. Student should start to use a scaphe in addition to a gnomon. By using a scaphe the experiment would be closer to the original experiment as pointed out by Decamp and Hosson (2012). Apart from this, students would learn how a protractor came to be used for measuring angles. Students would understand that it is not necessary to use trigonometry in order to measure the angle that the Sun's rays make with a gnomon.
b. Knowing Archimedes' relation between the circumference of the circle and its radius, $O/R = 2\pi$, one easily finds the value of the Earth's radius which follows from Eratosthenes' result, $R = 6631$ km. This value is close to the value $R = 6370$ km of the mean radius of the Earth, determined by modern techniques. But, an interesting historical question arises: did Eratosthenes know Archimedes' relation? Looking for the answer to this question through educational projects motivated by inquiry-based learning would be interesting, useful and stimulating.
c. To visualize Eratosthenes' reasoning using a DING by attaching sticks at few places along observer's meridian.

4. Mapping of the Earth's daily rotation onto a DING

The most important feature of a DING is that its illumination by the Sun's ray is analogous to the illumination of the whole Earth by the Sun's rays. We may say that there is a mapping between the Earth's illumination and the illumination of a DING. Due to this, by observing how the illumination of a DING changes during the day and during the year, students may simultaneously follow the effects of the daily rotation of the Earth and yearly revolution around the Sun on the whole Earth. As such, a DING has many advantages over two dimensional drawings presenting these effects in standard textbooks. It was pointed out by Szostak (1999), that such experience is very important for students because it directly shows

Figure 8. Jefferson's sundial was reproduced in Monticello in 2001. It is mounted on capital designed by Latrobe, for the columns in the vestibule of the senate chambers in Washington, DC.

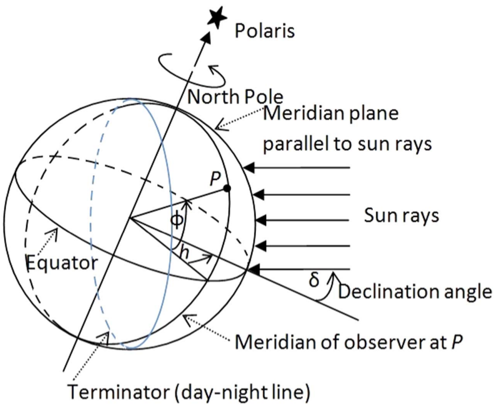

Figure 9. Declination of the Sun, hour angle and day–night line. The hour angle is denoted by h.

that phenomena happening on a large scale in the Universe may be studied and understood by observing phenomena in the local laboratory and environment on the Earth.

At any moment during a sunny day, students may observe the current position of the day–night line (circle) on the Earth (figure 1), i.e. where it is dawn and where the Sun is setting at the horizon. By following the motion of this circle around a DING, they may see the effect of the Earth's rotation around its own axis, which is analogous to the effect one could see by observing the Earth from a satellite. By measuring how fast the day–night line moves students may calculate the Earth's angular velocity.

Students may also follow how changes of certain optical quantities, which are due to this rotation, depend on the position on the Earth. Nice examples of such quantities are lengths and directions of shadows of vertical pins put around the equator of a DING (figure 7). Due to this, a DING with pins around the equator, or with a movable vane (figure 8), serves as a sundial–globe/spherical sundial.

4.1. DING with pins around the equator or a movable vane–the globe/spherical sundial

The spherical sundial erected in 2006 in the vicinity of the Observatory 'Max Valier' in Italy (Peer S.r.l 2016) is in fact a DING with metal pins along the equator. There is a pin at each 15° longitude, and a pin at the intersection point of the local meridian with the equator. A hands-on realization of such a spherical sundial (Božić and Ducloy 2008) is shown in figure 7.

The shadows of the pins show whether the Sun is north or south of the equator. At the equinoxes, the shadows of all pins fall along the equator. The shadow of any pin is shortest at local noon when the Sun 'crosses the local meridian plane' and reaches the highest point in the sky. At that moment the Sun's ray lie in the local meridian plane (figure 9)—the Sun is due south. With the help of the shadows of the pins one can determine approximately the local solar time. The current solar time at the sundial's location is read by looking for the pin with the shortest shadow and its longitudinal distance from the local pin.

This longitudinal distance is associated with the angular distance between the meridian of the observer and the meridian whose plane contains the Sun. In astronomy, it is called the hour angle (figure 9). The hour angle is zero at *solar noon* (12:00 h). The hour angle increases by 15° every hour.

There is an instrumental error in the readings on the globe with pins, due to the fact that the angular distance of the pins is 15°. In the case of Jefferson's spherical sundial (figure 8) this type of error is reduced because this dial has a movable vane instead of fixed pins. The current solar time can be determined by moving the vane, made of a thin sheet iron that pivots on the north and south poles. One rotates it about the polar axis until it casts the least shadow on the sphere. In this way one finds the meridian (the longitude) where it is the solar noon at that moment.

Despite the fact that it is strikingly simple to understand the functioning and scaling of a spherical/globe sundial, other types of sundial, horizontal sundials for example, have been and are still much more present all over the world. The scales of most widespread sundials are not uniform; they depend on the position on the Earth and usually it is necessary to apply space geometry, trigonometry and sometimes spherical trigonometry in order to determine their scales (Rohr 1970, Erichson 1974, Jasperson and Fitz-Randolph 1977, Zanetti 1984).

The globe sundial has advantages over other types of sundial not only because of its simplicity but also because it is useful as a starting point in teaching the history and principle of the functioning of sundials, as well as in facilitating the understanding of methods of determination of scales of various sundials (Božić and Ducloy 2008). In arguing the adventages of the spherical sundial, Jefferson's experience (Wilson 2005) in constructing and using a spherical sundial is particularly interesting.

Jefferson's spherical sundial was made in Monticello by Jefferson sometime between August 1809 and September 1816 (Wilson 2005). In 1806, the architect Benjamin Henry Latrobe sent Jefferson (then already retired president) the full-scale model of a capital he had designed for the columns in the vestibule of the senate chambers in Washington, DC and an the horizontal dial cut in Pennsylvanian marble of a proper size to be put on a capital. In 1816 Jefferson sent Letrobe the drawing of his own design of a sundial mounted on Latrobe's capital (Thomas Jefferson Foundation, Inc. 2002).

Jefferson explained that he came to this invention thanks to his efforts to find a simple method to determine the longitude of Monticello. At that time, the longitude problem, both at land and at sea, was a challenging problem worldwide, as was well described by Bensky (2010). Bensky also proposed a longitude-based international and general education physics course. Latrobe concurred in the uniqueness of the spherical dial and responded, 'In respect to your Dial, I can only say that its principles are so plain, and its construction so easy, that dials on Your construction might be brought into very general use, if once known and introduced'. (Wilson 2005). Later the dial was lost. The Thomas Jefferson Foundation reproduced it in 2001 (Beiswanger 2001).

4.2. Solar, sidereal and standard time, equation of time

It is useful to understand the functioning of a spherical sundial because it is tightly connected with the fundamental unit of time measurement—the mean solar day. The mean solar day is the average over the entire year of the solar day, which is the period of time during which the Earth completes one rotation with respect to the Sun. The time of one complete rotation with respect to the Sun is seen by an observer on the Earth as the time between two consecutive passages of the Sun through the plane of the local meridian.

The mean solar day is the base of the primary time scale, Universal Time (previously called Greenwich Team Time) which is still measured at the Prime Meridian. This is a 24 h time system, according to which the length of a day is 24 h = 86 400 s (more precisely 86 400.002 s in recent decades) and midnight is 0 h. There are about 365.2422 solar days in one mean tropical year.

The clock time which we read in our everyday life is based on the system of standard time zones, which were introduced around 1880 in such a way as to have 12:00 noon be approximately in the middle of the day regardless of the longitude. These are geographic regions, approximately 15 degrees of longitude wide, in principle centered about a meridian along which local standard time equals mean solar time. A DING with pins along the equator (figure 7) visualizes this principle. However, time zones often have unusual shapes to conform to social, economic, and political realities, so larger variations between standard time and means solar time sometimes occur.

Two effects contribute to the variation of the solar day over the course of the year. The first effect is due to the Earth's varying orbital speed along the orbit. The second effect is due to the tilt of the Earth's axis with respect to the ecliptic. Together, the two effects make the actual length of solar days vary up to about 25 s (either way) from 24 h. Because the effects accumulate, at particular times of year the apparent solar time can differ by as much as 17 min from the mean solar time. The net result is often depicted visually either as an analemma or on a graph as 'the equation of time'. The ordinate at any point of the equation of time is equal to the difference between the mean solar time (standard time) and the true solar time on the corresponding date.

In astronomy and orbital mechanics the concept of stellar or sidereal time is often used—the span of time it takes for the Earth to make one entire rotation with respect to the celestial background or a distant star (assumed to be fixed). This period of rotation is about 4 min less than 24 h (23 h 56 min and 4.1 s) and there are about 366.2422 stellar days in one mean tropical year (one stellar day more than the number of solar days). The reason that solar day is longer than the sidereal day lies in the fact that a sidereal day reflects one full rotation of Earth and the solar day reflects the full rotation of the Earth and its motion along the orbit. While 'orbiting' the Sun, one rotation still returns a fixed observer to pointing a distant star; but slightly more than one full rotation is necessary to return an observer to pointing at the Sun.

5. Mapping the Earth's revolution onto a DING

In addition to the rotation around its axis, the Earth orbits around the Sun (Copernicus 1543) in the plane, called ecliptic. The angle between the Earth's axis and normal to the ecliptic at

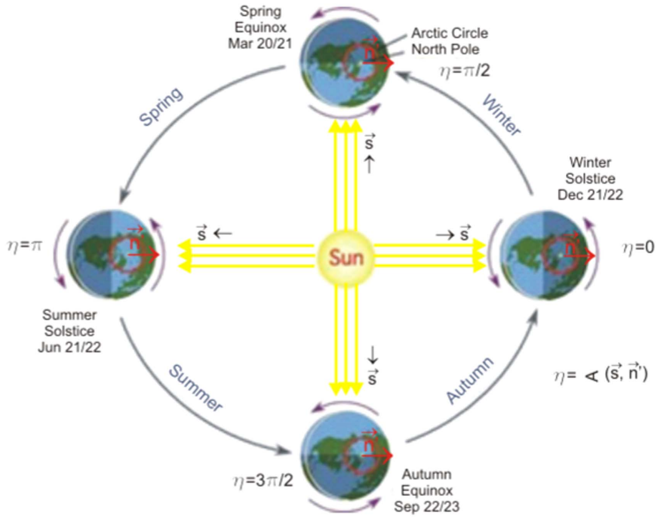

Figure 10. The angle between the plane of the circle of illumination and the Earth's axis changes during the Earth's revolution because the angle η between the direction of the Sun's rays (along the line connecting centers of the Sun and Earth) and the projection $\vec{n}'$ of the Earth's axis on the ecliptic changes. The eccentricity of the Earth's orbit is neglected in this figure.

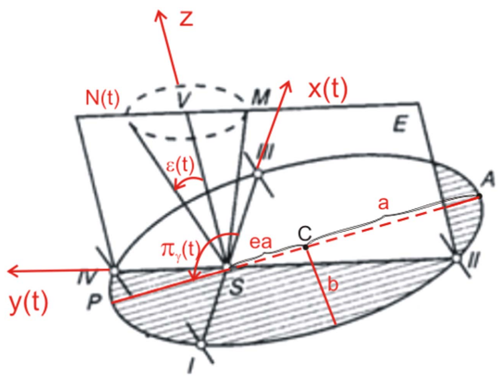

Figure 11. Drawing of essential parameters of the Earth's orbit considered in Milankovitch's (1941) theory. The Earth's orbit around the Sun is an ellipse with the Sun in one focus of this ellipse. The z-axis at the Sun's position is normal to the plane of the ecliptic. The z-axis and Earth's rotation axis determine the plane E. The y-axis is along the intersection of this plane with the plane of the ecliptic. The x-axis is normal to the y-axis. The cardinal points, denoted by I, II, III and IV, correspond to the spring equinox, summer solstice, autumn equinox and winter solstice, respectively. At present the angle between the major axis of the ellipse and the y-axis equals 12.5° (Goyder 2006).

present equals 23.5°. During one revolution of the Earth around the Sun, the direction of the Earth's axis is constant in space to a very good approximation. But, the angle between the direction of the Earth's axis and the Sun's rays changes during this motion. In figure 10 this change is presented by projecting on the plane of ecliptic, where η is the angle between the direction of the Sun's rays and the projection $\vec{n}'$ of the Earth's axis on the ecliptic. The angle η increases from 0 to 2π during one revolution of the Earth. The values $\eta = 0$ and $\eta = \pi$ correspond to winter and summer northern solstices, respectively. The values $\eta = \pi/2$ and $\eta = 3\pi/2$ are vernal and autumnal northern equinoxes, respectively.

The Sun's rays touch the Earth's surface along the circle of illumination (figures 1 and 9), which lies in the plane that is normal to the ecliptic and perpendicular to the Sun's rays. The angle between the plane of the circle of illumination and Earth's axis (figure 9) is equal to the declination of the Sun. The declination of the Sun by definition is equal to the angle between the Sun's rays (the line connecting the centers of the Earth and Sun) and the Earth's equatorial plane. This angle varies during the Earth's orbital motion (see for example figure 2.15 in Benett *et al* 2004). At equinoxes this angle is zero, the Earth's axis lies in the plane of the circle of illumination. At the summer solstice and winter solstice this angle is equal to 23.5° and −23,5°, respectively. During other days this angle lies in the interval (−23.5°, +23,5°).

On a DING, as a small Earth, the Sun's rays also trace the great circle analogous to the circle of illumination on the Earth. The angle between the circle of illumination on a DING and its axis change from day to day, following the above-described changes on the Earth. So, the Earth's revolution is mapped on a DING and may be followed from day to day during a year (figures 1(a) and (b)). Students may measure this angle during sunny days in the course of a year and compare the measured values with the values of the Sun's declination published in the literature, for example in the *Astronomical Almanac*.

In reality, the Earth's orbit around the Sun is an ellipse (Kepler 1609, Kemble 1966), the Sun being in one focus of this ellipse (figure 11). The focus S lies on the line connecting the perihelion (P) and ahelion (A) points. The eccentricity of the Earth's orbit at present is $e = b/a = 0.0167$. The cardinal points, denoted by I, II, III and IV correspond to the spring equinox, summer solstice, autumn equinox and winter solstice, respectively. Due to the elliptic shape of the orbit the time intervals between the Earth's passage through these points are not equal. Students could determine these intervals by recording the angle between the plane of the line of illumination and the Earth's axis as a function of time during the year (the Earth's position on the orbit) and compare these values with the values given in the literature.

In the long term (tens of thousands of years), the cardinal points I, II, III, IV do not remain at the same points along the orbit, but move along it with time (Milanković 1920, Milankovitch 1941). This means that the relative distance between the cardinal points and perihelion point P and aphelion point A change, too. This affects the length of seasons; summer half-year, and winter half-year. The causes of these variations are the secular changes of parameters of the Earth's motion (the eccentricity of its orbit, the direction and obliquity of its axis), which are due to the gravitational interaction between the Earth and other planets and to the non-spherical shape of the Earth. More specifically:

1. The Earth's long semi-axis a remains constant but its eccentricity $e = b/a$ changes quasi-periodically; the most important is the variation with period about 96 000 years.
2. With the period of 26 000 years (the Platonic year) the axis $SN(t)$ describes the circular cone, depicted in figure 11. These variations cause variation of the angle $\pi_\gamma(t)$ between the $x(t)$ axis and the major axis of the Earth ellipse.
3. The angle $\varepsilon = \varepsilon(t)$ which $SN(t)$ makes with the z-axis—Earth's obliquity—has been changing with a period of about 41 000 years and an amplitude of approximately 1.3°. Currently, the obliquity amounts to some 23.5°, which is close to the mean value over the period.

Therefore, the Earth's axis does not point always to Polaris (as is the case now). The maximal angle between the plane of the line of illumination and Earth's axis oscillates between 22.1° and 24.5°. Variations of π_γ cause variations of the length of time between equinoxes and solstices.

6. Applying a DING in teaching about insolation of the Earth and use of solar energy

A DING, as a model of the Earth, is also useful in teaching about various aspects of the insolation of the Earth. During a sunny day it is possible to feel by touching that the illuminated surface is much warmer than the surface of the shaded side. More subtle temperature differences exist even on the surface of the illuminated half of the DING. This is registered by touching at the equator and at the higher latitudes along the same meridian. Using a thermometer one can quantitatively measure these temperature differences, which are due to the differences in angle at which sunlight hits the surface. For example, in October, daylight in Antarctica lasts longer and longer. However, because of the difference in the angle of incidence between the equator and Antarctica, Antarctica is much cooler than the tropics.

In modern times, the studies of insolation of the Earth are very important in research on climate change (Berger *et al* 2005), as well as in research on the efficiency and usage of solar cells (Stine and Geyer 2001, Khavrus and Shelevytsky 2010). Regarding climate change on Earth, there has been an ongoing discussion and controversy between proponents of man-made causes and proponents of natural causes.

The secular variations of the parameters of the Earth's orbit give rise to changes in insolation (the amount of radiation received at the top of the atmosphere of the Earth), and on the physical mechanisms governing the propagation of the received energy through the atmosphere and the response at the Earth's surface. Milanković (1920) studied and computed in full detail this correlation in his mathematical theory of thermic phenomena caused by solar radiation. The secular changes of the parameters of Earth's orbit have caused the secular changes of climate on Earth, resulting in the series of ice ages with interglacial periods. Since 1950s much data have been gathered confirming Milanković's explanation of the climate change on Earth during last 600 000 years (Berger *et al* 2005, Knežević 2010). The most important were the results of an investigation of deep-sea sediments published by Hays *et al* (1976).

In studying the climate change of Earth it is important to consider the Earth as a whole and its relation to the Sun. In this respect a DING as an element of a learning environment is very useful because it reminds citizens and students to think about their role in climate change and how to preserve the conditions for life on Earth. The intensive research in modern times aimed at developing efficient solar cells has been motivated by this concern and the need for renewable energy sources.

In order to understand how to build energy-effective houses and how to optimize solar cell positions, one must first be able to predict the location of the Sun relative to the collection device. In addition, the relative motion of the Sun with respect to the Earth will allow surfaces with different orientations to intercept different amounts of solar energy. Therefore, there has been a renewed interest in knowledge of basic astronomy; the Sun's position in the sky, sundial problem, Earth's motion along the orbit, declination of the Sun, etc. Authors of books and articles in this developing field emphasize the need to visualize (using computer software) all employed coordinate systems and geometrical quantities, and to use geometry, vector algebra and matrices in transforming coordinates from one coordinate system to another (Stine and Geyer 2001, Probst 2002, Khavrus and Shelevytsky 2010, Jenkins 2013). This shows that visualization of the Earth–Sun relations is considered to be very necessary in the development and use of solar energy systems. Therefore, a DING as a visualizing tool in the learning environment might be very useful in teaching how to use power from the Sun.

7. Conclusion

Taking into account the elaborate arguments about the necessity of teaching the nature of science/how science works (Hosson 2008, Duschl and Grandy 2013, Krogh and Nielsen 2013, Abd-El-Khalic 2013) and to build an inquiring, inspiring and communicative learning environment (Božić *et al* 2009, Nielsen 2013), in this paper we described how an outdoor globe having the same orientation in space as the Earth (Day Night Year Globe—DING) is applicable in this context. Designed and created by R Anati in the Clore Garden of Science (Geva 2002, Sharon 2005) in Israel, it is the paradigmatic example of a cognitive installation for school and university yards (Božić *et al* 2005, Altamore *et al* 2010) as well as for science centers (Garoon Gateway to Science 2010).

In 2009, a DING was devised at Roma Tre University to celebrate the International year of Astronomy and was named the Oriented World Globe (or Parallel Globe). Altamore *et al* (2010) have been developing a set of educational activities addressed at secondary school students that were proposed to interested teachers. The authors also showed that the Oriented World Globe is a powerful tool to carry out simple and incisive educational activities for students of every age. A DING, constructed from concrete at the Center for Professional Advancement of Educators (CSU) in Šabac, Serbia (figure 1), has attracted substantial interest among students, teachers, citizens and the media.

In this paper we relate the historical development of knowledge about the form of the Earth, its size, tilt with respect to the ecliptic, internal rotation and orbital motion, time measurement and insolation to geophysical and astronomical concepts visualized on the DING. In particular, we elaborate how Eratosthenes, Jefferson and Milanković used an oriented world globe in their research and discoveries.

Eratosthenes used such a globe in order to argue about the spherical shape of the Earth and to determine its size. Collaborative educational school projects realized during recent decades show that Eratosthenes' method is ideal for implementation of inquiry-based learning sequences.

Jefferson used this globe to consider the daily motion of the circle of illumination in measuring time and determining the longitude of Monticello. A DING with pins around the equator or with a movable vane is useful to understand the functioning of a spherical sundial because it is tightly connected with the fundamental unit of time measurement—the mean solar day.

The orientation of the Earth's axis was essential to Milanković, who studied and evaluated the insolation of the Earth and related secular changes of the climate of the Earth to secular changes of the parameters of the Earth's orbit. In modern times, visualization of the illumination of the Earth is very necessary in the study of time dependence of the insolation of solar energy collectors at any place on Earth. As different from astronomy, where positions of celestial bodies on the celestial sphere are of interest, in these studies, the positions and orientations of solar collectors on the Earth are of interest. This implies that a DING might be useful in teaching how to build energy-effective houses and how to optimize solar cell positions.

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