A geostationary Earth orbit satellite model using Easy Java Simulation

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Abstract
We develop an Easy Java Simulation (EJS) model for students to visualize geostationary orbits near Earth, modelled using a Java 3D implementation of the EJS 3D library. The simplified physics model is described and simulated using a simple constant angular velocity equation. We discuss four computer model design ideas: (1) a simple and realistic 3D view and associated learning in the real world; (2) comparative visualization of permanent geostationary satellites; (3) examples of non-geostationary orbits of different rotation senses, periods and planes; and (4) an incorrect physics model for conceptual discourse. General feedback from the students has been relatively positive, and we hope teachers will find the computer model useful in their own classes.

Introduction
The concept of geostationary orbits is often inaccessible to physics students since it is nearly impossible for them to experience what it is like to be in outer space near the Earth in order to observe the relative motion of satellites.

In traditional classrooms, students can be asked to imagine Earth and geostationary satellites or watch YouTube videos of predefined geostationary orbits, with little or no opportunity for them to explore and understand cases where the orbits are non-geostationary. Thus we feel there is justification for using a computer model to support active experiential [1] student-centred learning.

We created a computer model, also known as a simulation, to allow our students to visualize the phenomena using a free authoring toolkit called Easy Java Simulation (EJS) [2]. We utilized a new feature in EJS, a Java 3D implementation as unveiled during the Multimedia in Physics Teaching and Learning Conference (MPTL 14) [3]. This allows ordinary teachers to create realistic 3D tools for physics education.

In addition, our quick literature review suggests that we are probably the first authors in a physics educational journal to come up with a simulation tool that is customized to GCE A-level physics standards to help students learn about geostationary orbits [4].

Building on open source codes shared by the Open Source Physics (OSP) community, such as Francisco’s ‘Examples of Earth and Moon 3D’ [5], and with help from Fu-Kwun’s NTNUJAVA Virtual Physics Laboratory [6], we
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Figure 1. EJS applet view of the simulation learning environment showing the orbital view of Earth and a geostationary satellite in the Java 3D implementation of the EJS 3D library with a bottom control panel for inquiry activities.

customized an EJS computer model as a 3D visualization tool (figure 1)\(^3\).

The recommended system requirement for running this EJS model in Java 3D is the Intel Pentium processor.

Physics model

In this model as implemented in EJS (figure 2), the rotating Earth as well as the geostationary satellite is governed by a simple constant angular velocity equation (1) about the \(z\) axis, where \(\vartheta\) is the ‘angle’ of rotation of the Earth and the constant on the right-hand side of equation (1) assumes that the time is in hours.

\[
\frac{d\vartheta}{dt} = \frac{2\pi}{24}. \tag{1}
\]

Users who wish to model non-geostationary orbits of different angular velocity \(\vartheta_k\) need to modify equation (1) into (2) with

\[
\begin{align*}
  k &= -1.0 & \text{for opposite rotational direction of geostationary satellite;} \\
  k &= 0.5 & \text{for half the geostationary angular velocity;} \\
  k &= 2.0 & \text{for double the geostationary angular velocity;} \\
  \frac{d\vartheta_k}{dt} &= \frac{2\pi k}{24}. \tag{2}
\end{align*}
\]

Advanced users who wish to model other non-geostationary orbits involving the rotation about the \(x\) or \(y\) axes need to introduce another angle, say ‘angle \(z\)’, using equation (1).

Thus, the satellite will need to be drawn with \(x\), \(y\) and \(z\) coordinates using equation (3) in relation to the angle \(\vartheta\), angle \(z\), \(\vartheta_z\) and \(R\) the geostationary distance from the centre of the Earth to the satellite.

\[
\begin{pmatrix}
  x \\
  y \\
  z 
\end{pmatrix} = \begin{pmatrix}
  R \cos \vartheta \cos \vartheta_z \\
  R \sin \vartheta \cos \vartheta_z \\
  R \sin \vartheta_z 
\end{pmatrix}. \tag{3}
\]

This physics model when implemented in a computer model allows users to explore the simulation productively [9], serving as a powerful visualization tool for learning.

Expert users who wish to model gravitational equations should refer to other models [10, 11] that use Newton’s gravitational force and initial velocities to predict satellites’ motions, but that is beyond the scope of this paper.

Four computer model design ideas

To add to the body of knowledge surrounding why simulations could be effective tools, we share four computer model design ideas—insights that we believe have raised the effectiveness and usefulness of the tool for students’ active learning.

\(^3\) Downloadable from https://sites.google.com/site/lookang/edulab.gravityearthandsatellitejs/ejs_EarthAndSatellite.jar?attredirects=0&d=1, digital libraries in ComPadre Open Source Physics [7] and NTNUJAVA Virtual Physics Laboratory [8], with a creative common attribution license.
Simple and realistic 3D view and associated learning in the real world

To achieve a realistic view of the Earth, we used a texture map such as can be found in the public domain online, for example the Natural Earth III [12]. We further used free graphics software (GIMP) to arbitrarily reduce the size to 2000 pixels × 1000 pixels to achieve a reasonable file size of 247 kB for use in EJS 3D sphere objects as texture.

To create a view of the universe as viewed from Earth, we used a texture map that can be found on the NASA website [13] inserted into the 3D drawing panel with the graphical aspect referring to that file.

To do this in the 3D drawing panel in EJS select JAVA 3D instead of simple 3D to produce a view of the Earth and the universe (figure 3).

To create associated learning in a real-world reference context, we created three positions with land masses around the equator: south-east Asia (Singapore), Africa and the Americas continent. We used equation (4) to position these three geostationary orbit points, where \( \vartheta \) is the ‘angle’ and \( \vartheta_0 = \vartheta_{\text{Singapore}} \approx 0.25, \vartheta_{\text{America}} \approx 3.6 \) and \( \vartheta_{\text{Africa}} \approx 5.2 \) radians, respectively (figure 4) and they have an angular velocity equal to the Earth’s rotation \( \frac{2\pi}{24} \) in hours.

\[
\vartheta_{k=1} = \vartheta_0 + \frac{2\pi}{24} dt.
\] (4)

To aid in the visualization from different perspectives, semi-transparent equatorial planes and axes of rotation for the Earth and satellites were added to help students gain a better visualization of the 3D space they were interacting with.

To further add realism, the radius of the Earth, \( R_{\text{earth}} \), and the orbits \( R \), were modelled by drawing on data collected from validated sources such as the NASA website and Wikipedia. We used a scale of \( 1 \times 10^6 \) m to represent the radius of Earth in the model, \( R_{\text{earth}} \approx 0.637 \) and the radial distance from the centre of the Earth to the geostationary orbit, \( R \approx 4.23 \).

Our internet research discovered some simulations, represented in only 2D [14] or commercial 3D [15], which show specifically geostationary orbits, but these are more complicated to use. Thus, we believe our computer model could be a simpler tool for teachers and students to use for visualization of geostationary orbits around the Earth.

Comparative visualization of permanent geostationary satellites

We found that the provision of a timer ‘\( t = XX \) h’ alone was insufficient for students to gain...
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Figure 5. Orbital view of the Earth from the North Pole with a (red) geostationary satellite above south-east Asia (Singapore) completing one revolution after 24 h, while a non-geostationary orbit at radius $R = 10.5 \times R_{\text{earth}}$ has completed half a revolution.

a clear understanding of non-geostationary orbits through observation. The act of observing the numerical value in the timer, say 48 h (figure 5) for an orbit that is twice the period of the rotation of the Earth can be better enhanced by showing another geostationary object simultaneously, in our case, for example, a red satellite above Singapore.

Thus, a checkbox was designed for students to activate the display of a permanent example of a geostationary orbit so that quick and clear interpretation of the meaning of a non-geostationary orbit in comparison with a geostationary orbit could be made.

Examples of non-geostationary orbits

To further improve understanding of the geostationary orbits, we also designed typical non-geostationary orbits for students to compare the differences.

Non-geostationary due to direction (rotation sense). Some students do not appreciate that for a geostationary orbit to occur it not only requires a period of 24 h and to lie on the equator plane of the Earth, it also need to be rotating in the same direction as the Earth’s rotation about its own axis (figure 6). The comparative visualization of the rotating Earth and orbiting satellite, as well as the two axes of rotations served to highlight the importance of the geostationary orbit’s rotation sense.

Non-geostationary circular motion at different periods. To illustrate that the period of a geostationary orbit needs to be 24 h or its angular speed needs to be equal to that of Earth’s, two non-geostationary orbits were designed on the equator plane and with the same rotation sense as the Earth’s, but with one orbiting faster at an orbital radius three times that of the Earth’s radius (figure 7) and the other orbiting more slowly at an orbital radius 10.5 times that of the Earth’s radius (figure 8).

One teaching point here was to introduce the free body diagram of the satellite and equate the net force on the satellite to its centripetal force (equations (5) and (6), respectively) to derive the predicted value of the period of $T_{R=3R_{\text{earth}}} = 7.3$ h and $T_{R=10.5R_{\text{earth}}} = 48.0$ h, respectively. Here students need to know that the universal gravitational constant $G = 6.67 \times 10^{-11}$ m$^3$ kg$^{-1}$ s$^{-2}$, the mass of the Earth $M_{\text{earth}} = 5.97 \times 10^{24}$ kg and the mass of the satellite, $m$ were independent in the determination of the period $T$. In addition, the conversion of seconds to hours proved to be challenging to
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Figure 7. Orbital view of the Earth’s non-geostationary circular orbit of $R = 3R_{\text{earth}}$ with a period of 7.3 h, in the equator plane and in the same rotation sense as the Earth.

Figure 8. Orbital view of a non-geostationary circular orbit of $R = 10.5R_{\text{earth}}$ with a period of 48 h, in the equator plane and the same rotation sense as the Earth.

novice students.

\[
\frac{GmM_{\text{earth}}}{3R_{\text{earth}}} = m(3R_{\text{earth}}) \left( \frac{2\pi}{T_{R=3R_{\text{earth}}}} \right)^2
\]

(5)

\[
\frac{GmM_{\text{earth}}}{10.5R_{\text{earth}}} = m(10.5R_{\text{earth}}) \left( \frac{2\pi}{T_{R=10.5R_{\text{earth}}}} \right)^2
\]

(6)

Non-geostationary due to planes such as polar orbits with period $T = 24$ h. Now that we have covered the need for the same rotation sense and the same period or angular speed as the Earth, we look at a polar orbit to show the need for the orbits to be on the Earth’s equatorial plane (figure 9).

To make the physics relevant to daily life, we typically shared with students the real-life applications of polar orbits, such as for Earth mapping, observations capturing the Earth as time passes and for some weather satellites.

Incorrect physics for conceptual reasoning

To represent a more general orbit not in the plane of the equator, we used equation (3) as mentioned in the ‘Physics Model’ section. This produced a simplistic orbit that can be used to allow visualization of non-geostationary orbits that are not in the plane of the equator of the Earth’s rotation (figure 10). By having incorrect physics [16] motion represented, we challenged students to explain and elaborate what is incorrect about this orbit, for instance in relation to its higher speed when nearer to the Earth and its lower speed when further away.

Lastly, an unlikely orbit (figure 11) that appears to be geostationary above a point on the northern hemisphere of Earth was used to challenge thinking about what is ‘wrong’ with this orbit. A free body diagram showing the equal and opposite forces acting separately on the Earth and the satellite helped students to use what they learnt about Newton’s third law in this context. Students explained that the direction of the force was towards the Earth’s centre when it was in a circular orbit, which would require the net force to point towards the centre of the circular path, which was not happening in this mode. We also got the students to think about the force that would need to be continually applied to the satellite in order for this unlikely orbit to be possible.
Feedback from students

We include excerpts from the qualitative survey results and informal interviews with the students to give some themes and insights into the conditions and processes during the laboratory lessons. Words in square brackets are added to improve the readability of the qualitative interviews.

(1) Improved 3D visualization from different perspectives

‘The lesson allows me to understand the movement of a satellite which we cannot see normally in real life and are unable to comprehend from the 2D [textbook] diagram. Thus, the 3D simulation allows me to learn better.’

‘Allow [me] to get a better understanding of the topic as simulation aids in visualizing the various questions easily, thus, [I am] able to solve the question. The lessons give me a clearer explanation of how things work thus, allowing me to understand.’

(2) Need for strong inquiry learning activities

‘Not enough group activities. The questions are not interesting enough.’

‘Not focusing on specific questions, and just focusing on concepts.’

We suspect that the students are requesting more open-ended inquiry activities to be designed for learning instead of embedding the simulation in existing tutorial questions that tend to be more theoretical and only test a subset of the knowledge regarding geostationary orbits.

(3) Need well designed simulation

Some students suggest having ‘more diverse options’ so that the simulations could be more interesting and appealing.

This suggestion has inspired us to expand the option of including non-geostationary orbits at different speeds by including a higher angular speed at $3R_E$ and a lower angular speed at an orbit radius of $10.5R_E$.

(4) Appreciative learners

‘I would like to show my appreciation for the [information and communication technology] ICT inventors and teachers who participated in this ICT learning programme as it is a new opportunity for us to pick up high technology skills to pick up physics.’

‘I would like to thank my teacher for allowing us to gain exposure to these simulations and how they are able to be used to allow us [to] understand the topic better.’

Conclusion

The simplified constant angular velocity physics model is discussed and implemented in EJS and equations (1)–(3) give a brief account of how to create a geostationary orbit simulation tool. Despite using only a simple constant
velocity equation, we were able to create this tool to help students in their understanding of geostationary orbits. The full computer model can be downloaded. 

We have discussed four computer model design ideas: (1) a simple and realistic 3D view and associated learning for the real world; (2) comparative visualization of a permanent geostationary satellite; (3) examples of non-geostationary orbits of different rotation senses, periods and planes; and (4) an intentionally incorrect physics model. We implemented these design ideas in our EJS model, which we believe can further support student learning.

Employing the learning theory of constructionism, teachers could get interested students to go through the process of model building as a pedagogical tool, for instance as a project assignment. This would heighten the relevance of this paper’s model construction details.

General feedback from the students has been relatively positive, triangulated from the survey questions, interviews with students and discussions with teachers and we hope more teachers will find the simulation useful in their own classes.

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