AAS03-502

VISUALIZATION OF ASTRODYNAMICS AND ATTITUDE CONCEPTS FOR EDUCATION

Adam Pederson*

James Woodburn†

John Carrico‡

Three-dimensional visualization of position and attitude information for satellites and other vehicles is highly beneficial to learning the concepts and applications of astrodynamics and attitude determination and control. Being able to see and manipulate a three-dimensional view of complex numerical data such as orbit trajectories and attitude profiles gives students the ability to interact with the data in a physical, intuitive medium, rather than simply learning to ingest large volumes of raw numerical data. In addition to making the basic concepts of trajectories and attitude profiles easier to comprehend, visualization can also help to clarify the physical meaning behind the data associated with orbit determination (especially covariance analysis), orbital navigation, and Earth area and asset coverage.

INTRODUCTION

Many of the concepts of astrodynamics and attitude determination and control are difficult to comprehend from description and data alone. Visual reinforcement is commonly used to help describe the fundamental nature of each concept, but it is usually presented in two dimensional (2D) drawings only. These 2D graphics can fall short of conveying true understanding - especially if they are created in a fashion that is subject to misunderstanding in the mind or imperfect skill in the hand of the creator. The use of three dimensional (3D) visualization, which is based on a strong analytical foundation so that the locations of objects rendered are known to be accurate, and which can be manipulated as the student desires, is of distinct benefit to the student. It assists in understanding the concepts depicted, and in learning to create accurate mental images to extend the concepts in the future.

Recent advances in the computational power and graphics capabilities of desktop PCs and the availability of student PC labs has made the use of 3D graphics teachings aids not just technologically feasible, but very accessible. As little as ten years ago, the computer hardware required to render 3D graphics applications cost thousands of dollars and was a luxury upgrade. Fortunately, the price of 3D graphics capabilities has fallen dramatically with the introduction of 3D graphics accelerator cards for PCs. With the cost of current 3D graphics cards, which provide many times the computational power of their predecessors, being measured in hundreds of dollars, 3D graphics rendering capabilities are all but standard on new PCs. The Educational Alliance offered by Analytical Graphics, Inc. also allows universities to obtain Satellite Tool Kit (STK) with the 3D Visualization Option (STK/VO) at no cost for use in teaching programs. As a

* Aerospace Engineer, Analytical Graphics, Inc.
† Chief Orbital Scientist, Analytical Graphics, Inc., Senior Member AIAA, Member AAS
‡ Senior Astrodynamics Specialist, Analytical Graphics, Inc., Member AAS

result, students and professors have accessibility to high end 3D visualization to enhance the educational experience with minimal expense.

EXAMPLES

We will present a number of examples where the use of 3D visualization can enhance the learning experience. While these examples will illustrate the benefit of using 3D visualization to understand simple and more complex concepts and processes, they barely scratch the surface of what is possible. We will present specific examples of the use of visualization in learning basic orbital geometry and attitude profiles. We will then present a number of more complex examples, including orbital maneuvers, formation flying, and covariance. Of course, the nature of this subject - and the point of this paper - predicates that the descriptions and illustrations included herein will not be able to fully bring home the impact of 3D visualization, especially interactive 3D visualization. For this reason, all of the material used to create this paper will be available via FTP. Animations and STK scenarios can be found at ftp.stk.com in the /dist/AAS03 directory. In a Web browser this directory can be reached using the following link: ftp://ftp.stk.com/dist/AAS03/

Orbit Elements

A classroom or textbook introduction to the basics of orbital geometry usually centers on the six classical orbital elements. Textbooks on astrodynamics will usually introduce the subject with a review of conic sections, an introduction to the 2-body problem, and a brief survey of Kepler's Laws. This leads directly into a definitive listing of each of the orbital elements, usually with a few 2D diagrams with each of the elements labeled. These diagrams are meant to present the orientation and meaning of each of the orbital elements in a concise fashion; what the diagrams have in clarity, they generally lack in variety. Especially in the case of the more complicated spatial orientation elements, the right ascension of the ascending node (RAAN) and the argument of perigee, the student is given very few different examples or views to clearly point out the references these angles are measured against, the differences and relationships between them, and the exact effect each element has on the orbit. All of these rotations and relationships must be constructed in the mental image of each student, and manipulated only there. This is an ideal situation for the use of 3D graphics, where the display of spatial information can be from intangible mental imagery and placed definitively on a computer screen. Instead of having to simply describe the new concepts figuratively, and try to illustrate how they rotate the orbit in space, the use of 3D visualization allows the student to see all of the reference angles directly, and to see how different values for the elements affect an orbit in space. The ability to pan around and view the orbit from different angles makes it far easier to discern how the orientation of the orbit has changed with each successive set of values for the orbital elements, and it does not rely on the ability of an instructor or an author to pick a single viewpoint that can be used to make a 2D figure that conveys the information succinctly (as we have done below in Figure 1).

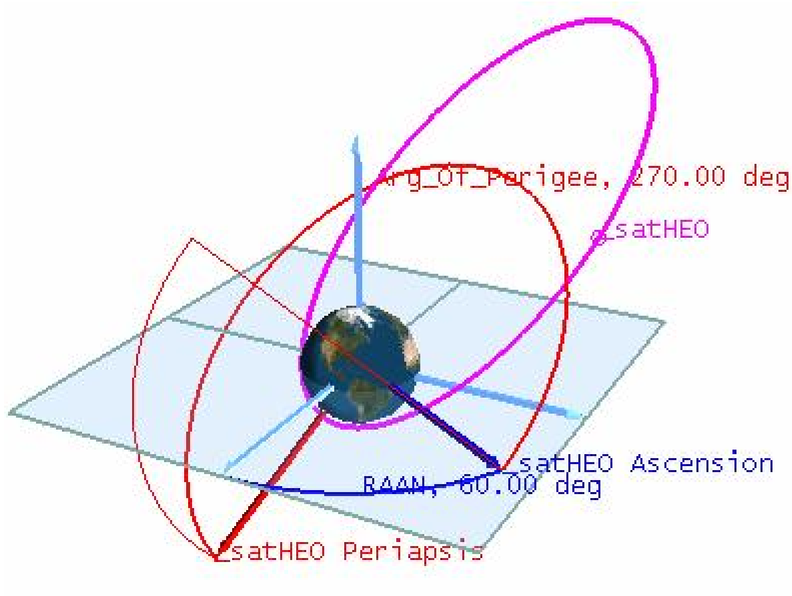

Figure 1. View of a highly elliptical orbit showing Keplerian elements (RAAN and Argument of Perigee) labeled with value

GEO Eclipse Season

An example of applied orbital geometry which is made clear by 3D visualization is the eclipse season for a geostationary (GEO) satellite. There are two times of the year when the Earth's equatorial plane, in which the GEO satellite lies, and the ecliptic plane, defined by the orbit of the Earth about the Sun, are oriented such that the line of their intersection passes through the Sun itself. When this geometrical configuration occurs, the GEO satellite passes through the umbra region created by the Earth. All other times of the year the GEO satellite is free from the shadow of the Earth, although it may fly through the shadow created by the Moon. On the sunlit side of the Earth, the GEO satellite passes near the Earth-Sun line. This results in a period each day when the Sun is almost directly behind the GEO satellite as observed from parts of the Earth's surface. During such a conjunction, energy coming from the Sun can interfere with the ability of ground stations to receive the signal from the GEO satellite. It is easy for a student to simply remember that in March and September of each year, their digital satellite TV will not work, knocking out afternoon March Madness and pre-season NHL games. But it is more instructive for the student to be able to see the relative geometry of the planes and understand the orientation of those planes with respect to the Sun, and seeing this geometry in a 3D display is much more easily understood than the dry technical description at the top of this paragraph. A visual depiction of this equinox condition is given in Figure 2, below.

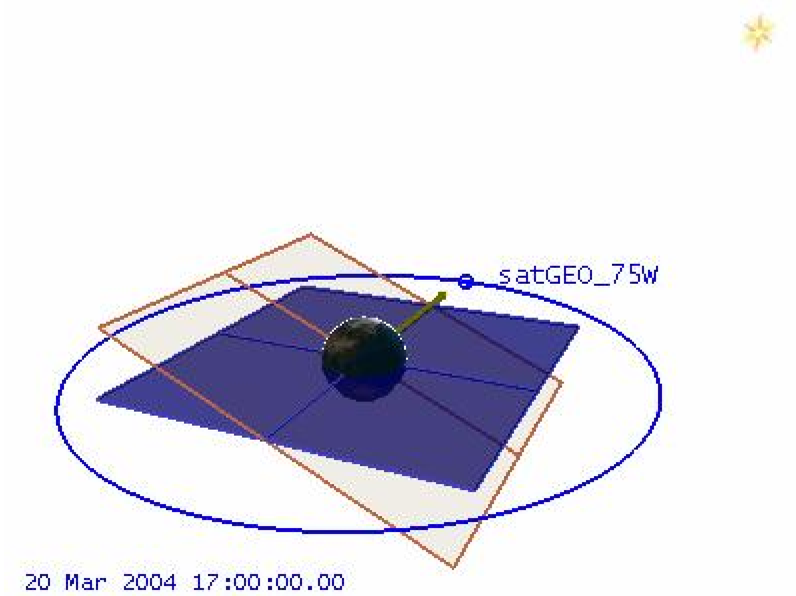

Figure 2. Geometry resulting in eclipse of a GEO satellite, shown at spacecraft noon for a vehicle over 75 Deg W. Earth equatorial plane shown dark, ecliptic plane shown transparent. Note Sun at upper right, to which the vector is pointing.

Ground Tracks

Another subject directly related to orbital geometry is the ground track traced out on the central body. Ground tracks are universally plotted and viewed on 2D media. Even simple ground tracks such as the sinusoidal pattern of an inclined circular orbit can be initially confusing to students. The difficulty increases when the ground tracks take on unexpected shapes, like loops and sections of apparent backtracking. These shapes can be better explained by showing in 3D the spacecraft orbiting above a rotating body, so that relative angular velocities can be interpreted visually to complement the mathematics. As the eccentricity of an orbit increases, Kepler's Second Law can make for strange behavior of the ground track as the spacecraft seems to stall or move backwards against the Earth's rotation. Observing a visualization of the spacecraft actually sweeping out equal areas in equal times demonstrates not only the reason for the oddity in the shape of the ground track of a highly elliptical orbit, but also clearly shows the long dwell time and wide field of view near apoapsis which makes the orbit useful from a mission design standpoint.

Launch Windows

Once a basic understanding of the relationship between ground positions and orbital locations has been achieved, the student is ready to build on these foundations to solve new problems. A common requirement for orbital systems is to launch a vehicle directly into a specific desired orbital plane. Equations for launching from a rotating Earth into a specific inertial plane can be worked out, and a student can be shown that there will be one or two opportunities for launch each day, depending on the latitude of the launch site and the inclination of the desired orbit. A 3D visualization can make it clear that the orbital plane is indeed an inertially fixed target, and the rotation of the Earth will place the launch location in that plane once or twice each day, with an opportunity to launch "up" or "down" into the plane assuming that the latitude is significantly less than the desired inclination. Of course most launch sites have range restrictions which only allow for a launch in one direction, thus limiting opportunities to once per day.

Orbit Trajectories

Visualizing orbits in 3D allows a single orbit to be displayed in multiple reference frames simultaneously. This tends to be an especially difficult concept for the student to comprehend. An orbit will trace out a familiar conic shape in inertial space, but it is often necessary to understand the shape of the orbit with respect to the fixed Earth. This is the analog of the simple 2D ground track, but displayed at the orbital altitude experienced at each point. Displaying an orbit in the reference frame of the fixed Earth (Earth-centered fixed, or ECF) will show the same unexpected loops and backtracks of the ground track. Displaying the orbit traces in both frames simultaneously - that is, ECI and ECF - will show the elliptical ECI orbit trace remaining fixed in space, with the non-elliptical ECF orbit trace rotating with the Earth, and will show that those two orbit traces will always have an intersection point, which is where the spacecraft is located at that time. A still image of this kind of display is given in Figure 3 below.

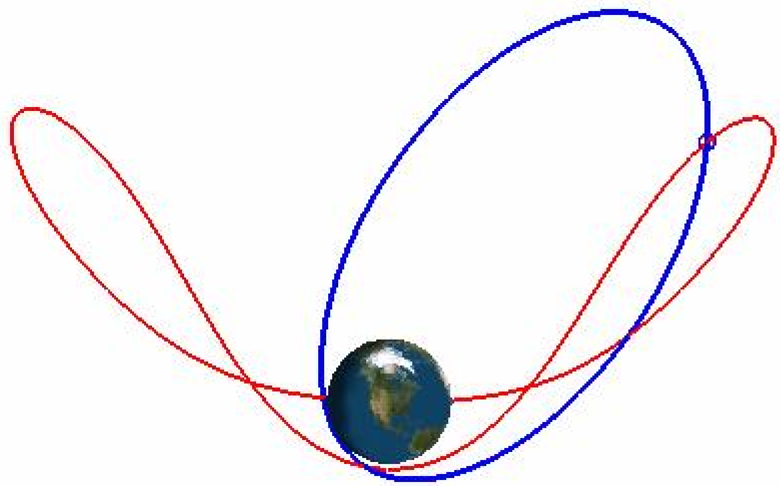

Figure 3. Highly elliptical orbit with trajectory shown in ECI coordinates (thick line) and ECF coordinates (thin line)

Attitude

The attitude of an orbiting spacecraft is a concept which is often reported by supplying a large amount of numerical data listing rotations about reference frames over time. Basic concepts are often easy to visualize in the mind's eye, like keeping a certain face of a spacecraft pointed in a certain direction. This is especially easy when the vehicle and the references used are already familiar - e.g. keep the instrument-studded "bottom" of a notional spacecraft pointed "down," and the relatively plain "front" of the spacecraft pointed in the velocity direction. When the references become more complex, like keeping one side pointed toward the orbit normal direction, or spinning the vehicle about some inertial axis, the intuitive mental image is more difficult to construct. At this point, the volumes of numerical data, often in the form of quaternions, can be introduced to define the attitude precisely - but such tables of numbers may be more difficult for the student or beginning engineer to grasp than the geometric references themselves. Viewing these data using 3D visualization allows the student to directly comprehend the attitude of the vehicle and to begin to understand how the data and the resultant attitude relate. This gives the student an accurate basis to use for gaining experience in how to correctly translate the attitude data into a mental image.

Spacecraft Lighting

Perhaps a new, inexperienced engineer will be given the task of determining whether a given portion of a vehicle will be subjected to long periods of sunlight over a given period of time. The inexperienced engineer may be able to manipulate numerical attitude data to answer this question in a general sense, but may miss some details which are not immediately obvious. For example, the engineer may not take into account the blockage of the Sun by Earth, or shadowing from other parts of the spacecraft itself. However, with knowledge of the attitude profile and orbital parameters of the vehicle, a 3D modeling and visualization tool can be quickly employed to observe the spacecraft during the desired time frame and watch the sun-sensitive hardware directly for a quick rough estimate. Better knowledge of the orbit and attitude of the vehicle, of the physical spacecraft structure, and more rigorous observation techniques can be used to refine the estimate, so that in a relatively short amount of time a useful conclusion can be drawn, or used as a sanity check against a more analytical approach.

Let us consider a more specific example of an analysis technique which makes use of 3D visualization for data analysis. One way to measure the lighting of a particular portion of a spacecraft would be to measure the angle to the sun experienced by a given portion of the spacecraft over time. To do this, the spacecraft could be approximated to a sphere, and the sphere covered with an equidistant grid of points. For each of these points, the angle between the vector from the center of the spacecraft to the point and the vector from the center of the spacecraft to the apparent position of the Sun could be measured over time. For each point, the minimum angle value measured would give the most direct instance of lighting for the given time period. This would quickly point out the areas of the satellite which received direct sunlight, where the angle would be 0 deg, and those areas which avoided the Sun. Since the points are arrayed in a sphere around the nominal center of the spacecraft, the most intuitive way to interpret them would be to map the data back to a sphere, and use colors to represent the minimum angle measured at each point. Displaying this sphere surrounding the satellite in 3D would give a very quick and intuitive way to look at the satellite and be able to immediately tell which areas had direct Sun coverage, without having to assimilate a large table of raw data. A simpler method to achieve a similar effect would be to simply create a trace around the satellite of the path taken by a satellite-to-Sun vector over the time of the analysis. This will still allow the viewer to immediately determine what areas have had the Sun pass directly overhead. An example of this effect is shown in Figure 4 below.

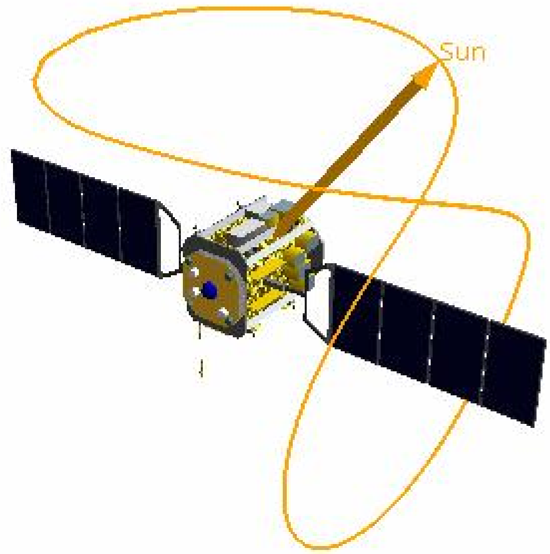

Figure 4. A satellite with the direction to the Sun traced out over time

Maneuvers

The effect of maneuver magnitude and direction on orbital geometry is another subject where 3D visualization can be highly beneficial. The impact of the maneuver location within the orbit can be easily seen when both the pre-burn and post-burn orbits are displayed simultaneously. Differences in trajectories due to the error and efficiency of true burns can be readily discerned, helping a student to understand how to design orbital maneuvers to accomplish general objectives, how to tune maneuvers to achieve more specific results, and what the impact of maneuver errors may be. A simple example of the benefit of viewing the results of a maneuver in 3D is to examine a situation where an identical burn is performed at different points in an orbit. Figure 5 below shows the results of three burns, all of the same magnitude and direction, executed at different points on the same orbit. The burn was intended as a combined maneuver to change the orbital plane and raise the apogee. The nominal burn was executed at the ascending node, while the other two burns were executed before and after the ascending node. It can be shown mathematically that performing an instantaneous delta V to change planes at a point other than an equatorial crossing (node) will also affect the RAAN of the orbit. This effect can also be clearly seen and understood by examining it in 3D, with all three burns done side-by-side for easy comparison.

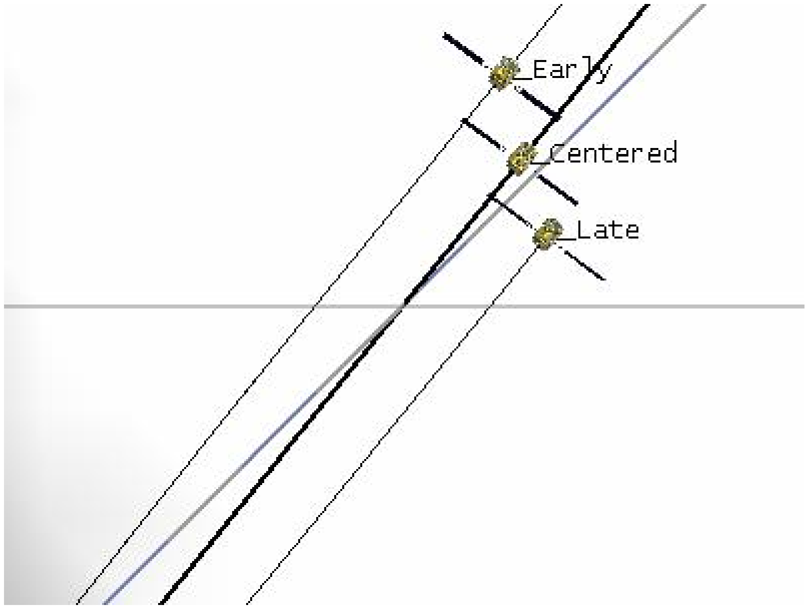

Figure 5. The effects of the same maneuver executed at different points in the orbit. This view is of the ascension, with the original orbit and the nominal post-burn orbit designated with a thick line

Formation Flying

Certain missions require that multiple space vehicles are flown in close proximity to one another, with the geometry of the vehicles within the formation with respect to each other being as important as the geometry of each orbit with respect to the orbital primary. The relationships between the positions of the vehicles over time can be as complex as the concepts of orbital geometry itself, or more so. Visualizing the formation flying situation in 3D can help to keep track of where the vehicles are in both relative and inertial space. This is a natural method for understanding how differences in orbital elements such as eccentricity and inclination can be used to design patterns of relative motion. Even a simple formation consisting of only two spacecraft can have unusual relative motion during initial formation establishment maneuvering, as shown in Figure 6 below.

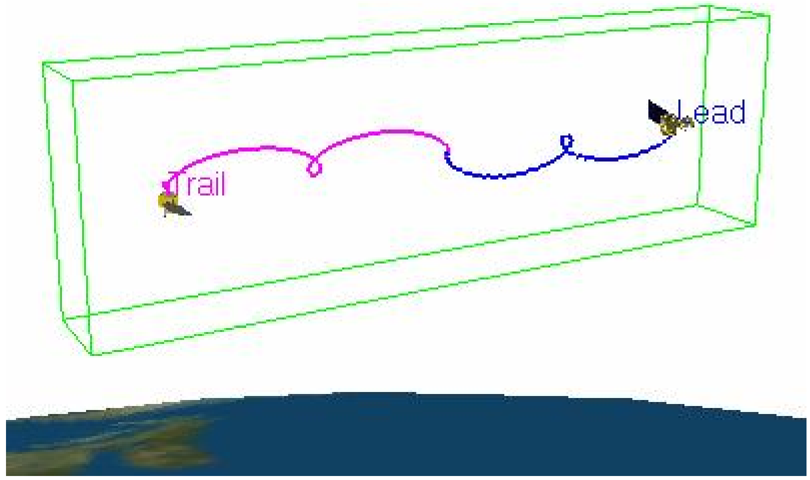

Figure 6. Relative trajectories during formation establishment for a 2-vehicle formation

Covariance

Orbit state error covariance is a product of the orbit determination process. The computation and propagation of the covariance is complex, but the meaning of the position error covariance is easy to understand and to visualize. The position error covariance can be represented as an ellipsoidal volume in space which changes with time where the surface of the ellipsoid is defined based on a desired probability that the true position of the satellite is within the volume. An example of this kind of display is given in Figure 7 below. Three dimensional visualization of position covariance can help a student understand how trajectory errors evolve with time, how they contribute to the overall error budget of a mission and introduce the problem faced in collision avoidance.

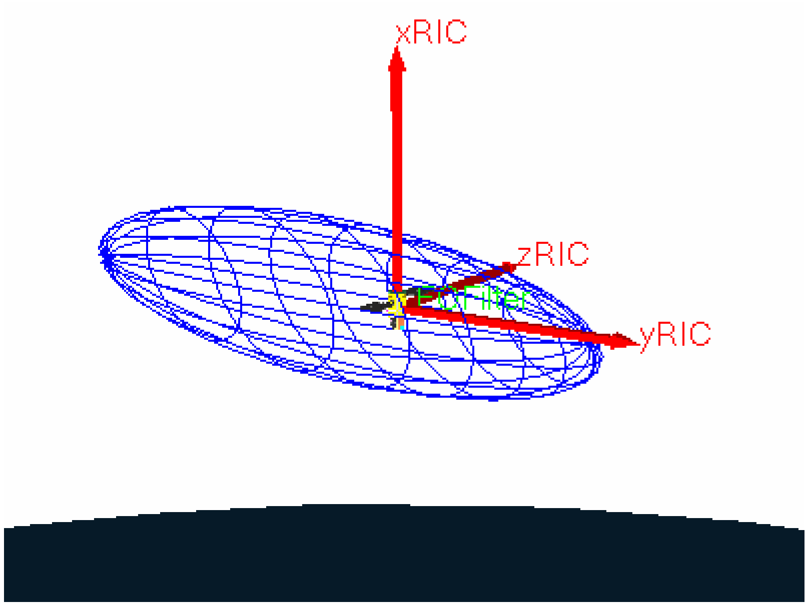

Figure 7. Position error covariance shown as an ellipsoidal volume

Likewise, attitude error is the result of the accumulation of error in the knowledge of the attitude of the vehicle over time. A related source of error is pointing error, which is the result of misalignment between the intended or nominal pointing of an instrument and its actual physical placement after manufacture, assembly and launch. These errors degrade the knowledge of the boresight direction of the instrument, and to the knowledge of the overall field of regard of the instrument. Depending on the application, these errors can be visualized by changing the shape of the field of regard of a sensor displayed in a 3D environment. For example, suppose a particular sensor has a conic field of regard with a nominal 30.0 degree half-cone angle, and the vehicle is also known to have a pointing accuracy of ±1.0 deg. in the axes orthogonal to its boresight. The sensor can then be displayed with a 31.0 deg. half-cone angle field of regard to include the possible volume that might be observed, taking into account the attitude error. In fact, the sensor could be represented with two envelopes, one inside the other, with half-angles of 29.0 and 31.0 deg. resp., to represent the full extent of the error in the edges of the sensor footprint. The boresight itself could be represented as a cone with a half-angle of 1.0 deg as a result of the errors in the attitude of the parent platform.

CONCLUSION

The use of 3D visualization to enhance education in astrodynamics and attitude concepts is only limited by the number of examples that an instructor can imagine. This paper has looked at a number of specific examples of the use of visualization in certain areas, but it is by no means an exhaustive, or even a particularly in-depth study. In fact the listing of examples herein only barely scratches the surface. Educators can take advantage of the opportunities for using 3D visualization in any fitting material in their coursework. It only requires a modern computer and applicable software. One such software package, and the one which was used in the creation of this paper, is Satellite Tool Kit from Analytical Graphics, Inc. (AGI) The software is available for free by ordering from www.stk.com, and educators can enter into an Educational Alliance with AGI to receive licenses for the Visualization Option at no cost. Thus it is easy and practical for any aerospace educator to add 3D visualization to their curriculum, enhancing the learning experience of the students.