Visually Observing Earth Satellites

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One of the most satisfying aspects of satellite predictions comes when you get to actually test out your satellite tracking software. It's one thing to have a slick software interface with lots of bells and whistles, showing where the satellite should be on a world map—it's quite another to point your antenna at the horizon and pick up your favorite satellite right on schedule.

Of course, humans tend to be visual creatures. We are often told how things work, but we want to see for ourselves. As the old saying goes, "Seeing is believing." The same is true for satellite predictions. From the earliest days of the Space Age, observers have looked up in the early evening sky to search for small points of light silently speeding through the heavens. From Echo 1 in the early 1960s to the Mir Space Station and the US Space Shuttle today, there is an endless fascination with being able to predict an event in the heavens and then watch it occur like clockwork.

A Bit of History

In fact, many of us have started professional careers from just such a foundation—myself included. I can still clearly remember that day in 1979 when I went out in my backyard to watch for Skylab to pass overhead. Skylab was getting lots of attention then because of the imminent decay of its orbit and the local television station in Kansas City (70 miles away) reported a particularly good pass would be visible that evening. I called some friends and we drug my ***Celestron 8*** telescope and some binoculars out in the backyard at the appointed hour and waited—we were not to be disappointed. Just as advertised, a bright light rose out of the western twilight and slowly slipped across the sky.

Of course, I wanted to be able to look at Skylab through the lens of my ***Celestron 8*** and track it across the sky, but it moved too quickly and there was no way to know exactly where to look. After all, the field of view of this telescope is only about half a degree—the width of the sun or the moon. Even to have Skylab simply pass through the field of view would take some pretty accurate calculations—a lot more than we got from the local weatherman.

As Skylab passed from sight, my mind was buzzing with all sorts of questions, not the least of which was: "Couldn't I do this myself?" After all, I had just bought my first computer a year earlier, a ***TRS-80 Model I***, and by now we had some reasonably sophisticated programming tools (BASIC and FORTRAN) available on that platform. Couldn't I write a program which would tell me where to look to find a given satellite?

My initial impression at the time was that this would be fairly straightforward. After all, I already understood basic two-body Keplerian orbits and had enrolled in an MBA program at the University of Missouri to get access to the ***IBM 360*** so that I could develop some FORTRAN code to predict the positions of the planets (in my spare time) and it worked reasonably well. It shouldn't be too difficult to adapt to this code to tracking earth satellites. But it seems things are never as easy as they first appear.

The first problem was getting orbital elements. It was one thing back then to go to the library and find a book with orbital elements for the planets—it was entirely another story to find a source for orbital elements for earth satellites. It wasn't until 1981 that I discovered that NASA distributed these on paper via the USPS and that you could get on distribution for up to ***twenty*** satellites.

Having the element sets before then probably wouldn't have done much good, though. The two-line element set format had a somewhat different set of Keplerian elements than what I was used to and—as many of you have discovered—won't produce particularly accurate predictions using a simple two-body orbital model. That's because the simple model ignores perturbations, such as precession of the nodes or atmospheric drag, in each satellite's orbit which causes the orbit to vary with time.

Fortunately, I found out about the NASA source for orbital elements when I purchased a BASIC program for the ***TRS-80 Model I*** called ***SAT TRAK***. Written by William N. Barker and David G. Cooke, it actually implemented the NORAD SGP orbital model. It wasn't until I attempted to convert their code to use double precision variables that I discovered from my friend, Robert Boren, that the ***SAT TRAK*** code was actually a BASIC version of the FORTRAN code used by NORAD and he got me a copy of ***Project Spacetrack Report Number 3*** which detailed this model. I spent a good part of the next 15 years making these element sets available electronically and getting people to understand that accurate predictions demanded that these element sets be used in conjunction with the SGP4 orbital model.

Today, access to the NORAD two-line orbital element sets and the corresponding SGP4/SDP4 orbital models is easy—all you need to do is point your WWW browser to http://celestrak.com. Current data, free software, and an ***Adobe Acrobat*** version of ***Project Spacetrack Report Number 3*** are all available at this site. In addition, orbital element sets are available at hundreds of sites worldwide and almost all satellite tracking software includes the NORAD SGP4 model—all thanks to a visual pass of the Skylab space station.

The Underlying Physics

But knowing where a satellite is going to be is only part of the story. A visual satellite pass requires a number of additional circumstances, without which you won't be able to see the satellite. These are:

- The satellite must be above the observer's horizon.
- The sun must be below the observer's horizon enough to darken the sky.
- The satellite must be illuminated by the sun.

We covered how to determine whether a satellite is above the horizon in a series of columns on ***Orbital Coordinate Systems*** from the September/October 1995 to the January/February 1996 issues of this magazine. To determine whether a pass satisfies the other requirements means we first need to know where the sun is.

How accurately the position of the sun must be determined depends upon the application. In most cases, the algorithm described in Chapter 24 of Jean Meeus's book ***Astronomical Algorithms*** will work quite nicely. The low-accuracy algorithm is accurate to 0.01 degree (a little over one percent of the sun's diameter) and can be calculated fairly quickly. The end result will need to be converted to ECI (Earth-centered inertial) coordinates in the same frame as we use for the satellite and observer's position (this is already done for you in my SGP4 Pascal Library (***sgp4-plb26a.zip***) in the routine ***solar.pas***).

Calculating the position of the sun relative to the observer once its position in the ECI coordinate system is known is fairly straightforward. We simply substitute the sun's position for the satellite's position in the equations we developed in ***Orbital Coordinate Systems, Part III***. In fact, all we really care about is the sun's elevation above (or below) the horizon.

The next question we must answer is: Just how far below the horizon does the sun have to be for the observer's sky to be dark? Well, the sun has to be 50 arcminutes below the horizon for it to be considered to have set (all of these results apply equally to sunrise conditions). Part of this angle is due to the semidiameter of the sun (about 16 arcminutes)—even without the atmosphere, when the center of the sun is on the horizon, half of its disk is still above the horizon.

The rest of this angle (about 34 arcminutes) is due to atmospheric refraction. In fact, when the sun's disk appears to be just touching the horizon, it is actually completely below the horizon. The earth's atmosphere, however, refracts the sun's image enough to make it appear to still be above the horizon. The point when the sun's center is 50 arcminutes below the horizon is considered to be the official time of sunset (or sunrise) and is the beginning (or end) of civil twilight. As you know, however, the sky is still quite bright at this point and no stars can be seen.

The point when stars (or satellites) begin to become visible marks the beginning of nautical twilight—when the sun's center is 6 degrees below the observer's horizon. Whenever the sun is more than 6 degrees below the horizon, it should be fairly easy to spot an illuminated earth satellite. The sun's effect on the night sky continues until the end of astronomical twilight when (if) it reaches 18 degrees below the horizon and the indirect light from the sun is less than the contribution from starlight. Of course, sky brightness and atmospheric refraction are influenced by actual meteorological conditions, so there may be some variance in the actual versus the predicted times.

To determine whether a satellite is illuminated is a little trickier. As seen in Figure 1, because the sun's disk is not a point of light, it does not cast a sharp shadow. There are actually two areas of shadow that trail the earth in the anti-solar direction. That cone where no portion of the sun's surface can be seen is referred to as the umbra. The tail of this cone reaches over a million kilometers beyond the earth (well past the orbit of the moon, thus giving rise to total lunar eclipses). The angle of this cone is somewhat affected by atmospheric refraction and may vary.

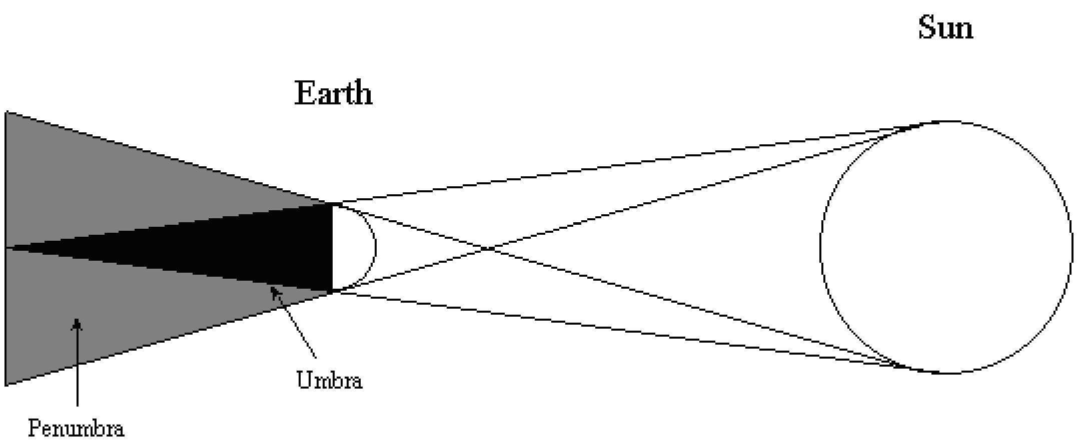

Figure 1. Earth-Sun Shadow Geometry

The shadow cone where only part of the sun's disk is obscured by the earth is referred to as the penumbra. This shadow is not a sharp transition, but rather a gradual transition from full sunlight to full darkness. For near-earth satellites, the transition across the penumbra occurs fairly quickly due to the smaller size (note that Figure 1 is ***not*** drawn to scale) and faster speed of the satellites.

To determine whether a satellite is in umbral or penumbral eclipse requires several simple calculations. First, we must determine the distances from the satellite to the earth (ρ_E), the satellite to the sun (ρ_S), and the earth to the sun ($\boldsymbol{r}_S$). These distances are simple vector distances determined from knowing the position of the satellite and the sun in the ECI coordinate system. The geometry is shown in Figure 2.

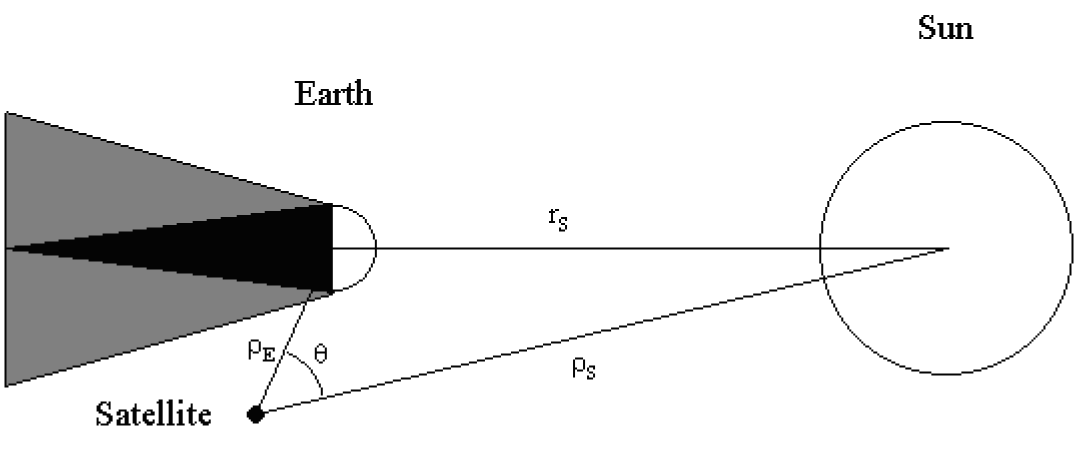

Figure 2. Satellite-Earth-Sun Geometry

From these values, we can then determine the semidiameters of the earth and the sun (θ_E and θ_S, respectively) and the angle between the center of the earth and the sun (θ), all from the vantage point of the satellite. The semidiameters are calculated as

$$\theta_E = \sin^{-1}(\boldsymbol{R}_E/\rho_E)$$

$$\theta_S = \sin^{-1}(\boldsymbol{R}_S/\rho_S)$$

where $\boldsymbol{R}_E$ and $\boldsymbol{R}_S$ are the radii of the earth and the sun, respectively. The angle between the center of the earth and the sun is calculated as

$$\theta = \cos^{-1}(\boldsymbol{\rho}_E \bullet \boldsymbol{\rho}_S/\rho_E\rho_S)$$

where the numerator is the vector dot product of the two distance vectors.

To have an umbral eclipse, the semidiameter of the earth must be greater than the semidiameter of the sun (not equal due to atmospheric refraction) and the angle between their centers must be less than the difference in their semidiameters. That is

$$\theta_E > \theta_S$$

$$\theta < \theta_E - \theta_S$$

An example of this geometry is shown on the left-hand side of Figure 3.

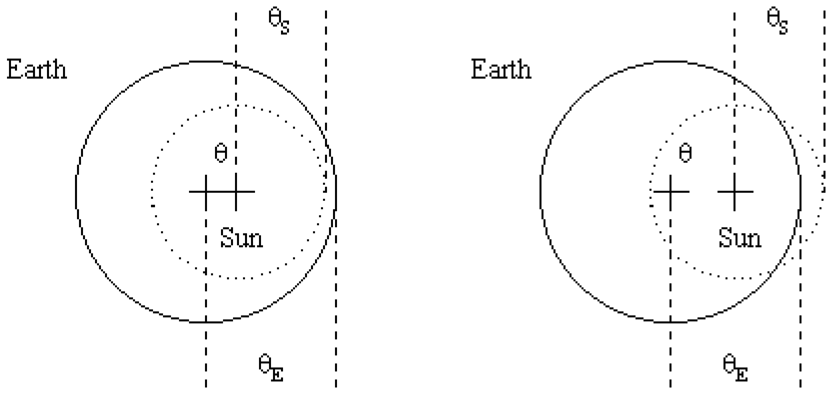

Figure 3. Umbral and Penumbral Eclipse

For a penumbral eclipse, the angle between the centers of the earth and the sun must be less than the sum of their semidiameters (the two disks are just touching) and greater than their differences (the beginning of an umbral eclipse). In the penumbral phase, though, there is no requirement that the semidiameter of the earth be greater than that of the sun. However, since this will be the case for all orbits within the moon's orbit, this condition will be the rule. The requirements for a penumbral eclipse are

$$|\theta_E - \theta_S| < \theta < \theta_E + \theta_S$$

An example of this geometry is shown on the right-hand side of Figure 3. If the semidiameter of the earth is larger than the sun under these conditions, a partial eclipse occurs. The condition when

$$\theta_S > \theta_E$$

$$\theta < \theta_S - \theta_E$$

however, describes an annular eclipse.

To adapt an existing satellite tracking program to show eclipse conditions becomes a fairly straightforward problem. At each time step, the program must calculate the position of the sun in the ECI coordinate system, the position of the satellite in the ECI coordinate system (this should already be done), and the distance from the satellite to the sun. Then, the semidiameters of the earth and sun are calculated, together with the angle between their centers. Using the simple boolean conditions above, it is easy to determine whether the satellite is in full sunlight, totally eclipsed, or somewhere in between.

To determine whether a satellite is visible from the ground only requires the additional step of calculating the sun's elevation relative to the observer. If the sun is more than 6 degrees below the observer's horizon and the satellite is above the horizon and illuminated, a visual pass is possible (weather permitting). It should now be possible for you to determine when a satellite pass is visible and even when it will fade into the earth's shadow!

Conclusion

Obviously, there are a number of other factors involved in determining good satellite passes. Size of the satellite and its distance from the observer play an important role. But understanding the fundamentals will not only make it possible to view earth-orbiting satellites, it will also help you understand things like eclipse seasons for geostationary satellites.

If you'd like more information on this subject, I invite you to attend my session entitled "Visually Observing Earth Satellites" at the upcoming Grove Expo in Atlanta on 18-20 October. We'll cover it all from the basics to advanced topics. Hope to see you there!

As always, if you have questions or comments on this column, feel free to send me e-mail at TS.Kelso@celestrak.com or write care of ***Satellite Times***. Until next time, keep looking up!

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