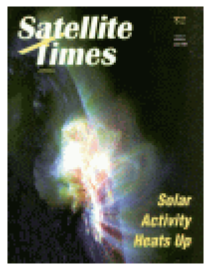
More on Geostationary Orbits

By Dr. T.S. Kelso



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In our last column, we discussed the basics of the geostationary orbit, describing the unique characteristics which make this particular orbit so valuable. In this issue, I would like to cover some operational considerations which can be important when working with satellites in these orbits. In particular, I would like to discuss how to determine the location of a geostationary satellite—relative to the earth's surface and any observer on its surface—and how the sun's position can affect onboard power management and communications.

Locating Geostationary Satellites

Ease of tracking—or, rather the lack of tracking—is one of the primary characteristics of the geostationary orbit which make it so valuable. An observer on the ground can simply point an antenna toward a fixed point in space and then forget it—no tracking is required. However, before the antenna can be pointed, the observer must first determine where the satellite is located.

As we saw in our series on orbital coordinate systems (in the September/October 1995, November/December 1995, and January/February 1996 issues of ***Satellite Times***), the first step to determining the location of a satellite relative to an observer is to determine both the satellite and observer's position in the same coordinate system. For this development, we are going to use the ***Earth-Centered Fixed (ECF)*** coordinate system—latitude, longitude, and radius (or altitude)—as our common coordinate system.

As it turns out, one of the common ways of expressing a geostationary satellite's position is to specify its longitude—that is, the longitude on the equator over which the satellite appears to hover. This information can be obtained from various sources including the "Geostationary Satellite Locator Guide" found in every issue of Satellite Times. This guide is generated using the latest two-line element sets and determines each satellite's longitude at its ascending node.

For the satellite to be geostationary, of course, its latitude must be zero and its altitude must be 35,786 kilometers (for this development, we will assume a true geostationary orbit and a spherical earth). Knowing the longitude of the satellite and the latitude and longitude of the observer, we can now determine where to look.

If $\boldsymbol{R}$ is the radius of the earth, $\boldsymbol{r}$ is the geostationary altitude, λ is the satellite's longitude, θ is the observer's longitude, and φ is the observer's latitude, then the satellite and observer's ECF positions are:

Satellite	***Observer***
$S_x = (R+r)\cos\lambda$	$O_x = R\cos\varphi\cos\theta$
$S_y = (R+r)\sin\lambda$	$O_y = R\cos\varphi\sin\theta$
$S_z = 0$	$O_z = R\sin\varphi$

and the range vector is the satellite's position minus the observer's position:

Range

$$\rho_x = (R+r)\cos\lambda - R\cos\varphi\cos\theta$$
$$\rho_y = (R+r)\sin\lambda - R\cos\varphi\sin\theta$$
$$\rho_z = -R\sin\varphi$$

To calculate azimuth and elevation, we use the same coordinate transformation described in "Orbital Coordinate Systems, Part II" in the November/December 1995 issue of ***Satellite Times***. As an example, let's calculate the position of Galaxy 4 from Pasadena, California.

Constants	***Satellite***	***Observer***
R = 6,378 km	λ = 99.0°W	φ = 34.15°N
r = 35,786 km		θ = 118.15°W

Using these values yields an azimuth to the satellite of 148.25°, an elevation of 45.32°, and a range of 37,390 km—values pretty close to the true values.

While this approach can be used to produce good estimates, these are probably not calculations you would want to do by hand (although they can be done fairly easily using a spreadsheet). Plus, if you do not know the satellite's longitude, you will need to start from the satellite's orbital elements, further complicating the process. Of course, you can use a program like ***TrakStar*** to calculate the latitude, longitude, and altitude or the look angles (azimuth, elevation, and range) of any satellite (geostationary or otherwise) for any time interval desired using two-line element sets found on the ***CelesTrak*** WWW site.

Power Management Issues

Geostationary orbits present some interesting challenges for power management. To understand these challenges, we must first understand a little about the attitude (orientation in space) of geostationary satellites and the position of the geostationary orbit relative to the sun.

All modern geostationary spacecraft use one of two forms of stabilization to maintain their attitude: dual-spin or three-axis stabilization (see Figure 1). With dual-spin stabilization, the satellite takes the shape of a cylinder which rotates about its long axis. This type of satellite has two sections: a spinning section upon which the solar arrays are mounted and a despun section where the communications antennas are mounted. The spinning section provides basic stabilization and can rotate as fast as 100 RPM (in the case of the early GOES satellites). The despun section rotates, too, albeit at a much slower rate of one rotation per orbit (day)—keeping the antennas pointed at the earth and preventing the satellite from going into a flat spin (which is the natural tendency).

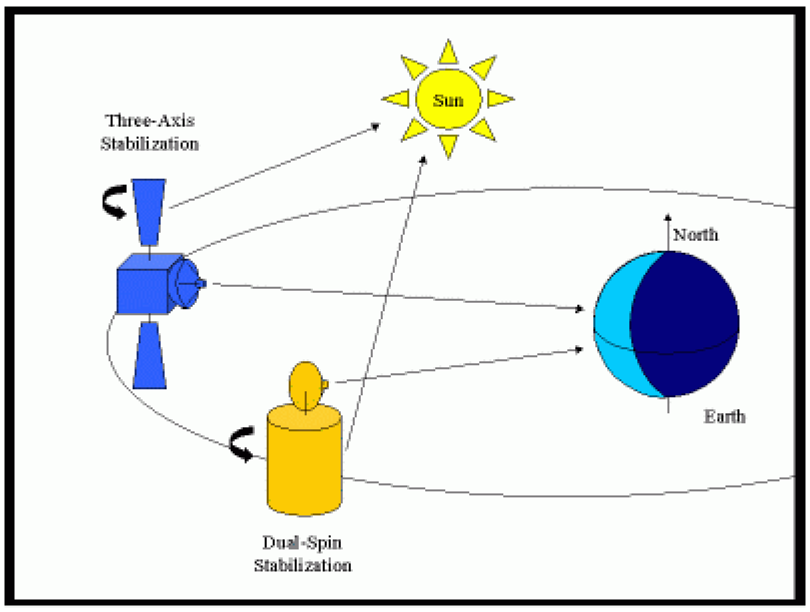

Figure 1. Geostationary Spacecraft Attitude Types

With three-axis stabilization, the spacecraft attitude is maintained through the use of momentum wheels or control moment gyros. The body of the spacecraft does rotate once per orbit (day) to keep the antennas pointed at the earth. The solar arrays are mounted on paddles which also rotate once per day to keep them pointed toward the sun.

In both cases, it should be noted that the rotation axis of the satellite is perpendicular to the satellite's orbital plane—which for geostationary orbits is the equatorial plane. We will see why this is important shortly.

As with all satellites, the solar arrays on geostationary satellites are subject to a number factors which can result in significant fluctuations in the amount of power available to onboard systems. To begin with, the position of the satellite relative to the sun varies throughout the year. As the earth goes around its orbit, its distance from the sun changes from a minimum of 0.983 astronomical units (AUs—the mean distance from the earth to the sun is approximately 1 AU or 149,597,870 km) to a maximum of 1.067 AU—a difference of 12,518,000 km. If we consider the energy received from the sun at 1 AU to be 100%, then the energy received varies from 97% to 103%, as shown in Figure 2.

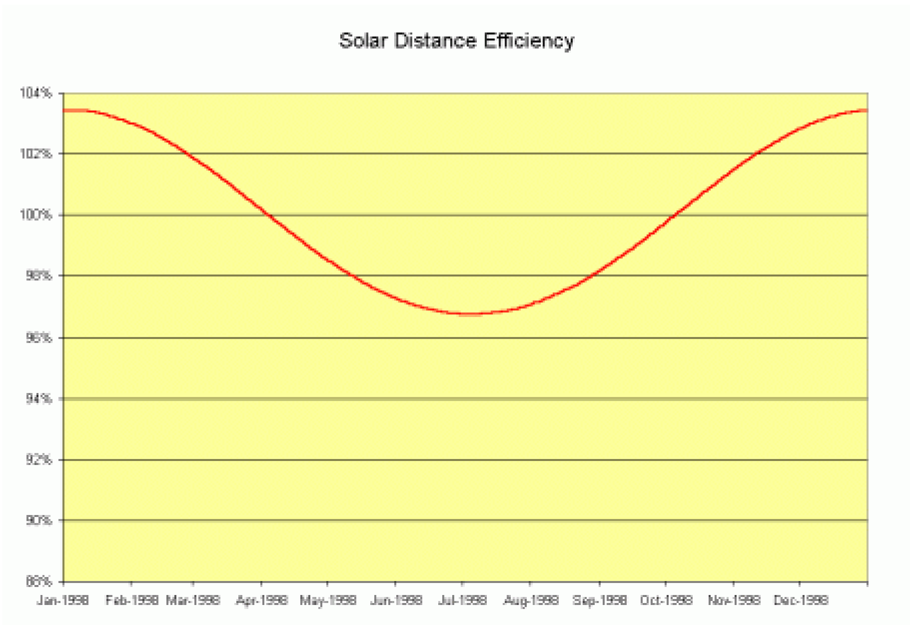

Figure 2. Solar Distance Efficiency

Not only isn't the earth's orbit truly circular, but the plane of the earth's equator does not lie in the plane of the earth's orbit (the ecliptic). Earth's seasons are a direct result of this circumstance. From our vantage on earth, it appears that the sun slowly moves from 23° below the equatorial plane (at the winter solstice) to 23° above the equatorial plane (at the summer solstice) and back again over the course of a year. As seen in Figure 3, our geostationary satellite sees the same thing.

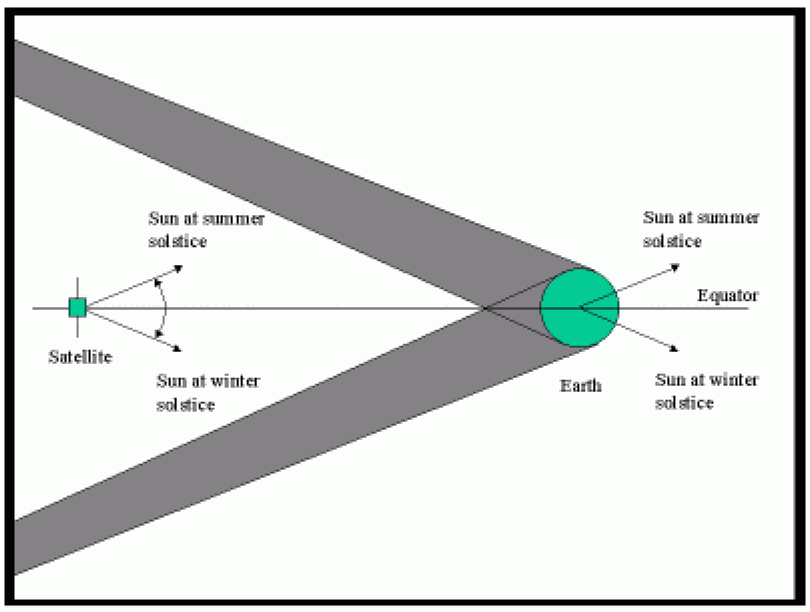

Figure 3. Sun-Earth-Satellite Geometry

The apparent motion of the sun above and below the equatorial plane has two effects. First, it changes the angle of incidence of solar energy received on the solar arrays since they must rotate about an axis perpendicular to the equatorial plane. As a result, the amount of solar energy absorbed by the solar arrays drops off as a factor of cos(δ), where δ is the sun's declination (angle relative to the equatorial plane). If we consider the amount of energy received when the sun's rays are perpendicular to the solar arrays to be 100%, then the energy received drops to less than 92% at the solstices, as shown in Figure 4.

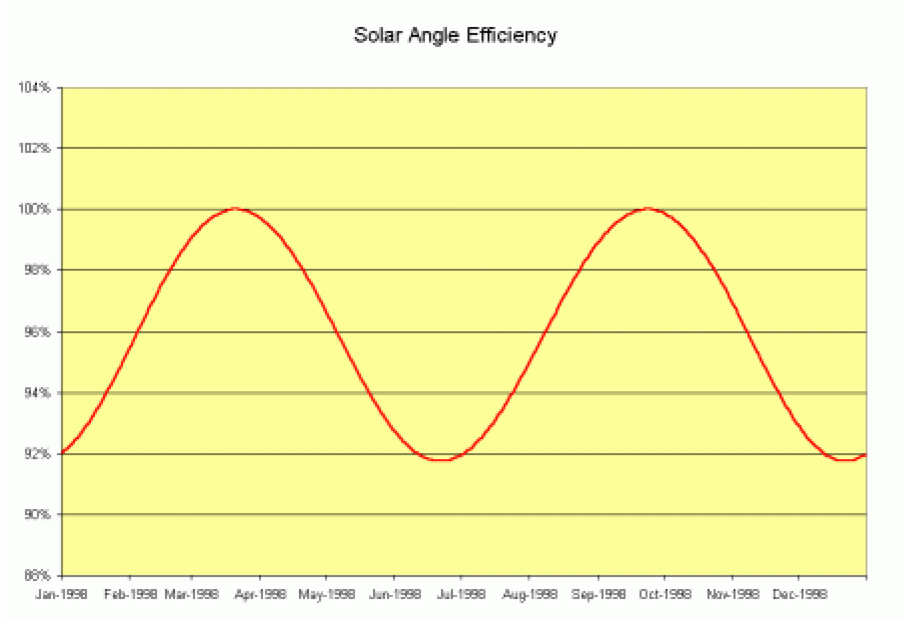

Figure 4. Solar Angle Efficiency

From Figure 3 we can also see that because of this sun-earth geometry, the geostationary orbit is usually outside the cone of the earth's shadow. That is, until around the times of the vernal and autumnal equinoxes (the beginning of spring and fall). At these times, geostationary satellites enter their eclipse season, when they can spend as much as 70 minutes of every day in shadow. These seasons run from the end of February through the middle of April and the beginning of September through the middle of October. The percentage of sunlight received for geostationary satellites is shown in Figure 5. To prepare for eclipse seasons, the satellite operators must ensure that the spacecraft batteries are properly conditioned to pick up the load during each day's eclipse.

Figure 5. Eclipse Efficiency

If we combine the effects of variations in solar distance, solar angle, and eclipses over the course of a year, we get the result in Figure 6. As can be seen in this figure, total solar energy available varies 12%—from a low of 89% to a high of 101%.

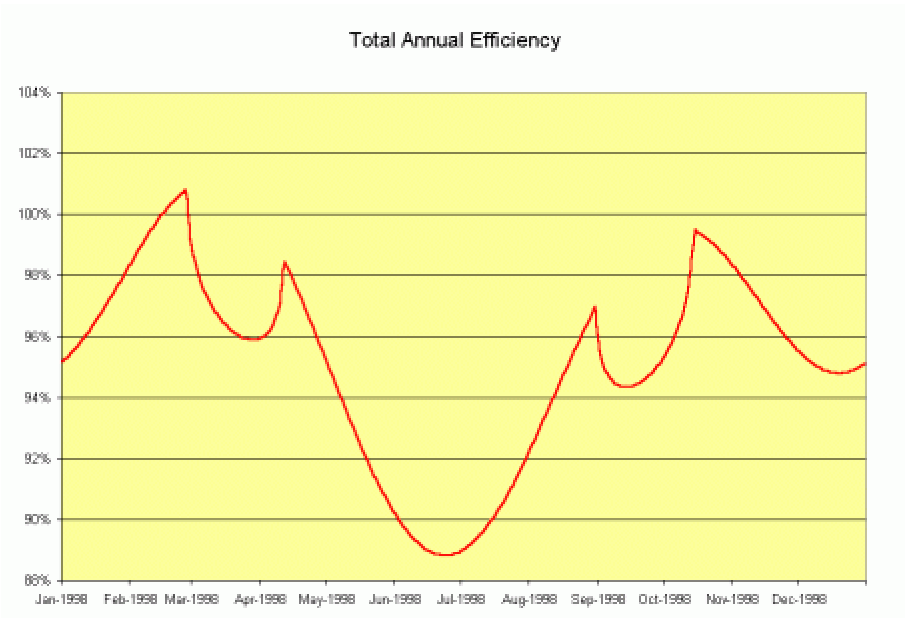

Figure 6. Total Annual Efficiency

If we also factor in the effects of degradation on the solar cells and their optical coverings due to the space environment and look at a nominal seven-year satellite lifetime, we get the graph in Figure 7. Typical results show the optical covering degrades about 7% the first year before stabilizing while the solar cells degrade about 3% their first year and 2% each subsequent year. As can be seen from the graph, the power levels drop from a high of 99% overall efficiency to a low of 72%. When designing the spacecraft power subsystem, that means if 7.5 kW of power are required for normal operations, the power subsystem must be designed to provide almost 10kW initially so that available power doesn't drop below the threshold before the end of the planned satellite lifetime.

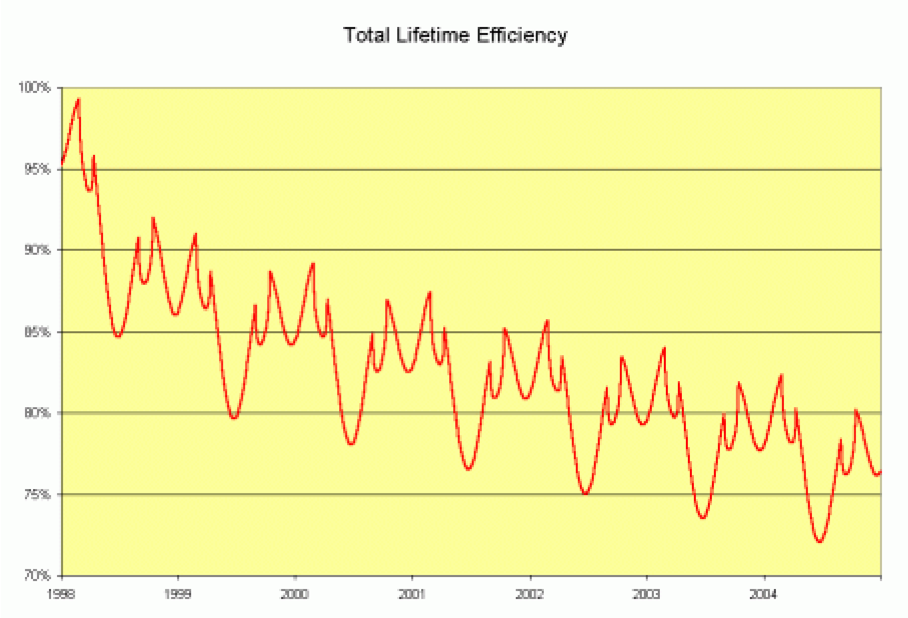

Figure 7. Total Lifetime Efficiency

Solar Interference

In addition to planning for variations in spacecraft power, satellite operators and users also need to plan for communications outages (or degradation) around the eclipse seasons. As the sun sweeps across the sky each day and gradually moves north or south with the seasons, there will come a time twice each year when the sun is directly behind a geostationary satellite as seen from a ground-based antenna. When this happens, the flood of solar radio energy into the antenna's main lobe can severely disrupt communications. Fortunately, such disruptions only last a couple of minutes. You may have actually seen one of these outages while watching your favorite cable channel (most of which are transmitted via geostationary satellites). For observers in the Northern Hemisphere, this happens prior to vernal equinox and after the autumnal equinox.

We covered a lot of ground in this article—orbital mechanics, spacecraft attitude, power management, and even materials—all factors important in the design and operation of any satellite, but particularly important for geostationary satellites. I hope I've shown how these various areas interact and overlap and, in the process, shed some light on the topic of spacecraft design. As always, if you have any questions, please feel free to write me at TS.Kelso@celestrak.com. Until next time, keep looking up!

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