YAW CONTROL - A SIMPLE WAY TO ENHANCE SOLAR ARRAY PERFORMANCE

Emery I. Reeves
Stanford University, Stanford, California, 94305

Solar cell arrays are used on substantially all earth orbiting spacecraft to produce electric power. Solar arrays are of three geometric types: planar, cylindrical, and omnidirectional. Oriented planar arrays have a geometric efficiency (ratio of solar energy capture area to total array area) of one and are used on most large spacecraft. Cylindrical arrays which have a geometric efficiency of $1/\pi$ are common on spinners while most small spacecraft including those that are earth pointed use omnidirectional arrays which have a geometric efficiency of only 1/4. An earth oriented spacecraft with a body fixed planar array can achieve a geometric array efficiency of $2/\pi$ by the simple expedient of yaw control (control about the local vertical). Body rates and torque requirements for this type of control are modest and can be provided by a variety of techniques. Parametric evaluation of this method of control is presented and various implementation schemes are discussed.

Introduction

The geometric relations between the bodyaxes of an earth oriented spacecraft and the line-of-sight to the sun can be described in terms of a solar aspect angle which is defined as the angle between the sun line and a vector normal to the orbit plane. A spacecraft equipped with a body fixed planar solar array can maximize the solar array output by rotating about the vertical axis (yawing) so that the array presents the largest possible area to the incident sunlight. If the solar aspect angle is zero, i.e. the sun line is normal to the orbit plane, a fixed yaw orientation which holds the array parallel to the orbit plane provides maximum power. However, solar aspect angles other than zero require continuous oscillatory motion of the yaw angle to maximize array output. In the limiting case when the sun is in the orbit plane, reorientation of 180° in yaw is required when the sun passes the vertical axis. However investigation of the these yaw orientation requirements shows that even with severe yaw angular rate limitations, the ideal yaw profile can be followed closely enough to provide excellent solar array performance, exceeding 60% of the performance of a fully oriented array. Implementation can be simply a sun sensor, processing electronics, and a yaw reaction wheel. The basic control technique also has a proven flight history going back to the 60's when it was used on the OGO series of scientific spacecraft[1].

Coordinates and Angle Definitions

The solar aspect angle and orbital geometry used here are shown in Fig. 1. A set of reference coordinates is defined with the x_r - z_r plane being the orbit plane and the sun line contained in the y_r- z_r plane. This coordinate set is almost inertial because the sun moves slowly relative to the orbit plane and in general the orbit plane elements vary slowly with time. The solar aspect angle S is defined as the angle between the y_r axis and a unit vector u_s pointed toward the sun. A second set of coordinates called orbit coordinates x_o y_o z_o are centered at the spacecraft. The x_o - y_o plane is the orbit plane and the z_o axis points toward the center of the earth (Nadir). Orbit coordinates are related to reference coordinates by the orbit angle θ which is measured about the y_r axis and is the angle between the z_r and z_o axes. The satellite position in orbit is also defined by the orbit angle θ.

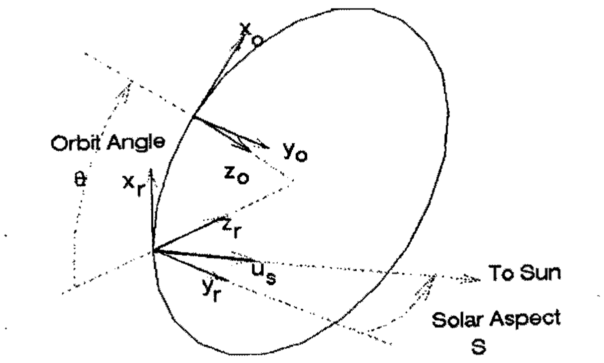

Figure 1 Coordinate Systems
Solar aspect angle S and orbital position angle θ shown

The simplified geometry of Fig. 1 is convenient for the discussion at hand. The solar aspect angle S can easily be related to more conventional quantities. Specifically, S is related to the right ascension of the sun RAS, the declination of the sun DecS, the right ascension of the spacecraft orbit ascending node RAAN and the orbit inclination i by:

$$S = \arccos[-\sin(i)*\sin(RAS-RAAN)*\cos(DecS)+\cos(i)*\sin(DecS)] \quad (1)$$

Spacecraft body axes x_b y_b z_b are defined in Fig 2. Since our discussion is confined to earth oriented spacecraft, the earth facing side is defined by the z_b axis which is coincident with the z_o axis. The x_b - y_b plane is horizontal, and the yaw angle W is defined as the angle between the x_o and x_b axes. The solar array plane is defined by the $+x_b$ axis; that is, the x_b axis is normal to the solar array.

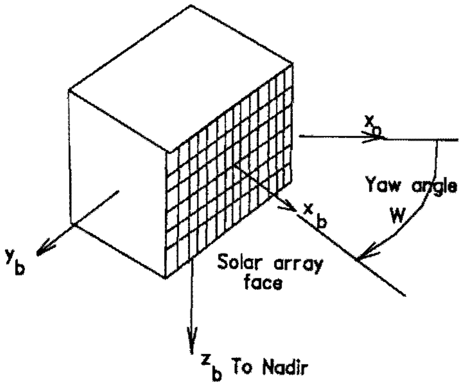

Figure 2 Spacecraft Body Coordinates
Yaw angle W shown

The unit vector $\mathbf{u_s}$ has components in spacecraft body coordinates u_{sbx} u_{sby} and u_{sbz} which are given by:

$$u_{sbx} = \cos(W)*\sin(\theta)*\sin(S) + \sin(W)*\cos(S) \quad (2a)$$

$$u_{sby} = -\sin(W)*\sin(\theta)*\sin(S) + \cos(W)*\cos(S) \quad (2b)$$

$$u_{sbz} = \cos(\theta)*\sin(S) \quad (2c)$$

These components of $\mathbf{u_s}$ show that the solar intensity on the earth facing side of the spacecraft (z) is independent of the yaw angle. The solar intensity on the solar array face of the spacecraft (x) is a function of yaw angle and is maximized by maximizing u_{sbx} or equivalently by minimizing u_{sby}. If the yaw angle W is controlled so that u_{sby} is zero, the sun line is constrained to lie in the u_{bx} - u_{bz} plane. The intensity of sunlight falling on the array face is proportional to u_{sbx}. The value of yaw angle W which produces this condition is called the ideal yaw angle W_i.

Ideal Yaw Angle

The ideal value for yaw angle, that is, the value which maximizes the solar intensity on the array face is computed by setting u_{sby} equal to zero. Using equation 2b, this value of W_i is

$$W_i = \arctan\left[\frac{1}{\tan(S)*\sin(\theta)}\right] \quad (3)$$

Equation 3 is plotted in Fig. 3 which clearly shows the oscillatory nature of W_i for values of S other than zero. For S equal to zero, the ideal yaw angle is 90°. For values of S other than zero, the value of W_i oscillates about 90°. The maximum deviation from 90° occurs at position angles θ of 90° and 270° and this deviation is equal in magnitude to the value of S.

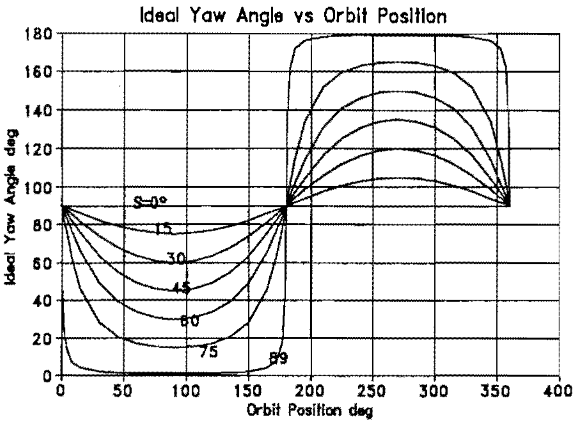

Figure 3 Ideal Yaw Angle
Plotted against orbit position angle for various values of solar aspect angle

Eclipses

A position angle θ of zero corresponds to spacecraft midnight. In the vicinity of θ=0 the spacecraft is eclipsed if S is sufficiently large. If S is 90° the eclipse duration is maximum corresponding to the spacecraft passing directly behind the center of the earth. If S differs from 90°, lesser duration eclipses occur. Figure 4 is a plot of eclipse duration (expressed in spacecraft position angle) as a function of solar aspect angle for various orbit altitudes.

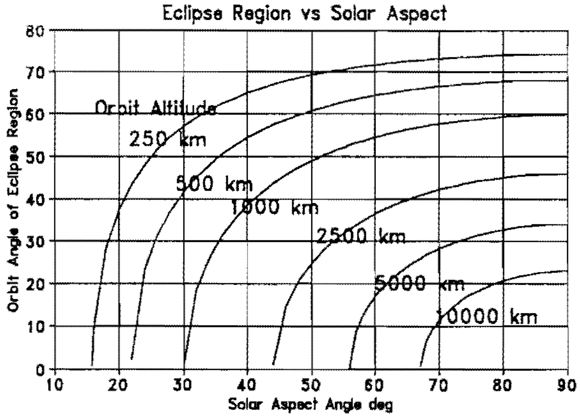

Figure 4 Eclipse Position vs Solar Aspect Angle
Various orbit altitudes shown

Figure 5 shows the eclipse region for various altitudes superimposed an a plot of ideal yaw angle W_i for various values of solar aspect angle S. Let the position angle of eclipse emergence be θ_s. Its value as a function of orbit altitude h, earth radius R_e, and solar aspect angle S is given by:

$$\theta_e = \arccos\left[\frac{(2*R_e*h+h^2)^{\frac{1}{2}}}{\cos(S)*(R_e+h)}\right] \qquad (5)$$

Obviously the solar array cannot produce power during eclipse. Therefore we are only interested in the rapidity with which the yaw angle converges to its desired value after emergence from eclipse and not in the value of yaw angle during eclipse.

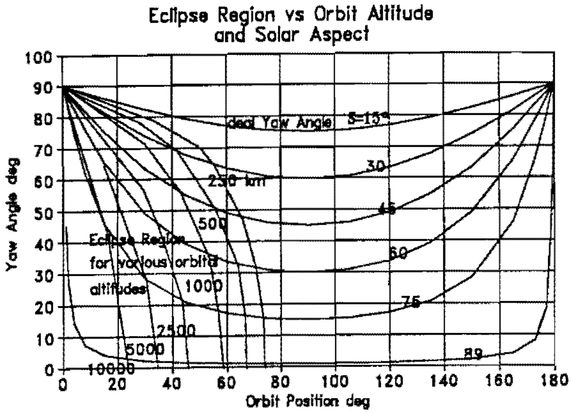

Figure 5 Eclipse Region For Various Orbit Altitudes
Ideal yaw angle for various values of solar aspect angle also shown

Area Efficiency

A good performance criterion for evaluating this proposed technique for yaw control is the integrated solar intensity falling on the solar array face. The instantaneous intensity is proportional to u_{sbx}. The integrated intensity is the integral of u_{sbx} from eclipse emergence $\theta=\theta_e$ to reentry into eclipse $\theta=2\pi-\theta_e$. The area efficiency is the ratio of this integrated intensity to the integrated intensity for a fully oriented array. This efficiency is:

$$\eta = \frac{1}{2\pi-2\theta_e}\int_{\theta_e}^{2\pi-\theta_e} u_{sbx}\, d\theta \qquad (6)$$

Plots of this array area efficiency for various values of solar aspect angle and orbit altitude are presented in figure 6. These plots show that the area efficiency is almost independent of orbit altitude and falls from a value of 1 at S=0 to approximately 0.7 at S=90°.

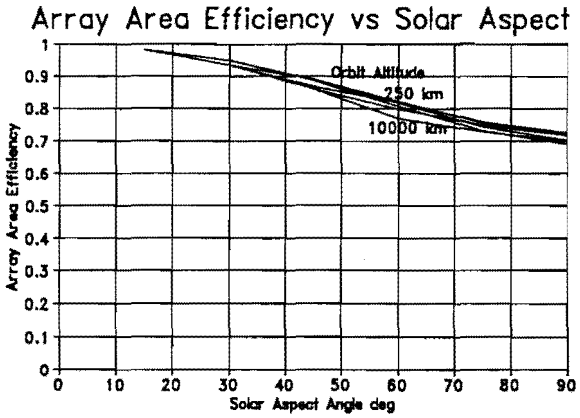

Figure 6 Array Area Efficiency vs Solar Aspect Angle
Various orbital altitudes shown

Solar Cell Electrical Performance

The foregoing discussion of array area efficiency shows that by proper yaw control the array can gather almost as much energy as it would if it were fully oriented. Fortunately illumination level primarily affects solar cell current. The cell voltage characteristics are substantially independent of illumination level. (A solar cell can be characterized as a current generator in parallel with a diode. The current is a proportional to illumination level. The diode electrical characteristics are independent of illumination level.) For this reason most array systems will supply power at satisfactory voltage levels in spite of variation in illumination level. Plots of typical cell short circuit current, open circuit voltage, and maximum power voltage are presented in figure 7 for various illumination levels[2].

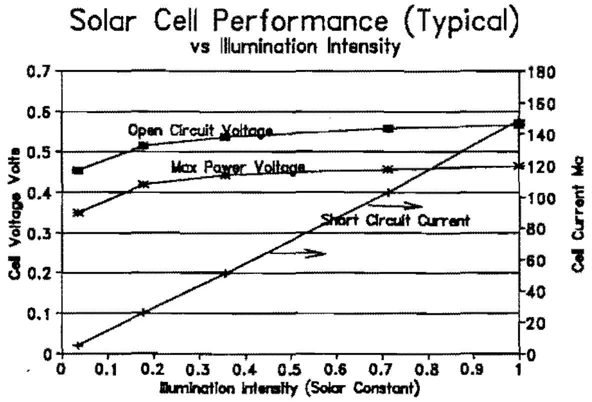

Figure 7 Solar Cell Electrical Performance vs Illumination Level (Typical)

Yaw Control Methods

A basic yaw control system consists of a sun sensor to measure the y body component of the sun line u_{sby}, processing electronics to amplify and shape the signal and a yaw reaction wheel. All of the components of such a control system are readily available[3][4]. Other mechanizations are also possible. A yaw estimator could be used to estimate yaw angle based on sun sensor outputs (and perhaps other system variables) and other torquing methods could also be used.

Wide angle sun sensors which provide outputs proportional to the components of solar intensity along a particular axis can be constructed by mounting solar cells on the faces of a cube. Cells mounted on opposing sides are connected together with opposing polarities. Normally the cells are pre-irradiated to stabilize their electrical characteristics. The cells are loaded with calibration resistors to provide the specified scale factor. Sensors that provide direct digital output have also been constructed. The amplification and shaping is a function of the stability design of the control loop and the transfer function of the reaction wheel. The OGO control system used lead-lag shaping and switching control of the reaction wheel.

It should be noted that the loop gain of the system shown varies with orbit position and is a function of solar aspect angle. The variation in gain can be derived by computing the partial derivative of u_{sby} with respect to W for $W=W_i$. This is:

$$\frac{du_{sby}}{dW} = -\cos(S)*[1+\tan^2(S)*\sin^2(\theta)]^{\frac{1}{2}} \quad (7)$$

This equation is plotted in figure 8 (the sign of this plot is inverted in order to emphasize that the highest magnitude gain occurs at S=90°). Although the gain variations are severe for large values of S, the regions where the gain is low correspond to regions where the sun is close to the z body axis and the array won't produce much power regardless of yaw orientation.

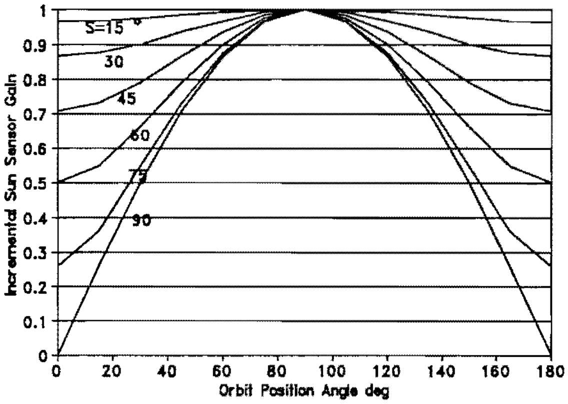

Figure 8 Yaw Sun Sensor Incremental Gain vs Orbit Position
Partial derivative of sun sensor output with respect to yaw angle for various values of solar aspect angle.

A yaw reaction wheel such as might be used in the simple yaw control system described above is sized by the desired speed of yaw orientation. For ideal yaw angle control this is infinite, however the array performance is not greatly degraded by limiting yaw rate to modest values. A yaw rate limit of 10 times orbit rate gives no discernable reduction in solar array performance whereas a yaw rate limit of 3 times orbit rate affects only orbits with S greater than 75°. If the yaw rate is limited to 3 times orbit rate, the array area efficiency for s=90° drops from 0.689 to 0.620 for an orbit altitude of 250 km.

Conclusions

The concept of yaw control for solar array power enhancement has been described. This concept is sound and has been used extensively. For earth oriented lightsats it offers solar array efficiency improvement and the concept meshes well with gravity gradient control. It is inexpensive and can be implemented with available hardware although some hardware innovation might reduce cost and weight.

References

[1] Reeves, E.;Martin, L.; and Otten, D.; "The Design of an Attitude Control System for an Earth-Sun Oriented Satellite"; Proceedings International Conference on Satellite Communication; Institution of Electrical Engineers, London England, 1962

[2] Rauschenbach, H.; "Solar Cell Array Design Handbook"; Van Nostrand Reinhold Co., New York, 1980

[3] Wertz, J., "Spacecraft Attitude Determination and Control", D. Reidel Publishing Co., Dordrecht, Holland, 1978

[4] Larsen, W. and Wertz, J., "Space Mission Analysis and Design", Kluwer Academic Publishers, Dordrecht, Holland, 1991