SPS ATTITUDE CONTROL AND STATIONKEEPING – REQUIREMENTS AND TRADEOFFS

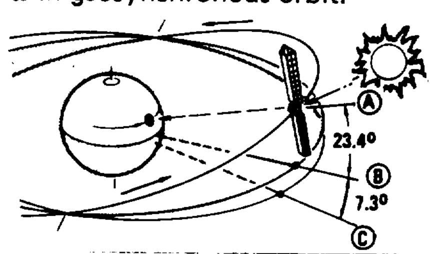
R.E. Oglevie
Rockwell International, Downey, California

This paper summarizes the results of attitude control and stationkeeping (AC&SK) studies[1,2,3] to define spacecraft and mission requirements, preferred control approaches, and feasibility issues.[4] The work was partially accomplished under NASA MSFC Contract NAS8-32475.

Three orbits with features attractive to SPS are shown in Figure 1. The ecliptic orbit permits direct solar viewing in a horizontal attitude, which minimizes gravity gradient disturbance torques. The 7.3° inclined orbit minimizes the north-south stationkeeping ΔV requirement. The geosynchronous equatorial orbit is preferred because of the large cost of the increased rectenna size associated with the two other orbits.

The large size of the SPS makes appreciable changes in AC&SK requirements relative to small contemporary spacecraft. Analyses[2,3] indicate that the solar pressure stationkeeping perturbation becomes dominant rather than the solar-lunar gravitational perturbation. Gravity gradient disturbance torques increase rapidly as a function of spacecraft size and can cause appreciable attitude control penalties without judicious choice of spacecraft reference orientation and spacecraft design parameters. Structural bending frequencies are appreciably reduced, raising concern about control system/structural dynamic interaction stability.

The stationkeeping ΔV and RCS propellant requirements are presented in Table 1; correction of the solar pressure perturbation dominates the requirements. If uncorrected, the solar pressure perturbation will cause a ±2.5° cyclical change in longitude with a one-year period. This is unacceptable in light of the heavy use of the geosynchronous equatorial orbit projected during the SPS time frame. The stationkeeping propulsion requirements necessitate the use of high-performance propulsion (such as ion thrusters) to minimize propellant resupply expense over the SPS lifetime. Flying the SPS spacecraft in clustered constellations offers promise of minimizing their space requirements in geosynchronous orbit.



GEOSYNC. ORBIT PLANE	INCLINATION (DEG)	RECTENNA SIZE INCREASE*	N-S STATION KEEPING: ANNUAL ΔV REQUIRED (M/SEC)	N-S STATION KEEPING: 30 YR. RCS PROPELLANT** (% S/C MASS)
ECLIPTIC Ⓐ	23.4	88.5%	TBD	TBD
EQUATORIAL Ⓑ	0	0	46 M/SEC	1.25
MIN. N-S STATION-KEEPING ΔV Ⓒ	7.3	13.9%	~ 0	~ 0

* FOR 34° LATITUDE (LOS ANGELES)
** I_{SP} = 13,000 SEC

Figure 1. Orbit Selection Trade

Table 1. Stationkeeping ΔV and Propellant Requirements

Orbit Perturbation	ΔV (M/S/Year)	Propellant Required Over 30 Years* (% of Spacecraft Mass)
Solar pressure (E-W)	282.5	6.65
Solar/lunar perturbation (N-S)	53.3	1.25
Earth triaxiality (E-W)	2.1	0.05
MW radiation pressure (E-W)	Negligible	Negligible
Station change maneuvers (E-W)	1.1	0.03
Total	339.0	7.98

*I_{sp} = 13,000 sec

[1]Satellite Power System Concept Definition Study. Vol. II. Rockwell International, SSD 79-0010-2-1 (March 1979).
[2]Oglevie, R.E., "Attitude Control of Large Solar Power Satellites," AIAA Paper 78-1266, AIAA Guidance and Control Conference (August 1978).
[3]Satellite Power System Concept Definition Study. Vol. III. Rockwell International, SD 78-AP-0023-3 (April 1978).
[4]The assistance of D. Camillone of Rockwell in performing this work is gratefully acknowledged.

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Microwave beam pointing is achievable with an antenna pointing accuracy of 0.05 deg and electronic beam steering for precise vernier pointing. Solar collector pointing accuracy requirements are a function of collector concentration ratio and are on the order of 0.5° for CR=2. These accuracies are achievable with existing technology and current studies indicate they can be met without active figure (structural shape) control. Simple active figure control in the microwave antenna may prove to be useful in simplifying the structural design and assembly tolerances.

Attitude control techniques considered for the SPS include: spin and gravity gradient stabilization, solar pressure vanes, large erectable momentum wheels, quasi-inertial free drift modes, and various reaction control thruster types (Figures 2-4). The spin, gravity gradient, and solar pressure vane stabilized approaches were all found to be inferior to the selected baseline because of their larger mass and complexity penalties. The large erectable momentum wheels (Figure 3) and the quasi-inertial free-drift attitude mode are useful in eliminating propellant consumption due to cyclical disturbance torques. The propellant requirements for various RCS thruster types (Figure 4) indicate that high-performance propulsion (such as argon ion thrusters) is required to avoid the high propellant resupply costs of contemporary chemical propulsion systems for a 30-year spacecraft lifetime.

The attractiveness of RCS thrusters for attitude control is enhanced by combining attitude control and stationkeeping requirements, and satisfying them jointly with the same propulsion systems.[1] The approach is illustrated in Figure 5. Thruster groupings are at each corner of the spacecraft and nominally thrust continuously toward the sun to correct solar pressure orbit perturbations. Other stationkeeping perturbations are considerably smaller and are corrected by gimbaling the thrusters through small angles. Similarly, the attitude control torques are obtained by a combination of differential throttling and gimbaling. The system is capable of simultaneously providing stationkeeping forces and attitude control torques about all three axes. Since the required gimbal angles are small, these functions are satisfied with a propellant quantity that is only slightly greater than that required to correct the solar pressure stationkeeping perturbation. Gimbaled thrusters are preferable to body-fixed thrusters because of a significant reduction in the number of thrusters and propellant required. During earth eclipse periods only attitude control torques are provided. This control approach minimizes the system requirements for attitude control and is selected for the baseline reference configuration (Figure 5). Nominally 36 thrusters are required; however, 64 are provided to accommodate for failures and servicing. The mass of the overall AC&SK

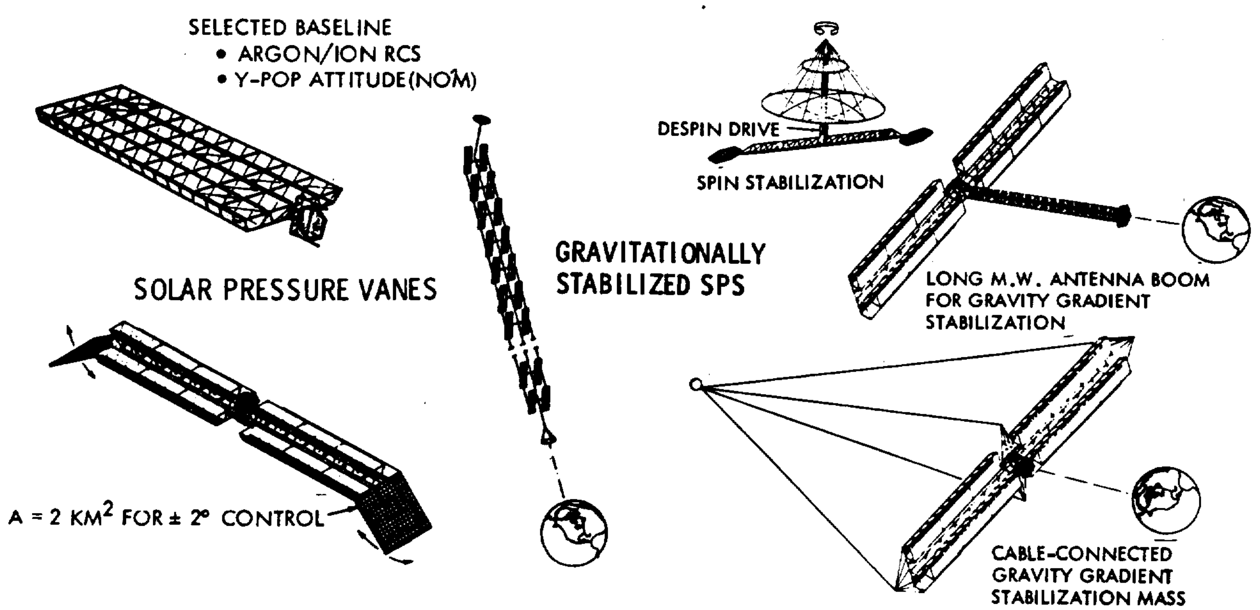

Figure 2. Attitude Control Concepts

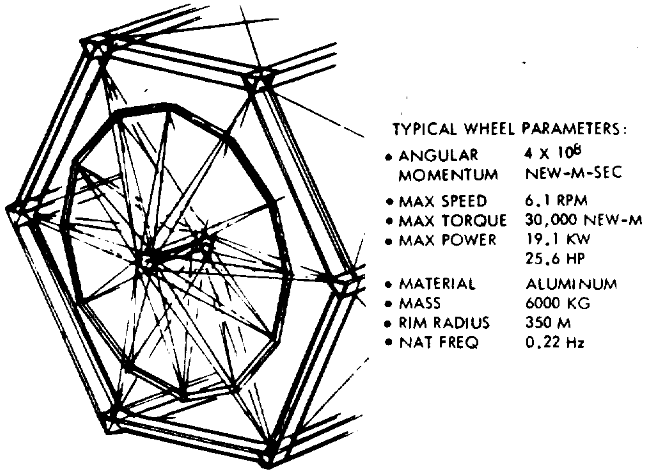

Figure 3. Erectable Momentum Wheel Conceptual Design

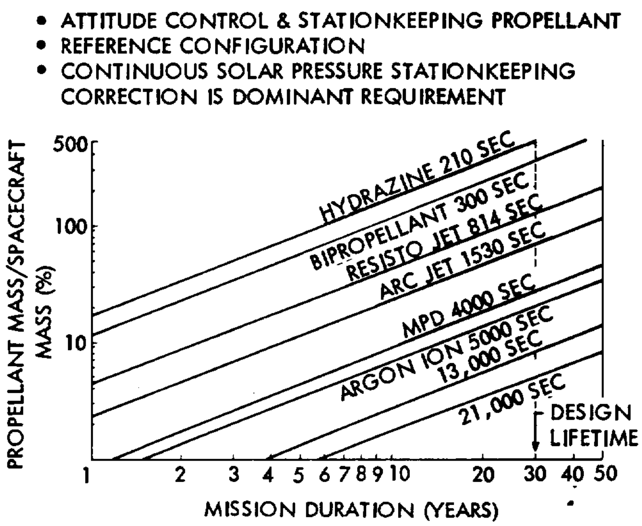

Figure 4. Propellant Requirements for Various RCS Propulsion Types

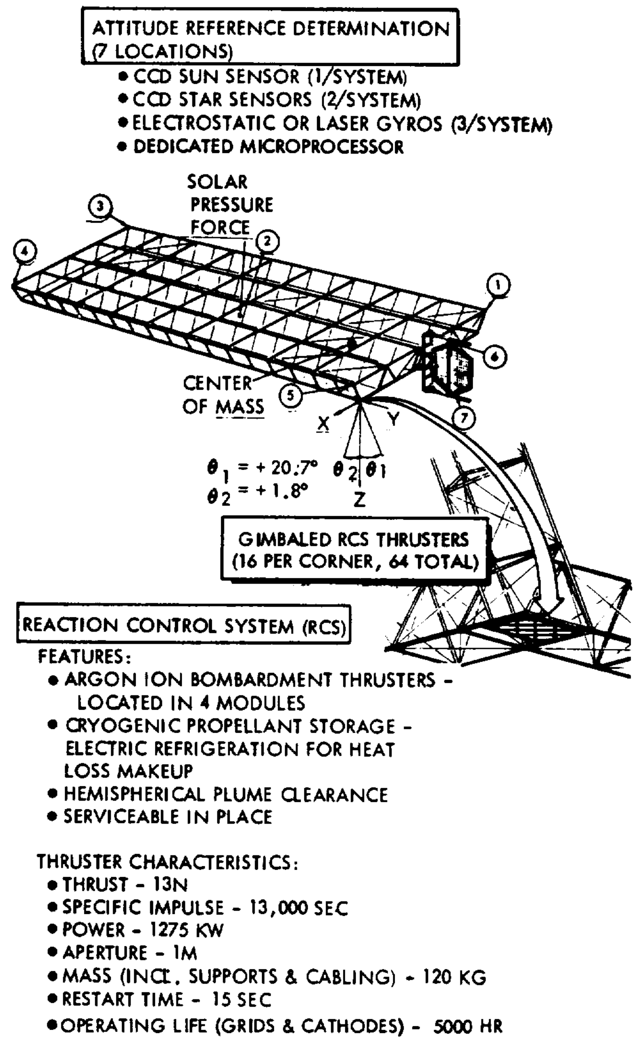

Figure 5. Baseline Attitude Control and Stationkeeping System

system is given in Table 2 and is 0.08% of the spacecraft mass (dry) and 0.37% with annual propellant requirement. The average operating power is 34 megawatts.

Dynamic stability is a concern because of low SPS structural frequencies in the order of 6 cycles/hour. Preliminary simplified analyses have been performed[3] to establish control bandwidth requirements and system stability. Quasi-linear control torques are obtained with a combination of throttling and on-off thruster commands. The results indicate that substantial separation between control bandwidth and structural frequencies exists (Figure 6) and that stability is achievable using classical control techniques. This is due primarily to the low SPS bandwidth requirements for the sun-staring application. Small increases in depth of the structure can appreciably increase structural frequencies with only minor increases in structural mass. However, technology advancement in control of large space structures is recommended to support potential structural mass savings and spacecraft design simplifications.

A variety of SPS configurations have evolved, with significantly different AC&SK requirements. The solid-state SPS configuration depicted in Figure 7 has a larger solar pressure stationkeeping propellant requirement than the reference spacecraft due to larger area/mass and area/power ratios.

Table 2. AC&SK System Mass Summary

Item	Mass (x 10^{+3} kg)
Attitude reference determination systems (7)	0.32
Thrusters – including support structure (64 at 120 kg/thruster)	7.68
Tanks, lines, refrigeration	15.07
Power processing equipment	TBD
Argon propellant – annual requirement	85.39
Total (dry)	23.07
Total (With Propellant)	108.46

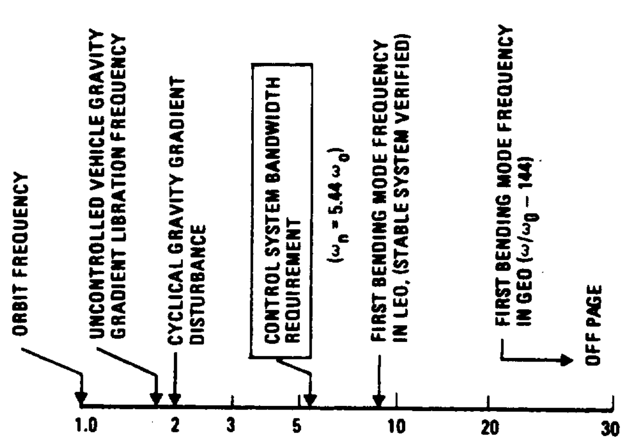

Figure 6. Frequency Distribution

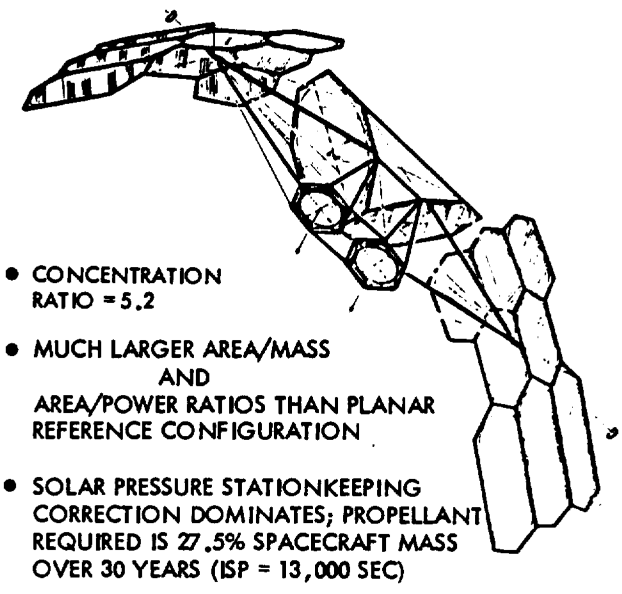

Figure 7. AC&SK Dual Solid-State Configuration

The symmetrical "dual" configuration is preferable to an unsymmetrical "single" energy conversion system spacecraft because of the large propellant requirements (41.1% of spacecraft mass over 30 years) due to additional large gravity gradient and solar pressure torques which arise from the asymmetry.

In summary, the dominant control requirements of SPS change appreciably relative to small contemporary spacecraft. The trade studies and analyses have illustrated preferred control approaches and that the AC&SK requirements are tractable. No major feasibility issues are visible at this time. Supporting conclusions include:

1. Geosynchronous equatorial orbit is preferred over the alternative orbits considered.
2. The solar pressure orbit perturbation dominates stationkeeping propulsion requirements. High-performance propulsion is necessary to avoid large propellant resupply costs.
3. A combined AC&SK system using ion electric propulsion can satisfy the attitude control requirements with very small propellant increases over that required to correct solar pressure orbit perturbation.
4. Gravity gradient and solar pressure disturbance torques can cause large attitude control propellant penalties for asymmetric configurations.
5. Control system/structural dynamic interaction stability can be obtained through frequency separation with reasonable structural requirements. Modern controllers can potentially ease structural dynamic requirements and simplify spacecraft design.