SUN-SYNCHRONOUS ORBITS NEAR CRITICAL INCLINATION

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Abstract. The long period dynamics of Sun-synchronous orbits near the critical inclination 116.6° are investigated. It is known that, at the critical inclination, the average perigee location is unchanged by Earth oblateness. For certain values of semimajor axis and eccentricity, orbit plane precession caused by Earth oblateness is synchronous with the mean orbital motion of the apparent Sun (a Sun-synchronism). Sun-synchronous orbits have been used extensively in meteorological and remote sensing satellite missions. Gravitational perturbations arising from an aspherical Earth, the Moon, and the Sun cause long period fluctuations in the mean argument of perigee, eccentricity, inclination, and ascending node. Double resonance occurs because slow oscillations in the perigee and Sun-referenced ascending node are coupled through the solar gravity gradient. It is shown that the total number and infinitesimal stability of equilibrium solutions can change abruptly over the Sun-synchronous range of semimajor axis values (1.54 to 1.70 Earth radii). The effect of direct solar radiation pressure upon certain stable equilibria is investigated.

1. Background

It is well-known that Earth oblateness causes the orbital angular momentum vector of a near-Earth satellite to precess about the Earth's polar axis. A Sun-synchronism results if the initial semimajor axis, eccentricity, and inclination are selected such that ascending nodal precession is easterly with secular rate 0.986°/day, the mean orbital rate of the apparent Sun. It is also well-known that a Sun-synchronous orbit must be retrograde (i.e., inclination greater than 90°). If the Earth's equatorial plane coincided with the ecliptic plane, such an orbit would, on the average, maintain a fixed orientation with respect to the Earth–Sun line throughout the year. In reality, the orientation of a Sun-synchronous orbit plane oscillates about the Earth–Sun line due to the North–South motion of the apparent Sun with respect to the equator, not to mention periodic fluctuations in the inclination and node due to orbit perturbations.

Sun-synchronous orbits are useful because the orbit plane follows the Sun. Remote sensing missions such as LANDSAT use Sun-synchronous orbits because the illumination of the subsatellite point is nearly constant on each successive pass. If initiated outside the Earth's shadow, certain Sun-synchronous orbits can, if high enough, remain continuously illuminated throughout the year. This clearly maximizes on-board power generation using solar cells.

Second-order (relative to oblateness) North-South gravitational forces cause slow changes in the inclination and ascending node of a Sun-synchronous orbit. These forces arise from the Earth's distortion from an oblate spheroid (modeled by the zonal harmonics), the Moon, and the Sun. These forces can disrupt the Sun-synchronism. For a class of nearly circular Sun-synchronous orbits, it is known that equilibrium configurations exist with the orbit line of nodes parallel and perpen-

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icular to the mean Earth–Sun line (see Duck, 1975). Only the latter configuration is stable. Small amplitude oscillations in inclination and ascending node range in period between 22 and 50 yrs.

Certain critically inclined orbits at 116.6° can be Sun-synchronous. These include a circular orbit with semimajor axis 1.539 Earth radii ('ER') and a near-collision orbit with eccentricity 0.40 and semimajor axis 1.700 ER. It is known that, at critical inclination, the averaged perigee location is unchanged (to first-order in $J_2$) by Earth oblateness (see Garfinkel, 1973). Near the critical inclination, zonal harmonics and lunisolar gravity cause slow changes in the perigee distance and angular location of perigee.

If the Sun-synchronism is not taken into consideration, it is known that equilibrium configurations exist with the orbit line of apsides perpendicular and (approximately) parallel to the line of nodes (see Hough, 1981). Only the former configuration is stable. Small amplitude oscillations in eccentricity and argument of perigee range in period between 280 yrs (nearly circular orbit) and 18 yrs (eccentricity 0.4).

Now, an eccentric Sun-synchronous orbit near critical inclination exhibits double resonance. Slow oscillations in the perigee and Sun-referenced ascending node are coupled through the solar gravity gradient. The long period dynamics has two degrees of freedom, necessitating a separate treatment. It is true that perigee oscillations are, for nearly circular orbits, much slower than nodal oscillations. Reduction from two to one degree of freedom is possible in this case by averaging over the faster motion. However, this procedure fails for larger eccentricities because commensurate oscillatory periods are predicted.

Non-gravitational forces can disrupt double resonance. For example, atmospheric drag will cause any orbit with perigee altitude less than 700 km to decay. If drag is to be included in the analysis, the geophysics of the upper atmosphere and the attitude dynamics of the spacecraft must be modeled. As it is beyond the scope of this paper to model drag, the results apply to orbits with perigees higher than 700 km. Solar radiation pressure can perturb balloon-type satellites significantly at altitudes above 1000 km. Since a Sun-synchronous orbit follows the Sun, the solar pressure perturbations do not average out over a year, even if the orbit is unshadowed. It is known that, if the orbit is unshadowed, long period changes occur in all the orbital elements except semimajor axis (see Kozai, 1961). With shadowing, secular changes in semimajor axis and eccentricity occur. Clearly, solar pressure cannot be neglected.

The long period dynamics of Sun-synchronous orbits near the critical inclination 116.6° are investigated in this paper. This work is an outgrowth of the author's investigation of the impact of lunisolar perturbations in the critical inclination problem reported in an earlier paper. The Hamiltonian includes gravitational perturbations arising from an aspherical Earth, the Moon, and the Sun. Moreover, all measured zonal harmonic coefficients from a recent Earth model are included. The method of averaging is used to eliminate short and intermediate period fluctuations from the Hamiltonian (Section 2). There results a two degree of freedom, autonomous Hamiltonian dynamical system involving the mean argument of perigee, eccentricity,