Averaged tumbling dynamics of defunct GEO satellites

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ABSTRACT

With continued launches and no natural de-orbit mechanisms, geosynchronous earth orbit (GEO) grows more crowded with active assets and debris. To protect valuable spacecraft and ensure GEO for future use, the long-term dynamics of GEO debris must be well understood. Extensive research has been conducted on the long-term orbital evolution of defunct GEO satellites and debris, but much less is understood about their long-term rotational dynamics. In spite of this, defunct satellite spin states are diverse and change over time with fast and slow rotators in both uniform rotation and non-principal axis tumbling . Albuja et al. proposed that the evolution of some defunct GEO satellites is driven by the Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect, torques due to the absorption, reflection, and thermal reemission of solar radiation. The YORP effect is known to change the spin states of asteroids. Using a representative model, Albuja et al. closely predicted the rapid observed spin down of the defunct GOES 8 satellite. Further observations and simulations indicate that GOES 8 then transitioned to non-principal axis tumbling. Albuja et al. hypothesized that some satellites cycle repeatedly between uniform rotation and tumbling due to the combined influences of YORP and energy dissipation from internal friction and residual fuel slosh. Further numerical simulations by Benson and Scheeres indicated that there is a strong tendency for the tumbling satellite's rotational angular momentum vector to track and precess about the time-varying sun line direction. They also found that the satellite can undergo tumbling cycles and transition between uniform rotation and tumbling with YORP alone, contrary to the hypothesis that energy dissipation is also required. Long-term observations of the GOES 8 and 11 satellites suggest they are undergoing such tumbling cycles. With numerous other satellites observed in tumbling motion, a fundamental understanding of the dynamics in this regime is needed.

A better understanding of defunct GEO satellite rotational dynamics promises a number of benefits. Satellite spin state predictions would improve estimates for attitude-dependent solar radiation forces and help predict material shedding. Most high area-to-mass ratio GEO debris is thought to be multi-layer insulation from defunct satellites and rocket bodies. Also, numerous organizations have proposed active debris removal (ADR) and satellite servicing missions that will require a chaser spacecraft to grapple and de-spin potentially large, non-cooperative satellites. Knowledge of a target's spin state will be crucial, preferably well before rendezvous. With some satellites exhibiting highly variable spin rates, identifying future capture windows with slow rotation would also be advantageous. Finally, end of life solar array orientations likely affect long-term YORP-driven evolution. Further study of these effects will help inform decommission procedures to reduce YORP susceptibility at end of life, resulting in slower and less variable satellite spin rates. This would further facilitate ADR and servicing missions.

In this paper, we conduct a detailed study of averaged defunct GEO satellite rotational dynamics in the non-principal axis (tumbling) regime, focusing particularly on the five well-documented GOES 8-12 satellites. A facet-based YORP model is used and only the satellite's heliocentric orbit is considered. Fixing the satellite's rotational angular momentum vector in the earth-sun rotating frame, freezing time, evolving the satellite in torque-free tumbling motion (constant angular momentum and kinetic energy), and averaging the YORP torque over many rotation cycles, the torques along the sun line, orbit normal, and velocity directions converge to constant values. Interestingly, much of the full dynamical behavior simulated previously by Benson and Scheeres is captured with this averaged approach. The averaged torque is nearly orthogonal to the sun-line over all sun line/angular momentum (coning) angles, consistent with the simulated sun-tracking behavior. The averaged sun line torque also retains the same sign over a wide range of coning angles, consistent with the steadily increasing coning angle observed in numerical simulations. Also, the averaged torque perpendicular to the sun line always acts in the same sense, providing the simulated precession motion.

Overall, our work shows that averaging provides an effective way to investigate the tumbling evolution of defunct GEO satellites. In addition, this tumbling averaged approach may help to efficiently characterize and propagate the non-principal axis dynamics of defunct GEO satellites and debris, complementing the uniform spin-averaged YORP coefficients developed previously by Scheeres.