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ABSTRACT

Observational studies of PAGEOS have indicated that the balloon satellite experiences very large periodic accelerations whenever the orbit intersects the Earth's shadow. In 1969 the amplitude of these anomalous accelerations was about 10^{-4} revolutions per day ^{2} with a period of 10 to 15 days and caused along-track deviations of the spacecraft from its expected position of 20 to 40 km. It has been suggested by Professor I. Shapiro of the Massachusetts Institute of Technology that these accelerations are abnormal solar radiation pressure perturbations caused by the non-sphericity of the spacecraft and its rotational motion on its axis.

During 3 months in 1969 the dynamical behavior of PAGEOS on its axis and the detailed shape of the balloon were determined by the USAF Aerospace Research Laboratories at Wright-Patterson AFB from photometric observations by new methods. These studies showed that PAGEOS is not spherical but ellipsoidal with major and minor axes approximately 34 meters and 27 meters, respectively and rotating about a minor axis which is itself precessing.

These results on the dynamical behavior of PAGEOS have been used in a new theory of radiation pressure perturbations developed at Goddard Space Flight Center that includes the effects of spacecraft attitude, rotational behavior and specular and diffuse reflection and used to predict the acceleration of PAGEOS for 3 months in 1969. The predictions, based on the observed rotational motion, a specular reflectivity of 85% and a spacecraft mass of 55 kg, show that the new theory computes the observed anomalous accelerations of PAGEOS to about 10^{-5} revolutions per day^2, or better than 10%. This is believed to be one of the first demonstrations of coupling between the rotational motion of a spacecraft on its axis and the dynamics of its orbit.

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ANOMALOUS ACCELERATIONS OF THE PAGEOS SPACECRAFT

INTRODUCTION

Satellites of large cross-sectional area to mass ratio are known to be strongly perturbed by the forces of solar radiation pressure. Such radiation pressure forces indirectly caused the demise of Echo I in 1968. Studies (1, 2) of the behavior of two other inflation-deployed spacecraft, the 2.5-meter diameter sphere 1963-30D (DASH 2) and the 30-meter diameter sphere 1966-56A (PAGEOS), both in high polar orbits, have demonstrated that our present theoretical treatment of radiation pressure indeed goes far in explaining the important secular and long period changes to the orbit. However, these same studies also indicate that both balloon spacecraft undergo accelerations that cannot be explained by the normal treatment of radiation pressure. Neither can these anomalous perturbations be explained by Earth-reflected radiation pressure, air drag, or luni-solar gravitational effects. Since these satellites were launched for study of high-altitude air drag and geodetic position, it is important that their orbital motions be well understood. These anomalous perturbations, recognized in 1969, are evidenced by regular motion of the spacecraft alternately ahead and then behind the position in its orbit to be expected on the basis of the most complete, normal theory. Such accelerations affect, therefore, the mean motion of the spacecraft in its orbit.

This paper reports on the perturbations in mean motion predicted by a new theoretical treatment of radiation-pressure which accounts for non-isotropic scattering of solar radiation from a rotating ellipsoidal body and a comparison of these perturbations with the observed mean motion of the PAGEOS spacecraft during a time interval when the rotational dynamics had been determined by a new method; namely, photoelectric photometry. The theory necessarily incorporates the orientation for and precessional movement of the rotation axis of the satellite. This development is similar to that given by Shapiro (3) for the radiation pressure effects on a cylindrical satellite. We will show that there exists a coupling between the spin and orbital dynamics of the low mass-to-area satellites if their scattering is isotropic and that the effect is noticeable in the orbital behavior.

DISCUSSION OF THE OBSERVED PERTURBATIONS

A polar orbit at an altitude of about 4000 km intersects the Earth's shadow for a period of approximately 3 months followed by an almost equal period of full sunlight until the orbit again enters the Earth's shadow as the Earth moves around the sun. This behavior is observed for both DASH 2 and PAGEOS. During the all-sunlight period, in agreement with theory, virtually no long-period or secular mean-motion perturbations of these spacecraft were detectable in these studies. As soon as the orbits entered the shadow, however, a large perturbation due to solar radiation pressure was observed as expected. Unfortunately, the character of the acceleration of both spacecraft, during every shadow period, differed significantly from what was anticipated. In addition, to the normal radiation pressure perturbations, there appeared to be a very large periodic perturbation with an amplitude nearly as large as the normal perturbation. The period of the effect on DASH 2 was many weeks during the first shadow period after launch and steadily decreased so that four years after launch, the period of the anomalous acceleration for DASH 2 had reached 2 weeks. Three years after launch the period for PAGEOS was about 11 days.

Since the PAGEOS launch in 1966, the OPOS Observatory of the USAF Aerospace Research Laboratories at Wright-Patterson AFB, Ohio, has been making photoelectric brightness measurements of the spacecraft (4) as part of a program to explore the capabilities of passive optical photometry for the remote-sensing of spacecraft properties. By utilizing the variations with time of the sunlight scattered from the PAGEOS aluminized outer surface, it has been possible to deduce, during certain periods, the spin rate, spin-axis orientation and precession, and the shape of the balloon (5). These studies indicate that the PAGEOS balloon has gradually become prolate and that it is spinning about a minor axis with a period varying between 190 and 350 seconds. In addition, the spin axis is found to be precessing at varying rates about an axis that always points toward the sun. Figure 1 shows the location of the rotation axis during the period August-December 1969. It is to be noted that the spin axis precessed very rapidly, at about 25 deg/day during August, increasing to 45 deg/day at the beginning of November, then dropping again to 25 deg/day in late November. The angle between the spin and precession axes was about 65 degrees. The physical cause of this dynamical behavior of PAGEOS on its axis remains unexplained, but, because its precession axis appears locked to the sun, the forces of solar radiation pressure might well be the driving mechanism.

THEORETICAL ANALYSIS

The possibility has been examined theoretically (6) that the anomalous orbital accelerations are coupled with the non-sphericity of the balloon and its observed rotational behavior. In particular, a theory has been elaborated for the effect of solar radiation pressure on the orbit of an ellipsoidal-shaped spacecraft, spinning about an axis that is precessing and including the effects of both diffuse and specular reflection of sunlight from the satellite's surface. The essential

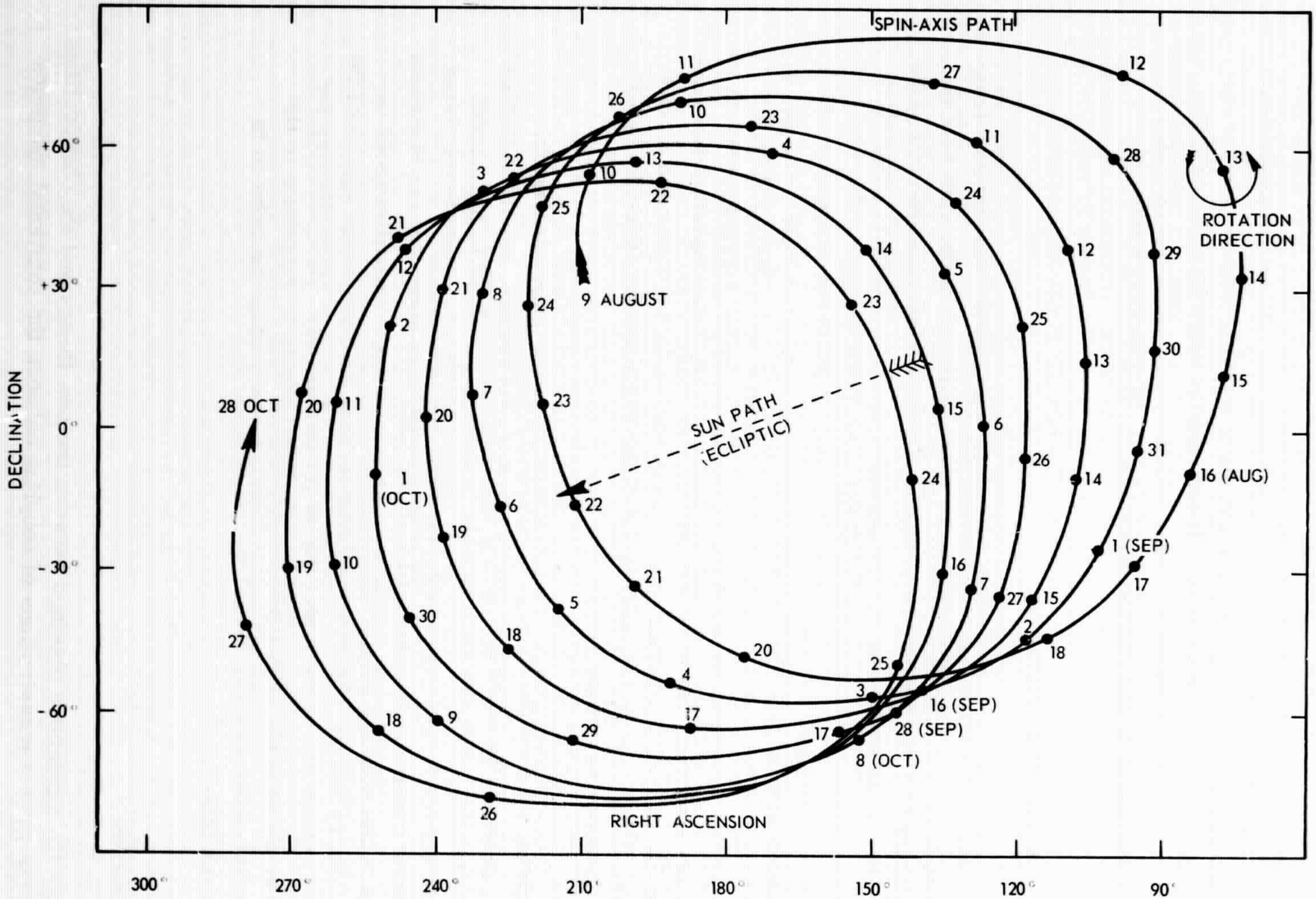

Figure 1. Smoothed Spin-Axis Positions From August 9 To October 28, 1969

modification made to the normal treatment of radiation pressure is that account was taken of the direction in which sunlight is reflected from the satellite. In the normal treatment it is assumed that the reflected radiation is symmetric about the satellite-to-sun line so that the acceleration is always directed away from the sun: this is obviously true for spherical satellites but is not true, in general, for an ellipsoid. Under these circumstances there is a "sideways" component to the radiation pressure force which causes additional perturbations of the orbit, analogous to the lateral accelerations of a tacking sailboard.

APPLICATION OF THE THEORY

This theory has now been tested numerically against orbital data obtained from the Smithsonian Astrophysical Observatory. The positions of the spin axis of PAGEOS obtained by the Aerospace Research Laboratories, together with their estimate of the prolate shape of the spacecraft and of its reflective properties were used to compute the acceleration of the spacecraft between July and October 1969. During most of this time the orbit of PAGEOS intersected the Earth's shadow and large perturbations of the orbital mean motion were observed. The accelerations computed from the normal and modified theories together with the acceleration observed by the Smithsonian Astrophysical Observatory are shown in Figure 2. The spacecraft parameters used in the computation of the balloon's behavior were: polar radius 15.0 meters; major equatorial radius 17 meters; minor equatorial radius 13.5 meters; mass 55 kgm; specular albedo 0.85, diffuse albedo 0.0.

The agreement between the theory and observations is clearly evident in Figure 2. It should be noted that the theory does not indicate any perturbation of the acceleration when the orbit is fully in sunlight, a result in agreement with the theory for a spherical satellite. When the orbit is partially shadowed, an oscillation caused by the precession of the spin axis about the sun is clearly evident as is the steadily increasing rate of precession. The differences between the theory and the observations suggest that the root-mean-square of the residuals is about 10% of the amplitude of the perturbation after allowing for an apparent phase drift. The residuals are comparable in magnitude to the slight accelerations actually observed during periods when the orbit is in complete sunlight.

CONCLUSIONS

We believe the agreement obtained between the new theory and the observations is one of the first demonstrations of coupling between the rotational dynamics

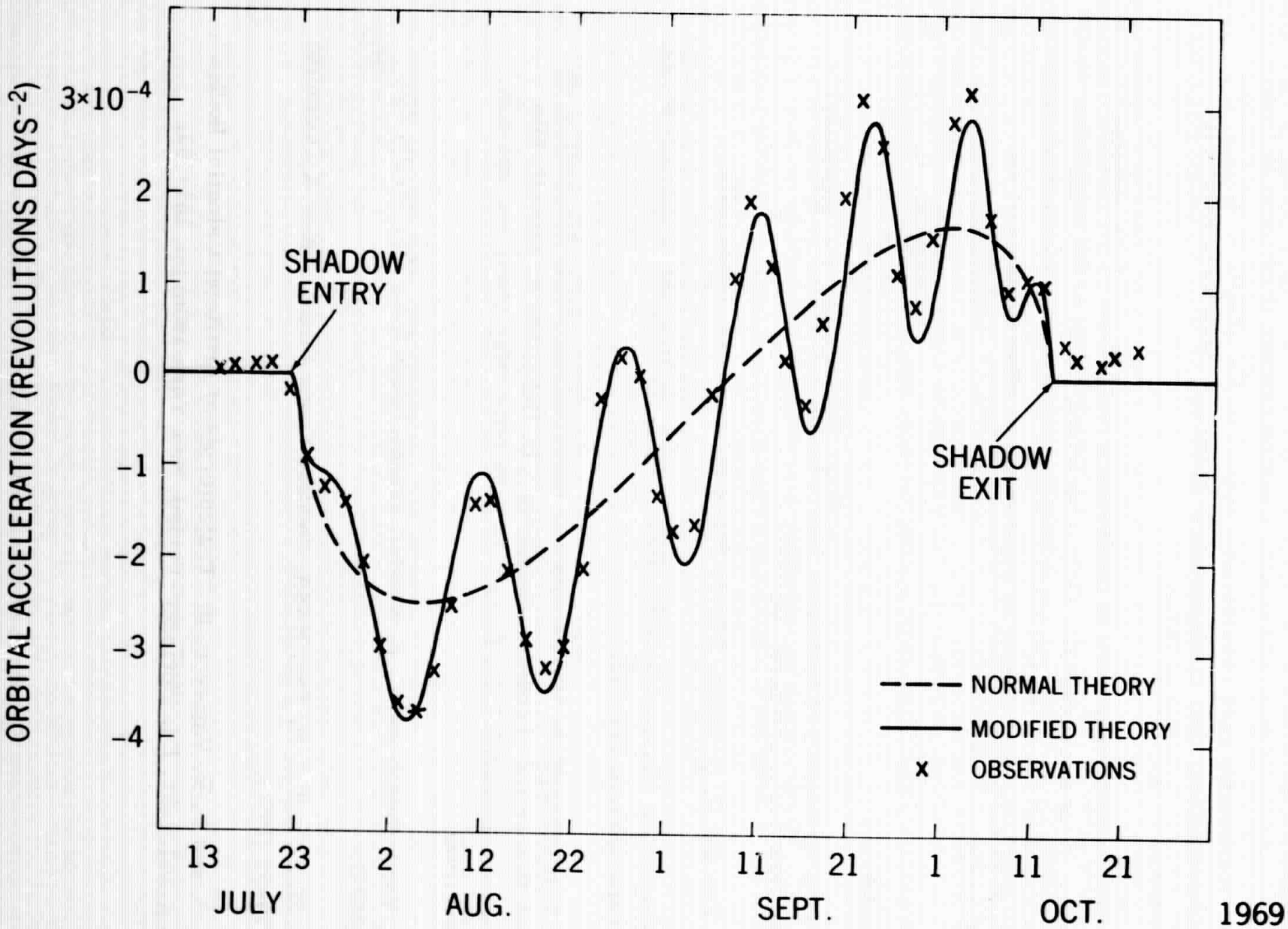

Figure 2. PAGEOS Comparison of Observed and Theoretical Accelerations ($\alpha_S = 0.85$, $\alpha_D = 0.0$)

of a spacecraft about its center of mass and the orbital dynamics of the spacecraft about the Earth. The perturbing acceleration produces large along-track oscillations of the PAGEOS spacecraft which, during July to September 1969, had an amplitude of 20 to 40 km with a period ranging from 10 to 15 days. Such large perturbations have considerable impact on the quality of orbit determination and prediction. For the topocentric observer these were errors of 0.5 to 1.0 degrees in apparent position.

A problem deserving further work is the torquing mechanism of the rotation and precession of these spacecraft. Only a beginning exists in the suggestion by Mar and Vigneron (7) of the Canadian Defense Research Telecommunications Establishment of a thermal distortion mechanism to allow torquing of the Echo II spacecraft.

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