INFLUENCE OF SOLAR RADIATION PRESSURE ON ORBITAL ECCENTRICITY

OF A GRAVITY-GRADIENT ORIENTED LENTICULAR SATELLITE

By W. F. Hodge

NASA Langley Research Center
Langley Station, Hampton, Va.

Presented at Symposium on Passive-Gravity-Gradient Stabilization

Moffett Field, California
May 10-11, 1965

INFLUENCE OF SOLAR RADIATION PRESSURE ON ORBITAL ECCENTRICITY OF A GRAVITY-GRADIENT ORIENTED LENTICULAR SATELLITE

By W. F. Hodge

NASA Langley Research Center
Langley Station, Hampton, Va.

22542

ABSTRACT

The change in the orbital eccentricity of a passive inflatable lenticular satellite due to solar radiation pressure is investigated to determine if the change becomes large enough to cause difficulty in using gravity gradient for attitude control purposes. Numerical data for a perfectly absorptive lenticule of 200-foot radius placed in an initially circular 2000-mile orbit were calculated for a range of orbit inclinations from 0° to 113°. Corresponding data for an Echo-type sphere were also generated to provide a comparison with established results. All of the calculations cover satellite lifetimes up to 1 year which is of sufficient duration in most cases to demonstrate any long-period variation in the orbital eccentricity. The results show that the eccentricity can increase in a year's time from an initial value of 0.001 to values ranging from 0.04 to 0.21, depending upon the orbital inclination. These values appear large enough to warrant careful consideration in regard to the use of gravity gradient for attitude stabilization of low-density lenticular configurations since they could lead to large-amplitude librations or unstable attitude motion. At present, mesh-type materials are being studied as a possible means of reducing the solar pressure perturbations. When compared on an equivalent area-to-mass-ratio basis, the effects of solar radiation pressure on the orbital eccentricities of perfectly absorptive lenticular configurations and Echo-type spheres appear nearly the same. The well-established results for spheres therefore give a sufficiently accurate estimate of the orbital motion of a lenticular satellite having the same effective area-to-mass ratio.

author

INTRODUCTION

The effect of orbital eccentricity on attitude stability is an important problem with gravity-gradient satellites since it can lead to large-amplitude librations or instability. Elliptical orbital motion causes a forced libration in pitch that increases in amplitude with the eccentricity. This problem is of interest in the case of gravity-gradient oriented lenticular satellites which are being studied as a means of improving Echo-type passive communications satellites. Like

Echo, they are lightweight structures and are subject to large changes in orbital eccentricity caused by solar radiation pressure. The eccentricity of the Echo I orbit, for example, periodically becomes as large as 0.08 (ref. 1). It is therefore of interest to determine how large the eccentricity might become for low-density lenticular satellites. The present paper describes a recent study (ref. 2) of this problem for the case of a perfectly absorptive lenticular satellite.

THE LENTICULAR SATELLITE CONCEPT

One of the basic problems with communications satellites is that the signal power losses are large for the long transmission paths that are involved. For active-type satellites, these losses can be reduced through the use of spacecraft antenna gains, and amplifiers. In the case of passive reflectors, such as Echo-type spheres, the strength of the reflected signal varies directly as the effective area of the reflecting surface and inversely as the square of the wavelength. Since it is not desirable to vary the wavelength appreciably because of noise considerations, it appears that the only practical way to increase the signal power of a passive reflector would be to enlarge its effective area. Ordinarily, this means adding weight which tends to become prohibitive, in terms of booster payloads, before a significant gain in signal power is realized.

The lenticular concept offers a way of increasing the effective area without adding weight by taking advantage of the fact that only a relatively small segment of a sphere can be used for reflecting communications signals. (See fig. 1.) The idea is to eliminate all but the usable segment of the sphere, which is a small polar cap on the side facing the earth, then use the weight saved to build a larger segment. Two such polar cap segments, joined along their chord circles to provide an inflatable structure, form the basic lenticular configuration. This type of satellite obviously requires radial attitude orientation since its symmetry axis must continually point along the local vertical in order to function properly as a passive communications link. Gravity-gradient systems are desirable for this purpose since they provide radial attitude orientation and are inherently passive devices.

PERTURBATION CALCULATIONS

The perturbing force exerted by solar radiation pressure is generally difficult to determine because of complexities introduced by the reflective properties of the body on which it acts. A perfectly absorptive satellite was selected for initial study since most of the complexities can be avoided with this type of surface, and the orbital data can be compared directly with corresponding results for Echo-type spherical configurations. Direct comparisons are suggested by the result with Echo I that good agreement between theory and observation is obtained when only the forces due to the direct solar radiation are considered. In this case, the solar pressure perturbations are essentially the same for spheres regardless of whether their surfaces are perfectly absorptive or perfectly reflective.

For a perfectly absorptive satellite of given mass, the solar pressure force varies directly as the effective area exposed to solar radiation. Since lenticular satellites must be oriented to always face the earth, the area exposed to the sun will not be constant as in the case of a sphere, but will vary continually over each orbital revolution as indicated in figure 2. If the sun direction is parallel to the orbit plane as shown, the exposed area will oscillate between the lens-shaped area at points Q and the circular one at points P twice each orbital revolution provided shadowing by the earth is ignored. No variation occurs for the case where the sun's rays are normal to the orbit plane, and the exposed area remains equal to its value at points Q. Except for the shadow region where the solar pressure force is zero, it is clear that this variation in effective area depends solely on the angle between the sun direction and the satellite symmetry axis.

Although the resulting variation in the disturbing force appears to be primarily a short-period effect that would be expected to average out with little or no change in the overall results, it was decided to calculate its influence to be sure no long-period changes which could be significant are overlooked. Perfect attitude orientation was assumed for the study so that the effect of the variation due to the lenticular shape alone could be determined. An existing computer program (Lifetime 18), modified to handle lenticular configurations, was used to calculate the data for the study. This program, which was developed at the NASA Goddard Space Flight Center, employs a variation-of-parameters method and provides time histories of the satellite's orbital elements.

RESULTS AND DISCUSSION

Data for a 770-pound lenticular satellite of 200-foot radius, which has a maximum area-to-mass ratio of nearly 150 cm^2/gm as compared to about 120 for Echo I, were generated for seven orbital inclinations ranging from 0° to 113° to determine the effect of the sun position relative to the orbit plane. The calculations, which were based on an initial eccentricity of 0.001 and an initial altitude of 2000 nautical miles, provide time histories of the satellite's orbital elements for a period of 1 year. Only the time histories of the eccentricity are presented, since those for the other elements are not of interest in the present paper.

An important consideration associated with the orientation of the orbit plane relative to the sun direction is the possibility of resonant orbital motion. For certain critical orientations, the perturbations due to solar radiation pressure can cause nonperiodic changes that would eventually destroy the orbit if allowed to continue for a sufficiently long period of time. The process by which resonant orbital motion can occur is illustrated in figure 3 which represents an initially circular orbit oriented parallel to the sun's rays. As the satellite moves away from the sun in the region of point P, solar pressure accelerates its motion and thereby causes it to seek a higher altitude. The situation is reversed in the vicinity of point A where solar pressure decelerates the motion, and causes the satellite to then seek a lower altitude. The continuation of this process causes the eccentricity to increase, and will create a perigee at P and an apogee at A provided the sun direction does not change relative to the apsidal line PA that is produced normal to the sun line. Thus, resonance can occur whenever the orbital inclination is such that the orbit plane rotates in step with the sun's apparent motion. The orbital inclinations used in the study were chosen so that some of the resonant possibilities could be examined.

The eccentricity data for each of the seven cases are plotted in figure 4. All of these curves exhibit the same type of large-amplitude, long-period variation that is obtained for spherical configurations. These results indicate that the minimum amplitude occurs for an inclination near 70°. However, this inclination is close to a resonant one and a change of just a few degrees could lead to very large changes in the eccentricity. The inclinations for curves C and G of figure 4 were chosen to correspond to resonances. These curves have no apparent period and exhibit a monotonic or secular type of resonant trend. Curves D, E, and F were not intended to have resonant characteristics, but the orbital inclination for each is sufficiently close to a resonant one to show a tendency toward a "stair-stepping" type of resonant behavior. These two types of resonance are sometimes referred to as resonances of the first and second kind, respectively.

In addition to describing the physical nature of resonances it is of interest to mention the critical conditions for which they can occur. There are six possible cases, which appear as conditions on the rates of change of the long-period arguments in the equations for the perturbations to the orbital elements. Since the relative orientation of the orbit and the sun position varies mainly with the inclination, semimajor axis, and eccentricity of the orbit, the six resonant conditions for a given orbit may be plotted as was done in figure 5. The points where each curve passes through zero correspond to resonances since zero rate of change implies that the orbital elements will then change at a constant rate in one direction as indicated in figure 3.

A comparison of the lenticular and spherical configurations, is presented in figure 6 for two of the seven inclinations used in figure 4. These curves show that the change in eccentricity is nearly the same when the two configurations are compared on an equivalent area-to-mass-ratio basis. The differences in the curves for each case are due mainly to a slight error introduced in using a single area-to-mass ratio for the sphere to represent the average value of the lenticule for the entire year. This procedure has the effect of averaging out the long-period variation in the area-to-mass ratio of the lenticule due to the annual variation in the angle between the orbit plane and the sun direction. However, the results generally show that the error due to neglecting this long-period variation is not large. On this basis, it appears that reasonably accurate results can be obtained using an average area-to-mass ratio to account for periodic variations in the solar pressure disturbing force that occur for nonspherical satellites.

Although the tolerable limits of eccentricity will vary with the particular application, the results for the configuration considered here appear large enough to warrant careful consideration. The situation is such that attitude stability might set the limit in one case, while other requirements such as station keeping may be critical for another. A large part of the work on passive communications satellites at the NASA Langley Research Center since Echo I was orbited has been devoted to developing the technology in areas such as passive attitude control and station keeping. This work has included study contracts with industry as well as several in-house studies. It is planned to make use of the results from these efforts in a general systems study to determine what the limitations are regarding orbital eccentricity and other relevant considerations.

In connection with the results presented here, it is of interest to mention that part of the effort in these previous studies has been directed toward finding a practical way of avoiding or reducing the effects of solar radiation pressure. The use of wire grid or mesh materials shows promise of reductions that should be adequate in most cases. Simple intensity measurements for mesh samples and small models, using a schlieren system as indicated in figure 7, suggest that the reduction should be at least 70 percent or more. However, this approach is not completely desirable for applications where station keeping is required since the most promising passive technique for this purpose involves using the solar pressure forces rather than eliminating them. The possibility of adding solar sails to a wire-mesh lenticule is currently being studied as a means of developing a station-kept lenticular satellite. Advanced concepts of this type will probably receive considerable attention in the planned systems study and other future work.

CONCLUDING REMARKS

A study of the orbital motion of a gravity-gradient oriented lenticular satellite has indicated that solar radiation pressure alters the orbital eccentricities of lenticular and spherical configurations in much the same manner. The following remarks are stated on the basis of the results obtained:

1. The solar pressure perturbations for low-density lenticular satellites are sufficiently severe that a means of controlling the orbital eccentricity appears necessary unless the problem can be substantially avoided through the use of mesh materials or some other means.

2. The orbit orientation should be chosen to avoid the critical orbital inclinations for which resonant changes in the satellite's orbital elements can occur.

3. The use of an average value for the solar pressure disturbing force yields reasonably accurate results for the orbital motion of a lenticular satellite.

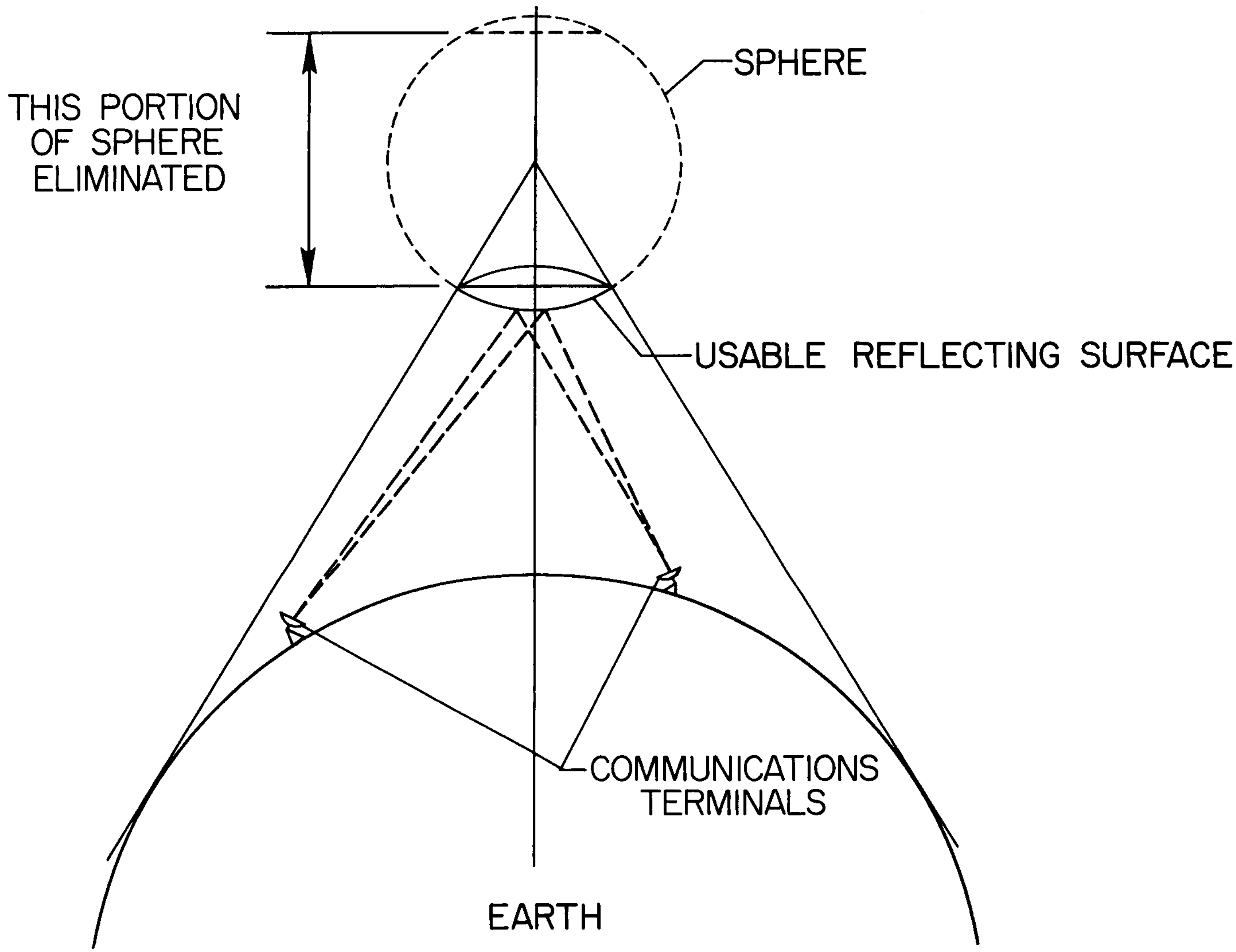
REFERENCES

1. Westrick, Gertrude C.; and Johnson, Katherine G.: The Orbital Behavior of the Echo I Satellite and Its Rocket Casing During the First 100 Days. NASA TN D-1366, 1962.

2. Adams, William M., Jr.; and Hodge, Ward F.: Influence of Solar Radiation Pressure on Orbital Eccentricity of a Gravity Gradient Oriented Lenticular Satellite. NASA TN D-2715, 1965.

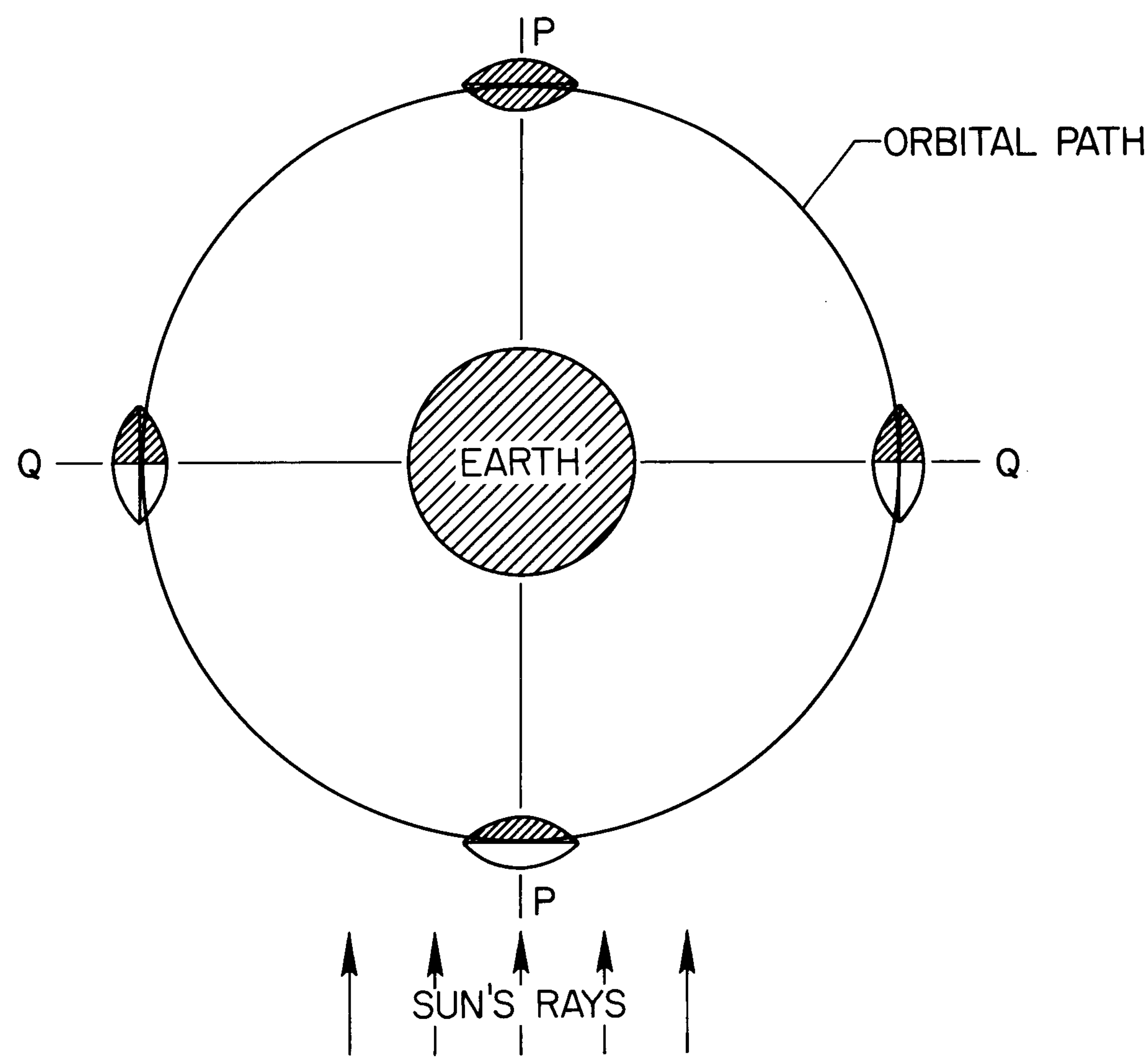
BIOGRAPHICAL SKETCH

The author is a native of Detroit, Michigan. He was graduated from the NACA Langley Laboratory Apprentice School in 1952, and from the University of Virginia in 1959. Since rejoining the Langley staff in 1959, he has done research work in aerodynamic heat transfer and his present field of flight mechanics.



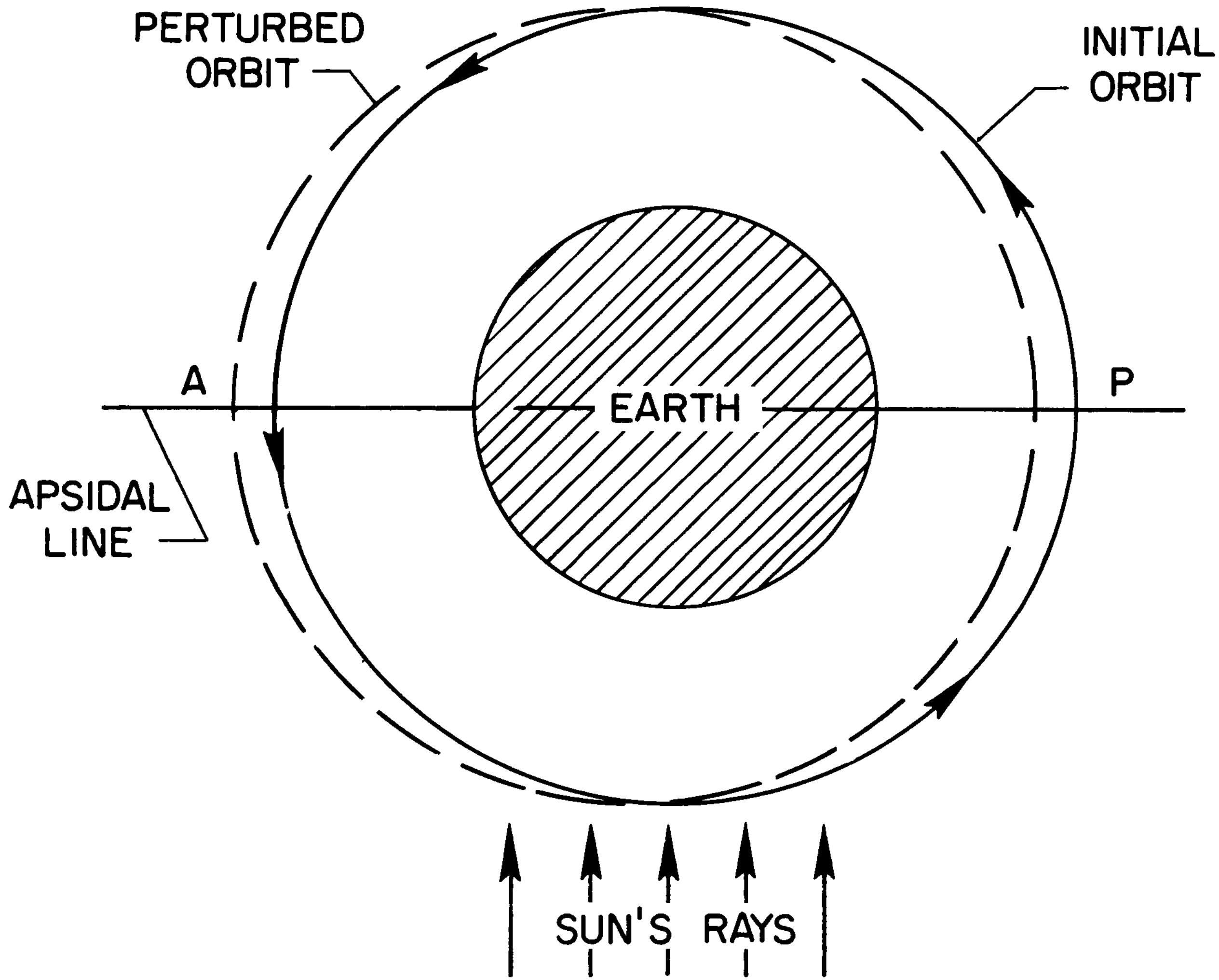
NASA

Figure 1.- Illustration of lenticular satellite concept.



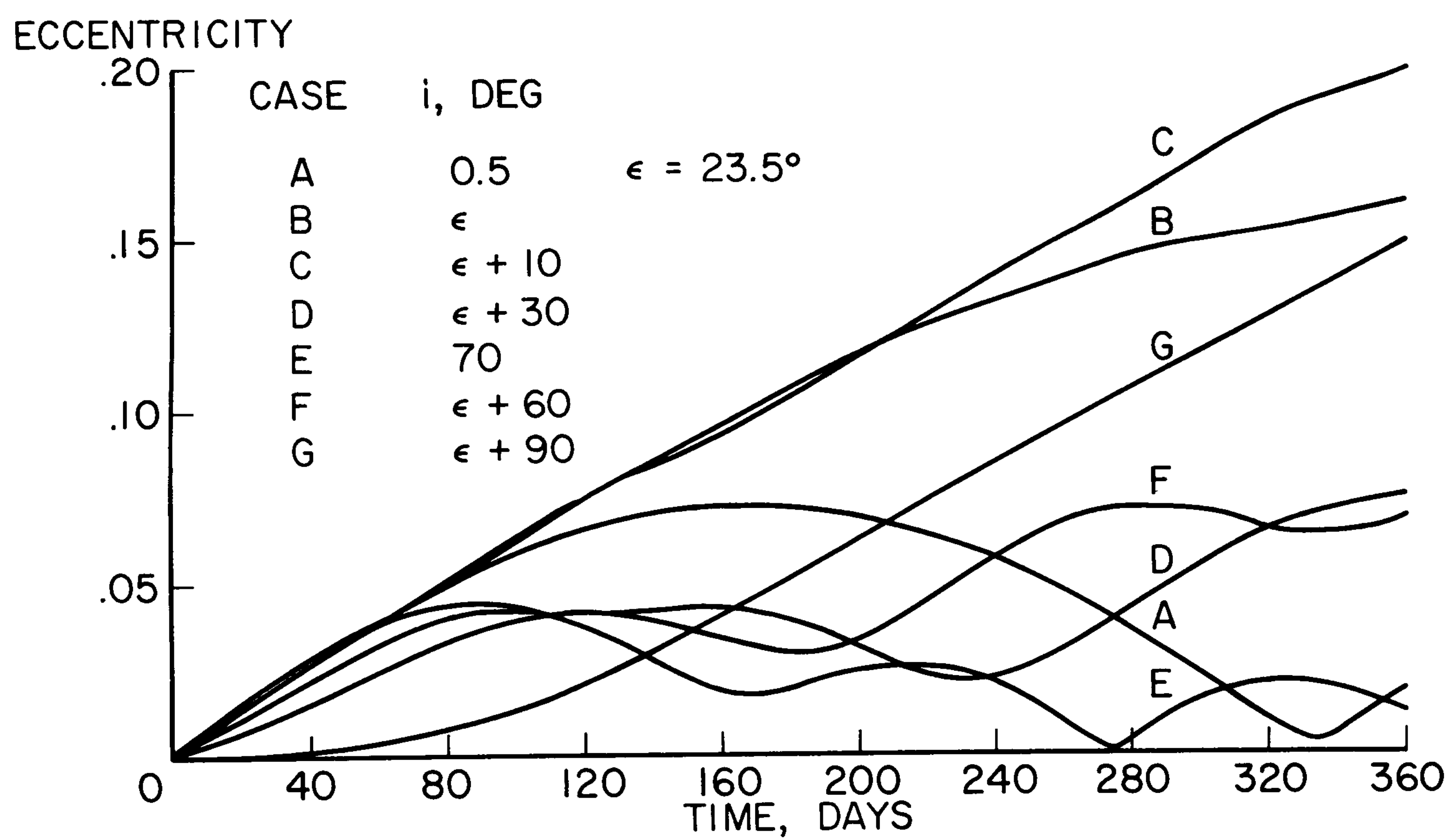
NASA

Figure 2.- Variation in effective area of lenticular satellite over a full orbital revolution.



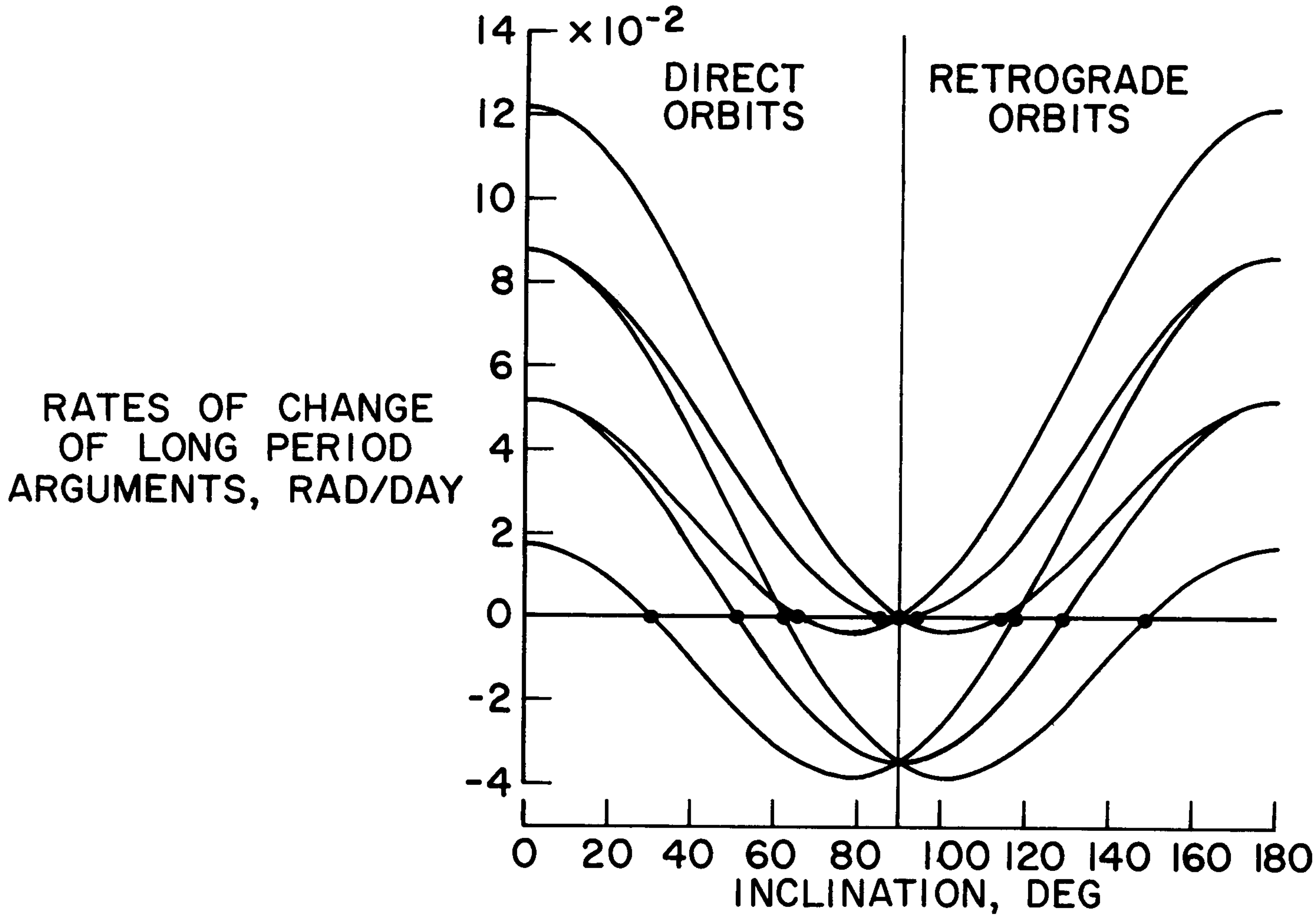
NASA

Figure 3.- Illustration of resonant change in eccentricity.



NASA

Figure 4.- Time histories of eccentricity.



NASA

Figure 5.- Variation of resonant conditions with orbital inclination.

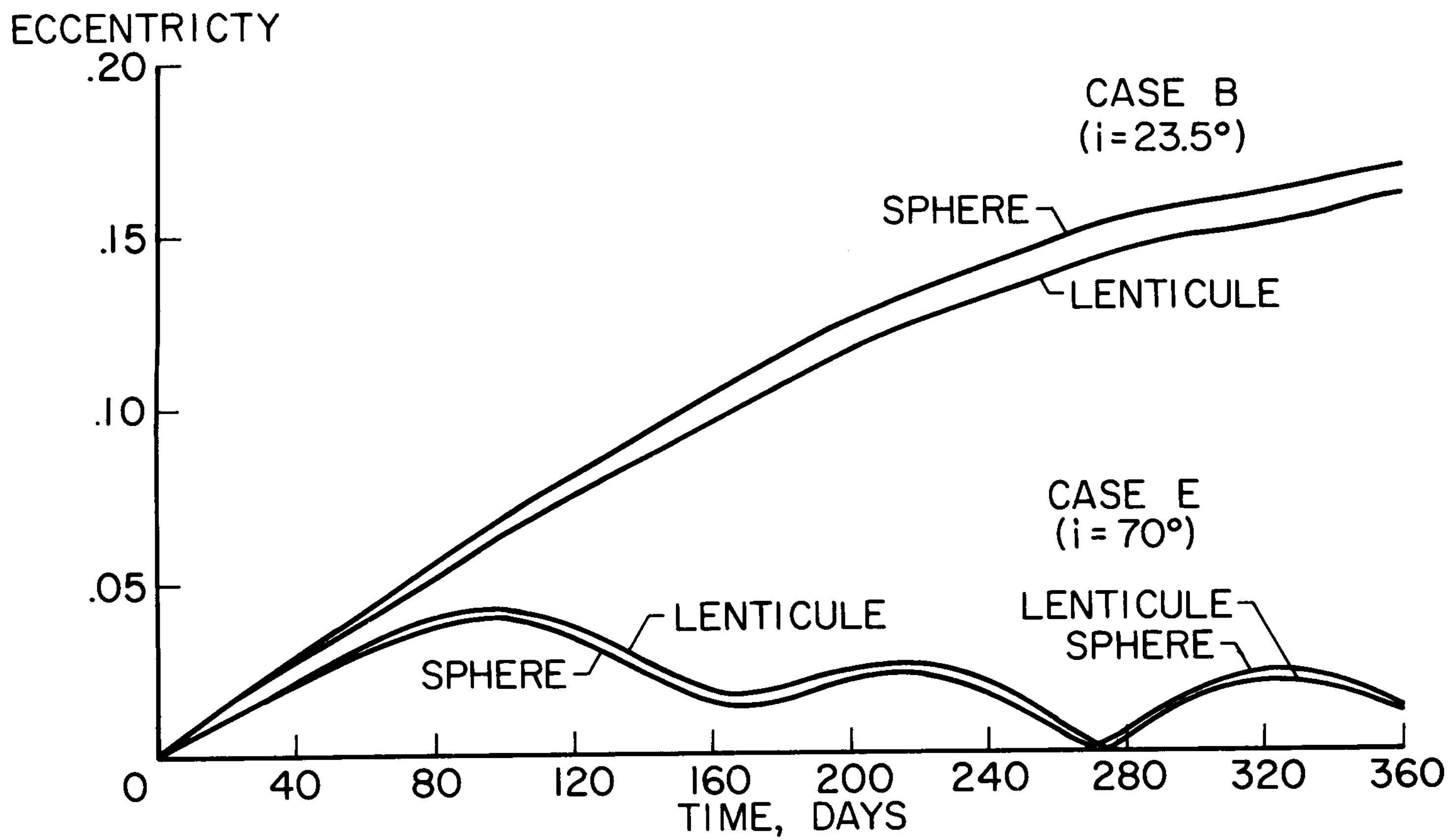
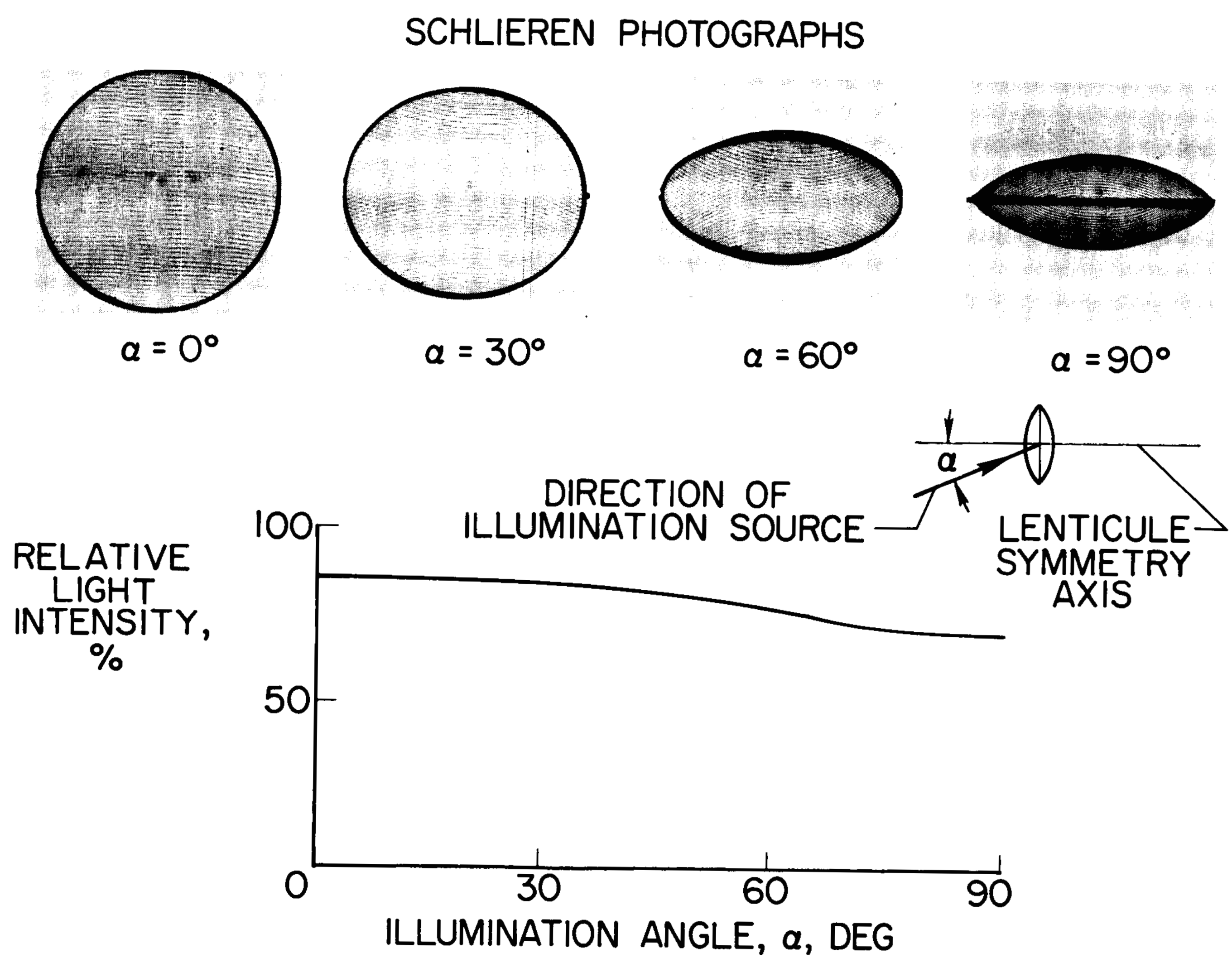


Figure 6.- Comparison of eccentricities for a lenticular and a spherical satellite.

NASA-Langley, 1965



NASA

Figure 7.- Variation of light intensity with illumination angle for 6-inch-diameter wire-mesh model lenticule.