APPLICATION OF INFLATABLE STRUCTURES TO STATION KEEPING OF PASSIVE COMMUNICATIONS SATELLITES

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INTRODUCTION

To accomplish future goals of the nation's communications program, it will be necessary to establish a network of communication satellites. Regardless of whether the network consists of either active or passive communications satellites, a suitable method of station keeping must be employed in order to minimize the number of satellites required in a world-wide continuous communication satellite system. Results of previous NASA statistical studies (refs. 1 and 2), illustrated in Figure 1, have shown that the required number of randomly spaced communication satellites increases rapidly as the requirement for 100-percent continuous service is approached for various communication links. However, this number of required satellites can be significantly reduced and the 100-percent continuous service attained if suitable initial placement and station keeping techniques can be accomplished.

The term "station keeping" is used in different ways depending on whether one is considering synchronous or nonsynchronous orbits. For synchronous orbits, station keeping refers to maintaining the satellite at an apparent fixed position in space with respect to viewing it from fixed ground stations. The apparent fixed position is attained by placing the satellite in a circular equatorial orbit at approximately 22,300 statute miles altitude so that the orbital period of the satellite matches the period of the earth's rotation. Under these conditions the satellite appears to remain fixed in the sky when viewed from a fixed position on earth and the problem of station keeping lies in maintaining the orbital period equal to the earth's rotational period. However, when considering nonsynchronous orbits; station keeping refers to maintaining constant altitude, near circular orbits, and equal spacing, as measured from the center of the earth, between a group of satellites in a common orbital plane as illustrated in Figure 2. This can be achieved by initially spacing the satellites around the orbit and then keeping their orbital periods equal to one another. It is this latter definition of station keeping that is meant when referred to further in this paper.

From the tracking data (ref. 3) of the NASA Echo I experimental passive communication satellite, launched August 12, 1960, it is seen that such a satellite, when put into a near circular orbit, can experience significant variations in apogee and perigee due to differential perturbation effects on the orbit. Such variations in altitude cause large unwanted fluctuations in the radio signal strength received at the ground station from the communication satellite. The solar perturbation is the dominant contributor of these differential orbit perturbation effects. Even though the solar photon flux imparts a small force per unit area on the satellite, its effect is significant on the low-density large area-to-mass-ratio satellites, such as Echo I, required for efficient passive communication satellites. One can see (ref. 4) that even if a group of low-density passive communication satellites were initially spaced in orbital patterns, that due to the inherent differential orbit perturbation effects and the initial orbit injection errors between satellites the spaced system would eventually randomize and discontinuities in service would occur between ground stations. Therefore, some method of station keeping to initially place and maintain constant altitude and angular spacing of satellites is needed in order to reduce the number of satellites required in a practical and economical continuous communications satellites system.

A method of attaining the orbit position control necessary to accomplish station keeping of low-density passive communications satellites was originally proposed by Westinghouse Electric Corporation. The purpose of this paper is to present the concepts and results of the investigations of the proposed method performed both in-house and on contract, with Westinghouse Electric Corporation, under the direction of the Langley Research Center of the National Aeronautics and Space Administration.

ORBIT POSITION CONTROL METHOD FOR STATION KEEPING

The orbit positioning control methods that have been utilized or proposed in the past have generally been limited to mass dispensing techniques such as thrusting jets. In addition to having limited lifetime dependent on the quantity of mass carried onboard the satellites, the techniques of using point sources such as jets are not consistent with the structural capabilities of large inflatable passive communication satellites. Therefore, investigations were made into the controlled variation of unsymmetrical passive forces on inflatable Echo type low-density satellites throughout the satellite's orbital period so as to develop a passive control force for positioning a group of satellites with respect to each other in similar orbital planes. The control force is derived from the reaction on the satellite's surface of direct solar photon flux (both incident and reflective components), earth's radiation, and the satellite's reradiation (thermal emission). The forces are passive by nature since they do not depend on moving parts or mass expenditure but on the solar reflectance, absorptance, and emittance properties of the materials and are small values per unit area and therefore consistent with the structural characteristics of thin film materials. The total control force is compiled of small components distributed over the surface area of the satellite and therefore its magnitude and orbit positioning capability are directly dependent on large area-to-mass-ratio satellites which, due to booster and launching requirements, are applicable to the utilization of inflatable, expandable, or erectable structures in space.

As illustrated in Figure 3, this passive control force is used to control the orbital energy of the satellite. For simplicity let us assume a flat plate of unit area in a circular orbit about the earth with the sun in the orbital plane. One side of the plate is assumed to be a perfect absorber and the other side a perfect specular reflector. When considering the plate normal to the incident solar radiation pressure, the force per unit area when the reflective side faces the sun will be twice the value of the force when the absorptive side faces the sun. If the reflective side is oriented toward the sun during that half of the orbit when the satellite is receding from the sun and the absorptive side is oriented toward the sun during that half of the orbit when the satellite approaches the sun, then the energy of the orbit is increased and the satellite will seek a higher altitude thereby causing the period of the orbit to become longer and the angular rate about the center of the earth to decrease. The satellite will seem to fall back in orbit with respect to other unaltered satellites and is considered in the "Slow Mode" of operation. If the procedure is reversed and the absorptive and reflective sides are oriented toward the sun during the receding and approaching halves of the orbit, respectively, then the orbital energy is decreased and the satellite seeks a lower altitude causing the orbital period to decrease and orbital angular rate about the earth to increase. The satellite will then speed up in orbit with respect to other unaltered satellites and is considered in the "Fast Mode" of operation.

Therefore, orbit position control can be attained to accomplish station keeping by orienting different surface areas, which have different solar reflectance and absorptance characteristics, toward the sun throughout different intervals of the orbital period. Since this technique utilizes the solar radiation pressure, normally considered a perturbing force, its usable lifetime is unlimited and the force is available everywhere in space, except in the earth's shadow where a satellite remains for only a small fraction of its lifetime.

SPHERICAL SATELLITES

Initial studies were performed to apply this orbit position control technique to Echo type inflatable spherical satellites. Satellite sizes from 100 to 400 feet in diameter were investigated in the altitude ranges of 500 to 3500 statute miles. Various coating patterns and characteristics were investigated in order to determine the best configuration with respect to obtaining large force differentials on opposite sides of the satellite in addition to minimizing the torques on the satellite due to radiation. Naturally, coatings possessing the properties of the ideal perfect absorber or reflector are hypothetical, and therefore a literature search was performed to determine realistic coating characteristics. Based on these considerations, a two hemispherical pattern coating scheme was chosen to be most suitable for orbit positioning control, where one side of the satellite is an absorber and the other side predominantly a diffuse reflector.

Attitude Maneuver Systems

Two different attitude maneuver systems, illustrated in Figure 4, were studied with regard to their capability of controlling the orbital energy. For the Dual Flip or Solar Oriented case, the axis of symmetry with respect to the surface coatings is alined toward the sun and two 180° flips about either the yaw or pitch axis are performed near points A and B of the orbital path so as to present the opposite hemispherical surfaces towards the sun during the approaching and receding halves of the orbit. For the Vertically Oriented case, the axis of symmetry is alined along the velocity vector so that the satellite rotates in pitch once per orbit and thereby varies the surface coatings facing the sun over the orbital period. For this case, the 180° flip about the yaw axis is required only when it is desired to change the mode of operation from Fast to Slow or vice versa.

Each system requires some method of attitude control for the desired alinement in addition to a torquing system for the required flips. The initial concept was to utilize magnetic torquing by equipping the satellite with three mutually orthogonal current-carrying coils to react against the geomagnetic field and produce the desired three-axis control. This system (ref. 5) requires continuous sensing throughout the orbit of the sun's direction and the earth's magnetic field vector with respect to the satellite's symmetry axis. In addition, it requires solar and geomagnetic ephemeris information, expressed in orbital coordinates, stored onboard the satellite and supplied to the control system on a continuous basis. From these data, the attitude control system determines the attitude error of the satellite and programs the required currents in the coils necessary to make the desired attitude corrections. Therefore, in addition to the coils, there is required onboard the satellite solar cells for power and sun sensing, magnetometers, storage devices, and logic and computer circuitry for orientation and damping.

Although the Dual Flip system yielded slightly greater orbital energy changes per orbit, it was found to be inconsistent with the structural capabilities on the thin film Echo materials due to the large torquing requirements in performing the two 180° flips per orbit in short periods of time. Since the flips required for the Vertically Oriented system are needed only when changing modes, the torquing effects on the structure are greatly reduced by performing the flipping maneuver slowly over the period of several orbits. Also, the power requirements for the Vertically Oriented system are approximately only one-fourth the requirements of the Dual Flip system. Therefore, the Vertically Oriented system was chosen to be pursued in the studies.

Mobility

A measure of the capability of this orbit position control technique to accomplish station keeping is termed "mobility" and is defined as the change in angular separation as a function of time between two identical satellites started from the same point in a common orbit with one in the Fast Mode and the other in the Slow Mode of operation. A sample mobility curve is shown in Figure 5 which is derived from the effect of the direct solar incident and reflective forces upon 200-foot-diameter, 2000-pound spherical satellites in 45° inclination, 1500-mile-altitude orbits with realizable surface coating characteristics as illustrated. The curve indicates a constant angular acceleration rate of separation between the two satellites and shows that after 30 days the total angular separation would be 100° and the satellites would be in different orbits and still separating as the altitude and periods of the satellite would differ slightly. However, if after 15 days the mode of operation of each satellite were reversed so that the one in the Fast Mode was put in the Slow Mode and vice versa, then the curve from 15 days to 30 days would indicate a constant angular deceleration rate of separation equal to the acceleration rate of the curve for the first 15 days and is shown as the dotted curve in Figure 5. For this situation the two satellites would be back into the same common orbit as they started from after 30 days with an angular separation of 50° between them. The satellites could then be put into the same mode or neutral mode and would remain separated 50° as they orbit the earth except for slight deviations due to possible small differences in other orbital perturbations. Should the procedures of orbit positioning control be performed on one satellite with respect to a neutral satellite, the curve would resemble that of Figure 5 but the separation rates and total angular separation with time would be one-half those shown for corresponding time intervals.

In addition to the incident and reflective direct solar radiation, the effects of earth's radiation, albedo, and the satellite's own reradiation (thermal emission) on mobility or change in orbital energy were investigated as a function of the coating characteristics of various inside and outside surface areas of the satellite. The mobility of the satellite is largely dependent on the differential tangential forces along the orbital path rather than differential radial forces. Therefore, the effect of earth's radiation and albedo is insignificant compared to the direct solar radiation. However, the effect of the satellite reradiation force can be significant with different emissivity characteristics for the two hemispherical outside surface areas, especially since the temperature differentials diametrically across the spherical balloon are significant due to the large distances in separation of the surface areas involved. When considering the Vertically Oriented case, the reradiation forces, while an order of magnitude smaller than the direct solar force, is almost continually alined to the velocity vector of the satellite while the direct solar force varies with respect to the velocity vector sinusoidally throughout the orbit.

Figure 6 shows a comparison of mobility curves for the various coating patterns illustrated. Curve 1 indicates the mobility when considering just the direct solar force effect on Configurations A or B, where the absorptivity is 0.85 and corresponding reflectivity is 0.15 on one hemispherical side and the diffuse reflectivity is 0.65 and corresponding absorptivity is 0.35 on the other side. Curve 2, representing mobility of Configuration A when considering the total forces on the satellite, is considerably less than curve 1 and therefore indicates that the effect of the differential reradiation forces available from realizable emissivity values is in opposition to the direct solar forces. This is more apparent in curve 3 where the mobility from the total forces on Configuration B is plotted. The curve is dotted to represent a negative or reverse mobility, where the Fast

Mode when considering direct forces now becomes the Slow Mode when considering total forces and the Slow Mode becomes the Fast Mode, etc. For this case the reradiation forces are dominant due to the large difference in emissivity values for the two hemispherical coatings. Since the effects of the direct solar and reradiation forces were in opposition, it was believed that by eliminating the differential direct solar effect over the orbit, an even greater mobility could be obtained. Curve 4 confirms this belief by utilizing Configuration C which has uniform outside absorptivity and reflectivity and therefore also minimizes the solar torques on the spherical satellite. Investigations into the variations of the emissivity values on the inside surfaces resulted in little effect on the mobility and were therefore chosen as 0.9 to maintain the temperature distribution over the satellite within tolerable limits.

All of these mobility curves were computed with the sun in the plane of the orbit. Actually the sunline moves out of the plane of the orbit as the earth orbits around the sun. The inclination of the sun, defined as the angle between the sunline and the orbital plane of the satellite, varies periodically over a yearly cycle and its amplitude will reach 90° for orbital inclinations between 67° and 157°. Accordingly, the mobility will be reduced when the sun moves out of the orbital plane. However, the resulting Configuration C will have sufficient mobility even when the sun is normal to the orbital plane since the differential reradiation forces are mainly dependent on the energy received from the sun rather than the incoming direction.

Resonance

This technique of orbit position control depends solely on controlling the orbital energy and thereby the orbital period of the satellite. However, the effect of orbital eccentricity on the system is an important consideration. Normally the eccentricity varies in a cyclic manner throughout the lifetime of the satellite as experienced by Echo I (ref. 3). The period and amplitude of this oscillation are dependent on the area-to-mass ratio of the satellite as well as the orbital inclination and altitude. The solar radiation pressure is the dominant perturbing factor on low-density satellites causing the eccentricity variations, and its effect on spherical satellites has been widely investigated (refs. 6, 7, and 8). However, there are certain critical combinations of orbital inclinations and altitude where the eccentricity does not vary periodically but continues to build up as a direct or stairstep function. These conditions (ref. 8) are termed "resonance" and must be avoided as they would eventually destroy the orbit if continued over a long period of time.

Computer studies were performed to predict the maximum limit on eccentricity buildup for various orbits and satellite sizes. A sample case is shown in Figure 7, where the maximum eccentricity buildup is plotted against orbital inclination for a 200-foot-diameter, 2000-pound spherical satellite in a 1500-mile-altitude orbit. The peaks on the curve indicate areas of resonance which must be avoided. However, these inclinations can be used at other altitudes, where the resonance conditions will then occur at different inclinations. Since the maximum eccentricity is directly porportional to the area-to-mass ratio of the satellite, it can be easily computed for all satellite sizes for any given curve of constant altitude.

LENTICULAR SATELLITE

As a spherical passive communications satellite, such as Echo I, orbits the earth only that segment of the sphere which faces the earth at any given time contributes significantly to the reflected communication signals back toward the earth. Therefore, a considerable portion of the sphere, which reflects the radio signal received outward into space, may be eliminated, and thereby achieve a considerable reduction in weight, by utilizing an earth-oriented passive segment of the sphere. This concept, illustrated in Figure 8, consists of using a similar segment on the top half of the satellite to form a membrane for inflation techniques and is termed a "lenticular" satellite. As illustrated, the angular extent of such a satellite should be approximately 84° in a 2000-nautical-mile-altitude orbit in order to reflect communication signals back to any point on the earth that can be seen when viewed from the satellite. Subsequent studies are being performed under the direction of NASA Langley Research Center into the feasibility and design of this lenticular satellite concept utilizing gravity gradient stabilization for the vertical earth pointing requirement. The communication advantages of the lenticular satellite and the structural and stabilization concepts involved are discussed in another paper (ref. 9) to be presented at this Conference and therefore will not be dealt with further in this paper. However, the application of the solar sailing orbit position control technique to the gravity gradient stabilized lenticular satellite is discussed in the following paragraphs.

Since the results of the station keeping studies on spherical satellites indicate a preference for vertical orientation, the technique readily applies to the lenticular satellite which also has the vertical orientation requirement based on its use as a passive communications reflector. Also the use of the passive gravity gradient stabilization for two-axis control eliminates the need for the complex and active magnetic three-axis attitude control system presented earlier for the spherical satellite. However, some additional method of control and flipping is required about the yaw (vertical) axis in order to accomplish station keeping.

Various lenticular configurations with corresponding orbit position control schemes were investigated, and the two most feasible concepts are presented in Figure 9 with the resulting dimensions and weights as shown. The configuration on the right obtains its mobility in the same manner as the spherical satellites, as it consists of a solid lens having two different surface areas with different emissivities. The line of symmetry through the patterns, indicated by the x-axis, is alined along the velocity vector and flipped 180° about the yaw axis when changes in mode of operation are desired. The configuration on the left obtains its mobility through the use of flat sails attached between the stabilization booms of one plane and having different reflective properties on either side, by alining the plane of the sails normal to the velocity vector. This method also requires the same 180° flipping about the yaw axis for mode changes. The total required sail area is split equally above and below the lens so as to assist in distributing the mass symmetrically and thereby minimize the solar torquing disturbances on the stabilization systems. This configuration uses a photolyzable material on the lens as a gas barrier for the inflation system (ref. 9). The material then disappears in the space environment leaving behind a wire grid mesh lens which is suitable as a microwave reflector for passive communications.

Advantages of using the mesh lens with flat sails over the solid lens are as follows: First, a neutral orbit positioning control mode can be obtained by alining the plane of the sail parallel to the orbital plane. Second, the maximum eccentricity limit can be decreased by reducing the projected area-to-mass ratio of the satellite towards the sun during critical eccentricity buildup periods by alining the plane of sail parallel to the sunline, since the mesh lens projects a considerably smaller area towards the sun than the solid opaque lens. However, the photolyzable mesh material is still in the development stages as well as a sail material yielding the required optical properties for station keeping and still being microwave transparent so as to avoid communications interference. A mobility in the range of 100° per 30 days is feasible with either configuration at 2000 miles.

Two concepts of obtaining the required three-axis damping and yaw control are also indicated in Figure 9. The Ames-X principle (ref. 10) of using inertial coupling for three-axis damping of gravity gradient stabilized satellites is schematically shown on the configuration on the right. DeHavilland type extendable yaw and damper booms with tip masses provide the satellite with the necessary moments of inertia distribution and are skewed to the satellite body axis in such a way (ref. 10) as to aline the x-axis in the orbital plane. By utilizing either magnetic hysteresis or eddy current dampers with this Ames-X concept, three-axis damping can be achieved. The yaw flipping for mode changes, etc., is accomplished through the use of a step-servo motor and hermetically sealed harmonic drive which rotates the satellite beneath this stabilized boom structure to the desired positions for performing station keeping. In the configuration on the left is illustrated the Rice/Wilberforce damper concept, investigated by Goodyear Aerospace Corporation, consisting of a lossy spring and viscous damper. The required moment-of-inertia distribution between the x-axis and the y-axis is obtained by placing weights around the rim of the lens and the required yaw torquing obtained by use of a reaction wheel. Either system could possibly be utilized with either configuration; however, the feasibility studies so far indicate a preference for the Ames-X concept.

CONCLUDING REMARKS

The results of the studies have demonstrated feasibility in utilizing the passive solar radiation force and the satellite's reradiated thermal emission force to perform orbit position control to accomplish station keeping of low-density Echo type spherical and lenticular passive communication satellites by controlling the orbital energy and thereby controlling the orbital period of the satellites. The studies have shown that the technique depends on large area-to-mass-ratio satellites and therefore due to launching requirements are directly applicable to inflatable, expandable, and erectable structures in space. The amount of mobility available is dependent on the differences in solar reflectance, absorptance, and thermal emittance that can be achieved through the use of realizable lightweight coatings. In addition, semipassive attitude stabilization and damping systems have been shown feasible for the lenticular satellite.

The resulting data so far have been limited to low-altitude 2000-nautical-mile range. However, studies are being initiated under the direction of Langley Research Center to extrapolate the mobility results of the lenticular satellite parametrically from the existing data with respect to variations in inclinations, shapes, and altitudes up to and including synchronous orbit. In addition, subsequent overall trade-off studies are being planned to determine the most economical satellite communication system feasible now and in the near future utilizing orbit position controlled lenticular passive communication satellites.

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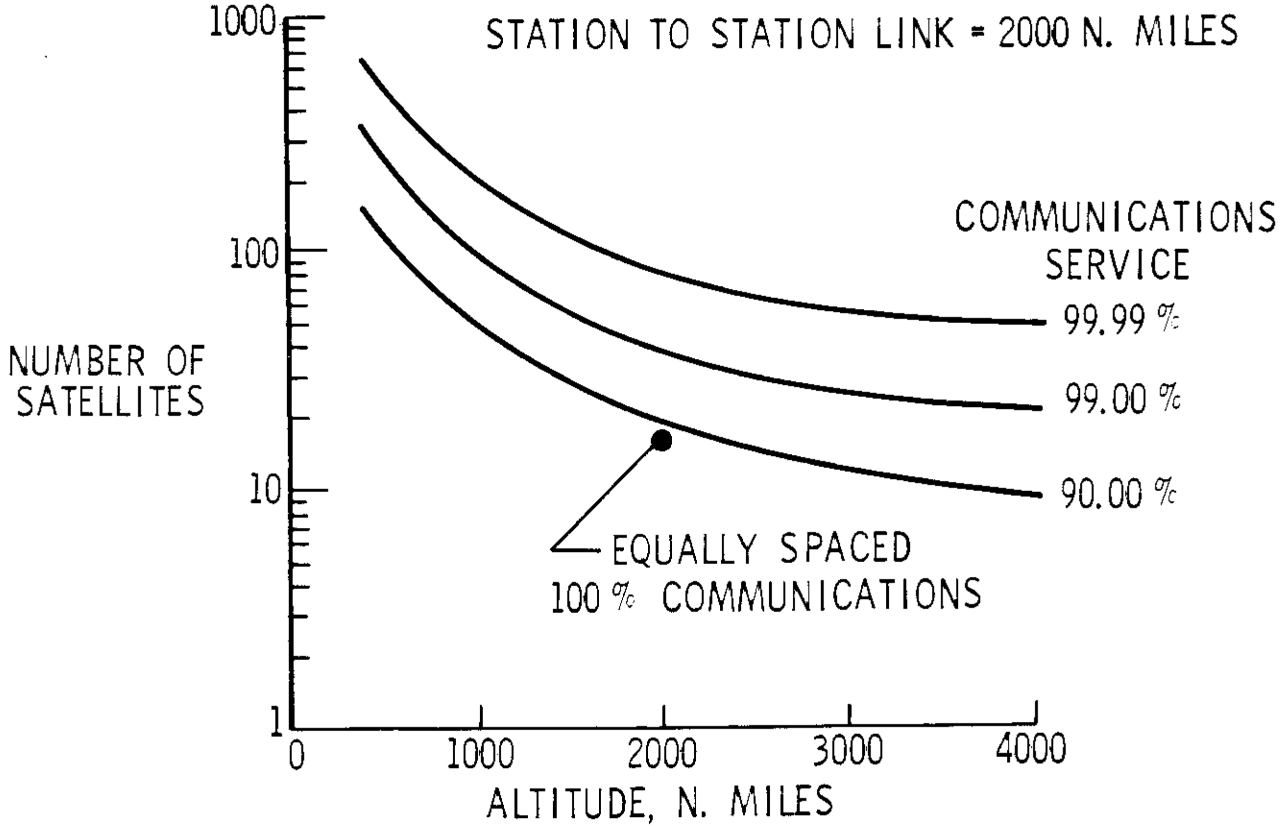

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Figure 1.- Random system.

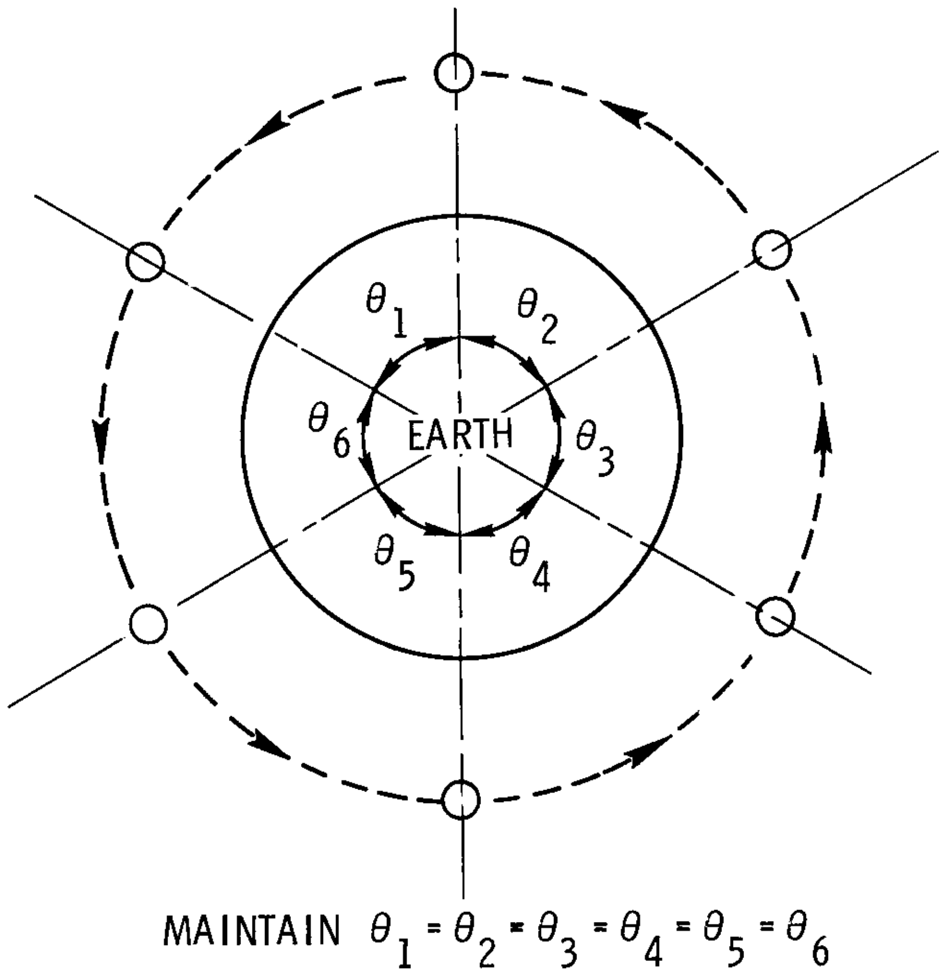

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Figure 2.- Station keeping concept.

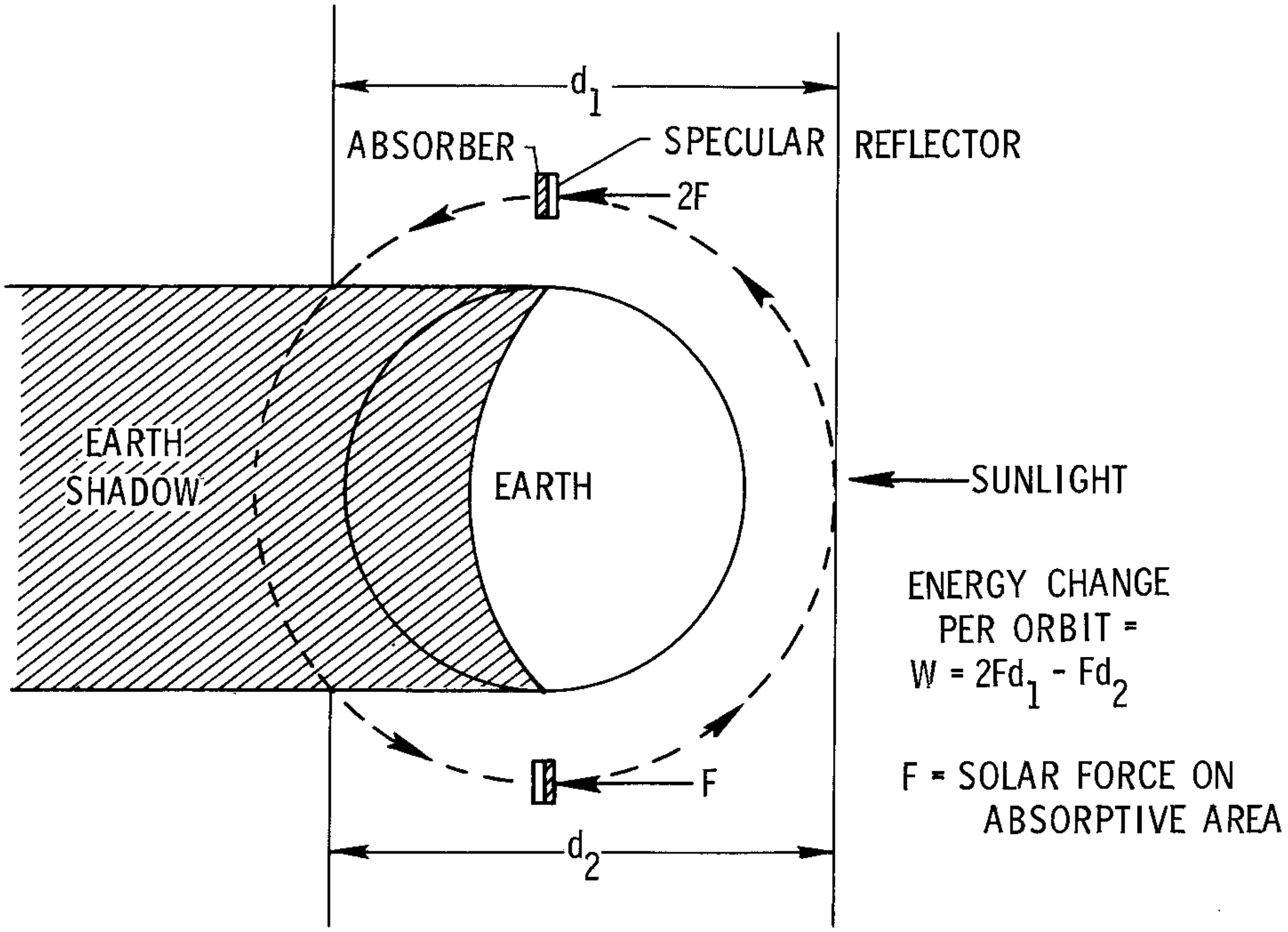

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Figure 3.- Orbit position control method.

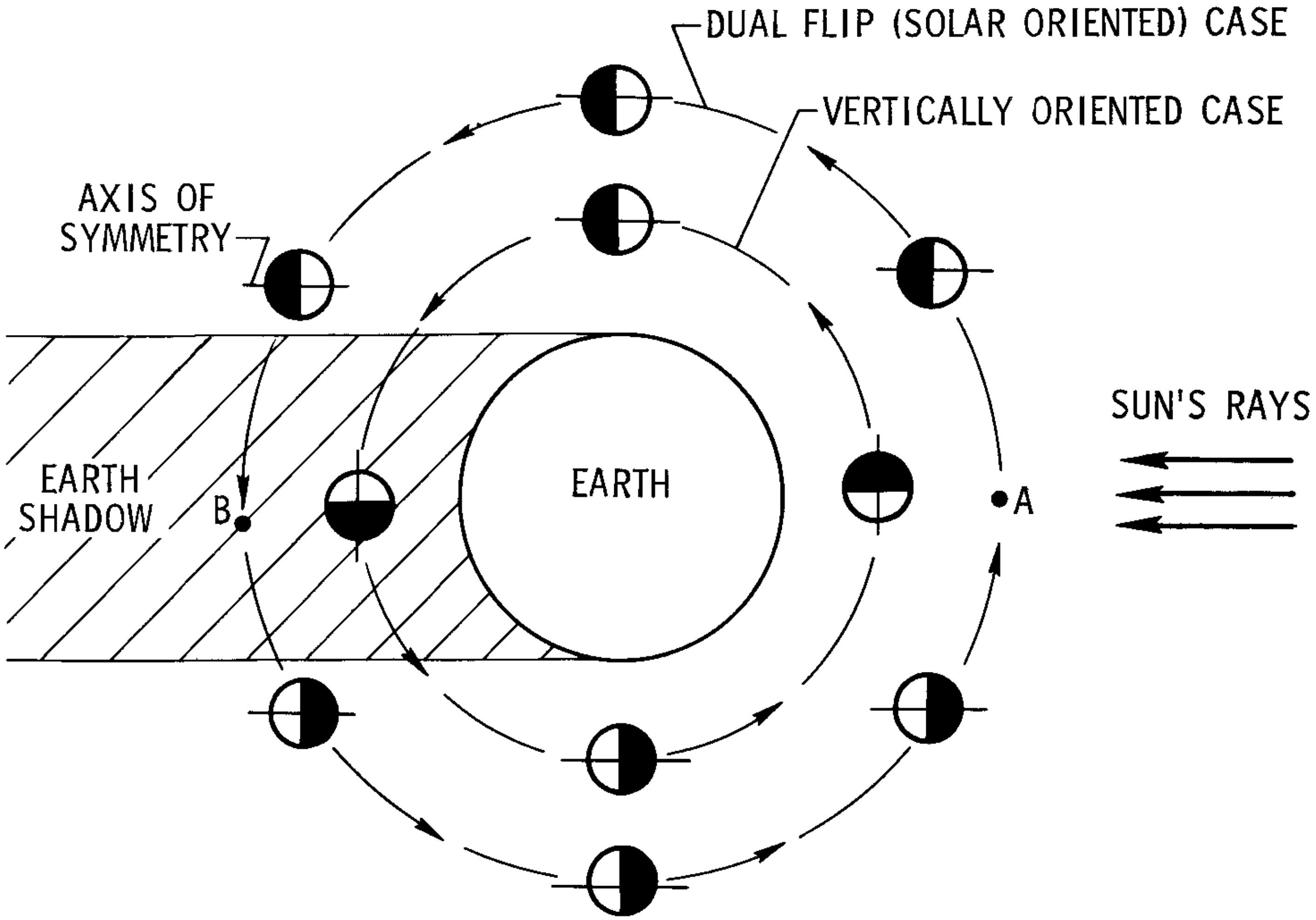

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Figure 4.- Attitude maneuver systems.

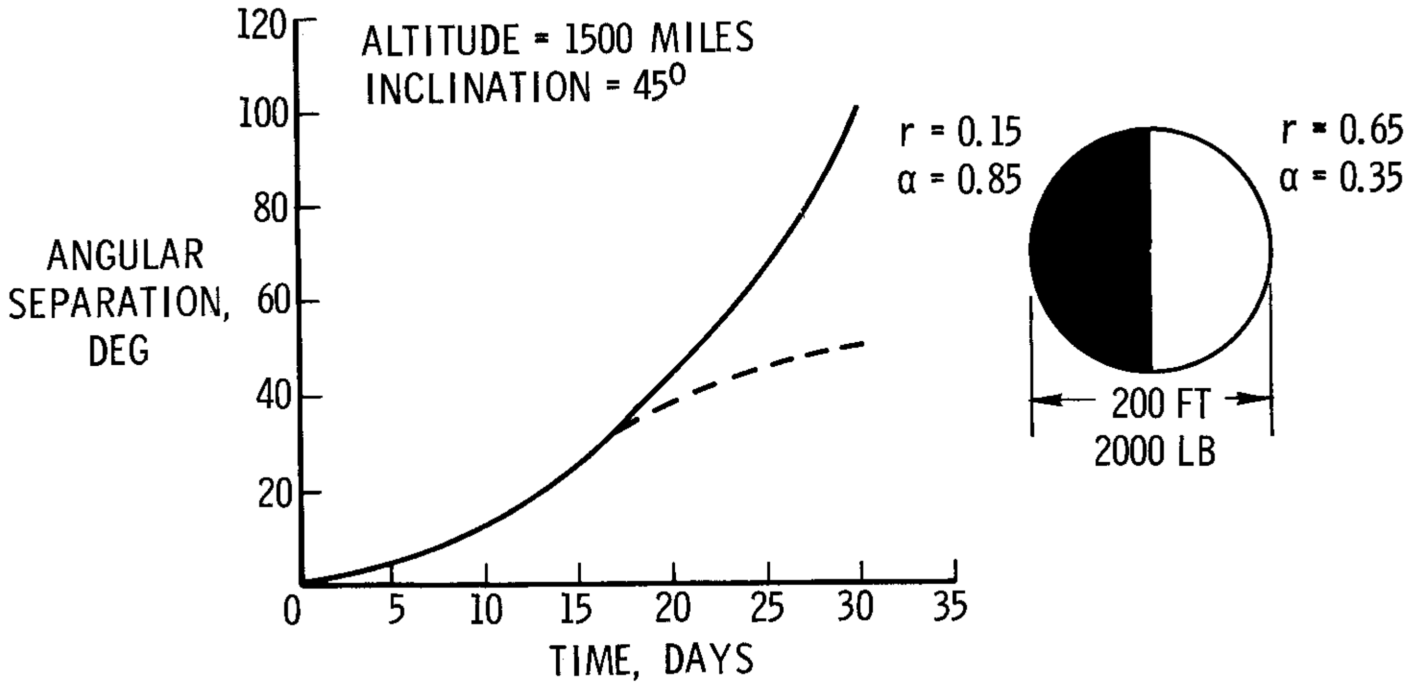

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Figure 5.- Mobility.

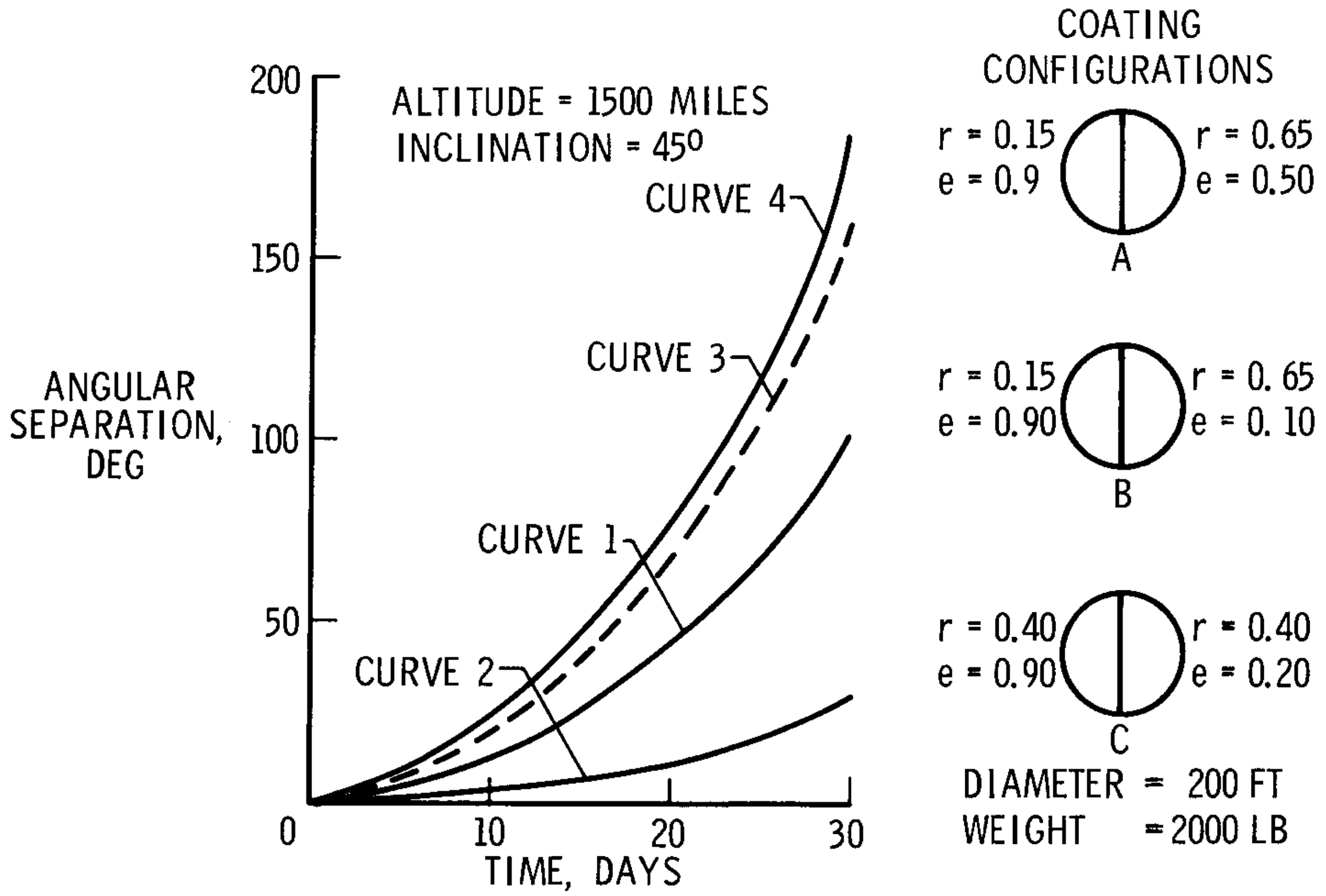

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Figure 6.- Mobility comparisons.

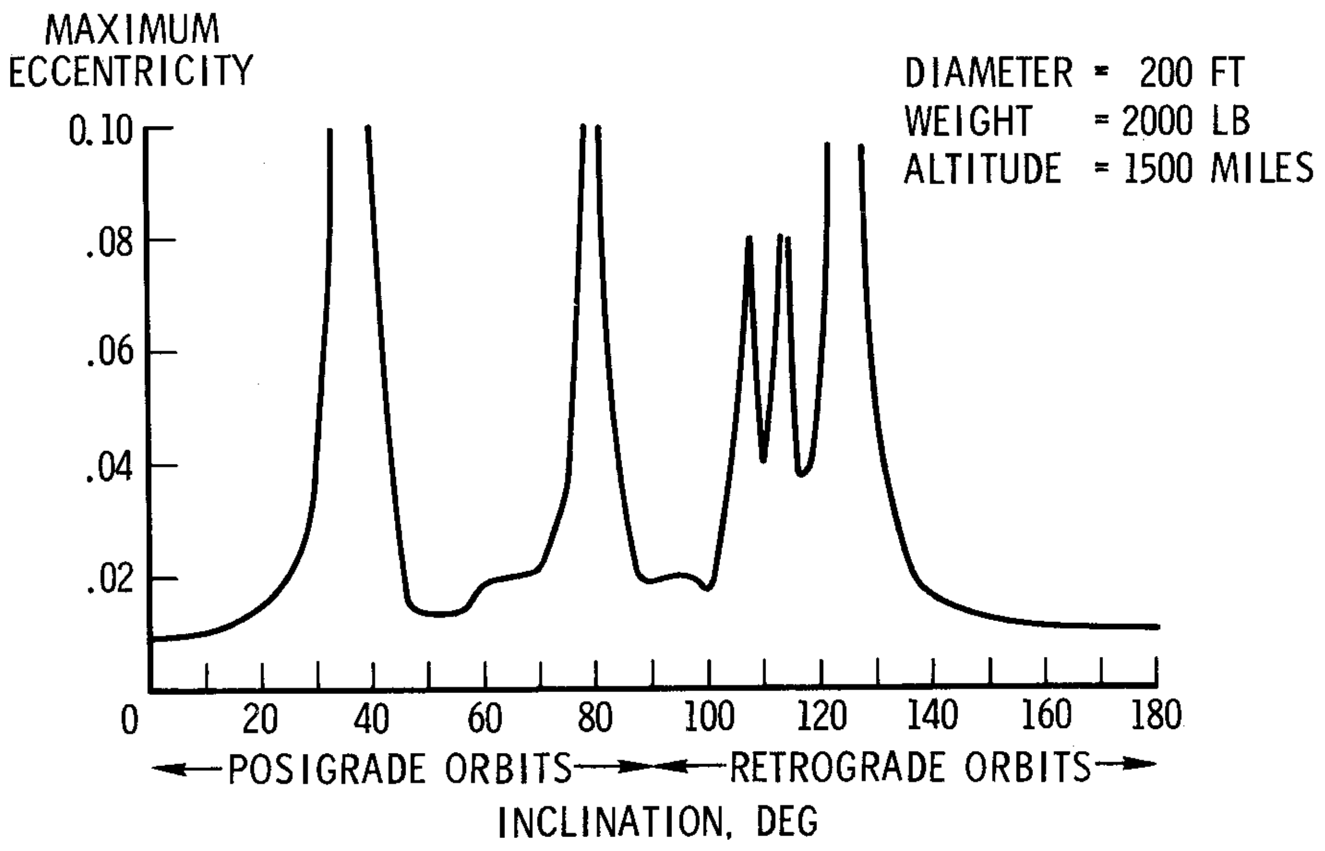

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Figure 7.- Resonance conditions.

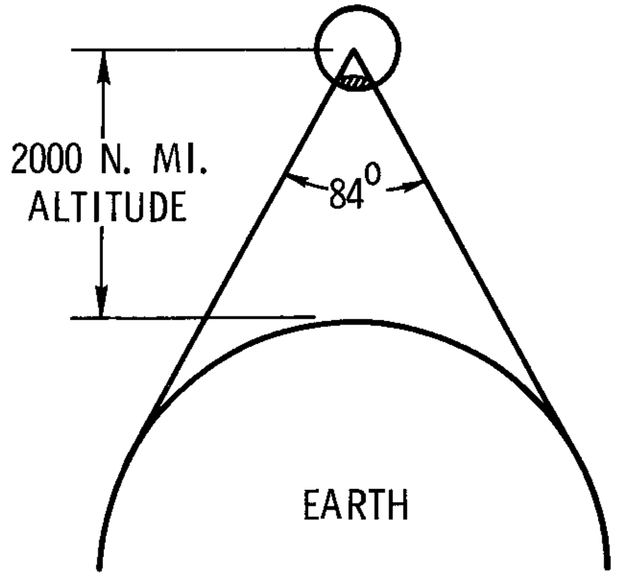

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Figure 8.- Lenticular concept.

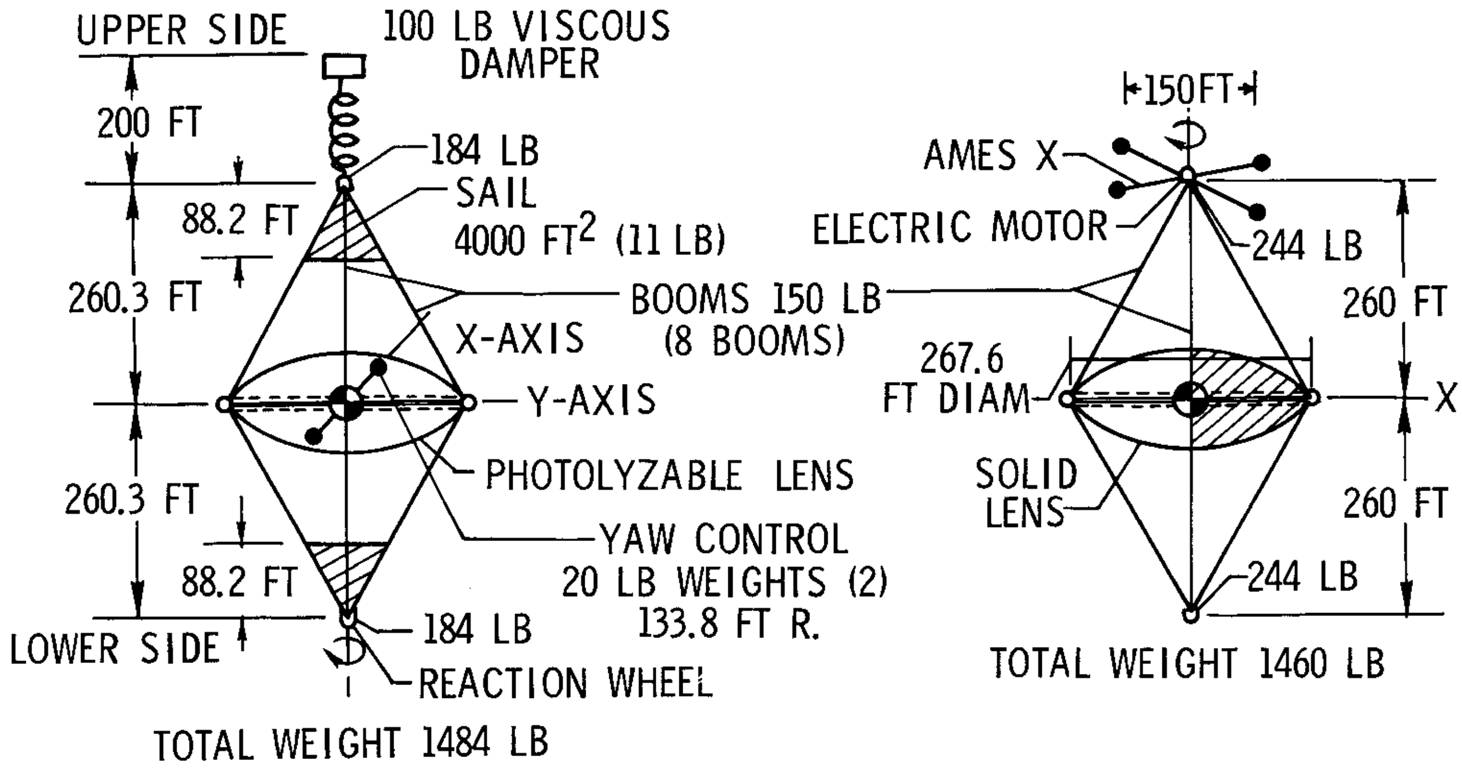

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Figure 9.- Station kept lenticular satellite.