SESSION III

STRUCTURAL CONSIDERATIONS FOR AN EXPANDABLE

LENTICULAR SATELLITE

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INTRODUCTION

Communications systems in general, as with practically anything of potential commercial value, must ultimately be evaluated from an economic standpoint. In a space oriented communications system, the satellites themselves, as the orbital subsystems, must likewise be economically evaluated. Several factors enter into this evaluation. Passive communications satellites inherently have a long effective life and their bandwidth capability allows a great many communications channels per satellite. But aside from the advantages inherent to one type satellite or the other, two basic parameters always appear. The satellite subsystem's weight affects the launch cost and the signal return which the satellite is capable of reflecting or retransmitting affects the ground station cost. Thus, the efforts in passive communications satellites are oriented toward achieving a better microwave return signal for a minimum of satellite weight.

The NASA Langley Research Center has made a continuing effort in the area of passive communications satellites and in very lightweight expandable structures in general. The gravity-gradient stabilized lenticular passive communications satellite with an orbital position control capability is the latest of the devices to be considered in this effort.* Langley Research Center directed studies dealing with the lenticular satellite have been preliminary in nature to this point, with very little emphasis on optimization but they clearly indicate the feasibility of the concept. It has been shown that the lenticular concept can produce a satellite with communications capabilities superior to the passive spheres for a given satellite weight.

PART I

LENTICULAR CONCEPTUAL PHILOSOPHY

To indicate the basic lenticular conceptual philosophy, first consider a spherical passive communications satellite in Earth orbit (fig. 1). One

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*This paper is based on work performed by the NASA Langley Research Center and by the Goodyear Aerospace Corportation, Akron, Ohio, and the Westinghouse Electric Corporation, Aerospace Division, Baltimore, Maryland, under contracts directed by the Langley Research Center.
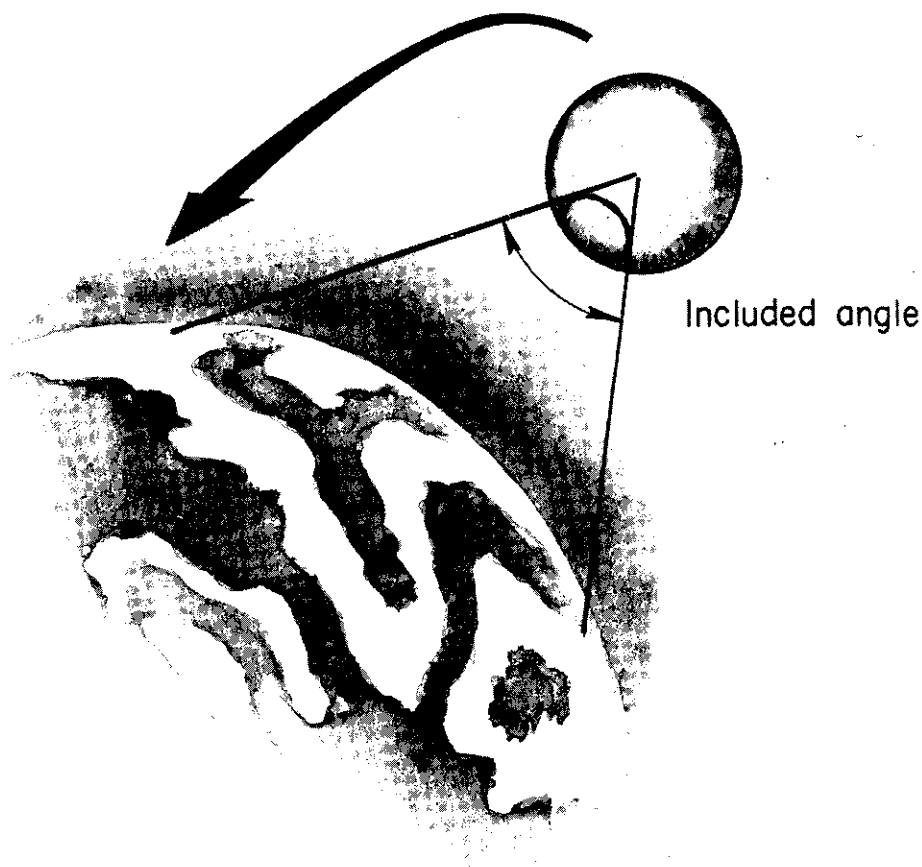
Included angle

Figure 1.- Basic lenticular concept.

might note that the only part of the spherical surface which is necessary for
communications between two ground stations is that segment defined by an
angle from station to station, through the center of the sphere. This
included angle is then, at a maximum, slightly more than that from horizon
to horizon. Any point on the spherical surface outside that segment can con-
tribute very little to a microwave return signal. One could maintain essen-
tially the same communications capability and realize a great deal of savings
in satellite weight (and consequently launch cost) if only this spherical
segment were placed in orbit. The radar reflection cross-section-to-weight
ratio of the satellite could increase tremendously.* For example, at a
2000 n.mi. orbital altitude, the nominal horizon-to-horizon included angle
is 84°, and approximately 87 percent of a spherical satellite weight is
attributed to surface areas unnecessary for communications. The restriction
to this train of thought is, of course, that the spherical segment must be
Earth oriented to achieve this savings.

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*No great deal of elaboration on microwave theory will be made for pur-
poses of this paper except to say that the radar reflection cross section may
be considered to be a measure of the communications capability of the satel-
lite. The microwave return signal is stronger with higher reflection cross
sections. The value of this cross section is essentially $\pi\rho^2$ for a
reflecting spherical surface, where ρ is the radius of curvature.

A very attractive orientation/stabilization technique, also passive, is that of gravity gradient. A more thorough delineation of gravity-gradient methods and theory will be dealt with later, but for now let it suffice to say that gravity-gradient techniques supply a local vertical orientation and a means of close tolerance stabilization around that reference. More simply, the spherical segment's axis of revolution always points toward the Earth's center.

In order to effectively utilize satellites in a communications system, it is desirable to provide some means of accurately positioning the satellites in an orbit relative to each other or to some point on the Earth's surface. The feasibility of solar sailing a lenticular satellite has been established in studies under the direction of the Langley Research Center. Briefly, this technique involves, in principle at least, providing a sail surface on the satellite, oriented along the local vertical and perpendicular to the orbital plane. One might note then (fig. 2), that as the satellite moves around in its orbit, opposite sides of the sail face the sun at any two points in the orbit 180° apart. By applying coatings with different thermal characteristics to the two sides of the sail, one could attain different forces, a combination of direct solar and reradiation forces, at two points 180° apart in the orbit (fig. 2).
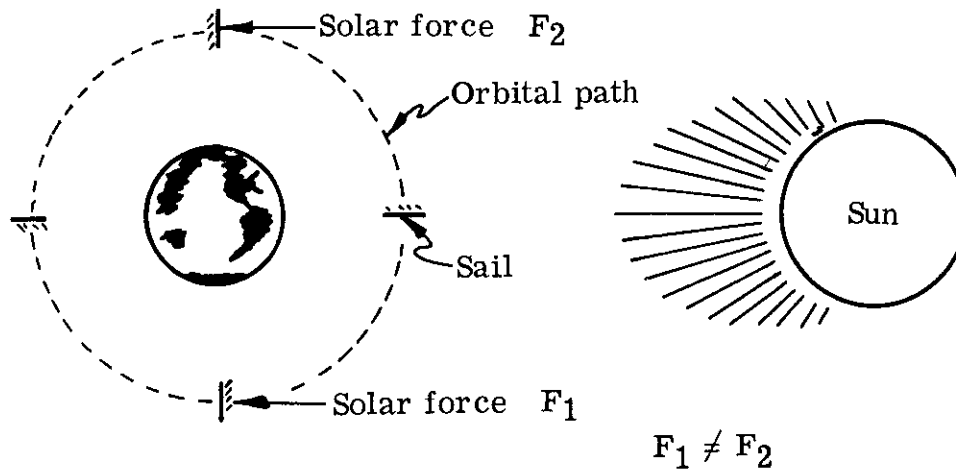

Figure 2.- Orbital solar sailing.

The net effect of these forces is that the satellite's orbital rate will either increase or decrease, depending on what thermal characteristics are provided and which side of the sail is oriented down the satellite's tangential velocity vector. Thus, the satellites have the capability of varying the separation angle between them (fig. 3).
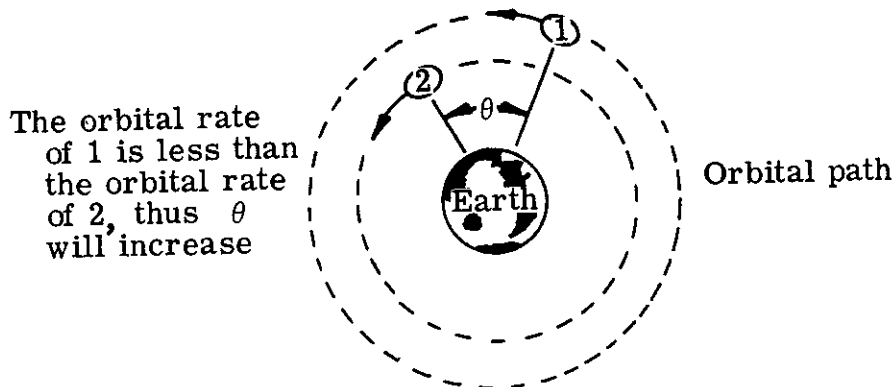
The orbital rate of 1 is less than the orbital rate of 2, thus θ will increase

Orbital path

Figure 3.- Orbital position control.

PART II

CONFIGURATIONAL DEVELOPMENT - MATERIALS AND LOADS

One might now proceed with the configurational development of a gravity-gradient stabilized lenticular passive communications satellite.

The spherical segment itself is of primary interest as the microwave reflector and its shape is of utmost importance. Any technique, within the state of the art, for the deployment of a good microwave reflecting spherical surface requires straining the surface material, either to form the spherical shape or to remove wrinkles left from package folds. The inflation and strain-rigidization technique of membrane deployment is compatible with this require-ment, and has received intensive research. For this inflation/rigidization procedure, a diaphragm or another spherical segment must be attached to the reflector segment around its periphery to form a gas enclosure (fig. 4). Inflation gas pressures then stretch the membraneous material beyond its yield point to form the spherical segment surface. Some peripheral restraint must be added to prevent the reflector/diaphragm combination, or lens, from attempting to assume a complete sphere under inflation pressures. The edge restraint can be supplied by an inflatable torus (fig. 4).

Assuming two identical spherical segments for the lens, one might note that the loads placed on the torus are dependent on two factors (fig. 5), the lens included angle and the lens material yield strength. The in-plane components are the only loads considered in the torus design as the out-of-plane components cancel each other. The included angle is a communications system consideration and is not a variable for structural design purposes. Thus the lens material must have a very low tensile yield strength for mini-mization of torus loads. The lens material on the other hand, must be capable of withstanding solar pressure (i.e., 13.6×10^{-10} psi for specular reflection) without buckling. The need for a lens material with a low yield strength and some value of skin section area moment of inertia, for a given radius of cur-vature, is established.
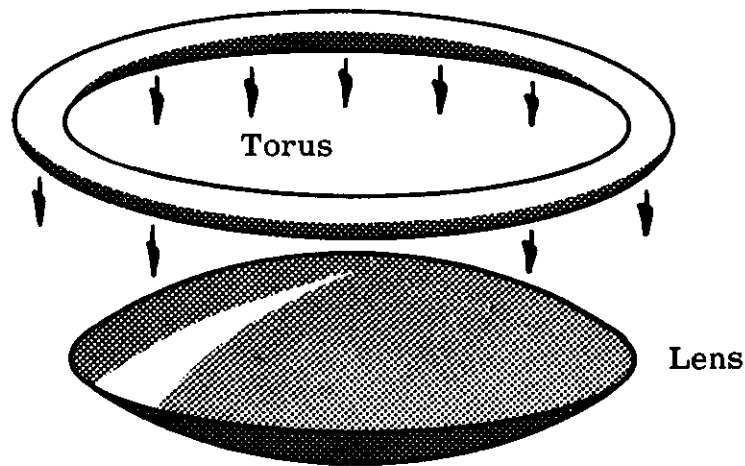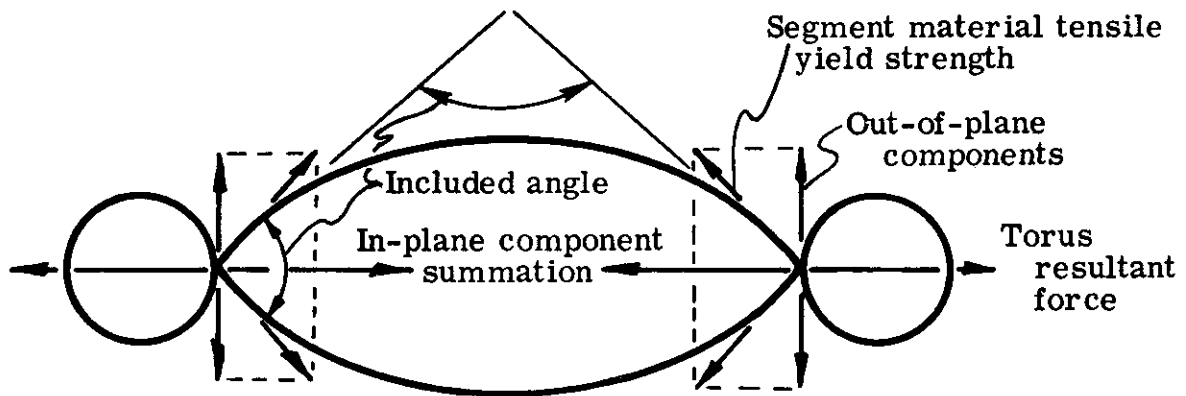
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Figure 4.- Lens/torus.

Figure 5.- Torus loads.

Several possibilities for a lens material do exist which provide a low area to area moment of inertia ratio cross section desirable for this application. The grid materials (fig. 6), such as the wire mesh and chemically milled metallic sheet, simulate the rings and stringers of more conventional semi-monocoque structures, in principle at least. The lens' function as a microwave reflector is only nominally impaired by the use of the grid materials, and preliminary studies have indicated their potential in this application.

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Wire mesh
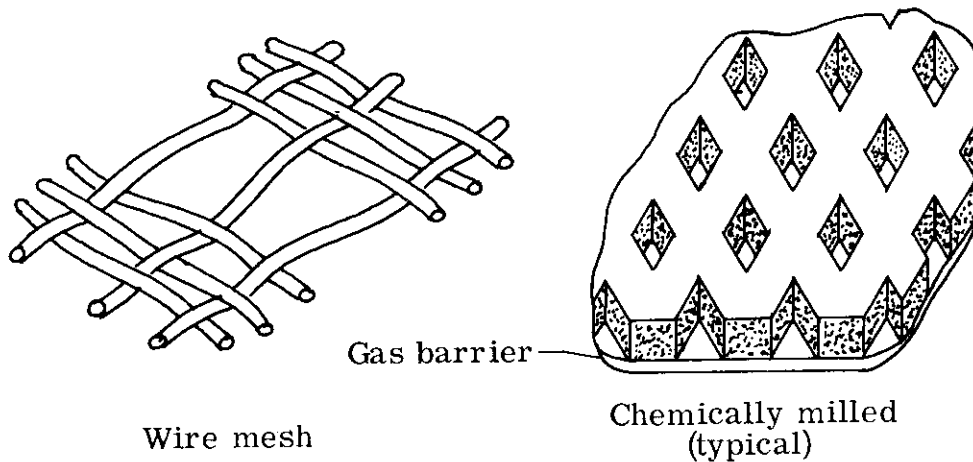
Gas barrier

Chemically milled
(typical)

Figure 6.- Representative grid materials.

The gas barrier to be utilized on a metallic grid material is largely determined by orbital position control and gravity-gradient stabilization considerations. If the lens is not to be used as the solar-sail, one might choose a "photolyzable" film as the gas barrier. The gas barrier film is not needed in this case after inflation, its mass distribution is actually detrimental to the gravity-gradient stabilization system, as will be discussed later, and it provides a greater surface area exposed to solar pressure. Solar pressure acting on the lens surface could produce a torque large enough to appreciably affect the gravity-gradient stabilization system, and it could contribute to an orbital eccentricity which also decreases the effectiveness of the stabilization system. Studies have indicated that low-strength photolyzable films, suitable for use as a gas barrier, can be made available.

"Photolyzable" film "evaporates" when simultaneously exposed to ultraviolet radiation and an increased film temperature. The film temperature may be increased to the desirable level passively by using various dyes to provide the proper film thermal characteristics. Heat inputs and ultraviolet radiation are, of course, very easily acquired in an orbital environment.

If the lens is to be used as the solar sail, one can choose one of the many very thin plastic films, vacuum deposited and coated to the proper thermal characteristics, as the gas barrier for the grid materials. A continuous surface is desirable in this case to provide more sail area.

"Solid" laminate materials (fig. 7) have also been produced which are very lightweight. In principle, these materials simulate conventional monocoque structures. The use of these materials for the lens is limited to the case where the lens is utilized as the solar sail.

Low elastic modulus,
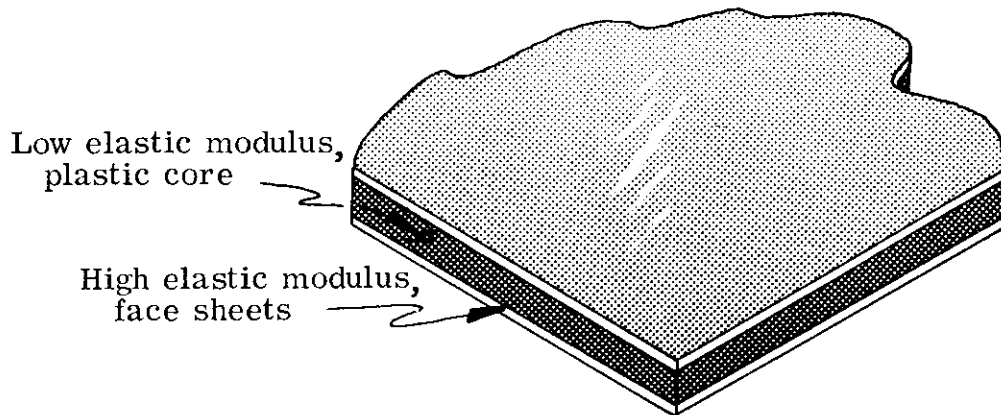plastic core ⎯

High elastic modulus,
face sheets ⎯

Figure 7.- "Solid" laminate material.

The importance of an optimized lens material can hardly be overemphasized.
The loads placed on the torus and the weight of the lens are minimized by
proper lens material selection. The lens and torus constitute a very large
percentage of the total satellite weight. An optimum lens material is not
readily defined, however, as some uncertainty exists concerning the true buck-
ling pressure such a very large radius of curvature to skin thickness ratio
spherical structure can withstand. Ground tests are generally inconclusive
due to the appreciable effects of a one "g" environment on the very light-
weight material. Consequently, lens material designs generally tend to be
conservative.

The torus, as previously mentioned, is intended to maintain an accurate
lens constraint during inflation, and the loads placed on it for a given
included angle, are directly proportional to the tensile yield strength of the
lens material. After completion of the inflation process, the torus serves no
further purpose and in fact makes the job of acquiring the mass distribution
desirable for gravity-gradient stabilization more difficult. Ideally, one
would prefer that the torus simply evaporate after completion of the inflation
cycle. A high-strength photolyzable film could do just that. However, in
their present state of development, these films are far too brittle to allow
packaging. If the high-strength films are not further developed, the major
materials requirement for the torus would be that it be light-weight, high
strength, and, to avoid communications interference, microwave transparent.
The design criteria for the torus can be shown to be wrinkling, which requires
only that the torus skin remain in tension at all times during lens inflation,
and strength to withstand inflation pressures.

To apply a gravity-gradient stabilization technique to the lens or lens-
torus combination, one must closely examine a few basic physical phenomena.

First, acceleration placed on the satellite due to gravity must be con-
sidered vectorially in a three-dimensional geocentric coordinate system, in
spherical coordinates if one chooses. On the other hand, orbital centrifugal
accelerations placed on the satellite may be considered, vectorially, in a

two-dimensional coordinate system with the origin at any appropriate point along an axis through the Earth's center and perpendicular to the orbital plane, or in cylindrical coordinates (figs. 8 and 10). The point of this rudimentary dissertation is that the difference in direction cosines of the gravity and centrifugal related acceleration vectors, acting on some incremental mass particle away from the satellite mass centroid, is one contributing factor to the gravity-gradient stabilization torques. Further, one must
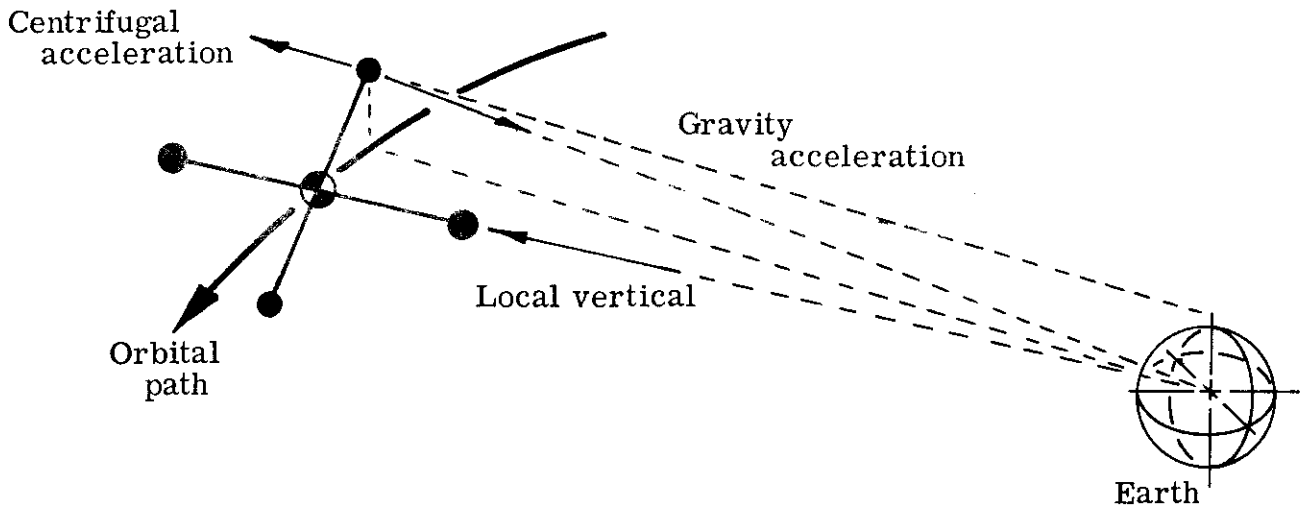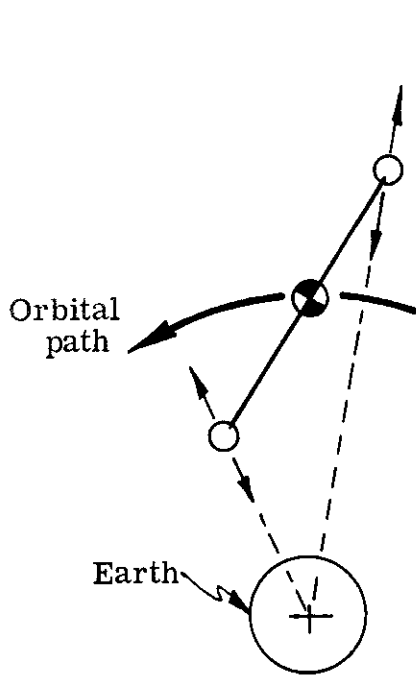

Figure 8.- Yaw accelerations.

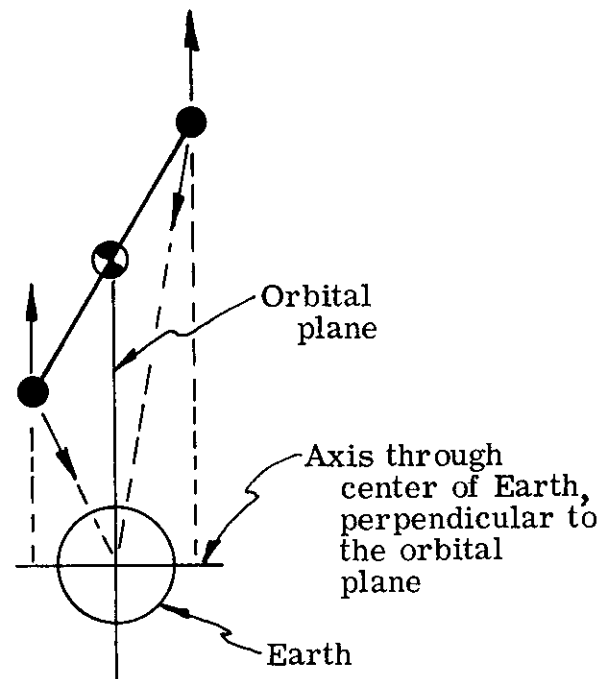Figure 9.- Pitch accelerations.

Figure 10.- Roll accelerations.

realize that only the mass centroid of any satellite is truly at zero "g" (i.e., net centrifugal acceleration equals net gravity acceleration). The gravitational attraction term is essentially compatible with the well-known inverse square law of Newtonian origin and the centrifugal accelerations ideally vary directly as the geocentric orbital altitude. The gravity acceleration is greater than the centrifugal acceleration acting on a mass particle closer to the Earth than the satellite mass centroid. The opposite is true of a mass particle farther from the Earth than the mass centroid (figs. 9 and 10). Gravity-gradient stabilization techniques require that the satellite mass be distributed in such a manner as to effectively utilize these small differential accelerations (fig. 11). The result is that the satellite is capable of sensing the local vertical and the orbital plane, and a restoring torque exists any time there is an angular displacement of the satellite from these two references.
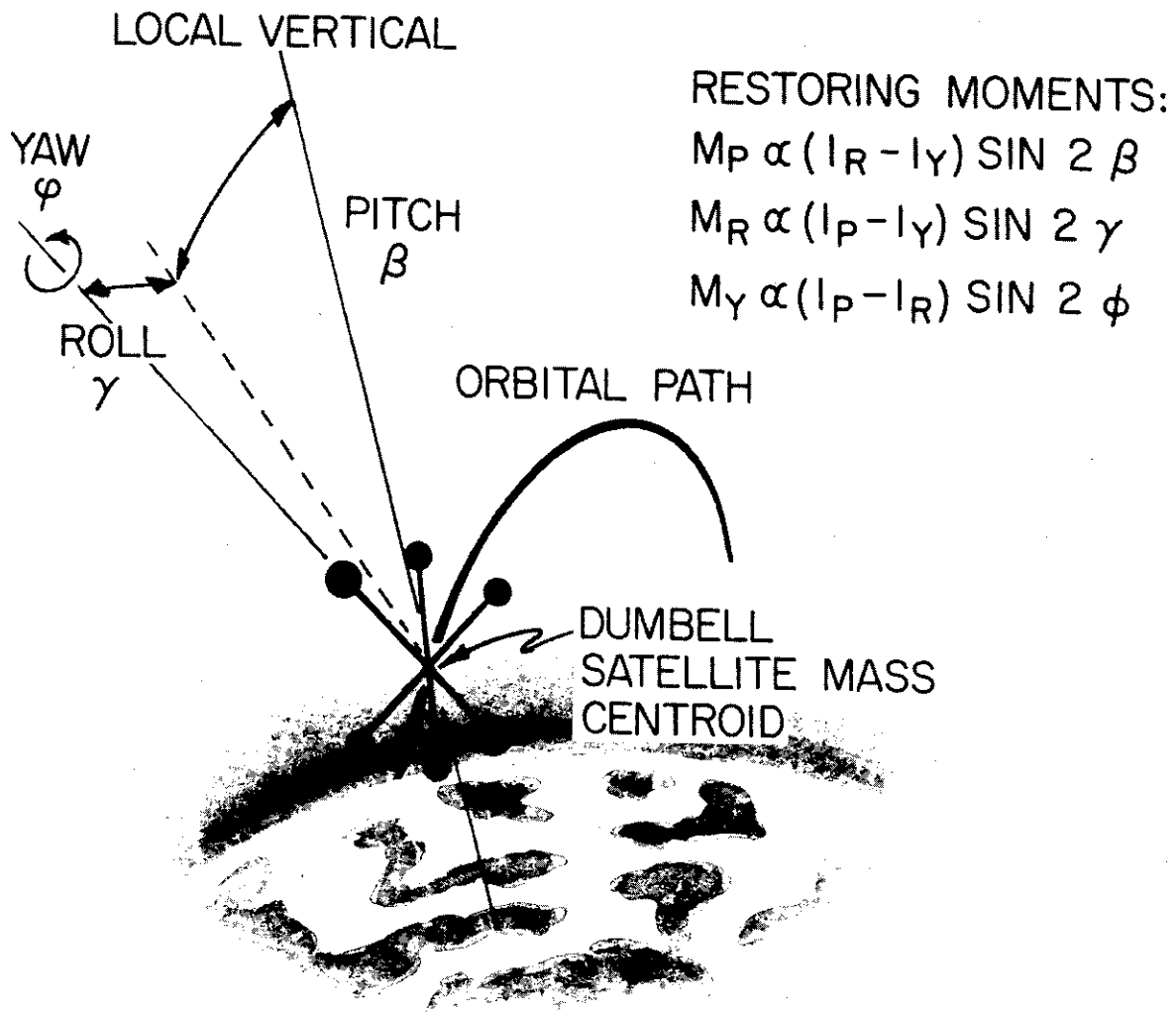

RESTORING MOMENTS:

$$M_P \propto (I_R - I_Y) \sin 2\beta$$

$$M_R \propto (I_P - I_Y) \sin 2\gamma$$

$$M_Y \propto (I_P - I_R) \sin 2\phi$$

Figure 11.- Gravity-gradient restoring moments.

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For the particular application of the lenticular satellite, the mass distribution is achieved basically by attaching the canister halves, in which the satellite is packaged for launch, the inflation system and controls to the lens by long boom arrangements. One can now clearly see the detrimental effects on gravity-gradient stabilization of the torus and lens gas barrier mass distribution (fig. 11). It is desirable to keep the yaw inertia as small as possible so that the pitch and roll inertias may remain small, thus requiring shorter booms. A lighter damping device may also be utilized as the energy which it must dissipate, being proportional to the absolute mass moment of inertia of the satellite, is kept to a minimum.

To gain some insight into the loads placed on the satellite by this mass/boom arrangement, one might observe a simple two-dimensional case of a pitch pointing error (fig. 12).
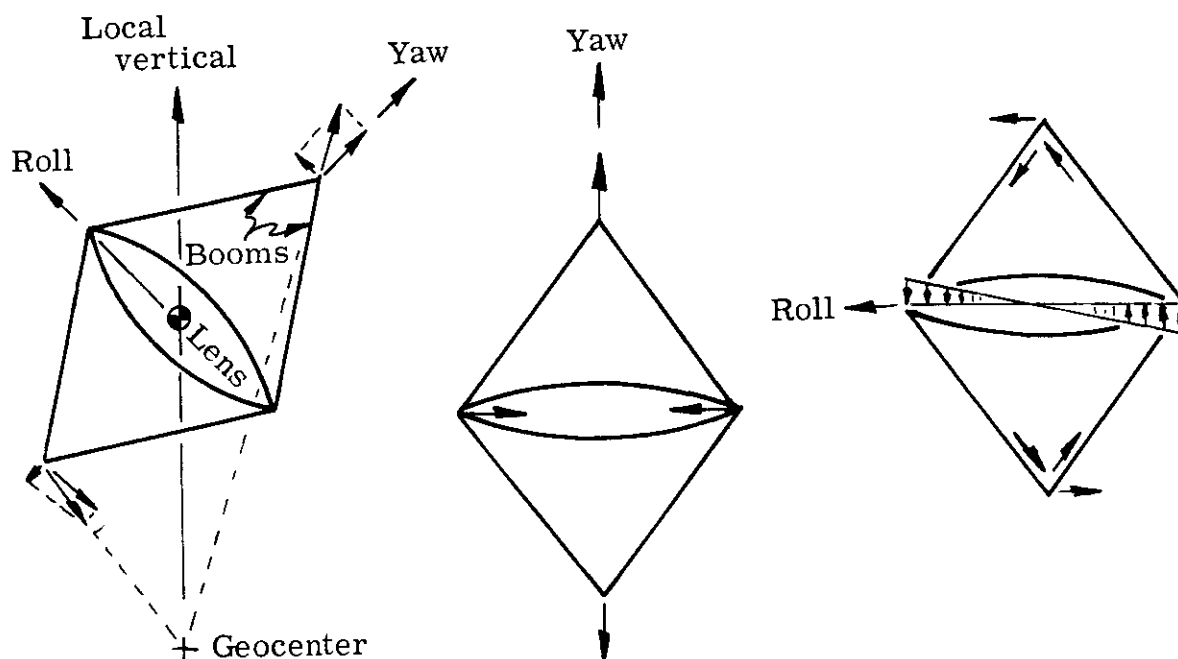
Figure 12.- Rim/boom loads.

Consider only the gravity-gradient resultant forces placed on the canister halves and the components of these forces in a satellite oriented coordinate system. The components along the yaw axis apply a tensile force to the booms and consequently a load around and in the plane of the lens periphery. The roll axis components apply a compressive load to one boom and a tensile load to the other. The roll axis loads which rotate the satellite in pitch are resisted by the inertial mass of the lens. The combination of these resultant loads placed on the lens and its periphery would certainly distort it, reducing its effectiveness as a microwave reflector, if some additional structural member were not provided to absorb them. A relatively rigid rim with a collapsible cross section around the lens periphery could absorb the loads; it could also serve as a "solid" attachment point for the booms and as

Figure 13.- General features, baseline configuration.
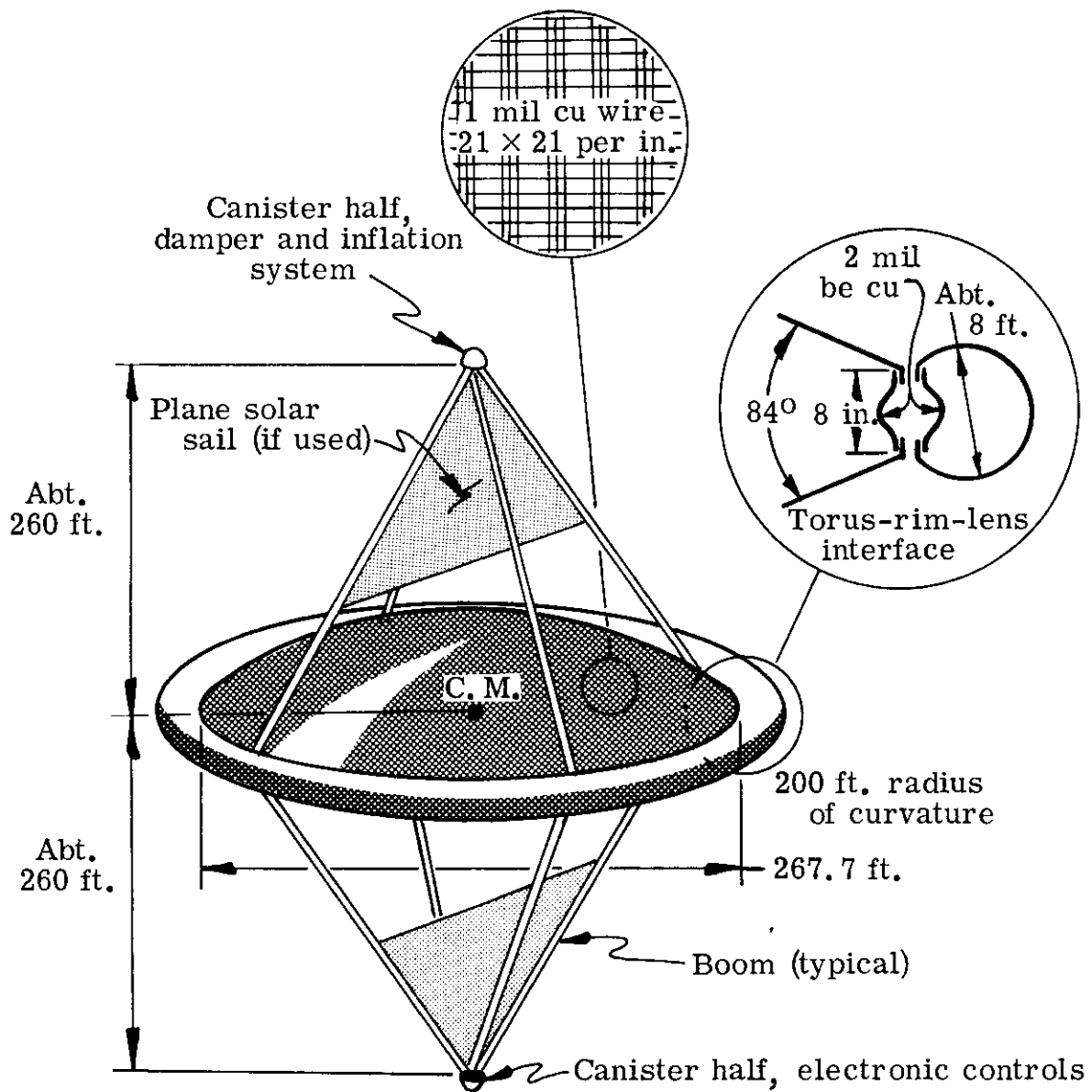
Total weight, 1450 lb. launch

Lens inflation pressure, 3.16×10^{-4} psi

Lens material tensile yield strength, 3.8×10^{-1} lb/in.

Torus inflation pressure, 1.678×10^{-1} psi

a convenient interface between the torus and lens. The major design consideration for the rim is to keep its deflections small, thus avoiding lens distortion. The booms themselves are designed to a conservative compressive load and are not allowed to have large transverse deflections due to solar pressures.

However, unless some means of energy dissipation is provided, the perturbed satellite would continue to oscillate indefinitely, much like a frictionless pendulum. Therefore, some damping system must be added. Several damping systems, primarily passive, can be utilized in this application.

Figure 13 shows the general dimensions and features of the completed configuration. This particular configuration is designed for a 2000-nautical-mile orbital altitude with an 84° included angle.

A wire mesh grid, although not necessarily optimum, was chosen in the preliminary studies as being reasonably representative of probable lens materials characteristics. Copper wire was a compromise selection based on the many characteristics desirable in this application, including small thermal expansions, low yield strength, the ability to be woven in very small diameters, and preferably nonmagnetic.

PART III

PACKAGING AND DEPLOYMENT

Very little has been said to this point concerning the packaging and deployment of the lenticular satellite. This area is, in fact, one of the primary design considerations. Structural members such as the rim do not have a specific shape purely by chance. Packaging and deployment analyses of such an inflatable satellite are however, at best, a qualitative affair. The packaging procedure is illustrated in figure 14. Note that the rim is of a collapsible cross section with two hinges nearly 180° apart. For packaging, the hinges are used to fold the rim and torus back on themselves. The rim and torus are then rolled up, leaving the lens in a cone shape. Accordion folding the lens completes the packaging procedure.

After the package is placed inside the canister, the canister is evacuated. This is done so that very close control and monitoring of the canister and package internal pressures can be maintained. Air trapped inside the package folds is a contributing factor to what are called residual gases. Since such very low pressures are required for inflation, residual gases have previously contributed to deployment and inflation problems with very light inflatables. One might intuitively expect a residual gas problem with this packaging technique since it leaves an open space inside the package, but this does not seem to be the case. A programed number of holes in the satellite skin and a perforated "basket" inside the canister assist in the canister and package evacuation.

Packaging efficiency (i.e., actual volume of expandable material as compared to the internal volume of the canister), for the lenticular satellite is

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probably low with the packaging procedure shown in figure 14. How low it will be after the detailed satellite design is not known, but the studies to this point indicate that compatibility of the canister with available launch vehicles is no serious problem.
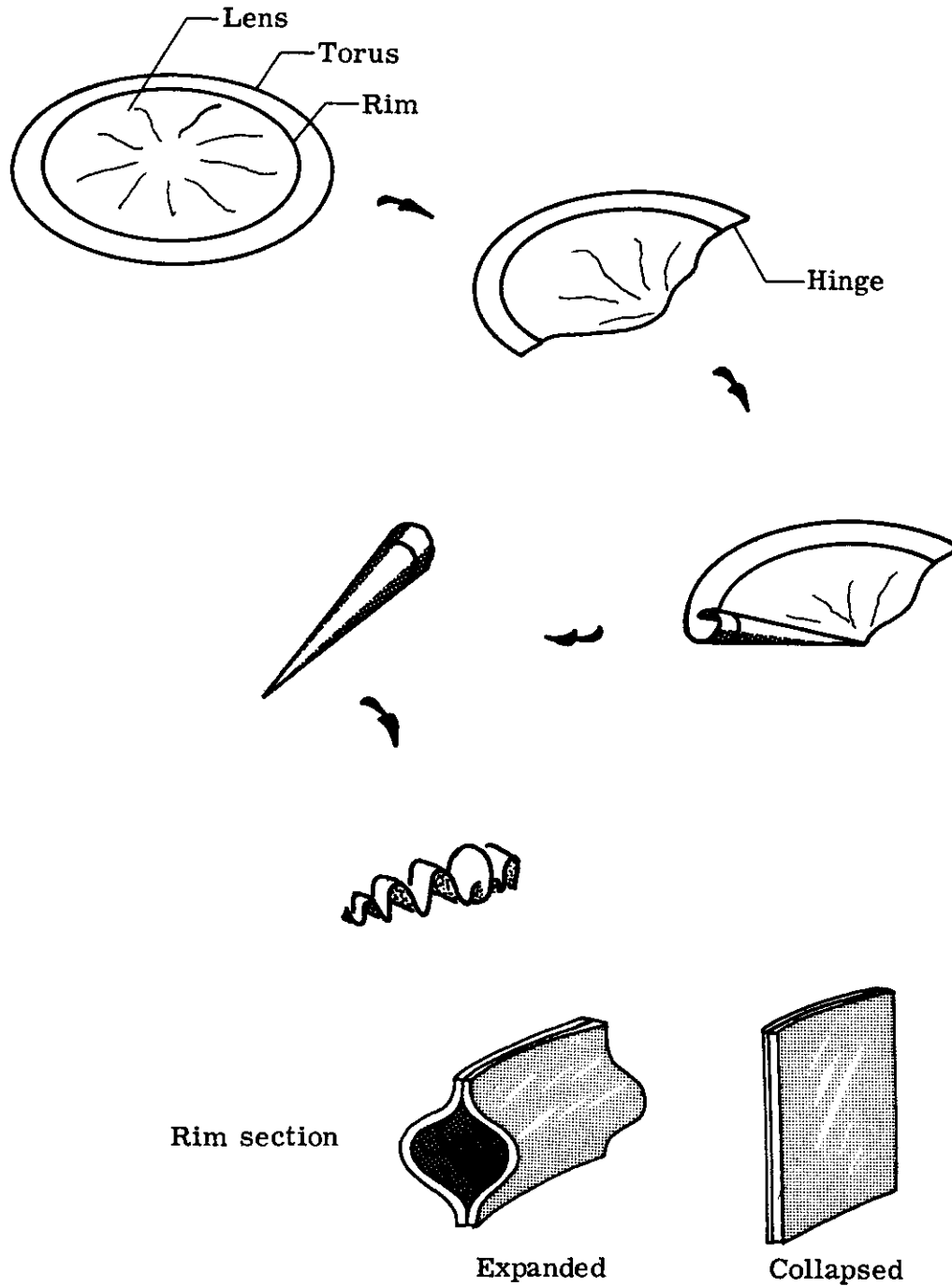
—Lens

—Torus

—Rim

—Hinge

Rim section

Expanded

Collapsed

Figure 14.- Packaging sequence.

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Deployment is accomplished by inflating the torus (fig. 15). The outside torus section is first inflated, and the remaining torus inflation is controlled by diaphragms with orifices built into the torus. Thus the deployment rate and direction are controlled. The rim cross section expands to its rigid condition after torus inflation. Only after the torus is fully deployed and
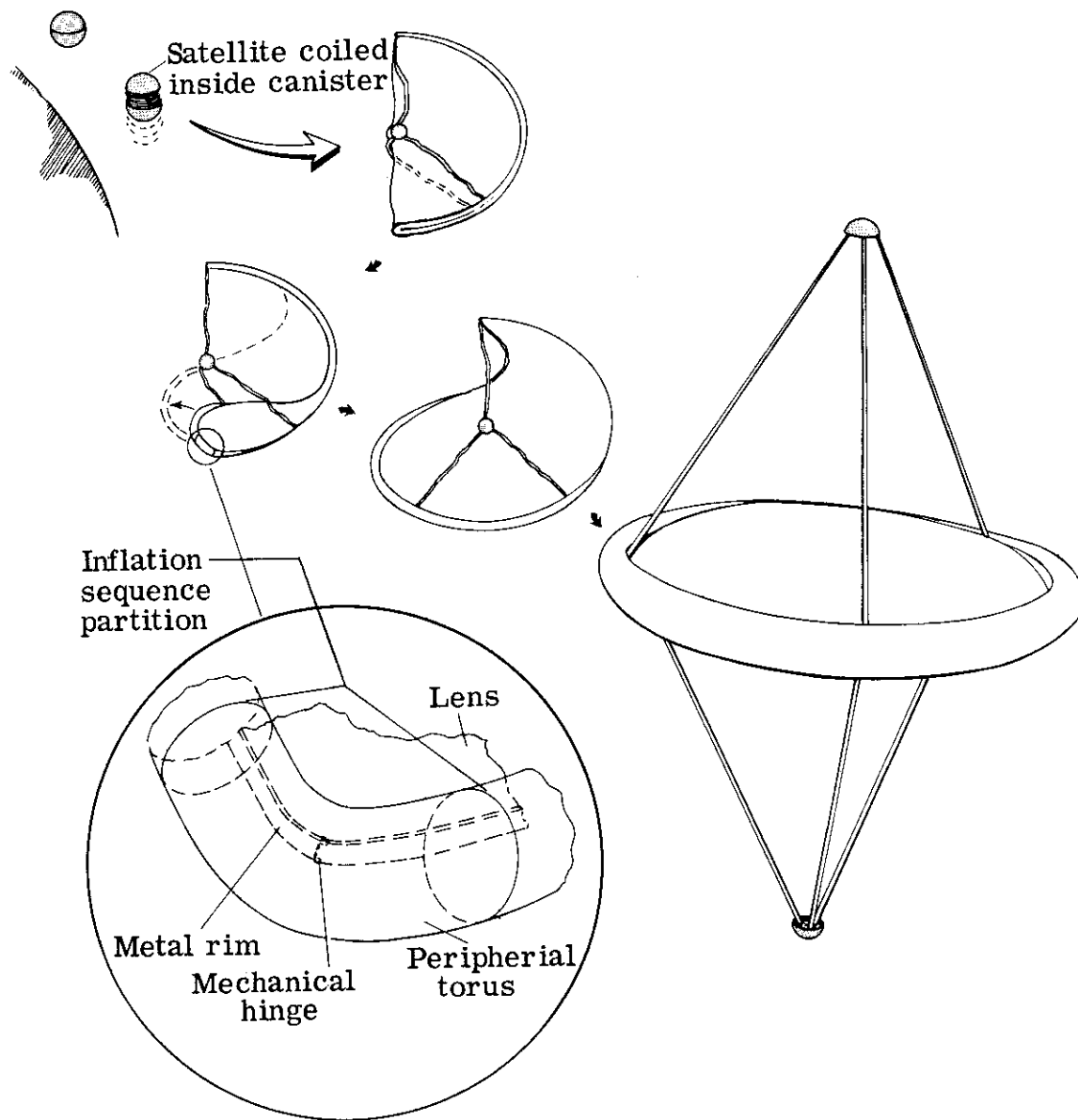

Figure 15.- Deployment sequence.

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inflated does the lens pressurization/rigidization process begin. All inflation is done through the booms. Deflation is accomplished by permeation of the inflation gas, helium, through the materials and through a programed number of holes in the satellite skin.

A series of deployment tests have been conducted at Langley Research Center using 20-foot-diameter lens models. The models were packaged in the canisters and evacuated, and were then successfully deployed in a 60-foot vacuum sphere.

PART IV

LENTICULAR POTENTIAL

The major effort on the lenticular satellite has been, to this point, concerned with the satellite design for a 2000 n.mi. orbital altitude, horizon-to-horizon included angle and a 400-foot sphere equivalent lens. An effort is now under way to expand on this presently available data to determine the effects of variations in these three basic parameters on the satellite's performance and physical characteristics. It should be iterated here also that very little effort has been directed toward optimization of a lenticular satellite, and its potential should not be overlooked. Preliminary studies indicate that the weight of the 2000 n.mi. configuration shown in figure 15 may be reduced by more than 50 percent, still without damaging its communications capabilities.