AERODYNAMIC TORQUE
ON A SPINNING SPHERICAL SATELLITE

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Calculations have revealed that a spinning spherical satellite moving through a rarefied atmosphere experiences precessional torque as well as the expected "slow down torque." The objective of this investigation is to determine the angular displacement of a gyroscopic satellite due to aerodynamics for comparison with the small angular displacement due to a general relativity effect described by Schiff.[1] The analysis has shown that the directional movement of the spin axis due to aerodynamic effect is of such magnitude as to dictate the altitude at which the relativity experiment must be orbited in order to reduce the angular displacement in comparison with the 5 to 7 sec of arc per year expected from the Schiff effect. Also of great importance is the finding that measurements of the satellite spin axis movement due to aerodynamics could be used for accurate determination of the molecular accommodation coefficient in the orbital environment. Studies are being made to determine the best way to utilize this new method to measure the accommodation coefficient under actual orbital conditions. Through the use of various material surfaces, surface temperature, and surface roughness, a series of experiments to study gas-surface interactions could be designed.

A torque about the center of mass of the rotating sphere results from the surface interaction of the rarefied gas molecules. The subject of rarified gas dynamics and surface interactions can be found reviewed in references 2 and 3. In this analysis, the accommodation coefficient (α_d) equals the percentage of impinging molecules that are diffusely reflected. The remaining percentage ($1-\alpha_d$) are specularly reflected from the surface. At the orbital altitudes of interest, the flow is free molecular and the random or thermal motion of the molecules can be neglected in comparison with the orbital velocity of the satellite.[2] Therefore, all the molecules impinge on the surface with an initial velocity equal to the orbital velocity. We also impose the following restrictions; the accommodation coefficient is constant with time and position on the surface, a circular orbit is fixed with respect to inertial space, and a constant atmospheric density for any one given orbit. Although future work will analyze the effect of removing the above assumptions, the results obtained here are a first order approximation of the aerodynamic effects. The evaluation of the aerodynamic effect seems to be similar to the analysis used by the Nam Tum Po[4] for application to a satellite having a large surface area to mass ratio and the equations for torque of both analyses are in agreement; however, we apply the analysis to an entirely different satellite.

The torque caused by gas surface interactions was analyzed by viewing the specularly and diffusely reflected molecules separately. The resultant force due to a specular reflection is normal to the surface. Therefore, for a spherical surface, no torque about the center of mass results from specularly reflected molecules. For the diffusely reflected molecules, we evaluate the torque in the following way. First, the force due to the impingment of the molecule depends on the angle of the surface to the flow and in general causes a torque about the center of mass. Second, we take into consideration the dynamical effect of the reflection. After accommodation to the surface, the molecule is diffusely reflected with a velocity component normal to the surface. This component results in only a normal force as required by the definition of diffuse reflection. However, since the molecules have been accommodated to the surface, each diffusely reflected molecule has also a component of velocity tangent to the surface and equal to the angular velocity of the surface at the point of reflection. Therefore, the diffusely reflected molecules cause a normal force which produces no torque and a tangential force which produces a torque proportional to the angular velocity of the surface at the point of reflection. It is, in fact, this mechanism which produces not only the expected "slow down torque" but also the precessional torque which causes the directional movement of the spin axis.

The coordinate systems to be used in the analysis are shown in Figs. 1 and 2. The X, Y. Z axis is the inertial set with Z toward Polaris and X along the vernal equinox. The x, y, z coordinate system is attached to the orbit with the z axis normal to the orbital plane and the x axis as the ascending node of the orbit. The x_s, y_s, z_s set is attached to the gyro and the x_s axis can be thought of as the line formed where the plane normal to the spin axis intersects the orbital plane. i,j,k, and i_s,j_s,k_s are unit vectors along the x,y,z and x_s, y_s, z_s axes respectively. Also shown in the figures is the gas flow velocity vector which is always in the x,y plane and can be thought to rotate about the center of the satellite

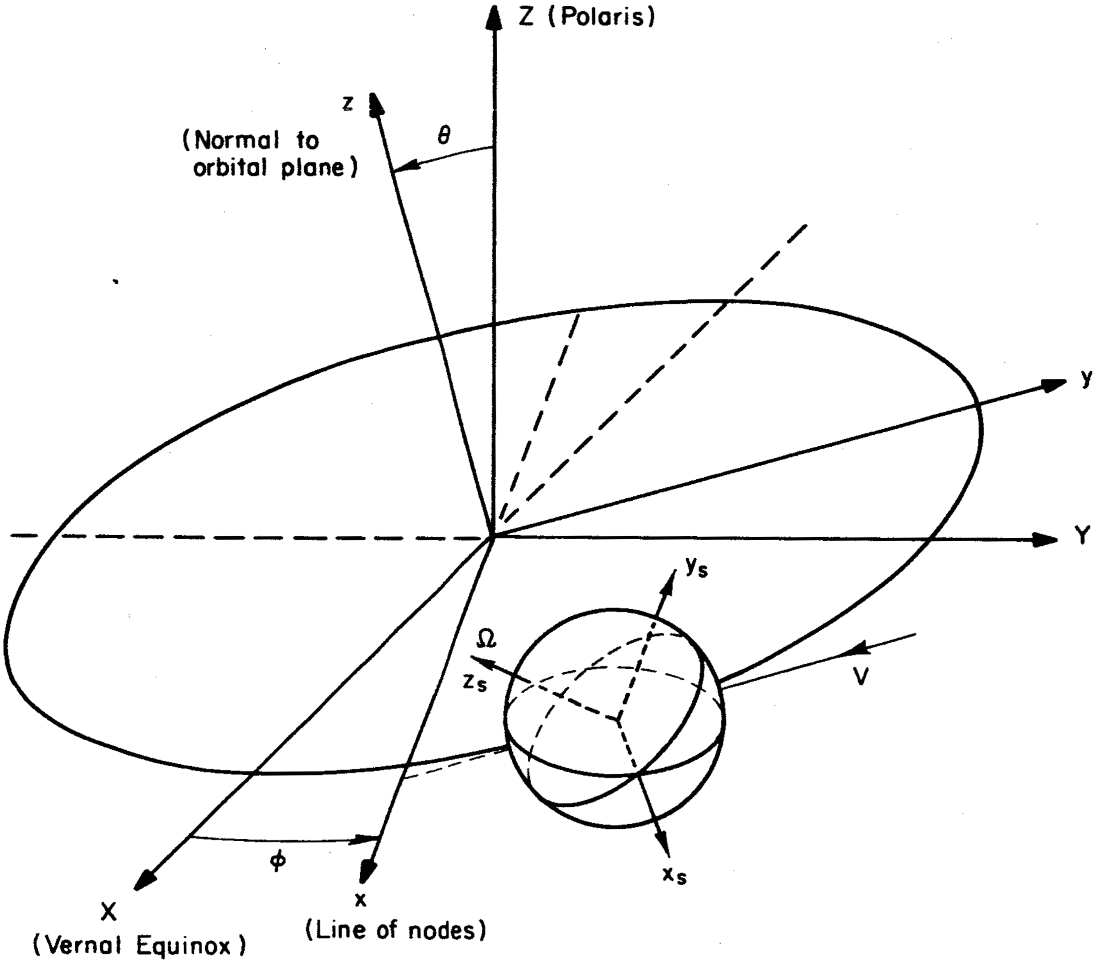

Fig. 1 Arrangement of Co-ordinate Systems

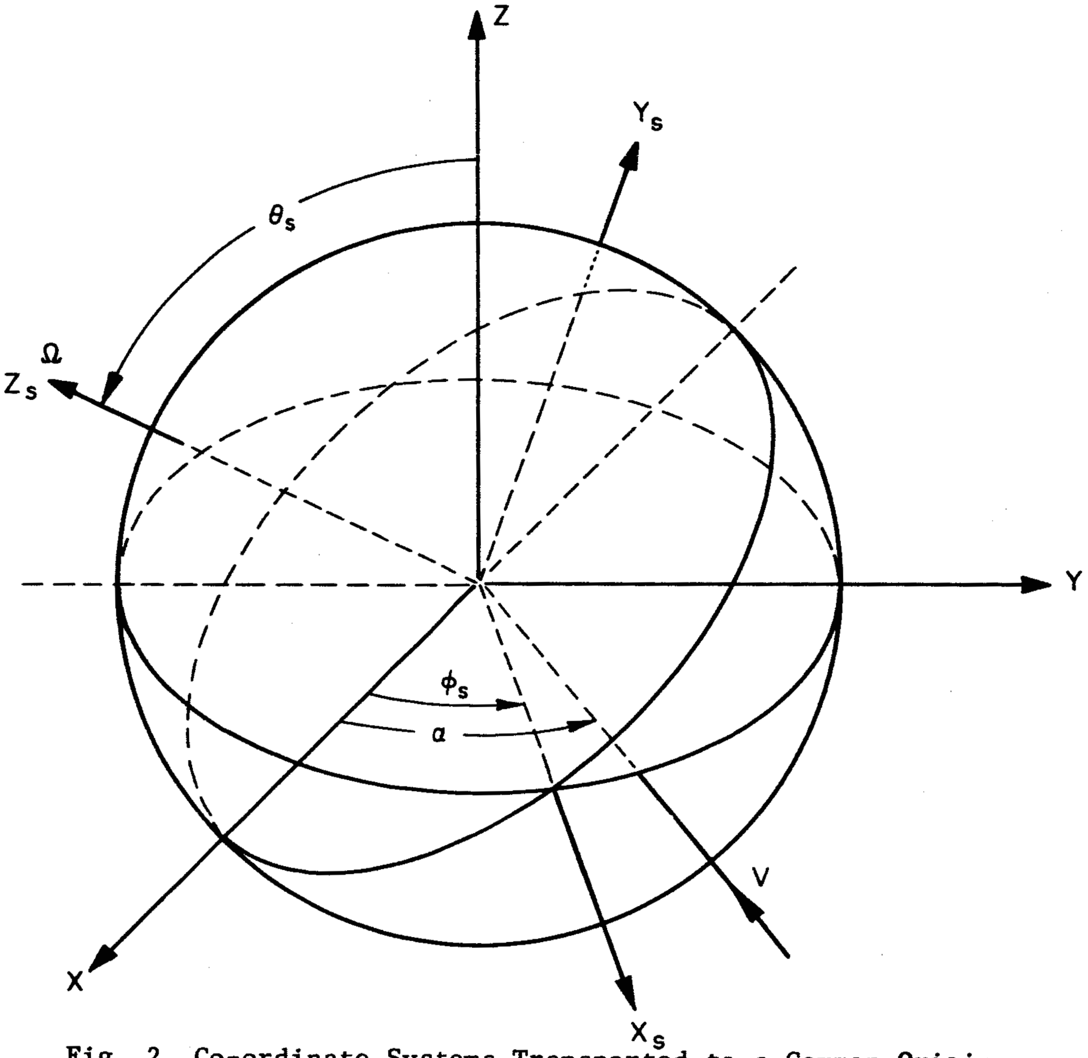

Fig. 2 Co-ordinate Systems Transported to a Common Origin

at the orbital angular velocity. The velocity vector is tangent to the orbital path at all times. Fig. 3 illustrates the spherical coordinate system (η, ξ, R) used to integrate over the surface of the sphere. The angles η and ξ are measured in the x,y,z system. The other angles shown in the figures are defined as follows:

θ_s = angle between satellite spin axis and the normal to orbital plane.

ϕ_s = angle between satellite "line of nodes" and line of nodes of orbit.

θ = angle between the normal to orbital plane and Z axis of the inertial system.

ϕ = angle of nodes of orbit.

α = angle between negative gas flow velocity vector and the orbital line of nodes.

The mass flux of gas molecules impinging upon an element of surface dA is

$$\rho \overline{V} \cdot \overline{n}\, dA$$

where ρ is the atmospheric density at the orbital altitude, $\overline{V}$ is the velocity vector equal to the orbital velocity, and $\overline{n}$ is the normal to the surface area dA.

Since only the diffusely reflected molecules enter in the torque analysis, we ignore the specularly reflected ones. The impinging molecules exert a torque

$$-\ (\overline{R} \times \overline{V})\ \alpha_d\ (\rho \overline{V} \cdot \overline{n}\, dA)\ .$$

The reflecting molecules exert a torque

$$\overline{R} \times (\overline{\Omega} \times \overline{R})\ \alpha_d\ (\rho \overline{V} \cdot \overline{n}\, dA)$$

where $\overline{\Omega}$ is the spin vector of the gyro and $\overline{R}$ is the radius vector to

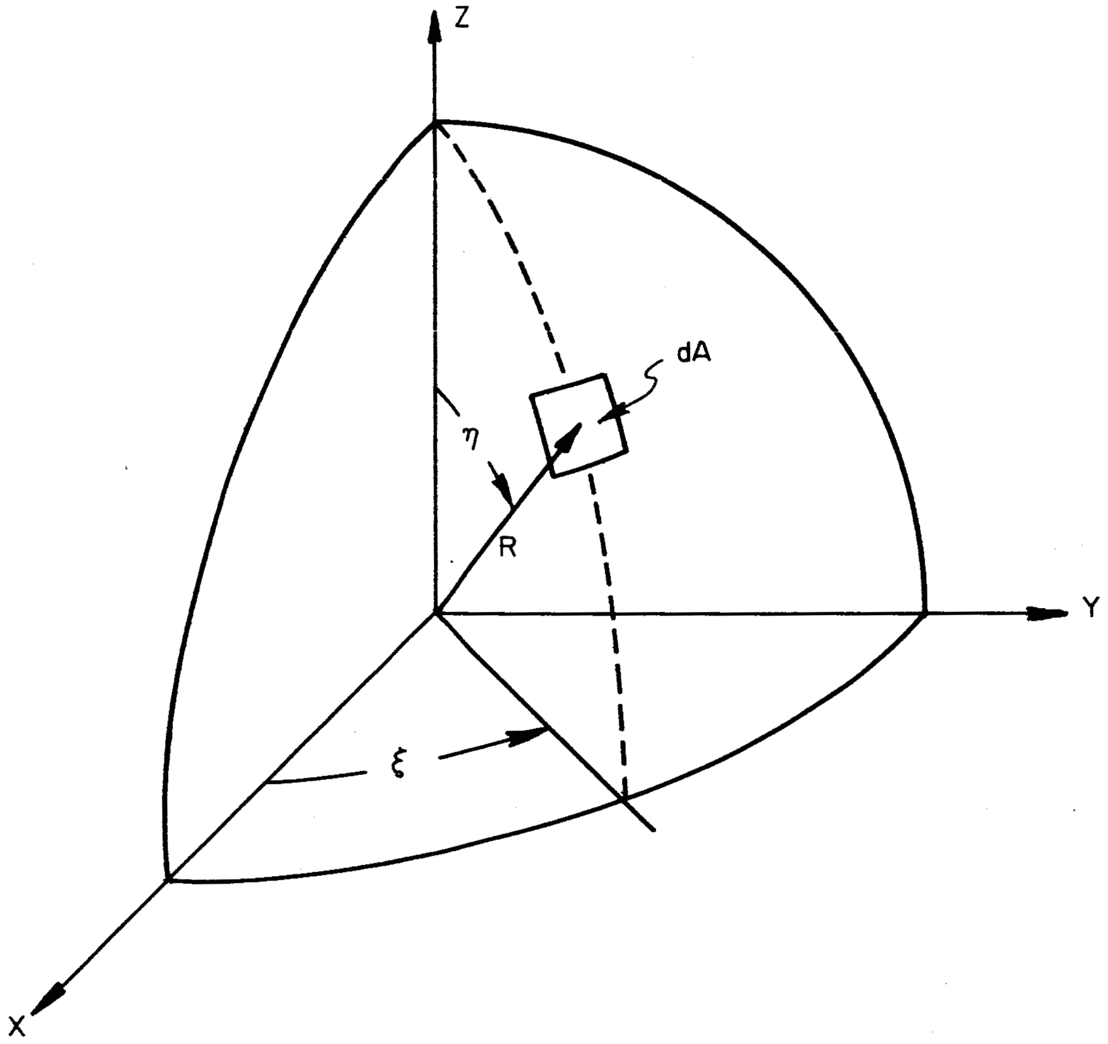

Fig. 3 Co-ordinate System Used for Surface Integration

the surface from the center of mass. The elemental torque $d\bar{L}$ produced by the complete interaction is then the sum of the above expressions, i.e.,

$$d\bar{L} = - \alpha_d \left[\bar{R}\times(\bar{V} - \bar{\Omega}\times\bar{R}) \; (\rho\bar{V} \cdot \bar{n} \; dA)\right] .$$

Referring now to Figs. 2 and 3 we define the following vectors and terms:

$\bar{\Omega} = \Omega k_s = \Omega\sin\theta_s \sin\phi_s \, i - \Omega\sin\theta_s \cos\phi_s \, j + \Omega \cos\theta_s \, k$

$\bar{V} = -V\cos\alpha i - V\sin\alpha \, j$

$dA = R^2 \sin\eta \, d\eta \, d\xi$

$\bar{R} = R\sin\eta\cos\xi \, i + R\sin\eta\sin\xi \, j + R\cos\eta \, k$

R = radius of sphere

$\bar{n} = \sin\eta\cos\xi \, i + \sin\eta\sin\xi \, j + \cos\eta \, k.$

We substitute these vectors into the expression for $d\bar{L}$ and integrate over only the surface area in the velocity stream. This is accomplished by first integrating over η from 0 to π. We then integrate over ξ from $\alpha - \frac{\pi}{2}$ to $\alpha + \frac{\pi}{2}$ because α defines the direction of the velocity vector $\bar{V}$. After integration the instantaneous torque reduces to a function of the angles α, θ_x, and ϕ_s.

$$\begin{aligned}\bar{L} = &-L_o \left[\sin\theta_s \sin\phi_s(\sin^2\alpha + 2) + \sin\theta_s \cos\phi_s(\sin\alpha\cos\alpha)\right]i \\ &+L_o \left[\sin\theta_s \sin\phi_s(\sin\alpha\cos\alpha) + \sin\theta_s \cos\phi_s(\cos^2\alpha + 2)\right]j \\ &+3L_o \left[\cos\theta_s\right]k\end{aligned}$$

where

$$L_o = \alpha_d \frac{\rho V \pi R^4}{4} \Omega .$$

If we now consider the orbit fixed in inertial space, the problem is similar to the classic top or gyro problem where the torque is defined with respect to a nonmoving frame. To find the resulting motion of the spin axis under the action of the above torque, we must first find its components in the x_s, y_s, z_s system. The torque referred to in this system, $\overline{L}_s$, becomes

$$\begin{aligned}\overline{L}_s = {} & L_o[\sin\theta_s \sin\phi_s \cos\phi_s(\cos^2\alpha - \sin^2\alpha) + \sin\theta_s \sin\alpha \cos\alpha \\ & (\sin^2\phi_s - \cos^2\phi_s)]i_s \\ & + L_o[\sin\theta_s \cos\theta_s \cos^2\phi_s(\cos^2\alpha+2) + \sin\theta_s \cos\theta_s \sin^2\phi_s(\sin^2\alpha+2) \\ & + 2 \sin\theta_s \cos\theta_s \sin\phi_s \cos\phi_s \sin\alpha \cos\alpha - 3 \cos\theta_s \sin\theta_s]j_s \\ & + L_o[-2 \sin^2\theta_s \sin\phi_s \cos\phi_s \sin\alpha \cos\alpha - \sin^2\theta_s \cos^2\phi_s(\cos^2\alpha+2) \\ & - \sin^2\theta_s \sin^2\phi_s(\sin^2\alpha+2) - 3 \cos^2\theta_s]k_s\end{aligned}$$

Since the spin rate of the gyro will be much higher than the angular movements of the spin axis, the Euler equations can be simplified by neglecting terms of small magnitude. The movement of the spin axis is then defined by the following:

$$\dot{\theta}_s = - \frac{L_{y_s}}{I\Omega}$$

$$\dot{\phi}_s \sin \theta_s = \frac{L_{x_s}}{I\Omega}$$

where L_{y_s} and L_{x_s} are the y_s and x_s components of torque, respectively, and I is the moment of inertia about the spin axis. Therefore, the angular displacement for any time t becomes

$$\Delta\theta_s = \int_o^t - \frac{L_{y_s}}{I\Omega}\, dt$$

$$\Delta\phi_s = \int_0^t \frac{L_{y_s}}{\sin\theta_s \; I\Omega}\, dt.$$

Now, for a circular orbit $\alpha = \omega_o t$ where ω_o is the constant orbital angular velocity. Therefore,

$$d\alpha = d\omega_o t = \omega_o dt$$

$$dt = \frac{d\alpha}{\omega_o}\ .$$

When t = 0 say $\alpha = 0$ and when t = T = time over which measurements are made, $\alpha = 2n\pi$, where n is the number of completed orbits in the time T. Therefore,

$$\Delta\theta_s = \int_0^{2n\pi} - \frac{L_{y_s}}{I\Omega} \frac{d\alpha}{\omega_o}$$

$$\Delta\phi_s = \int_0^{2n\pi} \frac{L_{x_s}}{\sin\theta_s \; I\Omega} \frac{d\alpha}{\omega_o}\ .$$

Looking now at the expressions for L_{y_s} and L_{x_s} we note that the functions of α are periodic within the range 0 to 2π. We can then express the integrals from 0 to $2n\pi$ as n times the integral from 0 to 2π. Also contained in the expressions for $\dot{\theta}_s$ and $\dot{\phi}_s$ are terms containing the trigonometric functions of θ_s and ϕ_s. However, since the change in θ_s and ϕ_s is small over the time of interest, the trigonometric functions of these angles can be considered constant during integration. Therefore,

$$\Delta\theta_s = \frac{n}{I\Omega\omega_o} \int_0^{2\pi} - L_{y_s}\, d\alpha$$

$$\Delta\phi_s = \frac{n}{\sin\theta_s \; I\Omega\omega_o} \int_0^{2\pi} L_{x_s}\, d\alpha\ .$$

Now,

$$\int_o^{2\pi} L_{x_s} \, d\alpha = 0$$

while

$$\int_o^{2\pi} - L_{y_s} \, d\alpha = \pi L_o \sin \theta_s \cos \theta_s \; .$$

Therefore,

$$\Delta\theta_s = \frac{n\pi L_o}{I\Omega\omega_o} \sin \theta_s \cos \theta_s$$

and the movement of the spin axis is a precession causing the spin axis to move into the plane of the orbit if initially out of the plane. However, no precession exists if the spin axis is initially perpendicular to the orbital plane ($\theta_s = 0$) or if the spin axis is in the orbital plane ($\theta_s = \pi/2$). The maximum value of $\Delta\theta_s$ occurs when $\theta_s = \pi/4$. We now substitute the expression for L_o and note the spin rate Ω is not contained in the result,

$$\Delta\theta_s = \frac{m \, \alpha_d \rho V \; \pi^2 R^4}{8I \; \omega_o} \sin 2\theta_s \; .$$

Now, for a solid sphere made of material density ρ_s, the moment of inertia is

$$I = \frac{8}{15} \rho_s \; \pi R^5 \; .$$

Also, V, the orbital velocity, can be expressed as

$$V = R_o \omega_o$$

where R_o is the radius of the orbit measure from the center of the earth. With these substitutions

$$\Delta\theta_s = n\alpha_d \frac{15\pi}{64} \frac{\rho}{\rho_s} \frac{R_o}{R} \sin 2\theta_s \ .$$

The final expression is seen to be a function of various parameters but only two, ρ and θ_s, are of any importance in reducing or increasing $\Delta\theta_s$. If $87^o < \theta_s < 93^o$ (the spin axis between $\pm 3^o$ of the orbital plane), $\Delta\theta_s$ is reduced by an order of magnitude of its maximum value at $\theta_s = \pi/4$. The effect of atmospheric density is best illustrated by choosing, as a basis for calculation, a solid glass sphere of one foot diameter and take $\alpha_d = 1$, $\theta_s = \pi/4$. Therefore,

$$\rho_s = 2.2 \times 10^3 \text{ kg/m}^3$$

$$R = 1/2 \text{ ft} = 1.5 \times 10^{-1} \text{m} \ .$$

With these constants, we plot $\frac{\Delta\theta_s}{\alpha \sin 2\theta}$ versus altitude for a one year experiment. The maximum atmospheric density occuring during an average sunspot cycle[5] was used at the given altitude. (See Fig. 4)

Through the range of altitude from 100 to 1000 miles, the density decreased by six orders of magnitude. The effect of other parameters is small compared to this, and the angular displacement then also decreases by many orders of magnitude as seen in the plot. By using a 500-mile or higher orbit and retaining the spin axis within $\pm 3^o$ of the plane of the orbit, the angular displacement can be kept an order of magnitude less than the Schiff effect.[1] On the other hand, an orbit below 300 miles will cause the aerodynamic effect to dominate and afford accurate determination of the accommodation coefficient.

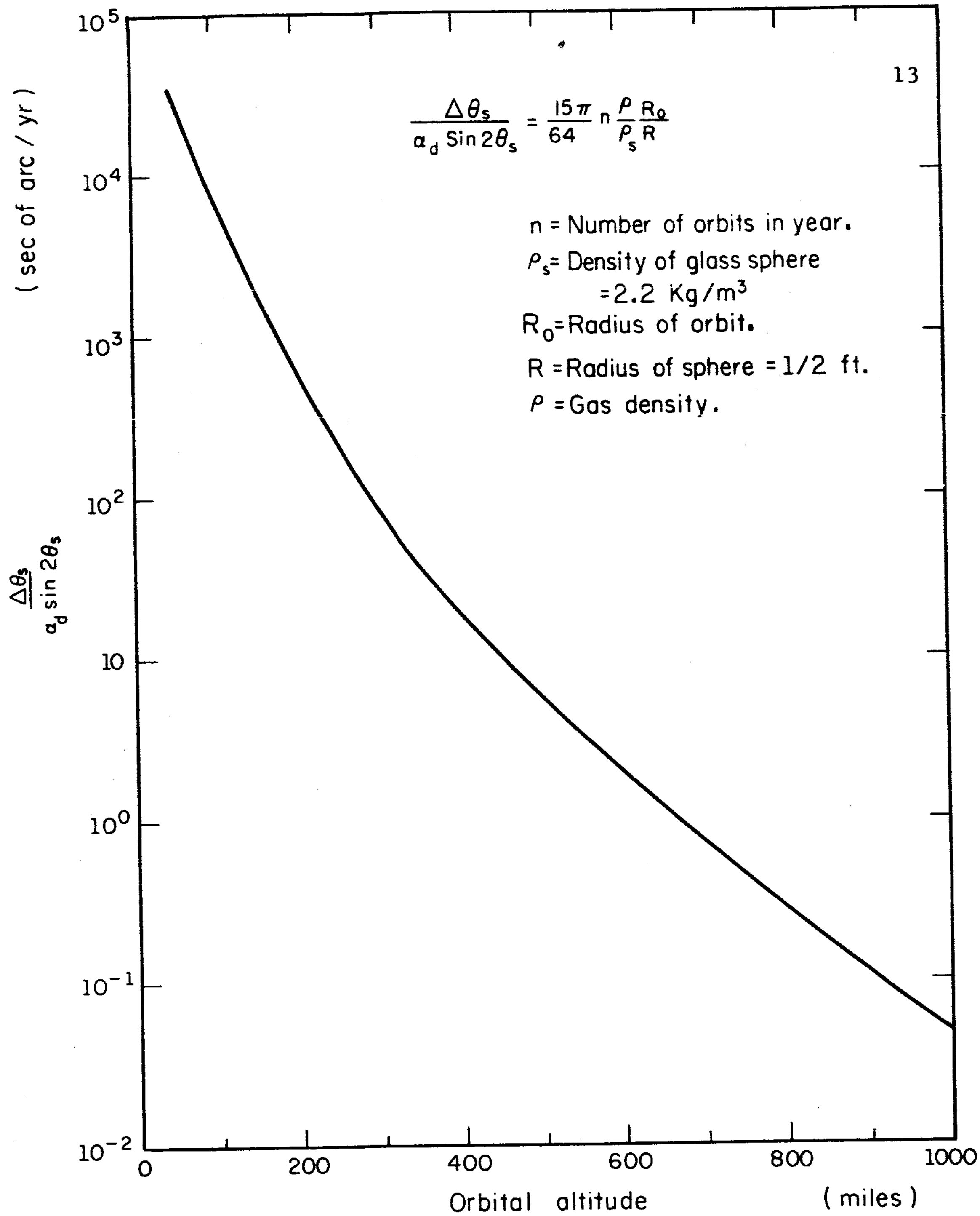

Fig. 4 Results of Analysis; $\frac{\Delta\theta_s}{\alpha_d \sin 2\theta}$ vs Altitude

To measure the accommodation coefficient we merely find the ratio between the measured $\Delta\theta_s$ to the calculated $\Delta\theta_s$ with $\alpha_d = 1$. This ratio is equal to the actual α_d for the satellite which will range from zero to unity. This illustrates basically how the accommodation coefficient could be measured under actual orbital conditions. The accuracy of the measurement would depend on the accuracy with which the other parameters could be measured. Of those parameters, the atmospheric density (ρ) is the least accurate. However, θ_s will be known to a sec of arc by the method proposed by the Coordinated Science Laboratory[6] and the other parameters (ρ_s, R, R_o, and n) can be measured to at least one part in one thousand. Therefore, accommodation coefficient could be made to at least one part in one hundred. At the lower altitudes, this accuracy could be realized in a time much less than a year.

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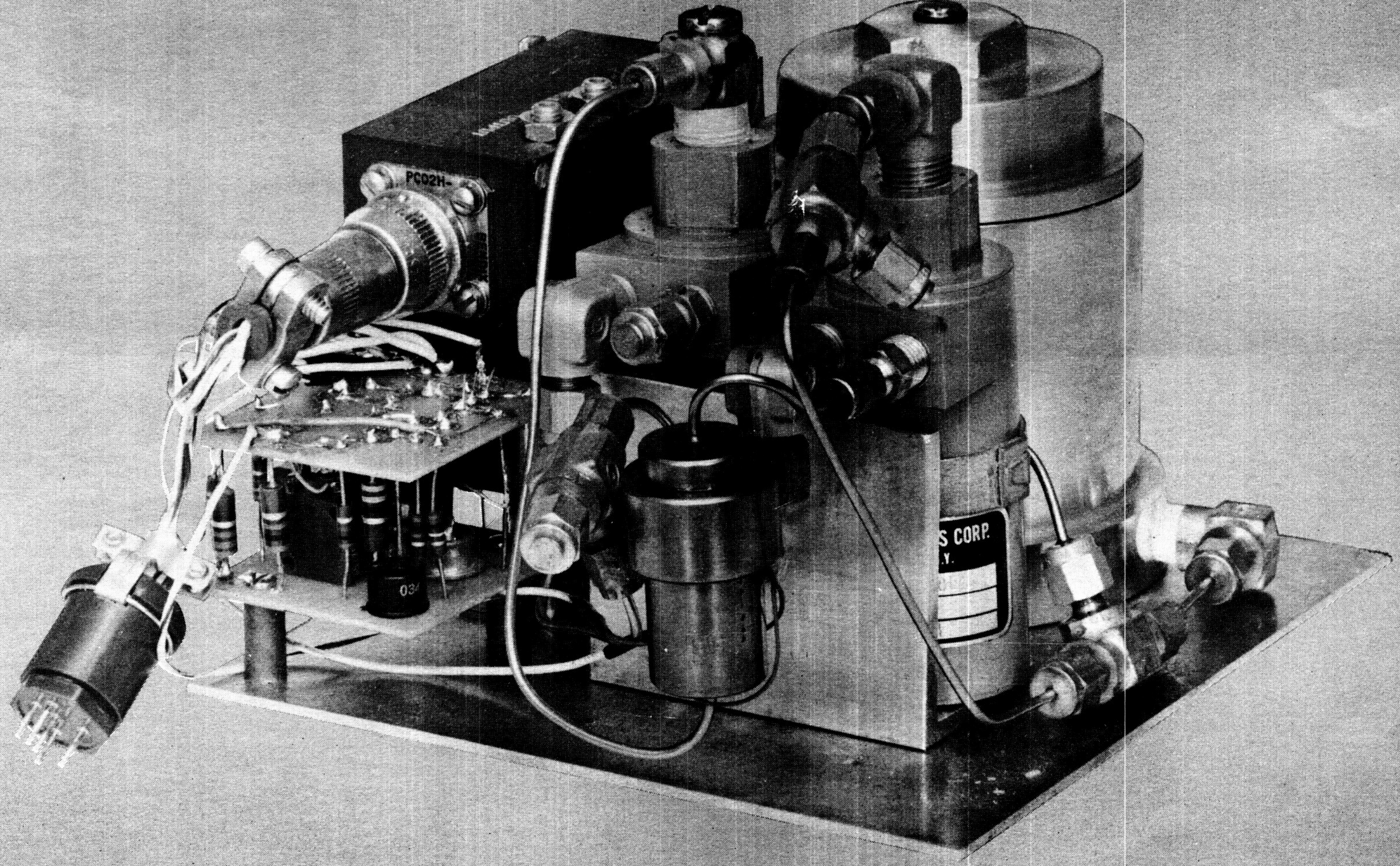

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13. ABSTRACT

Calculations have revealed that a spinning spherical satellite moving through a rarefied atmosphere experiences precessional torque as well as the expected "slow down torque." The objective of this investigation is to determine the angular displacement of a gyroscopic satellite due to aerodynamics for comparison with the small angular displacement due to a general relativity effect described by Schiff. The analysis has shown that the directional movement of the spin axis due to aerodynamic effect is of such magnitude as to dictate the altitude at which the relativity experiment must be orbited in order to reduce the angular displacement in comparison with the 5 to 7 sec of arc per year expected from the Schiff effect. Also of great importance is the finding that measurements of the satellite spin axis movement due to aerodynamics could be used for accurate determination of the molecular accommodation coefficient in the orbital environment. Studies are being made to determine the best way to utilize this new method to measure the accommodation coefficient under actual orbital conditions. Through the use of various material surfaces, surface temperature, and surface roughness, a series of experiments to study gas-surface interactions could be designed.

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