ATTITUDE DRIFT ANALYSIS FOR THE WIND AND POLAR MISSIONS

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Abstract

The spin axis attitude drift due to environmental torques acting on the Global Geospace Science (GGS) Interplanetary Physics Laboratory (WIND) and the Polar Plasma Laboratory (POLAR) and the subsequent impact on maneuver planning strategy for each mission is investigated. A brief overview of each mission is presented, including mission objectives, requirements, constraints, and spacecraft design. The environmental torques that act on the spacecraft and the relative importance of each is addressed. Analysis results are presented that provided the basis for recommendations made pre-launch to target the spin axis attitude to minimize attitude trim maneuvers for both spacecraft their respective mission lives. It is presented that attitude drift is not the dominate factor in maintaining the pointing requirement for each spacecraft. Further, it is presented that the WIND pointing cannot be met past 4 months due to the Sun angle constraint, while the POLAR initial attitude can be chosen such that attitude trim maneuvers are not required during each 6 month viewing period.

INTRODUCTION

This paper investigates the attitude drift due to environmental disturbance torques on the Global Geospace Science (GGS) Interplanetary Physics Laboratory (WIND) and the Polar Plasma Laboratory (POLAR) spacecraft during routine mission conditions. Spin axis attitude drift due to environmental disturbances will be predicted and compared against mission requirements to determine the attitude control strategy required. A portion of this work is the compilation of several analysis memoranda prepared from November, 1991 to January, 1996. These memoranda were prepared by Computer Sciences Corporation (CSC) under the direction of the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) Flight Dynamics Division (FDD)(References 1-5).

MISSION OVERVIEW AND SPACECRAFT DESCRIPTION

The GGS program is part of the overall International Solar Terrestrial Physics (ISTP) program which will use multiple spacecraft in complementary orbits to assess processes in the Sun-Earth interaction chain. The two specific objectives to be accomplished by the GGS portion are investigations of the solar wind-magnetosphere coupling and the global magnetosphere energy transport. These include: solar wind source and 3-D features, global plasma storage flow and transformation, deposition of energy into the atmosphere, and basic plasma states and characteristics. Both spacecraft have a common design heritage and have been constructed by Lockheed Martin Corporation (formerly the Astrospace Division of General Electric) to be spin stabilized cylindrical spacecraft about 2.44 meters in diameter and 1.85 meters tall. The individual WIND and POLAR missions are presented below.

WIND

The nominal WIND spacecraft attitude is South Ecliptic Normal, with the spin axis aligned within 1 degree of the South Ecliptic Pole and the spin rate is 20 revolutions per minute (rpm). The Sun angle is constrained to be 89.65 to 91 degrees, measured from the +Z-axis, due to thermal considerations. The initial spacecraft orbit is a dayside double lunar swingby that will require about 2 years to traverse. This is followed by an insertion into a halo orbit about the Sun-Earth libration point (L_1). Orbit maneuvers will occur at regular intervals throughout the mission. Attitude maneuvers will consist of trim maneuvers as necessary. The WIND spacecraft, shown in Figure 1, was launched in November 1994.

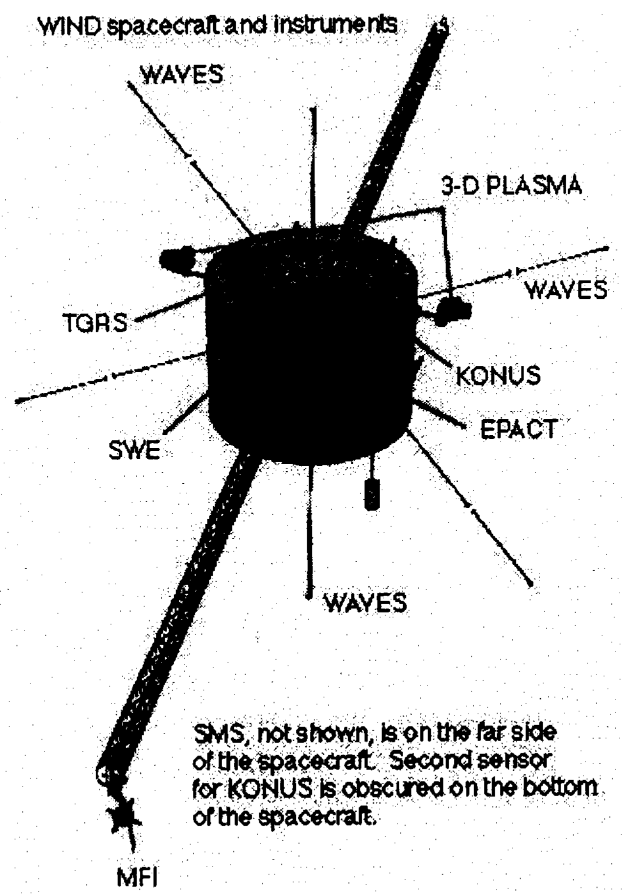

Figure 1: WIND Spacecraft

POLAR

In the normal mission mode, POLAR will point its spin axis within 1 degree of ± orbit normal, and will maintain a spin rate of 10 rpm. The selection of ± orbit normal is based on a Sun angle constraint of 90 to 160 degrees from the +Z-axis due to power and thermal needs. The nominal POLAR orbit is 1.8 X 9.0 Earth Radii (Re) with an inclination of 86 degrees. Upon reaching the mission orbit, no other orbit maneuvers are required, however, 180 degree attitude maneuvers will be performed every 6 months in order to maintain the Sun angle constraint. The minimization of attitude trim maneuvers between reorientation maneuvers is desirable in order to save fuel to increase mission life. The POLAR spacecraft, shown in Figure 2, was launched in February 1996.

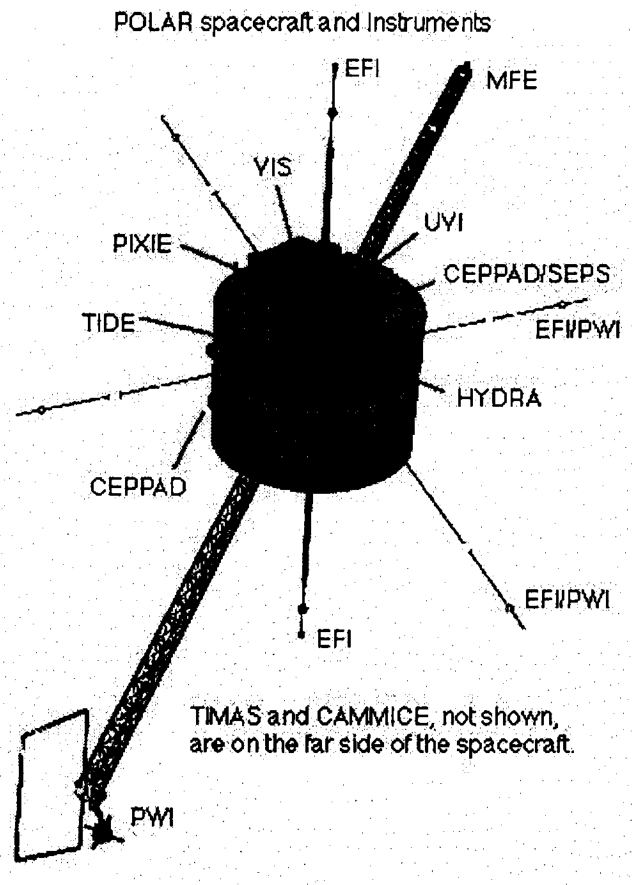

Figure 2: POLAR Spacecraft

ENVIRONMENTAL TORQUES

The WIND and POLAR spacecraft main bodies are modeled as simple right circular cylinders. The booms on WIND were also considered for their effect on the center of pressure (Reference 6). The spacecraft spin axis (+Z-axis) is assumed to lie along the principal axis, as does the location of the center of mass. Therefore, there is no nutation or coning. The environmental disturbance torques considered for the spacecraft are solar radiation pressure, Earth gravity gradient, and magnetic dipole moment.

Solar Pressure Torque

The center of pressure for a right circular cylinder is located at the volume centroid. The total force due to solar radiation can be assumed to act at the center of pressure, which lies along the principal axis. Therefore, the lever arm from the center of mass to the center of pressure also lies along the principal axis. Under the assumptions stated, the solar pressure torque is always perpendicular to the spin axis, and, thus, the spin rate is unchanged.

The force on a right circular cylinder is given in Reference 7 as:

$$\vec{F} = -P(\{[\sin\beta(1+\frac{1}{3}C_s)+\frac{\pi}{6}C_d]A_1 + (1-C_s)\cos\beta A_2\}\hat{S}$$

$$+[(-\frac{4}{3}C_s\sin\beta - \frac{\pi}{6}C_d)\cos\beta A_1 + 2(C_s\cos\beta + \frac{1}{3}C_d)\cos\beta A_2]\hat{A})$$

where:

$A_1 = 2rh$

$A_2 = \pi r^2$

$P \approx 4.5X10^{-6}$ N / m^2 = solar mean momentum flux

r = radius of the cylinder (48 inches for each spacecraft)

h = height of the cylinder (73 inches for each spacecraft)

$\hat{S}$ = unit vector from spacecraft to Sun

$\hat{A}$ = spacecraft spin axis (+Z - axis for each spacecraft)

β = Sun angle

C_s = probability that radiation is reflected specularly (16.9%)

C_d = probability that radiation is reflected diffusely (8.5%)

C_a = probability that radiation is absorbed (74.6%)

and $C_a + C_d + C_s = 1$

The above equation is good for Sun angles less than or equal to 90 degrees, but only minor changes are required for Sun angles greater than 90 degrees. In addition, the relationship between the radiation reflection and absorption probabilities was used to eliminate the coefficient of absorption, C_a, from the equation. The torque on the spacecraft then is :

$$\vec{N}_{sp} = (\vec{R}_{cp} - \vec{R}_{cm}) \times \vec{F}$$

where:

$\vec{R}_{cp} - \vec{R}_{cm}$ = vector from the center of mass of the spacecraft to the center of pressure

Gravity Gradient Torque

The gravity gradient torque for a spacecraft, assuming that the center of mass is at the geometric center of the body, is given in Reference 7 as:

$$\vec{N}_{GG} = \frac{3\mu}{R_s^3}[\hat{R}_s \times (I \cdot \hat{R}_s)]$$

where:

R_s = geocentric position vector of the origin of the body reference system

I = moment of inertia tensor

For a spinning spacecraft, it is convenient to average the torque of one rotation period. Let the spin axis be the Z-axis and the spin rate ω. The body coordinate system at time t can be expressed at $t = 0$ as:

$$\hat{X} = \cos\omega t\hat{X}_0 + \sin\omega t\hat{Y}_0$$
$$\hat{Y} = -\sin\omega t\hat{X}_0 + \cos\omega t\hat{Y}_0$$
$$\hat{Z} = \hat{Z}_0$$

The unit vector $\hat{R}_s$ can be written as:

$$\hat{R}_{s1} = \hat{R}^0{}_{s1}\cos\omega t + \hat{R}^0{}_{s2}\sin\omega t$$
$$\hat{R}_{s2} = -\hat{R}^0{}_{s1}\sin\omega t + \hat{R}^0{}_{s2}\cos\omega t$$
$$\hat{R}_{s3} = \hat{R}^0{}_{s3}$$

The instantaneous gravity gradient torque is averaged over one spin period to obtain

$$\vec{N}_{GG_s} = \frac{1}{2\pi}\int_0^{2\pi}\vec{N}_{GG}d\theta$$

substitution, then provides the spin-averaged gravity gradient torque as:

$$\vec{N}_{GG_s} = \frac{3\mu}{R_s^{\,3}}\left[I_{zz} - \left(\frac{I_{xx}+I_{yy}}{2}\right)\right](\hat{R}_s\cdot\hat{Z})(\hat{R}_s\times\hat{Z})$$

Magnetic Disturbance Torque

Magnetic disturbance torques are a result of the interaction of the residual magnetic field surrounding the spacecraft with the geomagnetic field. As described in Reference 7, the primary sources of magnetic disturbance torques are the spacecraft magnetic moments, eddy currents, and hysteresis. The magnetic moment is the dominant source of magnetic disturbance torques, and it is the only one considered here. The instantaneous magnetic disturbance torque is:

$$\vec{N}_{mag} = \vec{m}\times\vec{B}$$

where:

$\vec{m}$ = effective magnetic moment ($\mathrm{A\cdot m^2}$)

$\vec{B}$ = geocentric magnetic flux density ($\mathrm{Wb/m^2}$)

EQUATIONS OF MOTION

The total disturbance torque then is the sum of the solar pressure, gravity-gradient, and magnetic moment torques discussed above. The attitude equations of motion are simply:

$$\frac{d\vec{L}}{dt} = \vec{N}_{total}$$

where $\vec{L}$ is the spacecraft angular momentum vector in the inertial frame. There is assumed to be no nutation, so the spin axis, and the angular momentum vector will remain along the Z-axis.

RESULTS

WIND

Due to the nature of the WIND orbit, only solar pressure torques were considered. The analysis indicated that the attitude drift would not exceed 0.8 degrees over a 180 day period. In fact, the attitude drift caused by solar pressure only was such that the spacecraft spin axis would sweep out a path that almost closes upon itself at the end of one year, and the angular distance from the target attitude would not exceed 1 degree. Therefore, the 1 degree control box could be maintained without using attitude trim maneuvers by selecting the proper initial attitude. A closer examination of the Sun angle requirement to maintain the Sun angle between 89.65 and 91.0 degrees was then performed. A set of representative attitudes were examined for both attitude drift and change in Sun angle over time. The change in Sun angle was found to be such that the constraint was violated within at most 4 months, and subsequent flight data has confirmed this result.

Operationally, WIND is required to perform orbit maneuvers to maintain proper targeting to make the most efficient use of the double lunar swingby trajectory. For efficiency of operations planning, attitude maneuvers, if required, are designed to immediately follow the orbit maneuvers. Whenever possible, the spin axis attitude is trimmed such that a subsequent attitude trim burn is not required prior to another orbit maneuver. During the long phases of the outer loops of the double lunar swingby, the effect of the Sun angle change dictates the need for attitude trims without an accompanying orbit maneuver.

POLAR

The POLAR mission has an obvious interest in fuel conservation, since the mission lifetime is dictated by the ability to perform 180 degree attitude reorientation every 6 months. The less fuel used to maintain the 1 degree attitude pointing requirement, the longer the mission life. Since POLAR is in an Earth orbit, albeit a highly elliptical one, gravity gradient and magnetic moment disturbance torques were considered along with the solar pressure torque. A residual magnetic moment of $1\ \mathrm{A} \cdot \mathrm{m}^2$ was used based on manufacturer analysis (Reference 6).

The spacecraft manufacturer examined the effect of each of the disturbance torques individually, then combined the results to form a worst case. The result of that worst case indicated that there would be cases in which the spacecraft attitude constraint could not be maintained over the 6 month period between attitude maneuvers. The FDD then analyzed the effect of the three disturbance torques acting simultaneously. Since each torque is a function of the spacecraft attitude, any attitude changes will affect the magnitude and direction of subsequent torques acting on the spacecraft. Therefore, the approach was expected to produce different results than those provided by the manufacturer. The maximum attitude drift over a 6 month period was determined to be about 0.4 degrees for the disturbance torques considered. As was the case for WIND, the attitude control box could be maintained without attitude maneuvers when only the disturbance torques were considered.

The requirement for POLAR is to maintain the attitude within 1 degree of the orbit normal. What if the orbit normal is moving? The drift of the orbit normal due to orbit perturbations was examined. The Keplerian elements and force models used to create a representative ephemeris are presented in Table 1. The effect of orbit normal drift is illustrated in Figure 3. The orbit normal at the epoch points out of the page at the center of the plot. The subsequent orbit normal calculated for each day of the next 6 months is projected onto the initial orbit plane. The circle indicates a 1 degree separation from the original orbit normal. The result determined was that the orbit normal will move about 2.0 degrees over a 6 month period. In light of this result, the combination of orbit normal drift and attitude drift due to the application of external disturbance torques was next examined to determine if it is possible to maintain the 1 degree attitude constraint without performing attitude trim maneuvers between the reorientation maneuvers.

Table 1: POLAR Orbit Elements

Orbit Element	Value
Epoch	3/21/96 11:04:42
Semimajor axis	34483.62918 kilometers
Eccentricty	0.6577685
Inclination	86.248803 degrees
Right ascension of the ascending node	3.55071 degrees
Argument of Perigee	288.89277 degrees
Mean Anomaly	221.01808 degrees
Spacecraft area	4.8 square meters
Spacecraft mass	1112.0 kilograms
Solar radiation pressure	ON
Sun/Moon perturbations	ON
Earth geopotential model	JGM-2 4x4

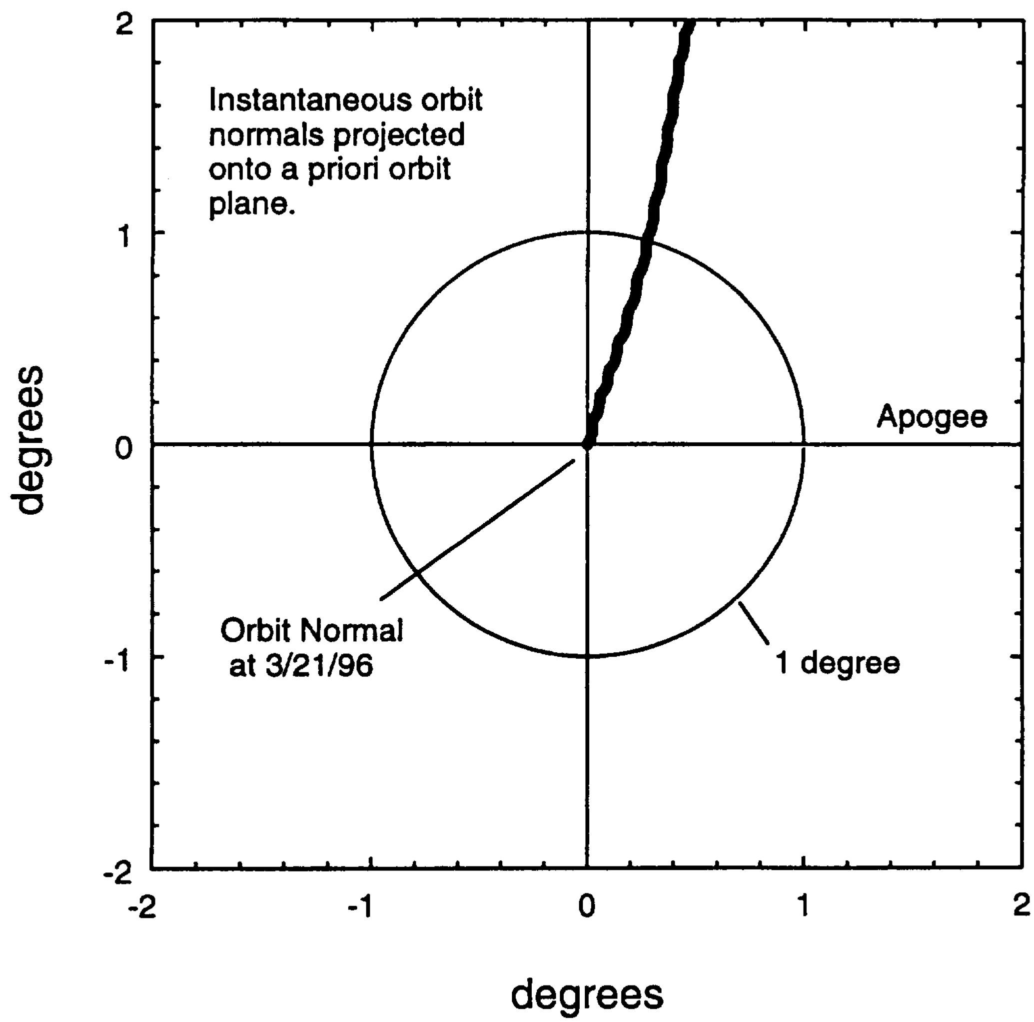

Figure 3: POLAR Orbit Drift from 3/21/96 through 9/21/96

The equation of motion presented previously was integrated numerically, using the parameters presented in Table 2, and with the initial attitude that of the orbit normal vector at time 0, 60, 70, 80, 85, 90, 95, and 100 days since epoch. Figure 4 illustrates the effect of combining the orbit normal drift with the attitude drift due to the disturbance torques. In this case, the initial attitude is aligned with the orbit normal vector at the beginning of the investigation.

Table 2: Input Parameters for Attitude Propagation

Parameter	Value
Moments of inertia	I_{xx} = 3290.988 kg-m^2 I_{yy} = 3805.400 kg-m^2 I_{zz} = 5974.542 kg-m^2
Spin rate	10 rpm
Spacecraft radius	1.2192 m
Spacecraft height	1.8542 m
Distance from center of mass to center of pressure	-0.3048 m
Coefficient of specular reflection	16.9%
Coefficient of diffuse reflection	8.5%
Spacecraft residual magnetic dipole moment	1.0 ATM^2

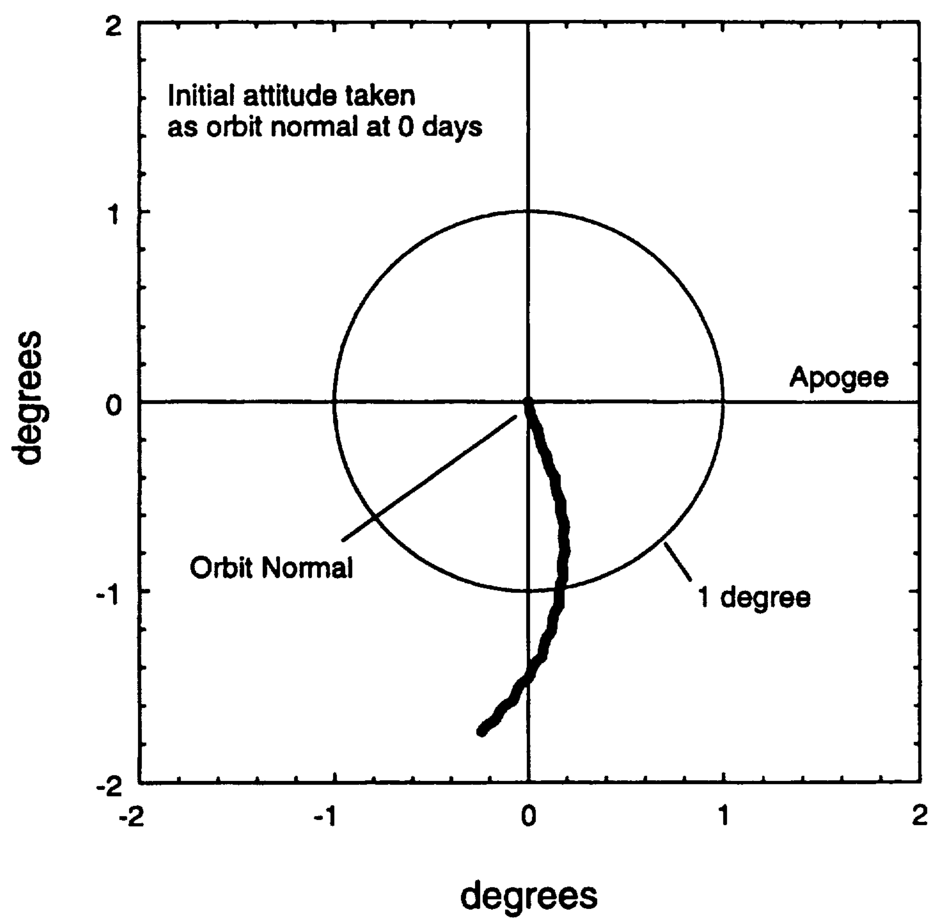

Figure 4: Attitude Drift Projected onto Instantaneous Orbit Plane
Initial Attitude is the Orbit Normal at 0 days from Epoch

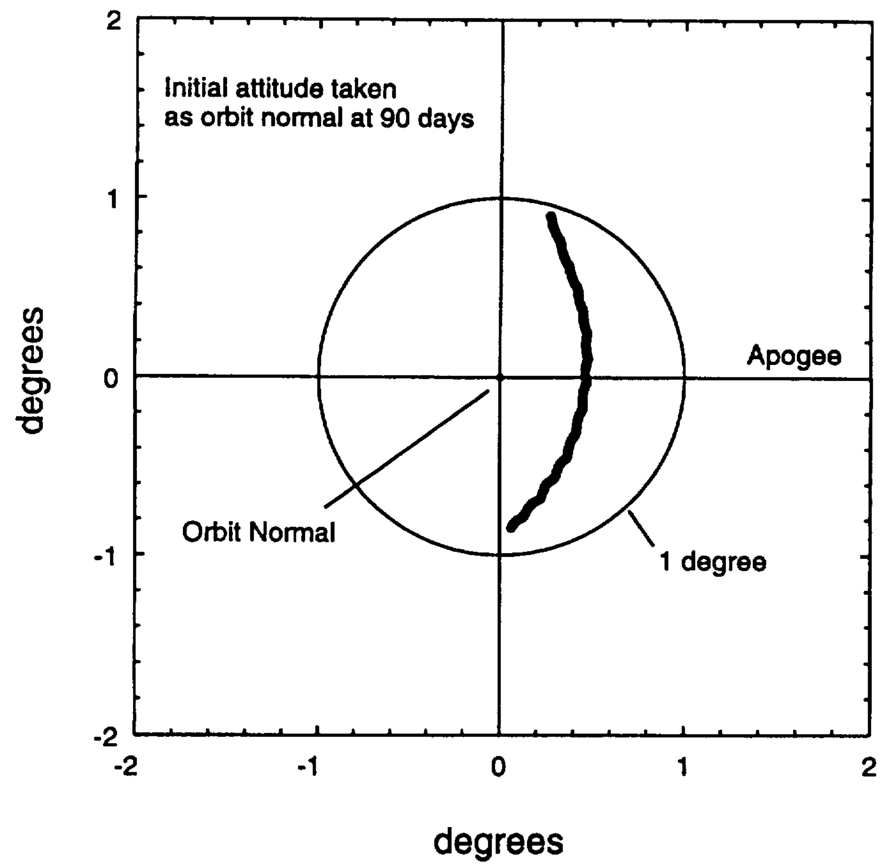

Figure 5: Attitude Drift Projected onto Instantaneous Orbit Plane
Initial Attitude is the Orbit Normal at 90 days from Epoch

As illustrated in Figure 5, by selecting the initial attitude to be aligned with the orbit normal vector at 90 days into the investigation, it is possible to maintain the 1 degree pointing requirement. In Figure 4, the requirement was violated about midway through the investigation. Figure 6 presents the maximum separation angles between the instantaneous orbit normal and the attitude vector over the 6 month period for each of the cases examined. The figure indicates that for this particular period, the maximum separation angle between the attitude vector and the orbit normal vector would occur when the initial attitude is selected to align with the orbit normal at about 86 days from epoch.

The relative importance of the individual torques was also examined. In Figure 7, the attitude drift is plotted for the case of the initial attitude chosen to coincide with the orbit normal vector at 90 days. The attitude drift is calculated for the three following cases: no external torques applied, torque due to solar radiation pressure only, and torque due to solar radiation, magnetic moment, and gravity gradient. As expected, solar radiation pressure is the dominant environment disturbance torque, although the effect of the orbit normal drift is the most important aspect to consider when devising a strategy to maintain the attitude pointing constraint.

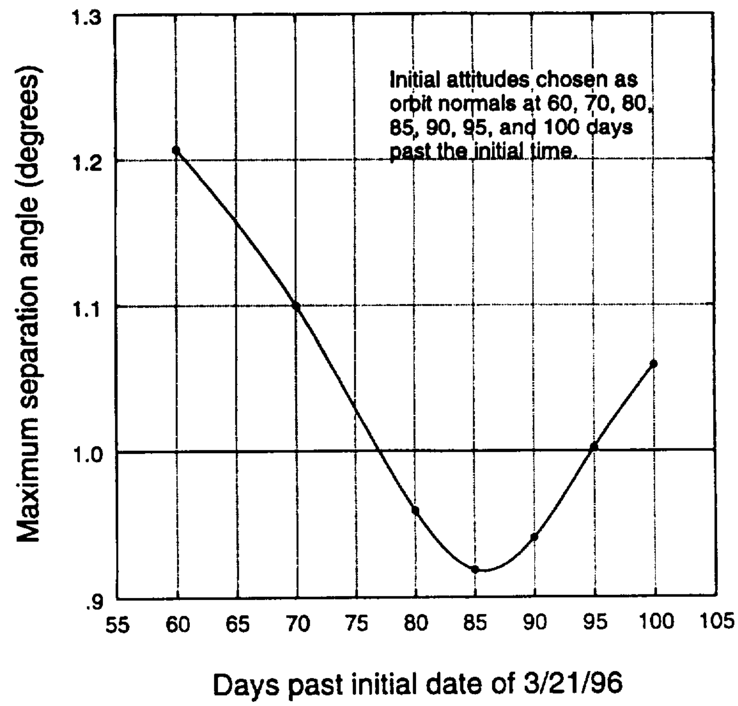

Figure 6: Maximum Separation Angle Between Attitude and Orbit Normal

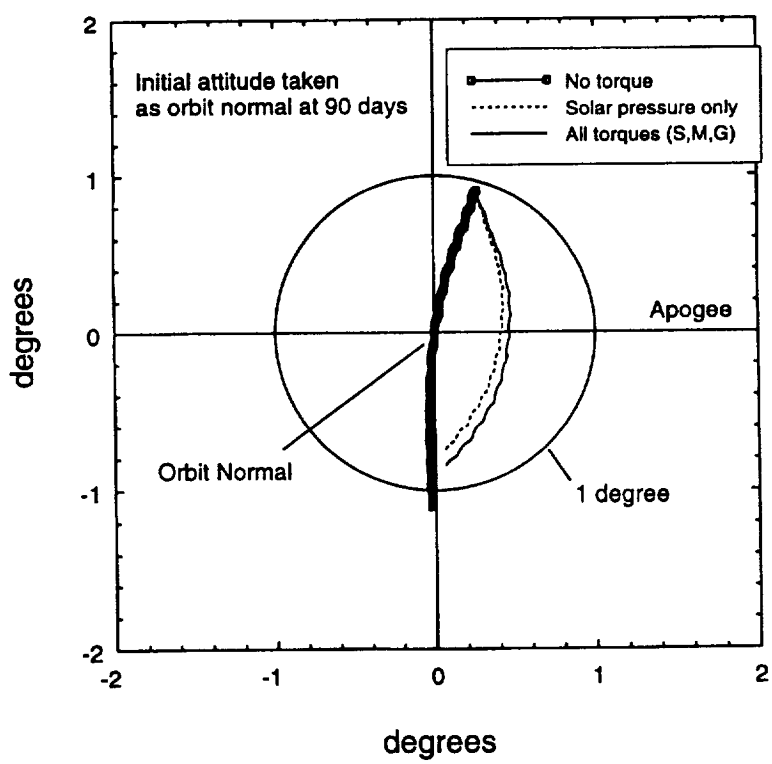

Figure 7: Relative Effect of the Disturbance Torques

CONCLUSIONS

The attitude drift for due to environmental disturbance torques was examined for both the WIND and POLAR spacecraft. It was determined that the drift due to environmental disturbance torques was sufficiently small that the pointing constraints for each mission could be met if attitude drift was the only factor. In the case of WIND, it was discovered that the additional Sun angle constraint makes it impossible to eliminate attitude trim maneuvers between orbit maneuvers. The maximum amount of time that can be expected between attitude trim maneuvers is about 4 months due to the Sun angle variation over time. In the case of POLAR, it was discovered that the drift of the location of the orbit normal itself was the major factor to be considered in determining how to eliminate trim burns between reorientation maneuvers. It was illustrated that the pointing constraint could be achieved, without additional trim burns required, by selecting the initial attitude to be the location of the orbit normal vector near the center of the 6 month period. Further, it was also illustrated that of the three disturbance torques considered, the solar radiation pressure torque dominates the others.

ACKNOWLEDGMENTS

The author wishes to thank the individuals, both civil servants and contractors, who have contributed to the success of the Flight Dynamics Division support for the WIND and POLAR missions. The author especially acknowledges the efforts of Jefferey Dibble, Dave Niklewski, and Neil Ottenstein for their efforts over the past 5 years on the attitude drift analysis for both WIND and POLAR.

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