AIAA

AIAA-82-1457

A Survey of Nongravitational Forces and Space Environmental Torques with Applications to the Galileo Spacecraft

J.M. Longuski, Jet Propulsion Lab, Pasadena, CA; and W.W. König, DFVLR, German Space Operations Center, Oberpfaffenhofen, FRG

AIAA/AAS Astrodynamics Conference

August 9-11, 1982
San Diego, California

A82-40011

A SURVEY OF NONGRAVITATIONAL FORCES AND SPACE ENVIRONMENTAL TORQUES WITH APPLICATIONS TO THE GALILEO SPACECRAFT

James M. Longuski*
Jet Propulsion Laboratory
Pasadena, California

Wolfgang W. König**
DFVLR, German Space Operations Center
Oberpfaffenhofen, FRG

Abstract

A detailed survey of nongravitational forces and space environmental torques acting upon the Galileo spacecraft during its interplanetary flight to Jupiter is given. It includes simple analytic equations to model the first order effect of: solar, planetary and spacecraft radiation, solar wind, meteoroids, cosmic rays, magnetic fields, atmospheric forces and gas leakage of the propulsion system. The model parameters are taken from recent spaceflight data. The result is a probabilistic error model of the magnitudes of the disturbing forces and torques. It provides a useful tool for the analysis of the Galileo and future spaceflight missions.

Introduction

In 1985 the Galileo spacecraft will be launched on an interplanetary trajectory to Jupiter in order to study the Galilean moons and the Jovian environment and atmosphere. During the mission the spacecraft will be exposed to a variety of space environmental forces and torques, which will directly or indirectly influence the spacecraft motion. Due to the high performance required by science experiments a detailed survey of all possible nongravitational forces and space environmental torques and an analysis of their effects on the spacecraft is necessary. To provide a profile of the magnitude of the forces and torques with respect to the spacecraft during the mission, the calculation was performed for three different reference points: near Earth (1AU + 10 R_E), interplanetary (3AU) and near Jupiter (5.2AU + 4R_J).

Fig. 1 shows the AVEGA trajectory which is a ΔV (change of velocity) Earth Gravity Assist that enables the Galileo to reach Jupiter with a greater mass than on a direct trajectory. Critical to the trajectory is a deep space maneuver of 460 m/s, which initiates the earth swingby. The advantage of greater payload is offset in part by a longer mission, since approximately over two years are added by the AVEGA approach. In addition, the spacecraft is subjected to an environment closer to the sun than originally planned.

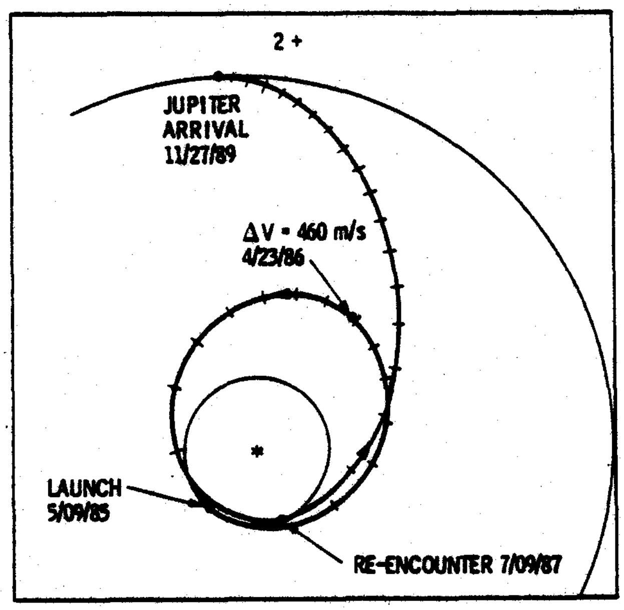

Figure 1. AVEGA Trajectory

Fig. 2 indicates the configuration of the Galileo spacecraft and its coordinate system. Galileo is one of the first interplanetary dual spin spacecraft. The high gain antenna (HGA), the radioisotope thermal electric generators (RTG's), the large magnetometer science boom and the retro propulsion module (RPM) are all located on the rotor which spins at 3.15 rpm, while the scan platform and probe (which will enter the Jovian atmosphere) are located on the stator, which remains inertially fixed.

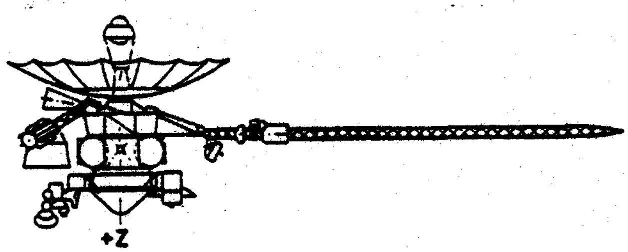

Figure 2. Cruise Configuration of the Galileo Spacecraft

* Senior Engineer, Guidance and Control Section, Jet Propulsion Laboratory
**Member of Technical Staff, DFVLR, German Space Operations Center

Due to the stringent scientific and navigational requirements (which include the capability of accurately mapping the gravitational fields of Jupiter and its satellites and the exciting possibility of discovering gravity waves) the '3σ' uncertainties in the knowledge of the average acceleration (the difference between the modeled and unmodeled accelerations) must not exceed 3×10^{-12} km/s^2 (3σ). (Throughout this paper, the terms '3σ' and 'better than 99.73% probability' are used synonymously. This is equivalent to assuming that all error sources or the combined effect of the error sources have a Gaussian distribution.)

A general approach was taken in the analysis of the forces and torques on the Galileo spacecraft so that the results can be useful in the analysis of other spacecraft. An attempt was made to survey all sensible forces and torques and to numerically estimate their order of magnitudes by simpleanalytic formulas. The forces considered include

1) electromagnetic radiation (sun, earth, Jupiter and spacecraft),
2) particle collisions (solar wind, meteoroids, cosmic rays, and atmospheric particles),
3) magnetic field forces (sun, earth and Jupiter)
4) nonpropulsive mass expulsion.

The torques considered include those arising from the above forces as well as gravity gradient torques from the sun, earth and Jupiter. The simplest equations are reported for each source in the interest of brevity (whole books and lengthy reports have been written about practically each item). These equations are the basis for the probablistic error models as well as the calculation of the mean effect.

The forces ignored in this study include gravitation (Newtonian and relativistic) which is modeled carefully in the trajectory analysis and electric field effects, which may be present in the earth and Jovian environment, but are not well understood. Intentional spacecraft propulsive maneuvers are also ignored. The torques ignored include all nonenvironment torques induced by spacecraft moving parts such as fuel slosh, damping and structural flexing, and torques caused by spacecraft propulsive maneuvers. The only exception is the unintentional spacecraft mass expulsion due to gas leakage of the propulsion system. This is a well-known effect which was considered too important to ignore. Environmental torques ignored include interaction of any nonsymmetric charge distribution on the spacecraft surface with the weak electrostatic fields of the earth or Jupiter as well as any other effects that are small by comparison with the effects included in the study.

Electromagnetic Radiation Forces

When electromagnetic radiation strikes a surface, there is a reaction force (similar to that of particle collisions) which is proportional to the area of the surface and the momentum flux. To precisely determine the force, the momentum flux incident on the surface and the reflected flux must be known. Edwards and Bevans[1] have shown that the reflected flux can be determined analytically from the reflection distribution function and the directional emissivity. In practice, these surface properties are not usually well known. Instead, the electromagnetic radiation forces are modeled by assuming that the incident radiation is either specularly reflected, absorbed, diffusely reflected or some combination of these.[2] Fig. 3 indicates the basic models.

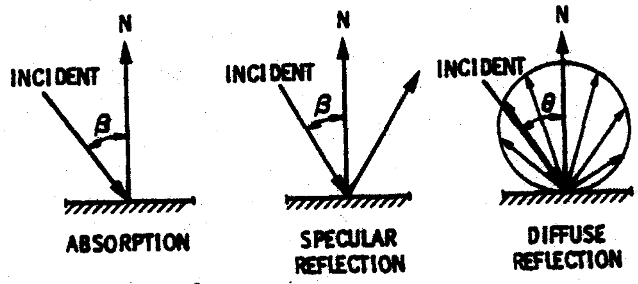

Figure 3. Absorption and Reflection of Incident Radiation.

Sophisticated models can be built up for complex geometric shapes to obtain the electromagnetic force. This is being done to obtain the solar radiation force on the Galileo spacecraft. These details are beyond the scope of this paper.

For our purposes the magnitude of the force acting upon the spacecraft due to external electromagnetic radiation is given by

$$F = k_{elm} A f_{elm}/c \qquad (1)$$

where

k_{elm} = a dimensionless constant,
  $k_{elm} < 1$ for translucent material
  $k_{elm} = 1$ for a perfect black body
  $k_{elm} = 2$ for a total reflective body

f_{elm} = mean integrated energy flux [W/m^2]

c = speed of light [m/s]

A = effective spacecraft surface area [m^2] (see Table 1 for Galileo spacecraft)

The factors k_{elm} and A can be adjusted to obtain the best effective values which model the overall radiation force.

Eq. 1 can now be used in the discussion and evaluation of forces from solar radiation, reflected solar radiation, thermal radiation and radio waves.

Solar Radiation

The magnitude of the force of solar radiation on most interplanetary spacecraft is second only to that of gravity. Thus, solar radiation is modeled in the trajectory analysis of the Galileo spacecraft (and so far, this is the only nongravitational force that is modeled). Eq. 1 gives the magnitude, when f_{elm} is replaced by f_o/r_{ss}^2, where $f_o = 1353 \pm 21$ [W/m^2] is the solar constant[3] which specifies the mean solar flux at 1 AU and r_{ss} is the spacecraft distance relative to the sun in units of AU.

Reflected Solar Radiation

A practical approach to modeling the intensity of reflected radiation from a planet is given by Blanco and McCuskey[4]. The energy flux received by a planet of radius R_p and distance r (in AU) from the sun is $\pi R_p^2 f_o/r^2$ see Fig. 4. Let P(0) be the reflected energy flux from the planet, received by an observer at a distance r_{ps} being in the sun-planet line ($\alpha = 0$) and let $P(\alpha)$ be the reflected energy flux at the same distance r_{ps} but under an angle α.

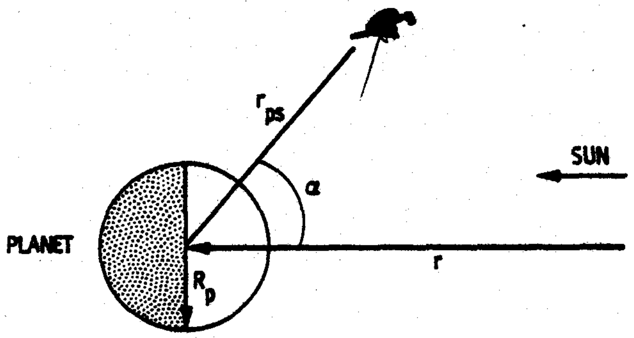

Figure 4. Reflected Solar Radiation

The phase function $\phi(\alpha)$ is then defined by

$$\phi/(\alpha) = P(\alpha)/P(0).$$

and P(0) can be obtained using the equation:

$$2\pi r_{ps}^2\, P(0) \int_0^{\pi} \phi(\alpha)\, \sin\alpha\, d\alpha = a\pi R_p^2 f_o/r^2$$

which expresses the fact that the reflected total integrated energy flux is equal to the total energy flux received times the Bond albedo, a. For a diffusely reflecting sphere obeying Lambert's law the phase function is given by:

$$\phi(\alpha) = [\sin\alpha + (\pi - \alpha)\cos\alpha]/\pi$$

and the integral is found to be:

$$\int_0^{\pi} \phi(\alpha)\, \sin\alpha\, d\alpha = 3/4$$

so that

$$P(0) = 2\, a\, R_p^2\, f_o/(3\, r^2\, r_{ps}^2)$$

Thus, the magnitude of the force due to the reflected solar radiation is given by replacing f_{elm} in Eq. 1 by P(0):

$$F = k_{elm} A\ 2\, a\, R_p^2\, f_o/(3\, c\, r^2\, r_{ps}^2)$$

The upper limit of this force is given at $\alpha = 0$ where $\phi(\alpha{=}0) = 1$

The data for earth and Jupiter are

earth[5]: r = 1 AU, a = 0.39

Jupiter[6]: r = 5.2 AU, a = 0.52

Planet Thermal Radiation

The average power E_o emitted by a planet with surface temperature T is determined by the Stefan-Boltzmann law

$$E_o = \sigma\xi T^4$$

where E_o = emissive power in W/m^2

ξ = nondirectional emissivity, dimensionless

σ = Stefan-Boltzmann constant

$= 5.67 \times 10^{-8}\ W/m^2\ (^{\circ}K)^4$

T = surface temperature in degrees Kelvin

The total emitted power is given by:

$$P = E_o\, 4\pi R_p^2$$

A spacecraft at a distance r_{ps} (in planet radii) from the planet, will receive a power per square meter $E(r_{ps})$:

$$E(r_{ps}) = E_o\, R_p^2/r_{ps}^2.$$

due to the fact that the total emitted energy is conserved. Thus, the force (Eq. 1) due to thermal radiation is determined by:

$$F = k_{elm}\, A\, E_o\, R_p^2/c\, r_{ps}^2 \qquad (3)$$

According to Harris and Lyle[2] the diffusely emitted thermal radiation of the earth is approximated by a 255° K blackbody ($\xi = 1$) and the Jupiter blackbody temperature is found to be 134° K referring to Newburn and Gulkis.[6]

Spacecraft Radiation

The thermal radiation parallel to spin axis (z axis) of the spacecraft was analyzed. In the -z direction the thermal radiation from the antenna and the sun shield is taken into account within the solar radiation model by modifying the coefficient k_{elm} in Eq. 1. The total average thermal power radiated in the +z direction is approximately 50W with an uncertainty of 3σ = 25W. The force resulting of this radiation is given by:

$$F = P/c \qquad (4)$$

where

P = emitted power [W].

The maximum power due to emitted radio signals from the antenna is 30W and the resulting force can be calculated using Eq. 4. All radiation forces perpendicular to the spin axis of the spacecraft are assumed to cancel out over a spin period.

Particle Collision Forces

During its flight the spacecraft will be hit by particles (such as meteoroids or nucleons) which impose an impulsive force on the spacecraft for each collision. To calculate an average continuously acting force, it is assumed that the spacecraft surface can be described by an effective plane area, which is hit by particles with a relative velocity V_R with respect to the spacecraft (Fig.5).

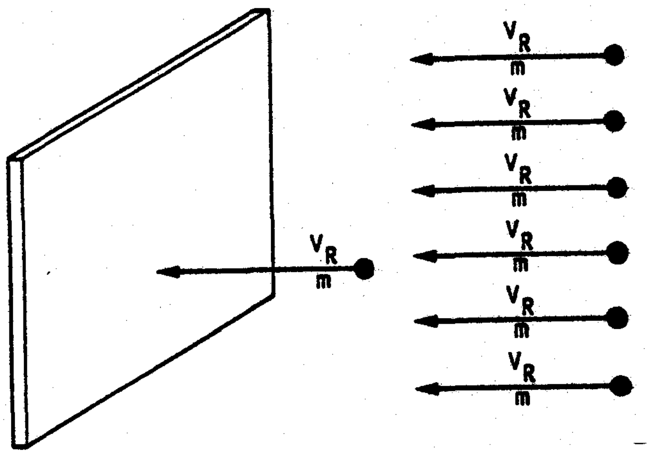

Figure 5. Collision Force Model

The momentum change of the spacecraft in the case that the particles stick after the collision is approximately

$$\Delta p \approx m V_R$$

with the assumption $m_{spacecraft} >> m$.

The average force due to collisions with particles of mass m and relative velocity V_R is now given by:

$$F = dp/dt \approx \Delta p \, \dot{n}$$

$\dot{n}$: number of particles per second

where $\dot{n}$ is given by:

$$\dot{n} = \rho A V_R / m$$

ρ = density of particle clouds

A = effective surface area

The disturbing force is given then by:

$$F = \rho A V_R^2 \qquad (5)$$

The term ρV_R [kg/m²s] can be interpreted as mass flux rate and if the particle velocity is very large compared to the spacecraft velocity, then V_R is approximately $V_{Particle}$ (this is true for solar wind particles and cosmic rays) and the term ρV_R^2 [kg/ms²] can be regarded as kinetic energy density or momentum flux rate of the particle clouds. These interpretations are useful to apply given astrophysical quantities to this problem.

Solar Wind

The momentum flux of the quiet solar wind at 1AU in the ecliptic plane is given by:[7]

$$\rho V^2 = 2.3 \times 10^{-9} \; [\text{kg/ms}^2]$$

In Eq. 5 ρV^2 is then replaced by $\rho V^2 / r_{ss}^2$ where r_{ss} is the distance sun-spacecraft in units of AU.

Meteroids

The following different cases of meteroid environment have been analyzed:

Near Earth Meteoroid Environment At $10R_E$. Cour Palais[8] developed a total meteoroid flux mass model which combines sporadic and stream meteoroids but assumes only cometary meteoroids neglecting the asteroidal component. The average total cumulative meteoroid flux at 1AU is given by the following expression:

$$\log_{10} N(m) = a + b \log_{10} m + c (\log_{10} m)^2 \qquad (6)$$

$$N(m) = A\, m^{b + c \log m}, \quad A = 10^a$$

N(m) = number of particles with mass m or greater per square meter per second

a,b,c = model constants which yield for a defined mass range $m_e < m < m_o$

For the purpose of a force calculation it is necessary to convert N(m) into a mass flow rate ρV_R.

Let $\Delta m = (m_o - m_e)/N$ (N integer) and m_i the center of an i-th interval:

$$m_i = m_o - i\,\Delta m + \Delta m/2$$

then the mass flow rate can be expressed by:

$$\rho V_R = \lim_{k \to \infty} \sum_{i=1}^{k} \rho V_R(m_i)$$

$\rho V_R(m_i)$ = mass flow rate of particles with mass m_i

and $\rho V_R(m_i)$ is given by:

$$\rho V_R(m_i) = m_i \, [N(m_i - \Delta m/2) - N(m_i + \Delta m/2)]$$

Considering the limits:

$$\rho V_R = \lim_{k \to \infty} \sum_{i=1}^{k} m_i \, [N(m - \Delta m/2) - N(m + \Delta m/2)] \qquad (7)$$

the flow rate is found to be

$$\rho V_R = \int_{N(m_o)}^{N(m_e)} m \, dN(m) \qquad (8)$$

In case that the quadratic term in Eq. (6) vanishes (c = 0), the mass flow rate can be calculated analytically by setting

$$dN(m)/dm = A\, b\, m^{b-1}$$

$$\rho V_R = \int_{m_o}^{m_e} m \,(A\, b\, m^{b-1})\, dm = A\, b\, (m_e^{b+1} - m_o^{b+1})/(b+1)$$

If $c \neq 0$ which is the case for the very small mass range of the meteoroid models, the integration has to be performed numerically using Eq. (7).

According to Cour-Palais[8], the model constants are:

$a = -14.339$, $b = -1.584$, $c = -0.063$
for: $10^{-12} < m < 10^{-6}$ (m in gram)

and: $a = -14.37$, $b = -1.213$
for: $10^{-6} < m < 10^{0}$

The numerical evaluation of Eqs. (7) and (9) give a total cummulative mass flow rate

$$\rho V = 6.29 \times 10^{-16} \ [kg/m^2 s]$$

This value does not include any body shielding effects or lunar ejected particles. So far the velocity V included in the mass flow rate ρV describes only the relative velocity of the meteoroids with respect to the earth. To calculate the force of Eq. (5) first the density ρ has to be calculated by dividing ρV by the average meteoroid velocity (V_c = 20 km/s at the entry of earth's atmosphere) and then to be multiplied by V_R^2 where V_R is the relative velocity between meteoroids and the spacecraft at $10R_E$. The spacecraft velocity at $10R_E$ is $V_s = 9.7$ km/s with an orientation away from earth, while the meteoroids have an average velocity of $V_e = G \times 20$ km/s at $10R_E$ directed towards the earth. Therefore, the relative velocity is given by: $V_R = V_S + G\, V_c$ = 21.9 km/s where $G = 0.61$ is a defocussing factor which corrects the earth gravity enhancement effect at $10R_E$.[8]

__Interplanetary Meteoroid Environment__. During an interplanetary spaceflight meteoroids of cometary as well as of asteroidal origin have to be considered. D. J. Kessler[9] developed an interplanetary meteoroid environment model whose cometary component is based on Cour-Palais'[1] meteroid flux model at 1AU with corrections for heliocentric latitude and radial variations. The cometary meteoroid model is given by:

$$\log_{10} N_c = -18.173 - 1.213 \log_{10} m - 1.5 \log_{10} R - 0.869 |\sin\beta|$$

for $10^{-6} < m < 10^{2}$

and:

$$\log_{10} N_c = -18.142 - 1.584 \log_{10} m - 0.063 [\log_{10}(m)]^2 - 1.5 \log_{10} R \ - 0.869 \ |\sin\beta|$$

for $10^{-12} < m < 10^{-6}$

and the average relative velocity of cometary meteoroids with respect to the spacecraft is given by:

$$V_c(R,\sigma,\gamma) = R^{1/2}\ 31.29 \times 10^3 \times (1.3 - 1.9235\ \sigma \cos\gamma + \sigma^2)^{1/2}$$

N_c = number of meteoroids with mass m or greater per cubic meter

m = meteoroid mass in gram

R = distance of the spacecraft from the sun in AU

β = heliocentric latitude (-0.56° at 3AU for Galileo 2[+] trajectory)

V_c = average relative velocity in m/s

σ = ratio of the spacecraft's heliocentric speed at R to the speed required for a circular orbit of radius R
$\sigma = (a - R/a)^{1/2}$

γ = angle between the spacecraft velocity vector and the surface of an imaginary sphere of radius R in degrees

$\cos\gamma = [(a - ae^2)/(2R - R^2/a)]^{1/2}$

a = semi-major axis in AU (3.092 for Galileo)

e = eccentricity (0.672)

The cometary meteoroid density is calculated similar as in the near earth case the flux was calculated:

$$\rho_c = \lim_{k\to\infty} \sum_{i=1}^{k} m_i \left[N_c(m_i - \Delta m/2) - N_c(m_i + \Delta m/2)\right]$$

or $$\rho_c = \int_{N_c(m_o)}^{N_c(m_e)} m \, dN_c$$

The cometary meteoroid density at 3AU is found to be:

$$\rho_c = 2.372 \times 10^{-20} \ [kg/m^3]$$

and the average relative velocity is:

$$V_c = 16.982 \times 10^3 \ [m/s]$$

D. J. Kessler also developed a model for the asteroidal meteoroid environment which is described by the following equations:

$$\log_{10} N_a = 15.73 - 0.84 \log_{10} m + f(R) + g(R) \cos\lambda + h(\beta)$$

for $10^{-6} < m < 10^{2}$

$$\log_{10} N_a = -8.23 + f(R) + g(R) \cos\lambda + h(\beta)$$

for $10^{-12} < m < 10^{-6}$

and the relative velocity of the asteroidal meteoroids is

$$V_a\,(R,\sigma,\gamma) = R^{-1/2}\ U_a\,(R,\sigma,\gamma)$$

$f(R)$ = asteroid radial distribution function ($f(3)$ = 0.12). For numerical values see Ref. 9.

$g(R)$ = asymmetry function of the asteroid belt with heliocentric longitude. ($g(3) = 0$)

$h(\beta)$ = latitudinal distribution function of asteroidal particles ($h(-0.56°) = 0$)

$U_a(R,\sigma,\gamma)$ = average relative velocity of asteroidal particles $U_a(R{=}2.5AU,\sigma,\gamma)$ =

$$29.84 \times 10^3 \ (1.0391 - 1.9887\sigma\cos\gamma + \sigma^2)^{1/2}$$

The asteroidal meteoroid density is found to be:

$$\rho_a = 1.33 \times 10^{-18} \ [kg/m^3]$$

and the calculated average relative velocity is:

$$V_a = 9.61 \times 10^3 \ [m/s]$$

Jupiter Meteoroid Environment at 4 R_J. To model the meteoroid environment at Jupiter the same model of Kessler was used with four changes according to the experimental results of Pioneer 10 and 11 as discussed by Humes[10] and Beck.[11] The modifications are:

- neglection of the asteroidal component
- assuming a constant spatial density with radial distance
- assuming a constant spatial density with latitude
- assuming that the spatial density is 2 times that at 1AU given by D J. Kessler.

Therefore, the spatial density of cometary meteoroids near Jupiter are described by:

$$\log_{10}(N_c/2) = -18.773 - 1.213 \log_{10} m$$

for $10^{-6} < m < 10^{2}$

and $$\log_{10}(N_c/2) = -18.142 - 1.584 \log_{10} m - 0.063 (\log_{10} m)^2$$

for $10^{-12} < m < 10^{-6}$

and the meteoroid density is then calculated in the same way as in the interplanetary case. The average relative velocity according to D. J. Kessler is found to be:

$$V_c = (V_p{}^2/r + V_s{}^2)^{1/2}$$

where

r = distance from spacecraft to planet in units of R_J

V_p = escape velocity from the planet's surface

V_s = velocity of the spacecraft relative to the planet.

The total integrated meteoroid density for particle masses within the range $10^{-12}<m<10^{2}$ [m in gram] is found to be:

$$\rho_c = 9.55 \times 10^{-20} \text{ [kg/m}^3\text{]}$$

with an average relative velocity of:

$$V_c = 4.24 \times 10^{4} \text{ [m/s]}$$

Cosmic Rays

According to Divine[12] the galactic cosmic rays have a typical energy density of the entire population of: $\rho V^2 = 10^{-13}$ [J/m^3], which leads to a negligible force.

Atmospheric Particles

Earth. According to Allen[5] the density of the earth's atmosphere at 50,000 km altitude is $\rho = 2.5 \times 10^{-19}$ [kg/m^3]. This value was chosen to estimate the upper limit of the aerodynamic force. The velocity of the Galileo spacecraft relative to the earth's atmosphere at 10 R_E is 9.7 km/s. It should be mentioned that in the case of the 200 km earth flyby altitude, the atmospheric density is[7]: $\rho = 2.789 \times 10^{-10}$ [kg/m^3] which creates a maximum force of 10^{-4} [N].

Jupiter. The atmospheric particles effect near Jupiter at 4R_J is primarily due to the atmosphere of Io (which has a semi-major axis of 5.95 R_J). The closest data available for the atmospheric density is found in Bagenal and Sullivan[17], where the composition of the plasma in the dayside magnetosphere of Jupiter at 4.96 R_J is reported from Voyager measurements. By summing the results for the individual ions (hydrogen, oxygen, sodium and sulfur), we obtain a density of $\rho = 2.3 \times 10^{-17}$ kg/m^3. The greatest density appears to be at 5.3 R_J where $\rho = 6.9 \times 10^{-17}$ kg/m^3. The velocity of the Galileo spacecraft relative to the Jovian atmosphere is 30 km/s.

Magnetic Field Forces

The interaction between the spacecraft with a charge q and an environmental magnetic field B is described by the Lorentz Law:

$$F = q \mid V_R \times B \mid \qquad (10)$$

where

q = spacecaft charge in coulombs [Cb]

V_R = relative velocity [m/s]

B = magnetic induction in teslas [T]

In most cases the magnitude of the magnetic field is known at the planet's surface and therefore B will be replaced by $B_o/r_{ps}{}^3$ where B_o is the magnetic induction at the surface and r_{ps} is the distance from the planet to the spacecraft in units of the planet radius.

The calculation of the relative velocity V_R is based on the asumptions that the magnetic fields rotate with the same frequency that the originating body does and that the angular velocity is parallel and in the same direction to the spacecraft velocity $V_{s/c}$. Then the relative velocity is given by:

$$V_R = 2\pi r_{ps}/T - V_{s/c}$$

where T is the rotational period. The following data were considered:

-near earth

$B_E = 3.0 \times 10^{-5}$ [T] at equator[13]
$T_E = 86400$ [s]
$V_{s/c} = 9.7$ [km/s]

-interplanetary

$B_s = 6.0 \times 10^{-9}$ [T] at 3AU[13]
$T_s = 2.16 \times 10^{6}$ [s]
$V_{s/c}$ = negligible

-near Jupiter

$B_J = 4.0 \times 10^{-4}$ [T] at 4R_J[6]
$T_J = 3.25 \times 10^{4}$ [s][6]
$V_{s/c} = 30.0$ [km/s]

Nonpropulsive Mass Expulsion Force

The resulting force due to pressurized gas leakage in the propulsion system can be calculated by using the rocket equation:

$$F = p_e A_e + \dot{m} V_e \qquad (11)$$

where

p_e = exit pressure at the leak $[N/m^2]$

A_e = leak surface $[m^2]$

$\dot{m}$ = gas mass flow rate [kg/s]

V_e = exit velocity [m/s]

The upper limit of the leakage rate, $\dot{m}$, is provided by spacecraft design tests. While the nominal operating temperature and pressure are known, nothing is known about the area through which the pressurized gas leaks, nor the pressure over this area so that Eq. 11 cannot be applied directly. The following development circumvents this problem by providing an equation which gives the mass expulsion force in terms of the mass flow rate, stagnation temperature and other known parameters. Using the one dimensional continuity equation for the mass flow rate:

$$\dot{m} = \rho A V$$

one obtains:

$$F = p_e A_e + \rho A_e V_e^2$$

Assuming a perfect gas, the following equation yields:[14]

$$\rho V^2 = k p M^2$$

where

k = ratio of specific heat

p = pressure $[N/m^2]$

M = mach number

Therefore F can be written as:

$$F = p_e A_e (1 + k M^2)$$

For an isentropic flow the mass flow rate divided by the area is given by[14]

$$\dot{m}/A = pM (k/RT_o)^{1/2} [1 + (k-1)/2 M^2]^{1/2}$$

where

R = gas constant for the pressurization gas [J/kg °K]

T_o = stagnation temperature, assumed to be identical with the pressurized tank temperature [°K]

Assuming sonic conditions at the exit (M = 1) we obtain

$$F = \dot{m} (2 RT_o (1 + k)/k)^{1/2} \qquad (12)$$

Torque Models

A detailed survey study of spacecraft torques can be found in "Space Environmental Torques on Program P-11 Vehicles" by L. E. Wiggins.[15] There are three different kinds of torques which have to be considered:

1. Spin axis torques which effect a spin rate change. They may be fixed in inertial space or in the body and the spin rate change is given by: $\Delta\omega = T_z \Delta t / I_z$

2. Precessional torques which cause spin axis drift. These are torques normal to spin axis which are inertially fixed. They cause the spin axis and the angular moment vector to drift by:

   $\Delta H/H = (T_x^2 + T_y^2)^{1/2} \Delta t / I_z\omega$

3. Body fixed torques normal to the spin axis which have no secular effect. These torques have a bounded effect on the perturbation of the spin axis and the angular moment vector where the average value is given by:

   $\Delta H/H = (T_x^2 + T_y^2)^{1/2} / I_z\omega^2$

This effect is quite small compared to inertially fixed torques considered and is therefore neglected in the following torque discussion. All of the forces discussed so far apply a precessional and/or spin axis torque. An additional torque is produced by the gravity gradient.

Torque Model for the Electromagnetic Radiation Particle Collision and Mass Expulsion Forces

These kind of torques can be calculated by

$$T = |r \times F| \qquad (13)$$

where

r = average torque arm [m], averaged over one spin period

F = force [N]

where the torque arm is evaluated from the spacecraft surface model. The values of the torque arms in Table 2, show that electromagnetic radiation forces cannot cause a spin rate change because force, torque arm and spin axis would have to have orthogonal components to each other. The only case is that of a flow from the ±X-direction with respect to spacecraft coordinates, but in this case the average torque cancels out due to the fact that the torque arms are equal for both directions.

In the case of particle collision forces, spin rate decay is possible. Wiggins[15] has shown that an upper bound on the aerodynamic spin decay torque for a cylinder is roughly given by

$$T_p = -F\omega r^2 / 2V_R \quad \omega \text{ parallel to } V_R \qquad (14)$$

$$T_o = -F\omega r^2 / V_R \quad \omega \text{ orthogonal to } V_R \qquad (15)$$

where:

F: particle collision force [N], Eq. 5

ω: spin rate [s^{-1}]

r: radius of the cylinder [m] (for Galileo r = 1.0m)
V_R: relative velocity between spacecraft center of mass and atmospheric particles.

The Galileo spacecraft attitude and vector angles are given in Table 3. Mass expulsion forces cannot create a secular precession torque, but may decrease or increase the spin rate.

__Model for Magnetic Field Torques__

There are basically four sources of magnetic disturbance torques:

Permanent magnetism in the spacecraft
Spacecraft generated current loops
Magnetism induced by an external field
Currents induced by and external field

The first two torques can be described by:

$$T = |M \times B| \qquad (16)$$

where

M = spacecraft magnetic dipole moment [Am^2]

B = ambient magnetic flux density [T]

The Galileo magnetic dipole moment is expected to be:

$$M = 2.0 \pm 1.0 \; [A\ m^2]$$

but the orientation of the moment is unknown. For an upper limit it is assumed that the orientation is parallel to the spin axis which then leads to an effective processional torque. Torques created by dipole components perpendicular to the spin axis are assumed to cancel out. Torques created by induced magnetism are negligible due to the usage of impermeable materials for the Galileo spacecraft. The torque due to the interaction of induced currents (Eddy currents) with an external field can be described by[16]:

despin component: $T_p = k_e\,(B_o)^2\,\omega_s$ (17)

precession component: $T_o = k_e\,\omega_s\,B_p\,B_o$ (18)

where:

B_o = component of the ambient magnetic field orthogonal to the spin axis [T]

B_p = component of B parallel to the spin axis [T]

ω_s = spin angular velocity [rad/s]

k_e = constant [m^4/ohm] which depends on the geometry and conductivity of the spinning surface[16]

-thin spherical shell of radius r, thickness d and conductivity σ:
$k_e = (2\pi/3)\, r^4\, \sigma\, d$
-circular loop, located in a plane through the spin axis, with radius r, cross sectional area S and conductivity σ:
$k_e = (\pi/4)\, \sigma\, r^3\, S$
-thin-walled cylinder with length L, radius r, thickness d and conductivity σ:
$k_e = \pi\, \sigma\, r^3\, L\, d\,(1 - 2d/L \tanh L/2d)$

For the numerical torque calculation, Galileo was approximated by a thin-walled cylinder: L = .46m, d = 3.8 x 10^{-3} m, r = .78 m, σ = 3.8 x 10^7 ohm^{-1} (beryllium), which represents the spacecraft bus structure. The spin angular velocity is given as: ω_s = 3.15 x 2π/60 s^{-1}. The magnitudes of the considered magnetic fields are:

earth magnetic field at $10R_E$[13]

$$B_E = 3 \times 10^{-5} / (10^3) = 3 \times 10^{-8}\ [T]$$

interplanetary magnetic field at 3AU[13]

$$B_I = 4.0 \times 10^{-8}/(3^3) = 2.5 \times 10^{-9}\ [T]$$

Jupiter magnetic field at 4 R_J[6]

$$B_J = 4.0 \times 10^{-4}/(4^3) = 6.3 \times 19^{-6}\ [T]$$

__Gravity Gradient Torque__

This torque is created due to the change of gravitational force over the distributed mass of the spacecraft. A detailed discussion of this torque is provided by Wiggins[15] and Harris and Lyle[18]. Assuming a central inverse square field, the gravity gradient torque is given by

$$T_G = 3G/R^5\ (\bar{R} \times \bar{\bar{I}} \cdot \bar{R}) \qquad (19)$$

where

G = planet gravitational constant [m^3/s]

$\bar{R}$ = radius vector from the attracting planet to the satellite center of mass [m]

$\bar{\bar{I}}$ = moment of inertia tensor of the spacecraft [kg m^2]

Eq. (19) can be expanded by using body fixed coordinates axes so that the product of inertia vanishes. If the resulting torques are then transformed in an inertially fixed coordinate system, the following equations can be obtained by using coordinates as shown in Fig. 6.

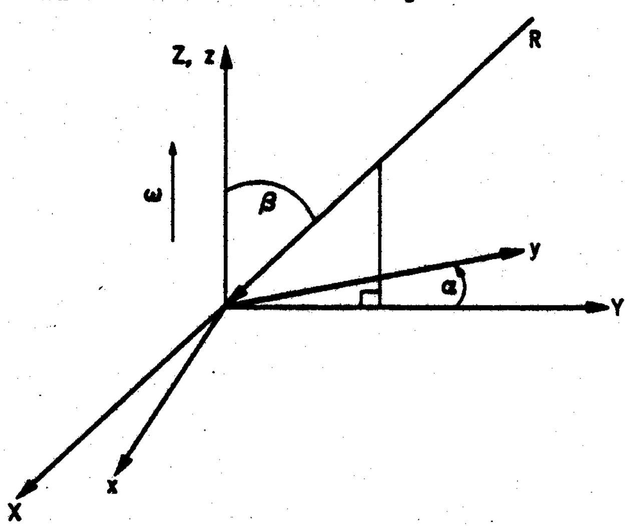

Fig. 6 Coordinate Reference System

X, Y, Z inertially fixed axis

x, y, z body fixed axis, z-axis = spin axis

R radius vector planet-spacecraft center of mass (R lies in the Y-Z plane)

β angle between spin axis and planet

$$T_X = 3G/R^3\ [I_z - (I_x \sin^2\alpha + I_y \cos^2\alpha)] \sin\beta \cos\beta$$

$$T_Y = 3G/R^3\ (I_x - I_y) \sin\beta \cos\beta \sin\alpha \cos\alpha$$

$$T_Z = 3G/R^3\ (I_y - I_y) \sin^2\beta \sin\alpha \cos\alpha$$

Due to the fact that: $\alpha = \omega t$ the torque components T_Y and T_Z cancel out over one complete spin revolution and $T_Z = 0$ means that gravity gradient torques can not cause spin rate changes.

The effective torque averaged over one spin revolution is given by:

$$T_X = 3G/R^3\ [I_z - 1/2\ (I_x + I_y)] \sin\beta\cos\beta \quad (20)$$

The following parameters were used to calculate the average effective torque:

Near earth:

$R = 10R_E = 63.781 \times 10^6$ [m]

$G = G_E = 3.986 \times 10^{14}$ [m^3/s^2]

Interplanetary:

$R = 3AU = 4.5 \times 10^{23}$ [m]

$G = G_{sun} = 1.32 \times 10^{20}$ [m^3/s^2]

Near Jupiter:

$R = 4R_J = 2.856 \times 10^8$ [m]

$G = G_J = 1.267 \times 10^{17}$ [m^3/s^2]

Probabilistic Error Modeling

Probabilistic error models will now be obtained from the governing equations for electromagnetic radiation forces, particle collision forces, magnetic field forces, nonpropulsive mass expulsion force and the torque models. Since the method is standard practice only a brief outline of the derivations are discussed. The details can be supplied by the interested reader.

Electromagnetic Radiation Force Error Model

We will derive the probabilistic error model for the electromagnetic radiation force from Eq. 1 in the following form

$$F = kAf/c$$

Assuming each variable in Eq. 16 has an error, ξ, associated with it we can write

$$F + \xi_F = (k+\xi_k)(A+\xi_A)(f+\xi_f)/(c+\xi_c) \quad (21)$$

The variance of this random variable $F + \xi_F$ is defined by the following equation:

$$\sigma^2 = E(F+\xi_F)^2 - \mu^2 = E(F+\xi_F)^2 - (E(F+\xi_F))^2 \quad (22)$$

For the evaluation of the variance, Eq. 21 is expanded by keeping only first order terms to:

$$F + \xi_F = (kaf/c)[1+(\xi_f/f)+(\xi_k/k)+(\xi_A/A)-(\xi_c/c)]$$

Assuming zero mean errors:

$E(\xi_i) = 0$ for all i

$E(\xi_i^2) = \sigma_i^2$ for all i

we obtain:

$$E\ (F+\xi_F) = E(F) + E(\xi_F) = E(F) = kAf/c \quad (23)$$

For the calculation of $E(F + \xi_F)^2$ we assume that the errors ξ_i, ξ_j are uncorrelated, so that

$E\ (\xi_i\ \xi_j) = \sigma_i^2$ for all i = j

$E\ (\xi_i\ \xi_j) = 0$ for all $i \neq j$

and we find:

$$E\ (F+\xi_F)^2 = (kaf/c)^2((\sigma_k/k)^2+(\sigma_A/A)^2+(\sigma_f/f)^2+(\sigma_c/c)) \quad (24)$$

The combination of Eq. (23) and (24) according to (22) provides us with the final error model

$$\sigma^2 = (kaf/c)^2((\sigma_k/k)^2+(\sigma_A/A)^2+(\sigma_f/f)^2+(\sigma_c/c)^2)$$

or:

$$(\sigma/F)^2 = (\sigma_k/k)^2+(\sigma_A/A)^2+(\sigma_f/f)^2+(\sigma_c/c)^2 \quad (25)$$

Eq. 25 provides the basic error model for electromagnetic radiation forces. Of course, it is still necessary to evaluate the standard deviations of k, A, f and c. For most practical purposes, the speed of light, c, is known so accurately that its uncertainty can be ignored. The three other parameters can have significant variances. In the case of the Galileo spacecraft, the following uncertainties were estimated:

$(\sigma_A/A) = 5\%$

$(\sigma_k/k) = 3\%$

The uncertainty in the mean integrated energy flux varies considerably depending on the energy source. In order to obtain these values separate error models for solar radiation, reflected solar radiation from a planet (earth and Jupiter) and spacecraft radiation must be developed. Here we will only report the results:

solar radiation: $(\sigma_f/f) = 1\%$

reflected solar radiation: $(\sigma_f/f) = 5\%$

earth radiation: $(\sigma_f/f) = 20\%$

Jupiter radiation: $(\sigma_f/f) = 20\%$

spacecraft radiation: $(\sigma_P/P) = 20\%$

Note that in most cases, the uncertainty in mean integrated energy flux is far greater than the other uncertainties. This is largely due to uncertainty in the radiation distribution.

Particle Collision Force Error Model

For the particle collision force due to meteoroids and atmospheric particles the following model was derived from Eq. 5:

$$(\sigma/F)^2 = (\sigma_A/A)^2+(\sigma_\rho/\rho)^2+(2\sigma_V/V)^2 \quad (26)$$

with:

$(\sigma_\rho/\rho)=(700/3)\%$ for cometary meteoroids[9] (near earth, Jupiter)

Since the expected leakage rate, $\dot{m}$, is zero, Eq. 9 the error model from (Eq. 12) is given by

$$\sigma_F = \sigma_{\dot{m}} \ (2RT_o \ (1+k) \ /k)^{1/2}$$

where for the Galileo spacecraft

$$\sigma_{\dot{m}} = 1.79 \times 10^{-10} \text{ kg/s}$$

Torque Error Model

The precessional torque error model for electromagnetic radiation and particle collision forces and the spin axis torque error model for the forces are derived from Eq. 13:

$$T = r \ F \sin \alpha$$

Disturbing this equation we obtain:

$$T+ \xi_T = (r + \xi_r) \ (F + \xi_F) \sin (\alpha + \xi_\alpha)$$

where $\sin (\alpha + \xi_\alpha)$ can be approximated to:

$$\sin (\alpha + \xi_\alpha) \approx \sin \alpha + \xi_\alpha \cos \alpha$$

The remaining calculation is similar to the one presented for the forces and one obtains:

$$(\sigma/T)^2 = (\sigma_r/r)^2 + (\sigma_F/F) + (\sigma_\alpha \cot\alpha)^2 \quad (28)$$

The following spacecraft parameters were used:

$(\sigma_r/r) = 10\%$

(σ_F/F) = given by the force error models

$(\sigma_\alpha \cot \alpha)$ has to be individually calculated for each angle α, $3\sigma_\alpha$ is assumed to be constant 10^o.

The error model for spin axis torques due to particle collision force are derived from Eqs. 14 and 15 and one obtains in both cases:

$$(\sigma/T)^2 = (\sigma_F/F)^2 + (\sigma_\omega/\omega)^2 + (2\sigma_r/r)^2 + (\sigma_V/V)^2 \quad (29)$$

with:

$(\sigma_\omega/\omega) = 0.05\%$

$(\sigma_r/r) = 30\%$

$(\sigma_V/V) = 30\%$

The error model for the magnetic field forces due to the spacecraft dipole moment is given by:

$$(\sigma/T)^2 = (\sigma_M/M)^2 + (\sigma_B/B)^2 + (\sigma_\alpha \cot \alpha)^2 \quad (30)$$

with:

$(\sigma_M/M) = 20\%$

$(\sigma_B/B) = 30\%$ earth magnetic field

$= 300\%$ interplanetary field

$= 50\%$ Jupiter magnetic field

For the Eddy current precessional torques we obtain:

$$(\sigma/T)^2 = (\sigma_{ke}/k_e)^2 + (\sigma_\omega/\omega)^2 + (2\sigma_B/B)^2 + (2\sigma_\alpha \cot 2\alpha)^2 \quad (31)$$

with:

$(\sigma_{ke}/k_e) = 20\%$

and the error model for the Eddy current spin axis torque is given by:

$$(\sigma/T)^2 = (\sigma_{ke}/k_e)^2 + (\sigma_\omega/\omega)^2 + (2\sigma_B/B)^2 + (2\sigma_\alpha \cot \alpha)^2 \quad (32)$$

In the case of the gravity gradient torque, the relative uncertainty in the angle between the spacecraft spin axis and the planet is at least one order of magnitude greater than the relative uncertainties of the spacecraft moments of inertias and other constants. Therefore this model is reduced to:

$$(\sigma/T)^2 = (2 \ \sigma_\alpha \cot 2 \ \alpha)^2 \quad (33)$$

Numerical Results for the Galileo Mission

The analytic models can now be applied to the Galileo spacecraft to obtain mean and 3σ for nongravitational forces and space environmental torques.

The following spacecraft related parameters (along with values given in Tables 1-3) were used to obtain the numerical results

$k_{elm} = 1.5 \pm 0.23$		Eq: 1,2,3
$q = 0. \pm 10^{-8}$	[Cb]	Eq: 10
$\dot{m} = 0. \pm 5.36 \times 10^{-10}$	[kg/s]	Eq: 12
$R = 2.077 \times 10^3$	[J/kg °K]	Eq: 12
$T_o = 300$	[°K]	Eq: 12
$k = 1.667$		Eq:12
$M = 2.0 \pm 1.2$	[Am²]	Eq: 16
$k_e = 9.739 \times 10^4$	[m⁴/ohm]	Eq: 17, 18
$I_Z = 4.11 \times 10^3$	[kg m²]	Eq: 20
$I_X \approx I_Y = 3.44 \times 10^3$	[kg m²]	Eq:20
$r_{spin} = 1.30$	[m] (mass expulsion spin axis torque arm)	Eq: 13
$r_{eff} = 0.045$	[m] (effective secular processional torque arm)	Eq: 13

Table 1. Effective Surface Areas

EFFECTIVE SURFACE AREAS IN M^2 FOR FLOW FROM SPECIFIED DIRECTIONS			
DIRECTION	A_x	A_y	A_z
+z	0	0	10.2
−z	0	0	13.2
+y	0	5.2	0
−y	0	4.1	0
+x	7.2	0	0
−x	7.2	0	0

Table 2. Torque Arms

CP-CM OFFSET IN M FOR FLOW FROM SPECIFIED DIRECTIONS			
DIRECTION	r_x	r_y	r_z
+z	0.09	0.40	0
−z	0.06	1.74	0
+y	0	0	−0.49
−y	0	0	−0.40
+x	0	2.10	−0.43
−x	0	2.10	−0.43

Table 3. Spacecraft Attitude and Velocity Angles in Degrees.

BETWEEN	NEAR EARTH	INTER-PLANETARY	NEAR JUPITER
ω, SUN	10	10	10
ω, PLANET	80	-	10
ω, V	80	135	80
ω, B	70	45	80
V, B	70	45	80

For the environmental forces Table 4 clearly shows that the solar radiation pressure dominates. In fact this force and its uncertainty exceeds the requirements for the interplanetary and near earth portions of the mission. For this reason the solar radiation force on the Galileo spacecraft will be accurately modeled within the trajectory analysis, but in practice it is difficult to reduce the uncertainties of the model parameters (especially that of the effective surface area) to the requirement level. So an inflight calibration will be performed during the early part of the mission. Next to the solar radiation pressure is the meteoroid particle collision force in the asteroid belt due to the large uncertainty in the meteoroid density. The next largest terms are the atmospheric particles at Jupiter, nonpropulsive mass expulsion, spacecraft radiation and reflected solar radiation from earth. These are approximately one order of magnitude less than the requirements and the remaining terms are much smaller.

Table 5 presents the numerical results for precessional torques. The largest effects are magnetic dipole moment torque at Jupiter, gravity gradient, Eddy current at Jupiter and solar radiation with values of 10^{-5} to 10^{-6} Nm. These precessional torques will disturb the angular momentum vector and, hence, the attitude of the HGA (High Gain Antenna). Since the HGA has a deadband requirement of 2.14 mrad, the average amount of time between HGA pointing corrections due to just the magnetic dipole moment torque at Jupiter is

$$\Delta t = (0.33 \text{ rad/s})\ (5000 \text{ kg m}^2)\ (2.14 \times 10^{-3} \text{ rad}) /$$

$$(3.22 \times 10^{-5} \text{ Nm}) = 1.1 \times 10^{5} \text{ s} = 1.3 \text{ days}$$

Table 4. Mean and 3σ of Environmental Forces in Newtons

SOURCE	NEAR EARTH (1 AU + 10 R_E) MEAN	3σ	INTERPLANETARY (3 AU) MEAN	3σ	NEAR JUPITER (5.2 AU + 4 R_J) MEAN	3σ
1. ELECTROMAGNETIC RADIATION FORCES						
• SOLAR RADIATION	8.80×10^{-5}	2.50×10^{-5}	9.78×10^{-6}	3.25×10^{-6}	3.25×10^{-6}	9.25×10^{-7}
• REFLECTED SOLAR RADIATION	1.04×10^{-7}	3.33×10^{-8}	-	-	7.04×10^{-8}	2.25×10^{-8}
• PLANET THERMAL RADIATION	7.12×10^{-8}	4.01×10^{-8}	-	-	7.43×10^{-8}	4.93×10^{-8}
• SPACECRAFT RADIATION	2.67×10^{-7}	4.01×10^{-8}	2.67×10^{-7}	4.01×10^{-8}	2.67×10^{-7}	4.01×10^{-8}
2. PARTICLE COLLISION FORCES						
• SOLAR WIND	2.99×10^{-8}	1.52×10^{-8}	3.32×10^{-9}	1.69×10^{-9}	1.10×10^{-9}	5.63×10^{-10}
• METEOROIDS	8.95×10^{-11}	6.24×10^{-8}	9.35×10^{-10}	2.62×10^{-6}	1.02×10^{-9}	7.11×10^{-7}
• COSMIC RAYS	-	1.3×10^{-12}	-	1.3×10^{-12}	-	1.3×10^{-12}
• ATMOSPHERIC PARTICLES	1.40×10^{-10}	4.24×10^{-10}	-	-	7.02×10^{-8}	8.42×10^{-7}
3. MAGNETIC FIELD FORCE	-	1.43×10^{-12}	-	2.05×10^{-12}	-	1.18×10^{-9}
4. NONPROPULSIVE MASS EXPULSION FORCE	-	7.57×10^{-7}	-	7.57×10^{-7}	-	7.57×10^{-7}
REQUIREMENT (MEAN + 3σ)	6.9×10^{-6}		6.0×10^{-6}		3.3×10^{-6}	

Table 5. Mean and 3σ of Secular Precessional Torques in Newton Meters

SOURCE	NEAR EARTH (1 AU + 10 R_E) MEAN	3σ	INTERPLANETARY (3 AU) MEAN	3σ	NEAR JUPITER (5.2 AU + R_J) MEAN	3σ
1. ELECTROMAGNETIC RADIATION TORQUES						
• SOLAR RADIATION	6.88×10^{-7}	2.48×10^{-7}	7.64×10^{-8}	2.75×10^{-8}	2.54×10^{-8}	9.14×10^{-9}
• REFLECTED SOLAR RADIATION	4.63×10^{-9}	2.08×10^{-9}	-	-	5.50×10^{-10}	5.94×10^{-10}
• PLANET THERMAL RADIATION	3.16×10^{-9}	2.29×10^{-9}	-	-	5.81×10^{-10}	7.13×10^{-10}
2. PARTICLES COLLISION TORQUES						
• SOLAR WIND	2.34×10^{-10}	2.70×10^{-10}	2.59×10^{-11}	2.95×10^{-11}	8.63×10^{-12}	9.84×10^{-12}
• METEOROIDS	3.64×10^{-12}	2.55×10^{-11}	2.98×10^{-11}	8.34×10^{-10}	4.51×10^{-11}	3.16×10^{-10}
• COSMIC RAYS	-	5.85×10^{-16}	-	5.85×10^{-16}	-	5.85×10^{-16}
• ATMOSPHERIC PARTICLES	6.18×10^{-12}	1.88×10^{-11}	-	-	3.11×10^{-9}	3.73×10^{-8}
3. MAGNETIC FIELD TORQUES						
• MAGNETIC DIPOLE MOMENT TORQUE	5.64×10^{-8}	6.11×10^{-8}	3.14×10^{-10}	2.84×10^{-9}	1.23×10^{-5}	1.99×10^{-5}
• EDDY CURRENT TORQUE	9.38×10^{-12}	1.77×10^{-11}	8.00×10^{-16}	1.44×10^{-14}	2.17×10^{-7}	6.64×10^{-7}
4. GRAVITY GRADIENT TORQUE	1.32×10^{-6}	3.96×10^{-8}	NIL	NIL	4.66×10^{-6}	4.66×10^{-6}

Table 6. Mean and 3σ of Secular Spin Axis Torques in Newton Meters

SOURCE	NEAR EARTH (1 AU + 10 R_E) MEAN	3σ	INTERPLANETARY (3 AU) MEAN	3σ	NEAR JUPITER (5.2 AU + 4 R_J) MEAN	3σ
1. EDDY CURRENT TORQUE	2.58×10^{-7}	4.90×10^{-7}	5.10×10^{-10}	5.31×10^{-9}	2.00×10^{-5}	6.12×10^{-5}
2. MASS EXPULSION TORQUE	-	9.84×10^{-7}	-	9.84×10^{-7}	-	9.84×10^{-7}
3. PARTICLE COLLISION TORQUES						
• SOLAR WIND	1.25×10^{-13}	1.71×10^{-13}	1.39×10^{-14}	1.91×10^{-14}	4.61×10^{-15}	6.32×10^{-15}
• METEOROIDS	4.59×10^{-16}	3.21×10^{-15}	3.75×10^{-15}	1.05×10^{-13}	2.64×10^{-15}	1.85×10^{-14}
• ATMOSPHERIC PARTICLES	6.94×10^{-17}	2.28×10^{-16}	-	-	1.13×10^{-14}	1.36×10^{-13}

In Table 6 the spin axis torques are reported. All of the values given here are despin torques except for the mass expulsion torque which may be either a spin up or a despin torque. The predominant effect is that of Eddy current torque near Jupiter which is 8×10^{-5} Nm for mean plus 3σ. The result of this is that in order to maintain a spin rate of 0.33 rad/s to within 4%, a spin rate correction would be required every:

$$\Delta t = (4\%)\ (0.33\ \text{rad/s})\ (5000\ \text{kg m}^2)/(8 \times 10^{-5}\ \text{Nm})$$

$$= 8.25 \times 10^5\ \text{s} = 9.5\ \text{days}$$

due to the Jovian magnetic field alone.

Further Discussion

The numerical results of the previous section indicate that the nongravitational forces and space environmental torques can have an important effect on the spacecraft motion. In this section we will consider some of the consequences of these effects when the knowledge of the spacecraft motion is used to deduce the nature of these forces and torques. For example, one of the reasons for the stringent requirement on the knowledge of the Galileo spacecraft acceleration is to enable the gravitational fields of Jupiter and its satellites to be measured, but from the present analysis it is clear that there are forces which act inversely proportional to the square of the distance from the gravitating body such as solar radiation, solar wind and reflected and emitted radiation from the planets. These effects may not be easily separated from the gravitational effects. Another area of interest is the search for gravity waves. The sporadic effects of solar wind and other forces discussed here may not be easily separated from the gravity wave effect. A careful study of the nature of the forces and torques may be necessary to determine if the characteristics of each source permits identification and separation from the others. If this can be adequately done then the Galileo spacecraft may be used as an instrument for the detailed measurement of these previously considered error sources.

It is suggested then that a further study into the analysis of the spacecraft motion may enable an enriched scientific return.

Conclusion

In this paper a detailed survey of nongravitational forces and space environmental torques acting upon an interplanetary spacecraft has been given. The forces considered include electromagnetic radiation forces, particle collisions forces, magnetic field forces and nonpropulsive mass expulsion forces. The torques considered include those arising from the above forces as well as gravity gradient torques. The analysis was applied to the Galileo spacecraft mission to Jupiter as an example, but is developed in a general sense so that the models can be useful in the analysis of other space missions.

In the application to the Galileo spacecraft the models indicate that solar radiation effects must be accounted for in the trajectory analysis in order to satisfy mission requirements. This was no surprise - all recent interplanetary spacecraft trajectories are modeled to include gravitational fields and solar radiation forces. What is surprising is the fact that effects which were thought to be negligible such as atmospheric particle collisions near Jupiter, nonpropulsive mass expulsion, spacecraft radiation and reflected solar radiation from earth are now within one order of magnitude of current mission requirements. In future missions, some of these effects may have to be modeled in the trajectory analysis along with the gravitational and solar radiation forces and a better understanding of the nature of these forces may be necessary to reduce the uncertainties in the models.

Acknowledgements

The authors thank all those who contributed to this study, especially T. N. Divine, M. Greenfield, G. Gulkis, N. S. Hanner, H. R. Long, R. T. Mitchell, A. D. McRonald, R. L. Newburn, Jr., and J. W. Stultz. We also thank Ms. P. Warner for a beautiful typing job.

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

References

1. Edwards, D. K. and Bevans, J. T., "Radiation Stresses on Real Surfaces", AIAA Journal, Vol. 3, p. 522-523, 1965.

2. Harris, M. and Lyle, R., "Spacecraft Radiation Torques," NASA SP-8027, October, 1969.

3. Thekaekara, M. D., "Solar Electromagnetic Radiation," NASA SP-8005, revised May, 1971.

4. Blanco, V. M. and McCuskey, S. W., Basic Physics of the Solar System, Addison-Wesley Publishing Company, Inc., Reading, Massachusetts, 1961.

5. Allen, C. W., Astrophysical Quantities, University of London, The Athlone Press, 1976.

6. Newburn, Jr., R. L. and Gulkis, G., "Planets and Satellites of the Outer Solar System, Asteroids and Comets," Chapter 5 of Foundations of Space Biology and Medicine, Vol. I, Space as a Habitat, Edited by Melvin Calvin and Oleg G. Gazenko, Joint USA/USSR Publication, Scientific and Technical Information Office, NASA, Washington, D. C., 1975.

7. Wertz, J. R., Spacecraft Attitude Determination and Control, Boston: D. Reidel Publishing Co., 1978.

8. Cour-Palais, B. G., "Meteroid Environment Model - 1969 [Near Earth to Lunar Surface]," NASA SP-8013, March, 1969.

9. Kessler, D. J., "Meteoroid Environment Model - 1970 [Interplanetary and Planetary]," NASA SP-8038, October, 1970.

10. Humes, D. H., "The Jovian Meteoroid Environment," Jupiter, University of Arizona Press, 1976.

11. Beck, A., "Galileo Orbiter Meteoroid Assessment," IOM-3574-79-69, March 1, 1979, JPL Internal Memorandum.

12. Divine, T. N., "Interplanetary Charged Particle Models (1974)," NASA SP-8118, March, 1975.

13. Harris, M. and Lyle, R., "Magnetic Fields - Earth and Extraterrestrial, NASA SP-8017, March, 1969.

14. Shapiro, A. H., The Dynamics and Thermodynamics of Compressible Fluid Flow, Volume I, The Ronald Press Company, New York, 1953.

15. Wiggins, L. E. "Space Environmental Torques on Program P-11 Vehicles," Lockheed Missiles and Space Company Technical Memorandum, LMSC/579844, 79-00647, July 23, 1965.

16. Schalkowsky, S., and Harris, M. "Spacecraft Magnetic Torques," NASA SP-8011, March, 1969.

17. Bagenal, F. and Sullivan, J. D., "Direct Plasma Measurements in the Io Torus and Inner Magnetosphere of Jupiter," Journal of Geophysical Research, Vol 86, No. A10, pages 8447-8466, September 30, 1981.

18. Harris, M. and Lyle, R., "Spacecraft Gravitational Torques," NASA SP-8024, May, 1969.