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Technical Memorandum 33-582

The Solar Radiation Pressure on the Mariner 9 Mars Orbiter

R. M. Georgevic

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PREFACE

The work described in this report was performed by the Mission Analysis Division of the Jet Propulsion Laboratory.

CONTENTS

ABSTRACT

The refined mathematical model of the force created by the light pressure of the Sun has been used to compute the solar radiation pressure force acting on the Mariner 9 (Mariner Mars 1971) spacecraft, taking into account the reflectivity characteristics of all its components. The results have been compared with values obtained from Mariner 9 observations during the cruise phase and found to be in agreement within 0.1% of the values.

I. INTRODUCTION

In this study of the solar radiation force acting on the Mariner 9 (Mariner Mars 1971) Mars orbiter, we shall use the refined mathematical model derived in Ref. 1, and apply the formulae to each component of the spacecraft, the reflectivity characteristics of which being known from ground measurements.

The Mariner 9 Mars orbiter is a complex spacecraft consisting of a number of components of various shapes asymmetrically arranged about its roll axis, pointing toward the Sun (Fig. 1). The orientation of the spacecraft is maintained by the Sun and Canopus sensors so that a non-inertial spacecraft-fixed frame of reference can be defined in the following manner. Taking the Sun-spacecraft direction as the positive direction of the z-axis and denoting $\bar{r}$ as the heliocentric position vector of the spacecraft, we have (Refs. 2 and 3)

$$\bar{k} = \frac{\bar{r}}{r}$$

where $r = |\bar{r}|$, and $\bar{k}$ is the unit vector along the z-axis.

We now define the unit vector $\bar{u}_C$ along the direction in which the fixed star (Canopus) is viewed from the spacecraft. (Because of the presumably infinite distance of the star, this direction is the same as the geocentric direction of the star.) Then the expressions

$$\bar{j} = \frac{\bar{u}_C \times \bar{k}}{|\bar{u}_C \times \bar{k}|}$$

and

$$\bar{i} = \bar{j} \times \bar{k}$$

define the unit vectors along the y- and x-axes, respectively (Fig. 2).

We obtain the pitch-yaw-roll system of coordinate axes (Fig. 1) by rotating the above described frame of reference about the x-axis by the angle K = 180° + ϕ, where (Fig. 3)

$$\phi = 32.2°$$

The unit vectors along the axes of this system are given by

$$\bar{e}_1 \text{ (pitch)} = -\bar{i}\cos\phi - \bar{j}\sin\phi \qquad \text{(X-axis)}$$

$$\bar{e}_2 \text{ (yaw)} = \bar{i}\sin\phi - \bar{j}\cos\phi \qquad \text{(Y-axis)}$$

$$\bar{e}_3 \text{ (roll)} = \bar{k} \qquad \text{(Z-axis)}$$

or, explicitly,

$$\bar{e}_1 = \bar{u}_C \frac{\cos\phi}{\sin\gamma} - \frac{\bar{r}}{r}\cos\phi \cot\gamma - \left(\bar{u}_C \times \frac{\bar{r}}{r}\right)\frac{\sin\phi}{\sin\gamma}$$

$$\bar{e}_2 = -\bar{u}_C \frac{\sin\phi}{\sin\gamma} + \frac{\bar{r}}{r}\sin\phi \cot\gamma - \left(\bar{u}_C \times \frac{\bar{r}}{r}\right)\frac{\cos\phi}{\sin\gamma}$$

$$\bar{e}_3 = \frac{\bar{r}}{r}$$

where

$$\gamma = \arccos(\bar{u}_C \cdot \bar{k}) \neq 0$$

Denoting $\bar{u}'$ as the projection vector of the vector $\bar{u}_C$ in the XY-plane, and counting the cone angle from the roll axis (Z) and the clock angle from the vector $\bar{u}'$ in the XY-plane in the positive direction, we can list the positions of the main spacecraft components, relative to the XYZ frame of reference (Ref. 4), as follows:

(1) Four solar panels, 213.9×90.2 cm^2 each, flat, perpendicular to the Z-axis.

(2) Main body of the spacecraft, containing propulsion module, fuel tanks, thermal blanket, etc., wrapped in a protective cover, thus forming an approximately spherically shaped body of an average radius 78.5 cm.

(3) High-gain antenna in the form of a paraboloidal dish of radius 50.8 cm and depth 18.0 cm. In the deployed position, the cone angle of the antenna's axis of symmetry is -38.3° and its clock angle is 80.1°.

(4) Medium-gain antenna, clock angle of its axis of symmetry 55.0°, cone angle 158.0°.

(5) Low-gain antenna, parallel to the Z-axis, radius 14 cm, depth 6.4 cm.

(6) Maneuver engine, approximately paraboloidal, radius 11 cm, depth 24 cm, parallel to the Z-axis.

Other smaller components, illuminated by solar rays, will be mentioned later.

II. THE SOLAR RADIATION FORCE

Using the same notations as in Ref. 1, we can write the vectorial expression for the solar radiation force in the form of a surface integral over the illuminated surface area S:

$$\overline{F} = - K(r) \iint_S B(\theta)\ d\overline{S} - C_2 K(r) \overline{u} \iint_S \cos\theta\ dS \tag{1}$$

In this expression, θ is the angle of incidence, given by

$$\cos\theta = \overline{u} \cdot \overline{N} \tag{2}$$

where $\overline{N}$ is the unit vector along the local normal to the illuminated surface area S. Hence,

$$d\overline{S} = \overline{N}dS$$

$\overline{u}$ is the unit vector along the spacecraft-Sun direction, i.e.,

$$\overline{u} = -\frac{\overline{r}}{r}$$

Denote γ as the portion of reflected photons, β as the portion of photons reflected specularly, and k as a constant which depends on temperatures and emissivities of the front and back sides of the reflecting surface (Ref. 5), such that

$$k = 1$$

for adiabatic surfaces;

$$k = \frac{e_F T_F^4 - e_B T_B^4}{e_F T_F^4 + e_B T_B^4}$$

for structures which have different temperatures on the front and back surfaces (e_F and e_B are emissivities and T_F and T_B are temperatures of the front and back surfaces, respectively);

$$k = \frac{e_F - e_B}{e_F + e_B}$$

for structures where the front and back surfaces have the same temperature, i.e., for which $T_F = T_B$.

In further calculations, we shall assume that $T_F = T_B$ for all components of the Mariner 9 spacecraft.

Having defined γ, β, and k, we can now write the explicit form of the function $B(\theta)$:

$$B(\theta) = C_1 \cos\theta + 2C_3 \cos^2\theta \tag{3}$$

and the constants C_1, C_2, and C_3, which appear in Eqs. (1) and (3), are

$$\left.\begin{aligned} C_1 &= \frac{2}{3}\left[\gamma(1 - \beta) + k(1 - \gamma)\right] \\ C_2 &= 1 - \beta\gamma \\ C_3 &= \beta\gamma = 1 - C_2 \end{aligned}\right\} \tag{4}$$

The function $K(r)$, where $r = |\overline{r}|$ is the heliocentric distance of the spacecraft, is defined by

$$K(r) = \frac{K_{SR}}{r^2} \tag{5}$$

where K_{SR} is the solar radiation constant:

$$K_{SR} = 1.010 \times 10^{17}\ \text{kg-m/s}^2 \tag{6}$$

The values of reflectivity characteristics β, γ, e_F, e_B, and surface areas S for Mariner 9 spacecraft components are listed in Table 1 (Ref. 6). The quantities k, C_1, C_2, C_3, derived from these values, are also listed in Table 1.

III. THE FLAT-SURFACE COMPONENTS OF THE MARINER 9 SPACECRAFT

For flat surfaces which, due to the orientation of the roll axis of the spacecraft, are perpendicular to the direction of the incoming solar radiation,

$$\bar{N} = \bar{u} = -\frac{\bar{r}}{r}, \quad \theta = 0$$

Hence, from Eqs. (1) and (3),

$$\bar{F} = K(r)(C_1 + C_2 + 2C_3)S\frac{\bar{r}}{r}$$

and the normal force is

$$F_N = P_n K(r) \tag{7}$$

where, from Eqs. (4),

$$P_n = 1 + \frac{\gamma}{3}(2 + \beta) + \frac{2k}{3}(1 - \gamma) \tag{8}$$

The values of P_n are given in Table 1. The total value of P_n for flat surfaces (solar panels and small parts which can be approximated by flat surfaces) is

$$P_n = 9.698 \text{ m}^2 \tag{9}$$

IV. THE HIGH-GAIN ANTENNA

The high-gain antenna has the form of a paraboloidal dish. The axis of symmetry of the dish is inclined to the roll axis of the spacecraft by an angle of 38.3° (Fig. 4). The clock angle of the axis of symmetry of the antenna is 80.1°, which means that the angle between the line $\overline{OC}$ and the positive direction of the X-axis is $X = 47.1°$, as shown in Fig. 4.

The formulae for the components of the solar radiation force for the parabolic antenna, which we take from Ref. 1, are given in an antenna-fixed coordinate frame of reference, defined in the following manner. The z-axis of the system is the axis of symmetry of the antenna, so that the unit vector along this axis is given by

$$\bar{e}_z = \begin{pmatrix} \cos X \ \sin \alpha \\ \sin X \ \sin \alpha \\ - \cos \alpha \end{pmatrix}$$

or, in other words,

$$z = X \cos X \sin \alpha + Y \sin X \sin \alpha - Z \cos \alpha \tag{10}$$

The unit vector along the x-axis of the system is then defined by

$$\bar{e}_x = \frac{\bar{u} \times \bar{e}_3}{\sin \alpha}, \quad \cos \alpha = \bar{u} \cdot \bar{e}_z > 0$$

or

$$\bar{e}_x = \begin{pmatrix} \sin X \\ - \cos X \\ 0 \end{pmatrix}$$

and, finally, the unit vector along the y-axis is given by

$$\bar{e}_y = \bar{e}_z \times \bar{e}_x$$

or

$$\bar{e}_y = \begin{pmatrix} -\cos\chi\cos\alpha \\ -\sin\chi\cos\alpha \\ -\sin\alpha \end{pmatrix}$$

Hence, the transformation between the components of the solar radiation force in the XYZ-system and the components in the xyz-system is given by

$$\begin{pmatrix} F_X \\ F_Y \\ F_Z \end{pmatrix} = \begin{pmatrix} \sin\chi & -\cos\chi\cos\alpha & \cos\chi\sin\alpha \\ -\cos\chi & -\sin\chi\cos\alpha & \sin\chi\sin\alpha \\ 0 & -\sin\alpha & -\cos\alpha \end{pmatrix} \begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix} \qquad (11)$$

or

$$\begin{pmatrix} F_X \\ F_Y \\ F_Z \end{pmatrix} = \begin{pmatrix} 0.7420 & -0.5261 & 0.4155 \\ -0.6704 & -0.5823 & 0.4599 \\ 0 & -0.6198 & -0.7848 \end{pmatrix} \begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix} \qquad (12)$$

Following Ref. 1, we shall denote δ as the diameter of the antenna reflector and ζ as the depth of the dish and introduce the auxiliary angle Ω defined by

$$\tan\Omega = 2\frac{\zeta}{\delta}$$

The components of the solar radiation force are then

$$\left.\begin{aligned} F_x &= 0 \\ F_y &= K(r)(C_3 I_{21} + C_1 I_{22} - C_2 I \sin\alpha) \\ F_z &= -K(r)(C_3 I_{31} + C_1 I_{32} + C_2 I \cos\alpha) \end{aligned}\right\} \tag{13}$$

where

$$\left.\begin{aligned} I_{21} &= -\pi\delta^2 (1 + 2\cot^2\Omega \ln\cos\Omega) \sin 2\alpha \\ I_{22} &= -\frac{1}{3}\pi\delta^2 \frac{1 - \cos\Omega}{1 + \cos\Omega} (2 + \sec\Omega) \sin\alpha \\ I_{31} &= \frac{1}{2}\pi\delta^2 \Big[1 - 2\cot^2\Omega \ln\cos\Omega \\ &\quad - (1 + 6\cot^2\Omega \ln\cos\Omega) \cos 2\alpha\Big] \\ I_{32} &= 2\pi\delta^2 \frac{\cos\Omega}{1 + \cos\Omega} \cos\alpha \\ I &= 2\pi\delta^2 \cos\alpha \end{aligned}\right\} \tag{14}$$

For the Mariner 9 high-gain antenna, $\tan\Omega = 0.7087$, $\pi\delta^2 = 0.8107\ m^2$, and

$$\begin{aligned} I_{21} &= -0.1496\ m^2 \\ I_{22} &= -0.0548\ m^2 \\ I_{31} &= 0.8682\ m^2 \\ I_{32} &= 0.5717\ m^2 \\ I\cos\alpha &= 0.4993\ m^2 \\ I\sin\alpha &= 0.3943\ m^2 \end{aligned}$$

From Table 1, we find that $C_1 = 0.47$, $C_2 = 0.80$, $C_3 = 0.20$, and, therefore, the components of the force are

$$F_x = 0$$

$$F_y = -0.371\ K(r)$$

$$F_z = -0.842\ K(r)$$

Finally, from the transformation Eqs. (12), we obtain

$$\left.\begin{aligned} F_X &= -0.155\ K(r) \\ F_Y &= 0.171\ K(r) \\ F_Z &= 0.891\ K(r) \end{aligned}\right\} \qquad (15)$$

By analogy with Eq. (7), we can write that

$$\left.\begin{aligned} P_X &= -0.155\ m^2 \\ P_Y &= 0.171\ m^2 \\ P_Z &= P_n = 0.891\ m^2 \end{aligned}\right\} \qquad (16)$$

V. THE MEDIUM-GAIN ANTENNA

For the medium-gain antenna, Table 1 yields $P_n = 0.086\ m^2$, but no reflectivity characteristics are given. Consequently, we have to consider the antenna as a flat surface. The antenna is shaped in the form of a circular cylinder of radius 4.8 cm with a dish at the end of radius 12.5 cm. The depth of the dish is approximately one-half of the protruding part of the cylinder. The total length of the antenna is h = 0.61 m. The surface area of the antenna is thus

$$A_P = 0.120 \text{ m}^2$$

Due to the lack of data, only the normal component F_Z of the solar radiation force can be determined. The other two components, F_X and F_Y, although different from zero, cannot be determined. The force F_Z is, therefore,

$$F_Z = F_N = 0.086 \; K(r) \tag{17}$$

VI. THE LOW-GAIN ANTENNA

The axis of symmetry of the low-gain antenna is parallel to the roll axis (Z-axis) of the spacecraft. Using the same denotations as in Eqs. (13) and (14), we find for the antenna reflector:

$$\alpha = 0$$

$$\tan \Omega = 0.914$$

$$\pi\delta^2 = 0.062 \text{ m}^2$$

$$I_{21} = I_{22} = 0$$

$$I_{31} = 0.090 \text{ m}^2$$

$$I_{32} = 0.053 \text{ m}^2$$

$$I = 0.062 \text{ m}^2$$

Hence, $P_n = 0.093\ m^2$, and

$$\left. \begin{aligned} F_X &= F_Y = 0 \\ F_N &= F_Z = 0.093\ K(r) \end{aligned} \right\} \tag{18}$$

VII. THE PROPULSION MODULE

The surface area of the propulsion module is approximately a sphere of radius 0.785 m. Since the top part of the module is shaded by the maneuver engine, the illuminated surface area of the module is a spherical belt between the latitudes 0 and 82° (Fig. 5). The equation of the surface is

$$\Phi(X, Y, Z) = X^2 + Y^2 + Z^2 - \delta^2 = 0$$

where δ is the radius of the sphere. The unit vector along the local normal on the surface is given by

$$\overline{N} = \frac{\text{grad}\ \Phi}{|\text{grad}\ \Phi|} = \frac{\overline{R}}{\delta}$$

where $|\overline{R}| = \delta$. Hence,

$$\cos\theta = \overline{u} \cdot \overline{N} = -\frac{\overline{r}}{r} \cdot \frac{\overline{R}}{\delta} = -\frac{Z}{\delta}$$

Introducing polar coordinates,

$$X = \rho \cos\phi$$

$$Y = \rho \sin\phi$$

$$dXdY = \rho d\rho d\phi$$

we have

$$dS = \frac{dXdY}{\left|\overline{N} \cdot \overline{k}\right|} = \delta\rho \frac{d\rho d\phi}{\sqrt{\delta^2 - \rho^2}}$$

and

$$\cos\theta = -\frac{\sqrt{\delta^2 - \rho^2}}{\delta}$$

$$Z = -\sqrt{\delta^2 - \rho^2}$$

Substituting these values into the expression for the solar radiation force, given by Eq. (1), we find, after the integration,

$$\left.\begin{aligned} F_X &= F_Y = 0 \\ F_Z &= \pi(\delta^2 - a^2)K(r)\left(\frac{2C_1}{3\delta}\sqrt{\delta^2 - a^2} + C_2 + C_3 - \frac{a^2}{\delta^2}C_3\right) \end{aligned}\right\} \qquad (19)$$

where a is the radius of the maneuver engine at the top. Denoting

$$\sin\mu = \frac{a}{\delta} = 0.140$$

we find, because $C_2 + C_3 = 1$, for the normal force

$$F_Z = F_N = \pi\delta^2 K(r)\left(1 + \frac{2C_1}{3}\cos\mu - C_3 \sin^2\mu\right)\cos^2\mu$$

or

$$\left.\begin{aligned} F_Z &= F_N = 2.358\ K(r) \\ P_n &= 2.358\ m^2 \end{aligned}\right\} \tag{20}$$

and, also, for the surface area illuminated by sunrays,

$$A_P = 1.936\ m^2 \text{ (with maneuver engine)} \tag{21}$$

VIII. THE MANEUVER ENGINE

The axis of symmetry of the maneuver engine is parallel to the roll axis of the spacecraft. We assume that the engine nozzle has the shape of a paraboloid of revolution and once again apply the formulae (13) and (14). Here

$$\tan \Omega = 4.364, \qquad \alpha = 0$$

Hence, we obtain

$$I_{21} = I_{22} = 0$$

$$I_{31} = 0.012\ m^2$$

$$I_{32} = 0.014\ m^2$$

and, accordingly,

$$\left.\begin{aligned} F_X &= F_Y = 0 \\ F_Z &= F_N = 0.032\ K(r) \\ P_n &= 0.032\ m^2 \end{aligned}\right\} \tag{22}$$

IX. THE TOTAL SOLAR RADIATION FORCE

Summing up all the components of the solar radiation force acting on all parts of the spacecraft, given by Eqs. (9), (15), (17), (18), (20), and (22), we find

$$\left.\begin{aligned} F_X &= -0.155\ K(r) \\ F_Y &= 0.171\ K(r) \\ F_Z &= F_N = 13.158\ K(r) \end{aligned}\right\} \tag{23}$$

and the total force $F_{SR} = \sqrt{F_X^2 + F_Y^2 + F_Z^2}$ is

$$F_{SR} = 13.160\ K(r) \tag{24}$$

At the average distance of Mars, this force is

$$F_{SR} \cong 2.558 \times 10^{-5} \text{ newtons}$$

During the cruise phase, the weight of the spacecraft was W = 558.8 kg. Hence, its acceleration due to the solar radiation was

$$a_{SR} = 4.58 \times 10^{-11} \text{ km/s}^2$$

X. COMPARISON WITH OBSERVATIONS

The simplicistic solar radiation force model, currently used in the Jet Propulsion Laboratory's double precision orbit determination program, is given by

$$\overline{F} = (G_r\overline{k} + G_x\overline{i} + G_y\overline{j})A_P K(r)$$

where A_P is the effective cross-sectional area of the spacecraft, and G_x, G_y, G_r are solve-for parameters that are to be determined from observations.

Since G_x and G_y are small, their determination from observations is rather inaccurate. However, the value of G_r has been evaluated during the cruise phase of the spacecraft. Its value is

$$G_r = 1.2275 \tag{25}$$

A comparison of the two models yields

$$G_r = \frac{P_n(\text{TOTAL})}{A_P(\text{TOTAL})}$$

We have already found in Eq. (23) that the total value of P_n is

$$P_n = 13.158 \text{ m}^2$$

We also find that the total surface area of the illuminated part of the spacecraft is

$$A_P = 10.708 \text{ m}^2$$

Hence, we find

$$G_r = 1.2288 \tag{26}$$

Comparing the observed value (25) with the computed value (26), we see that they agree within 0.1% of the value of G_r.

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Table 1. Reflectivity characteristics of spacecraft components

Spacecraft component	γ	β	e_F	e_B	k	C_1	C_2	C_3	$S(m^2)$	$P_n(m^2)$
Solar panels	0.21	1.00	0.81	0.81	0	0	0.79	0.21	7.718	9.339
Propulsion module	0.64	0.67	0.80	----	1.00	0.38	0.57	0.43	Curved (1.732)	(3.135)
High-gain antenna	0.30	0.67	0.84	0.06	0.87	0.47	0.80	0.20	Curved (0.605)	(1.010)
Low-gain antenna	0.70	0.67	0.82	0.05	0.89	0.33	0.53	0.47	Curved (0.055)	(0.099)
Solar panel outriggers	0.80	1.00	0.05	0.05	0	0	0.20	0.80	0.123	0.221
Medium-gain antenna	----	----	----	----	----	----	----	----	Curved	0.086
Cruise Sun sensor	0.80	1.00	0.05	0.05	0	0	0.20	0.80	0.004	0.007
Solar panel end beams	0.14	1.00	0.86	0.86	0	0	0.86	0.14	0.067	0.076
Solar panel boost dampers	0.15	1.00	0.85	0.85	0	0	0.85	0.15	0.009	0.010
Pin pullers	0.80	1.00	0.05	0.05	0	0	0.20	0.80	0.011	0.020
Attitude control jets	0.15	1.00	0.85	0.85	0	0	0.85	0.15	0.022	0.025

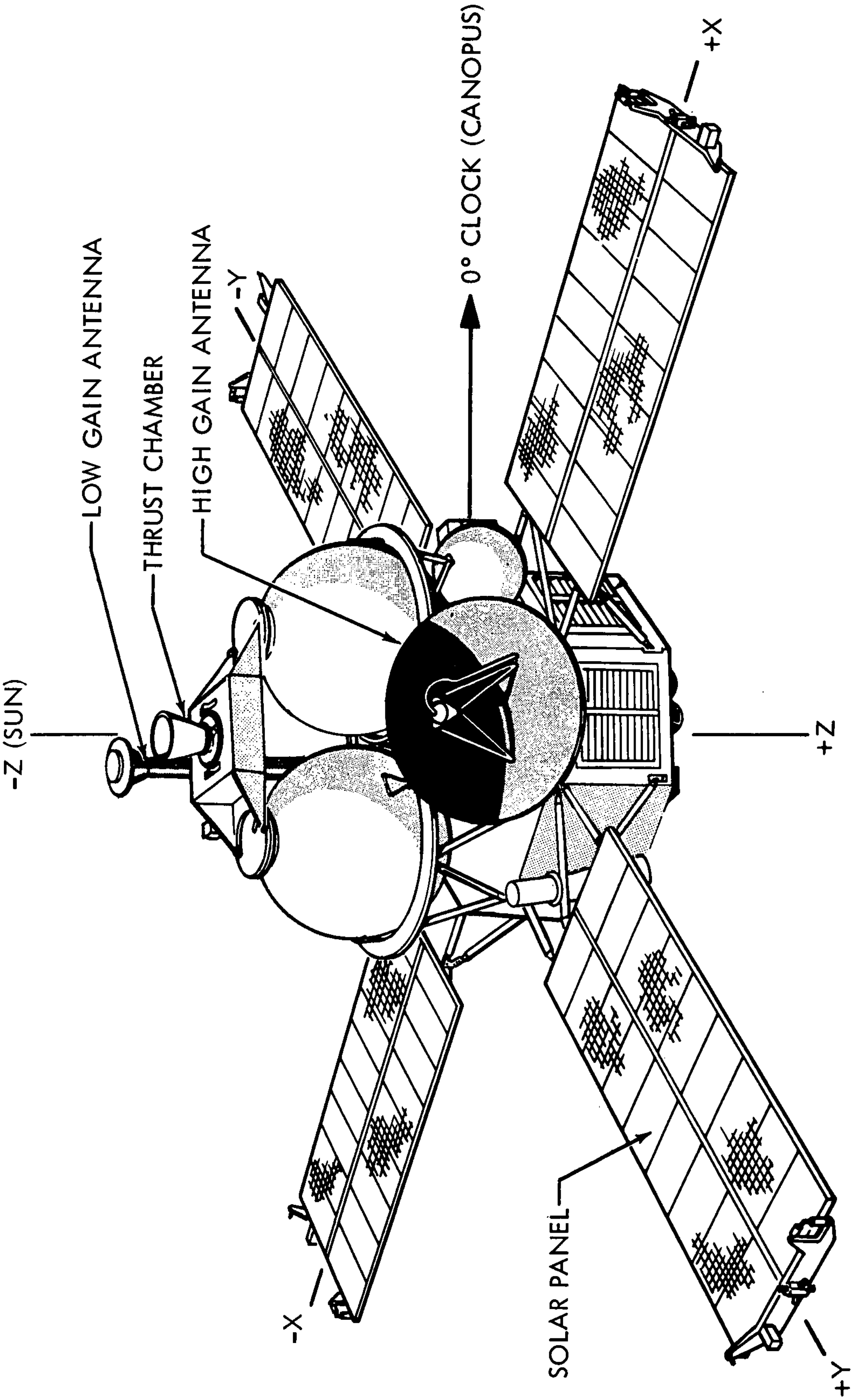

Fig. 1. Mariner 9 spacecraft

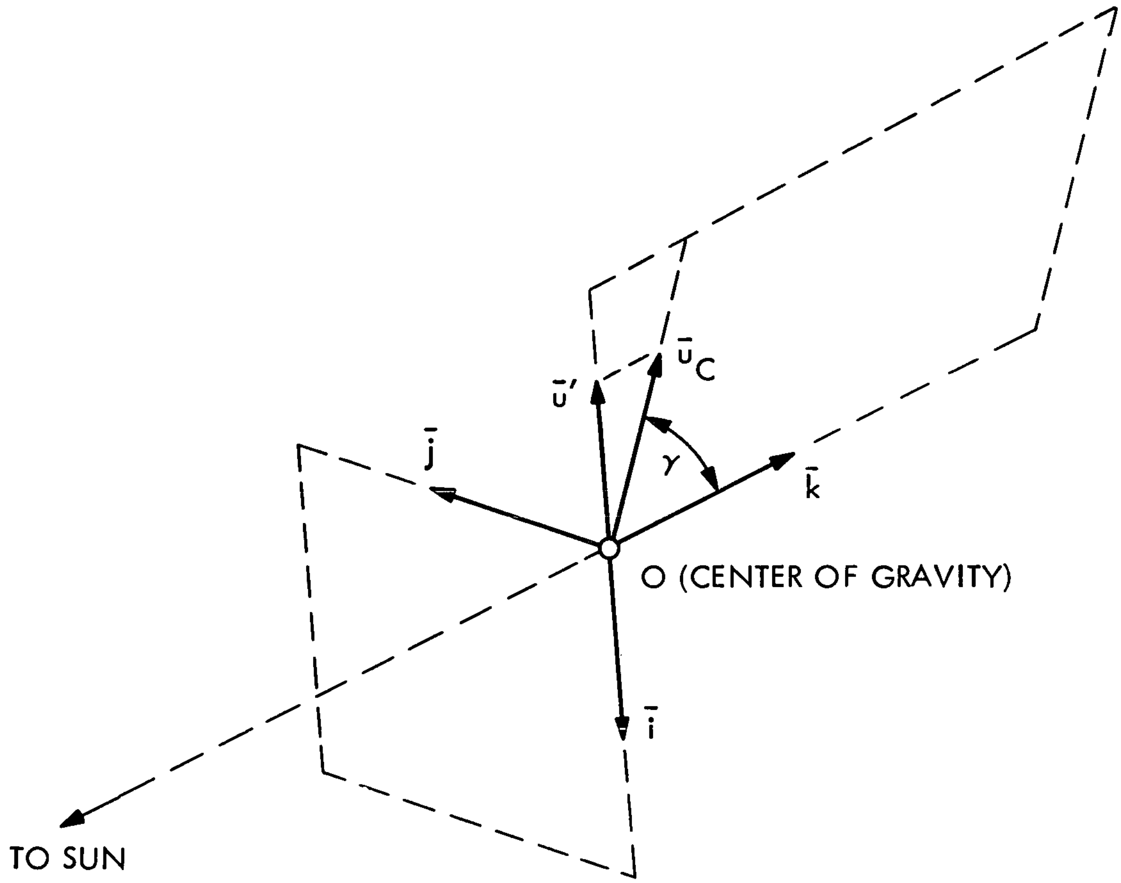

Fig. 2. Orientation of the spacecraft

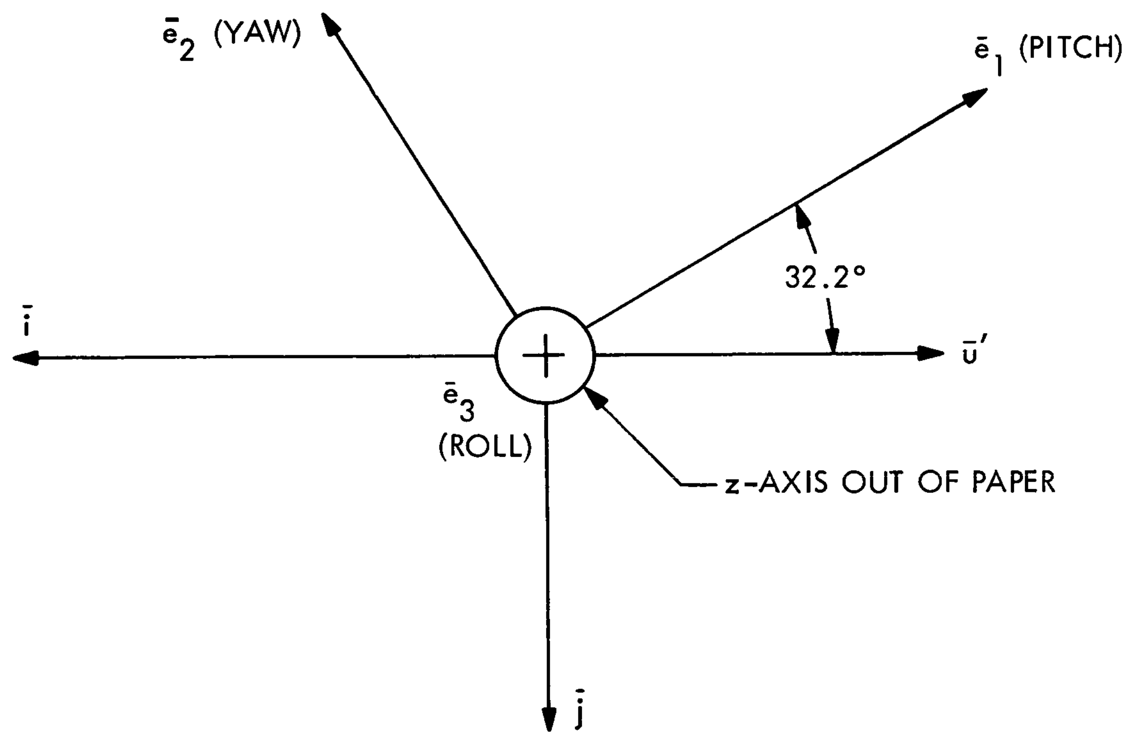

Fig. 3. Pitch-yaw-roll system of reference axes

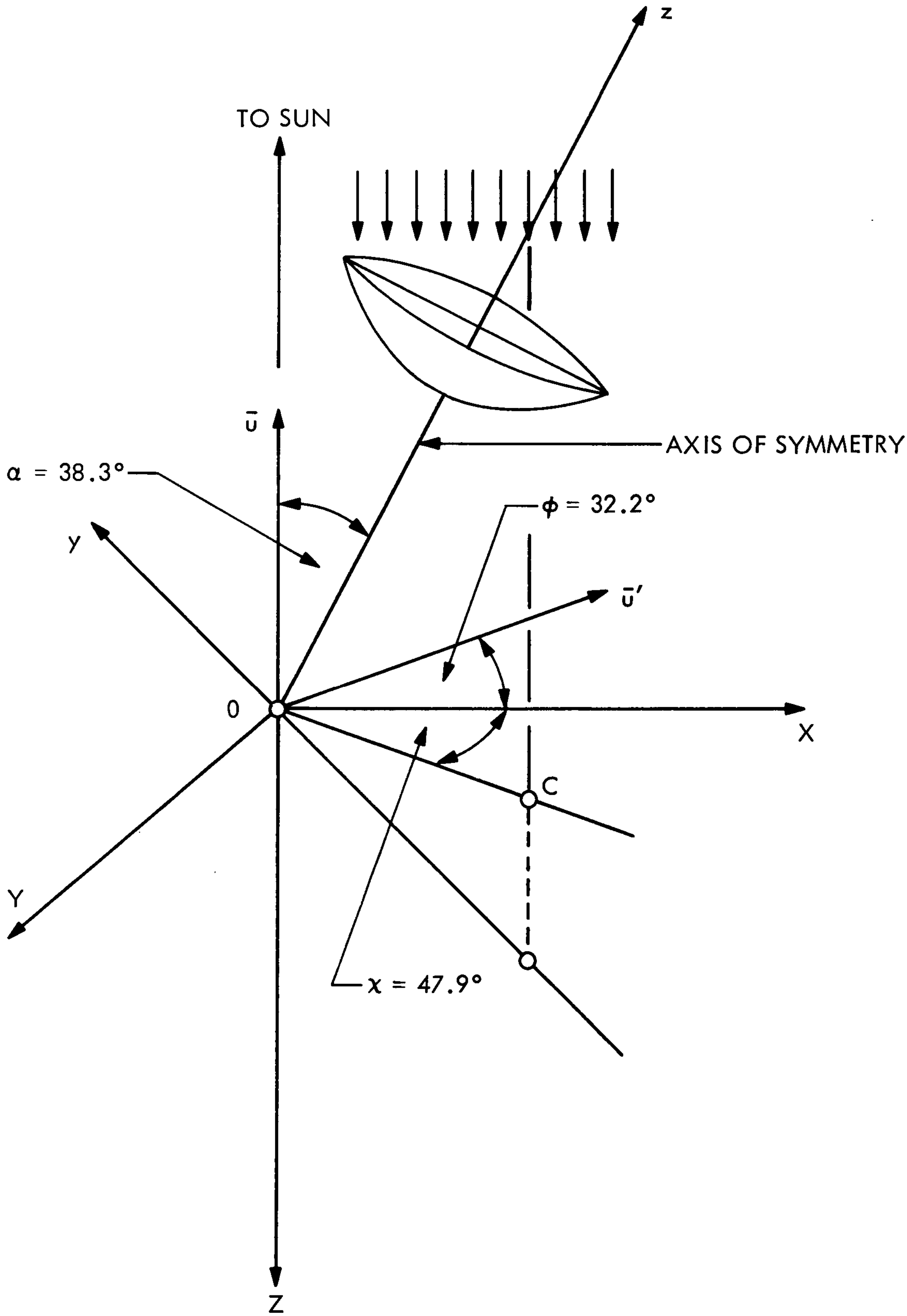

Fig. 4. The high-gain antenna

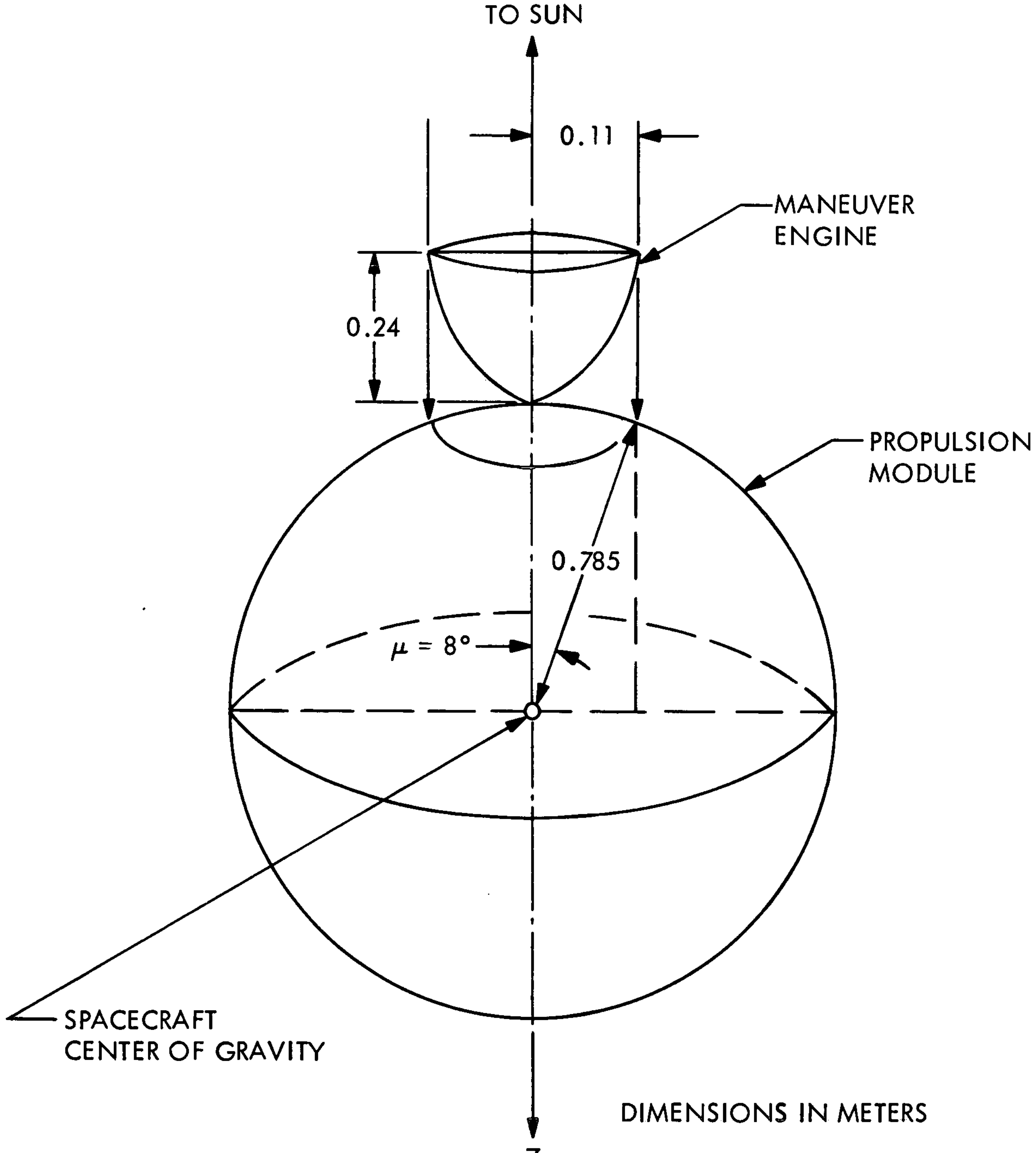

Fig. 5. Propulsion module

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