Impulse Measurement of a Pulsed-Plasma Engine on Engineering Test Satellite-IV

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A space test of a pulsed-plasma engine was carried out on the Engineering Test Satellite-IV. The engine was operated successfully more than 300,000 times in space. The spin rate of the satellite was measured with a high accuracy for the impulse estimation of the engine. The spin rate change was, however, smaller than that given by simple estimation based on the impulse measured by the ground test. It was observed that the variation of the spin rate was the same order of magnitude as the variation due to the natural damping by air drag or the temperature variation of the satellite. The impulse of the engine calculated from the space test data taking account of these effects agreed with the impulse measured by ground tests using a pendulum.

Nomenclature

AM	= operational mode, pulsed plasma engine is operated continuously at the repetition rate of 1.4 pps
ETS-IV	= Engineering Test Satellite-IV
f	= repetition rate of firing for an engine module
HM	= operational mode, pulsed plasma engine is operated continuously at the repetition rate of 1.5 pps
HOST	= horizontal scanner of turning head
I	= moment of inertia of ETS-IV
I_{bit}	= impulse produced by engine
l	= effective moment arm length of the engine to increase or decrease the spin rate
m	= integer
N	= number of data
n	= integer, resampling rate of telemetry data of monitor solar cell
n_i	= number of engines to be fired
PPE	= pulsed-plasma engine
PPE-C	= controller of the engine
PPE-PC, PPE-PC1-4	= power conditioner of the engine
PPE-E, PPE-E1-4	= engine module
PPE-W	= wire harness of the engine
PPE00-28	= run number of the PPE space test
PPE #1/3 HM	= operational mode, a pair of engine modules (PPE-E1 and PPE-E3) are operated with HM mode
PPE #2/4 HM	= operational mode, a pair of engine modules (PPE-E2 and PPE-E4) are operated with HM mode
T	= time interval required for spin rate measurement
T_0	= original sampling period of telemetry data, 2.048 s
t_0	= spin rate period of the satellite
dt_0	= fraction of t_0
dt	= operating time of the engine
X	= spin rate of ETS-IV
dX	= spin rate change of ETS-IV produced by PPE operation
ΔX	= sensitivity of spin rate measurement by using the monitor solar cell
Z	= repetition rate of resampled telemetry data

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Introduction

A PULSED-plasma engine using Teflon propellant has been studied for attitude control and stationkeeping of a satellite. A space test of the engine was carried out on the Engineering Test Satellite-IV (ETS-IV).[1]

The engine produces the impulse by an acceleration of ablated Teflon due to an electric discharge. Some difficulties arise in impulse measurement since the impulse is rather small compared with the weight of the engine. On ground tests impulse was measured by the use of a pendulum.[2] In the first space test of the engine of this kind, on the Lincoln Experimental Satellite-6 (LES-6), the performance of the engine was demonstrated by achieving an east-west stationkeeping of the satellite.[3,4]

In this study, the spin rate of the ETS-IV is increased or decreased by the operation of the engine, and the impulse is calculated from changes of the spin rate. It is necessary to measure the spin rate with high accuracy. Three methods are considered for the measurement for high sensitivity. Another problem is to evaluate a spin rate change of the satellite caused by other reasons, such as an air drag or an inertia change due to a temperature variation.

Pulsed-Plasma Engine

Table 1 shows the key specifications of the engine to be tested in space and the ETS-IV satellite. The engine system consists of four engine modules (PPE-E), four power conditioners (PPE-PC), and a controller (PPE-C).[1] An energy storage capacitor of 2 μF is charged up to about 1.5 kV, and the charged energy of 2.25 J is dissipated across the front-end surface of the solid Teflon propellant. On the ground test, it was confirmed that the engine produced the impulse of 29 μN · s at the operating condition for space test and the impulse was approximately proportional to the discharge energy.[2] In each firing about 10 μg of Teflon was ablated. The specific impulse was about 300 s.

ETS-IV is a spin-stabilized cylindrical satellite.[5] The flight model of the engine is mounted on the experimental platform located in the middle of the satellite, as shown in Figs. 1 and 2. Each pair of engines is fired alternately and the spin rate of

Table 1 Key specifications of the pulsed-plasma engine and the ETS-IV satellite

Pulsed-plasma engine	
System weight	21.0 kg
PPE-E	1.9 kg × 4
PPE-PC	2.0 kg × 4
PPE-C	3.9 kg
PPE-W	1.5 kg
Power consumption rate	20 W (max)
Energy storage capacitor	2 μF
Charging voltage	1.5 kV
Discharge energy	2.25 J/shot
Impulse	29 μN · s
Propellant	Teflon
Propellant consumption rate	10 μg/shot
Specific impulse	300 s
No. of telemetry channels	24
No. of command items	15
ETS-IV	
Configuration	Column
Diameter	218 cm
Height	218 cm
Weight	638 kg
Moment of inertia	211 kg · m²
Stabilization	Spin
Spin rate	62 rpm
Orbit	Transfer
Apogee	35,600 km
Perigee	185 km
Inclination	28.75 deg
Launch vehicle	N-II
Launch date	Feb. 11, 1981

the satellite is changed. One pair (PPE-E1 and PPE-E3) increases the rate and the other pair (PPE-E2 and PPE-E4) reduces it. The impulse ($I_{\rm bit}$) is

$$I_{\rm bit} = I\,{\rm d}X/n_i fl\,{\rm d}t \qquad (1)$$

where I is a moment of inertia of the satellite, dX a spin rate change, n_i number of engines to be fired, f a repetition rate of firing for an engine, l effective arm length, and dt operating time of the engine.

The nozzle opening of the engine is canted to make the angle 51 deg between the direction of the impulse and the tangent of satellite exterior. Since it is not acceptable to install the engine on the outside of the satellite, the effective arm length l is restricted to 0.656 m. The moment of inertia of the satellite I is 211 kg · m² at the mission period.

The engine is fired in a manual mode or in automatic modes. In the former, it requires a command signal in each firing. In the latter, the firing is repeated continuously with a starting command signal. The maximum power consumption of 20 W limits the repetition rate of the firing up to 1.5 pps. It is fired alternately at the repetition rates of 1.4 pps (AM mode) or 1.5 pps (HM mode) for an impulse measurement.

The impulse estimation needs a highly sensitive measurement of the spin rate. When a pair of engines is operated for a period up to one orbital revolution (10.5 h) in the HM mode, the spin rate change estimated from the ground test data is only 0.09 rpm, as shown in Fig. 3. To obtain the impulse with 10% error, the spin rate must be measured with an accuracy better than 0.009 rpm, which is only 0.015% of the spin rate of the satellite about 60 rpm.

Spin Rate Measuring Method

The spin rate is measured by three methods. In the first method, a spin rate monitor provided with the ETS-IV is scrutinized. The spin rate data are obtained every 16 s, which is useful for in situ monitoring of the rate during the test. However, its sensitivity of about 0.09 rpm is not sufficient for

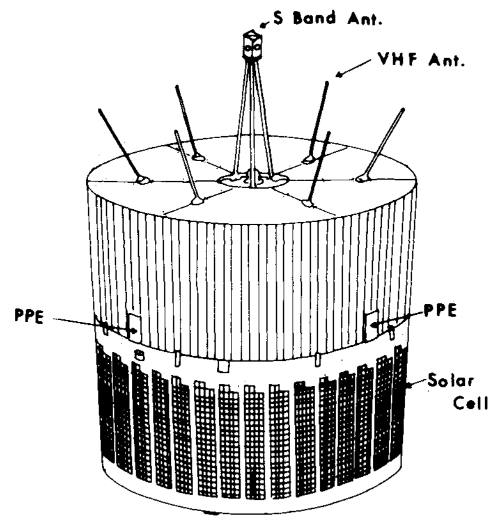

Fig. 1 Engineering Test Satellite-IV.

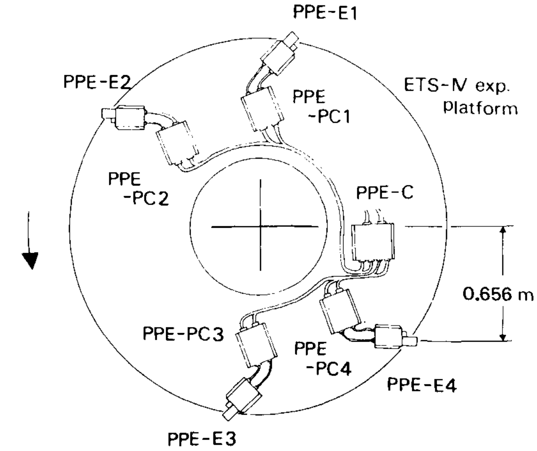

Fig. 2 Layout of pulsed-plasma engine on the experimental platform of ETS-IV.

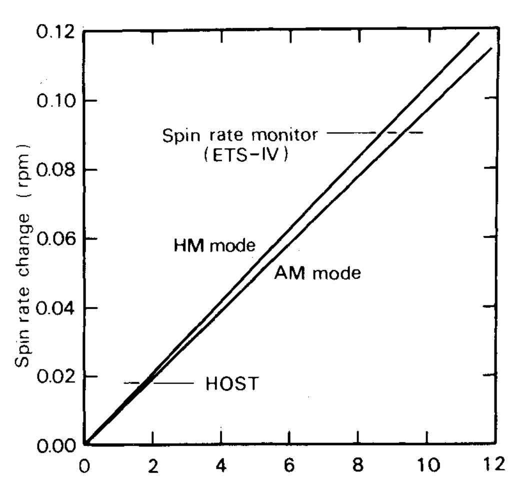

Fig. 3 Spin rate change estimated by using ground test data.

the impulse confirmation either, since the sensitivity is almost the same as the spin rate change produced by the engine itself.

The second method utilizes the horizon sensor with turning head (HOST), which is one of the onboard experimental instruments. It was developed as an attitude sensor of the satellite stabilized in three axes.[6] It can detect the roll and the pitch of the satellite by a rotating sensor which is designed to measure i.r. radiation of the Earth. The rotation of the sensor head is stopped to detect a spin period and a clock pulse is counted over the period for the spin rate measurement.

Figure 4 shows typical spin rate data obtained by this method. The counted clock pulses are averaged for 5 min (about 75 data) because of the scattering of the measured values. The sensitivity of about 0.018 rpm is five times better than that of the first method. The spin rate should be measured just before and after the engine operation. The measurement, however, is limited by the attitude and orbit of the satellite. It is effective only when the sensor detects the Earth; close to the AOS (acquisition of satellite) or LOS (loss of satellite) on each orbital revolution. (All spin rate data are obtained at the LOS because AOS occurred before or after working hours.)

The third method is based on the utilization of the output waveform of a monitor solar cell installed to evaluate its degradation by proton irradiation in the Van Allen radiation belt.

The output voltage of the cell changes with the spin period of the satellite (t_0). Let the original sampling period of telemetry be T_0, fixed to 2.048 s. If every nth data of the telemetry item is resampled, the relation between two periods is expressed as follows:

$$nT_0 = m \cdot t_0 + \mathrm{d}t_0 \tag{2}$$

where m is an integer. The resampled data corresponds to the value of the output voltage of the cell sampled at an interval of $\mathrm{d}t_0$. If every zth value of the resampled data gives the same value, the spin rate X is given as follows:

$$X = 60/t_0 \tag{3}$$

$$X = 60(m + \mathrm{d}t_0/t_0)/nT_0 \tag{4}$$

$$X = 60(m + 1/z)/nT_0 \tag{5}$$

The sensitivity ΔX and the time interval required for the measurement T are expressed as follows:

$$\Delta X = 60/nT_0 z(z+1) \tag{6}$$

$$T = nT_0 z \tag{7}$$

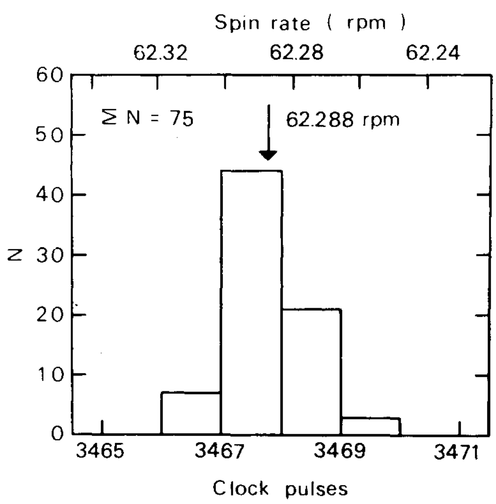

Fig. 4 Typical spin rate data obtained by the HOST.

Figure 5 shows typical spin rate data obtained by this method. The combination of n and m depends on the spin rate. If an appropriate number of n and m can be selected, the most accurate measurement is achieved by the third method. But the time interval for the measurement is longest in this method. Since the spin rate is about 62 rpm during the impulse measurements, m and n selected are 34 and 16, respectively.

Space Test

ETS-IV was launched into a transfer orbit to geostationary orbit on Feb. 11, 1981. The mission period of the satellite was scheduled to be three months and the test of the engine was concentrated in the period as shown in Table 2. The engine

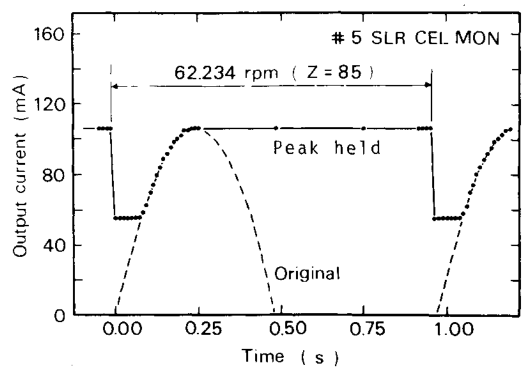

Fig. 5 Typical spin rate data obtained by using a monitor solar cell.

Table 2 Space test schedule of pulsed-plasma engine on ETS-IV

Run No.	Date	Space test of PPE	ETS-IV
PPE00	Feb. 12, 1981	1st AOS check	Mission period
PPE01	Feb. 28, 1981	Electric circuit check	
PPE02	March 20, 1981	Operation test (manual mode)	
PPE03	April 9, 1981	Operation test (AM mode)	
PPE04	April 12, 1981	Operation test (AM mode)	
PPE05	April 13, 1981	Impulse measurement test (#2/4 HM mode)	
PPE06	April 19, 1981	Impulse measurement test (#1/3 HM mode)	
PPE07	April 23, 1981	Impulse measurement test (#1/3 HM mode)	
PPE08	April 26, 1981	Impulse measurement test (#1/3 HM mode)	
PPE09	May 3, 1981	Impulse measurement test (#1/3 HM mode)	
PPE10	May 4, 1981	Impulse measurement test (#1/3 HM mode)	
PPE11	May 7, 1981	Operation test	
PPE12	May 11, 1981	Operation test	
PPE13	May 21, 1981	Health check	Post-mission period
PPE14	May 24, 1981	Health check	
PPE15	July 18, 1981	Health check	
PPE16	Sept. 2, 1981	Health check	
PPE17	Oct. 3, 1981	Health check	
PPE18	Oct. 15, 1981	Operation test in eclipse	
PPE19	Nov. 16, 1981	Health check	
PPE20	Feb. 10, 1982	Health check	
PPE21	April 22, 1982	Health check	
PPE22	June 28, 1982	Health check	
PPE23	July 22, 1982	Health check	
PPE24	Sept. 21, 1982	Health check	
PPE25	Nov. 17, 1982	Health check	
PPE26	Dec. 7, 1982	Health check	
PPE27	March 24, 1983	Health check	
PPE28	May 24, 1983	Health check	

produces the impulse by a high voltage electric discharge which might damage or interfere with the function of highly sensitive instruments of the satellite, such as a command receiver amplifier. Although the electromagnetic noise was reduced almost to the level of the interface specification defined,[7] the space test of the engine was planned and carried out scrupulously.

First, the electric circuits of the engine were checked. Next, the engine was fired 10 times in the manual mode. The engine operated normally and nothing unusual was observed on the satellite system due to the firing of the engine. After these confirmations the engine was operated in the automatic modes. The number and the repetition rate of the firing were increased step by step. Finally, the engine was fired consecutively for several hours for the impulse measurement.

Results and Discussion

The space test of the engine was carried out successfully 12 times in the mission period, as scheduled. The engine operated well about 300,000 times. Any electromagnetic interference by the engine was not observed. The impulse was measured six times in the period.

Figure 6 shows a typical change of the output waveform of the monitor solar cell resampled every 16th interval during an impulse measurement test. The change of the repetition interval shows that the spin rate is obviously changed by the engine operation. In the seventh test, the spin rate change could be detected even by the ETS-IV spin rate monitor.

Figure 7 shows the spin rate change during the impulse measurements. The spin rate is decreased once by the operation of PPE-E2 and PPE-E4 in the HM mode. It is increased five times by the operation of PPE-E1 and PPE-E3. Spin rate measurement by the HOST is carried out at the end of every test, and the data are compared with the data measured prior to the test. The difference of the data obtained by the monitor solar cell and the HOST is reasonably small. The former detects the sun to obtain the spin rate and the latter refers to the Earth. As a result, the total spin cycles measured differs by one cycle in an orbital revolution. In the case of circular orbit, the difference is constant because it is the product of the reciprocal of the period of the satellite and spin rate. In this case, it depends on the altitude of the satellite, because the orbit of the ETS-IV is elliptical. At the apogee the difference is about 0.0007 rpm and at the perigee it is about 0.01 rpm. Since the spin rate is obtained using the HOST at the time close to the perigee, the difference in Fig. 7 is reasonable.

Table 3 shows the summary of the spin rate change. Obvious changes by the engine operation are recognized, however, the changes are smaller than those estimated from the ground test data. To evaluate the accuracy of the space test, the spin rate change of the satellite by other causes should be investigated. Even when the engine was not in operation, considerable spin rate change was observed, as shown in Fig. 8. First, a long-term spin rate change of about 0.005 rpm/day was recognized. An air drag is responsible for the change since the satellite goes through a low-altitude orbit.

Second, a short periodic variation of about 0.01 rpm in an orbital revolution was recognized. The inertia change of the satellite due to the temperature variation is considered to be responsible, because the temperature at the main structure of the satellite changes about several degrees during a test, as shown in Fig. 9. If any external force is not applied to the satellite, the spin rate is proportional to the reciprocal of the inertia. As the main structure is made of aluminum alloy, the inertia change can be estimated using its linear expansion coefficient of 2.3×10^{-5}/deg. When the spin rate is about 62 rpm, it changes by about 0.0028 rpm/deg. Therefore, the spin

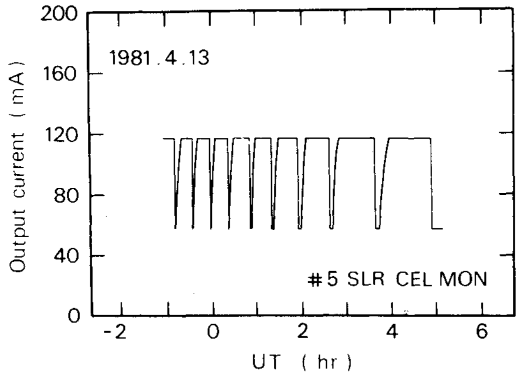

Fig. 6 Typical output waveform of a monitor solar cell sampled every 16th run.

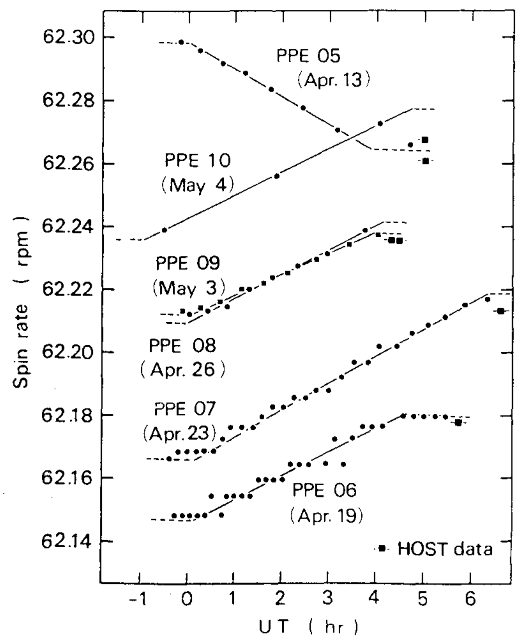

Fig. 7 Spin rate changes on impulse measurement tests.

Table 3 Spin rate changes of ETS-IV by engine operation

Run No.	Date	Mode	No. of firing	Spin rate change, rpm: Expected value	HOST data	Solar cell Monitor data
PPE05	April 13	PPE#2/4HM	3.4 E4	0.033	0.037	0.034
PPE06	April 19	PPE#1/3HM	4.3 E4	0.041	0.037	0.035
PPE07	April 23	PPE#1/3HM	6.2 E4	0.058	0.047	0.052
PPE08	April 26	PPE#1/3HM	4.5 E4	0.041	0.023	0.033
PPE09	May 3	PPE#1/3HM	4.0 E4	0.035	0.029	0.026
PPE10	May 4	PPE#1/3HM	5.9 E4	0.057	0.032	0.042
			2.8 E5	0.265	0.203	0.222

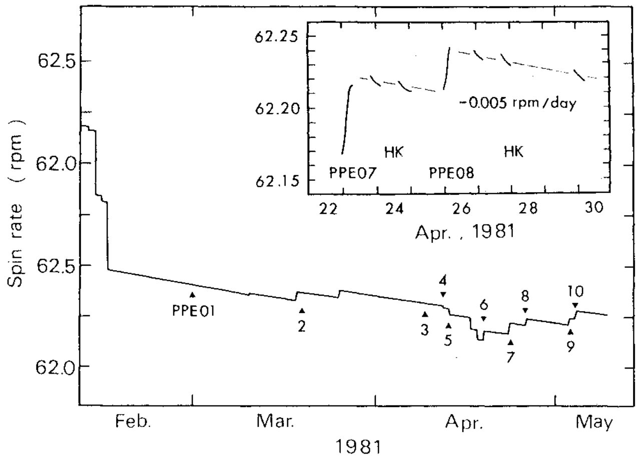

Fig. 8 Spin rate change of ETS-IV.

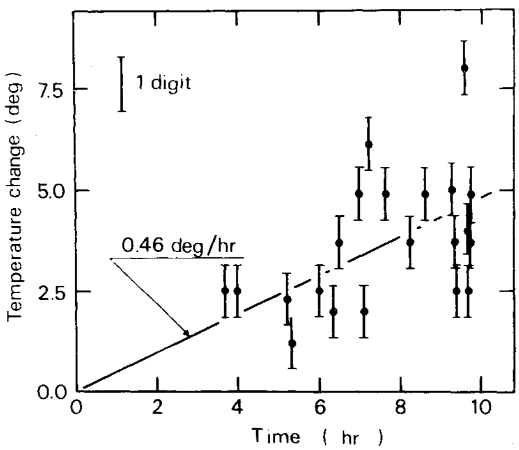

Fig. 9 Total temperature change at the experimental platform of ETS-IV in space test.

Table 4 Corrected data of spin rate changes for temperature variation

	Spin rate change, rpm	
Run No.	Corrected value	Solar cell Monitor data
PPE05	0.040	0.034
PPE06	0.036	0.035
PPE07	0.051	0.052
PPE08	0.034	0.033
PPE09	0.028	0.026
PPE10	0.050	0.042
	0.237	0.222

rate change of about 0.011 rpm is speculated in a revolutional period by temperature variation. This value coincides with the space data.

Table 4 shows the spin rate change corrected for the temperature variation. The value of the variation during the impulse measurement depends on the operating period of the engine and the orbit of the satellite. Taking into account the operating period, the values of spin rate change calculated from the ground test data are corrected for 0.007 rpm. The corrected spin rate changes are in fair agreement with that measured by the monitor solar cell in space as shown in Table 4. In the same manner, the spin rate changes corrected for 0.005 rpm/day agree approximately with that measured using the HOST.

The value of the impulse calculated from the spin rate change correcting temperature effect is 28 $\mu N \cdot s$. It is 94% of the ground test data. Taking into account the measurement error, it is confirmed that the engine produces the impulse in space the same as that measured on the ground.

Concluding Remarks

An impulse measurement of a pulsed-plasma engine was carried out on the ETS-IV satellite in space. The engine was mounted on the satellite in a manner to change the spin rate, and the impulse was calculated from the change in the rate. The measurement of the spin rate with high sensitivity was accomplished by using the HOST and the output waveform of a monitor solar cell. The spin rate change, however, was smaller than that estimated from the impulse obtained by ground tests. A natural damping of about 0.005 rpm/day by air drag, and a periodic variation of about 0.01 rpm due to the temperature change of the satellite in an orbital revolution of the satellite, were recognized. After correction for these effects, the impulse calculated from the spin rate change agreed well with the ground test data.

The engine operated normally 300,000 times in space. Any electromagnetic interference on the satellite was not induced by the engine operation. The number of operations is not enough to judge the engine in regard to future mission lifetime and performance requirements. But the above space test data are available for future use of this engine. The space test is now being carried out every two months for the health check of the engine.

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