In Orbit Operation of 20mN Class Xenon Ion Engine for ETS-VIII

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The Engineering Test Satellite VIII (ETS-VIII) of Japan Aerospace Exploration Agency (JAXA) uses a 20mN class xenon ion engine subsystem (IES) for North-South Station Keeping (NSSK). The IES was modified for a larger satellite with longer lifetime based on the former IES. ETS-VIII, a three-ton class geosynchronous satellite with 10 years bus lifetime, was launched 18 Dec. 2006 JST; it reached the planned orbit and all bus systems were checked out. The IES showed good results and is now under normal operation. The accumulated operation time of the IES in orbit was about 1100 hours for the half year.

Nomenclature

g	=	gravity acceleration
Ia	=	acceleration grid current, mA
Ib	=	beam current, mA
Ick	=	main hollow cathode keeper current, A
Id	=	discharge current, A
Ink	=	neutralizer keeper current, A
M	=	mass of xenon
m_{MHC}	=	main hollow cathode flow rate, SCCM
m_{MPF}	=	main propellant feeder flow rate, SCCM
m_{NHC}	=	neutralizer flow rate, SCCM
Ptrs	=	thruster power consumption, W
q	=	electric charge
T	=	thrust, mN
Va	=	accelerator voltage, V
Vb	=	beam voltage, V
Vck	=	main hollow cathode keeper voltage, V
Vd	=	discharge voltage, V
Vnk	=	neutralizer keeper voltage, V
η_u	=	propellant utilization efficiency
η_T	=	thruster efficiency

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I. Introduction

The first-generation IES was applied for NSSK to two JAXA satellites, ETS-VI and Communications and Broadcasting Engineering Test Satellite (COMETS), a two-ton class geosynchronous satellite with 6 years' bus lifetime. ETS-VI and COMETS were launched respectively in 1994 and in 1998. Although both satellites unfortunately failed to be inserted into their planned orbits, the thrusters were successfully operated in orbit and the thruster characteristics agreed with the ground test results[1-11]. Based on the first-generation IES results, the IES was modified to extend the lifetime[12]. The objective of the modification was to apply for NSSK propulsion of a very large geosynchronous satellite. Development of the ETS-VIII was initiated on 1998. The satellite was a three-ton class geosynchronous satellite with 10 years' bus lifetime; its main mission objective was to verify the mobile satellite communication and multimedia system technology by using a large-scale deployable reflector (LDR). The ETS-VIII image in orbit is shown in Figure 1. The satellite is 2.45 m wide, 2.35 m deep and 7.3 m high. The width of the deployed solar paddles is 40 m. The LDR size is 37 m. The regulated bus voltage is 100 V. The satellite used the IES for NSSK maneuver because the modest low thrust level of electric propulsion was suitable for a flexible structure such as LDR as well as propellant mass reduction attributable to high specific impulse. The IES successfully completed all ground tests including the thruster life test[20].

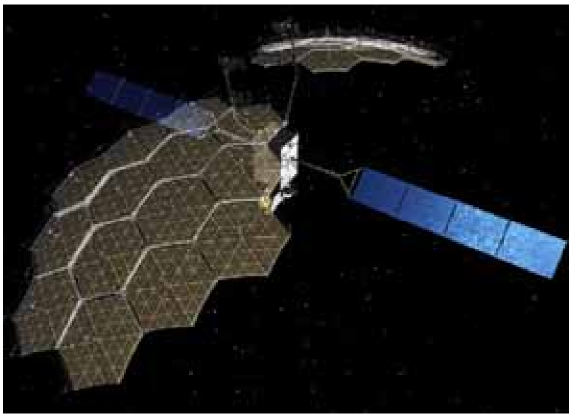


Figure 1 ETS-VIII image in orbit

II. 20mN class ion engine subsystem[13-19]

A. Main specific parameters and construction

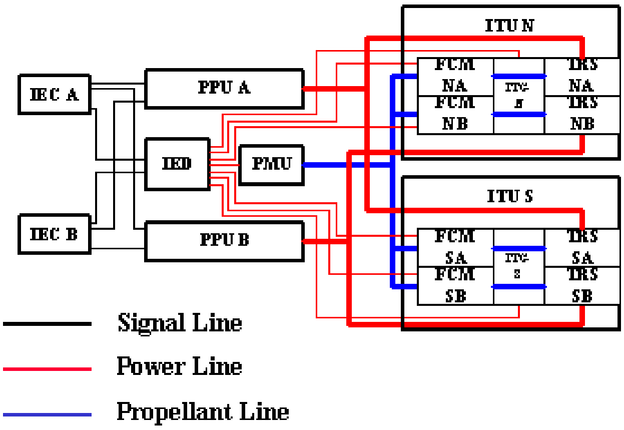
The main specific parameters of the IES are presented in Table 1. In orbit, the north and south ion thrusters will fire for about 5-6 hours, 11 times each two weeks for NSSK alternately.

Table 1 The Main Specific Parameters

Thrust Method	Kaufman-type xenon ion thrusters
Average Thrust from BOL to EOL	>= 20 mN
Average Isp from BOL to EOL	>= 2,200 sec
Total mass of IES	96 kg
Total Impulse	1.15×10^6 N-sec
Total Operation Time	16,000 hours
Total Number of Firing	3,000 cycles
Power consumption during beam firing	<= 880 W
Thrust vector changing range	+/-5 deg

The ETS-VIII IES comprises five components; two Ion Engine Controllers (IEC), two Power Processing Units (PPU), one Propellant Managing Unit (PMU), one Ion Engine Driver (IED) and two Ion Thruster Units (ITU). A block diagram of the IES is portrayed in Figure 2. The IEC controls the operation of PPUs and IED in accordance with sequence logic. The IEC has a command and telemetry interface with ETS-VIII interface unit. The PPU has seven power supplies for operating thrusters. The output of one PPU is switched to north or south thrusters by internal relays. The PMU stores pressurized the xenon propellant and supplies regulated xenon gas to the ITUs. The PMU consists of two xenon storage tanks (TKX), two pyro valves, one Pressure Regulation

Module (PRM), some pressure transducers, and some latching valves. The IED supplies electrical power to actuate the latching valves in both PMU and ITUs and to actuate the gimbal stepping motors. One ITU consists of two thrusters (TRSs) flow control modules (FCMs) and ion thruster gimbal (ITG). The TRS generates thrust for NSSK under the supply of electrical power from PPU and xenon propellant from PMU via FCM. The FCM is constructed with four orifices, including an additional orifice, which increases the flow rate for the neutralizer ignition, and two latching valves. It controls the mass flow rate of three routes to TRS independently. The ITG controls thrust vector by mechanical gimbaling under the supply of electrical power from IED. Each ITU is mounted on north and south edges of the anti-earth panel of ETS-VIII. The ITU on the north edge and ITU on the south edge are respectively called the ITU-N and the ITU-S. The PMU is mounted on the lower deck panel of the satellite. The IEC, PPU and IED are installed in the satellite bus module.



Note : IED/PMU have an internal redundancy

Figure 2 ETS-VIII IES Block Diagram

B. Operational mode of the IES

The IES has several operating modes for hollow cathode conditioning, beam firing, grid cleaning and thrust vector adjustment.

1. Idling Mode (IDLG mode)

In IDLG mode, low power is supplied to hollow cathode heaters (both the Main Hollow Cathode (MHC) and the Neutralizer Hollow Cathode (NHC)) for degassing.

2. Neutralizer Mode (NEUT mode)

In NEUT mode, NHC is supplied xenon propellant, the cathode is heated by the heater and the keeper is supplied electric power. The NHC keeper discharge is ignited and maintained.

3. Discharge Mode (DISC mode)

In DISC mode, the MHC and main discharge chamber are supplied xenon propellant, the cathode is heated by the MHC heater and the MHC keeper and the anode are supplied electric power. After the MHC is ignited, the main discharge between the MHC and anode is ignited and maintained. Then plasma is generated.

4. Beam Mode (BEAM mode)

In BEAM mode, after NHC, MHC and the main discharge are ignited, the grid system of the thruster is supplied electric power and the ion beams are extracted. The NHC supplies electrons during ion extraction in order to maintain electrical neutrality. The IES generates thrust for NSSK maneuvering.

5. Grid Cleaning Mode (CM mode)

During long periods of TRS operation, a short circuit might be created between grid plates by metal flakes. In CM mode, PPU supplies electric power to grid plates to release a short circuit between grid plates.

6. ITG Operation Mode

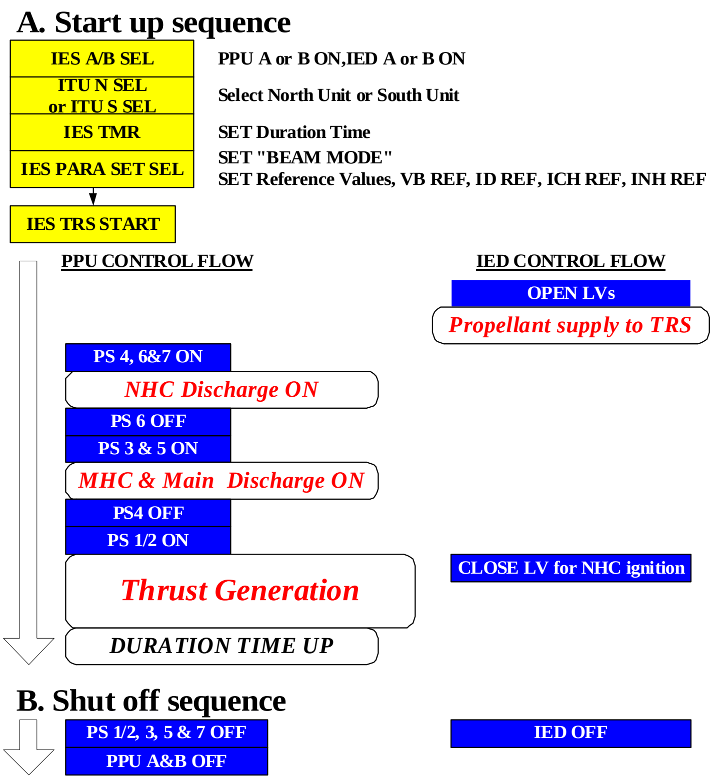
The center of mass of the satellite will move as the propellant is consumed. In this mode, ITG moves the cant angle of TRS to aim the thrust vector at the mass center.

C. Operation

For the NSSK maneuver, one thruster on the south edge generates thrust in the south direction during the required period at the descending node and one thruster on the north edge generates thrust in the north direction at the ascending node.

The control in the IES is performed by the software logic installed in IEC and the hardware logic installed in PPU. Major functions of PPU hardware logic are the high-speed control for the protection of the PPU circuits and TRS critical parts. (e.g., High voltage break down in the thruster's beam extraction system occurs.) The total control of the IES is executed by the sequential commands from IEC to PPU and IED.

For practical NSSK maneuvers by the IES, the IES is operated in BEAM mode. The control sequence is presented in Figure 3. The IES starts its operation when the IEC receives the operation start command, 'IES TRS START' from the Remote Interface Module (RIM) after receiving the thruster selection (primary or secondary and North or South) command, 'IES A/B SEL' and 'ITU-N/ITU-S SEL', duration time of beam firing setting command, 'IES TMR' and operating parameter setting command, 'IES PARA SET SEL'. Then the IEC sends the command to the IED for opening necessary latching valves of both the PMU and FCM and to PPU for supplying electric power to the TRS. According to each PPU operating status signals, the ON/OFF control and output level control for proper power supplies are performed by the IEC. After the duration time reaches the setting period, the IES operation is terminated. Every power supply of the selected PPU is turned off and every latching valve of PMU and FCM is closed.



PS1: Beam Power Supply
PS2: Accelerator Power Supply
PS3: Main Discharge Power Supply
PS4: MHC Heater Power Supply
PS5: MHC Keeper Discharge Power Supply
PS6: NHC Heater Power Supply
PS7: NHC Keeper Discharge Power Supply

Figure 3 Control sequence (Beam mode)

III. Operational Results in progress of the Ion Engine in orbit

ETS-VIII (Figure 4) was launched from Tanegashima Space Center on 18 Dec. 2006 JST using H-IIA booster rocket, as shown in Figure 5. The satellite successfully reached the planned geosynchronous orbit.

Before normal operation, satellite bus systems were checked out for function and performance. The IES was checked out for function modes and performance from 22 Jan. 2007 JST to 29 Jan. 2007 JST. All thrusters showed good operational results. Subsequently, normal operation of the NSSK started from 3 March. To date, both the thruster NA and SA are running smoothly. Secondary thruster operation has not occurred.

Figure 4 Photograph of ETS-VIII on ground

Figure 5 Photograph of the launch

A. In orbit Operation of IES during check out

Four thrusters of the IES were checked out for function modes such as IDLG, NEUT, DISC, CM and BEAM mode. Total beam firing time and high voltage break down number are shown in Table 2. High voltage break down occurs between grid plates with degassing at the beginning of life. Even if a break down occurred, the IES automatically started to fire. The number of high voltage break downs was much smaller than we expected. The ignition times of NHC and MHC are about 1.5 minutes.

Table 2 Total firing time of each thruster at check out

	Total firing time	High voltage break down number
Thruster NA	11 hours 36 minutes	12
Thruster NB	7 hours 51minutes	17
Thruster SA	11 hours 53minutes	6
Thruster SB	8 hours	11

As an example, the BEAM mode telemetry data for Vb, Ib, Ia, Vd, Id, Vck, and Vnk of the thruster SA are shown in Figure 6. Because the discharge current changed from 3.25A to 4.0A, the beam current and keeper voltage of the MHC changed. On the other hand, acceleration grid current, discharge voltage, and keeper voltage of NHC were almost fixed. In Figure 6, Vb and Ib were zero when the break down occurred.

B. In-Orbit Performance Evaluation of Thrusters

A comparison of the performance values in orbit and those of the ground test are shown in Table 3. The values in orbit are the telemetry and design parameter. T, Isp and Ptrs were calculated using the following equations. The design values of Va, Ick, Ink, mMHC, mMPF, and mNHC are, respectively, -500 V, 0.5 A, 0.5 A, 2 sccm, 6.5 sccm, and 0.6 sccm. The value of η_T is assumed as 0.93[8]. Results of the check out indicate that all thrusters of the IES showed good operation and performance.

$$T=\eta_T \cdot Ib\,(2M \cdot Vb/q)^{1/2}$$

$$Isp=\eta_T \cdot \eta_u/g(2q \cdot Vb/M)^{1/2}.$$

$$\eta_u = M \cdot Ib/(q(m_{MPF}+m_{MHC}+m_{NHC}))$$

$$Ptrs=Vb \cdot Ib+|Va| \cdot Ia+Vd \cdot Id+Vck \cdot Ick+Vnk \cdot Ink$$

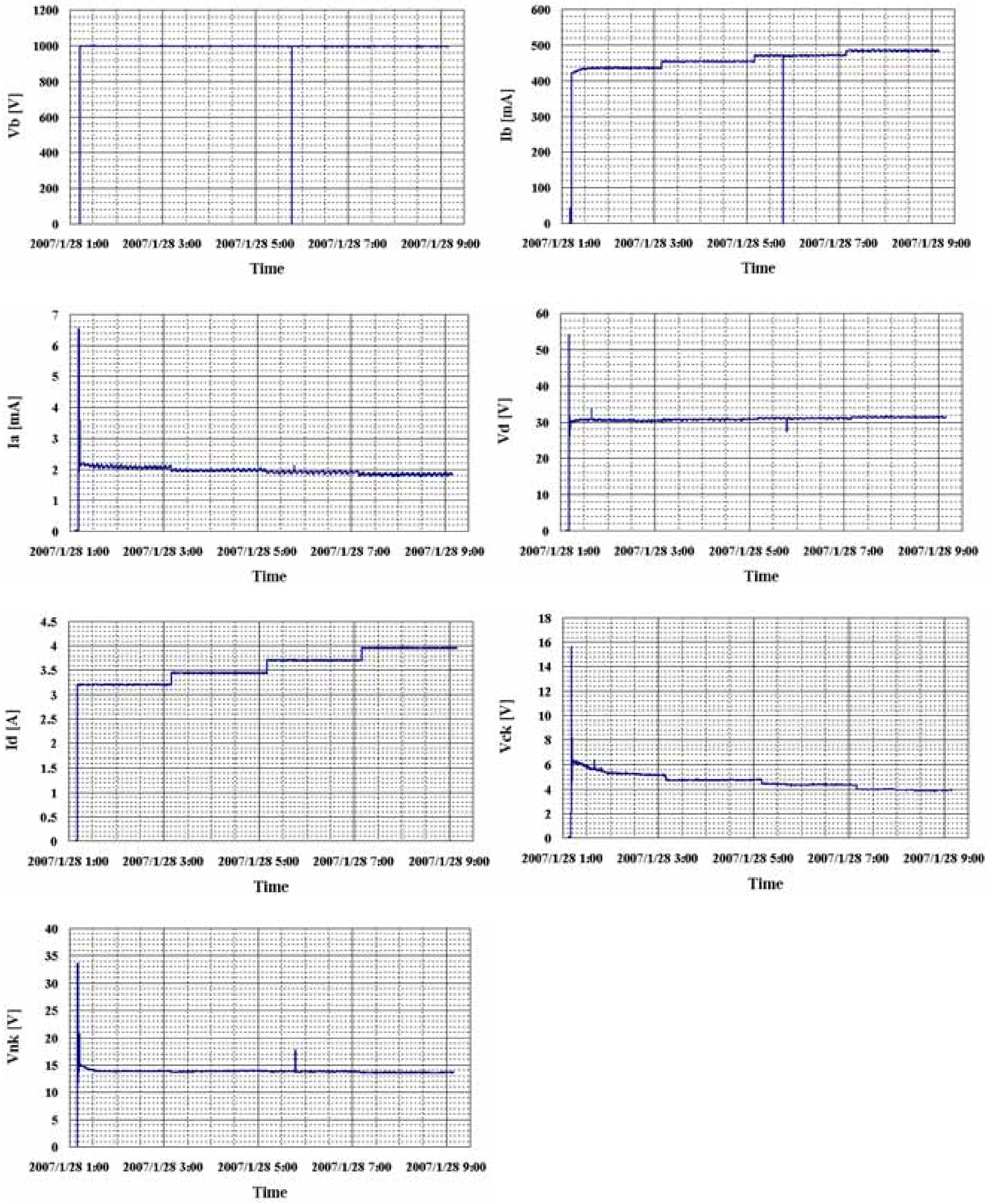


Figure 6 Operational parameter telemetry example of thruster SA

Table 3 Operating parameter comparison of in-orbit and ground tests

Parameter	Thruster NA								Thruster NB							
	BEAM1		BEAM2		BEAM3		BEAM4		BEAM1		BEAM2		BEAM3		BEAM4	
	In orbit	Ground	In orbit	Ground	In orbit	Ground	In orbit	Ground	In orbit	Ground	In orbit	Ground	In orbit	Ground	In orbit	Ground
Vb, V	979	1003.4	979	1002.8	979	1002.3	979	1001.9	991	1003	991	1002.3	991	1002.2	991	1002
Ib, mA	427	442	445	462	461	480	473	494	429	450	450	465	467	482	475	497
Va, V	(-500)	-502.6	(-500)	-506	(-500)	-508.9	(-500)	-511.4	(-500)	-503.5	(-500)	-506.5	(-500)	-509.3	(-500)	-511.8
Ia, mA	1.89	2.2	1.89	2.1	1.89	2	1.89	2	1.88	2.1	1.88	2	1.88	1.9	1.88	1.9
Vd, V	30.7	30.73	30.7	31	30.7	31.22	30.7	31.52	31.3	28.64	31.3	31.54	31.3	31.65	31.3	31.8
Id, A	3.2	3.247	3.45	3.497	3.7	3.747	3.95	4.002	3.22	3.253	3.47	3.498	3.72	3.749	3.98	4.004
Vck, V	4.98	6.4	4.58	6.1	4.19	5.7	3.79	5.3	5.91	6.8	5.08	6.3	4.55	5.7	4.06	5.2
Ick, A	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499
Vnk, V	13.2	14.5	13.2	14.3	13.2	14.2	13.2	14	13.6	15.9	13.6	15.5	13.6	15.3	13.6	15.2
Ink, A	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499	(0.5)	0.5	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499
mMHC, sccm	(2)	9.38	(2)	9.42	(2)	9.38	(2)	9.4	(2)	9.36	(2)	9.36	(2)	9.36	(2)	9.36
mMPF, sccm	(6.5)		(6.5)		(6.5)		(6.5)		(6.5)		(6.5)		(6.5)		(6.5)	
mNHC, sccm	(0.6)		(0.6)		(0.6)		(0.6)		(0.6)		(0.6)		(0.6)		(0.6)	
T, mN	20.5	21.5	21.4	22.5	22.1	23.3	22.7	24	20.7	21.9	21.7	22.6	22.5	23.4	23	24.1
Isp, sec	2352	2392	2452	2489	2537	2596	2606	2666	2376	2440	2496	2520	2586	2612	2635	2693
Ptrs	526	553	551	581	574	607	594	630	536	555	565	586	589	611	605	635

Parameter	Thruster SA								Thruster SB							
	BEAM1		BEAM2		BEAM3		BEAM4		BEAM1		BEAM2		BEAM3		BEAM4	
	In orbit	Ground	In orbit	Ground	In orbit	Ground	In orbit	Ground	In orbit	Ground	In orbit	Ground	In orbit	Ground	In orbit	Ground
Vb, V	996	1002.8	996	1002.3	996	1001.9	996	1001.4	993	1003.3	993	1002.7	993	1002.2	993	1001.6
Ib, mA	434	455	453	475	470	483	485	497	434	447	454	469	470	486	482	501
Va, V	(-500)	-504.3	(-500)	-507.6	(-500)	-508.8	(-500)	-511.1	(-500)	-503.6	(-500)	-507.2	(-500)	-509.7	(-500)	-512.3
Ia, mA	1.95	2.2	1.95	2.1	1.95	2	1.95	2	2.05	2.3	2.05	2.2	2.05	2.1	2.05	2.1
Vd, V	30.9	31.17	30.9	31.2	30.9	30.89	30.9	30.87	31.2	31.03	31.2	31.2	31.2	31.23	31.2	31.46
Id, A	3.23	3.245	3.45	3.496	3.7	3.746	3.95	4.001	3.22	3.246	3.47	3.497	3.72	3.747	3.98	4.003
Vck, V	5.43	6.9	4.77	6.4	4.38	5.6	3.93	5.3	6.65	7.9	5.84	7.4	5.29	6.8	4.79	6.4
Ick, A	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499	(0.5)	0.498	(0.5)	0.498	(0.5)	0.498	(0.5)	0.498
Vnk, V	13.8	19	13.8	18.7	13.8	18.6	13.8	18.5	14.4	20.1	14.4	19.6	14.4	19.1	14.4	18.7
Ink, A	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499
mMHC, sccm	(2)	9.48	(2)	9.46	(2)	9.44	(2)	9.46	(2)	9.3	(2)	9.28	(2)	9.28	(2)	9.28
mMPF, sccm	(6.5)		(6.5)		(6.5)		(6.5)		(6.5)		(6.5)		(6.5)		(6.5)	
mNHC, sccm	(0.6)		(0.6)		(0.6)		(0.6)		(0.6)		(0.6)		(0.6)		(0.6)	
T, mN	21	22.1	22	23.1	22.7	23.5	23.5	24.1	21	21.7	22	22.8	22.7	23.6	23.3	24.3
Isp, sec	2413	2436	2520	2547	2610	2595	2694	2664	2411	2440	2520	2565	2607	2657	2674	2738
Ptrs	542	569	569	597	592	611	614	632	544	562	571	592	594	616	614	639

C. Normal operation status

The IES has functioned smoothly and continuously during 3 March - 15 August. Attitude disturbance attributable to firing is sufficiently low by adjusting the thrust vector by ITG in comparison with that attributable to natural factors. An example of the thrust level of the thrusters is shown in Figure 7. The accumulated beam firing time and number are shown in Table 4.

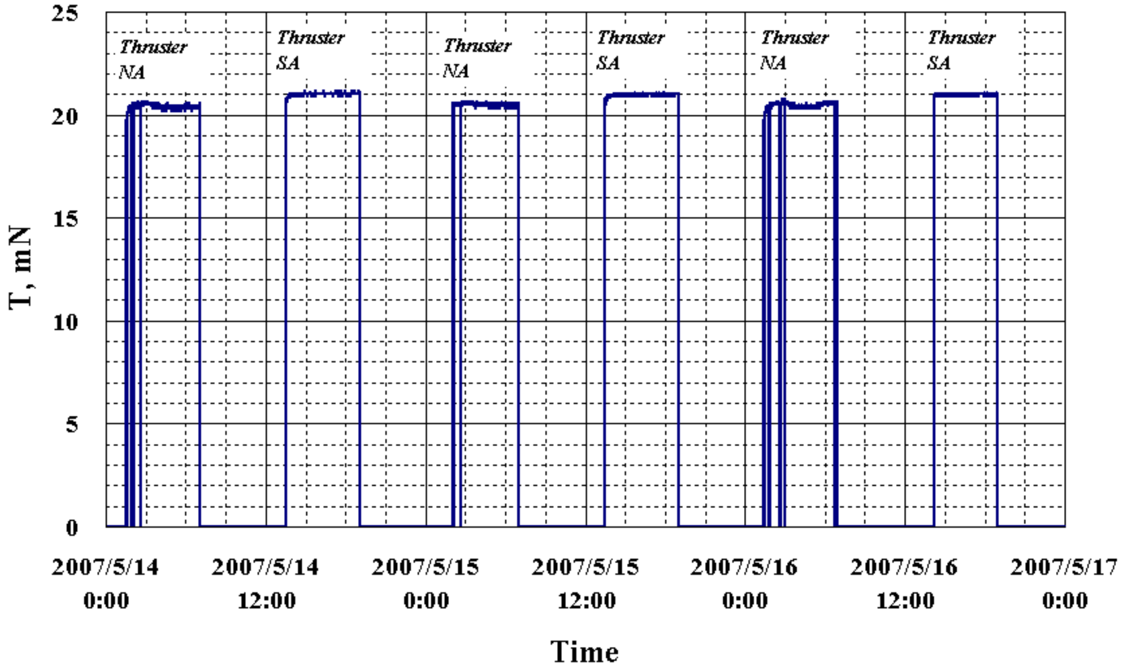


Figure 7 Example of thrust in normal operation (14 - 16 May, 2007)

Table 4 Beam firing time and number in normal operation (22 Jan.-15 Aug.)

	Thruster NA	Thruster NB	Thruster SA	Thruster SB
Accumulated beam firing time	480 hours	83 hours	559 hours	8 hours
Accumulated beam firing number	88 times	15 times	98 times	2 times

IV. Conclusion

The IES on ETS-VIII is now under normal operation on geosynchronous orbit. All thrusters showed good operational results at the check out and primary thrusters are firing for NSSK. The beam firing time of the IES in orbit accumulated about 1100 hours during roughly a half year. We expect to use the 20mN class ion engine with a grid to the wide application such as aerodynamically drag free and deep space exploration.

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