

# ETS-VIII Ion Engine and its Operation on Orbit

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**Abstract:** This paper describes the Ion Engine Subsystem (IES) of the Engineering Test Satellite VIII (ETS-VIII) and its operation on orbit. ETS-VIII was launched by an H-II A launch vehicle on December 18th, 2006, and became the first Japanese geostationary satellite that conducted north-south station keeping (NSSK) by ion propulsion. Despite some anomalies the total operation time of ETS-VIII IES exceeded 6000 hours on orbit.

## I. Introduction

THE Engineering Test Satellite VIII (ETS-VIII) was launched by an H-II A Launch Vehicle from Tanegashima Space Center, one of the Japanese launch sites which is located in the southern part of Japan, in December, 2006. The Ion Engine Subsystem (IES) was installed on ETS-VIII to perform north-south station keeping (NSSK).

ETS-VIII is the third satellite with IES used for NSSK; however, the first two satellites, the Engineering Test Satellite VI (ETS-VI) and the Communications and Broadcasting Satellite (COMETS) with IES did not reach the geostationary orbits because of a malfunction in the apogee engine and a failure in the launch vehicle respectively. So ETS-VIII is the first Japanese geostationary satellite operated by IES for NSSK.

The operation of IES started in March 2007, after thorough tests. This paper describes the operation status of IES on orbit during two and a half years.

## II. Features of the Ion Engine Subsystem

The IES for ETS-VIII was developed by Mitsubishi Electric Corporation (MELCO) as prime contractor for JAXA to provide the delta-V required for NSSK. Figure 1 portrays ETS-VIII and its ion thrusters. Table 1 indicates the main characteristics of IES. Its diagram appears in Figure 2.

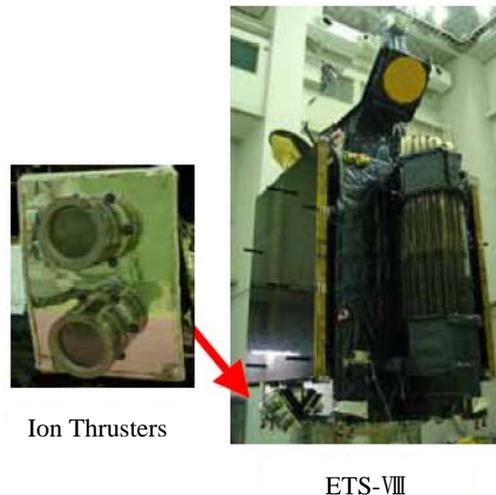


Figure 1 ETS-VIII and Ion Thrusters

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Table 1 Main Characteristics of IES

Parameters	Values
Thrust method	Kaufman-type xenon ion thrusters
Operation configurations	One north thruster at ascending node and one south thruster at descending
Average thrust	$\geq 20\text{mN}$
Average Isp	$\geq 2,200\text{sec}$
Total impulses	$1.15 \times 10^6 \text{N} \cdot \text{sec}$
Total operation times	16,000 hours (with average thrust of 20mN)
Total number of firings	3,000 cycles
Power consumption	$\leq 880\text{W}$
Thrust vector changing range	$\pm 5\text{deg}$

Also Table 2 exhibits the IES components. Certain design changes were made to IES and its components to make it conform to the ETS-VIII system requirements. Table 1 also includes an ion engine subsystem on-board ETS-VI, so as to show the differences between the two subsystems. The main design changes are described below.

**A. Subsystem**

In the case of ETS-VI and COMETS, thrusters were located on the east and west panels of the satellites. One thruster on each panel worked during NSSK. However, in the case of ETS-VIII, thrusters were installed on the north and south edges of the satellite, and one of them fires at an ascend or a descend node of the orbit.

Therefore no balancing between the two thrusters is necessary, but gimbals are required in order to adjust the thrust vector and the center of gravity of the satellite.

**B. Thrusters**

While the previous two satellites weighed approximately two tons on orbit, ETS-VIII weighs approximately three tons. And given the single-thruster operation, the total firing time is expected to be longer than with the former two ion subsystems. So ETS-VIII ion engine thrusters are required to have a lifetime of 16,000 hours.

To meet this requirement a coating on grid materials which resists ion spatters was installed and the discharge voltage was reduced.

**C. Gimbals**

As the misalignment resulting from a single-thruster firing may cause unfavorable momentum, it is necessary to control the thrust vector. Gimbals are adopted to reduce this misalignment for the first time. They can change a thrust vector from +5 deg to -5 deg, and then direct it to the center of gravity of the satellite.

**D. Propellant Management Units (PMU)**

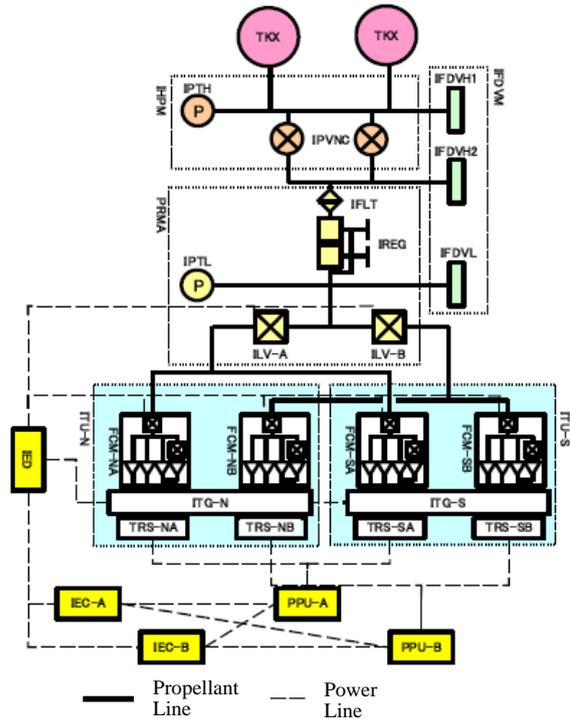


Figure 2 IES Diagram

Table 2 IES Components

Items	Abbr	Num	Note
Ion thruster unit	ITU	2	North/South (N/S)
Thruster	TRS	2/ITU	Primary/Secondary (A/B)
Gimbals	ITG	1/ITU	
Flow control module	FCM	2/ITU	Primary/Secondary (A/B)
Flow control device	FCD	4/FCM	
Isolation valve	ILV	1/FCM	
Bypass valve	ILV	1/FCM	
Xenon tank	TKX	2	
High pressure module	IHPM	1	
HP transducer	IPTH	1	
Pyrovalve (NC)	IPVNC	2	Primary/Secondary (A/B)
Fill and drain valve module	IFDVM	1	
High pressure FDV	IFDVH	2	
Low pressure FDV	IFDVL	1	
Pressure regulator module assem	PRMA	1	
Pressure regulator module	PRMA	1	
HP filter	IFLT	1	
Regulator	IREG	1	Internal redundancy
Isolation valve	ILV	2	Primary/Secondary (A/B)
LP transducer	IPTL	1	
Power processing unit	PPU	2	Primary/Secondary (A/B)
Controller	IEC	2	Primary/Secondary (A/B)
Driver	IED	1	Internal redundancy

It is not necessary to keep a balance of thrust between two ion engines on opposite panels, so precise propellant flow control is not required. While PMUs on ETS-VI and COMETS controlled the propellant flow by thermal valves, PMU of ETS-VIII adopts some orifices to control the flow rate.

### E. Power Processing Units (PPU)

The design of the PPU was changed to multi variable discrete outputs from analog outputs. And a cleaning grid function was added to burn off any foreign objects that might cause a short circuit between grids. In addition, switching relays were used to supply power from one PPU to the thrusters.

## III. Progress of Ion Engine Operation on Orbit

IES was primarily tested in January 2007, approximately one month after the launch. And then NSSK by IES began in March 2007. Figure 3 indicates a history of accumulative operating time of each thruster.

The main discharge plasma sometimes disappeared off a primary thruster on the north panel (TRS-NA) during operations, and it caused some difficulties that required sending a restart command. So a thruster was switched to a secondary one on the north panel (TRS-NB) in July. Both north and south gimbals adjusted the thrust vectors towards the center of the satellite mass for primary thrusters, so only the north gimbals were adjusted again for TRS-NB.

After this change, NSSK was conducted by a primary south thruster (TRS-SA) at an ascend node and by TRS-NB at a descend node in orbit for a half year. However, TRS-SA did not start operating on January 15, 2008, and therefore NSSK by IES had to be halted for about two months.

A failure was found in a power processing unit that was to supply power to primary thrusters (PPU-A). Therefore, it was impossible to operate the primary thrusters, i.e. both TRS-SA and TRS-NA. As a result, TRS-SB and TRS-NB had to be used for NSSK.

Figure 4 and 5 show a history of the pressure of propellant tanks and the change in regulated pressure in the downstream of a regulator respectively.

The pressure of propellant tanks gradually decreased due to xenon consumption, as predicted. Also the regulated pressure during beam injection indicated a normal value, as previously planned.

Figure 6 shows the histories of temperatures at TRS-NB and a propellant flow control module (FCM) provided to this thruster, as examples of telemetry data. The temperature of the thruster which was installed on the outer panel of the satellite was affected by solar heat and by the satellite attitude, whereas that of FCM was quite stable as it was located inside of the satellite. Both sets of data agreed with the results of thermal analyses, and it was confirmed that there were enough margins for a thermal subsystem design.

Figure 5 shows that a propellant management unit fed xenon flow under stable regulated pressure and Figure 6 shows that the temperature of FCM was relatively kept constant, so that a constant propellant feed could be conducted to a thruster during beam injection.

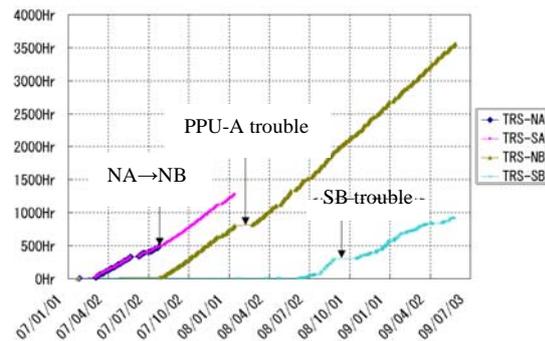


Figure 3 Cumulative Operation Time of Thrusters

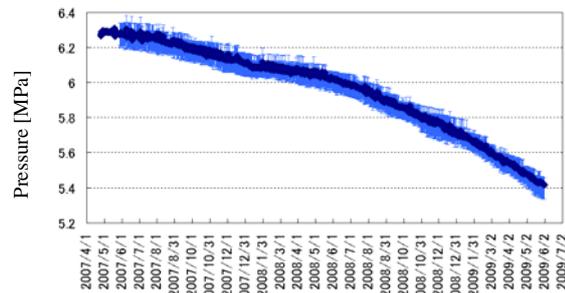


Figure 4 History of Propellant Tanks Pressure

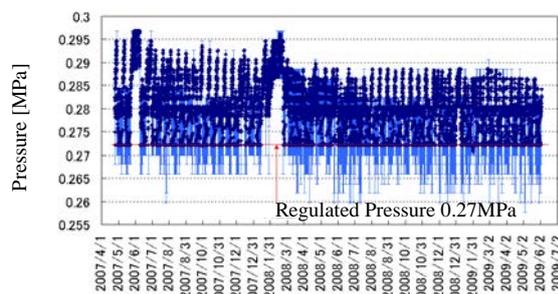


Figure 5 Change of Regulated Pressure

Figure 7 indicates the histories of current and voltage values at TRS-NB, measured by telemetry. And Figure 8 shows the change in TRS-NB thrust. The thrust gradually decreased from the beginning of the operation under the same conditions, and then it increased in January 2009 by changing operational parameters after it had fallen below 20mN. A decrease in thrust was considered as a change with a lapse of time, which was a similar change to that observed in ground tests.

Currents and voltages showed normal and stable values initially; afterwards these values varied with resetting operational conditions, but the variation was within expectations.

Low thrusting phenomena observed before 3500 hours of cumulative operating time were caused by a recovery operation for high voltage break downs (HVBD).

#### IV. Some Anomalies that Occurred on IES

##### A. Malfunction on PPU-A

A failure occurred in the primary thruster on the south panel three consecutive times, where the thruster could not ignite a discharge in the main chamber; this resulted in the automatic beam injection sequence becoming discontinued in an operation on January 15, 2008. After thorough investigation a malfunction was found in a power processing unit that supplied power to the primary thrusters (PPU-A).

A lot of analysis efforts supposed that a fault happened on a logic circuit component installed in the beam and accelerating power supply, and then the voltage of the auxiliary power unit seemed to drop.

Initially the analyses also concluded that it might be a random failure in this component, because it had continued to work normally for more than 1,800 hours and no problems were found in the log.

However, a similar problem occurred recently on PPU-B after 10,000 hours of operation as described in IV.C; the failures were suspected to depend on some defects in the design.

##### B. Unstable Ignition of TRS-SB

A primary south thruster (TRS-SA) was also planned to be changed to a secondary south thruster (TRS-SB) when a primary north thruster (TRS-NA) was changed to a secondary north thruster (TRS-NB). Thus the performance of TRS-SB was checked, but some instability was observed on the ignition of the neutralizer.

TRS-SB could be used again after the primary troubleshooting, but TRS-SA still worked normally at that time, so NSSK was conducted by the combination of TRS-SA and TRS-NB.

Because of the malfunction of PPU-A mentioned above, an attempt was made to switch the thruster on the south panel to TRS-SB, and then a failure in the neutralizer occurred again. Troubleshooting for this phenomenon started in January, 2008.

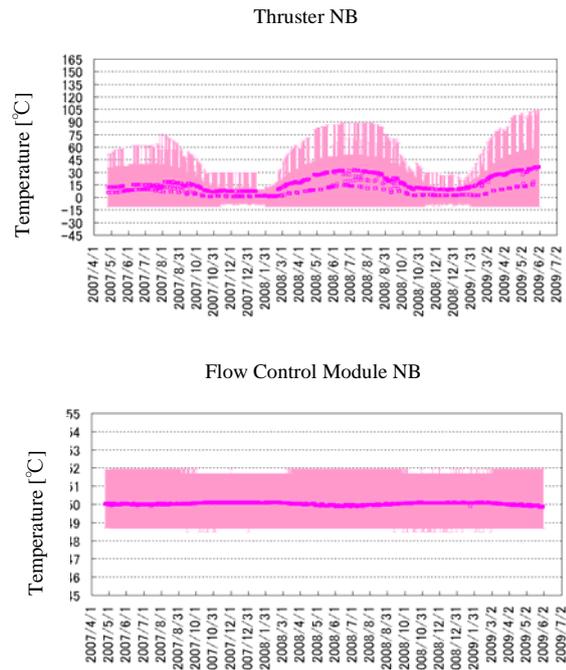


Figure 6 Temperatures at TRS-NB

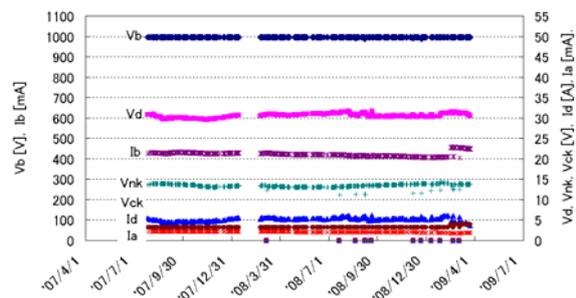


Figure 7 Telemetry Data of Currents and Voltages at TRS-NB

Two root causes were suspected right after the failure happened. First the phenomenon seemed to occur due to a short-circuiting between the neutralizer keeper and the ground. Second, this short-circuiting depended on the temperature of the neutralizer and its surrounding environment.

There were some locations of short-circuiting suspected, and then it was concluded that the short-circuiting could happen between a neutralizer keeper and the outer rim of the thruster, and something conductive might be located there. It was also observed that the phenomenon strictly depended on thermal conditions like daylight.

Now TRS-SB continues to operate with troubleshooting while the short-circuiting disappears, and is monitored in idling mode and discharging mode, which are two of the operation modes of the ion engine subsystem.

### **C. Failure in PPU-B**

TRS-SB was considered for use in the beginning of the operation of July 7, 2009; however, this thruster was not selected. It was suspected that the anomaly was on PPU-B, while a thruster had not yet been selected, after changing a combination of PPU-B and Ion Engine Controllers.

NSSK maneuvering by TRS-NB was normally conducted before TRS-SB operation on the same day; nevertheless restart once occurred due to extinction of a neutralizer discharge. Yet telemetry data at the restart and recoveries from HVBDs that occurred during beam injection differed from those in normal operation.

A failure point was looked for based on these flight data from the previous operation and a failure that occurred in the same component, caused by a PPU-A fault, was supposed to be the source. However no problem was observed in the quality log. Both thermal and mechanical environments around PPU-B were found to be within normal ranges; the temperature history around PPU-B was normal and the operation time of PPU-B had already exceeded 10,000 hours according to the ETS-VIII operational record on orbit.

The original assumption that the PPU-A failure had occurred by accident was rejected because the PPU-B failure was similar to the PPU-A one. Moreover an effect of HVBD where frequencies had been increasing was suspected to be the source of this failure.

## **V. Operation of IES after PPU-A Failure**

The power processing unit providing power to the primary thrusters (PPU-A) died about one year after the launch, so it was impossible to operate the primary thrusters. Thus the secondary thrusters were used for NSSK after PPU-A was eliminated. The statuses of the two thrusters rest were as follows:

### **D. TRS-NB**

After a cumulative operating time on orbit that exceeded 3,400 hours, firing interruptions caused by HVBD frequently occurred in TRS-NB. However, TRS-NB was recovered through warming up by discharging mode and by a beam injection under low discharge current mode; the beam injection could be normally applied.

The frequency of HVBDs temporally increased and then gradually decreased; throughout the maneuver there were between 9 and 15 HVBDs.

### **E. TRS-SB**

A short-circuiting of the inner thruster alternated by the temperature distribution of TRS-SB is described in section IV.B.

The TRS-SB condition was unstable so that sometimes a beam mode could be started and sometimes it could not. However once the thruster initiated the beam injection, no problems were observed during the maneuver, and the operation was normally completed.

The sum of accelerations by TRS-NB and TRS-SB contributed to NSSK, and chemical thrusters made up the deficiency.

Table 3 gives the cumulative beam injection time and numbers. Both TRS-SA and TRS-NA naturally did not work after January 15th, 2009.

## **VI. Conclusion**

The ETS-VIII ion engine subsystem worked on orbit for NSSK until failures occurred. Thrusters operated 1,100 times and 6,400 hours in total through these maneuvers, no harmful impacts to the satellite system were observed, and station keeping was normally conducted.

Table 3 Cumulative Beam Injection Time and Numbers

Items	Life	Thrusters	Firing time on ground	Firing time on orbit	Total firing time
Firing time	15,600 hours	TRS-NA	100 hours 26 minutes	480 hours 8 minutes	580 hours 34 minutes
		TRS-NB	114 hours 36 minutes	3569 hours 50 minutes	3684 hours 26 minutes
		TRS-SA	110 hours 12 minutes	1276 hours 32 minutes	1386 hours 44 minutes
		TRS-SB	110 hours 46 minutes	925 hours 4 minutes	1035 hours 50 minutes
Firing frequency	3000 times	TRS-NA	29 times	88 times	117 times
		TRS-NB	57 times	467 times	524 times
		TRS-SA	46 times	202 times	248 times
		TRS-SB	28 times	401 times	429 times

As of May 31, 2009

Some failures, including a fatal one, happened in orbit. They taught us important lessons. A few of them occurred quite recently, so failure analyses will continue for a while.

JAXA has a few projects on-board an ion engine subsystem right now. The experience obtained from the events described above should be applied throughout these developments.

ETS-VIII is still in operation for NSSK by bipropellant thrusters.

#### References

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