Development of Redundant Integrated Navigation System (RINS) for launch vehicle

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ABSTRACT

The Redundant Integrated Navigation System (RINS) is a navigation sensor developed using redundant commercial automotive CPUs system, GNSS modules with special firmware for space applications, and MEMS IMUs to lower the cost of launch vehicles. This paper shows the development and the superior performance of RINS launched on the Epsilon rocket F6 and H3TF#1.

1 Introduction

Research has focused on lowering the cost of vehicle systems to further enhance the international competitiveness of Japan's H3 and Epsilon launch vehicles. The cost of avionics equipment for the H-IIA rocket was analysed, and it was found that more than half of the total cost was due to custom electronic components. Special components have been needed because of the unique requirements of space―resistance to high vibration, operability over a wide temperature range, and strong radiation tolerance in space.

Commercial parts, such as automotive electronic elements, are less expensive than specially-made electronic components. Further, currently available components are of military-grade quality, have excellent resistance to high vibration, and operate over a wide temperature range, as shown in Table 1. JAXA has studied radiation mitigation based on special circuit technology using ordinary electronics, which are less expensive but do not have much radiation tolerance. The implementation includes redundant electronic circuits, current monitoring, and redundant modules.

Avionics systems require three independent navigation systems. One is needed for vehicle guidance and control and the other two for range safety operation. Cost reduction of these systems would contribute substantially to the competitiveness of launch vehicles.

Using special techniques, JAXA has developed a low-cost, accurate navigation system for launch vehicles named the Redundant Integrated Navigation System (RINS). RINS is a navigation system aiming for positional accuracy within 150m and velocity accuracy within 5m/s in an environment of launch vehicle. RINS uses automotive CPUs, commercial GNSS modules with special firmware for space applications, and commercial MEMS IMUs and applies the radiation mitigation techniques mentioned above.

This study evaluated RINS's functions and performance under severe launch vehicle conditions and developed an engineering model of RINS. RINS passed all the qualification tests we ran. We also did a flight demonstration of RINS during the launch phase by Epsilon rocket F6 launched on October 12, 2022. The RINS installed on the second stage of Epsilon rocket F6 worked normally and performed IMU-GNSS integrated navigation within the required accuracy during the launch. Another flight demonstration was done on the H3 rocket's first launch (H3TF#1) on March 7, 2023. Based on their results, RINS will be used as a flight trajectory monitoring system on the Japanese flagship rockets, the H3 and the Epsilon S.

This paper shows the system design and manufacture of RINS, which uses radiation mitigation techniques using special circuit technology and non-space electronic parts. This paper also presents the flight demonstration results of Epsilon rocket F6 and H3TF#1 during the launch phase.

Table 1 Environmental resistance requirements of parts test standard

Items	**Military Specified Parts (MIL-PRF-38535)**	**Automotive Parts (AEC-Q100)**
Temperature Range	-65°C ~ -150°C, 100 cycles	-65°C ~ -150°C, 500 cycles
Vibration	20 G (20 Hz to 2 kHz)	20 G (20 Hz to 2 kHz)
Shock	1500 G (5 msec, 5 pulses)	1500 G (5 msec, 5 pulses)

2 RINS Features

2.1 Configuration

This section shows the feature of RINS. Figure 1 shows the block diagram of RINS. RINS is composed to the redundant GNSS computer (GNCOM) and the MEMS advanced redundant inertial navigation system (MARIN). Figure 2 show the appearances of engineering model of GNCOM and MARIN. RINS is combined the following redundant systems and IMU-GNSS navigation.
(1) Triple redundant voting MPU system
(2) Redundant GNSS module system
(3) Redundant MEMS IMU system
Since GNSS navigation of launch vehicles must be available on any launch vehicle attitude for range safety, the GNSS module needs three GNSS antennas. In contrast, most commercial GNSS modules have only one GNSS signal input. To manage this discrepancy of the required number of RF inputs from the antenna system not matching the number of RF inputs of the GNSS module, we developed a special RF combiner/splitter system for RINS, which also simplifies the GNSS antenna and Redundant GNSS system. Also, another receiver can be mounted for future extensibility, the single GNSS module (SGNSS) which a proven receiver on satellite modified for rocket was mounted on the engineering of GNCOM.

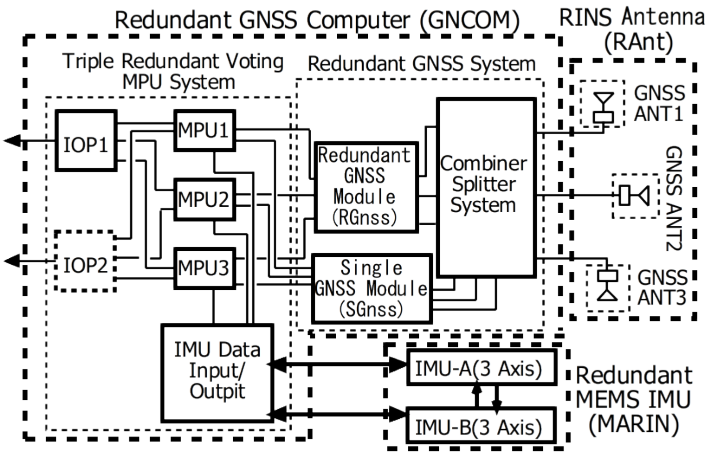

Figure 1. The block diagram of RINS

(a) (b)

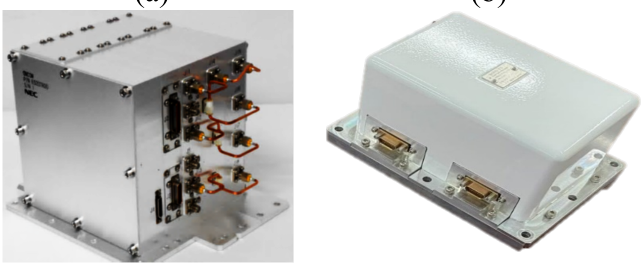

Figure 2. The appearances of Engineering model of (a) GNCOM and (b)MARIN

2.2 Triple redundant voting MPU system

Figure 3 shows the triple redundant voting MPU system which JAXA has been studying for the radiation mitigation to use non-space high-performance. This system is used in RINS. In this MPU system, three MPUs are synchronized by clock and voting of three MPUs is done at the instruction execution level, which means that there is no need for application-software designers to be aware of the redundant MPUs. The voting MPU system has recovery capability to triple MPU voting after MPU reset as well as error detection and isolation. The radiation mitigation capability of this system was evaluated by a radiation test using the breadboard model [1]. This paper reported that more than 40 SEE errors on MPU occurred in this radiation test and the voting MPU system detected all SEE errors, isolated incorrect MPU, and kept outputting correct calculation results.

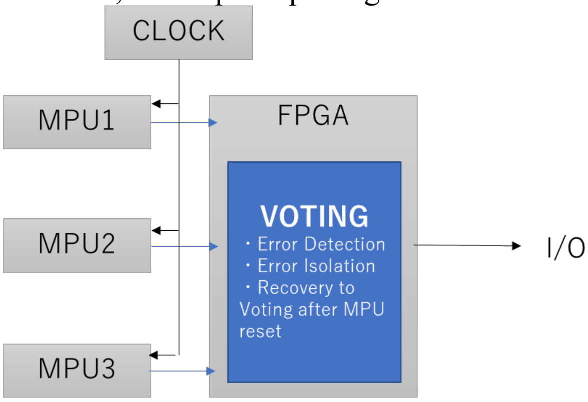

Figure 3. The block diagram of triple redundant voting MPU system

2.3 Redundant GNSS module system

JAXA applied the idea of triple redundancy to the GNSS module system, which has special voting logic for inputs with measurement errors. The breadboard model of the triple-redundant GNSS module system is shown in Figure 4. This study evaluated the radiation mitigation capability of this system with simulated SEE error inputs. The redundant GNSS system detected SEE errors, isolated incorrect GNSS modules, and continued to output the correct GNSS navigation results. The redundant GNSS module system also reset the incorrect GNSS module and caused the reset module to recover to triple GNSS voting after a predetermined period.

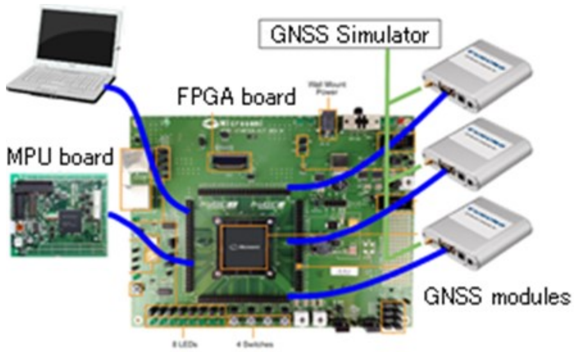

Figure 4. Bread Board Model of Triple Redundant GNSS module System.

2.4 Redundant commercial MEMS IMU system

Since launch vehicles fly in a special environment that entails high vibration, wide temperature range, and severe radiation environment, an IMU for launch vehicles needs to have environmental resistance to such a severe environment and must maintain accurate inertial measurements. The technical issues for a launch vehicle's IMU are as follows[3],[4]:

(1) Accurate inertial measurements for launch vehicles
(2) Maintaining accuracy for a wide temperature range
(3) Maintaining accuracy for a high vibration environment
(4) Ensuring normal operation in a radiation environment

To evaluate the accuracy and environmental resistance in the IMU configuration, an engineering model of MARIN was developed. The accuracy and environmental resistance for launch vehicle dynamics, high vibration, and wide temperature range were evaluated. As a result, the MEMS IMU has enough accuracy for launch vehicles in rocket environment of high vibration and wide temperature range as shown in Table 2.

The last issue of the MEMS IMU is radiation tolerance. We did a radiation test and found that the SEE error on the MEMS IMU could occur in the radiation region in orbit, even if the probability of an SEE error is very small. We used a redundant MEMS IMU system to manage this issue, as shown in Figure 5. The basic structure is a double-redundant system of MEMS IMU units. Each unit has three orthogonally oriented gyroscopes, three accelerometers, and two MPUs that are maturely checked for the consistency of the calculation results. There is a cross-communication link between two MEMS IMU units to output both data from both unit's outputs [3].

Table 2. The function and performance of MRN-01

Item	**Value**
Weight	1.3kg
Power	6W
Angle rate measurement	・Range：±400deg/s ・Scale factor：500ppm ・Random walk：0.051deg/√h ・Bias instability：0.2deg/h
Velocity rate measurement	・Range：±30g ・Scale factor：0.5mG ・Random walk：0.15m/s/√h ・Bias instability：0.09mg
Output data rate	100Hz
Interface	RS422

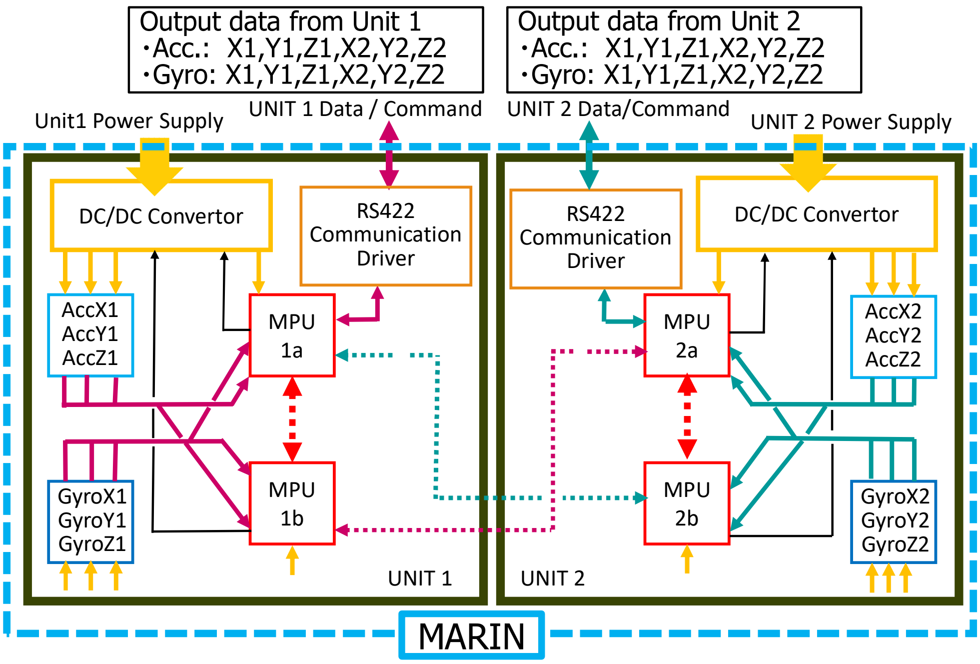

Figure 5 Block diagram of redundant MEMS IMU system

2.5 Radiation resistance of GNSS module and MEMS IMU

The radiation resistance of GNSS module and MEMS IMU were evaluated by JAXA [2][4]. In order to increase the number of samples, four GNSS modules were placed on the same board as shown in Figure 6. The MEMS IMU board of a gyro board, a control board, a power supply IF board, and an MPU board, and each board was irradiated. Protons and heavy particles (Ar, Kr) were irradiated, and the number of SEU/SEFI and SEL generated at each energy was counted. Weibull parameters were fitted from the results, and then the error rate for each rocket's representative trajectory was calculated using CREME96.

Table 3 shows the error rate on orbit calculated by CRÈME96 using Weibull curve obtained from the result of the irradiation test. The redundant GNSS module system has triple redundancy, and the MEMS IMU has double redundancy, and it was confirmed that the radiation errors occurring at the same time is small. In addition, the reliability of RINS using these values, it was confirmed that the required values for the rocket system were satisfied.

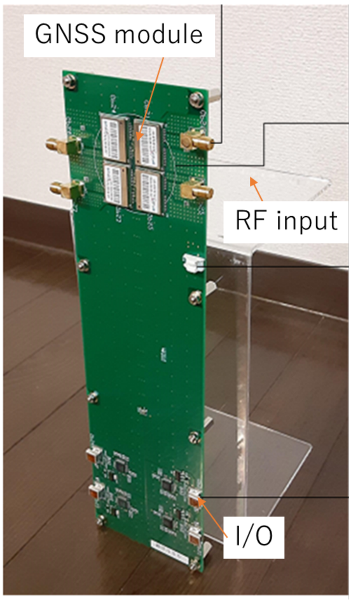

Figure 6. Setup image of GNSS module for radiation test

Table 3. Error rate on orbit calculated by CRÈME96 using Weibull curve obtained from the result of the irradiation test of proton and heavy particles beam.

		GNSS module(/device/sec)		MARIN(/device/sec)							
				Gyro		Control boad Acc		Power boad		MPU	
Vehicle		SEU/SEFI	SEL	SEU/SEFI	SEL	SEU/SEFI	SEL	SEU/SEFI	SEL※1	SEU/SEFI	SEL※1
H3	GTO	6.95E-06	3.35E-06	4.81E-07	5.92E-09	8.56E-08	6.24E-09	No upset No burnout	No latch up	7.24E-07	No latch up
	SSO 500km	1.31E-07	6.34E-08	9.91E-09	2.46E-10	1.92E-09	3.02E-10			1.24E-08	
	SSO 800km	6.05E-07	2.76E-07	3.94E-08	5.70E-10	7.36E-09	6.37E-10			6.98E-08	
ε	LEO 950×1150km	4.75E-06	2.15E-06	2.97E-07	4.47E-09	5.44E-08	3.24E-09			5.67E-07	
	SSO 750km	4.82E-07	2.20E-07	3.16E-08	4.77E-10	5.92E-09	5.39E-10			5.51E-08	

*1：Judged as "Available" because Lth>31 MeV/(mg/cm2).

3 Flight demonstration

3.1 Flight demonstration by Epsilon rocket F6

The RINS was mounted on the launch vehicle's second stage with two antennas 180º apart. The inertial navigation was started 18 s before liftoff, and the telemetry data was recorded from liftoff for 387 s.

Figure 7 show the measurement results during flight of epsilon rocket F6. (a) Mode-status, (b) Number of satellites, (c)Altitude, (d) Velocity, (e)Acceleration and (f)Angular rate. These results indicate that the function of mode transition, satellite tracking, acceleration, angular velocity measurement worked well in the flight environment.

Figure 8 show the position and velocity measured by RINS relative to the navigation sensors currently used in rocket system. The bule lines show the position and velocity measured by IMU-RGNSS integrated navigation, and the red lines show the position and velocity measured by the SGNSS system. These results indicated measurement performance of position and velocity was good in the flight environment.

Figure 9 show the attitude of the rocket measured by RINS and the navigation sensors currently used in rocket system. The left column shows the attitude of each sensor, and the right column shows the attitude measured by RINS relative to the navigation sensors currently used in rocket system. These results indicated that measurement performance of attitude was good in the flight environment.

In this flight test using the Epsilon F6, it was demonstrated that RINS has good measurement performance of position, velocity and attitude even under the environment unique to the Epsilon rocket.

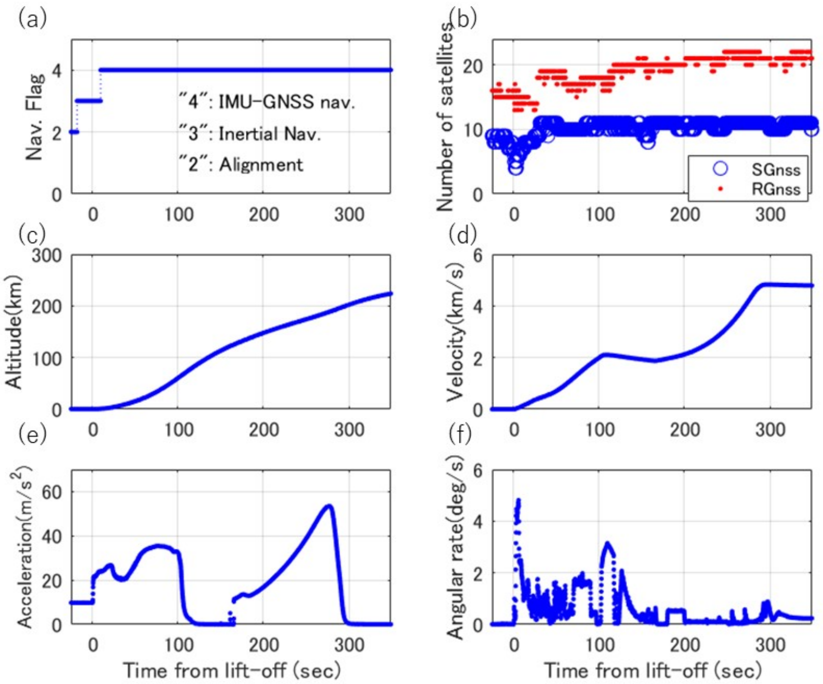

Figure 7. The measurement results during flight of epsilon rocket F6. (a) Mode-status, (b) Number of satellites, (c)Altitude, (d) Velocity, (e)Acceleration and (f)Angular rate.

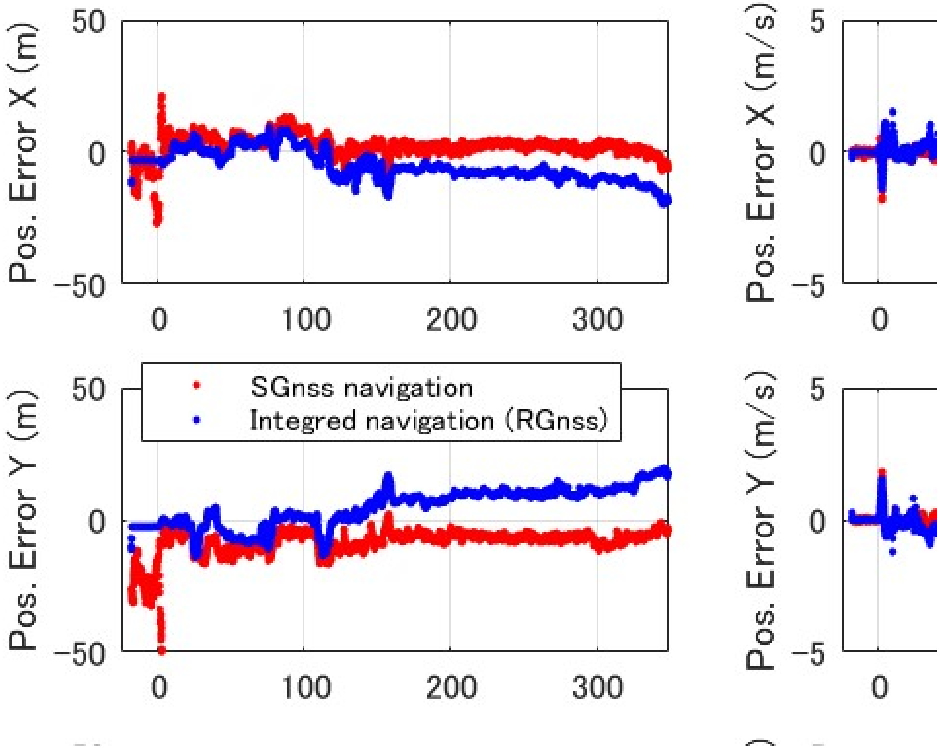

Figure 8. The position and velocity measured by RINS relative to the navigation sensors currently used in rocket system during flight of epsilon rocket F6

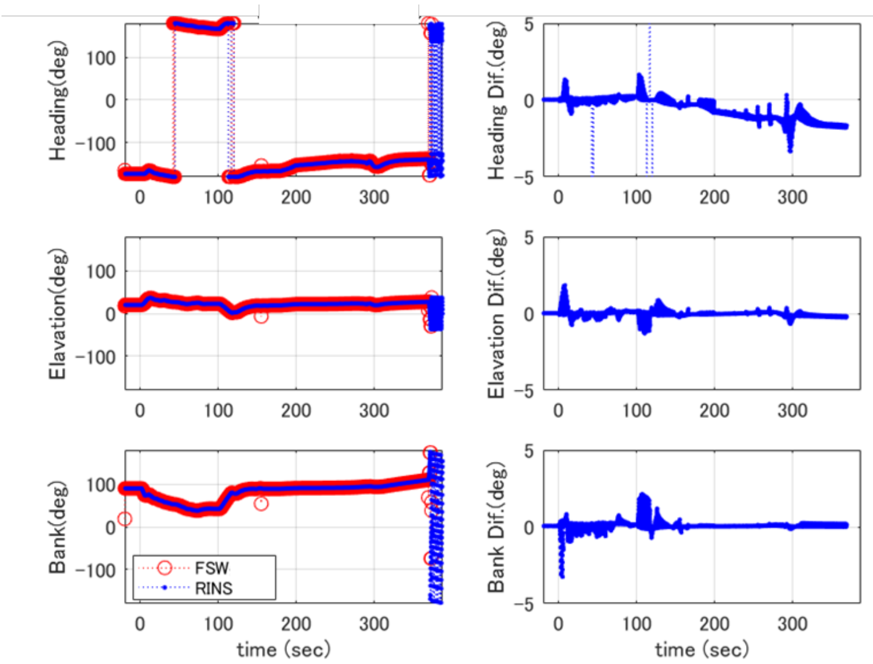

Figure 9. The attitude measured by RINS relative to the navigation sensors currently used in rocket system during flight of epsilon rocket F6

3.2 Flight demonstration by H3TF#1

The RINS is mounted on the launch vehicle's second stage, with three antennas at 120º intervals. The inertial navigation was started 18 s before liftoff. The telemetry data was recorded from liftoff until 847 s.

Figure 10 show the measurement results during flight of epsilon rocket F6. (a) Mode-status, (b) Number of satellites, (c)Altitude, (d) Velocity, (e)Acceleration and (f)Angular rate. These results indicate that the function of mode transition, satellite tracking, acceleration, angular velocity measurement worked well in the flight environment.

Figure 11 show the position and velocity measured by RINS relative to the navigation sensors currently used in rocket system. The bule lines show the position and velocity measured by IMU-RGNSS integrated navigation, and the red lines show the position and velocity measured by the SGNSS system. As shown in the right row of Figure 11, the difference of velocity increased about 20 m/s from 13 to 15 seconds after lift-off. This cause might be due to multipath of GNSS signal.

Therefore, off-line calculation when increased the altitude conditions for switching operating modes was attempted. Figure 12 shows the position and velocity calculated using measurement data of only MEMS IMU until reaching an altitude of 1 km. The error of velocity is smaller than the velocity calculated on-board. These results indicated measurement performance of position and velocity was good in the flight environment.

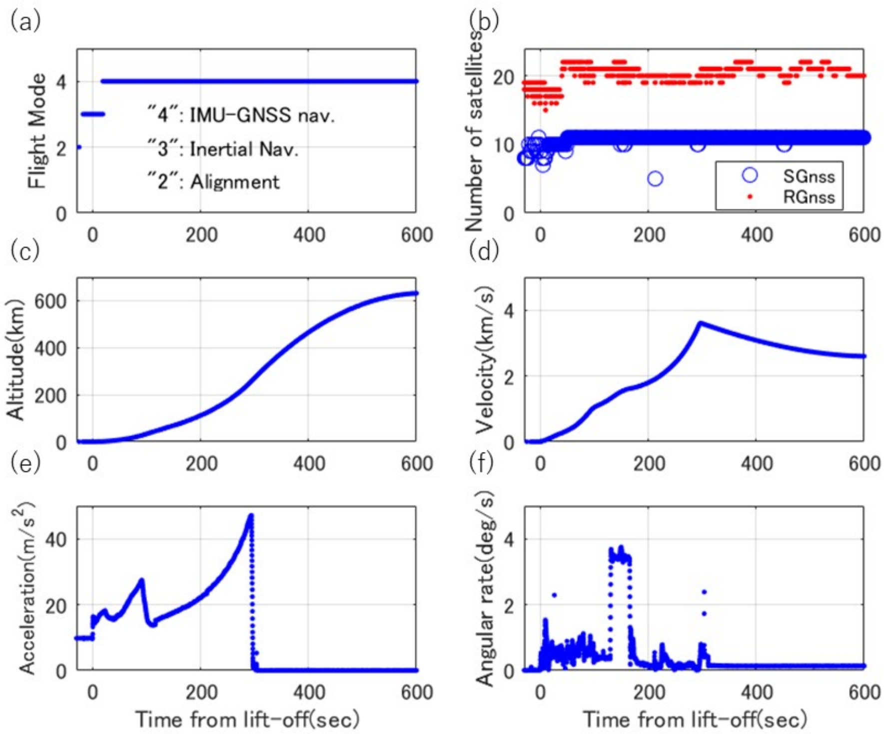

Figure 10. The measurement results during flight of epsilon rocket F6. (a) Mode-status, (b) Number of satellites, (c)Altitude, (d) Velocity, (e)Acceleration and (f)Angular rate.

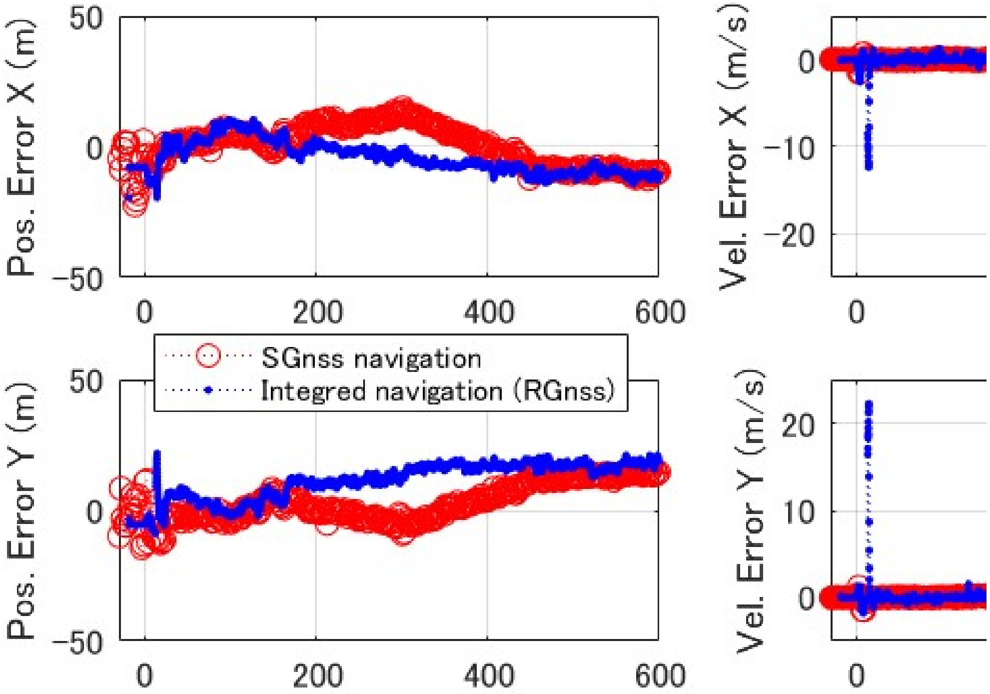

Figure 11. The position and velocity measured by RINS relative to the navigation sensors currently used in rocket system during flight of H3TF#1

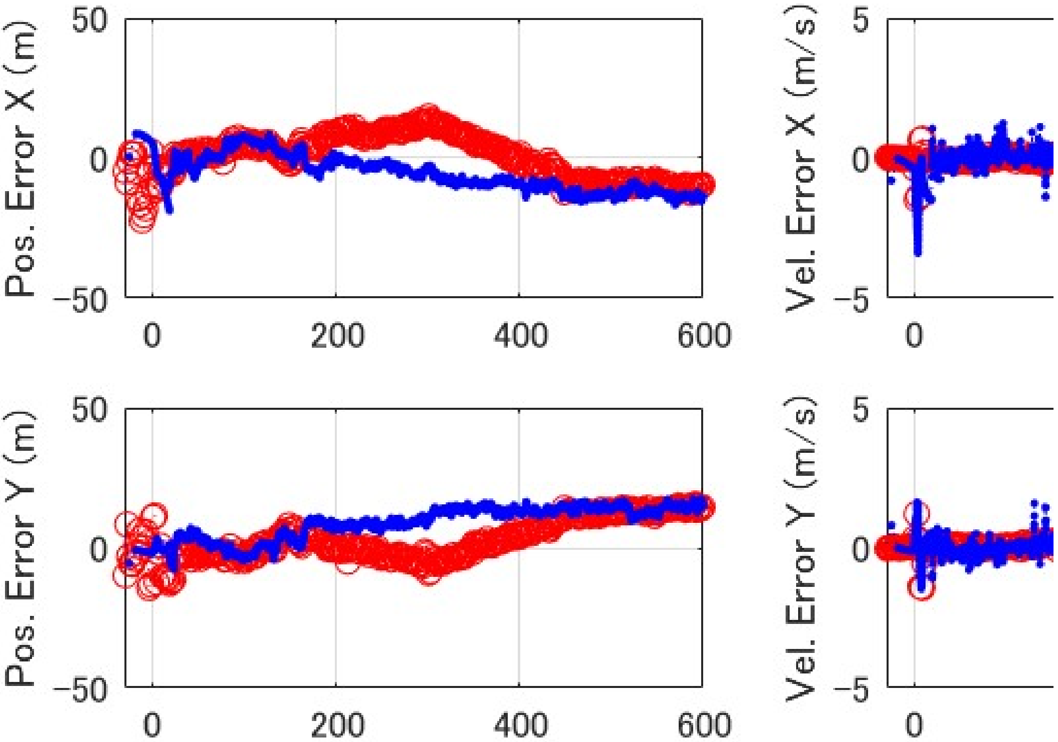

Figure 12. The position and velocity calculated using measurement data of only MEMS IMU until reaching an altitude of 1 km.

4 Conclusion

The RINS is a navigation system that uses redundant commercial-grade items for low cost and high reliability, and planned to be used on Japanese flagship rockets, Epsilon S and H3 rockets, as flight trajectory monitoring systems. The RINS was launched on the Epsilon F6 and H3TF#1 rockets and demonstrated that it has good measurement performance of position, velocity, and attitude under the rocket's actual flight environment. These technologies are expected to contribute to the cost reduction and development of spacecraft systems.

5 REFERENCES

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