Technical Challenges and Study on Guided Reentry Flight for Capsule Spacecraft

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ABSTRACT

Previously-realized Japanese capsule spacecraft, OREX (Orbital Re-entry EXperiment), USERS capsule, and HAYABUSA reentry capsule, were all ballistic reentry capsules, which flew without any guidance during reentry and had large splashdown areas. To establish practical recovery systems from the International Space Station (ISS), JAXA has been studying reentry capsules using guided reentry flight, which enable capsules to narrow their splashdown area within 5 km and reduce aerodynamic acceleration less than 4 G. To improve reentry guidance accuracy, we use accurate real-time prediction guidance using numerical integration for reentry spacecraft and IMU-GPS-ST integration navigation.

This paper describes the characteristics of guided reentry flight and technical challenges on guided reentry flight for capsule spacecraft and presents guidance and control methods of guided reentry flight for the technical challenges.

1. Introduction

OREX (Orbital Re-entry EXperiment) (Refs. 1, 2), USERS capsule (Ref. 3), and HAYABUSA reentry capsule (Ref. 4) were all ballistic reentry capsules and flew without any guidance during reentry, meaning their splashdown areas were very large. For example, OREX's splashdown area was a large error ellipsoid with a semi-major axis of 200 km, as shown in Fig. 1. To establish practical recovery cargo from the International Space Station (ISS), JAXA has been studying a Japanese unmanned reentry cargo capsule, HTV-R (Ref. 5) with a target recovery area within 5 km. JAXA has also been performing an advanced concept study of Japanese manned reentry capsules attempting to land on the Japanese mainland.

One of the key technologies for HTV-R and Japanese manned reentry capsules is guided reentry flight, which enables capsules to narrow their splashdown areas to within 5 km and reduce aerodynamic acceleration to less than 4 G. A small splashdown area is important for practical recovery cargo, while small aerodynamic acceleration is important for manned reentry capsule. To realize guided reentry flight, we investigated the technical challenges for guided reentry flight and have been studying guidance, navigation and control methods to solve the technical challenges. In this paper, we assume the shape, body characteristics and constraints of the reentry capsule as shown in Figs. 3 and 4 and Tables 1 and 2.

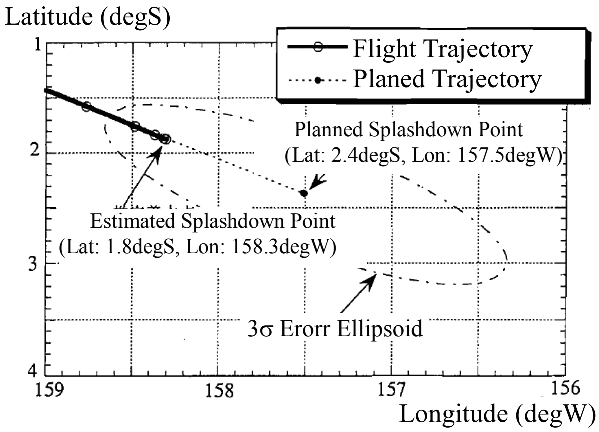

Fig. 1 Splashdown Area of OREX

Fig. 2 Photograph of OREX

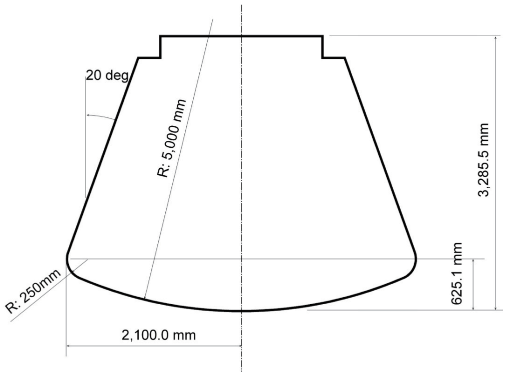

Fig. 3 Shape of Vehicle

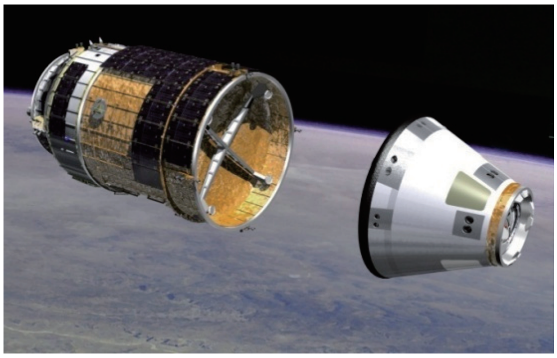

Fig. 4 Concept of the HTV-R

Table 1 Vehicle Model

Vehicle Weight	5900 kg
Reference Cross Section	13.9 m^2
L/D	0.3
Drag	1.4
Curvature radius of Nose	5.0 m

Table 2 Constraints of reentry

Aerodynamic Acceleration	less than 4 G
Aerodynamic Heating Rate	less than 1 MW/m^2
Total Aerodynamic Heating	less than 130 MJ/m^2
Bank Angle	within $\pm$90 deg
Angular Rate of Bank	within $\pm$20 deg/s
Angular Acceleration of Bank	within $\pm$2 deg/s^2

2. Technical Challenges on Guided Reentry Flight for Capsule Spacecraft

2.1 Characteristics of Guided Reentry Flight

Guided reentry flight of capsule spacecraft has the following characteristics, which is why improving the reentry accuracy of capsule spacecraft is difficult.

(a) Low lift-to-drag ratio (L/D)
(b) Range guidance by controlling bank angle only
(c) Low guidance capability on the final phase of reentry flight

The first characteristic is the low lift-to-drag ratio (L/D), due to capsule shape. The typical L/D of capsule spacecraft is within the range 0.2 to 0.4, whereas that of winged spacecraft such as the Space Shuttle exceeds 1.0. The low L/D limits the scope of range correction capability, which is a severe constraint for reentry guidance. The low L/D also results in large aerodynamic acceleration on spacecraft because low L/D spacecraft have small deceleration during flight in atmospheric areas of low density and flight of higher velocity in high-density atmospheric regions.

The second characteristic is the fact that the bank angle is the only controlling parameter for both downrange and crossrange guidance. A capsule spacecraft can generate aerodynamic lift by offsetting its center of gravity from the body center axis. By controlling the bank angle, a capsule changes the vertical component of lift for downrange guidance, while controlling the period to keep the bank angle at the right- or left-hand side allows a capsule to execute crossrange guidance. This cross coupling of downrange and crossrange guidance on the bank angle hinders accurate reentry guidance.

The third characteristic is the low guidance capability on the final phase of reentry flight. Since the flight path angle on the final phase of capsule reentry flight becomes deeper than that on the initial and middle phases of the reentry flight, the range guidance capability on the final phase becomes about one tenth of that on the middle phase. Accordingly, errors in the final phase such as wind errors make reentry guidance accuracy worse.

2.2 Technical Challenges on Guided Reentry Flight

Considering the characteristics of guided reentry flight for capsule spacecraft as mentioned in section 2.1, we identified the following technical challenges on guided reentry flight.

(1) Guided reentry flight to meet severe acceleration requirements for manned spacecraft

The acceleration requirement for Japanese manned spacecraft is less than 4 G, for which guided reentry flight is essential. This requirement is severe for low L/D spacecraft such as capsule, although not problematic for high L/D spacecraft such as the Space Shuttle. Since low L/D spacecraft have small deceleration during flight in low-density atmospheric regions and flight with higher velocity in high-density atmospheric regions, the aerodynamic force, which is in proportion to the atmospheric density and square of velocity, becomes large for low L/D spacecraft. For practical reentry guidance analysis in particular, we must consider the following condition and errors, which increase the aerodynamic force under certain circumstances.

(a) Nominal bank angle must set the medium range

The nominal bank angle must set the medium range to compensate for positive and negative downrange errors during downrange guidance, which means that the vertical component of the lift becomes small in proportion to the bank angle cosine. For example, if the maximum L/D is 0.3 and the nominal bank angle is 60 degrees, the vertical lift component is 0.15.

(b) Aerodynamic force error

Even if there is 25% aerodynamic force error and the L/D becomes smaller than nominal, maximum acceleration must be less than 4 G.

(c) Reentry flight path angle error

Capsules returning from the International Space Station (ISS) must consider the reentry flight path angle error due to the orbit altitude variation of the ISS from 350 to 450 km. The maximum error of HTV-R is 0.18 degrees and the error makes the aerodynamic force larger.

(2) High reentry accuracy under the worst conditions and maximum reentry flight errors

For practical logistic recovery such as the HTV-R, the reentry guidance accuracy required is less than 5 km. Moreover, in an advanced concept study involving the Japanese manned reentry capsule, the capsule attempts to land on the Japanese mainland. For this purpose, the targeted reentry guidance accuracy is within 1 km at the point of parachute deployment. Meeting these requirements is a significant technical challenge for capsule spacecraft with the characteristics mentioned in section 2.1 under the worst conditions and maximum reentry flight errors. In terms of reentry guidance accuracy, the following factors are critical:

(a) Large aerodynamic force error

The aerodynamic force error of capsule spacecraft has two kinds of error source: the estimation error of aerodynamic force via a wind tunnel test and computational fluid dynamics and aerodynamic force generated by center-of-gravity offset errors. We set 25 % of aerodynamic force errors on guidance analysis at this early study phase. Reentry guidance must cope with this significant aerodynamic force error, which is related to the guidance capability and must be considered at the stage of reentry trajectory design.

(b) Large upper-level wind error

Upper-level wind e.g. circumpolar westerlies is large and liable to variation at an altitude from 10 to 30 km, whereas the guidance capability of capsule spacecraft becomes small at the altitude range. The maximum upper-level wind exceeds 100 m/s. Even if the guidance uses an upper-level wind model, the variation in wind remains, which is the most severe error for accurate reentry guidance.

(c) Blackout of the GPS signal during the reentry flight

Since the onboard guidance cannot correct reentry errors caused by navigation errors, navigation accuracy is one of the critical factors for reentry guidance. If capsules can use GPS navigation during all reentry phase, navigation is not an issue for reentry guidance. However, there is the black out of GPS signal during reentry flight of an altitude around from 95 km to 40 km during which time capsule spacecraft cannot use GPS navigation and must use inertial navigation. This means that accumulated navigation errors on inertial navigation during GPS signal black out become critical for reentry guidance accuracy, due to the lack of time for guidance after recovery from blackout and the lack of guidance capability in the final phase of reentry flight.

(d) Angular acceleration

Since capsule spacecraft cannot perform closed-loop range guidance during bank reversals, which are attitude maneuvers involving changing the bank angle to the same angle on the opposite side, reentry guidance accuracy worsens in proportion to the time required for bank reversal. Capsule spacecraft are also subject to an angular acceleration limit caused by the gas jet thrusters used to control attitude. We set ± 2 deg/s^2 for the maximum/minimum angular acceleration of capsule spacecraft during this early study phase.

3. Guidance and Control Methods for the Technical Challenges on Guided Reentry Flight

3.1 Reference Reentry Trajectory Design to meet the acceleration constraint

(1) Relation between reference bank angle and maximum aerodynamic force

To limit the maximum acceleration to within 4 G, it is necessary for capsule spacecraft to use the vertical lift component, which helps keep capsule spacecraft in areas of low atmospheric density and decelerates velocity before they traverse high-atmospheric-density areas. To study the relation between the reference bank angle and maximum aerodynamic force quantitatively, in the case of the HTV-R's reentry path angle and maximum L/D, which are -1.35 degrees and 0.3 respectively, we evaluated the relation between bank angle and maximum aerodynamic force; shown by "no error" in Fig. 5. The figure indicates that the bank angle must be less than 60 degrees for maximum acceleration less than 4 G in the nominal case. We also evaluated the relation for ±25% aerodynamic force errors in Fig. 5. It is understood that the errors which make L/D smaller, -25% error on lift coefficient (CL) and +25% error on drag coefficient (CD), are more severe for maximum aerodynamic acceleration. Accordingly, to meet the maximum acceleration requirement under the aerodynamic force errors, the reference bank angle should be smaller than that in the nominal case.

(2) Range control capability under aerodynamic force errors

To carry out reentry guidance, the reference trajectory of the capsule spacecraft must be set carefully so that the capsule can reach the target point even if maximum errors are presumed in reentry flight. In this section, we examined the range of the reference bank angle from the range control perspective and subject to aerodynamic force errors. For simplification, the case of -25% error on CD represents the maximum L/D case, while that of -25% error on CL represents the minimum L/D case. Fig. 6 shows the relation between bank angle and the vertical L/D components. In the case of reentry flight with a constant bank angle, since the flight range is in proportion to the vertical L/D components, even if there are aerodynamic force errors, by choosing a bank angle which represents the same L/D as that of no aerodynamic force errors, the capsule can reach the same target point. Figure 6 shows that if a nominal reference bank angle is set to 52 degrees, in the case of a -25% error on CL and by flying at a bank angle of 35 degrees, the capsule can reach the target point within the acceleration constraint, and in the case of -25% error on CD, by flying at a bank angle of 62 degrees, the capsule can reach the target point within the acceleration constraint.

(3) Reference trajectory for guided reentry flight

Two reference reentry trajectories were designed for this study: one with an initial flight path angle (FPA) of -1.35 degrees and the other with an initial FPA of -2.0 degrees. The reference bank profiles are as follows:

(i) Reference reentry trajectory whose FPA is -1.35 degrees
Reference bank profile: 62 degrees (velocity≥7.5 km/s), 50 degrees (velocity<7.5 km/s)

(ii) Reference reentry trajectory whose FPA is -2.0 degrees
Reference bank profiles: 52 degrees (for all velocities)

The reference trajectories are shown in Figs. 6 and 7, while the results of error sensitivity analysis for aerodynamic acceleration, heat rate and total heat are shown in Tables 3 and 4. In the analysis for the reference reentry trajectory whose FPA is -1.35, maximum aerodynamic acceleration exceeds 4 G, which occurs in the error of the initial flight path angle of -0.18 degrees. Conversely, the reference reentry trajectory whose FPA is -2.0 meets all constraints.

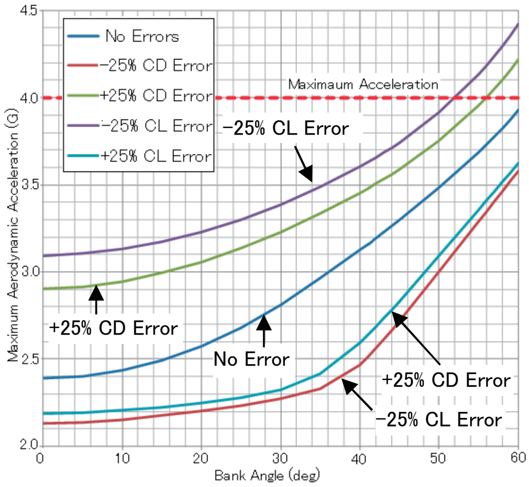

Fig. 5 Relation between bank angle and maximum aerodynamic force

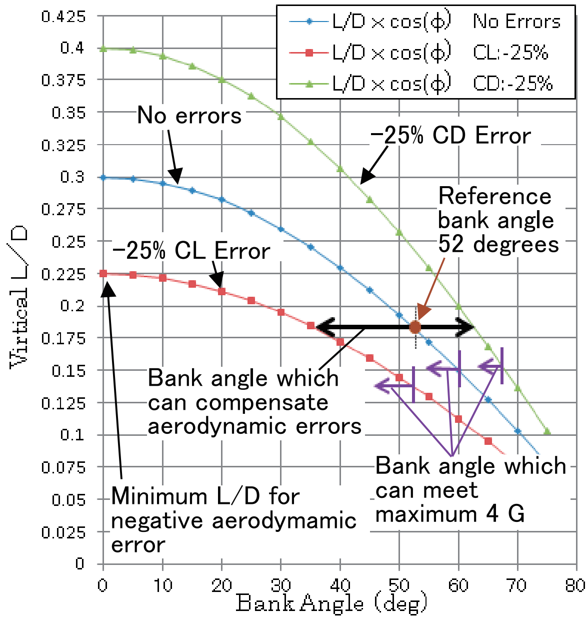

Fig. 6 Relation between bank angle and vertical L/D

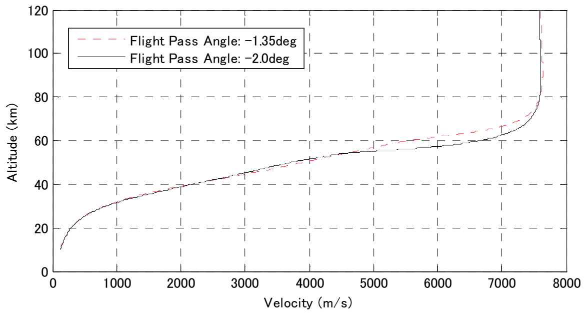

Fig. 7 Reference Trajectory (Velocity – Altitude)

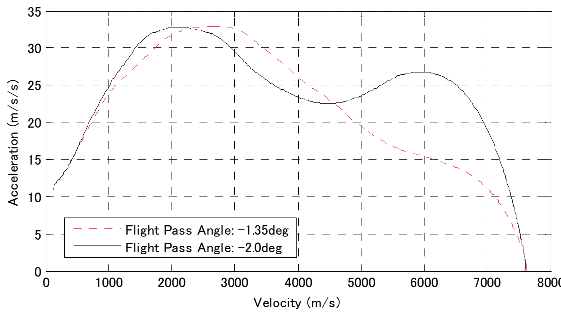

Fig. 8 Reference Trajectory (Velocity - Acceleration)

Table 3 Error analysis for the trajectory, FPA=-1.35

	Maximum Aerodynamic Acceleration	Maximum Aerodynamic heat rate	Total Aerodynamic Heat
Nominal	3.35 G	0.33 MW/m^2	90.64 MJ/m^2
Worst	4.60 G	0.47 MW/m^2	116.40 MJ/m^2

Table 4 Error analysis for the trajectory, FPA=-2.0

	Maximum Aerodynamic Acceleration	Maximum Aerodynamic heat rate	Total Aerodynamic Heat
Nominal	3.31 G	0.43 MW/m^2	72.89 MJ/m^2
Worst	3.66 G	0.60 MW/m^2	92.14 MJ/m^2

3.2 Accurate Reentry Guidance to meet the severe reentry accuracy requirement.

(1) Real-time prediction guidance using numerical integration

To realize high reentry accuracy under the worst conditions and reentry flight errors, we propose real-time prediction guidance using numerical integration, which is an explicit guidance law using real-time numerical integration to predict the accurate range during reentry flights (Ref. 6). This method is very accurate and robust for reentry flight errors. Although range prediction using numerical integration includes such advantages, the heavy computational load involved prevents its use for reentry guidance. We thus improved the range prediction algorithm to reduce the computational load while retaining guidance accuracy. The improvements are summarized as follows:

- Only one-time range prediction per guidance cycle
- Integration Time is valuable for the distance to target
- To omit integration terms which do not affect range prediction
- To use high-performance 64 bit space-qualified MPU, HR5000 (Ref. 7)

The range guidance equation for the real-time prediction guidance using numerical integration is shown in Eq. (1). The range prediction at the present cycle is R_1, while the bank angle command is shown in Eq. (2).

$$(L/D)_C = (L/D)_0 - \frac{\partial (L/D)_0}{\partial R_0} \cdot (R_0 - R_{ref}) = (L/D)_0 - \frac{\Delta(L/D)}{R_1 - R_0} \cdot (R_0 - R_{ref}) \quad (1)$$

$$\cos(\phi_c) = \cos(\phi_0) + \frac{(\cos(\phi_0 + \Delta\phi) - \cos(\phi_0))}{R_1 - R_0} \cdot (R_0 - R_{ref}) \quad (2)$$

where

$(L/D)_0$: L/D command at privious guidance cycle

$\Delta(L/D)_0$: Increment of L/D for increment of bank angle $\Delta\varphi$

ϕ_0: Bank angle commend at privious guidance cycle

$\Delta\phi$: Increment of bank angle for calculation of sensitivity matrix

R_{ref}: Range to target point from present point

R_0: Range to target point when spacecraft flies at the bank angle of privious gudaince cycle

R_1: predicted range to target point when spacecraft flies at the bank ange $(\varphi + \Delta\varphi)$

(2) Reentry guidance error analyses

We evaluated position errors at the end of reentry for the flights with and without reentry guidance by the single error simulation analysis, in which the guidance errors caused by the three sigma value of each solo error factor in reentry flight. In the analyses, reentry guidance commences from the reentry interface point at an altitude of 120 km and ends at an altitude of 10 km as shown in Fig. 10 and IMU inertial navigation is used. The error model used in reentry guidance analysis in this paper is shown in Table 5.

Figure 11 shows the position errors of the reentry flight without reentry guidance, in which more than 100 km position errors are remained. Using reentry guidance, the position errors are significantly reduced as shown in Figs. 12 and 13; Fig. 12 shows the reentry guidance error analysis results of the variable-gain guidance used by Gemini (Ref. 8) and Fig. 13 shows those of the real-time prediction guidance using numerical integration. Comparing the results of the variable-gain guidance (Fig. 12) and the real-time prediction guidance (Fig. 13), we found that the real-time prediction guidance using numerical integration is more accurate than the variable-gain guidance.

Table 5 Error Factors using Reentry Guidance Analysis

Error Factor		Error
Initial Position/ Velocity Error	Cross Range Direction	±100 km
	Down Range Direction	±4 km
	Inertial Velocity	±1 m/sec
	Flight Path Angle	±0.18 deg
	Flight Direction Angle	±0.04 deg
Initial Navigation Error	Position	±45 m
	Velocity	±0.09 m/s
	Attitude	±0.3 deg
IMU Error	Acceleration Bias	±130 μG
	Gyro Bias Drift	±0.096deg/hr
Air Density Error	Altitude 10-30km: ±10% 60-80km: ±50% 100-120km: ±70%	
Vehicle Error	Coefficient of Lift	±25%
	Coefficient of Drag	±25%
	Vehicle Weight	±1ton
Wind Error		See Figure 9

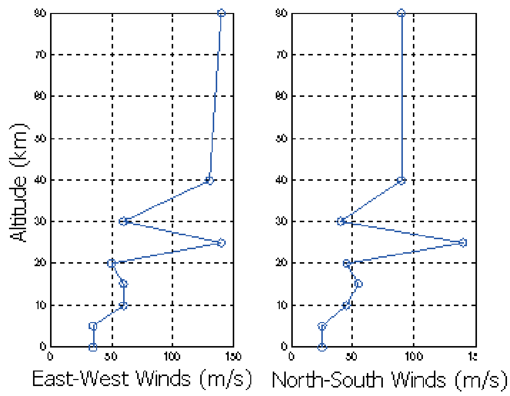

Fig. 9 Wind Error

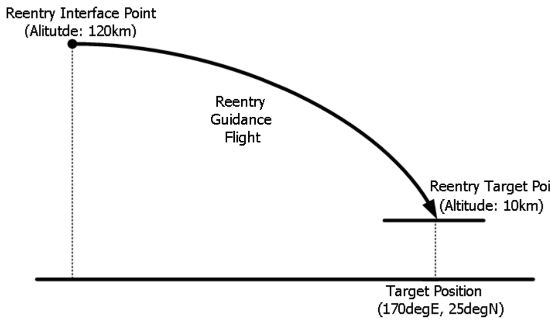

Fig. 10 Reentry Simulation Condition

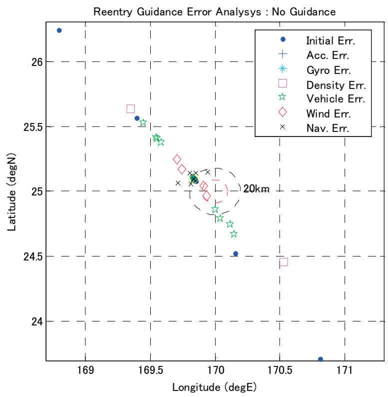

Fig. 11 Error Analysis results (No Reentry Guidance)

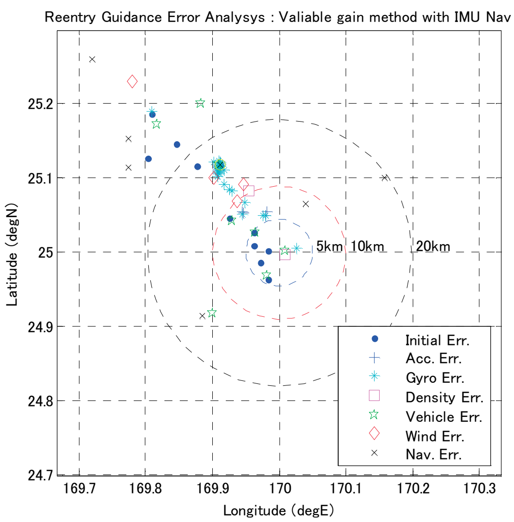

Fig. 12 Guidance Error Analysis results of Variable-Gain Guidance

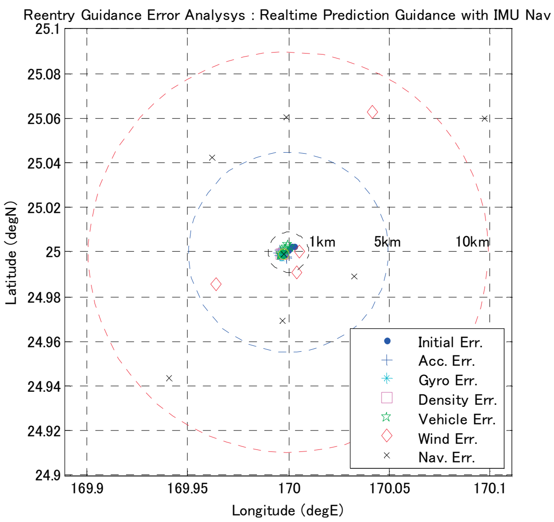

Fig. 13 Guidance Error Analysis results of Real-time Prediction Guidance

(3) Enhanced Navigation accuracy

As shown in Figure 13, there are two major error sources affecting guidance error, wind and initial navigation errors on attitude. To improve guidance error caused by the latter error, we applied IMU-GPS integrated navigation for reentry. We assumed the GPS navigation could not be used from an attitude of 95 to 40 km due to signal blackout during reentry. The guidance error analysis results using IMU-GPS integrated navigation are shown in Figure 14. The guidance error caused by the initial navigation errors on attitude are improved to within 10 km by using the IMU-GPS integrated navigation. We also applied on-orbit alignment using IMU-ST integrated navigation. Figure 15 shows the results of guidance error using IMU-ST integrated navigation, in which the guidance error caused by the initial navigation error on attitude can be reduced to within 5 km.

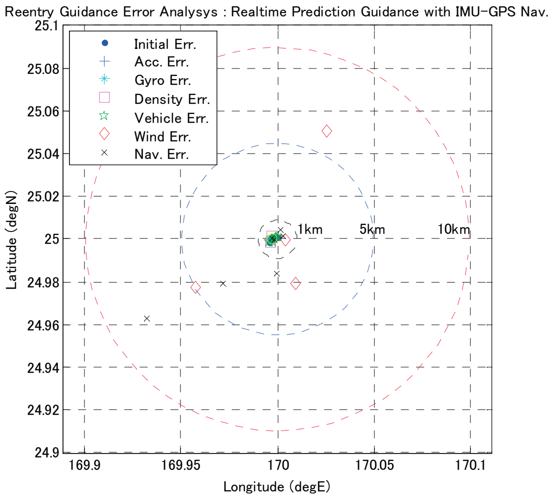

Fig. 14 Guidance Error Analysis results of Real-time Prediction Guidance using IMU-GPS Integrated Navigation

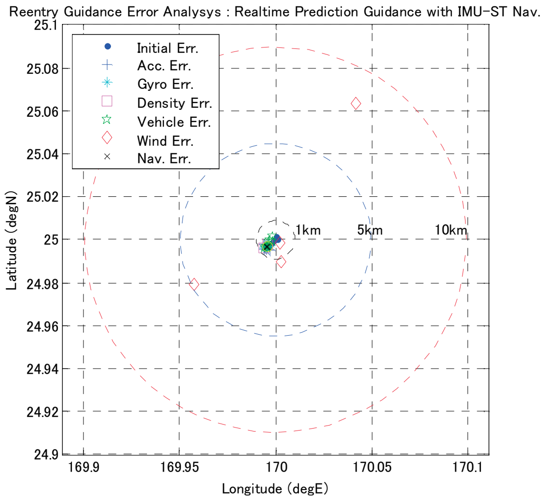

Fig. 15 Guidance Error Analysis results of Real-time Prediction Guidance using IMU-ST Integrated Navigation

4. Conclusion

In this paper we extracted technical challenges for capsule spacecraft and examined the guidance and control methods for guided reentry flight to solve the technical challenges. We designed a reference reentry trajectory, which satisfied reentry conditions under maximum errors in the reentry phase. Using real-time prediction guidance, which featured numerical integration and IMU-GPS integrated navigation and IMU-ST integrated navigation, we improved the reentry guidance to within 5 km excepting guidance error made by wind. If a recovery system including ground equipment can upload upper-wind information measured by the ground site to a reentry capsule spacecraft before its reentry flight, the guidance error caused by upper-level wind can be significantly reduced.

We will continuously improve reentry guidance accuracy by improving the real-time prediction guidance using numerical integration.

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