General

JERG-2-152A

DISTURBANCE CONTROL STANDARD

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Japan Aerospace Exploration Agency

This is an English translation of JERG-2-152A. Whenever there is anything ambiguous in this document, the original document (the Japanese version) shall be used to clarify the intent of the requirement.

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Contents

1. General Provisions

1.1 Purpose

This standard specifies the disturbance control of artificial spacecrafts and interplanetary probes developed by JAXA.

1.2 Scope

When being applied to specific projects, the standard shall be tailored according to the conditions of each project.

1.3 Related documents

(1) JERG-2-500 Control System Design Standard
(2) JERG-2-510 Attitude Control System Design Standard
(3) JERG-2-151 Mission and Orbit Design Standard

References

(1) Artificial Spacecraft Dynamics and Attitude Control Handbook, published by Baifukan in 2007

2. Philosophy of disturbance control

2.1 Spacecraft and disturbance

The forces that act upon the spacecraft and spacecraft's internal elements can be classified as shown in Figure 1. Of which change the spacecraft attitude, mission instrument functions and performance (including pointing accuracy) and affect the micro- vibration environment within the spacecraft, internal forces other than intended controlling force and control torque shall be defined as internal disturbance (disturbance for short). Internal forces are the general term for interacting forces and torques between elements in the spacecraft.

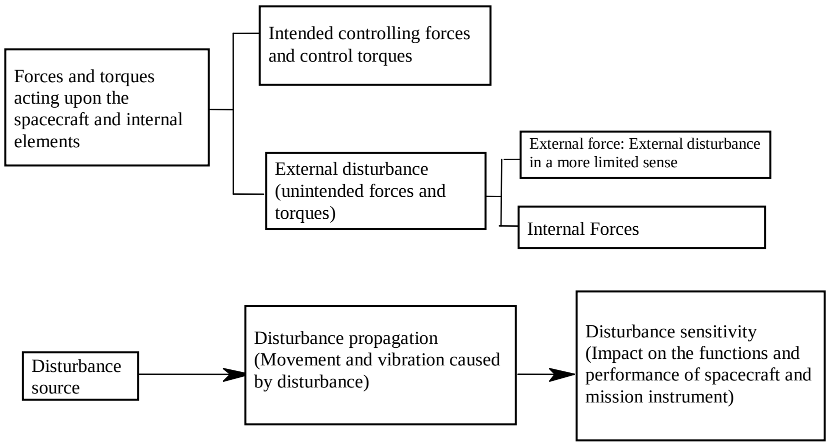

Figure 1 Definition of disturbance

The movement of a mass generating disturbance or the instrument including the moving mass shall be defined as a disturbance source. The generated disturbance causes movement (including vibration) of the spacecraft or mission instrument (referred to as disturbance propagation) and affects the functions and performance. When the functions and performance of a spacecraft and instrument are affected by disturbance-induced movement (vibration), the spacecraft and instrument are disturbance-sensitive.

This design standard specifies the process for controlling the disturbance sources, disturbance propagation and disturbance-sensitive instrument to achieve the functions and performance of the required spacecraft and mission instrument when there is a disturbance source inside the spacecraft and the spacecraft has disturbance-sensitive instrument. Examples of disturbance sources are as given in Table 1.

Table 1 Examples of disturbance sources

Type	Disturbance source	Operation frequency
External disturbance (reference)	Solar radiation pressure torque	Torque almost static
	Residual magnetic torque	
	Gravity gradient torque	
Stationary disturbance	Wheel for attitude control	10-200Hz
	Gyro	155 Hz (in the case of rotating at 9300 rpm)
	Solar cell paddle drive	
	Mechanical scanning antenna	1-10Hz
	Cooler	15-200Hz
	Mission instrument drive	
Transient disturbance	Mission instrument drive	
	Solar cell paddle drive	
	Wheel zero-cross	
	Deployment and extension of instrument	
	Robot arm drive	
	Thermal snap	

2.2 Influence and classification of disturbances

(1) Classification by disturbance band

The attitude angle shall be the angle of the spacecraft. The pointing angle shall be the three-axis angle of the instrument installed in the spacecraft. When the disturbance has a low frequency and causes only rigid motion, the on-board instrument moves as one with the spacecraft. Thus, the attitude angle is the same as the pointing angle (low-frequency domain). For a flexible structure attached to the spacecraft, when the disturbance frequency reaches the domain which excites the vibration of the flexible structure, the flexible structure and the coupled frame will vibrate. In the frequency domain (intermediate frequency domain), the attitude angle of the body is influenced by the flexible structure. When the instrument is installed in a rigid body, the pointing angle can be regarded as being equal to the attitude angle. When the disturbance frequency is in the domain of a few dozens Hz or more, in which the spacecraft and on-board instrument generate structural vibration (high-frequency domain), the pointing angle shall be determined mainly by the deformation caused by the local vibration of the spacecraft and on-board instrument. In low and intermediate frequency domains, the influence of disturbance to the attitude system shall be controlled. In the high-frequency domain, the structural characteristics and disturbance propagation characteristics of the frame (including the layout of disturbance sources) shall be controlled. The classification by the disturbance band (relationship between attitude angle and pointing angle) is shown in Table 2.

Table 2 Classification by the disturbance band (relationship between attitude angle and pointing angle)

<table>
<tr><th>Frequency (Order)</th><th>Low frequency domain
Order of 0.01 Hz or less</th><th>Intermediate frequency domain
Order of 0.01 Hz - 10 Hz</th><th>High frequency domain
Order of 10 Hz or more</th></tr>
<tr><td>Attitude angle and pointing angle</td><td>Attitude angle = Pointing angle</td><td>Attitude angle = Pointing angle</td><td>Attitude angle ≠ Pointing angle</td></tr>
<tr><td rowspan="3">Remarks</td><td rowspan="2">The spacecraft can be regarded as a rigid body as a whole.</td><td rowspan="2">The spacecraft structure which can be regarded as a rigid body is provided with a flexible structure. When the on-board instrument is installed on the flexible structure side, attitude angle ≠ pointing angle.</td><td>Local vibrations which transfer the structure are the principal component of disturbance.</td></tr>
<tr><td rowspan="2">In the frequency band, the pointing angle is determined by local deformation.</td></tr>
<tr><td colspan="2">When pointing control is performed, the attitude angle need not be equal to the pointing angle.</td></tr>
</table>

(2) Other classifications

Some spacecrafts which carry out missions in the stationary state steadily produce disturbance, with an instrument like a reaction wheel. Such disturbance is referred to as stationary disturbance. As mentioned in the previous section, stationary disturbance can be classified and controlled in the frequency band. Of internal disturbances, disturbances associated with the deployment and extension of solar cell paddles and antennas temporarily (deployment disturbance) have a significant impact on the spacecraft attitude. Such disturbances are referred to as “transient disturbances.” In the solar cell paddle drive, transient disturbances are regularly produced by the stepping motor. Disturbances shall be regarded as transitional for pulse-by-pulse response. Disturbances shall be regarded as stationary when focusing on the macroscopic influence on pulse strings as a whole. In intermittently-driven instrument, disturbance is transitional from a macroscopic viewpoint. However, short-term behavior during driving must be regarded as a stationary disturbance. Classification by waveform of disturbance is shown in Table 3.
Extremely micro disturbance shall be referred to as “micro-disturbance.” Micro-disturbance is generally vibrational disturbance in many cases and is referred to as micro-vibration in some cases.

Table 3 Classification by waveform of disturbance

Classification	Features and examples
Line spectrum disturbance	Steady state frequency, harmonics and subharmonics of instrument Vibration source in which the transfer rate increases sharply due to resonance produced by the structure and mount.
Random disturbance	Noise vibration, non-negligible background noise
Disturbance to be regulated in time domain (transitional)	Disturbance in which waveforms are regulated (torque or angular momentum variation) in time domain

2.3 Necessity for disturbance control

When mission requirements are evaluated and high pointing accuracy and pointing stability are required in the initial phase of spacecraft development, disturbance control shall be performed as part of the system design. When there is a large disturbance source inside the spacecraft, disturbance control must be performed as part of the system design. For disturbance control to be performed as part of the system design, guidance with regard to pointing accuracy, pointing stability requirements, and intensity of disturbance is as given in Table 4.

When a device with sensitivity to the acceleration environment is installed in the spacecraft, disturbance control must be performed in consideration of the acceleration environment. When the on-board instrument must be under a micro-acceleration environment of the order of 0.0001 m/s^2 to 0.001 m/s^2 (1 mG to 10 mG) or less, it is generally required that disturbance control is to be performed.

It is required that large disturbance produced by the deployment of solar paddles is to becontrolled to satisfy the basic functions and performance of the instrument and that the effect on the spacecraft operation be evaluated and controlled. In such cases, it is required to control only the operations associated with the deployment of the instrument such as solar paddles. Disturbance control may be performed even though it is not indispensable as part of the system design from the initial phase of the spacecraft development.

This design standard specifies the process of disturbance control to be performed as part of the system design from the initial phase of the spacecraft development.

Table 4 Guide on whether to perform disturbance control

Requirement		Value	
When high accuracy is required	Pointing accuracy	0.01 to 0.001° or less	Value shall be determined depending on the mission.
	Pointing stability	0.001 to 0.0001° (specified time) or less	
When there is a severe disturbance	Magnitude of disturbance source	Disturbance which either equals or surpasses 1/5 of the controlling force, control torque and angular momentum produced by the control instrument.	
Acceleration environment		0.0001 m/s^2 to 0.001 m/s^2 (1 mG to 10 mG) or less	

2.4 Details of disturbance control

Disturbance control shall be performed as part of the system design and include the control of disturbance sources, disturbance propagation (including instrument layout) and disturbance sensitivity. The details are as follows. The relationship between operations is shown in Figure 2. Disturbance control operations are surrounded by thick dotted lines in the figure.

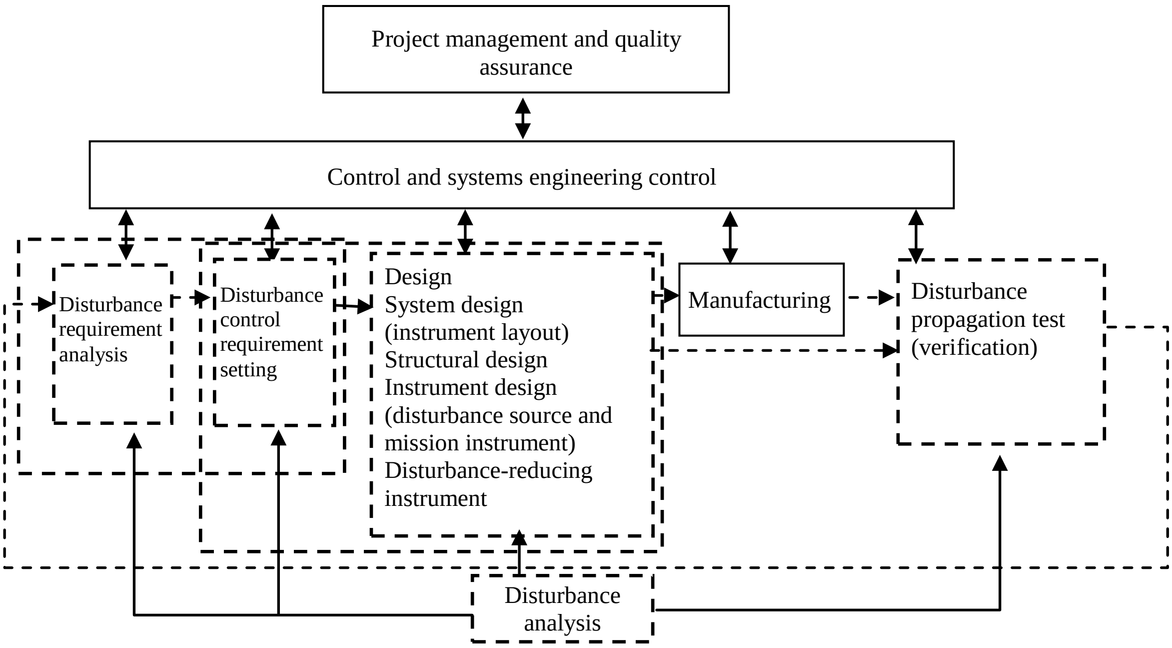

Figure 2 Process flow

(1) Disturbance requirement analysis

Disturbance requirement analysis in which mission requirements or system requirements are broken down

(2) Setting of disturbance control requirements

Basic disturbance control policy (including allocation to the following items)

Disturbance control items and disturbance requirements for disturbance-sensitive instrument

Disturbance control items and disturbance requirements for disturbance sources

Requirements (frequency, band) for structure and control systems

(3) Design related to disturbance instrument

The following designs shall be performed for instrument which acts as a disturbance source and disturbance-sensitive instrument:

System design (instrument layout)

Structural design

Instrument design (disturbance source and mission instrument)

Disturbance-reducing instrument (such as isolator and damper)

(4) Disturbance propagation test

(5) Disturbance analysis

3. Process of disturbance control

Disturbance control processes differ depending on the spacecraft development phase. This chapter explains the disturbance requirement analysis and disturbance control requirement setting which are disturbance control processes in the initial development phase.

3.1 Disturbance requirement analysis in accordance with mission requirements

The process shall be started with disturbance requirement analysis. Possible disturbance sources and instrument (disturbance-sensitive instrument) which are likely to be affected by disturbance shall be listed in accordance with the mission requirements.

(1) Listing disturbance sources

Disturbance sources are as shown in Table 1 in Paragraph 2. To facilitate control, classification may be performed as shown in Table 2 and Table 3 in Paragraph 2.

(2) Listing disturbance-sensitive instrument

Various types of mission instrument shall be listed as disturbance-sensitive instrument.

3.2 Disturbance control requirement setting

Mission requirements are specified as baseline requirements for system disturbance control. In concept designs, specific disturbance control requirements shall be specified as outputs using the baseline requirements as basic inputs.

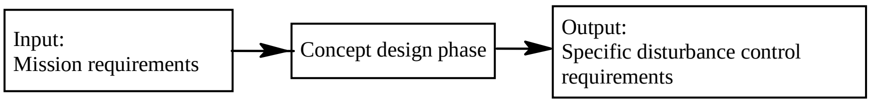

Figure 3 Input/output during concept design

The outputs should be put into document form to the extent possible. This standard recommends that the output be documented as a project-specific disturbance control standard or a disturbance control requirement (document).

For subsystem- and instrument-specific disturbance requirements, specific disturbance characteristic specifications shall be defined in accordance with the requirements specified in the document. The design results in each phase shall be validated in a design review meeting.

4. Disturbance control in each phase of spacecraft development

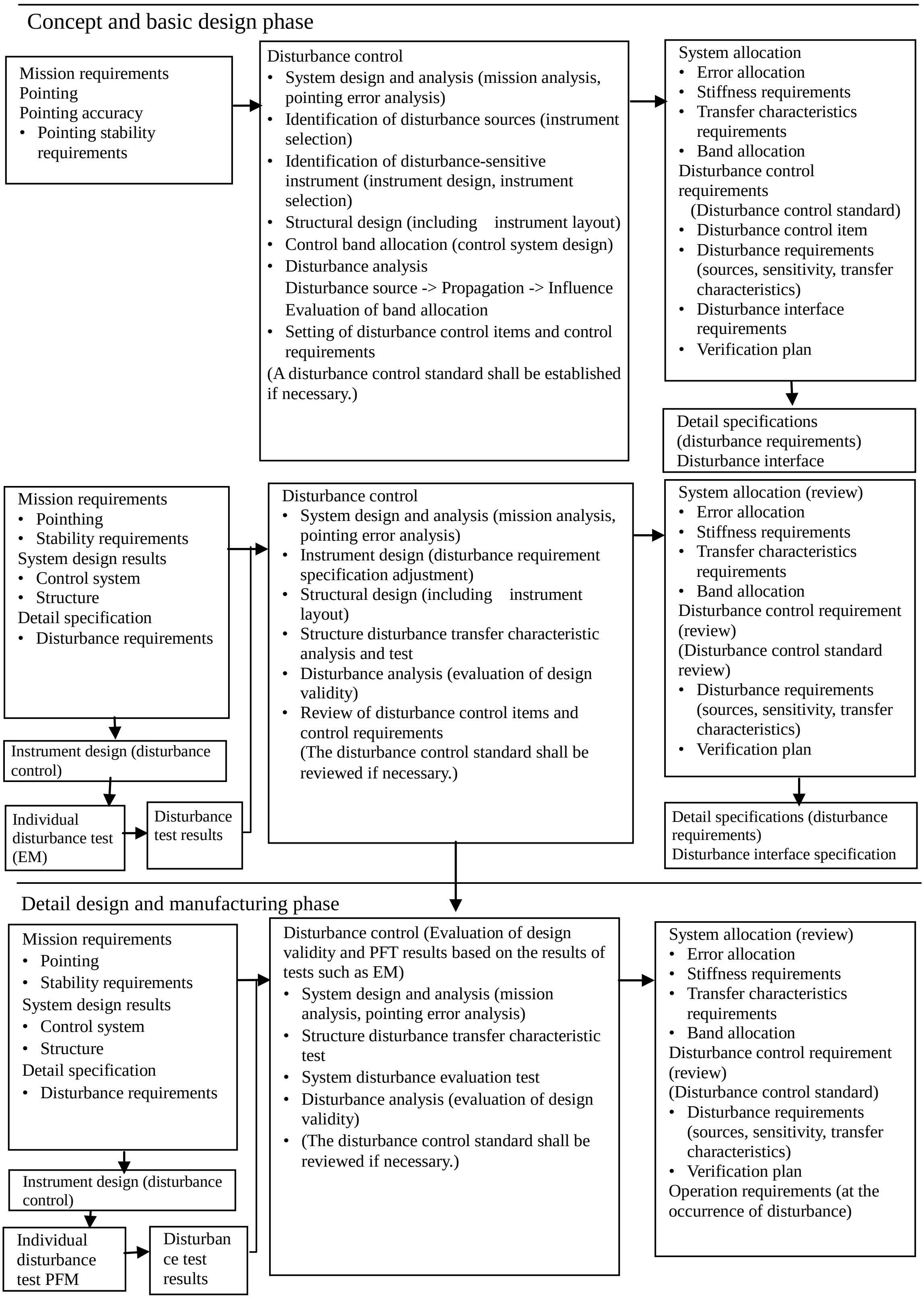

Figure 4 Disturbance control flow in each phase of spacecraft development

Figure 4 shows the flow of disturbance control in spacecraft design. The overview of disturbance control process in each phase and precautions in performing disturbance control are shown in the next chapter. This standard shows the overview of disturbance control to be performed in the system. Similar control can be performed in subsystems and instrument. The baseline requirements for disturbance control of subsystems and instrument shall not be regarded as mission requirements and system requirements but as individual disturbance requirements.
This chapter describes the disturbance control processes to be performed in each phase of spacecraft design in accordance with the flow of spacecraft development. In spacecraft development, a disturbance control plan shall be established with an eye to the input and output to disturbance control process.

4.1 Concept and preliminary design (conceptual design) phase

(1) System design and analysis

It shall be required to break down the mission requirements and evaluate the basic disturbance requirements (whether pointing error allocation assigned to disturbance causes problems). If the on-board instrument has a significant source of disturbance, it is required to perform a brief evaluation of the effects on the missions and determine the policy for controlling disturbances. In the control policy, it is required to clearly identify the instrument which must be free from the influence of the disturbance by imposing operational restrictions such as paddle deployment.
In the policy for controlling disturbances, it is required to clarify the concept of what analyses and tests are necessary for design and verification. It shall be required to estimate resources including budgetary measures without missing large test instrument or events. Depending on the circumstances, a BBM phase may be added (such as disturbance measurement test in the concept - preliminary design phase). (The policy for controlling disturbances shall be organized as a disturbance control standard when needed.) Allocation design is of importance in the phase of system design and analysis. It shall be required to control the allocation and summation and define the aggregation method at the time of allocation. When there are many newly developed items related to disturbance control and orbital verification is necessary, it is required to make an orbital verification plan in this phase and develop orbital disturbance measuring instrument in the artificial spacecraft development process.

(2) Understanding of disturbance sources and disturbance-sensitive instrument

First of all, it is necessary to check what on-board instrument is installed. In addition to bus instrument such as wheels, it is required to review whether the mission-system instruments such as coolers and compressors are possible sources of disturbance. It is necessary to regard non-stationary disturbances, including deployment disturbances, as disturbance sources. For any instruments identified as disturbance sources, it is required to temporarily specify the control items and values so that the instrument can be evaluated through disturbance analysis. When disturbance control standard is specified, it is required to evaluate in line with the disturbance control standard whether the instruments and systems meet the conditions. If the conditions are not met, feedback on the instrument design (including instrument selection) or system design (system allocation) shall be given. The disturbance-sensitive instrument shall be understood similarly. It shall be required to check bus-system instruments such as sensors (inertia sensors, optical sensors) and accelerometers as well as mission instrument for disturbance sensitivity. For any instruments identified as disturbance sensitive based on the investigation results, it is required, as in the case with disturbance sources, to temporarily specify the control items and values so that the instrument can be evaluated through disturbance analysis. It is of importance, in this phase, to determine the interfaces between the disturbance sources and disturbance-sensitive instrument and frame (including instrument-specific disturbance test environment). The interface shall be a disturbance control item when needed.

(3) Structural design and allocation of control band

Based on the characteristics of disturbance sources and disturbance-sensitive instrument understood in the previous section (including frequency characteristics), it is required in this phase to perform a preliminary disturbance analysis (evaluate the disturbance influence), instrument layout and band allocation to the control system. It is important in this phase to estimate the disturbance transfer rate based on empirical values and specify structural design requirements and instrument layout requirements as disturbance requirements. When a disturbance control standard is specified, it is necessary to evaluate whether the structural design results meet the stiffness requirements and damping requirements of the disturbance control standard.

A control band shall be allocated to the control system to avoid interference with the results of the above structural analysis and disturbance characteristics (disturbance frequency) of each instrument. As a goal, the control system should be separated from the disturbance source by a decade or more when possible. If this goal cannot be achieved, the control system shall be designed so that phase stability is ensured in the disturbance frequency band.

(4) Disturbance analysis

The purpose of analysis is to evaluate the effect of disturbance and understand whether the mission requirements can be satisfied. In this phase, enough information of disturbance control items is not available in many cases. However, analysis shall be performed using empirical values. If analysis results show that mission requirements are not satisfied, feedback shall be given to the mission analysis and disturbance control standard. If analysis results show that mission requirements are satisfied, the disturbance control items and the values are validated. Thus, disturbance control requirements will be specified.

(5) Setting of disturbance control requirements

The disturbance control items and the values established up to the previous section shall be organized as disturbance requirements. For each disturbance control item, verification requirements up to the flight shall be included. When instrument design (instrument selection) is not finished in this phase, it is required to establish a disturbance control standard and perform instrument design and instrument selection continually.

(6) Design reviews

In design reviews (system requirement reviews (SRR)), the above process results (disturbance control) shall be evaluated for validity in line with the mission requirements. In this phase, it is important to check whether the policy for controlling disturbances (disturbance control standard) is established according to the disturbance control level and whether rational disturbance control items are specified.

4.2 Basic design review (EM phase)

(1) System design and analysis

According to the design results based on the disturbance control requirements specified in the concept design and preliminary design phases (disturbance control standard), it is required to perform pointing error analysis in the system and evaluate the disturbance control for validity in the basic design phase. When needed, the policy for controlling disturbances (such as disturbance control standard) shall be reviewed.

(2) Subsystem/instrument design, specification adjustment

The subsystems (structure and control systems) and instrument shall be designed according to the disturbance requirements specified in the previous phase. As part of instrument design, it is required in the system to perform evaluation of whether the design of instrument and subsystems is performed according to the disturbance control requirements (or disturbance control standard). When instrument selection is performed in this phase, it is required to perform evaluation of whether the disturbance characteristics of instrument are valid in line with the disturbance control standard. In this phase, it is required to perform a disturbance measurement test on some instruments to provide results with regard to system analysis and disturbance analysis. Accordingly, it is required to adjust the disturbance requirement specifications and review the disturbance requirements if necessary.

(3) Disturbance characteristic test on instrument (test using EM)

Conducting testing to understand disturbance characteristics is technically difficult and large scale. Thus, it is necessary to make an elaborate test plan considering the related fields. To prevent discrepancies in interfaces, coordination shall be made properly with the system side before testing is conducted. It is desirable that test results shall be evaluated in a review meeting by related divisions including the system division.

(4) Structure disturbance transfer characteristic test

When necessary, structure disturbance transfer characteristic tests shall be conducted (using a system structure model, etc.) on the results of structural designs in the system to evaluate the disturbance transfer characteristics. If the disturbance transfer characteristics cannot meet the disturbance requirements, the structural design including the disturbance isolator shall be reviewed. In conducting disturbance transfer characteristic tests in the system, disturbance sources that are hard to evaluate individually and disturbance-sensitive instruments are installed in some cases to understand the disturbance transfer characteristics of the structure including instrument. Conducting disturbance transfer characteristic tests in the system is technically difficult and large scale. Thus, it is necessary to make an elaborate test plan considering the related fields.

(5) Disturbance analysis

Various types of disturbance characteristic data (disturbance sources, disturbance transfer characteristics, disturbance sensitivity) as EM (including structure models) trial results are available in this phase. Using the data validity for disturbance control and system feasibilty shall be checked. If analysis results show that mission requirements are not satisfied, feedback shall be given with regard to the mission analysis and disturbance control standard. If analysis results show that mission requirements are satisfied, the disturbance control items and the values are validated. Thus, disturbance control requirements will be specified.

(6) Reviewing of disturbance control requirements

According to the process results up to the previous section, it is required, if necessary, to review the disturbance control requirements as well as the disturbance-related requirements for subsystems and individual instrument.

(7) Design reviews

The following items shall be reviewed:

- Subsystems and instrument PDR

  It shall be required to perform validation of the disturbance characteristics of subsystems and instrument and interface parameters, and confirmation of the unit verification/test plan. When any testing such as BBM is conducted, it is required to perform validation of the test results.

- System PDR

  The validity of disturbance-related system design (including structural design and control system design) shall be evaluated based on the results of system analysis and disturbance analysis.

4.3 Detail design and manufacturing phase (PFM phase)

EM test results are available in this phase and thus it is possible to perform a realistic design review to some extent. First, the design baseline shall be checked with respect to disturbance control items through CDR. Based on the results, shift to the manufacturing phase. When the EM test results require changes in the disturbance requirements, it is necessary to perform validation of the changes through analysis. After the disturbance requirements are found to be valid, shift to the manufacturing phase in accordance with the disturbance control requirements (disturbance control standard) and individual disturbance requirement specifications. Basically, similar processes mentioned in Section (2) of the previous paragraph shall be performed in the following steps.

(1) System design and analysis

According to the design results and EM test results based on the disturbance control requirements specified in the basic design phases (disturbance control standard), it is required to perform pointing error analysis in the system and evaluate the disturbance control for validity in the detail design phase. When necessary, the policy for controlling disturbances (such as disturbance control standard) shall be reviewed. When the policy must be changed in this phase, design validation shall be performed again through EM. When operational restrictions are imposed due to disturbance in this phase, information shall be transferred to the operation phase as operation requirements (such as deployment and antenna slew.

(2) Subsystem/instrument design, specification adjustment

It shall be required to perform disturbance design validation including EM and carry out detail design of subsystems and instrument. As part of instrument design, it is required in the system to perform evaluation of whether the design of instrument and subsystems is performed according to the disturbance control requirements (or disturbance control standard).

(3) Disturbance characteristic test of subsystems and instrument (PFM test)

Conducting testing to understand disturbance characteristics is technically difficult and large scale. Thus, it is necessary to make an elaborate test plan considering related fields. To prevent discrepancy in interfaces, coordination shall be made properly with the system side before conducting testing. It is desirable that test results be evaluated in a debriefing session by related divisions including the system division.

(4) Structure disturbance transfer characteristic test and integrated disturbance characteristic test (PFM test)

When needed, structure disturbance transfer characteristic tests shall be conducted (using a system structure model, etc.) on the results of structural designs in the system to evaluate disturbance transfer characteristics. It shall be required to perform an integrated disturbance characteristic test on the system when needed and evaluate the disturbance control performance for validity. Conducting disturbance characteristic tests in the system is technically difficult and large scale. Thus, it is necessary to make an elaborate test plan considering related fields.

(5) Disturbance analysis

Different types of disturbance characteristic data (disturbance sources, disturbance transfer characteristics, and disturbance-sensitivity) as PFM test results are available in this phase. Disturbance control shall be checked for validity and system feasibility using the data. If analysis results show that mission requirements are not satisfied, feedback shall be given with regard to the mission analysis and disturbance control standard.

(6) Reviewing of disturbance control requirements

According to the process results up to the previous section, it is required, if necessary, to review the disturbance control requirements as well as the disturbance-related specifications for subsystems and individual instrument.

(7) Design reviews

The following items shall be reviewed:

- Subsystems and instrument CDR

The instrument disturbance characteristics and interface parameters shall be checked for validity. The unit verification and test plan shall be checked. When any testing such as BBM is conducted, it is required to perform validation of the test results.

- System CDR

  The validity of disturbance-related system design (including structural design and control system design) shall be evaluated based on the results of system analysis and disturbance analysis.
- PQR

  When the disturbance test is conducted through PFT, the design and operational restrictions shall be evaluated for validity in accordance with the results. Operational restrictions shall be reviewed if necessary.

4.4 Orbital operation phase

Occurrence of disturbance in orbit may lead to operational restrictions. First, it is necessary to check whether the operational restrictions related to disturbances specified in the design phase are reflected in the operational procedures (including the time required before solar paddle deployment disturbance and thermal snap-induced vibration are stable.).
In the orbit, it shall be confirmed that the conclusion in the design and manufacturing phases are correct through checkout (such as initial inspection). Just in case, avoidance shall be attempted in operation.

(1) Operational restrictions

Operational restrictions, such as stabilization of paddle deployment disturbance, disturbance during antenna slew and thermal snap vibration, are imposed in many cases. It shall be required to identify the disturbance-related operational restrictions and check that the restrictions are reflected in the operational procedures. The operational procedures shall be checked for validity through operation analysis in light of the restrictions.

(2) Checkout

This is an operation check in the initial operation stage. In accordance with the telemetry and system performance (circuit quality as for the communication system, shot image as for the imaging system), the expected performance shall be checked for. If necessary, operation for understanding disturbance characteristics shall be performed with the orbital-disturbance-measuring instrument installed. As a sensor measuring disturbance in the orbit, IRU is used as bus instrument in many places. A dedicated accelerometer or jitter sensor may be installed to measure disturbances associated with the deployment of paddles and antennas. Conducting testing to understand disturbance characteristics in the orbit (checkout) is technically difficult. Thus, it is necessary to make an elaborate test plan considering related fields.

(3) Nonconformance investigations

If the expected performance cannot be obtained, investigation shall be made as to whether disturbance is the cause of the nonconformance. It shall be required to check if the instrument which is a probable disturbance source is turned on or off and in the case of wheels, examine the correlation with the rotation speed. Avoidance shall be attempted in operation.

(4) Obtaining and evaluating field proven data

Important on-orbit data can be obtained in some cases if an accelerometer or an attitude sensor is used. If obtained and evaluated, such data will be useful in the next design.