General

JERG-2-510A

DESIGN STANDARD
ATTITUDE CONTROL SYSTEM

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Japan Aerospace Exploration Agency

This is an English translation of JERG-2-510A. 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

Chapter 1 General Provisions

1.1 Purpose

An attitude control system of a spacecraft is an important system determining the success or failure of the mission. The attitude control system is designed for controlling “attitude of a spacecraft” and basically the development process of the attitude control system specified in the “Control System Design Standard” shall be applied. This standard defines specific requirements for “spacecraft attitude control system”.

1.2 Scope

This standard describes the attitude control system of spacecrafts developed as part of space systems. This standard applies to all the elements in space systems including space segment, ground segment and launch service segment related to the attitude control system of spacecrafts.

This standard covers to all fields and life cycles of space systems development including requirement definition, analysis, design, manufacturing, verification, validation, transfer, spacecraft system test, operation and maintenance.

If the standard is applied to a specific project, the requirements specified in this standard shall be tailored in accordance with the project conditions.

1.3 Related documents

1.3.1 Document system

The system of documents related to “Control System Design Standard” shall be as follows. (The system is shown in Appendix 1.)

(1) Second-level: Control System Design Standard
(2) Third-level: Individual design standards
(3) Fourth- level: Handbooks and manuals

1.3.2 Applicable documents

The documents applicable to this standard shall be as follows. The following documents shall be part of this standard in the range specified in the standard. If the standard conflicts with any of the applicable documents, this handbook shall prevail unless otherwise specified. It is recommended that the user of this standard review the application of the latest version of applicable documents.

(1)		Basic concept of systems engineering, First edition
(2)		Project Management Guideline
(3)	JMR-001B	System Safety Standard
(4)	JMR-004C	Reliability Program Standard
(5)	JMR-005A	Quality Assurance Program Standard
(6)	JMR-006	Configuration Control Standard
(7)	JERG-2-610	Spacecraft Software Development Standard
(8)	JERG-2-700	Operation Design Standard
(9)		Spacecraft Design Error Prevention Standard
(11)	JERG-2-500A	Control System Design Standard
(12)	JERG-2-600	Software Development Standard

1.3.3 References

(1) Risk Management Handbook
(2) ECSS-E-60A Control engineering, Space engineering, ECSS Secretariat
(3) The handbooks and manuals related to this standard shall be as follows:
(Third- and fourth-level documents)

[1]	JERG-2-151	Mission and Orbit Design Standard
[2]	JERG-2-153	Pointing Control Standard
[3]	JERG-2-152	Disturbance Control Standard
[4]		Mission and Orbit Design Handbook
[5]		Disturbance Control Manual
[6]		Standard Coordinate System and Time System Usage Manual
[7]		Basic Manual for Attitude Kinematics and Dynamics of Spacecrafts

[8] Attitude Control System Technology Handbook
[9] Attitude Control System Component Technology Handbook
[10] Attitude Control System Verification Technology Handbook

1.4 Terminology and Abbreviations

1.4.1 Terminology

In addition to the terms specified in the design standard for control system, the following terms are defined. See the third level and fourth level handbooks and manuals for explanatory comments of each term.

(1) Static closed loop test
(2) Dynamic closed loop test
(3) Static open loop test
(4) Dynamic open loop test
(5) Actuator
Technical system or device which converts commands from the controller into physical effects on the controlled plant..
  [1] Reaction wheel
  [2] Momentum wheel
  [3] Wheel drive electronics
  [4] Control moment gyro
  [5] Valve drive electronics
  [6] Magnetic torquer and magnetic torquer drive electronics
  [7] Gus jets propulsion system
(6) Sensor
A sensor is a device to measure the state of the controlled plant and provide the measured state quantity as feedback input to the control system.
  [1] Earth sensor
  [2] Sun sensor
  [3] Star sensor
  [4] Inertial reference system
  [5] Rate gyro
  [6] Accelerometer
  [7] GPS receiver
(7) Attitude and orbit control electronic circuit
(8) Biase momentum attitude control system
(9) Zero momentum attitude control system
(9) Attitude maneuver
(10) Gain margin
(11) Phase and margin
(12) Flexible structure mode
(13) Disturbance
  [1] Solar pressure external disturbance
  [2] Gravity gradient external disturbance
  [3] Earth magnetic field external disturbance
  [4] Aerodynamic external disturbance
(14) Internal disturbance (external disturbance originated from the control system or plant are referred to as internal disturbance or disturbance)
(15) Control mode
A control mode is a functional unit to execute specific control functions of the control system.
(16) Operational mode
An operation mode is a functional unit to combine control modes and execute functions required as a control system for a specific operation.
(17) Operation mode
An operation mode is an operation state (including on/off state in the case of equipment) of software and equipment corresponding to the operational mode and control mode.

1.4.2 Abbreviations

In addition to the abbreviations specified in the design standard for control system, the following terms shall be defined.

(1)	SCLT	Static Closed Loop Test
(2)	DCLT	Dynamic Closed Loop Test
(3)	SOLT	Static Open Loop Test
(4)	DOLT	Dynamic Open Loop Test

(5) Actuator

A technology system or piece of equipment for converting the commands from the controller into physical effects for controlled plants.

[1]	RWA	Reaction Wheel Assembly
[2]	MWA	Momentum Wheel Assemble
[3]	WDE	Wheel Drive Electronics
[4]	CMG	Control Moment Gyro
[5]	VDE	Valve Drive Electronics
[6]	MDE	Magnetic Torquer Drive Electronics
[7]	SPS	Secondary Propulsion Subsystem

(6) Sensor

A device to measure the state of a controlled plant and provide the state as feedback inputs to the controller.

[1]	ESA	Earth Sensor Assembly
[2]	SSA	Sun Sensor Assembly
[3]	SS	Star Sensor
[4]	IRU	Inertial Reference Unit
[5]	RGA	Rate Gyro Assembly
[6]	ACC	Accelerometer
[7]	GPSR	GPS Receiver

(7)	AOCE	Attitude & Orbit Control Electronics
(8)	FDIR	Fault Detection, Isolation and Recovery (or Reconfiguration)
(9)	ACFS	Attitude Control Flight Software

1.4.3 Units

International system of units (SI) shall be used. (If it is difficult to use SI in a common fashion, conventional units shall be included.)

Chapter 2 Process of attitude control system design

2.1 General

2.1.1 Configuration of a general attitude control system

To indicate the scope of control engineering process to which this standard applies, the configuration of a general attitude control system shall be shown in Figure 2-1.

In Figure 2-1, whole attitude control system refers to "the control- relevant part of a system for achieving the attitude control objectives". To be more specific, the attitude control system consists of a controller part system (including elements such as control electronics, sensors and actuators for achieving control objectives) and the(a?) controlled plant of the satellite (attitude dynamics). Orbit control system is closely related to attitude control in that, generally speaking, attitude control is necessary for orbit control. Therefore, the orbit control and attitude control functions are often integrated hardware and software as the relevant hardware and softwares shall be included in the controller part and “the attitude and orbit control system.” This standard deals with the control system in which the attitude control is integrated with the orbit control. In this case, these of the orbit dynamics shall be included in the controlled plant shown in Figure 2-1.

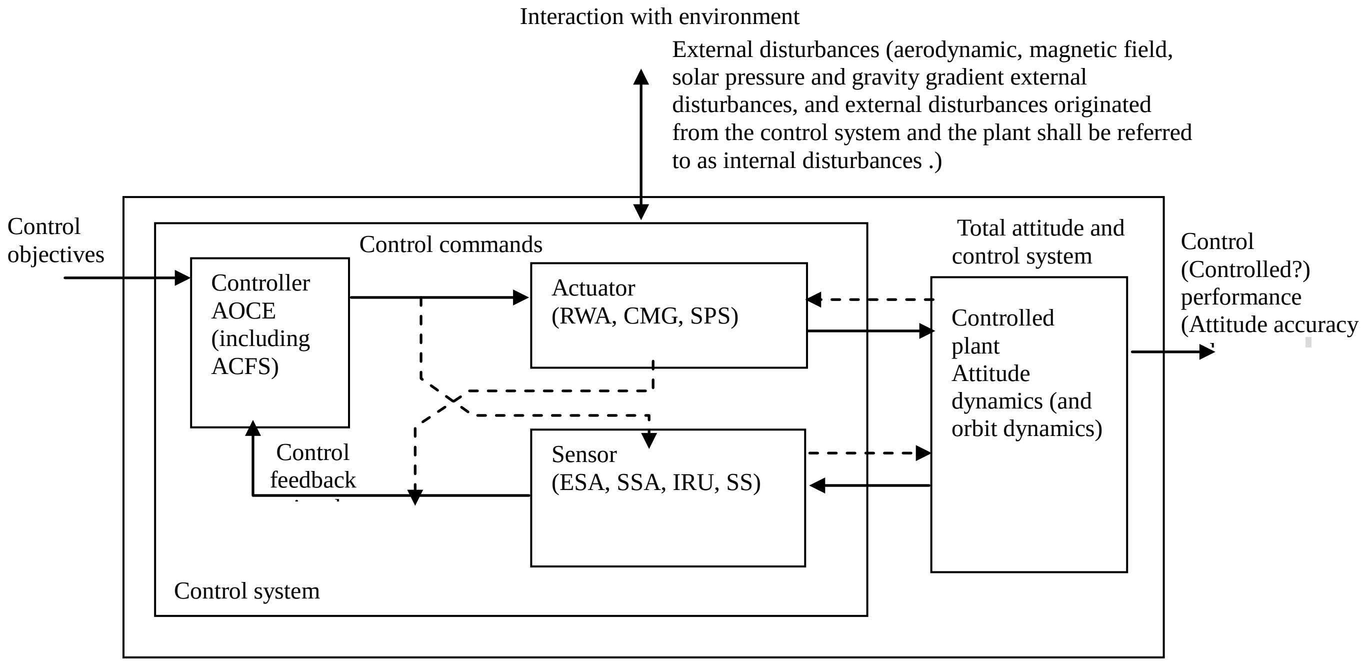

Figure 2-1 Configuration of general attitude control system

The purpose of control engineering in the attitude control system development is to allow controlled plants to achieve control objectives namely to achieve desired control performances, under disturbances from the environment by giving guidance for the development of control systems.

For this purpose, proper equipment such as an actuators (a technical system or piece of equipment for converting controller’s commands into physical effects in a controlled plant) and sensors (equipment for measuring the state quantity of a controlled plant and in order to control feedback signals to the controller) shall be used. The above-mentioned basic information flows (classical-style feedback loop) are shown by continuous lines in Figure 2-1. The secondary information flows are shown by in dashed lines. In some cases, control force or torque to be generated by the actuators, or the control commands is generated without referring to the sensor output directly (feed-forward control). In many cases, (raw) output data for attitude sensors have to be processed and connected (in AOCE) before being used for generating attitude-control commands.

The configuration and design of a spacecraft AOCS shall be looked upon and investigated from the following standpoints:

(a) AOCE (digital or analog Attitude and Orbit Control Electronics) hardware
(b) ACFS (Attitude Control Flight Software) and its (in-orbit) operation
(c) Functional allocation between the space segment and the ground segment (especially when the control loop is closed via the ground)
(d) Operation planning (off-line command generation) and command executing (on-line operation)
(e) Nominal and backup control (exception handling, FDIR function, operations in contingencies)

Generally, in the attitude control system, several control or operational modes must be taken before a particular phase or steady implementation phase in the mission. In these control or operational modes, the allocation of control functions among hardware, software and human operation; between space segment and ground segment; and between plan and implementation shall be determined by making trade-offs of status predictability (availability of reliable model), response time, usable resource of on-board computer, usable telecommunication band and coverage, complexity in decision making, development and operation cost and allowable risks.
Human operation and ground system are necessary elements to achieve control performances as a high level controller. In this standard, "Operation Design Standard" (JERG-2-700) is referred to for operation and ground system. Although not shown in Figure 2-1, the attitude control system shall include all functions, control mode switching (internal controller, sensors and actuators), the whole attitude control system and monitor in a plant state, model renewal, FDIR and so on.
The following items are general control performances in the attitude control system. However, general performances including mechanical environment and .electrical performances other than control performances shall be in accordance with .electrical and mechanical system design standard.

(1) Attitude accuracy
Attitude control accuracy is generally allocated from pointing accuracy, which is a mission requirement, but attitude control accuracy may be a direct mission requirement. Attitude accuracy shall be divided into the elements as shown below and [2] attitude determination accuracy is specified in some cases depending on the mission. When these performances are specified, the bandwidth of the attitude control system and attitude determination system, external disturbances (including internal disturbances), error sources such as noises, statistical meaning and summation method and so on must be specified.
[1] Attitude control accuracy
[2] Attitude determination accuracy

(2) Attitude stability
Attitude stability is generally allocated from pointing stability, which is a mission requirement, but may be a direct mission requirement. Attitude stability is divided into the elements as shown below and [2] attitude determination stability is specified in some cases depending on the mission. When these performances are specified, the bandwidth of the attitude control system and attitude determination system, external disturbances (including internal disturbances), error sources such as noises, statistical interpretation and summation method and so on must be specified.
It shall be defined as variation in the attitude or attitude determination value in the reference time required by the mission. If no reference time is specified by the mission side, attitude stability shall be an attitude or attitude determination value in a unit of time.
[1] Attitude control stability
[2] Attitude determination stability

(3) Response performances
The attitude maneuver may be required to the attitude control system. The attitude maneuver is required when spacecraft is directed to a specific attitude and the attitude is changed to a final pointing depending on the mission requirements (referred to as an acquisition maneuver). In any case, time is specified in a maneuver. Response performances involved with a maneuver shall be as follows:
[1] Attitude transition time
[2] Convergence time

When attitude accuracy during attitude change is required, [1] above shall be applied. (Dynamic errors are added.)
Transient response may occur at the start of orbit control mode or mode change. In such a transient response, the above-mentioned [2] above shall be required.

(4) Other functions and performances
As control engineering, in addition to the above-mentioned requirements from (1) to (3), the following functional and performance items shall be managed.
[1] Stability and robustness
[2] FDIR functions

2.1.2 Attitude control system design activities (design technology overview)

According to the structure of a general attitude control system as mentioned in the previous paragraph, control engineering includes the following activities as a minimum, in the attitude control system:

[1] Analysis of mission objectives for defining the control objectives
[2] Analysis of controlled plant modeling and interaction with the environment
[3] Modeling of sensors and actuators (configuration and characteristics) and analysis related to control requirements
[4] Requirements analysis and specification, design and configuration of the controller
[5] Verification of control performances
[6] Ground operation related to the attitude control system and ground operation

As a result, control engineering in the attitude control system is defined as systems engineering activities integrating the following engineering domains.

(1) The technology requires multidimensional knowledge including mechanics, dynamics, space environment and its effects, digital, analog electronic equipment, control theory, computer systems and networks, software engineering and operations.
(2) It is technology which has a system aspect and therefore a significant level of interaction with the systems engineering process.

In particular, activities related to the [1], [2] and [4] above are generally categorized in system analysis. Sharing roles with system shall be specified in the initial phase of the design process in the attitude control system.

2.2 Definition of control engineering process

Control engineering applied to the control system development shall be part of systems engineering and performed in close cooperation with system engineering. Phased Project Planning (PPP) is employed for reliable and efficient development of large-scale systems such as the whole attitude control system with high quality ensured. In PPP, it shall be required to divide the entire development into some phases and define activities to be performed in each phase.

Activities for control engineering vary depending on whether the attitude control system is developed together with the Spacecraft as a subsystem or system is developed independently from the Spacecraft. Activities to be performed as control engineering vary depending on the development method of the attitude control system. The activities to be implemented in each phase shall be basically in accordance with the “Control System Design Standard.” For the domains closely related to the system, sharing of roles with the system as well as the development method in the initial phase of development shall be clarified.

Phase 0 to Phase A	- Definition of mission requirements, determination of system requirements, Conceptual design.
Phase B	- Preliminary design and prototyping of systems, subsystems and components. Preliminary/Architectural design.
Phase C	- Detailed design of systems, subsystems and components. (including EM/STM test and assessment in the case of satellite). Detailed design.
Phase D	- Manufacturing, integration testing. Maintenance design.
Phase E	- Launch, operation.
Phase F	- Post-operational phase, disposal.

In each phase, control engineering shall consist of the following activities:

(1) Control engineering management (integration and management)
    Activities for integrating control-related domains through all phases of the project to define and realize the whole attitude control system.
(2) Design
    In each design phase, design activities shall consist of the following operations:
    (i) Requirements analysis: Proper interpretation of mission and system requirements, derivation of proper control requirements with consistency, requirement definition of lower level components, continual monitoring of state and traceability of these requirements
    (ii) Analysis: Analysis at all levels or of all domains to solve problems concerning functional and performance requirements related to attitude control. Including alternative solution assessment, control performance verification, and test supplement, and so on.
    (iii) Design (system design and control element design): Activities to design physical control architectures and controllers which satisfy control requirements while receiving proper support of analysis and trade-offs. Design includes activities to evaluate all functions and performances and

allocate as control system requirements by using a proper method in accordance with margin policies.

Design process includes the following operations:

- [1] System design
    - (a) Architectural design (including trade-offs)
    - (b) Configuration and functional design
- [2] Control element design
    - (a) Controller design
    - (b) Component design
    - (c) Implementation and operation design

(3) Manufacturing and testing

(4) Verification and validation

It shall be required to demonstrate that whole attitude control system conforms to the control objectives and requirements.

These activities related to control engineering shall be performed in parallel to support interactively under proper development of attitude control system and its component in various phases in system development. The interactions are shown in Figure 2-3.

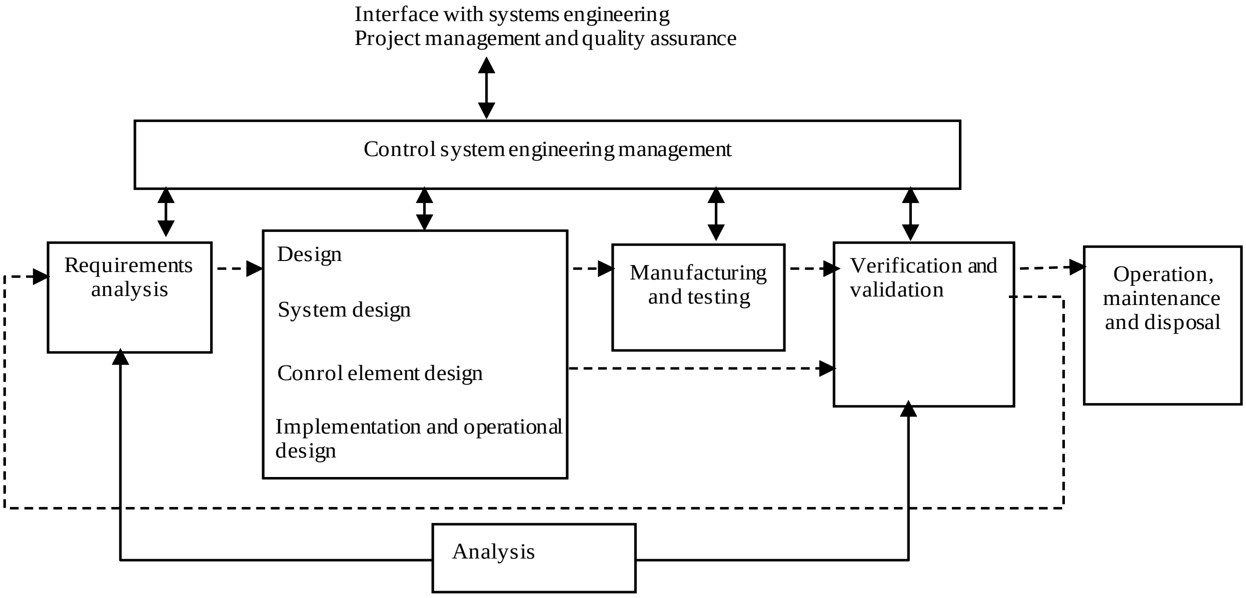

Figure 2-2 Interaction among control engineering activities
(From "Control System Design Standard")

* From ECSS-E-60A Control engineering (September 14, 2004)

2.3 Control engineering activities in each project phase

Activities shall be in accordance with "Control System Design Standard" (JERG-2-500).
However, activities can be omitted depending on the reliability and technology readiness level required in the system. (refer to Appendix II.)

Chapter 3 Attitude control system design process requirements

3.1 Control engineering management (integration and management)

Activities shall be in accordance with “Control System Design Standard” (JERG-2-500).
However, when the attitude control system is developed together with the Spacecraft and control engineering management is performed as part of a systems engineering of the satellite, management may be performed collectively as systems engineering management in consultation with the system side.

3.1.1 General

(1) Control engineering management shall be performed in accordance with the “Basic Concept of Systems Engineering” (BDB-06007) in conjunction with systems engineering activities.
(2) The control engineering management shall support systems engineering management activities from the standpoint of control engineering.
(3) The control engineering management shall be consistent with the systems engineering management plan (SEMP) and integration and management requirements related to systems engineering.

3.1.2 Control engineering plan management (organization and planning of activities)

Control engineering plan management shall be performed in accordance with “Control System Design Standard” (JERG-2-500).
When management is performed together with systems engineering management, support items and organization shall be clarified as the attitude control system.

3.1.3 Technology data management (data provision to systems engineering database)

Technology data management shall be performed in accordance with the “Control System Design Standard” (JERG-2-500).
When technology data is managed collectively as systems engineering management, support items and organization shall be clarified as an attitude control system.

3.1.4 Interface management with other fields

Interface management with other domains shall be performed in accordance with the “Control System Design Standard” (JERG-2-500).
Interface items with other domains shall be specified in the Interface Management Specification (managed by system), Interface Condition Document (managed by system) and Interface Control Drawing.

3.1.5 Human -machine interface control as part of controller

(1) The control engineering shall support human engineering activities when humans are involved in the control loop.
(2) The following items shall be reviewed.
    [1] Human performance and capabilities
    [2] Human-machine interface
    [3] Training of control operation

3.1.6 Requirement allocation and margin control philosophy

3.1.6.1 Performance and functional requirements for which allocation and margin are managed

Allocation values and margins to be controlled in the attitude control system design process shall be as follows.
The allocation and margin related to the following performance items of the attitude control system shall be managed with related conditions of external disturbances (including internal disturbances), and so on. In analysis of allocation and margin, proven analysis methods shall be used (Refer to paragraph 3.4.). Also, when attitude and orbit control is integrated/

(1) Attitude accuracy
    Clarify the bandwidth of the control system and allocate the accuracy which can be achieved in the bandwidth.
    [1] Attitude control accuracy
    [2] Attitude determination accuracy

(2) Attitude stability
    Clarify the bandwidth of the control system and allocate the stability which can be achieved in the bandwidth.
    [1] Attitude control stability
    [2] Attitude determination stability

(3) Response performance (Response associated with a maneuver and so on)
    [1] Control mode transition time

[2] Convergence time

When attitude accuracy during attitude transition is required, [1] above shall be applied. (Dynamic errors are added.)

(4) Other functions and performances
Beside direct requirements of control performances, the following control performances must be managed as control engineering.
- [1] Control stability and robustness (including control stability with respect to flexible structure and sloshing)
- [2] Control bandwidth
- [3] FDIR functions (including functional allocation to on-orbit and ground system)
- [4] Operational requirements and autonomous functions (including function allocation to on-orbit and ground system)
- [5] Controlling force

3.1.6.2 Margin policy

Margin policy and standards shall be established and applied.
For the standards related to margin control, proper margins shall be allocated and controlled in accordance with the development phase with referring the similar attitude control system. (Refer to the attitude control system design handbook.)

3.1.7 Assessment of control technology and cost efficiency (preliminary assessment)

Control technology and cost efficiency shall be assessed in accordance with the “Control System Design Standard” (JERG-2-500).
When the control technology and cost efficiency are assessed together as systems engineering management, the support items and organization for support shall be clarified as control engineering.

3.1.8 Risk management

Risk management shall be performed in accordance with “Risk Management Handbook” The control engineering shall support the system risk assessment from a technical viewpoint.

3.1.9 Technical support for the attitude control system component procurement

Technical support for the attitude control system component procurement shall be performed in accordance with the “Control System Design Standard” (JERG-2-500).
When the attitude control system component procurement management is performed together as systems engineering management, the support items and organization for support shall be clarified as control engineering.

3.1.10 Configuration management (control-related change management including in-flight maintenance)

Configuration management shall be performed in accordance with the “Control System Design Standard” (JERG-2-500).
When configuration management is performed together as systems engineering management, the support items and organization for support shall be clarified as control engineering.

3.1.11 Assessment of capabilities and resource related to control engineering (preliminary assessment)

Assessment of capabilities and resource related to control engineering shall be performed in accordance with the “Control System Design Standard” (JERG-2-500).
When assessment of capabilities and resource related to control engineering is performed together as systems engineering management, the support items and organization for support shall be clarified as control engineering.

3.1.12 Safety control

Safety control shall be performed in accordance with “System Safety Standard” (JMR-001).

3.1.13 Reliability control

Reliability control shall be performed in accordance with “Reliability Program Standard” (JMR-004).
When FDIR is specified in the attitude control system, it shall be performed subsystem FMEA, FTA and component functional FMEA and FDIR functional requirements shall be evaluated.

3.1.14 Quality assurance

(1) Quality assurance shall be performed in accordance with the “Quality Assurance Program Standard” (JMR-005).
(2) For software, quality assurance shall be performed in accordance with “Spacecraft Software Development Standard” (JERG-2-610).

3.2 Management of requirements analysis and requirements

3.2.1 General

In control engineering, activities for controlling requirements analysis and requirements are defined as requirement engineering. In this paragraph, requirements for requirement engineering activities related to the development of the attitude control system are specified. The requirements analysis and requirements specified in the "Control System Design Standard" (JERG-2-500) are basically applied. However, when requirement engineering activities are performed together as system of spacecraft development, the support items and organization shall be clarified as the attitude control system.

Control requirements applied to requirement engineering are divided into the following three categories:

(1) Requirements and design constraints from system:

Requirements which are derived from mission requirements and allocated to the attitude control system as system requirements (mission requirements become direct system requirements in some cases).The specific requirements related to the attitude control system are as follows:

[1] Attitude accuracy and design constraints: Mass properties, flexible structural characteristics, thruster characteristics, system alignment accuracy
[2] Operation requirement: Attitude constraints, convergence time and so on in each mode
[3] Field of view: Optical sensor, radio sensor (including GPS receiver) and antenna coverage and so on

(2) Subsystem-level requirements

Requirements that the attitude control system shall meet. The requirements shall be derived from the system level objectives and include the following items:

[1] Requirements applied to controller (AOCE and ACFS)
  (a) Attitude accuracy: Attitude control and attitude determination accuracy requirements that the controller shall meet
  (b) Attitude stability: Attitude control and attitude determination stability requirements that the controller shall meet
[2] Requirements applied to sensors and actuators
  (a) Sensor accuracy (bias, random noise and so on) and attitude determination method
  (b) Actuator external disturbances (including internal disturbances), output requirements and control method
[3] Requirements applied to controlled plants (such as field of view requirements or mass properties)

(3) Operation requirements

[1] Operation requirements in each mode and mission-specific operational requirements
[2] Requirements or constraints applied to ground operation by the attitude control system. In particular, ground processing requirements, and so on.

3.2.2 Requirements analysis

For performing requirements analysis, proven analysis methods shall be used. The requirements related to analysis method which must be applied specifically in requirements analysis are shown in 3.4.

(1) System-level requirements analysis

[1] Support for mission requirements analysis

Mission requirements related to the attitude control system are pointing accuracy, pointing stability requirements and mission operational requirements. Upon request, support to the mission requirements analysis of system shall be performed as the attitude control system and the requirements to be met as attitude control system shall be established and managed.

Upon request, the support shall be performed basically as a system support activity in Phase A and B.

[2] Support for system requirements analysis

Generally, the performances (attitude accuracy, stability) and functional requirements (autonomous and FDIR functional requirements) as the attitude control system specified in 3.1.6.1 shall be system requirements (including interface conditions and operational requirements). Upon request, analysis of system requirements shall be performed and support for the requirements establishment for the attitude control system shall be performed. The support shall be performed as a system support activities in Phase A and B.

[3] Analysis of reliability requirements and FDIR requirements

Support to reliability requirements and FDIR requirements definition for the attitude control system shall be performed according to the mission requirements analysis (including safety requirements). The support shall be performed as a system support activity in Phase A and B. Also, this activity shall be performed in conjunction with the reliability control activity in 3.1.13 performed as control engineering management.

(2) Subsystem-level requirements analysis

The above system-level requirements shall be translated into the attitude control system requirements.

3.2.3 Creating attitude control requirements

Attitude control requirements shall be summarized in the form of the attitude control system specifications in accordance with the requirements analysis results in the previous paragraph. Operational requirements derived directly from mission and system requirements, and system design constraints such as mass properties, flexible structural parameters, thruster characteristics, field of view and system alignment shall be summarized as ICD or equivalent documents. Consideration shall be given to the constraints imposed from other systems (electrical power, mechanical configuration, thermal conditions and operations). The allocation of requirements to lower-level shall be normally an iterative process shown in Figure 2-2.

(1) Allocation of requirements

The system-level requirements (including attitude accuracy requirements) shall be allocated to the attitude control system and its components.

Allocated requirements shall be summarized in the form for each component requirements specifications. For allocation, the following activities shall be performed as needed.

- (a) Analysis activities (analysis focused on the allocation and simulation)
- (b) Test (test using existing equipment or bread board)

(2) Requirements traceability

The attitude control requirements shall be conform to the system requirement engineering process and that traceability and validity shall be ensured. The requirements of each attitude control system components shall be traceable to mission requirements.

The traceability of requirements from system requirements to subsystem requirements and component requirements and so on shall be ensured. For example, the traceability among system pointing accuracy, attitude accuracy, component accuracy and controller requirements (control method, attitude determination method) shall be ensured.

(3) FDIR requirements

FDIR requirements and failure control requirements for system shall be broken down and FDIR functional requirements for the attitude control system shall be defined. The FDIR requirements for the attitude control system shall conform to the system FDIR requirements.

The requirements which must be clarified in the initial phase as FDIR requirements shall include the following requirements.

- [1] FDIR functional requirements
  - (a) Failure modes
  - (b) Fail operational or fail safe
  - (c) Function interruption time
  - (d) Autonomy and operability from the ground
- [2] Fault tolerant and fail safe requirements
  - (a) 1 fail safe or 2 fail safe
  - (b) Requirements for double failures
- [3] FDIR functional allocation

  Functions to be executed by software or hardware shall be allocated and requirements for the following elements shall be specified.
  - (a) Requirements for hardware
  - (b) Requirements for on-board software
  - (c) FDIR operational requirements

(4) Operational and autonomous requirements

Operational requirements and autonomous requirements from the system shall be broken down and requirements for the attitude control system elements shall be developed. The requirements which are broken down shall be reflected to the specifications of the following elements (design conditions).

- (a) Requirements for hardware
- (b) Requirements for on-board software
- (c) Attitude control system operational requirements

(5) Requirements for on-board software

The following requirements for on-board software shall be clarified and design and on-board implementation shall be performed.

Control algorithm specifications are important in developing on-board software. For the control algorithm of the requirement level, the validity of requirements for on-board software shall be reviewed based on the subsystem requirements and operational scenarios.

Distinction between the on-board software and subsystem requirements shall be clarified to correspond to the verification requirements.

[1] Language
The language shall conform to the on-board computer and have a reliable software development system.

[2] Memory, computing speed, computing accuracy
Requirements for the memory capacity to allocate each function, processing time and final output value shall be clarified.

[3] Development environment
Requirements related to development environment using BBM of AOCE and so on particular to the attitude control system shall be clarified.
Other requirements shall be in accordance with the “Spacecraft Software Development Standard” (JERG-2-610).

[4] On-board operating system (OS)
Specific items depending on the on-board OS to implement the on-board software implementation (processing contents, processing time and so on with the on-board OS) shall be clarified. Other requirements shall be in accordance with the “Spacecraft Software Development Standard” (JERG-2-610).

[5] Mode and exception handling
Mode change conditions including FDIR and the requirements related to processing of computing exceptions, overload, interrupt processing abnormal and other exceptional events shall be clarified.

[6] Control algorithm
Attitude determination, attitude control and actuator drive algorithm for each mode shall be clarified.

[7] Automation
Requirements for attitude acquisition at the area of loss of sight, attitude change and orbit control and the requirements and conditions for automatic mode change including FDIR shall be clarified.

[8] Interface
Interfaces with AOCE, sensors, actuators and other subsystems such as telemetry/command subsystem, mission subsystem, tracking antenna, solar paddle and so on shall be clarified.

[9] Reused program
When the assets of past satellites such as source code are reused, model and test specifications, reused portion and verification requirements shall be clarified.

[10] Verification method
Specific attitude control system algorithm verification by simulation, the verification method by SCLT and SOLT and so on using AOCE, and the requirements for software independent verification and validation (IV&V) shall be clarified. Other requirements shall be in accordance with the “Spacecraft Software Development Standard” (JERG-2-610).
Refer to 3.2.9 in this design standard for verification and test performed as a subsystem.

[11] On-board reprogramming
Requirements for on-board reprogramming with consideration of characteristics and operability of on-board programs shall be clarified.

(6) Support for system requirement development
As control of requirements for the attitude control systems, contradictions between requirements, ambiguities in requirements, contradictions between requirements and environment elements or between requirements and design constraints shall be specified and solved in support of system requirement engineering.

(7) Documentation of requirements
Through proper documents (such as specifications, ICD, Interface Condition Document and so on), the control engineering shall define and justify all the control requirements derived from special system constraints (minimum allowable thruster cant angle to plume effect limit, sensor field of view, actuator operational range, alignment, mechanical rigidity, natural frequency). Handle the on-board software as a component and create an independent requirement document. Appendix III shows an example of requirement documents which must be specified as the attitude control system (Attitude Control System Development Specifications and Interface Condition Document).

3.3 Attitude control system design

3.3.1 General

The design process in control engineering related to the attitude control system shall include the following activities.

(1) System design of attitude control system
(2) Design of control components

After system design of attitude control system, detailed design of the control components shall be performed. Generally, activities are performed after project Phase C or later; however, for control components which are assessed in system design to have high development risks, prototypes can be designed in Phase B. Followings are the parts of attitude control system design

[1] Controller design (AOCE, control algorithm, ACFS)
[2] Components design
  (a) Sensors
  (b) Actuators
[3] Implementation and operational design

In designing an attitude control system, proven design methods shall be used. Section 1.3.2 suggests some referenced documents for design methods. When specific control objectives are specified, lower level standard to be applied in the design process of the attitude control system is shown in Appendix I.

3.3.2 System design

3.3.2.1 General

In the initial phase of the project (Phase 0 and A), the basic system configuration shall be established to satisfy the function and the performance requirements of controlled system, specified as the results of requirement analysis.

In Phase B and later, detailed system configuration shall be designed, with allocating the functions and the performances to each component.

For system design, the following activities shall be performed:

[1] Control architectural design (including trade-offs)
[2] Control algorithm design
[3] Operation mode design
[4] Configuration design
[5] Functional design
[6] Component requirements design
[7] Interface design

3.3.2.2 Architectural design

It shall be performed as part of control engineering from the initial phases (Phase 0 and A) of the project, to support control engineering management. In the initial phase, it cooperates with various activities, which are parts of control engineering management process, and makes trade-offs of several possible architectures (basic control architecture and system configuration), and select the optimal one. In the activities as part of architectural design, it shall be required basically to use the results of requirements analysis specified in 3.2.2 and 3.2.3 as input and perform activities specified in steps [2] to [7] in 3.3.2.1 iteratively so as to establish an optimum system. The following activities shall be performed with respect to all the modes in the attitude control system including halfway stage of control modes to implement missions. If needed, analysis and verification shall be performed iteratively in this phase for the following activities. However, due to the existing technology available in control systems to be developed and system constraints, these procedures may be partially omitted (such as reuse of existing design or equipment).

- Analyzing functions necessary for achieving control requirements and developing a basic control mode, a system functional architecture and a system configuration plan to implement the functions
- Designing the functional architecture and operational architecture of control systems such as a control concept of control systems and interfaces with the controlled plant. In this phase, control systems in each control mode and a basic control bandwidth of control systems are determined and strategy against external disturbances and disturbance sources are specified from a view point of frequency domain in control systems.
  To support the operation, analysis, simulation, preliminary prototype development or other methods can be used.
- Allocating the control functions to the control hardware, control software and human operation in accordance with operational requirements in both preparation and usage (including allocation between ground and on-board functions).

- Detailed designing of physical architecture of control systems, and defining execution of all hardware and software functions.

In architectural design, a basic architecture of the attitude control system is determined as shown below.

(1) Basic control modes and mode sequences
In addition to the normal control modes for mission, all basic control modes reaching to the normal mode shall be determined. Control modes must be specified in consideration of system requirements for thermal, power, data link and so on. When it is necessary to perform orbit change before reaching the normal mode phase, control modes must be specified in consideration of orbit control requirements.

(2) Basic control algorithm and configuration in each control mode
In each mode specified in (1) above, the basic control algorithm and configuration shall be specified. The control algorithm and configuration shall be a pair and include the elements to determine functions and performances in the attitude control system. Such elements are as follows (for reference):

[1] Attitude control during orbit control
  (a) 3 axis attitude control (definition of external disturbances and external disturbances suppression performance, control system, control bandwidth)
  (b) Spin stabilized

[2] Sensor configuration and attitude determination algorithm
  (a) Gyro compass control system with earth sensor
  (b) Kalman filter-based attitude determination system with star sensor

[3] Actuator configuration/allocation and control algorithm
The actuator configuration and control algorithm can be selected from the following methods.

  (a) Wheel control
    (i) Definition of external disturbances (including wheel disturbances), external disturbance suppression performance, control system and control bandwidth
      · Bias momentum method: control using stabilization by angular momentum
      · Zero momentum method: control without using stabilization by angular momentum
    (ii) Wheel size, wheel configuration/allocation, wheel control system (torque control, speed loop, etc.)
      • 4 skew wheel layout
      • 3 axis orthogonal + 1 skew wheel layout

  (b) Control with gas jet propulsion system
    (i) Definition of external disturbances (including thruster external disturbances), external disturbance suppression performance, control system and control band
    (ii) Thruster size and layout, thruster control system (including thruster modulator, phase plane switch method etc.)
  (c) Magnetic torquer control
    (i) Definition of external disturbances (including torquer external disturbances), external disturbance suppression performance and control system
    (ii) Magnetic torquer control system (earth magnetic field model, cross product method)
  (d) CMG control

[4] Maneuver method and actuator configuration (for reference)
  (a) Single-axis maneuver method
  (b) 3 axis maneuver method

[5] FDIR functional requirements and FDIR algorithm in each modes
[6] Size of on-board software and configuration of controller

In architectural design in Phase A (conceptual design phase), it is necessary to support the selection of concept and architecture by trade-offs and optimize the performance, cost, schedule and risk in conjunction with the assessment of cost, risk, resource and feasibility performed as control engineering management.

3.3.2.3 Control algorithm design

For each control mode specified in the architectural design, a control theory or algorithm satisfying the requirements shall be designed in accordance with the required attitude accuracy and response characteristics. Performance, cost, schedule, risk and so on shall be optimized. In Phase A, the architectural design shall be supported. After Phase B, the requirements for controller (including ACFS) shall be clarified.

3.3.2.4 Operation mode design

In Phase A, the operation control architecture shall be defined as part of system design process of control engineering. This operation control architecture shall consist of the control modes and transition modes in which all designated (nominal and non-nominal) operation conditions of control systems are an application object. In operation mode design, necessary functions to satisfy control requirements shall be divided into some control modes. It is expected that the functional configuration and allocation to control modes are based on the existing general knowledge (experience) of the optimum usage method of the sensors, actuators, controllers and operation items. After Phase B, in the process of designing operation modes of the attitude control system, the following activities are performed to clarify the operational requirements for the attitude control system (reflected in operation procedure manual etc.).

[1] Definition of mode function
In design, the following items shall be specified for each control mode.
  (a) Related functions
  (b) Allocation of functions to hardware, software and humans
  (c) Allocation of ground and on-board functions
  (d) Validation conditions of control mode
  (e) Contribution to control objectives

[2] Definition of mode transition conditions
  (a) Transition between control modes shall be specified in design.
    (i) Starting conditions (previous mode and specific conditions)
    (ii) When transition occurs (trigger conditions)
    (iii) End conditions (subsequent mode and specific conditions)
  (b) The functions to be executed at transition shall be defined.

3.3.2.5 Functional design

Functional design process is also referred to as "functional analysis" and shall be comprised of the operations of translating control objectives into control system functions. To achieve this, the process of developing functions from higher level control objectives and functional requirements to lower level functional requirements can be used.

Functional architecture or operation architecture, which is comprised of a set of control modes and transition between control modes, shall be developed from the logical construction of functions.

In the control engineering design process, the coverage for operational and functional design of all control objects shall be reviewed. Functional design process includes the following activities.

[1] Definition of the functional design (logical configuration of functions) configured with control system functions (and secondary functions) for achieving control objectives.
[2] Design of the functions, covering nominal and off-nominal situations and individual functions for test and verification.
[3] Design of the functions, maintaining the compatibility with system functional analysis.

3.3.2.6 Configuration design

System configuration (physical architecture) refers to a set of components (comprised of sensors, actuators, controllers, controlled plants, software and hardware) to be used to achieve control objectives. In control system design, control engineering shall take the limitation of these physical elements into consideration and achieve a feasible design. Furthermore, in control engineering, the physical characteristics of these components shall be used to design controller. Since these operations often affect other domains and vice versa, it is expected that such operations on a complex system are implemented in coordination with systems engineering. In configuration design, the configuration of sensors and actuators shall be determined to achieve all control objectives in terms of performance, redundancy, observability, controllability and operability.

3.3.2.7 Component design

In response to the result of configuration design, basic requirements shall be defined for the components of the control system, to achieve the functions and performances of the controlled system, and to be consistent with the system design. The activities for components as part of control system design shall include the followings:

- Definition of sensor configuration and basic requirements for each sensor
- Definition of actuator configuration and basic requirements for each actuator
- Contribution to design the controlled plant with respect to system dynamics and kinematics, which affect control performance

- Contribution to the electrical system architectural design with respect to electrical interface, which affect control performance.
- Verification of conformity between the control system design and the physical configuration of designed controlled plants
- Contribution to the on-board data processing architectural design with respect to processing capability, data speed, input/output and memory, which affect control performance
- Verification of the compatibility of the control component design with the predicted failure or degradation of the control components (BOL and EOL), especially caused by the environmental conditions

3.3.2.8 Interface design

When another spacecraft is part of the system, as well as the ground facility and human interface definition, the control engineering shall verify that the control objects can be achieved by defining the interfaces with the spacecraft as well as the interfaces with the ground facilities and humans.

3.3.2.9 Design to support ground verification test

The control system shall be designed in such a way that all functions and performances can be verified by ground verification test without difficulty, at spacecraft system level, at controlled system level and at component level. In the verification at spacecraft system level, the interfaces with test equipment, jigs and tools shall be ensured so that the verification can be conducted with maintaining the integrity of the integrated system.

3.3.2.10 Design error prevention

In order to prevent design error in the control system design, “Artificial Satellite Design Error Prevention Standard” shall be referred to while designing.

Since any design error in polarity, phase or unit may cause a catastrophic trouble in the control system, control items shall be clearly defined from the initial phase of designing.

3.3.3 Control system elements design - Controller design

3.3.3.1 General

As shown in Figure 2-1, the controller shall generate and output actuator drive commands by control laws (control algorithm) based on the sensor measurement values and control command inputs, thereby controlling the attitude to achieve the control target. The controller shall include algorithms for control which are designed to achieve control objectives while maintaining robustness to uncertainty of the attitude dynamics model of the satellite and expected characteristic changes. When there are FDIR functional requirements, the controller (AOCE and ACFS) shall realize the functions. General FDIR functions can be realized by the controller’s hardware and on-board software.

The hardware and software configuring the controller shall be basically in accordance with the design standard for electronic equipment and software. General items to be considered in designing a controller are as follows (for reference) :

(1) Design a controller to achieve performance requirements specified by the whole attitude control system.
(2) In designing a controller, all the design conditions for the performance requirements and control loop of the whole attitude control system (including performances of control components, dynamic characteristics of controlled plant and environment-induced external disturbances) should be considered.
(3) In designing a controller (such as AOCE and ACFS), robustness against the uncertainty or predicted characteristic changes should be considered.
(4) Operational requirements
    Controller design shall conform to the following operational requirements.
    [1] Autonomy to the ground
    [2] Observability from the ground
    [3] Ground reaction delay due to transmission delay or availability of ground equipment or availability of ground operator.
(5) FDIR functions and autonomy
    In designing a controller, possible failures defined in accordance with the systems engineering should be dealt with in order to achieve the following targets.
    [1] Capability of detecting and specifying these failures by autonomous or ground operation.
    [2] Capability of making recovery after such a failure occurs (without loss of mission).
    [3] Capability of achieving specified performances after such a failure occurs.
(6) Fault tolerant and safety of controller (such as AOCE and ACFS)

[1] Fault tolerant and safety functional allocation

Well-balanced allocation of fault tolerant and safety functions to the software and hardware should be performed.

Example:	Software countermeasures:	Protection of safety functions, countermeasures at software runaway/dead lock
	Hardware countermeasures:	Watchdog timer (WDT) reset, switching to the redundant CPU, triple modular time difference redundancy, etc.

[2] Assurance of continuity or nonstop processing

Ensure the continuity of processing in allowable interruption period to the mission requirements and the attitude control system.

[3] On-orbit reprogramming function

3.3.3.2 Preventing design errors

In conjunction with design error prevention in the system design process specified in 3.3.2.10, it shall be necessary to prevent design errors on the interface and design a controller in reference to the “Standard for Preventing Artificial Satellite System Design Errors”.

3.3.4 Control system components design - Controller design

3.3.4.1 Sensor

Based on the results of configuration design, sensor requirements shall be detailed and the requirements shall be documented as development specifications.

[1] Support to the definition of sensor configuration (sensor specifications and manufacturing process requirements).
[2] Verify that the selected sensor configuration is compatible with the control system design.
[3] Support to sensor procurement (support to definition of necessary technology documents, specifications and operational requirements related to procurement)

3.3.4.2 Actuator

Based on the results of configuration design, actuator requirements shall be detailed and the requirements shall be documented as development specifications.

[1] Support to the definition of actuator configuration (actuator specification and manufacturing process requirements).
[2] Verify that the selected actuator configuration is compatible with the control system design.
[3] Support to actuator procurement (support to definition technology documents, specifications and operational requirements related to procurement)

3.3.4.3 On-board software

On-board software shall be basically in accordance with the design standard for on-board software. The following are specific requirements for on-board software in the attitude control system.

The on-board software described here is installed in the AOCE and consists of the following major functions.

- Sensor data processing algorithm
- Attitude determination algorithm
- Attitude control algorithm
- Actuator drive algorithm

Basically, software to realize these functions which are installed in the AOCE are the subject of this document. Software, firmware and FPGA installed in components, such as sensors and actuators, are out of the scope of this document. The requirements related to software shall be basically in accordance with the “Software Development Standard”(JERG-2-600) specified in 1.3.2 “Applicable Documents” of this design standard. The requirements related to on-board software shall be documented in accordance with the “Spacecraft Software Development Standard” (JERG-2-610).

(1) Timing management (including real-time management and multi-task processing)

[1] Timing management

Dead time has a significant impact on control performance in the control system design process. Thus, timing management is important. The major timing-related requirements are as follows:

- Sensor data input timing
- Actuator output timing
- Computing (executing) time, processing allowance
- Asynchrony (mainly asynchrony between sensors and CPU)

- Time accuracy (interface with mission system)

  The allowance shall be designed by setting a specific guideline. (For example, set a free time of 20% or more.)

[2] Priority and protection of processing of the attitude control system in multi-task processing

In multi-task processing in a consolidation computer, processing of the attitude control system shall not be stopped due to abnormality in other processing.

[3] Selection by scheduler or interrupt processing control

In the case of selection of interrupt processing, it shall be cared so that whole processing will not be abnormal due to a single interrupt anomaly.

(2) Fault tolerant and safety

[1] When the fault tolerant and safety functions are required by the on-board software, the conformity with the hardware and feasibility shall be evaluated.

[2] The fault tolerant and safety functions of the software shall be controlled by commands from the ground.

[3] On-orbit reprogramming function

The on-board software and attitude control computer of the attitude control system shall be reprogrammable. Attitude control processing shall not be interrupted during reprogramming. (Safety shall be ensured in case of interruption.)

The program size and configuration shall be specified in consideration of operability (including upload time and visibility).

(3) Verification requirements

Most of the functions and performances of the attitude control system are realized by the on-board software installed in the attitude control system. Final verification of the on-board software installed in the attitude control system (such as end-to-end test from on-board software to AOCE, the attitude control system artificial satellite system and operation system) shall be performed as subsystem or system test (3.6.4). Thus, in performing verification of the software installed in the attitude control system, a clear distinction shall be made in the initial phase of development between items to be verified as subsystem and items to be verified as software. For the items to be verified as software, verification requirements including verification method (such as SCLT if needed) shall be specified in the requirement documents of the on-board software. Software verification items in system and subsystem shall be clarified so that there will be no oversight in verification. (Ensure a proper overlap in verification.)

The verification requirements for general software shall be in accordance with the “Spacecraft Software Development Standard” (JERG-2-610).

[1] Clarification of verification items

The items to be verified as the attitude control system shall be differentiated from the items to be verified as software (such as abnormality case). The verification range and sharing between software test and the attitude control system subsystem test shall be clarified. In particular, the test configuration of software test shall conform to the subsystem side.

[2] Easiness of ground verification

To facilitate subsystem testing on the ground, assembling of verification functions to the on-board software shall be adjusted. It shall be cared so that the assembly of verification functions will not damage the required functions for on-board software and cause problems in actual operation.

[3] Compatibility with the spacecraft operation simulator

There shall be compatibility with the spacecraft operation simulator which performs simulation of on-orbit operation. In particular, corresponding to the on-orbit reprogramming should be easily achieved.

[4] Verification of FDIR functions (including redundancy switching function)

Failure case based on the analysis results of FMEA and so on shall be specified and system FDIR requirements shall be verified by simulation.

(4) Computing numerical accuracy

For CPU having a short bit length such as 8-bit and 16-bit MPU, particular care shall be given to the following points:

- Integer calculation - 1LSB weighting (fixed point)
- Real number calculation - variable accuracy (single accuracy or double accuracy). Particular care should be given to the cancellation of integrating variable.

(5) Hardware interface

For interfaces with the hardware, particular care shall be given to the following points:

- Conformity to the definition of sensor and actuator data (such as big-endian or little-endian).
- Polarity, phasing. In particular, data definition (Example: Complement on 2, code + magnitude).
- Signal processing (such as noise filtering and output limiter)

(6) Operability
On-orbit tuning of model parameters shall be design to be available, while the ground verification in difficulty increases, the importance increases.
Example: On-orbit reprogramming, command, program load by EEPROM, etc.

(7) Development process in consideration of attitude control system requirements change
The operational scenarios of the attitude control system and the specifications of requirements for on-board software have uncertainty to some extent at early stages of development for unavoidable reasons and are changed in many cases in accordance with the progress of development. In the development of on-board software, a flexible development process with due consideration shall be given to this and the operational scenario at early stages shall be clarified.

3.3.5 Implementation and operational design

3.3.5.1 General

Implementation design of each control system elements shall be performed in accordance with the system design in Section 3.2, and electrical and mechanical parts which are necessary for the implementation shall be designed. The design results shall be documented and managed as product specification, ICD and/or procedure, and so on. If there are subsystem-level requirements for verification, subsystem-level implementation and integration activities shall be performed in accordance with these documents. Upon request of the system, system implementation support shall be performed.

3.3.5.2 Control system implementation method into the operational system

For the following items, the interface design shall implement coordination of the installation method including verification method with the system side and put the method into document form as ICD and operation manuals. Upon request of the system, create procedures for installation to the operation system and perform installation support.

(1) Installation of on-board software (on-orbit reprogramming in particular)
(2) Alignment management
(3) Polarity management
(4) Field of view management
(5) Equipment layout (consideration to internal disturbances, etc.)

3.4 Analysis

3.4.1 General

Analysis is a basic activity to be performed in all phases of the control system development to achieve the objectives (1) to (3) below and include the following tasks. Controllers, sensors, actuators, controlled plants and environment shall be objects for analysis in the control engineering. (Refer to Figure 2-1.)

(1) Analysis for requirements analysis
  [1] Missions and system requirements shall be analyzed, and their validity and compatibility with the control requirements shall be assessed. It shall be implemented as mission analysis and system analysis support.
  [2] The allocation of requirements into various control functions shall be supported.

(2) Analysis for design
  [1] In system design, the following analyses shall be performed:
    (a) Actual functional or physical control architecture and its implementation method shall be selected.
    (b) Trade-offs between alternative control solutions shall be performed.
    (c) Design risk factors shall be identified.
  [2] In component design, the following analyses shall be performed:
    (a) The functions and performances in the whole attitude control system and assess the conformity with control requirements shall be evaluated.
    (b) The functions and performances of each control system element which comprise of the control system shall be assessed, and compatibility with control requirements shall be assessed.

(3) Analysis for verification
    (a) The relationship between the performances and requirements of the attitude control system shall be verified, and also the performances in applied environment shall be verified.
    (b) Based on the attitude control system test results, compatibility between the attitude control system requirements and the functions / performances of the attitude control system shall be assessed.
    (c) Based on the in-flight results, compatibility between the attitude control system requirements and the functions / performances of the attitude control system shall be assessed.

Note 1 Analysis process supports whole control engineering process as depicted in Figure 2-2.

Note 2 Analysis process has interacts strongly with all the other control engineering activities.

Note 3 The purpose of control system elements analysis is to assess whether the control objectives for whole control system are properly allocated into the control functions and performances.

For control system analysis, proven models and analysis methods shall be used.
In control system analysis, the references in Section 1.3.3 shall be available.

3.4.2 Analysis models, analysis methods and analysis tools

3.4.2.1 General

Analytical methods and tools shall be used for each process of control engineering and each phase of control system development, and these methods and tools shall be adopted for individual analysis tasks (for each project phase).
The list of usual analysis methods and tools are shown in Table 3-1.

Table 3-1: Analysis activities for supporting control engineering process

Control engineering activity	Analysis tasks	Usual methods and tools
Analysis for requirements analysis	- Analysis of requirements - Requirements feasibility assessment - Disturbance quantification - Error source identification and relevant numerical figures allocation to budgets	- Mission analysis and orbit designing tools - Analytical relationships and models - Spreadsheet analysis tools - Control CAE tools - Control, environment, sensors, actuators and plant models
Design	- Numerical trade-off studies in support of control architecture definition - Numerical analysis to supporting control design - Disturbance effects detailed analysis - Stability - Robustness - Sensitivity to additional or parametric disturbances - Performance against applicable requirements - Control budget numerical figures consolidation	- Analytical relationships and models * - Spreadsheet analysis tools - 3D CAD system models - Control CAE tools - Closed-loop simulation (including detailed control, environment, sensors, actuators and plant models)) - Simulation data analysis tools (for example, statistical methods) - Time-frequency domain method - Linear and non-linear methods
Verification	- Performance analysis - Test data analysis resulting from H/W-,S/W-, human-in-the-loop tests - In-flight data analysis - Support to payload data evaluation	- Closed-loop simulation (including detailed models of control, environment, sensors, actuators and applicable plants to be controlled) - Test data evaluation tools (for example, statistical methods) - Telemetry data processing tools - Control CAE tools

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3.4.2.2 Definition of analysis model

For analysis, proven models shall be used, and analysis models for mission and system analysis shall be specified for system interface conditions. The targets of modeling shall be all the components of the control system as shown in Figure 2-1, and shall include the following.

- Attitude control system (controller, sensors and actuators)
- Controlled plant
- External environment

According to the purpose of analysis and the development phase, an adequate precision model shall be used, and the following models shall be defined as needed. The number of models and detailed specifications shall be determined in accordance with a project. The characteristics which the models have in each phase shall be in accordance with the “Control System Design Standard” (JERG-2-500).

(1) Simplified model
(2) Mathematical model for performances analysis
(3) External disturbance and internal disturbance model
    [1] Internal disturbance sources (inside of the whole attitude control system)
    The bandwidth of the control system shall conform to the frequency bandwidth of developed disturbances in the initial phase as a system design condition. The sensors and actuators of the attitude control system shall be included as disturbance sources and disturbance sources shall be managed with the use of the disturbance management standard and disturbance management handbook. Internal disturbances (including actuators, vibration, friction and noise) shall be modeled by using

verified parameters (vendor data) or parameters identified by specific testing. However, in the case of initial phase of development or when a proper margin can be specified, it is possible to use a physical model in which the dynamic characteristics of disturbance sources are analytically evaluated.

[2] Source of external disturbances (from environment)
Included in sensors, actuators, controller, or plant models.

[3] Error sources
Model for error analysis. Error sources and its impact on performance shall be modeled.
Error sources shall be managed in accordance with the “Pointing Control Standard” (JERG-2-153).

(4) Simulation model
In Phase C and D, in order to optimize the design of control system and perform the verification process of control system, detailed closed-loop simulation model (including environment, plant, sensors, actuators, and controller, etc.) shall be developed.

3.4.2.3 Analysis methods and analysis tools

According to each phase of control engineering process, one analysis method or combination of two or more analysis methods shall be selected and used.

(1) General requirements for analysis tools
- [1] Perform analysis based on validated methods and tools.
- [2] Validate that control system analysis tools are proper.
- [3] In developing a new tool, and when the control engineering supports the definition, development and validation of the tool’s specifications, these activities shall be managed as part of control engineering process.
- [4] It is desirable to use the control analysis tools and simulation tools supporting the compatibility of data exchange with the tools used by other engineering domain.
- [5] It is desirable to use control analysis tools and simulation tools interchangeable among various platforms.

(2) Management of tools
Selected tools shall be identified and documented with respect to the following items.
- (a) Product name
- (b) Version
- (c) Executed method
- (d) Platform (hardware and operating system)

(3) Type of tools and models
In control engineering, analysis models shall be developed by using one of the following general methods and tool types or a combination of these.
- [1] Tools based on spreadsheet
- [2] Engineering (CAE) tools for supporting computer. For example, mathematical (analysis, value, symbol) control design tools and simulation tools.
- [3] Multi-body dynamics modeling tools and simulation tools
- [4] Environment simulation tools
- [5] Functional modeling tools
- [6] Auxiliary tools for creating model parameters (pre-treatment)
- [7] Kinematics analysis tools
- [8] Orbit analysis tools

Note: General analysis methods shall be as follows:
- (a) Method from higher level to lower level
- (b) Multilayered and hierarchical method
- (c) Simplified conceptual method
- (d) Analytical and equation-based method
- (e) Method based on value computer simulation
- (f) Test of in-loop hardware and in-loop software

(4) Simulation analysis
Performance analysis shall be performed based on detailed mathematical model simulation and in-flight performances evaluation of system including identification and solution of failures in the control system in-flight shall be supported.
By using simulation, the design activities for the following tasks shall be supported.
- [1] Evaluation of achievement level of control target
- [2] Design trade-offs and sensitivity analysis for optimizing the product selection

[3] Sensitivity analysis of variations and uncertainty of the whole attitude control system parameters for evaluating robustness of control design

The following simulation analyses shall be performed in the attitude control system:

(a) Static closed loop simulation
(b) Dynamic closed loop simulation

3.4.3 Analysis for requirements analysis

3.4.3.1 General

In system analysis, mission and system analysis shall be supported in accordance with mission requirements and system requirements. Within the framework of requirement analysis of which outline is explained in Section 3.2, analysis shall be used extensively, and the following activities shall be supported along with the hierarchical flow.

[1] A higher level mission objective (customer needs) shall be broken down into feasible control objectives.
[2] Numerical requirements for the control system shall be defined.
[3] Requirements for whole control system shall be allocated to lower level requirements for various control components (controller, sensors and actuators) and plants as shown in Figure 2-1.
[4] In-loop constraints for human shall be defined.
[5] By analysis, the feasibility of the requirements allocated to various control components shall be assessed.

3.4.3.2 Support for missions analysis, system analysis and control engineering requirements analysis

In each phase of the project defined in Tables 2-2 through 2-5, analysis related to system requirements for orbit, attitude and pointing control, for which mission requirements or system requirements directly become the attitude control system requirements, shall be supported, and based on the results, detailed control error budget shall be defined and used as input data to technical specifications of control components.

To support the optimized allocation of control error budget by analysis, maturity of available new technology readiness level shall be reviewed by performing trade-off study, market investigation and risk analysis.
In each phase, for these system requirements, mission analysis and system analysis of the system shall be supported and analysis results and the conformity of the requirements for the attitude control system shall be evaluated.

For mission analysis, “Mission and Orbit Design Standard” (JERG-2-151) and “Mission and Orbit Design Handbook” can be referred to. For pointing error analysis, “Pointing Control Standard” (JERG-2-153) can be referred to.

3.4.3.3 External disturbance and disturbance analysis

In control engineering, in accordance with the definition in Figure 2-1, analysis for defining disturbances and internal disturbances to the control system shall be supported.
Disturbances which originate in a plant shall be defined based on system requirements.

(1) External disturbances generated from space environment shall be defined.
Note: Refer to the references in 1.3.3 for space environment.
(2) The following tasks shall be performed when using various models (used in special application examples):
    [1] Validate that used models are proper.
    [2] Obtain approval from the customer for each case.

Analysis of effects of external or internal disturbances on the attitude control system shall be performed by using the external and internal disturbance models shown in 3.4.2 (3). When external and internal disturbance analysis is a system requirement, support for external disturbance analysis of the system shall be performed and analysis results and conformity to the requirements for the attitude control system shall be evaluated. Analysis shall be performed with the accuracy required in each project phase. However, analysis may be omitted when robustness of the attitude control system is validated by worst value analysis of these external disturbances and disturbances. External disturbance analysis shall be performed on the total mission scenarios and total mission operating life of the whole attitude control system and include the following:

(a) Natural external disturbance model and external disturbance analysis
(b) Disturbing forces to orbit
(c) External disturbances from gas jet
(d) Flexible structural analysis
(e) Disturbances from on-board equipments

3.4.4 Attitude control system performance analysis

3.4.4.1 General

Attitude control system performance analysis shall be performed as part of the attitude control system design for determining the parameters which specify control system performance.
As part of allocation and margin management performed as control engineering, the performances specified in 3.1.6 shall be managed by analysis. Also in each phase of the project, it shall be assessed whether consistency is ensured between the attitude control system performance and the following requirements.

(a) Control objectives generated by requirements engineering process
(b) Numerical requirements defined by requirements analysis

Performance analysis to be performed in each phase of the project of control system development process shall be as follows.

(1) The initial phases of the project (Phase 0, A and B)
  [1] Simplified analysis models shall be developed to perform preliminary assessment of control performance.
  [2] By using these simplified models, input data shall be provided to feasible assessment of control requirements and error budget breakdown.
  [3] By using these simplified models, numerical trade-offs shall be supported, alternative control architecture and control concept (algorithm) shall be assessed, and trade-off among different control components shall be performed.
(2) Phase C and D and later
  By using detailed mathematical models, it shall be reviewed whether functions and performances required for the control system are satisfied. In this phase, performance assessment shall be performed by simulation analysis and so on, including backup mode and FDIR function.

3.4.4.2 Error budget analysis

Error budget analysis shall be performed as part of “Margin Management” in 3.1.6, which is performed as control engineering. In each phase of the attitude control system development, it shall be confirmed that proper error budget is allocated and a proper margin is ensured.

The error source and error analysis methods defined in Section 3.4.2.2 shall be used to analyze the error for control objectives, and it shall be assessed whether the allocated requirements are satisfied.
If a control target is attitude or pointing control, “Pointing Control Standard” (JERG-2-153) in 1.3.3 (2) can be referred to.

If a control target is orbit or in-flight position, “Mission and Orbit Design Standard” (JERG-2-151) and “Mission and Orbit Design Handbook” in 1.3.3 (2) can be referred to.

3.4.4.3 Stability analysis and robustness analysis

Stability analysis and robustness analysis are performed as part of “Margin Management” in 3.1.6, which is as control engineering. In each phase of the attitude control system development, it shall be confirmed that a proper margin is ensured.
The model defined in Section 3.4.2.2 shall be used to assess whether the allocated margin is satisfied.

3.4.5 Verification analysis

As finalized performance verification, performances analysis based on mathematical models shall be performed to evaluate the achievement level of requirements for the whole attitude control system with respect to the mission operational scenarios from the viewpoint described below.

Also, different verification analysis tools shall be used if needed, to avoid the dependence on analysis tools.
In Phase C and D, control system design shall be optimized and verification process of the whole attitude control system shall be premed. In the final phase of development, simulation analysis including backup mode, FDIR function and man-machine interfaces by simulation shall be performed. Basically, the requirements for the control system (specifications) for achieving control objectives shall be verified by analysis. Primary verification items are as follows:

(1) Time range requirement
  [1] Response to reference signals (response time, stabilization time, tracking error to command profile)
  [2] Accuracy error and stability error in case of external disturbances
  [3] Measurement error (attitude knowledge information, etc.)

(2) Frequency range requirements (bandwidth, etc.)

3.5 Manufacturing and testing

Manufacturing and testing process in control engineering is part of system verification process, manufacturing, and testing process and, it shall have consistency with manufacturing and testing defined in “Basic Concept of Systems Engineering”. Testing and other activities shall be conducted in accordance with the development plan established in the initial phase as part of control engineering management, and the verification plan specified in Section 3.6 shall be applied to testing.

3.6 Verification and validation

3.6.1 General

Design verification shall be performed in accordance with the “Control System Design Standard” (JERG-2-500). The verification policy and verification plan shall be established in the initial phase of the project (Phase 0 and A) including verification performed in design processes, and manufacturing and testing process of components and systems consist of the attitude control system. In accordance with the verification plan, verification shall be performed on to the whole attitude control system as shown below.

(1)	Preliminary performance verification	Verification at BBM and EM levels to be performed in Phase B and C
(2)	Final functions and performance verification	Verification at PFM level to be performed in Phase C and D

3.6.2 Planning of control system verification plan

3.6.2.1 General

Control engineering verification process shall be performed in accordance with the “Control System Design Standard” (JERG-2-500).

3.6.3 Preliminary verification of performance

3.6.3.1 General

In order to reduce risks, verification process shall be started in the initial phase of the project, as control concept and design become available, they shall be verified.

Particularly important characteristics shall be verified in the design and the development phase by using a simulation models or a development models (for example, prototype).

It shall be evaluated that fidelity of simulation models and validity of tools to verify.

Note This process can repeat according to the maturity of design.

3.6.4 Final functional and performances verification

3.6.4.1 General

In order to verify that all requirements for whole attitude control system are satisfied, verification task shall be performed at the following levels

(1) Verification by analysis
(2) Verification of on-board hardware and software
(3) In-flight validation

3.6.4.2 Verification by analysis

By using detailed models specified in Section 3.4, verification shall be performed by simulation and other analysis.

(1) Performance of the whole attitude control system shall be demonstrated by closed loop simulation by using a simulation models represented properly.

(2) Performance of the whole attitude control system shall be demonstrated with respect to defined worst-case scenarios in terms of system dynamical and geometrical conditions, including FDIR operations. Demonstrate the performances of the total the attitude control system in the defined worst case with respect to dynamics and geometrical conditions of the system including FDIR result conditions.

(3) Verification shall be performed all configurations including each control modes and operational modes for sensors and actuators, redundant configurations.

(4) It shall be verified compatibility with the hardware test when analysis for hardware was conducted.

Example: To be ensure the correlation between sensor mathematical model parameters and hardware test

3.6.4.3 Verification by on-board hardware and software

The verification shall be implemented with end-to-end test by using on-board hardware and software. Verification shall include the following. Verification methods shall be selected with referring to the “Attitude Control System Verification Technical Handbook”.

(1) The function and performance of on-board hardware component of the attitude control system shall be verified.
Interfaces between the attitude control system hardware and controllers (AOCE) shall be ensured by static or dynamic open loop test (SOLT, DOLT) and so on.

(2) The calculation accuracy of software installed on-board hardware (or emulator) shall be verified.
The validity of on-board software shall be verified with use of the simulated controller test equipment which is prepared independently from the hardware.

(3) Control verification process shall include the validation of functions by closed-loop test (SOLT, DOLT) with on-board software and hardware models or models equivalent to on-board models.

(4) Input shall be given to the actual sensors in the following methods.

[1]	Optical sensors:	Simulated light (including star simulator)
[2]	GPSR GPS:	GPS simulator
[3]	IRU, RIGA:	Servo table

(5) Mode transition including FDIR operations shall be tested and verified in accordance with the verification plan.

(6) After final integration, the polarity of the sensors and the actuators shall be verified. (field of view shall be verified, as needed.)
When final integration operation is performed as system activity, the procedure for polarity verification shall be provided with and the results shall be reviewed as the attitude control system.

3.6.5 In-flight validation

In-flight verification shall be performed by conducting in-flight validation analysis and evaluation after launch/orbital injection in order to validate whether the functions, performance sand operating life of the attitude control system satisfy the requirements in the in-orbit environment.
For detail validation, “Attitude Control System Verification Technical Handbook” shall be referred to.
In-flight verification shall be classified depending on the phase after launch as shown below. (The period is a guide line and differs among satellites.)

(1) Launch/attitude acquisition phase (one to several days after launch)
(2) Check-out phase (one to three months after launch)
(3) Normal/ post-operational phase (designed operating life or after)

The satellite designer (or developer) shall check that the attitude control system is normally in phase (1) and (2) prior to transfer the satellite to satellite operator. It is also required to support the evaluation of phase (3) performed by the satellite operator. The satellite designer shall clarify the requirements for in-flight validation in design phase. Attitude sensors, attitude control software and telemetry/command shall be designed so that the required in-flight validation can be performed.

In-flight validation in each phase shall be performed as follows.
In the launch or attitude acquisition phase, it shall be checked whether the attitude control system (and components) are operating normally. For the attitude control system, it is necessary to establish a normal operational attitude by performing a series of operation from satellite separation and orbital injection before checkout. Because the establishment is mainly performed by the automatic control function of the attitude control system, the attitude control system functions and performances shall be validated with normal operation of the attitude control system without performing positive command operation.

Data in the area of loss of sight shall be acquired by the stored telemetry from the tracking control station. With real-time telemetry in the area of sight, functions and performances check including the following items shall be evaluated by post analysis. When establishing a normal attitude mode through the safety mode (example: sun acquisition mode, earth acquisition mode), functions and performances check shall be performed for the each control mode.

[1] Mode transition of the attitude control system (from start of attitude control to normal control mode)
[2] Attitude control accuracy and stabilization time in each mode
[3] Attitude estimated value, measurement value of attitude sensors and control command to actuators in each mode
[4] Attitude fluctuation by deployment object at deployment and so on

3.7 Operation, maintenance and disposal

3.7.1 General

In accordance with the operational requirements specified in initial design phases (Phase A and B), the information necessary for operation in Phase C and D (including information for operation in case of abnormality) shall be described in the operational manuals, ICD and so on.

If there are requirements, operational documents shall be prepared, and operation and maintenance shall be supported. If disposal operation including de-orbit is necessary, required support shall be performed.

3.7.2 Operation and maintenance

(1) Operational documents
Operational documents (for example, SOOH and SOP) required for control system operation are prepared in the design phase, and verified in the test verification and initial checkout phases.

(2) Operation and maintenance
In the operation and maintenance phases, flight data of control systems shall be obtained, function of control system and performance degradation shall be monitored, and operation assessment analysis shall be performed. These shall be used for improving subsequent control system design as needed.

3.7.3 Disposal

If disposal operation including de-orbit becomes necessary, analysis for disposal operation necessary for de-orbit shall be supported, and control system function necessary for disposal operation shall be included in the design phase. If disposal operation including de-orbit becomes necessary, required support shall be implemented.

3.5 Manufacturing and testing

Manufacturing and testing process in control engineering is part of system verification process, manufacturing, and testing process and, it shall have consistency with manufacturing and testing defined in “Basic Concept of Systems Engineering” Tests and other activities shall be conducted in accordance with the development plan established in the initial phase as the control engineering management, and the verification plan specified in Section 3.6 shall be applied to testing.

3.6 Verification and validation

3.6.1 General

Design verification shall be performed in accordance with the “Control System Design Standard” (JERG-2-500). The verification policy and verification plan shall be developed in the initial phase of the project (Phase 0 and A) including verification performed in design processes, and manufacturing and testing process of components and systems of the attitude control system. In accordance with the verification plan, verification shall be performed on to the whole attitude control system as shown below.

(1)	Preliminary performance verification	Verification at BBM and EM levels to be performed in Phase B and C
(2)	Final functions and performance verification	Verification at PFM level to be performed in Phase C and D

3.6.2 Planning of control system verification plan

3.6.2.1 General

Control engineering verification process shall be performed in accordance with the “Control System Design Standard” (JERG-2-500).

3.6.3 Preliminary verification of performance

3.6.3.1 General

In order to reduce risks, control system verification process shall be started in the initial phase of the project, and the validity of control concept and design shall be ensured as they become available.

Particularly important characteristics shall be verified in the design and the development phase by using a simulation models or a development models (for example, prototype).

Representation and precision of simulation models and tools to be used for verification shall be assessed.

Note This process can be interactive according to the maturity of design.

3.6.4 Final functional and performances verification

3.6.4.1 General

This verification is used for ensuring that the attitude control system satisfies all the function and performance requirements, and it shall be performed at the following levels.

(1) Verification by analysis
(2) Verification of on-board hardware and software
(3) In-flight validation

3.6.4.2 Verification by analysis

Verification shall be performed by simulation with the use of detailed models specified in 3.4.

(1) Performance of the whole attitude control system shall be demonstrated by closed loop simulation with the use of the properly represented system simulation models.
(2) Performance of the whole attitude control system shall be demonstrated with respect to defined worst-case scenarios in terms of system dynamical and geometrical conditions, including FDIR mechanisms. Demonstrate the performances of the total the attitude control system in the defined worst case with respect to dynamics and geometrical conditions of the system including FDIR result conditions.
(3) Verification shall include all operational configurations of control modes and sensors and actuators, including back-up configurations.
(4) For performing verification by analysis, support from the hardware test shall be served. (Correction of the

hardware model as needed.)

Example: Assurance of correlation between sensor mathematical model parameters and hardware test

3.6.4.3 Verification by on-board hardware and software

The verification shall be implemented with end-to-end test by using hardware and software to be provided with On-board. Verification shall include the following. Verification methods shall be selected with referring to the "Attitude Control System Verification Technical Handbook"

(1) The function and performance of on-board hardware component of the attitude control system shall be verified.
Interfaces between the attitude control system hardware and controllers (AOCE) shall be ensured by static or dynamic open loop test (SOLT, DOLT) and so on.

(2) Verify the numerical accuracy of control software on the on-board hardware (or emulator).
The validity of on-board software shall be verified with use of the simulated controller test equipment which is prepared independently from the hardware.

(3) Control verification process shall include the validation of functions by closed-loop test (SOLT, DOLT) with on-board software and hardware models or models equivalent to on-board models.

(4) Perform inputs to the actual sensors in the following methods.

[1]	Optical sensors:	Simulated light (including star simulator)
[2]	GPSR GPS:	GPS simulator
[3]	IRU, RIGA:	Servo table

(5) Mode transition including FDIR mechanisms shall be tested and verified in accordance with the verification plan.

(6) After final integration, the polarity of the sensors and the actuators shall be verified. (field of view shall be verified, as needed.)
When final integration operation is performed as system activity, the procedure for polarity verification shall be provided with and the results shall be reviewed as the attitude control system.

3.6.5 In-flight validation

In-flight verification shall be performed by conducting in-flight validation analysis and evaluation after launch/orbital injection in order to check whether the functions, performance sand operating life of the attitude control system satisfy the requirements in the in-orbit environment.
For detail validation, "Attitude Control System Verification Technical Handbook" for details shall be referred to.
In-flight verification shall be classified depending on the phase after launch as shown below. (The period is a guide line and differs among satellites.)

(1) Launch/attitude acquisition phase (one to several days after launch)
(2) Check-out phase (one to three months after launch)
(3) Normal/ post-operational phase (designed operating life or after)

The satellite designer (or developer) shall check that the attitude control system is normally in phase (1) and (2) above before delivery to the satellite operator. It is also required to support the evaluation of phase (3) performed by the satellite operator. The satellite designer shall clarify the requirements for in-flight verification at design. Attitude sensors, attitude control software and telemetry/command shall be designed so that the required in-flight verification can be performed.

In the in-flight verification in each phase, below confirmation shall be performed.
In the launch or attitude acquisition phase, it shall be checked whether the attitude control system (and components) are operating normally. For the attitude control system, it is necessary to establish a normal operational attitude by performing a series of operation from satellite separation and orbital injection before checkout. Because this is mainly performed by the automatic control function of the attitude control system, the attitude control system functions and performances shall be checked with normal operation of the attitude control system without performing positive command operation.

Data in the area of loss of sight shall be acquired by the stored telemetry from the tracking control station. With real-time telemetry in the area of sight, functions and performances check including the following items shall be evaluated by post analysis. When establishing a normal attitude mode through the safety mode (example: sun acquisition mode, earth acquisition mode), functions and performances check shall be performed for the each control mode.

[1] Mode transition of the attitude control system (from start of attitude control to normal control mode)
[2] Attitude control accuracy and stabilization time in each mode
[3] Attitude estimated value, measurement value of attitude sensors and control command to actuators in each mode

[4] Attitude change by deployment object at deployment and so on

3.7 Operation, maintenance and disposal

3.7.1 General

In accordance with the operational requirements specified in initial design phases (Phase A and B), the information necessary for operation in Phase C and D (including information for operation in case of abnormality) shall be described in the operational manuals, ICD and so on.

If there are requirements, operational documents shall be prepared, and operation and maintenance shall be supported. If disposal operation including de-orbit is necessary, required support shall be performed.

3.7.2 Operation and maintenance

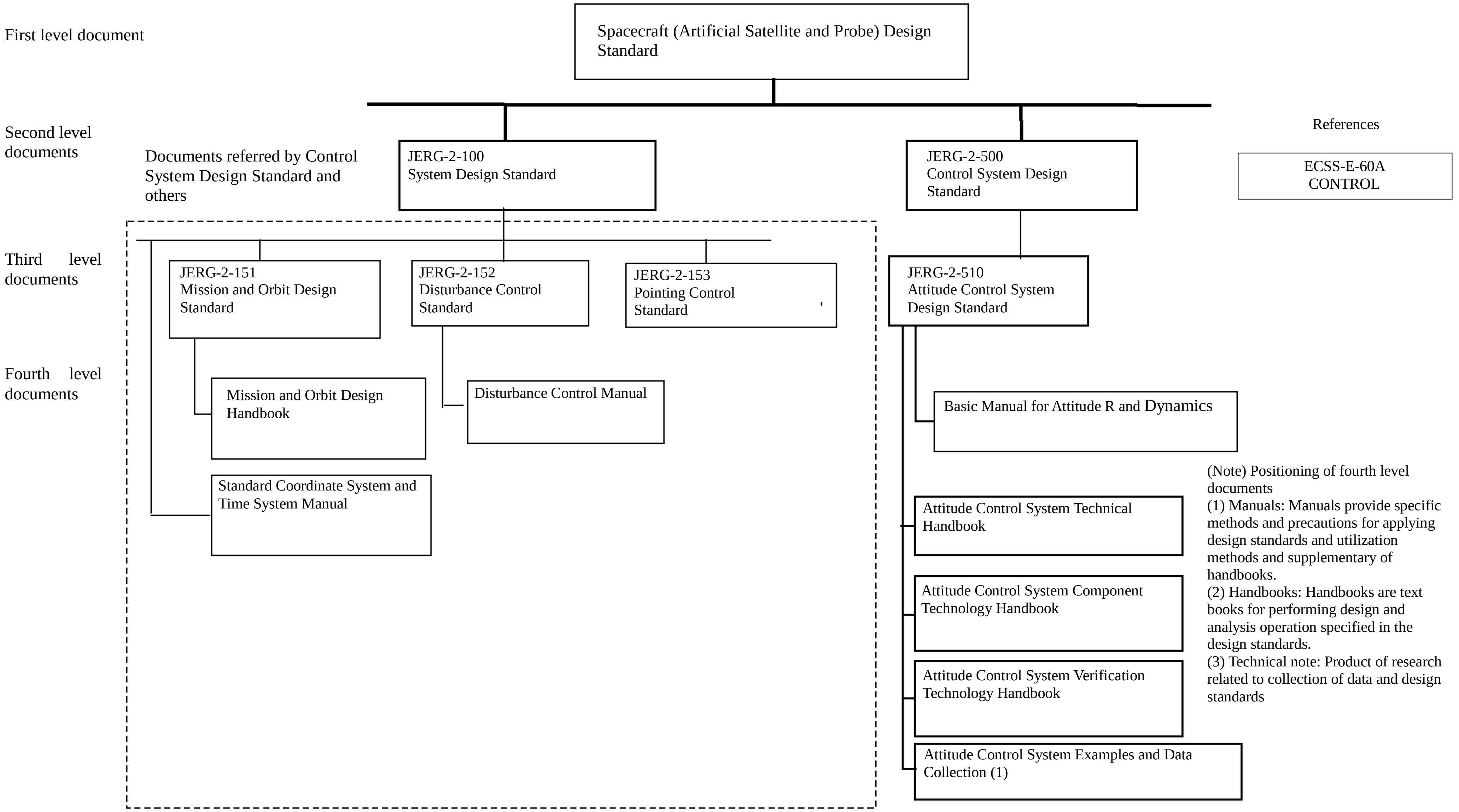
(1) Operational documents
Operational documents (for example, SOOH and SOP) required for control system operation are prepared in the design phase, and verified in the test verification and initial checkout phases.

(2) Operation and maintenance
In the operation and maintenance phases, flight data of control system shall be obtained, function of control system and performance degradation shall be monitored, and operation assessment analysis shall be performed. These shall be used for improving subsequent control system design as needed.

3.7.3 Disposal

If disposal operation including de-orbit becomes necessary, analysis for disposal operation necessary for de-orbit shall be supported, and control system function necessary for disposal operation shall be included in the design phase. If disposal operation including de-orbit becomes necessary, required support shall be implemented.

Appendix 1 System of documents related to “Control System Design Standard” (JERG-2-500)



(Note) Positioning of fourth level documents

(1) Manuals: Manuals provide specific methods and precautions for applying design standards and utilization methods and supplementary of handbooks.

(2) Handbooks: Handbooks are text books for performing design and analysis operation specified in the design standards.

(3) Technical note: Product of research related to collection of data and design standards

Appendix II The application requirements guidelines for control system design process

In the “Control System Design Standard” (JERG-2-500), the requirements for control system design process shall be specified in accordance with the project-specific reliability requirements and technology readiness level. According to the philosophy above, in the attitude control system design standard, the requirements for attitude control system design process shall be specified in accordance with the reliability requirements and technology readiness level. The guidelines of application to the attitude control systems in artificial satellite are shown in Table II-1.

Reliability requirements and technology readiness level for control systems are categorized as follows:

(1) Reliability requirements for control systems

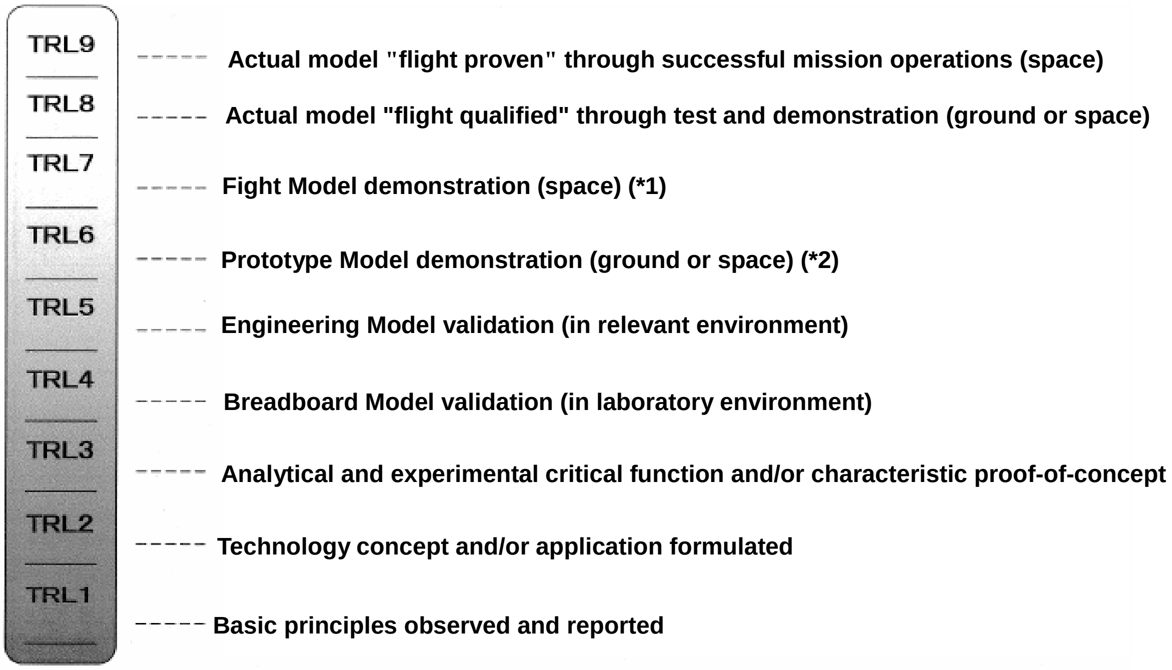
- Reliability Level I: Long-term mission with High-level reliability requirements from user (applications satellite and deep space exploration without backup)
- Reliability Level II: Short-term mission with High-level reliability requirements from user (engineering test satellite)
- Reliability Level III: Medium-level reliability requirements. A cost requirement is prior to the reliability requirements(low-cost-technology test satellite with short-term mission)
- Reliability Level IV: Low-level reliability requirements (low-cost-engineering development satellite or amateur satellite)

(2) Technology Readiness Level

Based on the indication of technology readiness levels of NASA, JAXA sets the classification shown in Attached Figure II-1 to assess the technology readiness levels, in order to implement development in accordance with each technology readiness levels.

The classification of technology readiness levels shall follow the definition specified by the project; however, The “Control System Design Standard” divides the classification of Figure II-1 into the one shown below and sets the application guidelines of design standard in accordance with individual readiness levels. In developing the attitude control system, technology readiness levels shall be evaluated in the initial phases of development, application items of design standard shall be specified in reference to Table II-1. Manufactured model in each development phase (such as BBM, EM, and PFM) and verification items (Results are summarized as development plan.) shall be specified

·TRL I: New mission and new control technology	JAXA-TRL 1, 2, 3, 4, and 5
·TRL II: Modification of existing technology	JAXA-TRL 6 and 7
·TRL III: Full existing technology	JAXA-TRL 8 and 9



(*1) An environment close to space environment which is anticipated in actual operation (for example, the operation orbit and use conditions of equipment)
(*2) A level at which an environment similar to space, such as thermal vacuum environment, is secured at minimum (Space environment is required for a kind of environment which can be secured only in space, such as one with microgravity over a long period of time)
(Note) Each level shall be determined only after all the activities at the level are thoroughly completed.

Figure II-1: JAXA Technology Readiness Level (TRL) Classification

Table II-1(1) Guidelines for applying requirements for Spacecraft attitude control system design standard: Reliability level I

Requirements	TRL I	TRL II	TRL III	Remarks
Chapter 3 Attitude control system design process requirements	○	○1)	○1)	
3.1 Control engineering management (integration and management)	○	○1)	○1)	
3.1.1 General	○	○1)	○1)	
3.1.2 Control engineering plan management (organization and planning of activities)	○	○	○	
3.1.3 Technology data management (data provision to systems engineering database)	○	○2)	×	
3.1.4 Interface management with other fields	○	○2)	×	
3.1.5 Human -machine interface control as part of controller	○	○	×	If there is any man- machine interface
3.1.6 Requirement allocation and margin control philosophy	○	○	×	
3.1.7 Assessment of control technology and cost efficiency (preliminary assessment)	○	○1)	×	
3.1.8 Risk management	○	○2)	○	
3.1.9 Technical support for the attitude control system component procurement	○	○2)	×	
3.1.10 Configuration management (control-related change management including in-flight maintenance)	○	○2)	×	
3.1.11 Assessment of capabilities and resource related to control engineering (preliminary assessment)	○	○2)	×	
3.1.12 Safety control	○	○	○	
3.1.13 Reliability control	○	○2)	○	
3.1.14 Quality assurance	○	○	○	
3.2 Management of requirements analysis and requirements	N/A	N/A	N/A	
3.2.1 General	○	○2)	×	
3.2.2 Requirements analysis	○	○2)	×	
3.2.3 Creating attitude control requirements	○	○2)	×	
3.3 Attitude control system design	N/A	N/A	N/A	
3.3.1 General	○	○1)	○1)	
3.3.2 System design	N/A	N/A	N/A	
3.3.2.1 General	○	○2)	×	
3.3.2.2 Architectural design	○	×	×	
3.3.2.3 Control algorithm design	○	○	○	
3.3.2.4 Operation mode design	○	○	○	
3.3.2.5 Functional design	○	○	○	
3.3.2.6 Configuration design	○	○	○	
3.3.2.7 Component design	○	×	×	
3.3.2.8 Interface design	○	○2)	×	
3.3.2.9 Design to support ground verification test	○	○	○	
3.3.2.10 Design error prevention	○	○	○	
3.3.3 Control system elements design - Controller design	N/A	N/A	N/A	
3.3.3.1 General	○	○2)	×	
3.3.3.2 Preventing design errors	○	○2)	×	
3.3.4 Control system elements design - Controller design	N/A	N/A	N/A	

Requirements	TRL I	TRL II	TRL III	Remarks
3.3.4.1 Sensor	○	×	×	
3.3.4.2 Actuator	○	×	×	
3.3.4.3 On-board software	○	○2)	×	
3.3.5 Implementation and operational design	N/A	N/A	N/A	
3.3.5.1 General	○	○	×	
3.3.5.2 Control system implementation method into the operational system	○	×	×	
3.4 Analysis	N/A	N/A	N/A	
3.4.1 General	○	○1)	○1)	
3.4.2 Analysis models, analysis methods and analysis tools	N/A	N/A	N/A	
3.4.2.1 General	○	○1)	×	
3.4.2.2 Definition of analysis model	○	×	×	
3.4.2.3 Analysis methods and analysis tools	○	×	×	
3.4.3 Analysis for requirements analysis	N/A	N/A	N/A	
3.4.3.1 General	○	○1)	×	
3.4.3.2 Support for missions analysis, system analysis and control engineering requirements analysis	○	○2)	×	
3.4.3.3 External disturbance and disturbance analysis	○	○2)	×	
3.4.4 Attitude control system performance analysis	N/A	N/A	N/A	
3.4.4.1 General	○	○	○	
3.4.4.2 Error budget analysis	○	○	×	
3.4.4.3 Stability analysis and robustness analysis	○	○	×	
3.4.5 Verification analysis	○	○	○	
3.5 Manufacturing and testing	○	○	○	
3.6 Verification and validation	N/A	N/A	N/A	
3.6.1 General	○	○	×	
3.6.2 Planning of control system verification plan	N/A	N/A	N/A	
3.6.2.1 General	○	○1)	×	
3.6.3 Preliminary verification of performance	N/A	N/A	N/A	
3.6.3.1 General	○	○1)	×	
3.6.4 Final functional and performances verification	N/A	N/A	N/A	
3.6.4.1 General	○	○	○	
3.6.4.2 Verification by analysis	○	○	○	
3.6.4.3 Verification by on-board hardware and software	○	○	○	
3.6.5 In-flight validation	○	○	○	
3.7 Operation, maintenance and disposal	N/A	N/A	N/A	
3.7.1 General	○	○	○	
3.7.2 Operation and maintenance	○	○	○	
3.7.3 Disposal	○	○	○	

Note 1) Partial applied (exemption items may be selected)
2) Applied only to modified portions

Table II-1(2) Guidelines for applying requirements for Spacecraft attitude control system design standard: Reliability level II

Requirements	TRL I	TRL II	TRL III	Remarks
Chapter 3 Attitude control system design process requirements	○	○1)		
3.1 Control engineering management (integration and management)	○	○1)		
3.1.1 General	○	○1)		
3.1.2 Control engineering plan management (organization and planning of activities)	○	○		
3.1.3 Technology data management (data provision to systems engineering database)	○	○2)		
3.1.4 Interface management with other fields	○	○2)		
3.1.5 Human -machine interface control as part of controller	○	○		
3.1.6 Requirement allocation and margin control philosophy	○	○		
3.1.7 Assessment of control technology and cost efficiency (preliminary assessment)	○	×		
3.1.8 Risk management	○	○2)		
3.1.9 Technical support for the attitude control system component procurement	○	○2)		
3.1.10 Configuration management (control-related change management including in-flight maintenance)	○	○2)		
3.1.11 Assessment of capabilities and resource related to control engineering (preliminary assessment)	○	○2)		
3.1.12 Safety control	○	○		
3.1.13 Reliability control	○	○2)		
3.1.14 Quality assurance	○	○		
3.2 Control of requirements analysis and requirements	N/A	N/A		
3.2.1 General	○	○2)		
3.2.2 Requirements analysis	○	○2)		
3.2.3 Creating attitude control requirements	○	○2)		
3.3 Attitude control system design	N/A	N/A		
3.3.1 General	○	○1)		
3.3.2 System design	N/A	N/A		
3.3.2.1 General	○	×		
3.3.2.2 Architectural design	○	×		
3.3.2.3 Control algorithm design	○	○		
3.3.2.4 Operation mode design	○	○		
3.3.2.5 Functional design	○	○		
3.3.2.6 Configuration design	○	○		
3.3.2.7 Component design	○	×		
3.3.2.8 Interface design	○	○2)		
3.3.2.9 Design to support ground verification test	○	○		
3.3.2.10 Design error prevention	○	○		
3.3.3 Control system elements design - Controller design	N/A	N/A		
3.3.3.1 General	○	○2)		
3.3.3.2 Preventing design errors	N/A	N/A		
3.3.4 Control system elements design - Controller design	N/A	N/A		
3.3.4.1 Sensor	○	×		

Requirements	TRL I	TRL II	TRL III	Remarks
3.3.4.2 Actuator	○	×		
3.3.4.3 On-board software	○	○2)		
3.3.5 Implementation and operational design	N/A	N/A		
3.3.5.1 General	○	○		
3.3.5.2 Control system implementation method into the operational system	○	×		
3.4 Analysis	N/A	N/A		
3.4.1 General	○	○1)		
3.4.2 Analysis models, analysis methods and analysis tools	N/A	N/A		
3.4.2.1 General	○	○1)		
3.4.2.2 Definition of analysis model	○	×		
3.4.2.3 Analysis methods and analysis tools	○	×		
3.4.3 Analysis for requirements analysis	N/A	N/A		
3.4.3.1 General	○	○1)		
3.4.3.2 Support for missions analysis, system analysis and control engineering requirements analysis	○	○2)		
3.4.3.3 External disturbance and disturbance analysis	○	○2)		
3.4.4 Attitude control system performance analysis	N/A	N/A		
3.4.4.1 General	○	○		
3.4.4.2 Error budget analysis	○	○		
3.4.4.3 Stability analysis and robustness analysis	○	○		
3.4.5 Verification analysis	○	○		
3.5 Manufacturing and testing	○	○		
3.6 Verification and validation	N/A	N/A		
3.6.1 General	○	○		
3.6.2 Planning of control system verification plan	N/A	N/A		
3.6.2.1 General	○	○1)		
3.6.3 Preliminary verification of performance	N/A	N/A		
3.6.3.1 General	○	○1)		
3.6.4 Final functional and performances verification	N/A	N/A		
3.6.4.1 General	○	○		
3.6.4.2 Verification by analysis	○	○		
3.6.4.3 Verification by on-board hardware and software	○	○		
3.6.5 In-flight validation	○	○		
3.7 Operation, maintenance and disposal	N/A	N/A		
3.7.1 General	○	○		
3.7.2 Operation and maintenance	○	○		
3.7.3 Disposal	○	○		

Note 1) Partial applied (exemption items may be selected)
2) Applied only to modified portions

Table II-1(3) Guidelines for applying requirements for Spacecraft attitude control system design standard: Reliability level III

Requirements	TRL I	TRL II	TRL III	Remarks
Chapter 3 Attitude control system design process requirements	○	○1)		
3.1 Control engineering management (integration and management)	○	○1)		
3.1.1 General	○	○1)		
3.1.2 Control engineering plan management (organization and planning of activities)	○	○		
3.1.3 Technology data management (data provision to systems engineering database)	○	○2)		
3.1.4 Interface management with other fields	○	○2)		
3.1.5 Human -machine interface control as part of controller	○	○		
3.1.6 Requirement allocation and margin control philosophy	○	○		
3.1.7 Assessment of control technology and cost efficiency (preliminary assessment)	○	○1)		
3.1.8 Risk management	○	○2)		
3.1.9 Technical support for the attitude control system component procurement	○	○2)		
3.1.10 Configuration management (control-related change management including in-flight maintenance)	○	○2)		
3.1.11 Assessment of capabilities and resource related to control engineering (preliminary assessment)	○	○2)		
3.1.12 Safety control	○	○		
3.1.13 Reliability control	○	○2)		
3.1.14 Quality assurance	○	○		
3.2 Management of requirements analysis and requirements	N/A	N/A		
3.2.1 General	○	○2)		
3.2.2 Requirements analysis	○	○2)		
3.2.3 Creating attitude control requirements	○	○2)		
3.3 Attitude control system design	N/A	N/A		
3.3.1 General	○	○1)		
3.3.2 System design	N/A	N/A		
3.3.2.1 General	○	○2)		
3.3.2.2 Architectural design	○	×		
3.3.2.3 Control algorithm design	○	○		
3.3.2.4 Operation mode design	○	○		
3.3.2.5 Functional design	○	○		
3.3.2.6 Configuration design	○	○		
3.3.2.7 Component design	○	×		
3.3.2.8 Interface design	○	○2)		
3.3.2.9 Design to support ground verification test	○	○		
3.3.2.10 Design error prevention	○	○		
3.3.3 Control system elements design - Controller design	N/A	N/A		
3.3.3.1 General	○	○2)		
3.3.3.2 Preventing design errors	○	○2)		
3.3.4 Control system elements design - Controller design	N/A	N/A		
3.3.4.1 Sensor	○	×		

Requirements	TRL I	TRL II	TRL III	Remarks
3.3.4.2 Actuator	○	×		
3.3.4.3 On-board software	○	○2)		
3.3.5 Implementation and operational design	N/A	N/A		
3.3.5.1 General	○	○		
3.3.5.2 Control system implementation method into the operational system	○	×		
3.4 Analysis	N/A	N/A		
3.4.1 General	○	○1)		
3.4.2 Analysis models, analysis methods and analysis tools	N/A	N/A		
3.4.2.1 General	○	○1)		
3.4.2.2 Definition of analysis model	○	×		
3.4.2.3 Analysis methods and analysis tools	○	×		
3.4.3 Analysis for requirements analysis	N/A	N/A		
3.4.3.1 General	○	○1)		
3.4.3.2 Support for missions analysis, system analysis and control engineering requirements analysis	○	○2)		
3.4.3.3 External disturbance and disturbance analysis	○	○2)		
3.4.4 Attitude control system performance analysis	N/A	N/A		
3.4.4.1 General	○	○		
3.4.4.2 Error budget analysis	○	○		
3.4.4.3 Stability analysis and robustness analysis	○	○		
3.4.5 Verification analysis	○	○		(applied if especially required)
3.5 Manufacturing and testing	○	○		
3.6 Verification and validation	N/A	N/A		
3.6.1 General	○	○		
3.6.2 Planning of control system verification plan	N/A	N/A		
3.6.2.1 General	○	○1)		
3.6.3 Preliminary verification of performance	N/A	N/A		
3.6.3.1 General	○	○1)		
3.6.4 Final functional and performances verification	N/A	N/A		
3.6.4.1 General	○	○		
3.6.4.2 Verification by analysis	○	○		
3.6.4.3 Verification by on-board hardware and software	○	○		
3.6.5 In-flight validation	○	○		
3.7 Operation, maintenance and disposal	N/A	N/A		
3.7.1 General	○	○		
3.7.2 Operation and maintenance	○	○		
3.7.3 Disposal	○	○		

Note 1) Partial applied (exemption items may be selected)
2) Applied only to modified portions

Table II-1(4) Guidelines for applying requirements for Spacecraft attitude control system design standard: Reliability level IV

Requirements	TRL I	TRL II	TRL III	Remarks
Chapter 3 Attitude control system design process requirements	○	○1)		
3.1 Control engineering management (integration and management)	○	○1)		
3.1.1 General	○	○1)		
3.1.2 Control engineering plan management (organization and planning of activities)	○	○		
3.1.3 Technology data management (data provision to systems engineering database)	○	○2)		
3.1.4 Interface management with other fields	○	○2)		
3.1.5 Human -machine interface control as part of controller	○	○		
3.1.6 Requirement allocation and margin control philosophy	○	○		
3.1.7 Assessment of control technology and cost efficiency (preliminary assessment)	○	○1)		
3.1.8 Risk management	○	○2)		
3.1.9 Technical support for the attitude control system component procurement	○	○2)		
3.1.10 Configuration management (control-related change management including in-flight maintenance)	○	○2)		
3.1.11 Assessment of capabilities and resource related to control engineering (preliminary assessment)	○	○2)		
3.1.12 Safety control	○	○		
3.1.13 Reliability control	○	○2)		
3.1.14 Quality assurance	○	○		
3.2 Management of requirements analysis and requirements	N/A	N/A		
3.2.1 General	○	○2)		
3.2.2 Requirements analysis	○	○2)		
3.2.3 Creating attitude control requirements	○	○2)		
3.3 Attitude control system design	N/A	N/A		
3.3.1 General	○	○1)		
3.3.2 System design	N/A	N/A		
3.3.2.1 General	○	○2)		
3.3.2.2 Architectural design	○	×		
3.3.2.3 Control algorithm design	○	○		
3.3.2.4 Operation mode design	○	○		
3.3.2.5 Functional design	○	○		
3.3.2.6 Configuration design	○	○		
3.3.2.7 Component design	○	×		
3.3.2.8 Interface design	○	○2)		
3.3.2.9 Design to support ground verification test	○	○		
3.3.2.10 Design error prevention	○	○		
3.3.3 Control system elements design - Controller design	N/A	N/A		
3.3.3.1 General	○	○2)		
3.3.3.2 Preventing design errors	○	○2)		
3.3.4 Control system elements design - Controller design	N/A	N/A		
3.3.4.1 Sensor	○	×		

Requirements	TRL I	TRL II	TRL III	Remarks
3.3.4.2 Actuator	○	×		
3.3.4.3 On-board software	○	○2)		
3.3.5 Implementation and operational design	N/A	N/A		
3.3.5.1 General	○	○		
3.3.5.2 Control system implementation method into the operational system	○	×		
3.4 Analysis	N/A	N/A		
3.4.1 General	○	○1)		
3.4.2 Analysis models, analysis methods and analysis tools	N/A	N/A		
3.4.2.1 General	○	○1)		
3.4.2.2 Definition of analysis model	○	×		
3.4.2.3 Analysis methods and analysis tools	○	×		
3.4.3 Analysis for requirements analysis	N/A	N/A		
3.4.3.1 General	○	○1)		
3.4.3.2 Support for missions analysis, system analysis and control engineering requirements analysis	○	○2)		
3.4.3.3 External disturbance and disturbance analysis	○	○2)		
3.4.4 Attitude control system performance analysis	N/A	N/A		
3.4.4.1 General	○	○		
3.4.4.2 Error budget analysis	○	○		
3.4.4.3 Stability analysis and robustness analysis	○	○		
3.4.5 Verification analysis	○	○		
3.5 Manufacturing and testing	○	○		
3.6 Verification and validation	N/A	N/A		
3.6.1 General	○	○		
3.6.2 Planning of control system verification plan	N/A	N/A		
3.6.2.1 General	○	○1)		
3.6.3 Preliminary verification of performance	N/A	N/A		
3.6.3.1 General	○	○1)		
3.6.4 Final functional and performances verification	N/A	N/A		
3.6.4.1 General	○	○		
3.6.4.2 Verification by analysis	○	○		
3.6.4.3 Verification by on-board hardware and software	○	○		
3.6.5 In-flight validation	○	○		
3.7 Operation, maintenance and disposal	N/A	N/A		
3.7.1 General	○	○		
3.7.2 Operation and maintenance	○	○		
3.7.3 Disposal	○	○		

Note 1) Partial applied (exemption items may be selected)
2) Applied only to modified portions

Appendix III Sample of the attitude control system development specifications and attitude control system interface condition document - Contents

The requirements and design conditions related to the attitude control system development are categorized as follows:

(1) Requirements related to the process of development and design

- [1] Requirements on design and analysis
  To be specified in procurement specifications and development plan.
- [2] Requirements on test and verification
  To be specified in procurement specifications and development plan. The technical requirements to be verified in each development phase (specified in Chapter 3) and the verification methods (specified in Chapter 4) shall be specified in the development specifications.

(2) Technical requirements

- [1] Technical requirements shall be basically specified in the development specifications. Attachment 1 shows a sample of the contents of development specifications.
- [2] The design conditions which is difficult to be specified in the above documents, shall be in accordance with the interface condition (control) document and so on. Attachment 2 shows a sample of the interface condition (control) document.
- [3] For the attitude control system requirements, items such as attitude control function, attitude accuracy, and FDIR functions shall be verified by SCLT, DCLT and simulation analysis. Basically, these test verification requirements shall be specified in the development specifications. However, attitude accuracy and so on cannot be verified only by testing in many cases. Thus, for requirements to be verified in combination with analysis, verification methods shall be specified also in the test verification plan and development plan not only in the development specifications.
- [4] The activity requirements related to test equipments (including AGE, GSE, BTE), which are specified in the procurement specifications and development plan and so on, shall conform to the test verification requirements specified in the development specifications. The basic technical requirements related to test equipment (such as performing DCLT and SCLT) shall be specified in the development specifications.
- [5] The activity requirements related to operation(training, manual and so on), which are specified in the procurement specifications, development plans and so on, shall conform to the operational requirements specified in the development specifications, interface condition document and so on. Basic technical requirements shall be specified in the development specifications or interface condition document.

Attachment 1 Sample of the attitude control system development specifications

It is required in the “Attitude Control System Design Standard” to perform requirements analysis in the initial phase of development and manage them as requirements for the attitude control system. Examples of requirements to be managed in developing and designing the attitude control system are shown below. In the following examples, requirements on stability and robustness of control systems are not specified but the “Attitude Control System Design Standard” requires these items shall be specified and managed with allocation of margins. These items shall be specified and managed in accordance with the project-specific design standards aside from the development specifications.

1. Scope

The scope shall be specified. The scope shall be specified in accordance with the technology readiness level shown in Appendix II.

2. Applicable documents

2.1 Applicable documents

2.1.1 Overview

2.1.2 Regulations

2.1.3 Documents generated by Japan Aerospace Exploration Agency

In addition to general documents generated by Japan Aerospace Exploration Agency, the following shall be specified.

(1) Attitude Control System Design Standard or Control System Design Standard
(2) Spacecraft Software Development Standard

3. Requirements

In Chapter 3, the basic requirements shall be specified. The requirements shown in Chapter 3 shall be verified by testing and or analysis in each phase of development.

3.1 Definition of items

3.1.1 Functions

3.1.1.1 Overview

2.1.1.2 Major functions

(1) Define all control modes (functional unit for executing specific control functions of control systems) and major functions for each control mode. When a combination of some control modes is defined as an operational mode, the relation between the control mode and operational modes shall also be defined. Normally, the following control modes are defined. When a sub-mode is defined under a major mode, the sub-mode shall also be defined.
    [1] Initial acquisition mode
    [2] Normal mode
    [3] Orbit control mode
(2) Define the disposal, de-orbit function (if required)
(3) Define the mode change functions.
(4) When a safety mode is required, define the functions of the safety mode.
(5) When an FDIR function involving mode change is required, define the FDIR function.
(6) Specify the functional allocation to components or major functions.
    [1] Attitude control electronics
    [2] On-board software
    [3] Sensors
    [4] Actuators and driving electronics

3.1.2 Configuration

(1) Define all the components.
    Sensors, attitude control electronics (or attitude and orbit control electronics), actuators (including driving electronics).
(2) When on-board software is defined independently from the attitude control electronics, identify the software as a component.
(3) Define the configuration diagram and functional system diagram.

3.1.3 Operational mode

(1) Define the operational mode of the major components (functional unit for executing specific functions of the components, in case of single function components, operational mode will be only on and off .) Define major functions for each operational mode.
    Among operational modes shall be as follows:

(Example)

Attitude control system electronic (AOCE)	ON, OFF, standby mode, initial boot mode, etc.
Inertial reference unit (IRU)	ON, OFF, high rate mode, low rate mode, etc.
Earth sensor (ESA)	ON, OFF, acquisition mode, single-scan mode, etc.
Valve drive electronic (VDE)	ON, OFF

(2) With respect to the control modes defined by the major functions in 3.1.1.2, define the operational modes of the components.

(Example)

	AOCE Primary	AOCE Backup	IRU	ESA	VDE	others
(1) Initial acquisition mode	ON	Standby mode	3 axis ON High rate mode	Primary and Backup ON	Primary and Backup ON	
(2) Normal mode	ON	Standby mode	3 axis ON Low rate	Primary and Backup ON	Both OFF	
(3) Orbit control mode	ON	Standby mode	3 axis ON High rate mode	Primary and Backup ON	Primary and Backup ON	

3.1.4 Interface definition

The following interface items are necessary for the attitude control system design, but those interface items are not defined and specified in the specifications. Those interface items shall be specified separately in ICD, interface condition document and so on.

(1) Time systems and coordinate systems. Body-frame coordinates (including equipment coordinate systems of other systems such as propulsion system and solar array paddle and so on)
(2) External disturbances (environmental disturbances, propulsion system disturbances)
(3) Internal disturbances
(4) Mass properties
(5) Solar array paddle (including paddle flexible structural characteristics)
(6) Characteristics of propulsion system (including thrust force, thrust vector, plume and sloshing characteristics)
(7) Field of view, antenna pattern
(8) Alignment (including installation alignment of sensors, thrusters and so on)
(9) Polarity, phasing
(10) Operational interface (basic requirements shall be described as the development specifications as possible)

The following are general requirements.

3.1.4.1 Definition of external interface

3.1.4.2 Definition of internal interface

3.1.5 Interface boundary

3.1.5.1 Electrical interface boundary conditions

3.1.5.2 Mechanical interface boundary conditions

3.1.5.3 Thermal interface boundary conditions

3.1.5.4 RF interface boundary conditions

3.1.5.5 Operational interface boundary conditions

3.1.5.6 Fluid interface boundary conditions (Not applied)

3.1.6 Interface conditions

3.1.6.1 Electrical interface conditions

In the electrical interface conditions between the propulsion system, operation conditions, temperature and so on shall be specified.

3.1.6.2 Mechanical interface conditions

3.1.6.3 Thermal interface conditions

3.1.6.4 RF interface conditions

When GPS and so on is used on-boarded, this condition should be specified.

3.1.6.5 Operational interface conditions

Basic operational interfaces shall be specified as development specifications as possible. The operational interfaces which are not specified as development specifications and necessary to the design of the attitude control system shall be specified in the interface condition (control) document.

3.1.6.6 Fluid interface condition (Not applied)

3.2 Characteristics

Specify the basic performances of the attitude control system.

Specified performances shall be subjected to verification by test or other method.

The “Attitude Control System Design Standard” requires to allocate the appropriate margins and to manage as the attitude control system for satisfying system requirements with respect to the following performances.

3.2.1 Performances

3.2.1.1 Major performances of the attitude control system

The performances of the major functions of the mode defined in 3.1.1.2 shall be specified.

The major performances are as follows:

(1) Attitude accuracy

The definition of attitude shall be clarified. The definition of attitude may be specified in the interface condition document,in addition to the definition of coordinate frame and coordinate transformation.

When pointing accuracy is specified, it is necessary to define the relation between pointing accuracy and attitude accuracy and clarify the allocation from pointing accuracy. These performances are closely related to the mission achievement level. Attitude accuracy requirements shall be defined within the control bandwidth of the attitude control system.

Some error sources of the attitude control system must be treated as random variables like sensor noise. The attitude accuracy is specified as variance or standard deviation in many cases. However, because many errors must be treated definitively as design conditions, care shall be taken to the statistical processing and counting method. (The external disturbance conditions which become control error sources and the alignment which becomes an error source of attitude determination should not be included in statistical processing targets when the worst values are provided as design conditions.) In other words, it is necessary to avoid statistical processing of control errors generated due to given external disturbance conditions, obtaining the standard deviation and performing RSS (root sum square) with control errors induced by sensor noise. When specifying the attitude accuracy as variance or standard deviation, it is also necessary to specify identification between definite errors induced by given design conditions and statistically processed errors such as sensor noise.

[1] Attitude control accuracy
[2] Attitude determination accuracy

The orbit control accuracy, orbit determination accuracy and time accuracy shall be specified when required.

(2) Attitude stability

When pointing accuracy is specified, it is necessary to clarify the allocation from pointing accuracy.These performances are closely related to the mission achievement level,. Basically, it is necessary that those requirements are defined within the control bandwidth of the attitude control system.

Stability requirements must be defined as an variation of the attitude and attitude determination value within the specific time duration. However, when there are no particular requirements, it may be specified as an attitude variation within the specific time duration.

[1] Attitude control stability
[2] Attitude determination stability

(3) Maneuver performance

[1] Attitude transition time
[2] Convergence time
[3] When attitude accuracy during attitude transition is required, that shall be specified as 3.2.1.1(1). (Dynamic errors must be included.)

(4) Other performances

[1] External disturbance control capability: Suppression, and absorption capability of external disturbances
[2] Recovery time from abnormal state: When required as FDIR performance
[3] Processing time: When the processing time for attitude control is specified

3.3 Component characteristics

The major functions and performances specifying the performances of the attitude control system must be allocated to the components.

3.3.1 Attitude control system electronics

3.3.2 Sensor

(1) Accuracy and so on allocated from the basic functions and performances of the attitude control system are specified.
The accuracy requirements for the sensors shall conform to the requirements in 3.2.1.1(1).

(2) The weight, power and dimensions requirements shall conform to resource requirements allocated from the attitude control system (including weight, power, dimensions, and so on).

3.3.3 Actuators and drive electronic

(1) The controllability (such as torque) allocated from the basic functions and performances of the attitude control system are specified.
The controllability related requirements for actuators shall conform to the requirements in 3.2.1.1(3) and (4).

(2)The weight, power and dimensions requirements shall conform to resource requirements allocated from the attitude control system (including weight, power, dimensions, and so on).

(3) The internal disturbances generated from the actuators shall conform to the requirements in 3.2.1.1(1).

3.3.4 On-board software

The basic requirements for on-board software are specified. Specify the following requirements as needed.

(1) Processing speed and delay time (processing time or time from input to output)
(2) Program size
(3) Reprogramming requirement

3.4 Physical characteristics

Physical characteristics such as mass properties, dimensions, and surface characteristics are specified. Details shall be in accordance with ICD and so on.

3.5 Design standard (Duplications with applicable documents must be avoided)

The design standard required in design of the attitude control system components shall be specified.

(1) Mechanical design standard
(2) Thermal design standard
(3) Space environmental design standard
(4) Electrical design standard
(5) Electromagnetic compatibility design standard
(6) Telemetry and command design standard
(7) Reliability design standard
(8) Parts program standard

3.6 Reliability

3.6.1 Reliability

3.6.2 Designed mission life

3.6.3 Single failure

3.6.4 Failure isolation (clarify the with FDIR functions)

4. Environmental conditions

4.1 Storage and transportation (Non-operating)

4.2 Manufacturing, assembly and test (except for at thermal vacuum test)

4.3 Launch and on-orbit

4.4 Thermal environment

4.5 Radiation environment

5. Quality assurance requirements

5.1 Test and inspection

The technical requirements in Chapter 3 shall be managed by developing a test verification matrix as shown in the example in accordance with the technology readiness level and so on defined in Appendix II, without dropouts or leakage for the test verification.

Example of test verification matrix

Phase	BBM		EM (Phase C and D)				PFM (Phase C and D)				FM (Phase C and D)			
Verification method Item	Analysis	Test	past records	Inspection	Analysis	Test	past records	Inspection	Analysis	Test	past records	Inspection	Analysis	Test
3. Requirements 3.1 Definition of items 3.1.1 Functions 3.1.1.1 Overview 3.1.1.2 Major functions 3.1.2 Configuration 3.1.3 Operational mode 3.1.4 Interface conditions 3.2 Characteristics	N/A N/A	N/A N/A	N/A N/A	N/A N/A	N/A N/A	N/A N/A	N/A N/A	N/A N/A	N/A N/A	N/A N/A	N/A N/A	N/A N/A	N/A N/A	N/A N/A
	For the items of which technology readiness level TRL is 3 or less, an experimental test in the BBM phase will be performed.		For the items of which technology readiness level TRL is 4, an EM manufacturing and test in phases C and D will be performed. For items besides manufacturing EM, verification by past records and or analysis are necessary. If it is difficult to be verified by ordinal l electrical performances test, clarify the test methods to be conducted(such as DCLT, SCLT, and so on).				For the items of which technology readiness level TRL is 5 or more, a manufacturing and test of PFM in phases C and D will be performed. For items besides manufacturing PFM, verification by the past records, analysis or AT shall be applied. If it is difficult to be verified by ordinal l electrical performances test, clarify the test methods to be conducted(such as DCLT, SCLT, and so on).				For the items of which technology readiness level TRL is 7 or more, perform a manufacturing and test of FM in phases C and D will be performed. If it is difficult to be verified by ordinal l electrical performances test, clarify the test methods to be conducted (such as DCLT, SCLT, and so on).			

Test and verification requirements in each design phase to the attitude control system and major components as follows shall be specified.

(1) Attitude control electronics
(2) On-board software
(3) Sensors, actuators and drive electronics

5.2 Environment test

(1) If the environment test is required for whole subsystem, it shall be specified.
(2) If the environment test is required for each component, it shall be specified.

Attachment 2 Sample of the attitude control system interface condition documents

The following interface items are necessary for the design of the attitude control system but these items are not defined and specified in the development specifications. Thus, these interface items shall be specified in ICD, interface condition documents, and so on. Although the verification of the interface requirements specified in the development specifications are to be specified in the development specifications, the verification of these items shall be specified in the test plan of the system and or in the test plan of the attitude control system and so on.

1. Scope

The scope shall be specified. The scope shall be specified in accordance with the technology readiness level shown in Appendix II.

2. Applicable documents

2.1 Applicable documents

2.1.1 Overview

2.1.2 Regulations

2.1.3 Documents generated by Japan Aerospace Exploration Agency

In addition to general documents generated by Japan Aerospace Exploration Agency, the following shall be specified.

(1) Attitude Control System Design Standard or Control System Design Standard
(2) Standard Coordinate System and Time System Usage Manual
(3) Pointing Control Standard
(4) Disturbance Control Standard
(5) Spacecraft Software Development Standard
(6) Attitude Control System Development Specifications

3. Requirements

3.1 Time system and coordinate system.

3.1.1 Coordinate system

(1) Spacecraft-fixed coordinate system
(2) Equipment-specific coordinate system installed in the spacecraft (solar array paddle, sensors)
    (a) Coordinate transformation to/from spacecraft-fixed coordinate system shall be defined.
    (b) For the solar array paddle and so on, the coordinate transformation including rotation shall be defined.
(3) Attitude referenced coordinate system
    (a) Coordinate system for specifying pointing requirements from the mission
        If the referenced coordinate system of the mission pointing and the attitude control differs, both coordinate systems as well as its relation (coordinate transformation) shall be specified.
    (b) Referenced coordinate system for attitude
        Attitude shall be defined as well as coordinate system. (The attitude shall be specified as the coordinate transformation from the spacecraft-fixed coordinate as a rigid body to the coordinate system of the attitude standard.) When the attitude angle is defined in Euler angle, the rotation sequence and so on shall be specified.
    (c) Coordinate transformation to/from referenced coordinate system shall be defined.
    (d) Error in the coordinate transformation above shall be defined.
(4) Referenced coordinate system
    (a) Star-based coordinate system: ICRF or ICRS
    (b) TOD coordinate system or pseudo TOD coordinate system propagated from above coordinate system
    (c) Coordinate system representing location on the earth: ITRF or WGS84

3.1.2 Time system

(1) Standard time system of the attitude control system
    Correlation between the following standard time systems and errors.
(2) Standard time system
    (a) Operation and life time: UTC
    (b) Star-based time system: TDT
    (c) Time used in GPS: GPS time

3.2 Environment model (plant model of the attitude control system and environment)

3.2.1 Celestial position

Celestial ephemeris of the sun and stars, and so on as reference of attitude determination

3.2.2 Environmental external disturbances

Specify the solar activity level and so on which are premises of the following external disturbances.

(1) Solar pressure external disturbances
(2) Aerodynamic external disturbances
(3) Gravity gradient external disturbances
(4) Erath magnetic field external disturbances

3.2.3 Internal disturbances

Internal disturbance source and disturbance model

3.2.4 Mass properties

(1) Mass properties (CG position, mass and inertia tensor) and changes (mass change due to BOL, EOL, rotation of solar array paddle, AEF, and others)
(2) Tolerance

3.2.5 Flexible structural characteristics

(1) Identification of flexible structure
(2) Flexible structural characteristics of identified flexible structure
    [1] Zero- and first-order coupling coefficient matrix, natural frequency and damping, and position vector of installation point.
    [2] Tolerance
(3) Coordinate transformation matrix if above flexible structural characteristics are described in the equipment coordinate system

3.2.6 Propulsion system

(1) Thrust force and variation in thrust force (unbalance)
(2) Minimum impulse and centroid time
(3) Thrust vector and alignment error
(4) CG movement due to propellant movement
(5) Plume pollution area and plume external disturbances
(6) Sloshing characteristics

3.3 Field of view, antenna pattern

(1) Sensor field of view
(2) Antenna pattern and multipath characteristics if there is GPS and so on

3.4 Alignment (ICD item)

(1) Alignment error of the attitude control system components
(2) Inter-alignment error between the mission equipment and sensors

3.5 Polarity and phasing (ICD item)

Specify the polarity and phasing of each sensors and actuators. Specify a specific verification method after integrated to system.

3.6 Operational interface

Basic operational interface shall be specified as development specifications as possible. It may be possible to separate it as the attitude control system interface condition documents as operational interface conditions.

3.6.1 Definition of operational modes and major events

3.6.2 Basic operational requirements in each operation mode

(1) Autonomic function, automatic operational functions and command operation requirements
(2) Criticality
(3) Telemetry, command operation requirements and evaluation standard

3.6.3 Operational constraints for each operation mode

(1) Operating time

(2) Number of stations