From science to mission in science projects (ISAS case)

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Self introduction

M. Ueno is working at Center for Planetary Science, Kobe University since Jan. 2016.
Ph.D in physics from Kyoto University, Japan in 1994
MU joined Department of Earth Science and Astronomy, Univ. of Tokyo.
MU moved to Institute of Space and Astronautical Science (ISAS), JAXA in 2009, and his former occupations in JAXA were head of mission instrument technology group, director of ISAS Program office, and Chief engineer of JAXA.
MU's research interests include infrared astronomy, solar system science, scientific instrumentation and systems engineering in space development.
MU has been involved in several space missions, AKARI (Infrared Astronomical Satellite), AKATSUKI (Venus orbiter), HISAKI (extreme-UV telescope in space), and also related activities like a recovered sample analysis project of HAYABUSA.

MU served as a director of Astronomical Society of Japan, and also serves chair of Standing Space Agency Subcommittee, International Project/ Programme Management Committee, (also vice-chair of Standing Space Agency Subcommittee, Knowledge Management Technical Committee), associate editor of Space Research Today, Committee on Space Research (COSPAR).

Lecture Outline

Institute of Space and Astronautical Science (ISAS) is now belonging to Japan Aerospace Exploration Agency (JAXA), and has rather longer history than other branches in JAXA. ISAS is based on a research institute, and has Inter-University research promotion system, which aims research in whole coverage of space technology and space sciences with high degree-of-freedom in choosing research topics. ISAS is promoting not only doing research but doing flight and missions (complimentary in R&D) like "Idea into Flight Missions and Missions Stimulate Research".

This lecture will introduce the promotion system of ISAS missions, importance of systems engineering approach in the early phase in mission development, and system engineering* approach itself.

Talking outline

- ISAS mission creation (ISAS case)
  - Fujimoto-san introduced half of this part yesterday, so I modified.
  - ISAS as a research institute
  - Bottom-up system in space science in Japan
- From scientific objective into the space mission
  - mission creation approach using systems engineering approach

ISAS as a Research institute

Research in

Whole Coverage of Space Technology & Space Sciences

High Degree-of-Freedom in Choosing Research Topics

Not Only doing Research

But doing Flight & Missions (Complimentary in R&D)

Technology Research in

Both "Supporting" and "Leading / Creating" in Space Science Programs

Idea into Flight Missions & Missions Stimulate Research

Research Activities based on Inter-University System

ISAS Space Science Projects

IR/Radio Astronomy and X-ray/High Energy Astrophysics
Space Plasma Physics and Atmospheric Science
Planetary Science & Solar System Exploration
Development & Evolution of Flight Tools
New Space Flight Technology & Future Space Utilization

Flight Tools and Opportunities at ISAS

Scientific Satellites and Spacecraft
Interplanetary Missions and Planetary Probes
Experimental Flight Vehicles
(Sounding Rocket & Stratospheric Ballooning)

Inter-University Research Promotion System

Space Science Research Committee

(Steering Body for Inter-University Research Promotion System)

Research Groups / Communities

X-ray/High energy astrophysics
Infrared astronomy
Radio astronomy
Solar physics
Upper atmosphere studies
Solar system studies (wide coverage)
Space plasma physics

Research Group Members (Professors and Associate Professors)

ISAS/University Researchers ~ 600

Inter-University Research Promotion System

Space Engineering Research Committee
(Steering Body for Inter-University Research Promotion System)

Research Groups / Communities

Propulsion
Aerodynamics and Thermophysics
Material
Structure and Mechanics
Navigation, Guidance & Control
Power and Energy Systems
Communication / Instrumentation
Micro-electronics

Research Group Members (Professors and Associate Professors)

ISAS/University Researchers ~ 250

Project Creation in ISAS as an inter-university institute

ISAS Space Science Projects

Space Science Committee

Space Engineering Committee

Working Group for Project Preparation

Encouragement, Supporting and Evaluation for New Research Promotion

Research Proposal

Space Science Communities

Space Engineering Communities

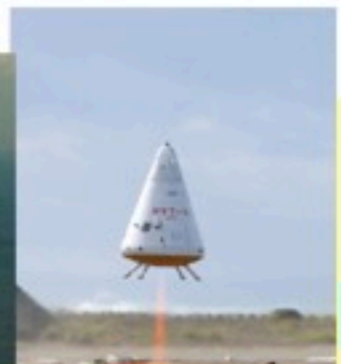
Technical Evolution Underway for Experimental Flight Tools

Stratospheric Balloon

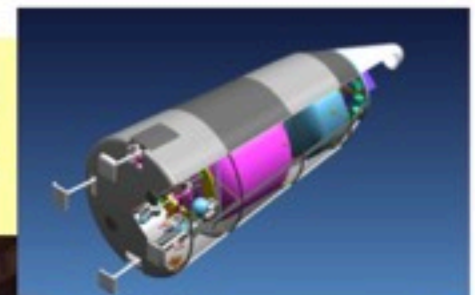
Ultra-Thin Film Balloon

Super Pressure Balloon

Sounding Rockets



Innovation for Propulsion



Reusable Sounding Rocket

As for the ISAS's spirit

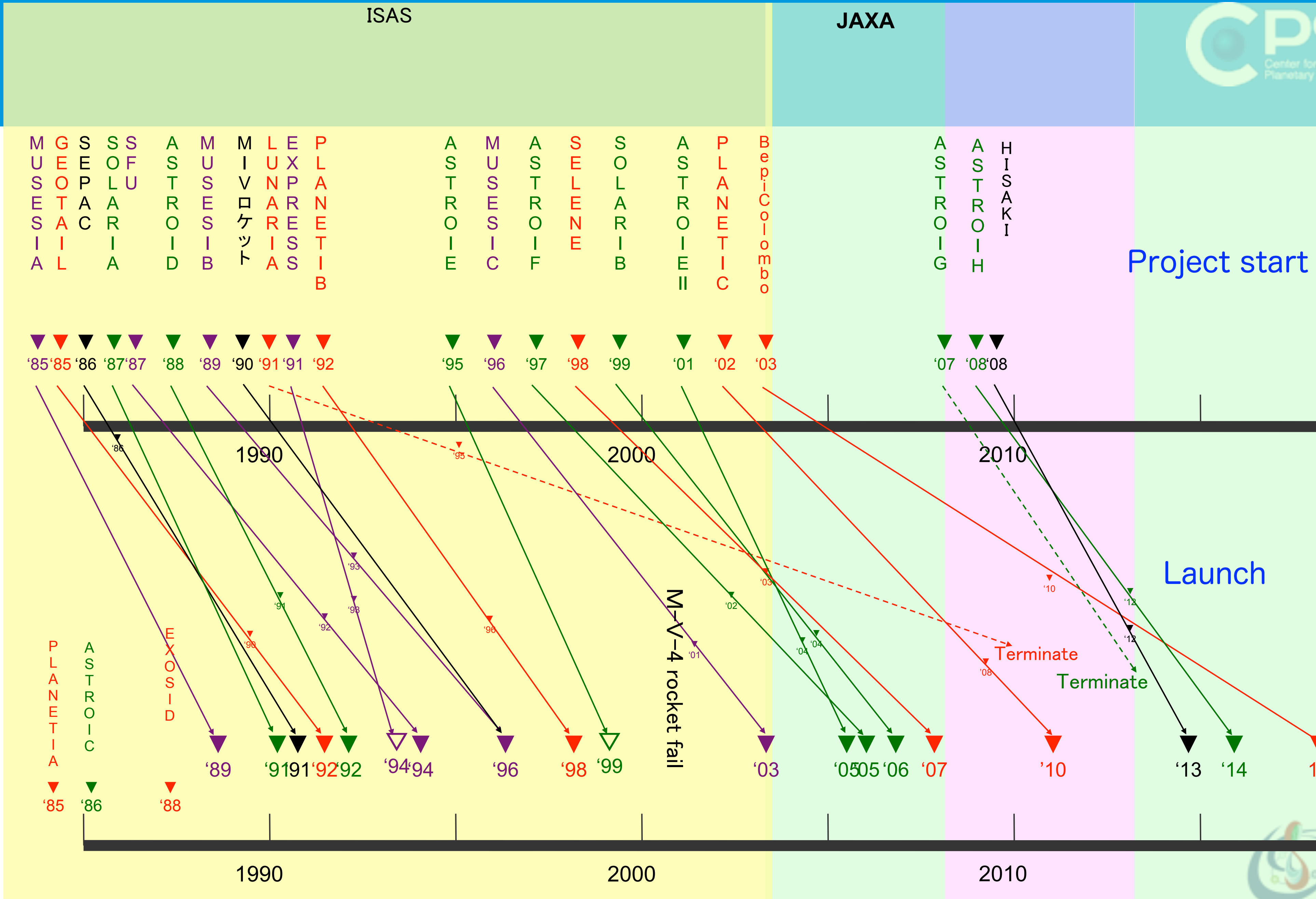
- I will talk a little bit at the end of this talk.

Why ISAS has made a **nice** job

- The mission size was limited by the lunching vehicle (M-IIIS-2/M-V rockets)
  - a typical size of the mission is rather small comparing to ESA's or NASA's one
- A typical timescale from a mission idea to the launch is very small.
  - This was really big merit because the progress of sensor technology especially in semiconductor device is very very rapid in late1980s - 2005
  - Thus ISAS mission could employ very up-to-date sensors (state-of-the-arts detector) at that time.
- A smaller mission can rival the bigger mission with conventional detector.
- BUT.....
  - The progress of the sensor device is getting saturated!
  - then only the size of the mission is the key factor for the competition
- Also inter-university system brings a large amount of human resource.

“Small but quick is beautiful!”

- Prof. Freeman Dyson gave this comment to Prof. Minoru Oda for the successive results of ISAS


ISAS
JAXA
MUSES-A
GEOTAIL
SEPAC
SOLAR-A
SFU
ASTRO-D
MUSES-B
M-V ロケット
LUNAR-A
EXPRESS
PLANET-B
ASTRO-E
MUSES-C
ASTRO-F
SELENE
SOLAR-B
ASTRO-E II
PLANET-C
BepiColombo
ASTRO-G
ASTRO-H
HISAKI
'85 '85 '86 '87 '87 '88 '89 '90 '91 '91 '92 '95 '96 '97 '98 '99 '01 '02 '03 '07 '08 '08
Project start
1990
2000
2010
Launch
Terminate
Terminate
M-V-4 rocket fail
PLANET-A
ASTRO-C
EXOS-D
'85 '86 '88
'89 '91 '91 '92 '92 '94 '94 '96 '98 '99 '03 '05 '05 '06 '07 '10 '13 '14 18
1990
2000
2010

a sample case of power of human resource, HITOMI's budget

- HITOMI's budget
  - ~300M＄ of JAXA budget
    - including spacecraft, science payload, launch, operation
  - ~100M＄ from NASA, ESA, and a couple of national space agencies
  - ~20M＄ competitive research fund by X-ray community in Japan
  - ~10M＄ supplemental research fund for the science operation by X-ray community
  - human resource from X-ray community in Japan for development
    - roughly 180 (persons) X 10 (year) = 1800 (person・year)
    - in-house development of the science payload, and which work corresponds about 360M＄, in case we ordered the work to the company.
  - In total, grand budget for HITOMI mission is roughly 800M＄
    - We do not count the human cost in the university staffs in the mission cost.
- This is real power of inter-university system in Japan
  - In this sense, "bottom-up competitive system" is very effective

From science into space mission

- We had plenty of “zone-of-avoidance” in any scientific field, at the very beginning phase of space observations.
  - New types of observations promised us tasty fruits.
- Scientific observations have accumulated more and more in most of fields of science, we have to carefully consider the best approach to get a breakthrough or a new scientific result.
- No good fruits found at the lower trees, said Dr. Fabio Favata in his seminar at ISAS last month, which is generally “YES”.
- To find out the best approach (suitable mission), systems engineering is one of very important scheme to fix the mission design.

From science into space mission Systems engineering approach

- Mission design and systems engineering
- Project Planning
- Objectives – Requirements - Solutions
- Why do we need requirements?
- Properties of Requirements
- Trade-off
- Requirements & Design Drivers
- Mission Definition
- Mission Phases

From science into space mission
Systems engineering approach

- When you fix a mission design
  - Design of the spacecraft shall be feasible
  - to confirm the readiness of the mission
    - one needs conceptual design work including
      - mission operation
      - verification plan of the requirements of the mission
- Systems engineering must be very important in these early phases of mission designing
-

Systems Engineering

"The objective of systems engineering is to see to it that the system is designed, built, and operated so that it accomplishes its purpose in the most cost-effective way possible, considering performance, cost, schedule and risk."

NASA Systems Engineering Handbook SP6105

Systems engineering is a methodical, disciplined approach for the design, realization, technical management, operations, and retirement of a system. A "system" is a collection of different elements that together produce results not obtainable by the elements alone. Elements can include people, hardware, software, facilities, policies and documents. All things required to produce system level results. Systems engineering is the art and science of developing an operable system capable of meeting requirements within imposed constraints, not dominated by the perspective of a single discipline, and that the responsibility of engineers, scientists, and managers working together.

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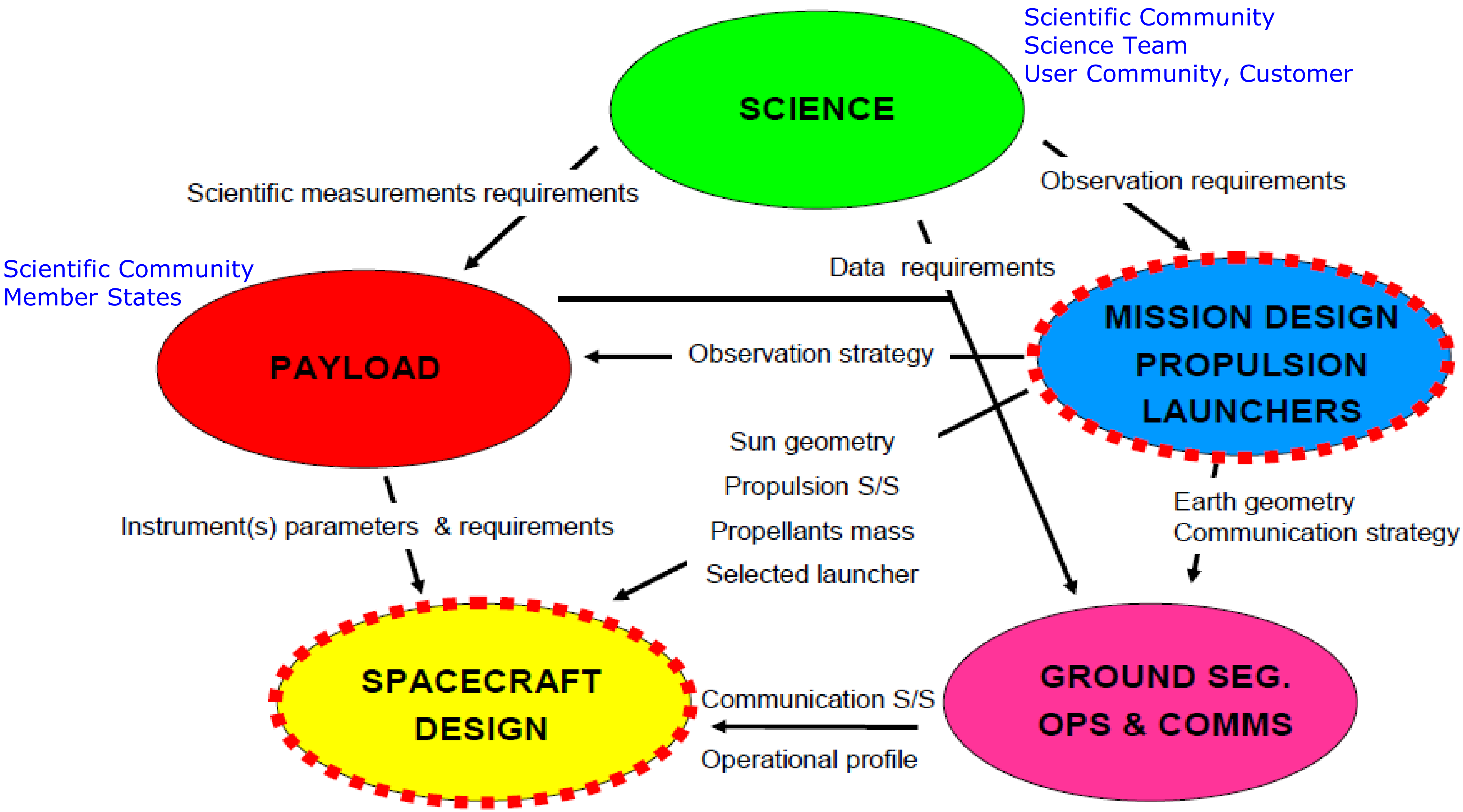
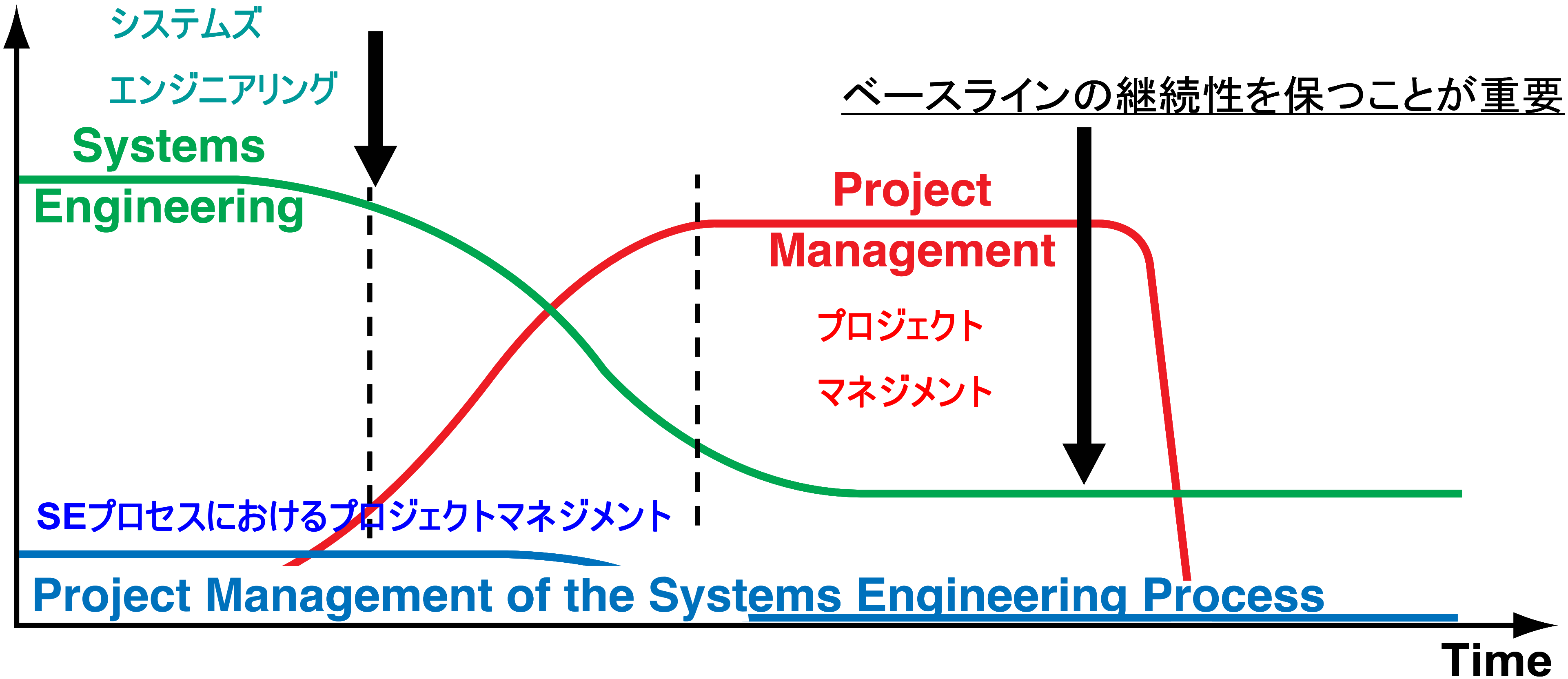
  - Not dominated by the perspective of a single discipline.
  - The responsibility of engineers, scientists, and managers working together

Mission design



Systems engineering and project management in the life cycle of the project

初期段階からアウトプットを意識した「システム思考」と「リスクの識別」を実践



概念検討／概念設計｜計画決定｜基本設計｜詳細設計｜製作・試験｜打上げ・運用｜廃棄　｜A

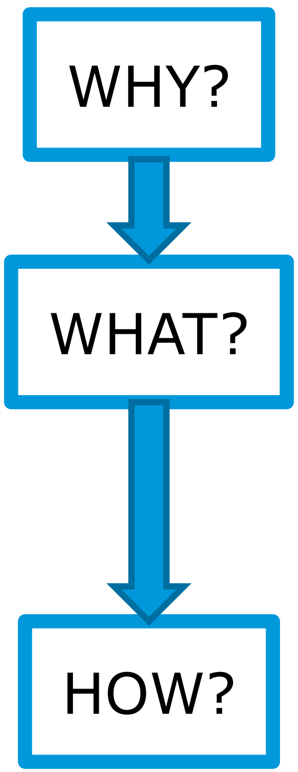
プリフェーズA／　フェーズA　｜フェーズB｜フェーズC｜フェーズ D ｜フェーズ E　｜フェーズF

Project Planning

- 1. Purpose and objectives of the project
  - a. Key questions to be answered
  - b. Key technical performance parameters
  - c. Technical and programmatic constraints
- 2. Technology availability and development needs
  - a. Potential cost and schedule drivers
- 3. Potential cost class (~350M$, ~500M$, ~1B$, and more)
- 4. Ability and need to re-use existing equipment/products
- 5. Availability and need for human resources, skills, technical facilities
- 6. Risk assessment
  - a. Risk management and mitigation actions
- Development approach:
  - a. Result from above considerations

Objectives – Requirements - Solutions

- Objective is the high level motivation
  - Which scientific question/application purpose shall the project address and what answer is sought
- Requirement is the translation of this objective into verifiable statements of what is needed to achieve the objective
  - have several levels of detail
  - are traceable, all the way back to the top level
  - Include quantities
- Solution is the response to the all requirements
  - There can be several solutions meeting requirements
  - Non-compliance needs to be negotiated



Mission Objectives

- Science objectives: Objectives should ...
  - a. respond to important scientific questions or topics
  - b. state why a space mission is needed clearly (no other approach?)
  - c. be appealing
  - to General public
  - to Science community

- Application objective: Objectives should ...
  - a. serve an important need of the general public – benefits!
  - b. state the unique contribution from space (why you need observations in space?)

Why do we need requirements? Very important process!!

- 1. To provide motivation and focus to the project
  - a. Communicating to others what shall be achieved
- 2. Requirements shall
  - answer the WHY?
  - by specifying the WHAT?
  - and not addressing the How?
- 3. To identify the trade-off for the best solution
- 4. Place priority on possible solutions/options
- 5. Priority helps resolving ...
  - a. Conflicting requirements
  - b. De-scope paths
- 6. Provide specifications to engineering and lower level subsystems

Properties of Requirements

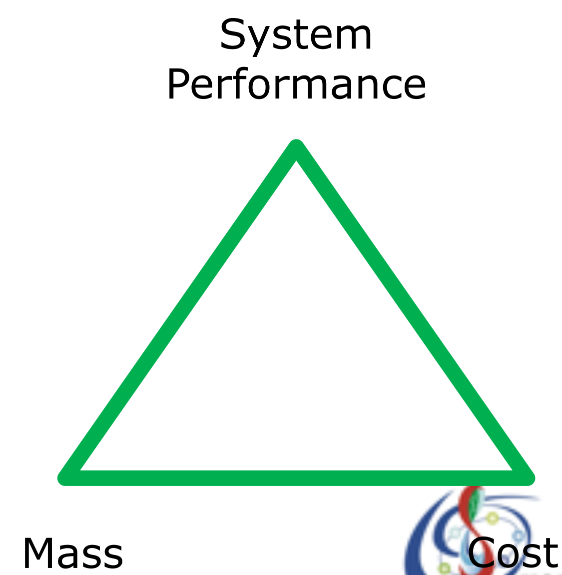
- 1. Mission statement: captures the objectives and measurements required in a single sentence
- 2. Requirements are formal statements expressing what is needed to fulfill the mission objectives
- 3. Requirements shall be product related, not process related
- 4. Clear requirements are key to good design
- 5. Requirements are hierarchical: lower level system requirements shall come from higher level mission requirements

Requirements – Examples

- 1. Good Examples:
  - a. The mission shall provide a measurement of the xxx constant with an accuracy better than 10^{-4}
  - b. The mission shall allow scanning of the sky with an angular rate of 20 arcmin/s around an axis of rotation which is $90^\circ \pm 1.5^\circ$ away from the Sun direction
  - c. The mission shall have a nominal in-orbit duration of 5 years
- 2. Bad Examples:
  - a. The system design shall maximize the spectral resolution
  - b. The mass shall be below 1000 kg

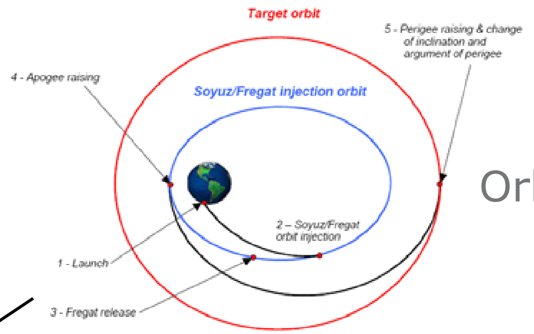
Trade-off

- 1. Trade-off allows exploring alternative solutions to a baseline
- 2. The parameter space needs to be prepared, and an evaluation criterion shall be established using requirements
- 3. Most common criteria: mass, cost; several system properties can be translated into them
  - a. Power consumption ? generation of more power ? solar array size ? mass
  - b. Higher telemetry volume ? larger HGA (High Gain Antenna), more power for communications ? mass
  - c. High performance ? complex solutions ? more effort for verification ? longer integration time ? cost



Elements of Space missions

Launcher



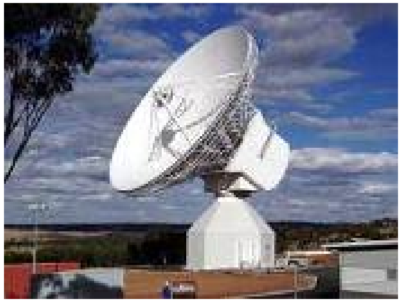
Orbit - Constellation

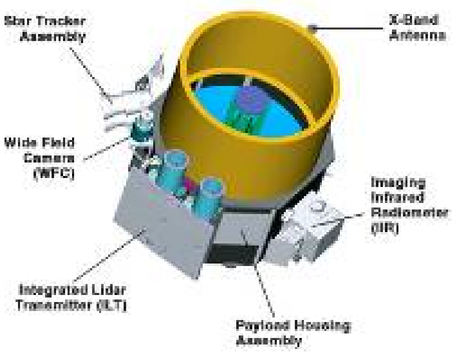
(Science) Data Center

Space Mission

Spacecraft

Mission Operation





Payload

Requirements & Design Drivers

- 1. Identification of design drivers is result of requirement analysis
  - a. First iteration during definition of mission concept
- 2. Design drivers constrain flexibility of system design ? there should be as few as possible!
- 3. Classification of requirements: unavoidable – negotiable
- 4. Typical (expected) unavoidable design drivers:
  - a. Mission profile
  - b. Communications
  - c. Power generation
- 5. Negotiable (examples):
  - a. Planning of telemetry downlink
  - b. Operations constraints

Mission Definition

- 1.“The art and science of developing an operable system capable of meeting mission requirements within imposed constraints including mass, cost and schedule.”
- 2. Satisfy in a (near-)optimal manner all the requirements
- 3. Requires trade-offs involving diverse systems and disciplines
  - Propulsion, power, communications, orbital dynamics, thermal, structure, mechanisms, navigation, control, aero-thermo-dynamics,…
- 4. You need to identify what the important parameters are and how they are related!
- 5. Define and compare a small number of different possible scenarios
- 6. Choose most promising option and perform more detailed design, including space & ground segments, operations, cost and risk

Thoughts on the explorer (a sample case for a lunar mission)

- Achievement of science objectives generally involves coupling one or more sensing elements to physical parameters of the environment, and measuring the effect.
  - a. Might be a quasi-continuous time series of one or more parameters, perhaps down-sampled or compressed, either at one location or along the path of the vehicle
  - b. Might be a field (gravity, magnetic) that varies in time as well as space.
  - c. Might be a remote measurement or in situ.
  - d. Might be a passive measurement (seismic monitoring) or an active one (active seismic sounding, Ground-Penetrating Radar)
  - e. Measurement performance may depend strongly on configuration, deployment and minimization of unwanted effects.

Some techniques with heritage

- 1. Radio science, in various forms – Doppler tracking, VLBI, signal strength vs. time/location.
- 2. Laser ranging of passing reflectors on the surface, or the surface itself
- 3. Gravimetry, gradiometry, seismology
- 4. Space physics' experiments – magnetic field, electric field, EM (Electric-Magnetic) waves, particles, radiation.
- 5. Atmospheric physical properties & profiles (measured during descent, remotely from the surface …)
- 6. Radar sounding (from orbit, of the surface and/or sub-surface, or ground penetrating probe at the surface, or upward-looking of the ionosphere,…)
- 7. Heat flow

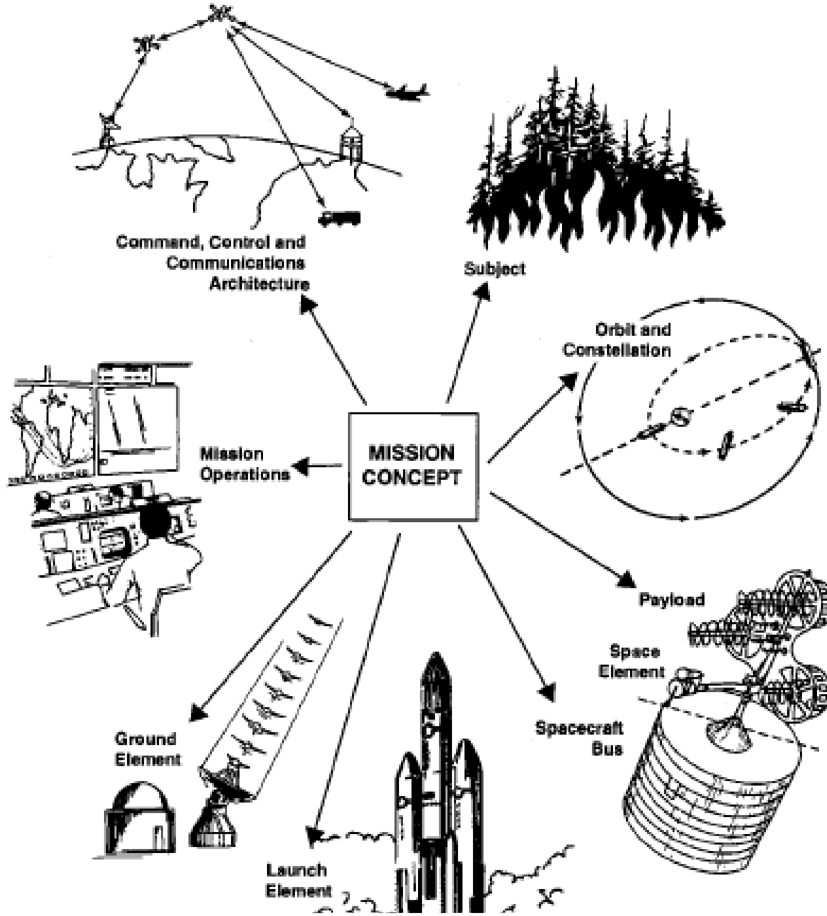
Mission Phases – Phases 0 & A

- 1. Phase 0 – Analysis/needs identification
  - a. Understanding of functional and technical requirements (correct requirements formulation and priorities), mission statement
  - b. Preliminary technical requirement specifications
  - c. Conduct trade-off studies to select preferred system concept
  - d. Definition of mission concept (design, profile, configuration)
  - e. Preliminary assessment of programmatic aspects
  - f. Preliminary risk assessment
- 2. Phase A – Feasibility
  - a. Elaborate possible system and operations concepts and propose technical solutions
  - b. Initiate pre-development of critical technologies
  - c. Conduct trade-off studies to select preferred system concept
  - d. Assess the technical and programmatic feasibility of the possible concepts by identifying constraints relating to implementation, costs, schedules, organization, operations, maintenance, production and disposal
  - e. Determine uncertainty levels update risk assessment

System designs

<u>Study Phase 0</u>:

- Analysis of Mission Objectives
- Analysis of Mission Constraints
- Definition of Science & Measurement Requirements
- Definition of Mission Architecture (s)
- Definition of payload / performance
- Analysis of Environment
- **Iteration / Trade phase**
- Cost, Risk, Schedule, Technology Development



<u>Goal:</u>

- **feasible mission profile**
- **satisfying requirements <u>and</u> constraints**

Mission Phases – Phase B

- Phase B – Preliminary Definition
  - a. Confirm technical solution for the system and operations concept and establish preliminary design
  - b. Preliminary organizational breakdown structure
  - c. Establish baseline master schedule and cost
  - d. Identify and define external interfaces
  - e. Finalize product tree and establish subsystem requirements and preliminary subsystem design
  - f. Initiate long lead item procurement
  - g. Update risk assessment

Mission Phases – Phase C

- Phase C – Detailed Definition
  - a. Detailed system and subsystem design
  - b. Performance simulations
  - c. Mathematical models (thermal, power, structural; observation, comm., etc)
  - d. Initiate production and qualification of engineering and qualification models
  - e. Detailed definition of internal and external interfaces
  - f. Update of risk assessment

Mission Phases – Phase D

- Phase D – Production & Qualification
  - a. Completion of qualification testing & verifications (thermal-vac, vibration, EMC, etc)
  - b. Manufacturing, integration and test of flight hardware
  - c. Verification of operations with ground segment
- Phase E – Utilization
  - a. Launch preparations and launch
  - b. in-flight verification (commissioning)
  - c. Mission operations planning
  - d. Science operations planning
  - e. Data analysis/exploitation
- Phase F – Disposal
  - a. Mission disposal (space debris mitigation)
  - b. Data archiving and final documentation

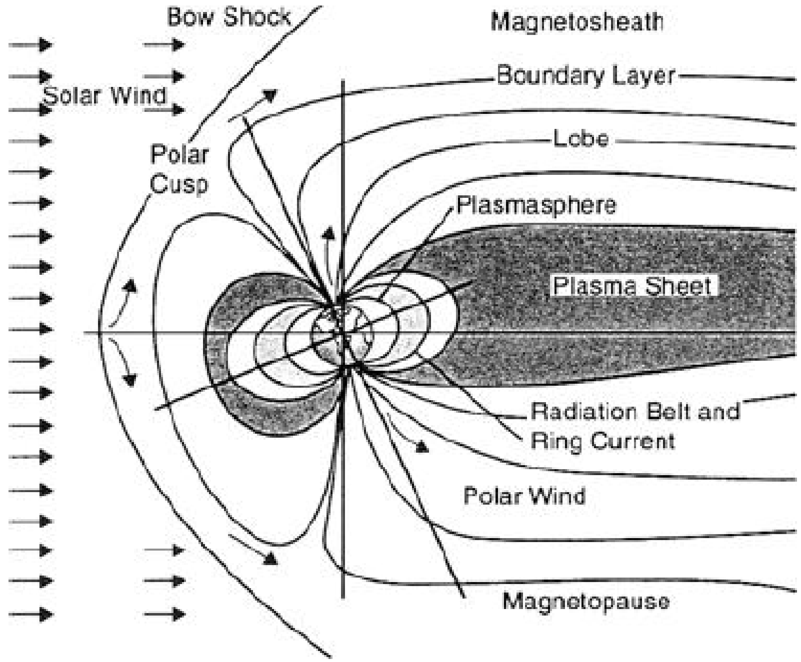
Margins – Contingencies

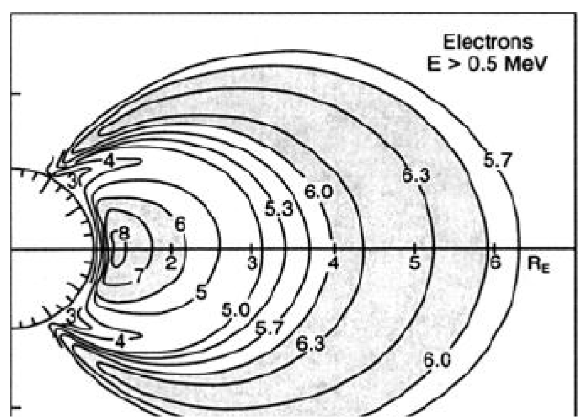
- 1. Equipment level margins according to maturity
  - a. 5% for off-the-shelf items (no changes)
  - b. 10% for off-the-shelf items with minor modifications
  - c. 20% for new designs, new developments, major modifications
- 2. System margin (at least 20%)
  - a. On top of and in addition to equipment margins; applied after summing best estimates + margin
  - b. Two options for the propellant calculation +10% margin + 2% residuals
    - Margin on total dry mass and margin on launcher: typically used during early study phases +10% margin
    - Margin on maximum separated mass: typically used later, when mission analysis and launcher analysis become available
- 3. Always keep lots of margins
- 4.Margin philosophy for Science Assessment Studies”

Space environment

- Solar cycle (11-years) – flares
  Solar Protons: 1 MeV to > 1 GeV
- Radiation belts of Earth, Jupiter,…
  electrons, protons
- Cosmic Rays
- Spacecraft charging
- Magnetic Field
- Solar Radiation Pressure
- Thermal environment
- Vacuum: Atomic Oxygene

- **Radiation effects electronics, materials and increase noise in detectors**





From mission definition into system definition

- Generally speaking, numbers of mission definition could apply the mission objective.
- System definition has the same situation as above.
  - We have various types of choice of system definition to satisfy the mission (science) objectives, however the most feasible(*) one is unique. Importance of "Best compromise"
    - *feasibility is usually on the balance of budget, necessary resource, and risks.
- [Exercise]
- Suppose that you were requested to measure the mass of Mars.
  - How do you approach without Wikipedia or current knowledge?
  - You could find so many approach to realize it.
    - then you have to choose the best way to measure it.

From mission definition into system definition

- We have to select the “best compromised” definition, after the cascades of "trade-off studies" starting from the purpose

- "Trade-off studies" shall be recorded in detail even for the very simple matter, because we frequently need to go back to modify (reconsider) the definition of previous phase, in case we find some difficulties to realize the spacecraft system.

  - Priority and traceability of the requirements are highly important.

- Concurrent Design Process is mostly helpful in the early phase, to check the feasibility of the mission design within the given resource budget.

systems engineering approach

- Yes, useful!
- Universal for any types of missions?
- Should we be slave under the systems engineering?
-

Is the space agency with systems engineering approach POWERFUL??

- [Exercise]
- Suppose the following case

- We have no bicycle in the world
  - no one knows the vehicle like a bicycle.

- Is the space agency like JAXA able to invent it?

In the systems engineering approach

- Can we fix the requirements for a bicycle without knowing it?
- riding on a bicycle is really pleasant and comfortable, however ...
  - Shall "comfortableness" be attributed to any requirements?
  - How can you image it comfortable luck of experience of riding it?

- Is a bicycle based on the extrapolation of any "HERITAGE"?
  - it must be a crazy at all, says reviewer. How can you argue?

Under the usual reviewing process in the space agency today

- A bicycle must be very risky to develop
  - Who needs it? (without knowing bicycle)
  - two wheels vehicle must be VERY unstable.
  - Many people must be injured by the bicycle.
- "Comfortable" is out of scope of space agencies.
- We WILL NOT nominate the idea into the mission candidate.!!!
  - This must be a general story in these days.
  -

ISAS realized HAYABUSA mission.

- The sample return was defined as extra, extra, extra success level.
- In the current reviewing process, ...
  - resource budget for the extra success shall not be allocated.
  - then well, can we re-define the sample return in the minimum success?
    - It must be too risky, because the mission might be evaluated as a fault mission in case we fail the sample return.
  - HAYABUSA employed many new technology without any heritage.
    - It must be rejected in the current reviewing process.
    - Also the TRL (Technical Readiness Level) of most subsystem of HAYABUSA were very low when HAYABUSA started developing.
- How can we create such a nice mission like HAYABUSA now?
- We have to keep ISAS's challenging spirit, overriding the project management process in some cases.
- This is ISAS's spirit. We have to challenge at any time.