システムズ
エンジニアリング

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Systems Engineering

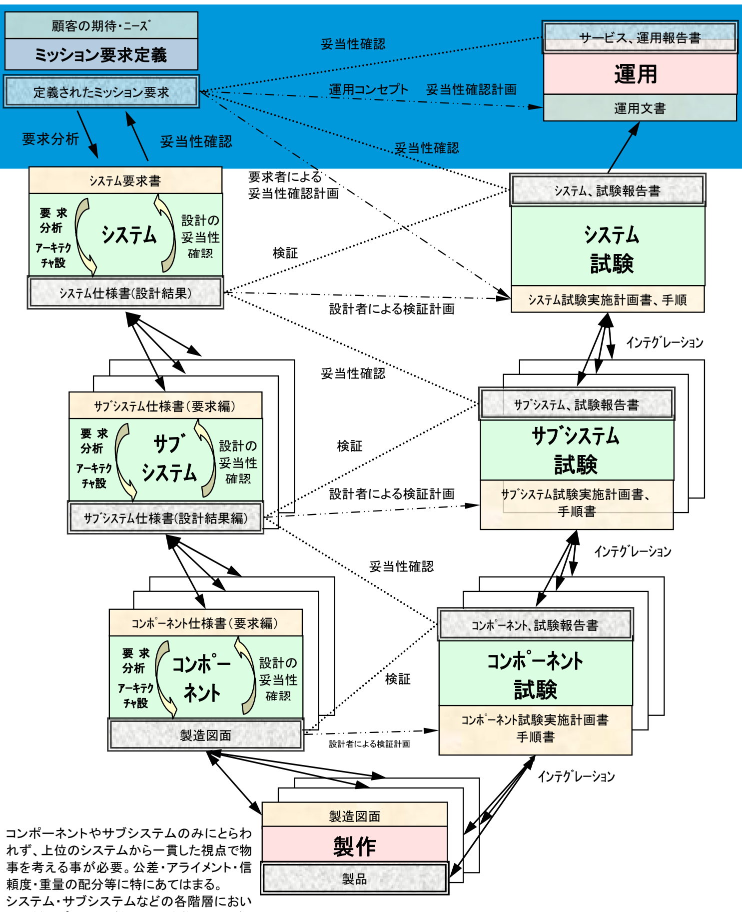
"The objective of systems engineering is to see to it that the system is designed, built, and operated so that it accomplishes its purpose in the most cost-effective way possible, considering performance, cost, schedule and risk."

NASA Systems Engineering Handbook SP6105

Systems Engineering

- 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.
  - The responsibility of engineers, scientists, and managers working together

システム開発のVチャート

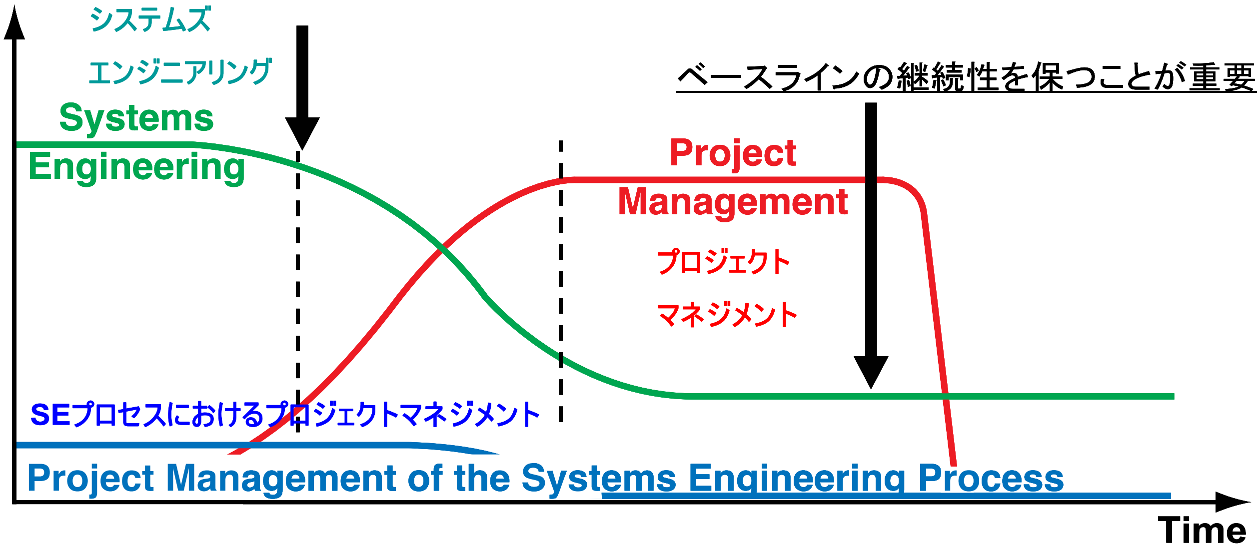


コンポーネントやサブシステムのみにとらわれず、上位のシステムから一貫した視点で物事を考える事が必要。公差・アライメント・信頼度・重量の配分等に特にあてはまる。
システム・サブシステムなどの各階層において同様なプロセスが繰り返し実施されるが、必要に応じて上位の階層にも立ち戻る。

CPS-ミッション立案スクール Jan.09, 2016

プロジェクトにおけるライフサイクル・作業量

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

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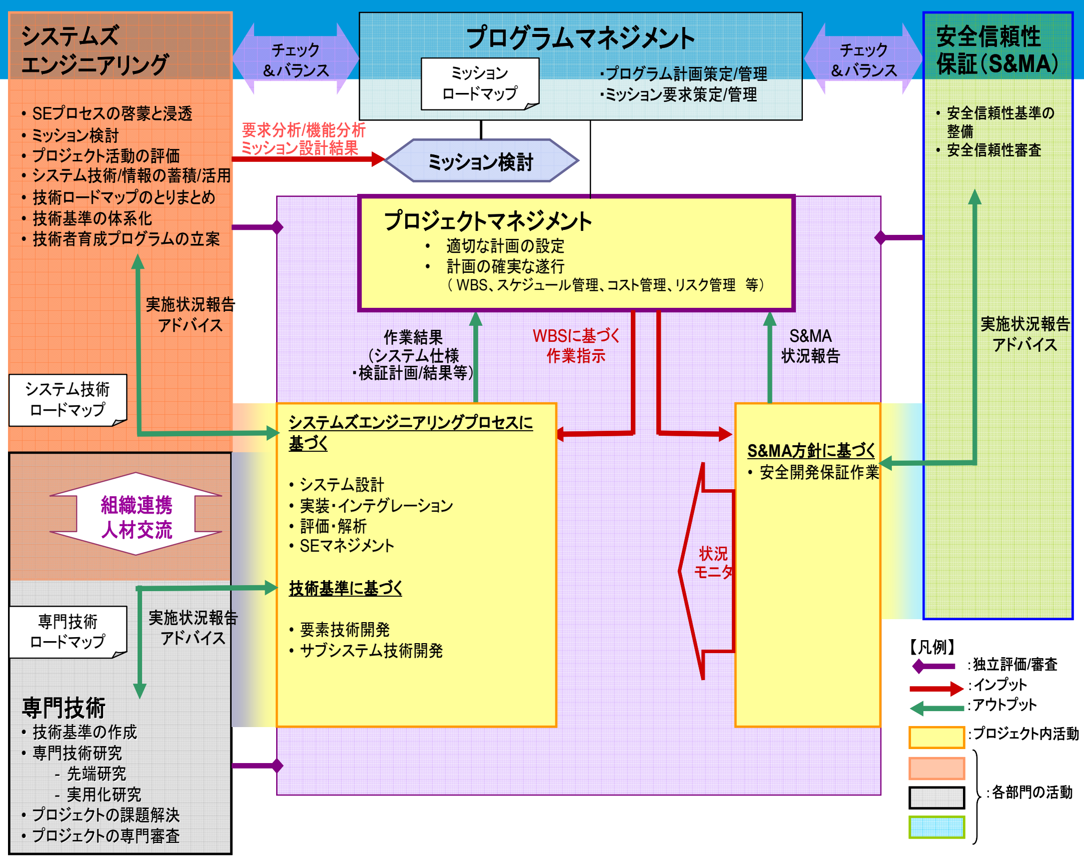
JAXAのプログラム/プロジェクトマネジメント



SEプロセス

システム設計（分割）プロセス群
- D1 ミッション要求定義
- D2 システム要求分析
- D3 機能設計
- D4 物理設計

評価プロセス群
- E1 トレードオフ
- E2 検証・妥当性確認

製作・インテグレーション（統合）プロセス群
- I3 運用・保守・廃棄
- I2 インテグレーション
- I1 製作

SEマネジメント群
- M1 SE計画管理
- M2 技術審査
- M3 リスクマネジメント
- M4 インタフェース管理
- M5 コンフィギュレーション管理
- M6 技術データ管理

CPS-ミッション立案スクール
Jan.09, 2016

Definition(ミッション定義)

- 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
  - a. Propulsion, power, communications, orbital dynamics, thermal, structure, mechanisms, navigation, control, soil mechanics, aerothermodynamics,…
- 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 to the moon

- 1. 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 waves, particles, radiation.
- 5. Atmospheric physical properties & profiles (measured during descent, remotely from the surface, from an aerial platform,…)
- 6. Radar sounding (from orbit, of the surface and/or sub-surface, or GPR at the surface, or upward-looking of the ionosphere,…)
- 7. Heat flow

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 (~200M$, ~350M$, ~500M$, ~1B$)
- 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
  - b. state why a space mission is needed
  - 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 do we need requirements?

- 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

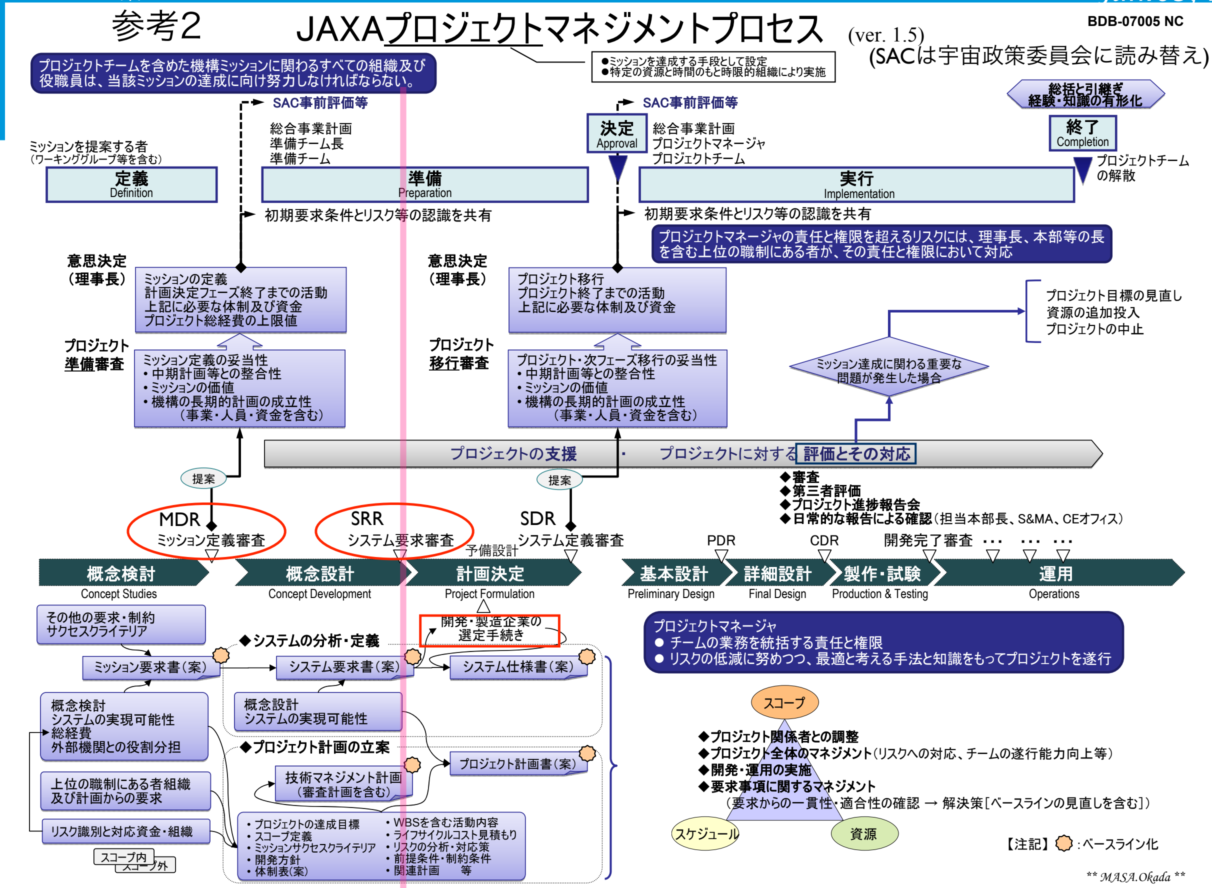
- 1. Good Examples:
  - a. The mission shall provide a measurement of the x constant with an accuracy better than 10^{-13}
  - b. The mission shall allow scanning of the sky with an angular rate of 60 arcsec/s around an axis of rotation which is $50^{\circ} \pm 0.1^{\circ}$ away from the Sun direction
  - c. The mission shall have a nominal in-orbit duration of 4 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, more power for TM&C ? mass
  - c. High performance ? complex solutions ? more effort for verification ? longer integration time ? cost

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 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

Mission Phases – Phase B

- 1. 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

- 1. 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

- 1. 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
- 2. 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
- 3. 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” (See appendix)