Basic Steps in Designing a Space Mission

- A Short Tutorial

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Space Mission Analysis and Design

This Tutorial is based on material to be found in the book "Space Mission Analysis and Design: 3rd Edition" by James R. Wertz and Wiley Larson (Eds.), published by Microcosm Press/Kluwer Academic Publishers (1999).

Outline

- Introduction to the Space Mission Analysis and Design (SMAD) Approach
- Mission Statement
- Definition of Mission Objectives
- Characterising a Mission
- Mission Evaluation
- Defining Mission Requirements
- Summary

SMAD

The Space Mission Analysis and Design (SMAD) Process consists of the following steps:

- Define Objectives
  - Define broad objectives and constraints
  - Estimate quantitative mission needs and requirements
- Characterize the Mission
  - Define alternative mission concepts
  - Define alternative mission architectures
  - Identify system drivers for each
  - Characterize mission concepts and architectures

SMAD (2)

- Evaluate the Mission
  - Identify critical requirements
  - Evaluate mission utility
  - Define baseline mission concept
- Define Requirements
  - Define system requirements
  - Allocate requirements to system elements

THIS IS AN ITERATIVE PROCESS !

Mission Statement

A useful starting point for any space mission is a broad statement of the goals and rationale for carrying out the mission. An example of such a Mission Statement is

FireSat (a hypothetical space mission)

Because forest fires have an increasing impact on recreation and commerce and ever higher public visibility, Europe needs a more effective system to identify and monitor them. In addition, it would be desirable (but not required) to monitor forest fires for other nations; collect statistical data on fire outbreaks, spread, speed, and duration; and provide other forest management data.

Ultimately, the Forestry Commision's fire-monitoring office and wardens in the field will use the data. Data flow and formats must meet the needs of both groups without specialised training and must allow them to respond promptly to changing conditions.

Mission Objectives

Using the FireSat example, we can define a set of mission objectives:

- **Primary Objective:**
  - To detect, identify, and monitor forest fires throughout Europe, in near real time.
- **Secondary Objectives:**
  - To demonstrate to the public that positive action is underway to contain forest fires
  - To collect statistical data on the outbreak and growth of forest fires
  - To monitor forest fires for other countries
  - To collect other forest management data.

Mission Requirements

To transform mission *objectives* into mission *requirements*, we need to consider 3 broad areas:

- **Functional Requirements:**
  - how well the system has to perform to meet its objectives.
- **Operational Requirements:**
  - how the system operates
  - how the users interact with the system to achieve the mission's broad objectives
- **Constraints:**
  - limitations imposed on system designer by cost, schedule, and implementation techniques

Functional Requirements

Typical Functional requirements are:

- **Performance:**
  - factors impacting this requirement include the primary mission objective, payload size, orbit, pointing
- **Coverage:**
  - impacting factors include orbit, number of satellites, scheduling
- **Responsiveness:**
  - impacting factors include communications architecture, processing delays, operations
- **Secondary mission (if applicable)**
  - In FireSat example, this would include additional measurement channels for forest management data (e.g. pest control)

Operational Requirements

Typical Operational requirements are:

- **Duration:**
  - factors impacting this requirement include nature of the mission (experimental or operational), level of redundancy, orbit (e.g., altitude)
- **Availability:**
  - impacting factors include level of redundancy
- **Survivability:**
  - impacting factors include orbit, hardening, electronics
- **Data Distribution:**
  - impacting factors include communications architecture
- **Data Content, Form, and Format:**
  - impacting factors include user needs, level and place of processing, payload

Constraints

Typical Constraints are:

- **Cost:**
  - factors impacting this constraint include number of spacecraft, size and complexity, orbit
- **Schedule:**
  - impacting factors include technical readiness, programme size
- **Political:**
  - impacting factors include Sponsoring organisation (customer), whether international programme
- **Interfaces:**
  - impacting factors include level of user and operator infrastructure
- **Development Constraints:**
  - impacting factors include Sponsoring organisation

Mission Concepts

Elements of the Mission Concept include:

- **Data Delivery:**
  - how mission and housekeeping data are generated or collected, distributed, and used (FireSat example: How is imagery collected? How are forest fires identified? How are the results transmitted to the fire fighting teams on the ground?
- **Communications Architecture:**
  - how the various components of the system talk to each other
- **Tasking, Scheduling, and Control:**
  - how the system decides what to do in the long term and the short term (e.g., Which sensors are active and when is data being transmitted and processed?)
- **Mission Timeline:**
  - overall schedule for planning, building, deployment, operations, replacement, and end-of-life

Mission Concepts (2)

The process for defining the Mission Concept could include the following steps:

- Data Delivery process:
  - key trade-offs include Space vs. Ground processing; Level of autonomy; Central vs. distributed processing
- Tasking, Scheduling, and Control:
  - key trade-offs include Level of autonomy; Central vs. distributed control
- Comms Architecture for Mission and Housekeeping Data:
  - key trade-offs include Data rates and bandwidth; Timeliness of Communications

Data Delivery

The principal trade-offs associated with data delivery are:

- Space vs. Ground:
  - how much of the data processing occurs on board the S/C vs. how much is done at mission operations or by the end user?
- Central vs. Distributed Processing:
  - is one computer talking to another computer, or does one large central computer on the S/C or on the ground process everything?
- Level of autonomy:
  - how much human intervention is needed to provide intelligent analysis and minimize costs?

Common System Drivers

- Size:
  - Driver limited by e.g. shroud or bay size (shuttle); available weight
  - Driver limits e.g. payload size
- On-Orbit Weight:
  - Driver limited by e.g. launch vehicle; altitude
  - Driver limits e.g. payload weight; survivability; design & manufacturing cost
- Power:
  - Driver limited by e.g. size; weight
  - Driver limits e.g. payload and bus design; on-orbit lifetime
- Data Rate:
  - Driver limited by e.g. storage; processing; antenna size
  - Driver limits e.g. information sent to end user; need for onboard processing

Common System Drivers (2)

- Communications:
  - Driver limited by e.g. availability of ground stations / relay satellites
  - Driver limits e.g. coverage; timeliness; ability to command
- Pointing:
  - Driver limited by e.g. cost; weight
  - Driver limits e.g. resolution; overall system accuracy; (increases cost)
- Number of spacecraft:
  - Driver limited by e.g. cost
  - Driver limits e.g. coverage; overlap
- Operations:
  - Driver limited by e.g. cost; communications; size of team
  - Driver is often key cost factor; can push need for autonomy

Mission Characterisation

The mission concept characterisation process consists of the following steps:

- Define the preliminary mission concept
- Define the subject characteristics
- Determine the orbit characteristics
- Determine payload size and performance
- Select mission operations approach (comms architecture; operations; ground system)
- Design S/C bus to meet payload, orbit and communications requirements
- Select launch and orbit transfer system
- Determine deployment, logistics, and end-of-life strategies
- Provide costing estimate

ITERATE !

Subject Characteristics

The mission subject can be part of the mission system (so-called “controllable” subjects), or phenomena to be sensed (so-called “passive” subjects). Typical characteristics of mission subjects could be

- Controllable Subjects (e.g., GPS navigation receivers)
  - quantity
  - location or range
  - receiver gain-to-noise temperature ratio; frequency and bandwidth
- Passive Subjects (e.g., clouds for meteorological satellite)
  - quantity
  - location or range
  - intensity of emission
  - temporal coverage needed

Subject Trade-Offs

Choosing the most appropriate mission subject is an important part of the overall mission design. For example, the trade-off process for FireSat could be as follows

- Determine fundamental mission objective(s)
  - Detect and monitor forest fires
- Determine what possible subjects could be used to meet these objectives
  - Heat, fire, smoke, atmospheric composition
- Determine broad ways the S/C can detect or interact with possible subjects
  - Heat => IR; flame, smoke => visual
  - composition => light detection and ranging (lidar)
- Determine whether multiple subjects and payloads should be used
  - Not initially
- Define and document initial subject selection (IR detection of heat)

Orbit Characteristics

Typical orbit characteristics include

- Altitude
- Inclination
- Eccentricity
- ΔV budget for orbit transfer
- ΔV budget for orbit maintenance
- Number and relative orientation of orbit planes (constellations)
- Number and spacing of S/C per orbit plane (constellations)

Payload Characteristics

Typical payload characteristics include

- Physical Parameters
  - Envelope dimensions
  - Mass properties

- Viewing and Pointing:
  - Aperture size and shape
  - Size and orientation of clear FOV needed
  - Primary pointing direction (e.g., Sun, nadir, star, etc.)

- Electrical Power
  - Bus voltage
  - Average and peak power; peak power duty cycle

Payload Characteristics (2)

- Telemetry and Commands
  - No. of commands and telemetry channels
  - Data rates or quantity of data (memory size)

- Thermal Control
  - Temperature limits (operating/non-operating)
  - Heat rejection to S/C (average/peak wattage/duty cycle)

NB. The above characteristics must be defined for each element of the payload

Mission Operations Characteristics

- Communications Architecture
  - No. and distribution of ground stations
  - Downlink and uplink path design
  - Communications link budget
  - Space-to-ground data rates
- Ground System
  - Use of existing or dedicated facilities
  - Required transmit and receive characteristics
  - Required data handling
- Operations
  - Level of automation
  - Full-time or part-time staffing; no. of personnel
  - Commanding requirements
  - Timeliness of data distribution

Spacecraft Characteristics

- General Arrangement (incl. payload FOVs, stowed and deployed)
- Functional Block Diagram
- Mass Properties
- Subsystem Characteristics
  - Electrical power
  - Attitude control
  - Navigation and orbit control
  - Telemetry and command
  - Propulsion
  - Data handling
  - Communications
  - etc
- System Parameters (Lifetime; reliability; level of autonomy)

Mission Evaluation

How well do different mission options satisfy the fundamental mission objectives?

In the case of FireSat, key mission evaluation questions would be

- Which FireSat requirement dominates the system design or is the most difficult or expensive to meet?
- How well can FireSat detect and monitor forest fires, and at what cost?
- Should the FireSat mission evaluation proceed, and if so, which alternatives should we pursue?

Critical Requirements

Critical requirements dominate the mission's overall design, and therefore most strongly affect performance and cost.

Common Critical Requirements are

- Coverage or response time
  - this affects e.g. no. of satellites deployed; communications architecture; payload FOV; scheduling; staffing
- Resolution
  - this affects e.g. instrument size; attitude control
- Sensitivity
  - this affects e.g. payload size; complexity; processing; thermal control
- On-orbit Lifetime
  - this affects e.g. redundancy; weight; power and propulsion budgets; component selection

Mission Utility Analysis

Mission Utility Analysis quantifies mission performance as a function of design, cost, risk, and schedule.

Typically, two types of quantities are involved

- Performance Parameters
  - quantify how well the system works (e.g., coverage statistics, instrument resolution as function of viewing angle)
- Measures of Effectiveness (MoE)
  - quantify directly how well the system meets the mission objectives (e.g., for FireSat, the MoE is a numerical estimate of how well the system can detect forest fires)

Mission Utility Analysis (2)

Examples of FireSat Performance Parameters are

- Instantaneous maximum area coverage rate
  - determined by analysis
- Orbit average area coverage rate
  - determined by simulation
- Mean time between observations
  - determined by analysis
- Ground position knowledge
  - determined by analysis
- System response time
  - determined by simulation

Mission Utility Analysis (3)

Examples of FireSat Measures of Effectiveness(MoEs) for various mission goals are

- Goal: Fire Detection
  - MoE: Probability of detection vs. time (estimated by simulation)
- Goal: Prompt Knowledge
  - MoE: Time delay from observation acquisition to availability at monitoring centre (estimated by analysis)
- Goal: Save Property and Reduce Costs
  - MoE: Value of property saved plus saving in fire-fighting costs (estimated by simulation + analysis)

Mission Concept Selection

The selection of a baseline concept for the mission involves top-level trade-offs that may not always be quantitative (e.g., political considerations are often important). The quantitative information assembled during the mission evaluation helps to make the selection an informed one.

Technical issues of importance to concept selection are

- Does the proposed system meet the overall mission objectives?
- Is it technically feasible?
- Is the level of risk acceptable?
- Are the schedule and budget within the established constraints?
- Do preliminary results show this option to be better than non-space solutions?

Mission Concept Selection (2)

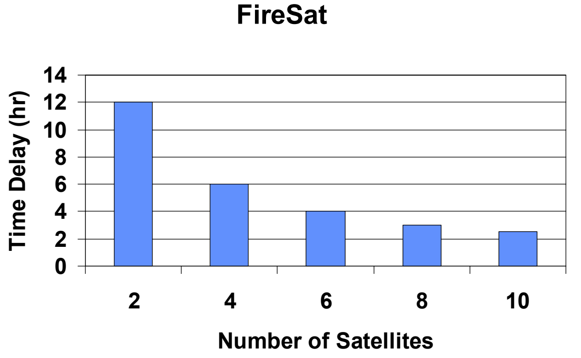
Non-Technical issues of (often even greater) importance to concept selection are

- **Does the proposed system meet the political objectives?**
- **Are the organisational responsibilities acceptable to all the organisations involved in the decision?**
- **Does the mission support the infrastructure in place or contemplated?**

Mission Concept Selection (3)

Example: FireSat constellation trade-off

Goal: Delay time no more than 5 hours => 6 satellites needed



BUT: If initial goal was arbitrary (i.e. delay time should be *approximately* 5 hours, then 4 satellites are probably acceptable, saving cost, etc.

Steps to a Requirements Baseline

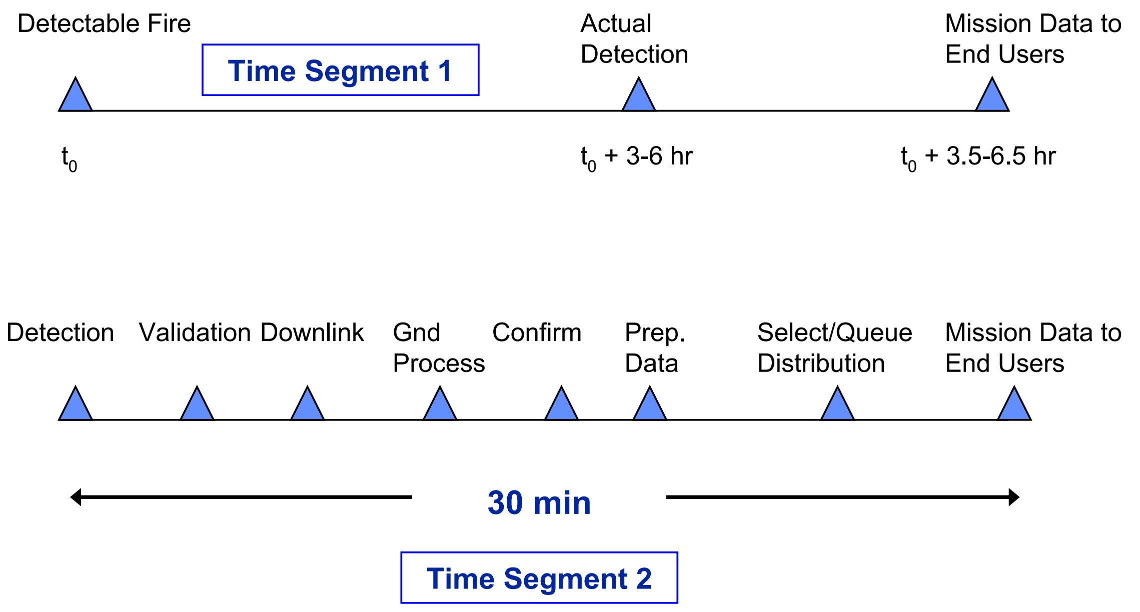
- Identify the customer and the user of the product or services (may not be the same)
- Identify and prioritize customer and/or user objectives and needs for the mission to be accomplished
- Define internal and external constraints
- Translate customer/user needs into functional attributes and system characteristics
- Establish functional requirements for system and provide for decomposition to system elements
- Translate functional attributes into technical characteristics which will become the requirements for the physical system
- Establish quantifiable requirements from all the above steps
- ITERATE AS NECESSARY AND DOCUMENT DECISIONS!

System Requirements

FireSat examples:

- Performance:
  - 4 temperature levels; 30 m resolution; 500 m location accuracy
- Coverage:
  - Daily coverage of n million square kilometers within continental Europe
- Responsiveness:
  - Send registered mission data within 30 min to up to 50 users
- Availability:
  - 98%, 3-day maximum outage
- Data Distribution:
  - Up to 500 fire-monitoring offices + 2000 rangers worldwide (max. of 100 simultaneous users)

Requirements Budgeting



Requirements Budgeting (2)

Time Segment 1 Requirements

Time to Actual Detection
- Coverage (No. of S/C, Orbit, Elev. Angle)
- Detection Time Given Coverage (Payload Scan Options & Sensitivity)

Time Segment 2 Requirements

Time from Detection to Data Delivery

	Initial Allocation
Initial Validation	1 min
Downlink	3 min
⋮	
Data Preparation	2 min
⋮	
Margin	5 min
	30 min