Spacecraft System Engineering

Space System Design, MAE 342, Princeton University
Robert Stengel

- ***NASA Systems Engineering Handbook, NASA-SP-610S***
- ***Chapter 20, Fortescue et al***
  - **Program Phases**
  - **Techniques**
  - **Concurrent Engineering**
  - **Case Study: CryoSat**

NASA-SP-610S Definition of System Hierarchy

- **System**
  - **Segment**
    - **Element**
      - **Subsystem**
        - **Assembly**
          - **Subassembly**
            - **Part**

NASA-SP-610S, 1995

Program Phases:
Project Life Cycle for Major Systems

- **Pre-Phase A (advanced studies)**
- **Phase A (feasibility)**
- **Phase B (detailed definition)**
- **Phase C (design guidelines)**
- **Phase D (development guidelines)**
- **Phase E (mission operations and data analysis)**

NASA-SP-610S, 1995

Pre-Phase A (advanced studies)

"find a suitable project"

Pre-Phase A—Advanced Studies

Purpose: To produce a broad spectrum of ideas and alternatives for missions from which new programs/ projects can be selected.
Major Activities *and their Products:* Identify *missions consistent with charter* Identify and involve users
Perform *preliminary evaluations of possible missions* Prepare *program/project proposals,* which include:
- Mission justification and objectives
- Possible operations concepts
- Possible system architectures
- Cost, schedule, and risk estimates.

Develop *master plans* for existing program areas
Information Baselined:
(nothing)
Control Gates:
Mission Concept Review
Informal proposal reviews

NASA-SP-610S, 1995

Phase A (feasibility)

“find a worthwhile project”

Phase A—Preliminary Analysis

<u>Purpose</u>: To determine the feasibility and desirability of a suggested new major system and its compatibility with NASA's strategic plans.

<u>Major Activities and their Products</u>:

Prepare *Mission Needs Statement*
Develop top-level *requirements*
Develop corresponding *evaluation criteria/metrics*
Identify alternative *operations and logistics concepts*
Identify *project constraints and system boundaries*
Consider *alternative design concepts*, including: *feasibility and risk studies, cost and schedule estimates, and advanced technology requirements*
Demonstrate that *credible, feasible design(s)* exist
Acquire *systems engineering tools and models*
Initiate *environmental impact studies*
Prepare *Project Definition Plan* for Phase B

<u>Information Baselined</u>:

(nothing)

<u>Control Gates</u>:

Mission Definition Review
Preliminary Non-Advocate Review
Preliminary Program/Project Approval Review

NASA-SP-610S, 1995

Phase A (feasibility)

“find a worthwhile project”

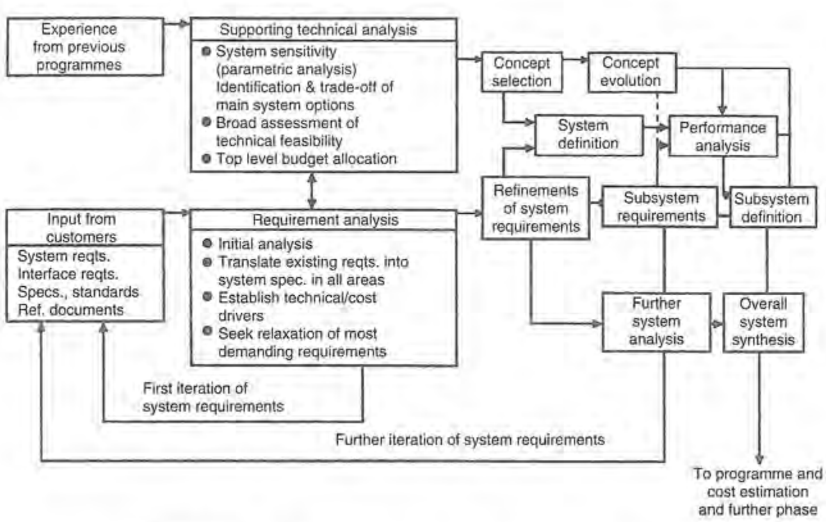


Figure 20.1 Phase A system engineering flow diagram

Phase B (detailed definition)

"define the project and establish a preliminary design"

Phase B – Definition

Purpose: To define the project in enough detail to establish an initial baseline capable of meeting mission needs.
Major Activities and their Products:
Prepare a *Systems Engineering Management Plan*
Prepare a *Risk Management Plan*
Initiate *configuration management*
Prepare *engineering specialty program plans*
Develop *system-level cost-effectiveness model*
Restate mission needs as *functional* requirements
Identify *science payloads*
Establish the initial system requirements and *verification requirements* matrix
Perform and archive *trade studies*
Select a baseline *design solution* and a *concept of operations*
Define *internal and external interface requirements*
(Repeat the process of successive refinement to get "design-to" *specifications and drawings, verifications plans,* and *interface documents* to lower levels as appropriate)
Define the *work breakdown structure*
Define *verification approach end policies*
Identify *integrated logistics support requirements*
Establish *technical resource estimates* and firm *life-cy-cle cost estimates*
Develop *statement(s) of work*
Initiate *advanced technology developments*
Revise and publish a *Project Plan*
Reaffirm the *Mission Needs Statement*
Prepare a *Program Commitment Agreement*
Information Baselined:
System requirements and verification requirements matrix
System architecture and work breakdown structure
Concept of operations
"Design-to" specifications at all levels
Project plans, including schedule, resources, acquisition strategies, and risk management

NASA-SP-610S, 1995

Phase C (design guidelines)

"complete the system design"

Phase C—Design

Purpose: To complete the detailed design of the sys-tem (and its associated subsystems, including its operations systems).
Major Activities and their Products:
Add remaining *lower-level design specifications* to the system architecture
Refine *requirements documents*
Refine *verification plans*
Prepare *interface documents*
(Repeat the process of successive refinement to get "build-to" specifications and drawings, verification plans, and interface documents at all levels)
Augment baselined documents to reflect the growing maturity of the system: system architecture, verification requirements matrix, work breakdown structure, project plans
Monitor project progress against project plans
Develop the *system integration plan* and the *system operation plan*
Perform and archive *trade studies*
Complete *manufacturing plan*
Develop the *end-to-end information system design*
Refine Integrated Logistics Support Plan
Identify opportunities for pre-planned product improvement
Confirm science payload selection
Information Baselined:
All remaining lower-level requirements and

NASA-SP-610S, 1995

Phase D (development guidelines)

"build, integrate, and verify the system, and prepare for operations"

NASA-SP-610S, 1995

Phase D—Development

__Purpose__: To build the subsystems (including the op-erations system) and integrate them to create the system, meanwhile developing confidence that it will be able to meet the system requirements, then to deploy the system and ensure that it is ready for operations.
__*Major Activities and their Products*__
Fabricate (or code) the *parts* (i.e., the lowest-level items in the system architecture)
Integrate those items according to the integration plan and perform verifications, yielding *verified components and subsystems*
(Repeat the process of successive integration to get a *verified system)*
Develop *verification procedures* at all levels
Perform system qualification verification(s)
Perform system acceptance verification(s)
Monitor project progress against project plans
Archive documentation for verifications performed
Audit "as-built" configurations
Document Lessons Learned
Prepare operator's manuals
Prepare maintenance manuals
Train initial system operators and maintainers
Finalize and implement Integrated Logistics Support Plan
Integrate with launch vehicle(s) and launch, perform orbit insertion, etc., to achieve a deployed system
Perform operational verification(s)
__Information Baselined:__
"As-built" and "as-deployed" configuration data
Integrated Logistics Support Plan
Command sequences for end-to-end command and telemetry validation and ground data processing
Operator's manuals
Maintenance manuals
__Control Gates__:
Test Readiness Reviews (at all levels)
System Acceptance Review
System functional and physical configuration audits
Flight Readiness Review(s)
Operational Readiness Review
Safety reviews

Phase E (mission operations and data analysis)

"operate the system, and dispose of it properly"

NASA-SP-610S, 1995

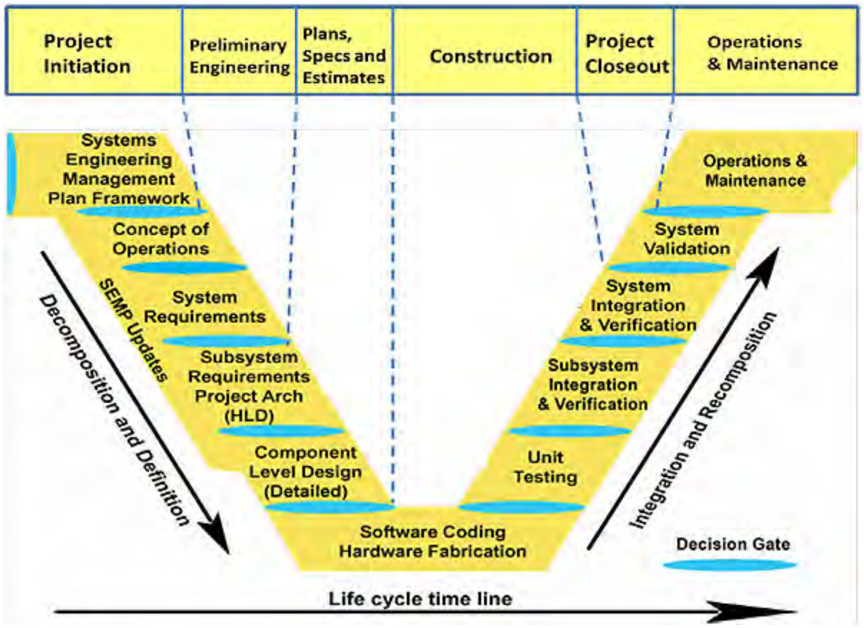
Phase E—Operations

__Purpose__: To actually meet the initially identified need or to grasp the opportunity, then to dispose of the system in a responsible manner.
Major Activities and *their Products:*
Train replacement *operators and maintainers*
Conduct *the mission(s)*
Maintain and upgrade the *system*
Dispose of the system and supporting processes
Document *Lessons Learned*
__Information Baselined__:
Mission outcomes, such as:
- Engineering data on system, subsystem and materials performance
- Science data returned
- High resolution photos from orbit
- Accomplishment records ("firsts")
- Discovery of the Van Allen belts
- Discovery of volcanoes on Io.

Operations and maintenance logs
Problem/failure reports
__Control Gates__:
Regular system operations readiness reviews
System upgrade reviews
Safety reviews
Decommissioning Review

Overview of Space Project Cycle:

V Diagram



System Engineering Techniques

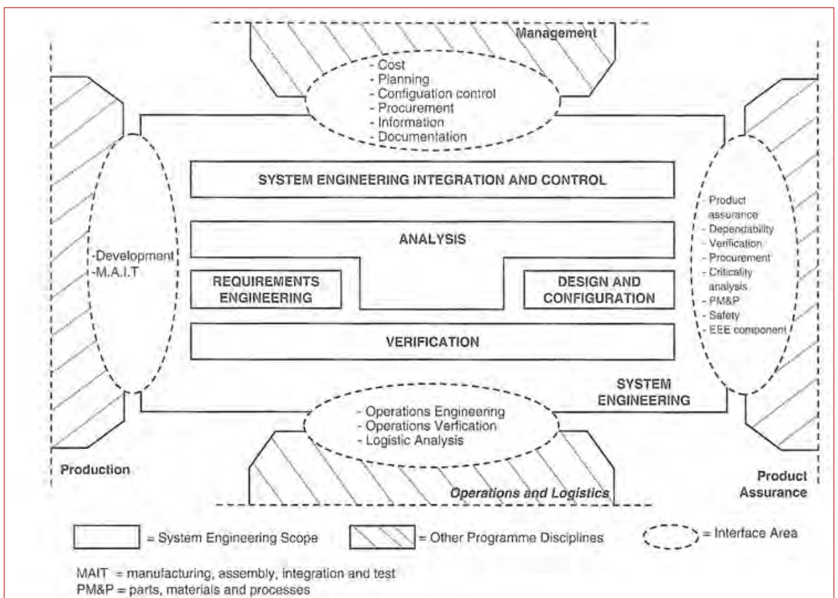


Figure 20.2 System engineering boundaries. (Figure reproduced from [1] by permission of ESA on behalf of the ECSS members)

Expansion/Translation of Top-Level Requirements

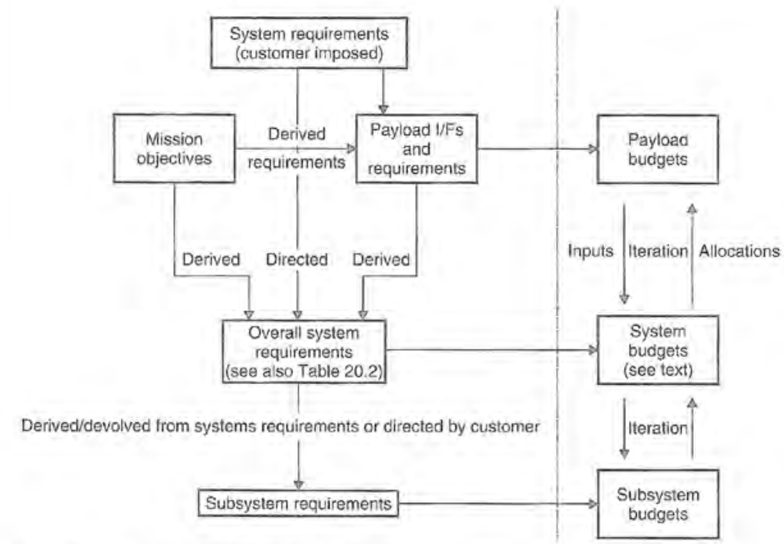


Figure 20.3 Expansion/translation of top-level requirements to system and subsystem level

Orbit Options for Astronomy Missions

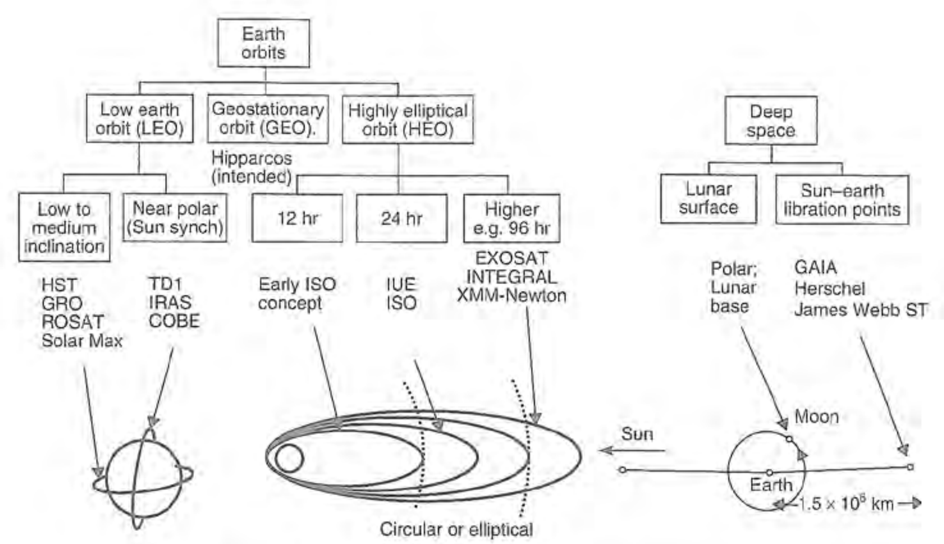
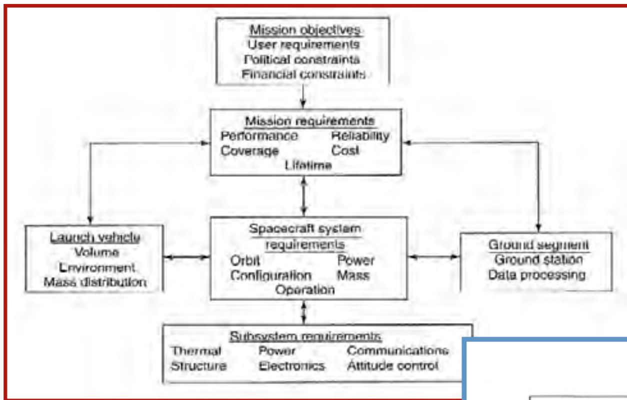
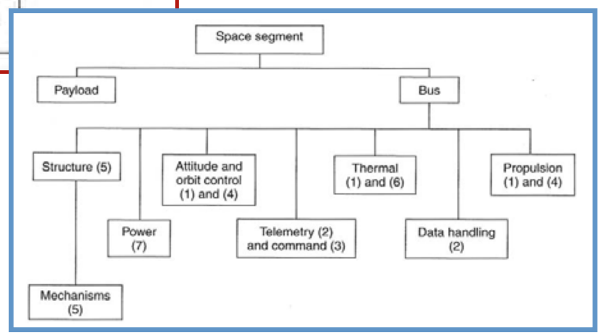


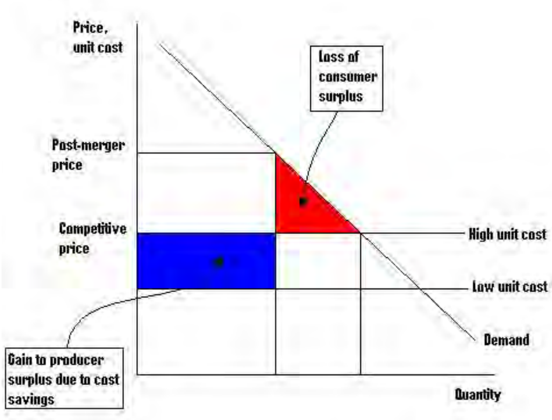
Figure 20.4 Orbit options for astronomy missions

Design Drivers





Tradeoffs



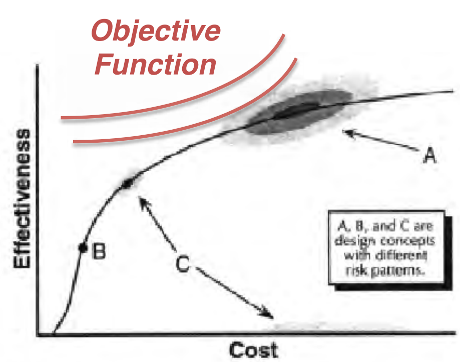
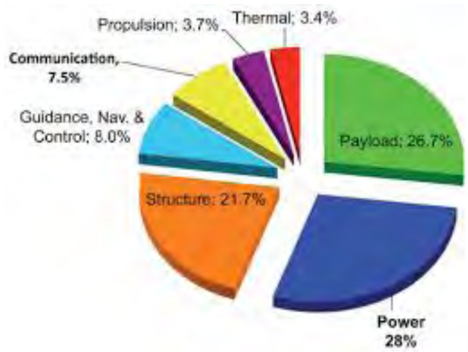


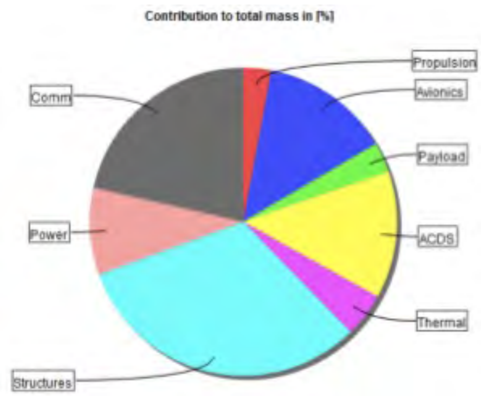
Figure 2--Estimates of Outcomes to be Obtained from Several Design Concepts Including Uncertainty.

https://en.wikipedia.org/wiki/Williamson_trade-off_model

https://commons.wikimedia.org/wiki/File:NASA_Systems_Engr_Handbook.pdf

System Mass and Power Budgets





Concurrent Engineering

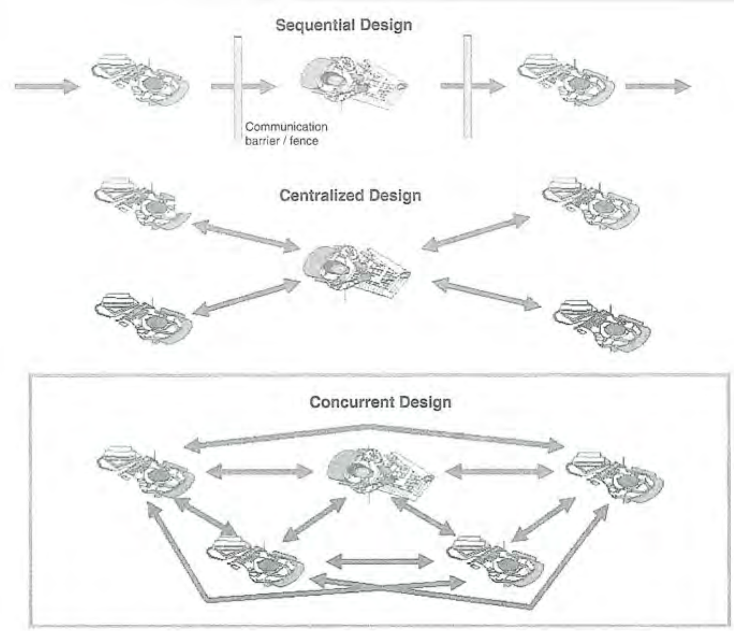
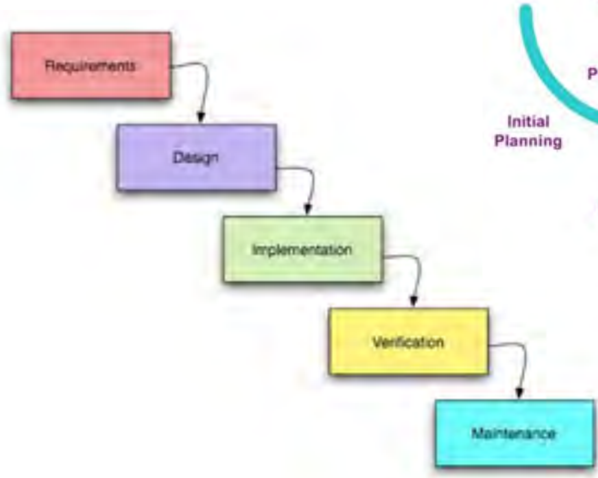
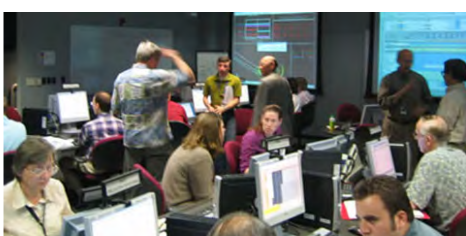


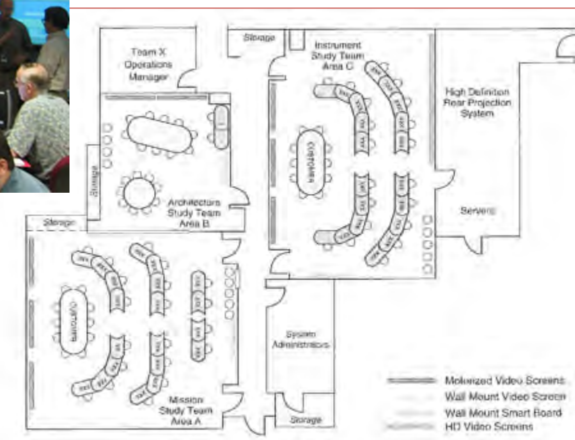
Figure 20.5 Alternative approaches to space system design

“Waterfall” vs. Concurrent Design



NASA JPL Team X





(b)

Figure 20.6 The JPL Project Design Center (PDC) operated by Team X in Pasadena CA, USA. (a) The Mission Study Team Area A. (b) PDC layout. (Reproduced by permission of NASA JPL-Caltech)

http://jplteamx.jpl.nasa.gov/

European Space Agency Concurrent Design Approach

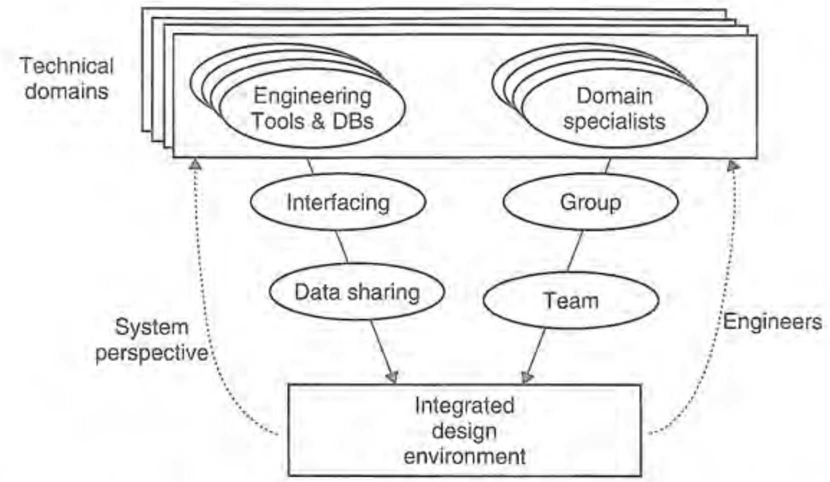


Figure 20.7 The ESA approach to the creation of an Integrated Design Environment

http://www.esa.int/Our_Activities/Space_Engineering_Technology/CDF

Process

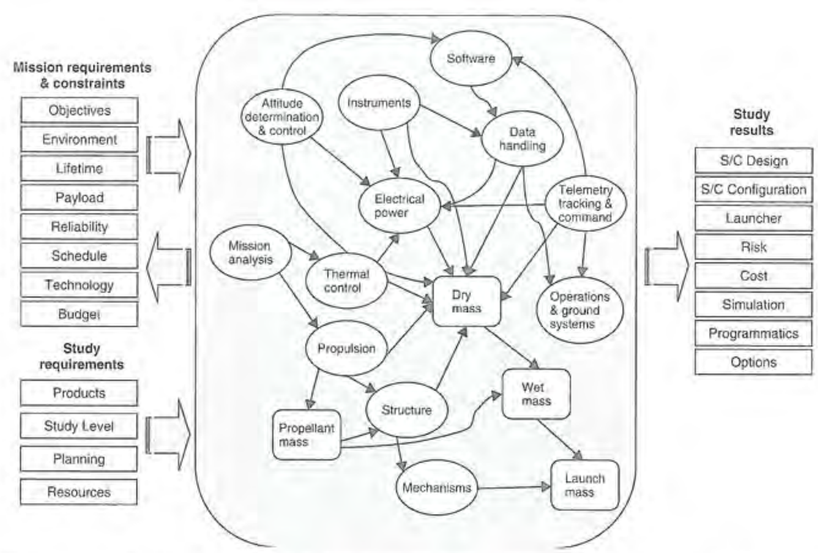


Figure 20.8 Conceptual model of the mission and spacecraft design process. The ovals represent the disciplines, the boxes represent aggregated key parameters, the arrows are interactions and data exchange. Each discipline contributes, directly or indirectly to the definition of the main mission parameters (or *key parameters*)

Spiral Model of the Design Process

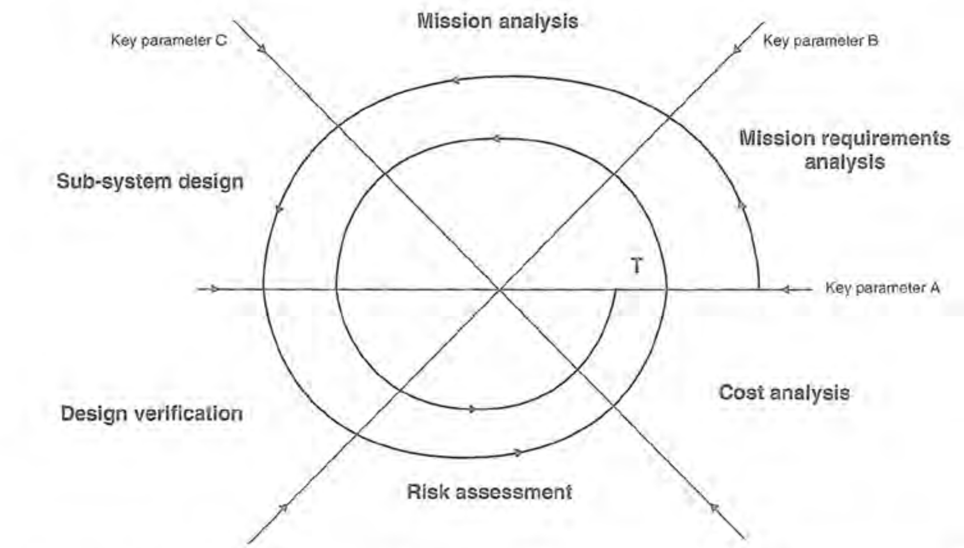


Figure 20.9 CE Iterative process: Spiral Model representation. In the example, point T is the target value of key parameter A

Design/Development Team

Integrated Product Development Teams

The detailed evaluation of product and process feasibility and the identification of significant uncertainties (system risks) must be done by experts from a variety of disciplines. An approach that has been found effective is to establish teams for the development of the product with representatives from all of the disciplines and processes that will eventually be involved. These integrated product development teams often have multidisciplinary (technical and business) members. Technical personnel are needed to ensure that issues such as producibility, verifiability, deployability, supportability, trainability, operability, and disposability are all considered in the design. In addition, business (e.g., procurement! representatives are added to the team as the need arises. Continuity of support from these specialty discipline organizations throughout the system life-cycle is highly desirable, though team composition and leadership can be expected to change as the system progresses from phase to phase.

NASA-SP-610S, 1995

Design Process Model

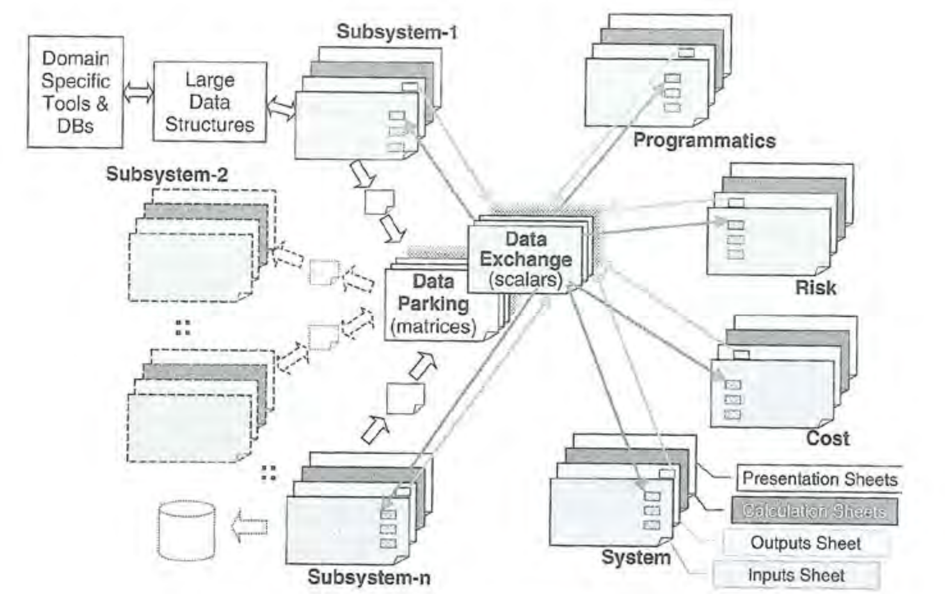
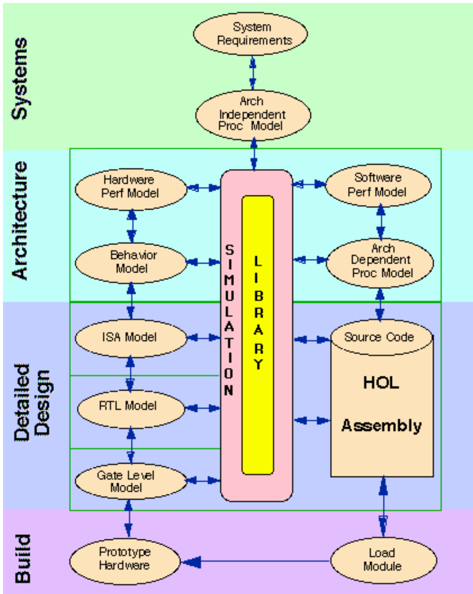
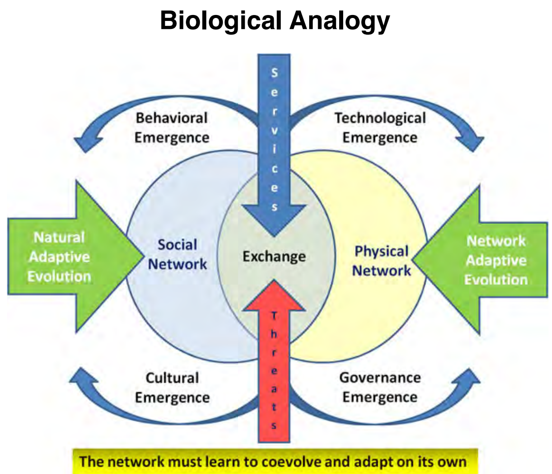


Figure 20.10 The CDF Integrated Design Model (IDM)

ESA Concurrent Design Facility

Hardware/Software Infrastructure for Concurrent Design



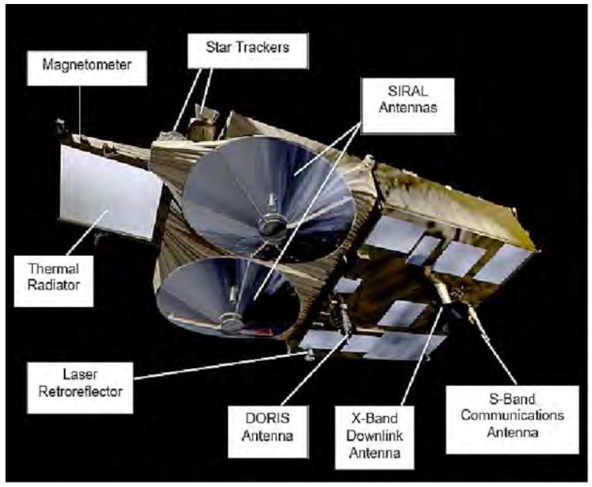


Benefits of Using Concurrent Design

- Reduced design time
- Reduced errors
- Increased quality
- Project management visibility
- Top-level change control
- Knowledge of how modules interface

Case Study: CRYOSAT

- **CryoSat-1 failed to reach orbit**
- **CryoSat-2 launched April 2010**

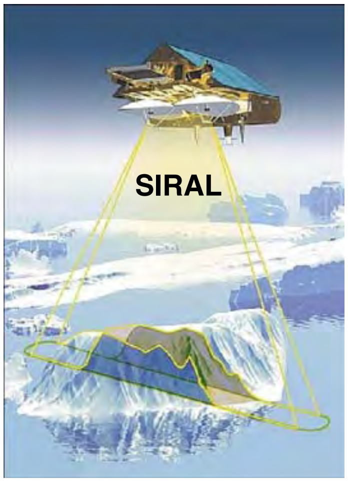


https://en.wikipedia.org/wiki/CryoSat-2

Mission Characteristics

- **CryoSat-2's mission: study the Earth's polar ice caps, measuring and looking for variation in the thickness of the ice.**
- **Primary instruments:**
  - **SIRAL-2, the SAR/Interferometric Radar Altimeters, which use radar to determine and monitor the spacecraft's altitude in order to measure the elevation of the ice. Two SIRAL instruments are installed aboard CryoSat-2.**
  - **Doppler Orbit and Radio Positioning Integration by Satellite, or DORIS, is used to calculate precisely the spacecraft's orbit. An array of retroreflectors allow measurements to verify the orbital data provided by DORIS.**
- **Launch and Early Orbit Phase operations: April 2010**
- **The spacecraft underwent six months of on-orbit testing and commissioning.**

Precision Measurements from Space

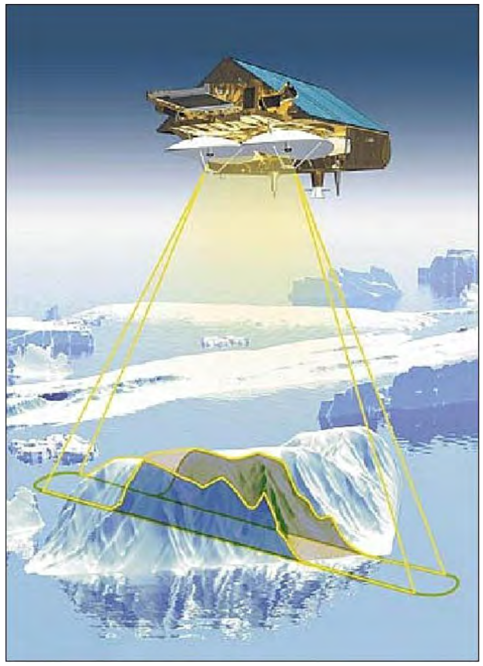


http://emits.sso.esa.int/emits-doc/ESRIN/7158/CryoSat-PHB-17apr2012.pdf

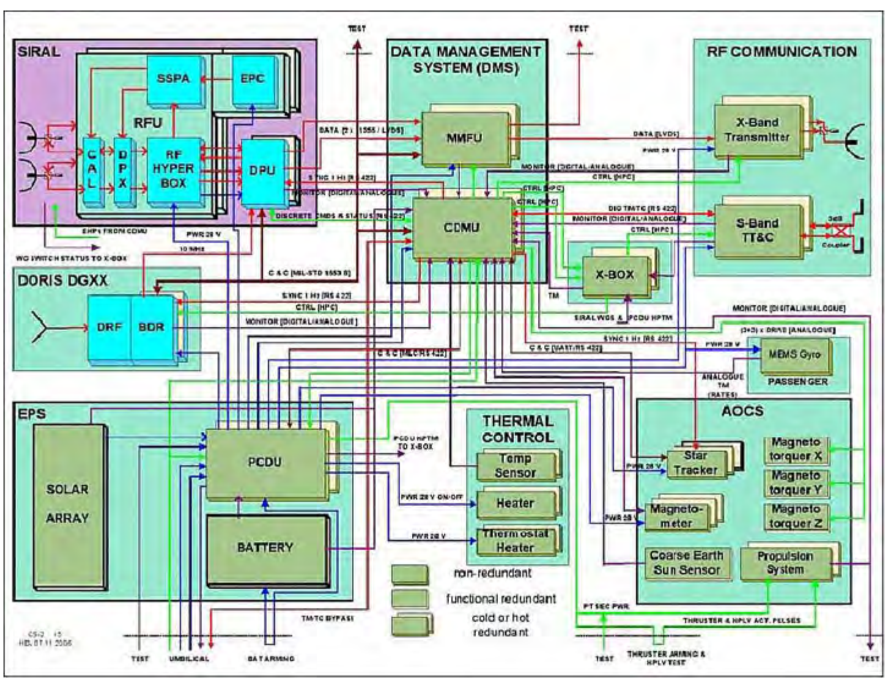
Designing the System

http://emits.sso.esa.int/emits-doc/ESRIN/7158/CryoSat-PHB-17apr2012.pdf

Payload: Re-use and Innovation



What Makes It Tick?

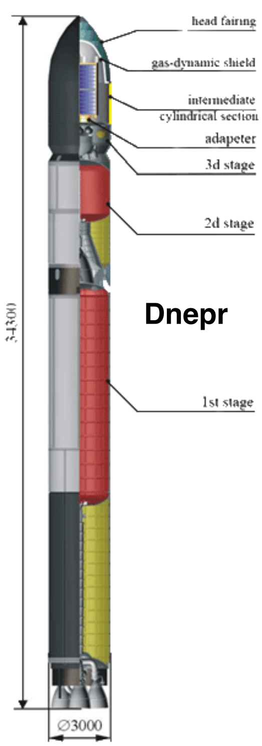


https://eoportal.org/web/eoportal/satellite-missions/c-missions/cryosat-2

Putting It Together

http://www.esa.int/Our_Activities/Observing_the_Earth/CryoSat/Entry_2_CryoSat-2_undergoes_surgery

CryoSat Launch



Next Time:
Product Assurance