Systems Engineering and Requirements

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AA420 Space Design

Outline

- What is Systems Engineering?
- Project Initiation: The Proposal Process
- Defining Mission Objectives and Requirements
- Forming a Team
- Developing a Schedule
- Managing Risk
- Managing Cost

- Flowdown of Mission Objectives to Technical Requirements or Specifications

What is Systems Engineering?

- Systems Engineering is the Process by which an organized Team Achieves efficiently works a project to achieve specific objectives (mission, technical, cost, risk)

- Typical Systems Engineering Duties
  - Routine Interaction with the Customer (5%)
  - Periodic Customer Reviews and Document Submittals (15%)
  - Reporting to Upper Management (5%)
  - Team Meetings/Preparation (5%)
  - Routine Program Monitoring with Available Tools (10%)
  - Requirements Definition/Mission Analysis/Performance Analysis (15%)
  - Making Sure that the Right People have the Right Information and the Proper Tools to do the Tasks They should be Doing (45%)

Systems Engineering Duties

Range of Duties Depends on Size of Project

- Interface with Customer
- Reporting to Upper Management
- Team Meetings and Decision Making
- Program Schedule and Resource Coordination - Project Administrator
- Cost Management - Cost Analyst
- Coordination of Engineering Teams - Project Engineer
- Mission Analysis - Project Engineer
- System Performance Analysis - Project Engineer
- Requirements Flowdown - Development Engineer

Large Project (> $2M)

Medium Project (> $1M)

Small Project

Systems Engineering Benefits

- Program Direction (but also Responsibility)
- Insight into Higher Level (or Customer) Processes
- Opportunity to Learn Something about Many Different Disciplines

- You Will Always Have Responsibility, but You Will not Always Have Authority

Systems Engineering Metrics

- Cost
  - Non-Recurring Engineering (NRE)
  - Production Unit Cost
  - Materials
  - Subcontracts
  - Travel
- Schedule
  - Design Reviews
  - Delivery Dates
  - Component Receiving Dates
  - Program Milestones
- Performance/Mission Requirements
  - Capability (Thrust, Isp, Power Efficiency, Bandwidth, Pointing Accuracy, etc.)
  - Reliability
  - Lifetime
- Any Two can be Optimized at the Expense of the Third

Project Initiation for Commercial Aerospace

1. Customer Issues Request for Proposal (RFP) for a Project
   - Proposal Guidelines
   - Draft Statement of Work
   - Draft Specification
2. RFP is Reviewed Internally
   - Ability to Meet Performance Requirements
   - Ability to Meet Schedule (Capacity Evaluation)
   - Ability to Meet Price Target or Estimated Win Price
   - Is Project within Company Goals?
3. Bid/ No Bid Decision
4. Proposal Team Defined
   - Proposal Budget (Part of Cost of Business)
   - Proposal Schedule
   - Proposal Manager and Team Members

Project Initiation for Commercial Aerospace (cont'd)

5. Proposal Document Developed and Reviewed (Mini-Project)
   - Complete First Cut Schedule, Budget, Work Breakdown Structure, etc.
   - Complete Preliminary Design Layout and Preliminary Performance Analyses
   - Department, Division, and Corporate Reviews as Required
   - Final Proposal Document (and Other Information as Required) Submitted to Customer
6. Customer Downselect
7. Contract Negotiations
   - Scope of Work
   - Price
   - Payment Method (Monthly. Milestones, On Delivery)
   - Terms and Conditions
8. Contract Signing
9. Kickoff Meeting

Mission/Project Objectives and Requirements

- Mission Objectives and Requirements Typically Defined in Contract and/or Statement of Work
  - May be Supplied by Customer or Jointly Developed
- Technical Requirements are Defined in Specification
  - Flow down from Mission Requirements
  - May be Supplied by Customer or Jointly Developed
  - Can Vary from Ten to Hundreds of Pages
  - May be a “Work in Progress” until Preliminary Design Review (PDR)

Mission Objectives

- Mission Goal: To do what by when for how much
- Example: Design and Qualify a New Rocket Engine Module (REM) for the Launch Vehicle Reaction Control System that Meets all Vehicle Requirements by June 2000 for $2 million.

- Mission Goal Explicitly States Metrics

- Smaller Scope Mission Goals Become Objectives
  - Milestones
  - Reviews
  - Key Performance or Design Goals

- In Reality, Mission Goals and Objectives are Stated in the Program Statement of Work and Agreed to per the Contract with the Customer

Mission/Project Requirements

- Contractual Documents Typically Include at Least Three Items
  - Contract (none in AA420)
    - Price
    - Payment Plan
    - Terms and Conditions
    - Proprietary Data/Hardware Rights
    - Other Legal Issues
  - Statement of Work (some in AA420)
    - Tasks to be Performed
    - Contract Deliverable Requirements List (CDRL)
    - Schedule
    - Program Milestones/Reviews
  - Specification (some in AA420)
    - Applicable Documents
    - Design Requirements
    - Physical Interfaces
    - Performance Requirements
    - Parts, Materials, and Processes (PM&P) Requirements
    - Testing Requirements

Nanosat Example

- From the BAA (similar to an RFP):
- “AFOSR and the Defense Advanced Research Projects Agency (DARPA) are jointly funding up to 10 research projects centered on the design and demonstration of nanosatellites. (Satellites sized 1 - 10 kg). AFOSR and DARPA encourage universities to pursue creative low-cost space experiments to explore the military usefulness of nanosatellites. Experiments in formation flying, enhanced communications, miniaturized sensors, attitude control, maneuvering, docking, power collection, deorbit at end of life, or other on-orbit demonstrations of advanced space technology are of particular interest.”

- Areas UW addressed:
  - formation flying (teamed with USU, VT)
  - nanosat design (15 kg because 10 kg was not feasible!)
  - did not do docking, de-orbit
- Led to mission objectives!

Nanosat Example

- From the BAA (similar to an RFP):
- “Universities may arrange their own launches or may design to an AFRL-funded DoD or NASA shuttle launch on or after Dec 2000. Satellite dimensions must accommodate ten satellites and the deployment structure fitting within a shuttle hitchhiker payload volume of 54" x 42.5" x 24." Example satellite envelopes are 20" x 19" x 7.5" or 25" x 12" x 10.5", but other dimensions will be accommodated to the extent possible. ”

- Shuttle Hitchhiker documentation led to requirements placed on UW Dawgstar:
  - mass no greater than 15 kg
  - must fit within envelope of a cylinder 20” wide, 12” tall

- Shuttle Hitchhiker Jr. will drive your requirements!

Developing a Team

- Sometimes in industry, termed “Integrated Product Development”
- What is Integrated Product Development?
  - Systematic Approach to the Integrated, Simultaneous Design of Products and Their Related Build Processes
  - Weaves Together Design, Analysis, Planning, Tool Design, Manufacturing Planning, and Test Planning

- Basic Concept: Early, Proactive, Interactive Involvement in the Design and Development Process by All Those Who will Eventually Make the Product a Success
- A Tool to Increase the Ability to Achieve Quality, Cost, Schedule, and Performance Goals

- Systems Engineers are the glue of the team!

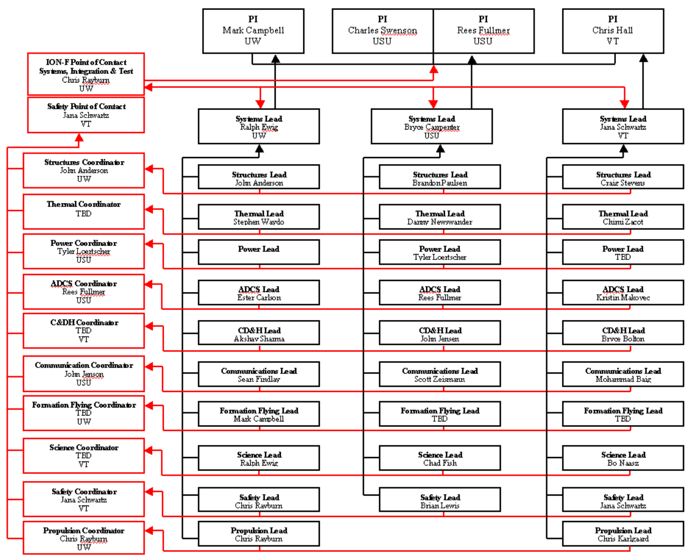
Teamwork and Planning

1. Generate an Overall Program Plan
   - Objectives
   - Requirements
   - Team Organization
   - Event-Based Plan and Schedule
   - Work Breakdown Structure (WBS)
2. Communicate the Program Plan to Team Members
3. Identify Potential Program Problems
   - Issues List
4. Conduct Internal Design Reviews
   - Internal Reviews prior to PDR, CDR
   - Internal Drawing, Test Procedure Reviews
5. Measure Team Performance
   - Design Simplicity
   - Requirements and Schedule
6. Prepare a Lessons Learned List
   - Based on Issues List

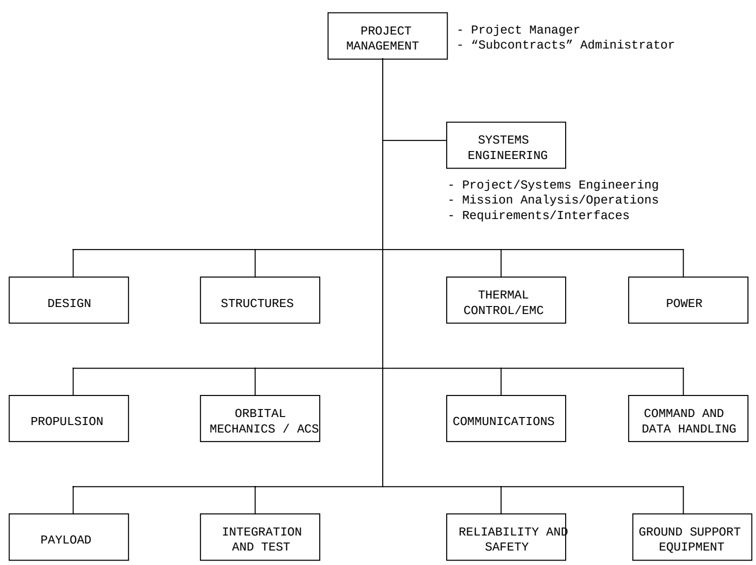
Team Principles and Practices
(from Boeing 777 Program)

- Use Facts and Data
- No Secrets (Be Forthright, No Hidden Agendas)
- Whining is OK Occasionally
- Propose a Plan Find a Way
- Listen to Each Other
- Help Each Other, Include Everyone
- Enjoy Each Other and the Journey
- Emotional Resilience
- Working Relationships
  - D Dignity
  - R Respect
  - A Appreciation
  - F Fairness
  - T Trust

ION-F: UW, USU, VT team Org Chart



Potential Team Organization



Event-Based Planning

- A Bottom-Up Way of Building a Program Schedule
- Based on Statement of Work and Requirements Specification, a List of All Tasks to be Performed to Complete the Project, Organized by Major Events and Accomplishments
  - Specific Tasks
  - Resources (Responsible Individuals)
  - Budget (Time)
- Advantages
  - Generally the Most Accurate Method for Building a Schedule
  - Less Chance of Omitting Important Tasks
  - Provides the Basis for Both Scheduling and Cost Accounting
- Disadvantages
  - Time Consuming

Event-Based Planning

- Typical Events
  - Conceptual Design Review - CoDR
  - Requirements Review - RR (Preliminary requirements defined, interaction with customer)
  - Preliminary Design Review - PDR (Requirements Frozen)
  - Critical Design Review - CDR (Design Frozen)
  - Completion of Qualification Testing
  - Flight Hardware Delivery
- Typical Accomplishments
  - Completion of Design/Analysis
  - Completion of Test or Manufacturing Procedures
  - Component Qualification
  - Completion of Development Testing
  - Completion of Thermal Analysis
  - Individual Test Setup/Completion

Approach to Building a Schedule

- First-Cut List of Events/Accomplishments/Tasks Distributed to Team Members (No Dates)
- Team Members Return Input to Systems Engineer
- Schedule Finalized by Systems Engineer and Reviewed by Team
- Responsible Individuals Now Have Ownership for Their Tasks
- Systems Engineer Responsible for Managing External Influences and Facilitating Task Completion

- Tool: Microsoft Project
  - Define the Project Start Date
  - Add All Events, Accomplishments, and Tasks Durations
  - Establish Logical Interrelationships between all Tasks (Predecessors and Successors)
  - Add Contractual Milestone Dates
- Schedule is Regularly Updated and Communicated to the Customer

Scheduling Advice

- An Unknown Date will Never be Met
- Long lead times (such as with hardware) should be known and planned for as much as possible
- Sense of Priority or Urgency of Tasks
- Knowledge of Critical Path
- Visibility of Key Future Dates for Customer and Internal Resources

- With a good schedule:
  - Effect of Delay in an Individual Task on the Overall Project is Immediately Known
  - Critical Path is Clearly Defined
  - Capability for Determining Project % Complete

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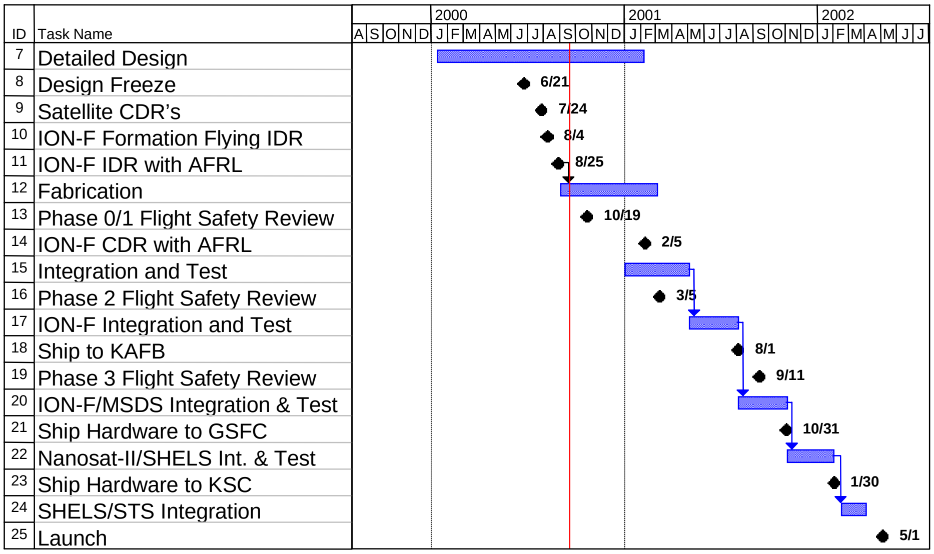
Nanosat Example of a Schedule



Full Schedule takes up half the wall in the Nanosat Lab!

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Risk Management

- Failures and/or Unanticipated Problems will Occur, Regardless of Planning!
- Extremely Important in Controlling the Schedule and Cost
- Goal: Evaluate all Potential Risk Areas and Manage Them Such That High/Medium Risk Items Become Low Risk
- Issues List is One of the Simplest tools to use:
  - Can be Project-Wide or by Subsystem
  - Issues are Elevated to the Top of the List by Priority and Due Date
    - A: Requires immediate attention and resolution; program schedule and/or cost are directly impacted
    - B: Requires timely resolution in order to protect program schedule
    - C: Requires monitoring to prevent adverse program impacts
    - D: Task completed
- At the End of the Program, Issues List Becomes Condensed into a "Lessons Learned" Document for General Distribution

Where We are Heading for AA420/421

- Establish a Team Organization and Assign Team Members to Roles
- Define Key Mission Constraints and Derived Requirements
  - preliminary structural ideas/analysis
  - preliminary thermal analysis
  - pointing (attitude) requirements
  - a lot of assumptions and simple analyses here!!
- Start System Technical Specification
  - Define Subsystems and Estimate Key Derived Requirements at Subsystem Levels, Including Interfaces
- Develop a preliminary Event-Based Plan/Schedule, with a more complex version once specifications are defined
  - Conceptual Design Review (several concepts, key requirements)
  - Requirements/Preliminary Design review (draft of technical specifications)
- Start and Maintain a Critical Issues List
- Follow IPD Principles Right from the Start

Systems Engineers for AA420 Design Course

- Meet with most subsystem groups to know and understand interactions, requirements
- Maintain schedule
- Lead and maintain specifications definitions
- Define and maintain interface (mechanical, electrical)
- Define and maintain critical issues list with priorities
- Maintain AA420/421 budget
- Reliability and safety
- Help particular subsystems when needed

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Requirements Definition and Flowdown

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Introduction

- Proper Derivation and Communication of Requirements is Perhaps the Most Important Aspect of a Space Development Project
  - Proper Design and Qualification for Flight
  - Consistent Subsystem Interfaces
  - Delineation between Mission Constraints and Derived Requirements for Trade Studies
  - Avoidance of Repeated Analyses
  - Resolution of Contractual Liability
  - Baseline for Future Changes or Follow-Ons

=> ***Cost, Schedule, and Performance Are All Driven by Requirements***

Space Mission Analysis and Design

1. Define Project Objectives and System Requirements
   - Define Project Goal and Principal Objectives
   - Identify Mission Constraints
   - Estimate Key Derived Requirements at System and Subsystem Levels Based on Payload Needs and Mission Constraints
2. Characterize System Concepts and Drivers
   - Define Alternative System and Subsystem Level Concepts
   - Identify Driving Requirements and Design Features
   - Establish Preliminary Subsystem Budgets for Mass, Power, Pointing, etc.
   - System Requirements Review (SRR)
3. Select the System Baseline
   - Perform Trade Studies of System and Subsystem Options Evaluated via Key Requirements, Drivers, Budgets, Performance, and Schedule
4. Define Detailed Technical Requirements
   - Evaluate Baseline System/Subsystems Against Technical Specification via Design, Analysis, Prototype; Update Requirements as Necessary
   - Preliminary Design Review (PDR)

Space Mission Analysis and Design

5. Complete the System Design
   - Finalize Performance Analyses
   - Development/Breadboard Testing as necessary to Reduce Risk
   - Complete and Release Engineering Drawings, Manufacturing Routings, and Test Procedures
   - Critical Design Review (CDR)
6. Build and Qualify the Hardware
   - Manufacture, Assemble, and Acceptance Test Qualification or Proto-Qualification System
   - Complete Qualification Test Program
7. Launch and Operate the System
   - Package and Ship to Launch Site
   - Launch Vehicle Integration/Checkout Test
   - On-Orbit Check-Out
   - Mission Operations

=> Requirements Definition and Analysis Permeates All Aspects and Time Phases of Mission Analysis and Design

Picture View of Requirements Definition and FlowDown

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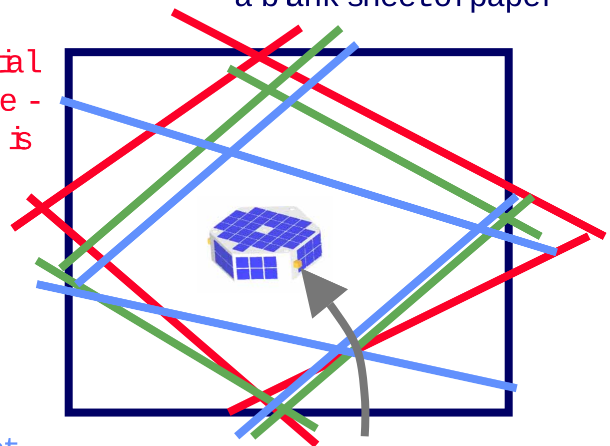
1. Mission Objectives

Initial concept very general - a blank sheet of paper

2. Reqmts based on initial assumptions/experience - usually very crude. This is ends in CoDR



3. Reqmts based on more analysis/simulation - SRR

4. Preliminary design process is a design just mature enough to freeze requirements - PDR

5. Critical design process is a design that fits in the box - do not let requirements slide! - CDR

Types of Requirements

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- Mission Constraints
  - Space Environment (Background Temperature, Solar Flux, etc.)
  - “Laws of Physics” (Gravity)
  - Delta-V
  - Lifetime
  - Launch Vehicle Requirements (Total Weight, Size Envelope, Launch Vibration, Separation Shock, Interfaces)
- Derived Requirements (Functional and Operational)
  - Thrust, Specific Impulse
  - Temperature Limits
  - Structural Design Margins/Safety Factors
  - Pointing Accuracy
  - On-Board Memory and Processor Speed
  - Command Time/Telemetry Resolution

=> ***Distinction is Important, as Derived Requirements can be Traded/Changed if Necessary but Constraints are Fixed***

Sources of Requirements

- Contractual Documents
  - Contract
  - RFP
  - Technical Specification
- Government and Public Standards
  - Military Specifications and Standards
    - MIL-HDBK-5 (Metallic Materials and Elements for Aerospace Structures)
    - DOD-HDBK-343 (Design, Construction, and Testing Requirements for One of a Kind Space Equipment)
    - MIL-STD-1540C (Test Reqmts for Launch, Upper Stage, and Space Vehicles)
    - MIL-PRF-26536 (Hydrazine Propellant Specification)
    - EWR-127-1 (Eastern and Western Range Safety Requirements)
  - Commercial/International Standards
    - ISO 9001 (Quality Registration)
    - AMS 5570 (CRES Tubing)
    - Launch Vehicle Payload Guides
- Company Procedures
- Derived based on analysis

Technical Specification

- Timing
  - Started Immediately
  - First Draft (not all Sections) by RR
  - "Released" Original Version at PDR
  - Minor Updates between PDR and CDR
  - Update at Your Own Risk after CDR
- Contents (see Dr. Vaughan's template at mid-Quarter)
  - Design Requirements
  - Physical Interfaces
  - Performance Requirements
  - Parts, Materials, and Processes (PM&P) Requirements (if Applicable)
  - Quality Requirements (if Applicable)
  - Testing Requirements
  - Packaging and Shipping Requirements
  - Compliance Matrix

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Example Specification: Lifetime of UW Nanosat

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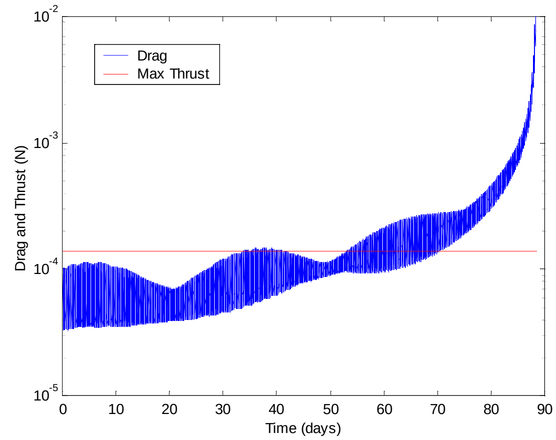
- RFP: Minimum requirement of 1 month, would like 4 month
- Shuttle based mission: Assume 2.5 years from now, most shuttle missions will be station servicing missions (51 deg inclination, 400 km). Assume 375 km. Simulate with STK.



Reexamine assumptions after mission manifested!

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Example Specification: Lifetime of UW Nanosat

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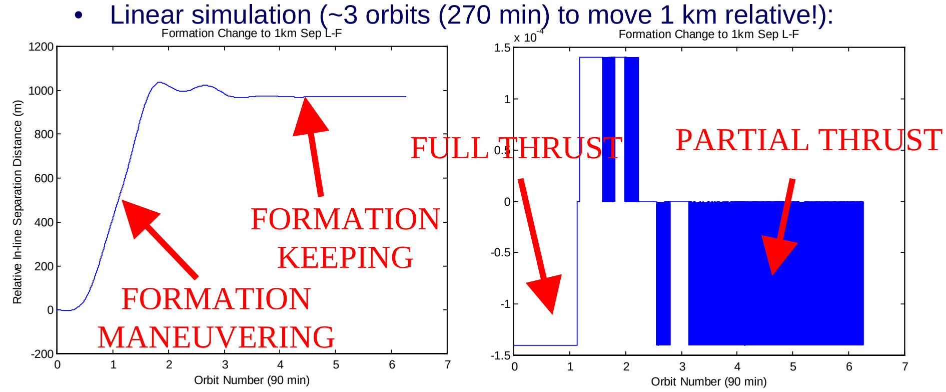
- Assume propulsion Ibit of 0.1 mNsec (why? - because this is about the size of very small electric thrusters. There will not be a a 1 Nsec Hydrazine thruster flown because of power/size)
- Linear simulation (~3 orbits (270 min) to move 1 km relative!):



Reexamine assumptions once propulsion system has been designed, use a nonlinear simulation, etc.

Example Specification: Lifetime of UW Nanosat

- Operational scenario:
  - 1 week checkout and debug
  - 2 weeks close formations and trying to maintain them
  - 1 week moving out to farther separations
  - 2 weeks of large formations and trying to maintain them
  - 2 weeks buffer (in case things go wrong, really fancy stuff)
- Bottom line: 2 month minimum lifetime requirement

This is one big assumption. After the design is more mature, a full mission simulation can be developed which will allow the above times to more accurately reflext the system.

Example Specification: Mass

Start with round figures from Larson and Wertz:

Update as more information from subsystem become available. Subsystems must deliver info on schedule!

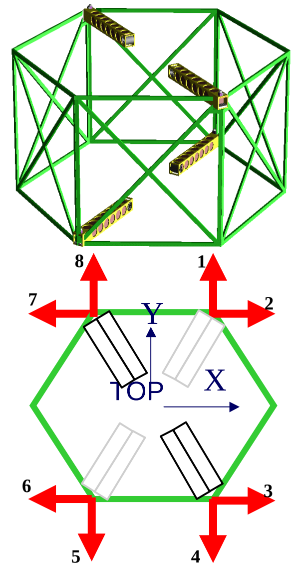
Subsystem	Percentage of Total	Allocated mass (kg)	Preliminary Mass Estimate (kg)	Variance (kg)
Structure	20%	2.0	2.0	0.0
Propulsion, Attitude Control & Determination	25%	2.5	3.8	-1.3
C&DH	5%	0.5	1.1	-0.6
Thermal Control	5%	0.5	0.5	0.0
Power	15%	1.5	2.5	-1.0
Science Payload	5%	0.5	0.9	-0.4
Communication & Guidance	5%	0.5	1.0	-0.5
Total Mass Allocation	80%	8.0	11.8	-3.8
Contingency	20%	2.0	2.0	0.0
Total Mass Allocation	100%	10.0	13.8	-3.8

If a subsystem is over reqmt:
- others must give
- customer is contacted to try to change reqmt

This is for systems engineers!

Mission: ΔV Requirement based on two month mission

- Ibit of 0.1 mNsec
- Attitude control: based on CP-CG = 2 cm, full drag model for 2002
- Formation keeping: based on USU-UW differential drag make-up (UW taller than USU)
- Formation Maneuvering: 100% thrust to get there as quick as possible!



	Phase I	
	ΔV (m/s)	% MISSION
Attitude Control	3.4	100
Formation Keeping	13.8	90
Formation Maneuvering	4.8	10
Margin	5	
Total	27.0	

- Now, go further in the design process, simulate, etc., then go back and update numbers!

Word of Advice

- Many requirements are based on others:
  - Delta V is dependent on mission operations definition
- For these examples,
  - make an assumption (say three month mission)
  - go through derivation of preliminary requirement (analysis)
  - If more solid numbers then come through, the re-derivation of the requirement should be simple!
- The systems engineers are responsible for tracking these preliminary requirements, updates, and conflicting requirements.
- Subsystems must communicate this information to systems engineers.
- I.E. A TEAM EFFORT!!

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Requirements References: Military http://dodssp.daps.mil/products.htm

- DOD-HDBK-343 Design, Construction, and Testing Reqmts for One of a Kind Space Eqpmt
- MIL-STD-100 Engineering Drawing Practices
- MIL-STD-1540C Test Requirements for Launch, Upper-Stage, and Space Vehicles
- MIL-STD-1833 Test Requirements for Ground Support Equipment
- MIL-STD-810 Environmental Test Methods and Engineering Guidelines
- MIL-HDBK-5 Metallic Materials and Elements for Aerospace Vehicle Structures
- MIL-STD-1547 Parts, Materials, and Processes Requirements for Space and Launch Vehicles
- MIL-STD-1539 Direct Current Electrical Power Space Vehicle Design Requirements
- MIL-STD-1541 Electromagnetic Compatibility Requirements for Space Systems
- MIL-STD-1686 Electrostatic Discharge Control for Protection of Electrical/Electronic Eqpmt
- DOD-E-8983 General Specification for Extended Space Environment Aerospace Electronic Eq
- DOD-W-83575 General Specification for Design and Testing of Space Vehicle Wiring Harness
- MIL-S-83576 General Specification for Design and Testing of Space Vehicle Solar Cell Arrays
- DOD-STD-1578 Nickel-Cadmium Battery Usage Practice for Space Vehicles
- MIL-STD-1246 Product Cleanliness Levels and Contamination Control Program
- MIL-STD-1574 System Safety Program for Space and Missile Systems
- MIL-STD-1522 General Requirements for Safe Design/Operation of Pressurized Space Sys.
- EWR 127-1 Eastern and Western Range Safety Requirements

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Requirements References: Government

- JSC 07700 Space Shuttle System Payload Accommodations
- NHB 1700.7 Safety Policy and Requirements for Payloads Using the Space Transportation System (STS)
- KHB 1700.7 Space Transportation System Payload Ground Safety Handbook