

## ENG 3310 - Space Mission Design Mission Analysis and Evaluation



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## Outline



- Identification of critical parameters
- Cost analysis
- Mission performance and utility analysis
- Mission utility and concept selection
- Mission Simulation
- Evaluating the propellant budget
- The critical design review
- Exercises

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## Critical Parameters



- Engineers work primarily with numbers and mathematical relations.
- System design trade-offs may also be expressed in terms of these parameter sets.
- Is there one specific choice of parameterization?
- How do we identify an optimal model?
- Example possibilities
  - Propulsion – Delta V, Specific Impulse, Delivery mass
  - Communications – Data rate, Band width, Coverage
  - Human presence – Volume, Area, Life support capability
- Leads to Step 7 in SMAD

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## Cost Modeling



- The most significant engineering parameter?
- What does 'cost' depend on?
- What are we trying to estimate?
  - Probable cost / most likely
  - Distribution of cost / spread
  - ROM cost, Fixed price, Cost plus.
- Ultimate maximizing performance subject to (multiple) constraints (one of which is cost).
- Uses of cost model
  - Win work for organization
  - Feasibly study
  - Go/No go decisions
  - Project revenue / spend require to complete porject
- What are the outputs of a cost modeling exercise?
  - Cost by year (RY/FY\$), Cost by subsystem, Cost by segment
  - Cost by phase (Design cost, build cost, repeat build cost, ops cost)
  - Risk, Uncertainty

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## Cost Analysis



- **Identify cost drivers**
  - cost analysis requirements descriptions
  - What are the cost drivers?
  - Typically cost alternatives, not just our best guess – why?
- **Costs formalized in Work Breakdown Structures (WBS)**
  - Divide job into cascaded series of work packages
  - Each package has dependencies (inputs), results or deliverables (outputs), a description of 'work' or 'objectives' and schedule information, expected cost, cost breakdown.
  - Provides formal documentation for project management, control and accountancy.
  - Top level packages breakdown into lower level hierarchical structure.
- **Ultimately need to cost a particular configuration in terms of units, elements, subsystems, hardware, software, staffing.**

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## Cost Analysis II



- **But how do we cost a subsystem of mission not yet designed?**
- **Options:**
  - Detailed Bottom-up costing – Ultimately going to be required.
  - Similar or analogy cost – does cost compare with existing system of similar complexity (usually used as sanity check).
  - Parametric estimation – use previously derived heuristics to estimate the cost of a “not too dissimilar system” – See textbook.
- **Formal procedures**
  - Large companies and agencies such as NASA have formal cost estimation procedures for cost estimation
  - May also be applied (in limited form) beyond organisation
  - See references in Ch. 20
- **Software**
  - Buy range of software packages to cost systems.
  - Ultimate objective of such approaches is to turn engineering design into expected mission cost in automated fashion (currently Sci-Fi!).
  - Beware – Garbage in, garbage out!!!

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## Types of Dollars



- **Currency changes value**
- **Need consistent basis for analysis**
- **Typically assume an epoch and cost everything in this year**
  - Eg. Fiscal Year (FY) 2004 CAD\$
- **Then convert to Real Year Dollars RY\$ by accounting for expected exchange rate (see p791)**
- **How much is \$10K (2000 FY\$) worth in (2010 RY\$)?**
- **Typically, agencies will specify these conversion rates in order to provide consistent cost analysis with which to judge proposals.**

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## Cost by element



- **Divide system into elements**
  - Payload
  - Spacecraft Bus
  - Structure
  - Thermal
  - Electrical Power
  - Tracking, Telemetry
  - Attitude Determination and Control
  - Propulsion
  - Integration, Assembly and Test
  - Program Level – Systems Engineering, Project control
  - Ground Support Equipment
  - Launch and Operations Costs
- **Use Table 20-6 p797 to cost for SCISAT-2 a Canadian low Earth orbit spacecraft mass 200 kg, 100 kg fuel.**
- **What is the error estimate for this cost?**

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## Mission Evaluation: Critical Requirements



- What are principal (critical) performance requirements?
- What are the “top level” requirements that we used to define mission objectives?
- What are the hidden requirements?
  - Use of existing systems?
  - Technology demonstration?
- Distinguish this analysis from system drivers (the mission parameters that most strongly effect performance cost and risk)

TABLE 3-1. Most Common Critical Requirements. See text for discussion.

Requirement	What it Affects	Where Discussed
Coverage or Response Time	Number of satellites, altitude, inclination, communications architecture, payload field of view, scheduling, staffing requirements	Secs. 7.2, 13.2
Resolution	Instrument size, altitude, attitude control	Sec. 9.3
Sensitivity	Payload size, complexity, processing, and thermal control; altitude	Secs. 9.5, 13.5
Mapping Accuracy	Altitude control, orbit and attitude knowledge, mechanical alignments, payload precision, processing	Sec. 5.4
Transmit Power	Payload size and power, altitude	Secs. 11.2, 13.5
On-orbit Lifetime	Redundancy, weight, power and propulsion budgets, component selection	Secs. 6.2.3, 8.1.3, 10.4, 19.2
Survivability	Altitude, weight, power, component selection, design of space and ground system, number of satellites, number of ground stations, communications architecture	Sec. 8.2

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## Mission Evaluation: Analysis Hierarchy



- Define typical process for mission evaluation
- Again cyclic (like all good engineering processes)
- Ultimate objective is quantification of performance and utility

TABLE 3-2. The Mission Analysis Hierarchy. These help us decide how much detail to study during the preliminary design phase.

Analysis Type	Goal	
Feasibility Assessment	To establish whether an objective is achievable and its approximate degree of complexity	Quick, limited detail
Sizing Estimate	To estimate basic parameters such as size, weight, power or cost	
Point Design	To demonstrate feasibility and establish a baseline for comparison of alternatives	
Trade Study	To establish the relative advantages of alternative approaches or options	More detailed, complex trades
Performance Assessment	To quantify performance parameters (e.g., resolution, timeliness) for a particular approach	
Utility Assessment	To quantify how well the system can meet overall mission objectives	

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## System trades of dependent parameters



TABLE 3-4. System Trade Process for Parameters with Multiple Effects. The example is the altitude trade for the FireSat mission. See also Fig. 3-1.

Step	FireSat Example	Where Discussed
1. Select trade parameter (typically a system driver)	Altitude	Sec. 2.3
2. Identify factors which affect the parameter or are affected by it	Coverage Deployment strategy (coverage evolution) Orbit period Time in view Eclipse fraction Response time Number of spacecraft needed Launch capability Resolution Payload weight Radiation environment Survivability Jamming susceptibility Communications Lifetime	Sec. 7.2 Sec. 7.6 Secs. 6.1, 7.2 Sec. 7.2 Sec. 5.1 Sec. 7.2 Secs. 7.2, 7.6 Sec. 18.2 Sec. 9.3 Sec. 9.5 Sec. 8.1 Sec. 8.2 Secs. 8.2, 13.5 Secs. 13.1, 13.2 Secs. 6.2.3, 8.1.5
3. Assess impact of each factor	Can launch up to 1,800 km Best coverage above 400 km Resolution—lower is better Survivability not an issue	
4. Document and summarize results	Launch Coverage Resolution Survivability	Fig. 3-1
5. Select parameter value and possible range	Altitude = 700 km 600 to 800 km	discussed in text

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## Performance Assessment



- Need to quantify performance demands
- Techniques include:
  - System Algorithms – geometric and physical formulae
  - Analogy with existing systems
  - Simulation – develop computer simulation of performance
- Previously designs nearly always used (1) and (2). Simulation now becoming widely deployed.
- MoE – Measures of effectiveness (scalar measure based on weighted averaged performance requirements)
- FoM – Figure of Merit (graphical description of design space)

TABLE 3-5. Common System Algorithms Used for Quantifying Basic Levels of Performance. These analyses use physical or geometrical formulas to determine how system performance varies with key parameters.

Algorithm	Used For	Where Discussed
Link Budget	Communications and data rate analysis	Sec. 13.3.6
Diffraction-limited Optics	Aperture sizing for optics or antennas; determining resolution	Sec. 9.3
Payload Sensitivity	Payload sizing and performance estimates	Secs. 9.4, 9.5
Radar Equation	Radar sizing and performance estimates	[Cantafio, 1989]
Earth Coverage Area Search Rates	Coverage assessment; system sizing; performance estimates	Secs. 5.2, 7.2
Mapping and Pointing Budget	Geolocation; instrument and antenna pointing; image sensing	Sec. 5.4

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## Mission Utility Analysis



- Step 8 in SMAD process.
- Provides quantitative analysis for decision making using (usually) a set of FoM and MoE.
- Describes mission performance as a function of design, cost, risk and schedule
- MUST BE CLEARLY STATED MEASURES PRESENTED IN A NON TECHNICAL MANNER (TO NON ENGINEERS)**
- MoEs typically fall into
  - Discrete events
  - Coverage of a continuous activity
  - Timeliness and other quality indicators
- What would be good MoEs for
  - Gravity probe-B?
  - RADARSAT?

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## MoE for Firesat Example



- Derive performance parameters first and use these to develop MoEs

TABLE 3-6. Representative Performance Parameters for FireSat. By using various performance parameters, we get a better overall picture of our FireSat design.

Performance Parameter	How Determined
Instantaneous maximum area coverage rate	Analysis
Orbit average area coverage rate (takes into account forest coverage, duty cycle)	Simulation
Mean time between observations	Analysis
Ground position knowledge	Analysis
System response time (See Sec. 7.2.3 for definition)	Simulation

TABLE 3-7. Representative Measures of Effectiveness (MoEs) for FireSat. These Measures of Effectiveness help us determine how well various designs meet our mission objectives.

Goal	MoE	How Estimated
Detection	Probability of detection vs. time (milestones at 4, 8, 24 hours)	Simulation
Prompt Knowledge	Time late = time from observation to availability at monitoring office	Analysis
Monitoring	Probability of containment	Simulation
Save Property and Reduce Cost	Value of property saved plus savings in firefighting costs	Simulation + Analysis

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## Mission Utility Simulation



- Forest fire warning time provides natural MoE for Firesat. This is contrasted to expected warning without system.
- Requires mission analysis and simulation steps.
- Can we improve on this MoE figure?

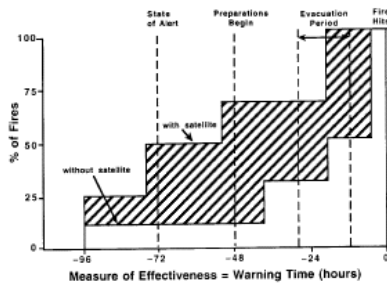


Fig. 3-2. Forest Fire Warning Time for Inhabited Areas. A hypothetical measure of effectiveness for FireSat.

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## Performing the Trade Studies



- Trade studies developed to inform simulator and processors

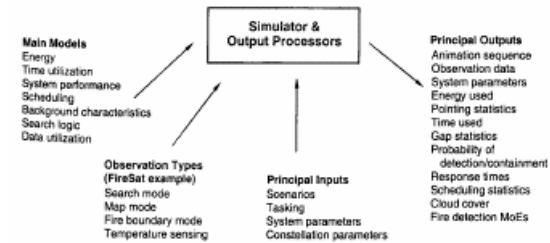


Fig. 3-3. Results of FireSat Altitude Trade. See Table 3-4 and Table 7-6 in Sec. 7.4 for a list of trade issues. Political constraints and survivability were not of concern for the FireSat altitude trade.

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## Typical Mission Utility Simulation (for Firesat)



TABLE 3-8. Typical Sequence Flow of a Time-Stepped Mission Utility Simulation. Following this sequence for many runs, we can create statistical measures of effectiveness that help us evaluate our design.

<b>Phase I — Data Generation</b>	
Advance time step	
Compute changes in target or background characteristics	
Update satellite positions	
Update viewing geometry parameters	
Schedule observations or operations	
Compute pointing changes	
Compute and save performance statistics	
Update satellite consumables	
Save data for this time step	
Go to next time step	
<b>Phase II — Output Generation and Statistics Collection</b>	
Compute scenario statistics	
Compute measures of effectiveness for the individual run	
Prepare output plots and data for the individual run	
<b>Phase III — Monte Carlo Runs</b>	
Set new scenario start time	
Repeat Phase I and II	
Collect multi-run statistics	
Compute statistical measures of effectiveness	
Prepare Monte Carlo output plots and data	

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## Mission Utility Animation

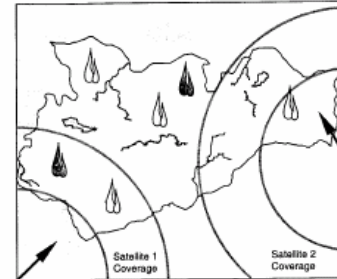


Fig. 3-4. Hypothetical Animation Output for FireSat Mission Utility Simulator. Color displays are very valuable for animation sequences because we need to convey multiple parameters in each frame.

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## Commercial Off the Shelf Software



- Massively reduce mission costs by not reinventing the wheel.
- COTS software and libraries becoming increasingly popular
- Someone else maintains code -- tested Before...
- Can directly develop required documentation formats (MIL-STD-499)

TABLE 3-9. Commercial Space Mission Analysis and Design Software. New versions are typically released roughly annually. Because of the very small size of the space market, commercial space software both enters and leaves the marketplace on a regular basis.

Product	Publisher	Approx. Cost	Purpose
Dance of the Planets	Arc Science Simulations	\$250	Amateur visual and gravitational model of the solar system useful for interplanetary mission design
Edge	Autometric	\$5,000 +	Professional mission analysis system; many modules; can be customized
EWB	Maxwell Labs	High	Professional tool for space mission trade studies; used for Space Station
MUSE module	Microcosm	\$6,500	Mission Utility/Systems Engineering tool; evaluates figures of merit; can be customized by user
ORB	AIAA	< \$100	Orbit analysis tool included with the book <i>Spacecraft Mission Design</i> ; primarily interplanetary
Orbit Works	ARS Software	\$700	Orbit analysis, pass geometry, related tools; used by many ground operations groups
SMAD Software	KB Sciences	\$500	10 software modules that implement equations in the SMAD book
Satellite Tool Kit, STK	Analytical Graphics	(*)	Professional mission analysis system; many modules

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\* Base program is free; module range from \$2,000 to \$30,000.

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## Concept Selection



- Meets Objectives? Feasible? Acceptable Risk?
- Better than alternatives (ground system solution)?
- Organizational responsibilities acceptable?
- Meets political objectives?
- Supported by existing infrastructure?

TABLE 3-10. Mathematical Model of Hypothetical Decision Process (costs in \$M). Numerically, we would choose B or A' if it were available. Realistically, any of the choices may be best depending on the decision criteria.

Current Cost		\$500M					
Potential Savings if Improvement is Successful		\$300M					
Option	Cost of Improvement	Probability of Success	Total Cost if Successful	Total Cost if Failed	Expected Total Cost	Expected Savings	
A	35	70%	235	535	325	175	
B	100	99%	300	600	303	197	
C	200	99.90%	400	700	400.3	99.7	
A'	35	80%	235	535	295	205	

f

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## ?v Budgets



- **Spacecraft propellant budgets traditionally computed in terms of velocity change required to achieve new orbit.**
- **Could use other units as computational basis but analysis developed for rocketry.**
- **For ?v we use momentum conservation analysis.**
- **Consider instantaneous change in momentum of a rocket mass  $m$  moving at velocity  $v$  and ejecting propellant at velocity  $v_0$ :**
  - $m dv = v dm$
  - Can show by integration that
  - $m_f = m_0 \exp(-v/v_0)$
  - Where  $m_0$  is the original mass of the spacecraft,  $m_f$  is the final mass and  $v$  is the change in velocity.
- **Spacecraft and rocket maneuvers traditionally accounted for in ?v a budget that include all the expected maneuvers during the vehicle lifetime.**
- **Conversion to fuel by Specific Impulse  $I_{sp} = V_0/g$  ( $g = 9.8 \text{ ms}^{-2}$ )**

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## Critical Design Review



- **Critical design review usual occurs after detailed design phase-B of project development**
- **Present intended mission solution, architecture and required elements**
- **Includes trade-off tables to indicate why this is desired solution**
- **Include analysis of system parameters**
- **Includes preliminary system engineering “budgets” and cost estimate**
- **Includes statement of performance, performance floor and measure of mission utility (how well does the system satisfy the original constraints).**
- **Our critical design review:**
  - Should be presented in 50 minutes up to three team members presenting.
  - Web-based version will be required following review.

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## Exercises



- **Earth Observation coverage**
  - A low Earth polar orbit spacecraft (~600 km, ~90 minute period) has a swath width of 500 km.
  - What coverage pattern will be required to cover the whole globe?
  - What is the repeat period?
  - If the spacecraft is allowed to slew 20 degrees from nadir, how often can the same target be observed?
  - If the planet was Mars instead of Earth, how would this analysis vary?
- **Design a simple thermal model of a space station in low Earth orbit.**
  - What happens if we choose to orbit L2 or the moon?
- **How much fuel is required to maintain a 1000 kg spacecraft in a 600 km Earth orbit for 5 years and under typical conditions.**
  - How does this compare with the fuel required to put the spacecraft in this orbit in the first place
  - What contingency would be required to counter solar output variations?

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