Professional Development Short Course On:

Space Mission Analysis and Design

Instructor:

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ATI Course Schedule:  http://www.ATIcourses.com/schedule.htm

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Introductions

- Brave new pioneers, who are you?
  - What is your interest in Space Mission Analysis and Design
- Where do you work?
  - What is your specialty
    - What other disciplines do you interface with?
- What are your goals with regards to Space Mission Analysis and Design

35 years ago, I wanted to retire and open a restaurant on top of the Martian peak of Olympus Mons, what a view. It seemed possible 35 years ago.
Breaks

- Classes start at 8:30 AM
  - Two breaks of 5-10 minutes in the morning
  - Lunch for 1-hour
  - Two breaks of 5-10 minutes in the afternoon
- Class ends at 4:30 PM

- The instructor is available during breaks for off-line discussions
- The instructor will be in class 30-minutes prior to the start of the day and 30-minutes after the class for questions and answers or other discussion
  - Use this time to expand your experience or rest those grey cells

- MY TIME IS YOUR TIME
Companion Book

• This class requires each student to own a copy of SPACE MISSION AND DESIGN, Third Edition.
• This book is under copyright protection, and slides in this class incorporate drawings from the book.
• Therefore, these slides are presented only on the condition that each student viewing the class owns the above book.
• This presentation has alternative interpretations and updates to bring the class to the present space era.

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The Class Outline

1. The Space Missions Analysis and Design Process
2. Mission Characterization
3. Mission Evaluation
4. Requirements Definition
5. Space Mission Geometry
6. Introduction to Astrodynamics
7. Orbit and Constellation Design
8. The Space Environment and Survivability
9. Space Payload Design and Sizing
10. Spacecraft Design and Sizing
11. Spacecraft Subsystems
12. Space Manufacture and Test
13. Communications Architecture
14. Mission Operations
15. Ground System Design and Sizing
16. Spacecraft Computer Systems
17. Space Propulsion Systems
18. Launch Systems
19. Space Manufacturing and Reliability
20. Cost Modeling
21. Limits on Mission Design
22. Design of Low-Cost Spacecraft
23. Applying Space Mission Analysis and Design
Squeezing 976 Pages Into 3-Days

- This three day class cannot cover every aspect of a 976-page book
  - We will cover the essentials, which means keeping each chapter to about 17 slides and one hour, on average
- Some More, Some Less (and there tends to be overlap in chapters which will be eliminated as much as practical)
The Book

- The companion book, your reference and text book, is a good compilation of experiences that fairly collects the process of creating space missions
  - With significant overlap
  - With engineering opinions (not science) as to reducing costs
  - With cost reduction strategies for specific niches
  - With lessons learned

- As we learn about Space Mission Analysis and Design, keep in mind that there are things we should change, things that are dangerous to change, things done without true understanding of why they are being done and decisions that are made that constrain us needlessly
  - As we shall see in the next four charts;
Why Shouldn’t We Change Things?

• According to Harrison Storms (1916-1992)* a problem occurred in the Apollo Program that baffled engineers
  – An NTO Tank under test with NTO (Nitrogen Tetroxide) suddenly failed, unexpectedly, and for no reason, twice
  – Eventually, the engineers questioned the suppliers of NTO \( (\text{N}_2\text{O}_4) \), asking “is there anything different with the batch of NTO you supplied?”
  – The answer was “yes, this is for the Moon program, so we double-purified the NTO!”

• It turns out that double purifying the NTO reduced the water content to a point that NTO unexpectedly attacked titanium, as it did not normally do so with “normal-grade” NTO

* According to the controversial Book by Mike Gray, Angle of Attack
Why Should We Change Things?

• A general visited Vandenberg AFB * in the early part of the space age to watch a payload being lifted to the top of a service tower or gantry
  – The procedure had the payload lifted by service tower overhead crane, paused, moved sideways, paused, lifted upward, paused, moved sideways paused, moved the other way, paused, moved upward to the payload level paused, and then moved in to the service tower
• At each pause, an inspector stamped a completion of the procedure step
• “Why didn’t the procedure have the payload go straight up, without moving sideways twice?” Asked the General
• “There used to be a beam we had to go around,” said the Test Conductor, “and we never changed the Procedure”

* Second-Hand Story, validity cannot be guaranteed
Why Flippant Decisions Can Haunt Us

• This from an Engineer on the team that designed the McDonnell-Douglas Thor (later Delta) in the mid-1950s
  – The USAF Thor IRBM rivaled the Army Jupiter IRBM
  – An engineer at a Review was discussing the advantages and disadvantages of putting the LOX tank above or below the Fuel tank
    • The engineer knew the LOX tank should be on top to shift the CG forward to nearer the Cp
    • “Where is the Army placing their LOX tank?” Asked the Air Force Program manager
    • “On top” replied the Engineer
    • “Then we’ll put ours on the bottom” the PM ordered
• The Delta-II still has the LOX tank on the bottom
• The original Delta-IV design in Late-1990s wasn’t working out, until the design was changed to put the LOX on top

* Second-Hand Story, validity cannot be guaranteed
Why We Need to Document Our Reasons

- The Viking Sounding Rocket, which later became the NASA Vanguard first stage, was an early American rocket design program
  - A design controversy involved the shape of Viking tail fins, should they be triangular or be like arrow feathers like the German V-2
  - At the next major Review, the V-2 style fins were favored
  - At the Review, a former German engineer asked why the tail fins were similar to the V-2 shape?
  - The engineer said it was because it was assumed the Germans had a good reason for their tail fin shape
  - “Yes,” said the German Engineer, “we had to use a long and narrow shape for the fins so they could be transported through railroad tunnels
- Eventually, the Viking had triangular fins

* Second-Hand Story, validity cannot be guaranteed
This Class Tailored to MSFC

• Space Mission Analysis and Design is a class that is so wide, but of limited depth, that it can be tailored to the needs of specific organizations
  – Some emphasis on propulsion issues will be made to be more relevant to Marshall Space Flight Center
• We want the training to help keep MSFC and NASA on the cutting edge of excellence, and avoid the kind of story, below;
• **Lawmakers Slash $670 Million From NASA Budget Request**
• WASHINGTON 6/8/09—In a move that reflects the uncertainty surrounding NASA's current strategy for replacing the space shuttle and returning astronauts to the Moon by 2020, House appropriators slashed by 16 percent the space agency's $4 billion request for manned space exploration in 2010.
The Space Missions Analysis and Design Process

Space, the final frontier!
Space Mission Analysis & Design Process

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

Characterize the Mission
- Characterize mission concepts and architectures
- Identify critical requirements

Evaluate the Mission
- Define and Evaluate mission utility
- Define mission concept (Baseline)

Define Requirements
- Define system requirements
- Allocate requirements to system elements

Reference Pages 2-5
Space Mission Analysis and Design

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Changes in Future Space Missions

- Maturation of Technology
  - Solid State Revolution
    - Tube era → Transistor era → Large Scale Integration
      - 1957 to present
- Increasing use of on-board processing
  - More processing on spacecraft, less on the ground
  - Less communication bandwidth requirements
  - Less ground intensive operations
- Continuing emphasis on low cost missions
  - Better, Faster, Cheaper era
  - Smaller satellites with greater capability
  - Lower budgets for space
    - Since end of the Cold War and collapse of Little LEO
Space Mission Life Cycle

• Life cycle phases vary from one organization to another
  – Concept Exploration
    • Early requirements and trade studies to refine the mission concept are explored and documented
  – Detailed Development
    • All requirements and specifications are published and the detailed design is executed to completion
  – Production and Deployment
    • The Hardware and software is produced. Loaded, tested, evaluated, changed as needed and finally launched into space
  – Operations and Support
    • The spacecraft, now in space, is operated to complete the mission objectives and problems are resolved

Reference Pages 7-12
Space Mission Analysis and Design

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Phases of a Space Mission

Table 1-2, Page 8
Space Mission Analysis and Design

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All space missions involve
- Subject of the mission
- Launch to the orbit
- The orbit location
- A payload and spacecraft
- Command and control
- Ground Elements
- Mission Operations
Multiple Organizations Involved

Customer or Scientists
i.e. Boeing et al

Government i.e. NASA

Figure 1-2, Page 9
Space Mission Analysis and Design

© 2009, Edward L. Keith
What is Wrong With This Figure?

Lowest cost ≠ Highest Value

Is the total cost curve realistic?

Spacecraft Design Life
Where is Revenue or Value Curve?

Figure 1-5, Page 17
Space Mission Analysis and Design

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Step 1 Definition of Mission Objectives

- Define mission objectives
  - Broad Goal from the mission statement
    - Primary and secondary
    - Incorporate the needs of the user
- The book does not suggest that the definition of mission objectives is a large document
  - The implication is that the Definition of mission objectives can be a paragraph
    - Shorter than the vague description
Step 2 Preliminary Estimates

• preliminary estimate of mission needs. Requirements and constraints
  – Functional Requirements
    • To define how well the system must perform to meet the mission objectives
  – Operational Requirements
    • How it will be operated and how users will interact with the results of the mission
  – Constraints
    • Limits on cost, schedule (deadlines), and implementation techniques selected
      – Example – Do ASPR apply, NASA SE Handbooks, ITAR, etc.
Is SMAD the Ultimate Roadmap?

• The textbook for this class is good, it has the points of view of a spectrum of authors
  – Like every technology, some is already obsolete
  – The methods and procedures suggested in the book are generally Business as Usual (BAU) and support the status quo
  – Some material suggests better ways of doing business
    • But they cannot necessarily be universally applied
  – Can more science be applied to better our way of doing business?
    • Optimization
    • Relationships
    • Decisions
Conclusions and Observations

• This is the start of a roadmap for developing space missions
  – Some of the roadmap is vague, philosophical and soft
  – Other parts are solid, like the Regime (USAF, NASA, ESA) managing programs with hard requirements like Quality, Inspection, Traceability and other standards than must be complied with

• There is a lot of iteration in the Space Mission Analysis and Design process
  – Which explains part of the reason it takes many years to create a space mission

• This class is invited to read the FIRESAT Mission example, but it will not be used in this class
The “Fuzzy” process of Mission Characterization is explored in this Chapter.
Introducing Mission Characterization

• Mission characterization is the process of selecting and defining the space mission
  – By applying requirements and constraints to pare down the list of alternatives
• Mission Concept
  – “A broad statement of how the mission will work, in practice”
• Mission Operations
  – “The details of how people will operate and control the mission”
• Mission Architecture
  – “Mission Concept plus a definition of each major element of the mission”

Reference Pages 19-20
Space Mission Analysis and Design
Concept Evaluation Flow

- The Concept Evaluation flow is not satisfactory because
  - Where is the exit?
  - Is this an invitation to analysis paralysis?
  - A justification for the fact it takes about seven years, if all goes well, to get a satellite program off Terra Firma?
- The Authors have probably mapped the process accurately, but is the process optimized?
  - You be the judge

Reference Figure 2-1, Pages 20

Space Mission Analysis and Design

ATI 0-27
Alternative Mission Concepts

• There are always different ways to skin the proverbial cat
  – The book implies that different mission concepts be created and judged
  – An alternative is to have one Mission Concept and trade the details
  – In practice, there are times when the Mission Concept is a “given” and the design team must work within the constraints of the given mission concept
• Example – Voyager “Grand Tour” mission began with the observation that the planetary alignment to visit all the outer planets was occurring shortly, and wouldn’t repeat for a couple of centuries, so the mission concept is to swing by all these planets
  – The trades were what measurements to make
Data Delivery

• Types of Data
  – Mission Data
    • Payload Purposes
  – Housekeeping
    • Support for the Mission
    • Attitude, orbit, temperature, battery voltage, etc.
• Principal Trades
  – Space vs. Ground Processing
    • How Split
  – Central vs. Distributed Processing
  – Level of Autonomy
    • Part of the Space-Ground Trade
• Mission and Housekeeping Fusion (as in attitude and Mission)

Reference Pages 24
Space Mission Analysis and Design
Space vs. Ground Processing Trades

- This trade made possible by high-capacity small computers and large-scale integrated circuits of all kinds
- Autonomy
  - How much interactivity is desirable?
- Latency of Data
  - How much delay in data delivery is acceptable?
    - Near real time or store and forward
- Space processing allows the data to be “compressed” to exclude unwanted data, thus reducing the communications requirements for the mission
- Space processing, or autonomy, allows some operations and decisions to be made on the spacecraft, reducing the ground segment burden
  - Decisions are normally ground-based

Reference Pages 25
Space Mission Analysis and Design
Alternative Mission Architectures

- A Mission Architecture consists of a Mission Concept plus specific set of options
  - We can have more than one Mission Concept
    - Each can have several options for each element of the mission
      - How do we gather the mission information?
      - How do we process the mission information?
      - How do we transmit the mission information?
      - What location (Orbit) do we gather the mission information from?
    - Etc.
- Each element is “Traded” internally to each architecture and more than one architecture is evaluated

Reference Pages 95-130
Space Mission Analysis and Design
System Drivers

• “System Drivers are the principal mission parameters or characteristics which influence performance, cost risk or schedule and which the user or designer can control”
  – Size
    • Size is limited by fairing size of the launch vehicle and affects antenna diameter, aperture size and the mechanisms required to deploy antennas, solar panels and other appendages
  – On-Orbit Weight
    • Heavier weight on orbit drives the design to require larger and more costly launch vehicles
  – Power Requirements
    • Power requires generation (solar panels) and storage (batteries), all which add to cost and weight

Reference Pages 95-130
Space Mission Analysis and Design
System Drivers (Continued)

- Data Rate
  - Selection of data rates drive processing and antenna size (higher rates may require more effective power, obtained from antenna gain from larger antenna and greater power amplifier output)

- Communications
  - Drives coverage, availability and ground station or relay satellite requirements

- Pointing
  - Resolution and system accuracy pushes up system cost

- Number of Spacecraft
  - Coverage, frequency of observations and overlap increased at an increase of cost
System Drivers (Continued)

- Altitude
  - Launch vehicle performance (payload capacity) is reduced with altitude, but coverage increases
  - Should include inclination choice at this point, as higher inclination decreases payload capacity but increases the portion of the world covered by the mission
    - Should be included in On-Orbit Weight
- Coverage
  - Geometry and timing affected by coverage
  - A function or Orbit, Altitude and maneuvering requirements
System Drivers (Continued)

– Scheduling
  • Timeline, operations, timing and communications can be traded for mission utility, coverage and responsiveness

– Operations
  • Cost, ground station manpower and communications
  • Operations identified (wrongly?) as a frequent cost driver, principal error source (really?) and “pushes demand for autonomy”
    – Note: the author / editor of this text is a strong proponent of spacecraft autonomy
    – Operations, especially NASA operations, has a history of saving lost missions
      • Apollo 13, Galileo, Hubble, etc.
Characterizing Mission Architecture

- This is the Authors (Wertz and Reinert) view of the process of characterizing the Mission Architecture
  - Looks like organized chaos? Where does the Rat get out? Where is the Cheese?
  - The process can be complicated, but do we really need to institutionalize it?
  - What do you think?
Conclusions and Observations

• The Authors have really done a good job of mapping the processes, and even in adding clarity and organization
  – The critique of this chapter especially, and the book in general, is that we should be doing much better in Space Mission Analysis and Design than we are
    • That will be your long term assignment;
      – Make the system work Better, Faster, Cheaper
        • So we can get more bang for the Buck
    • The purpose of this chapter is to make sure we have explored alternatives to a depth that we are making good decisions
      – Not throwing the baby out with the proverbial Bathwater
**Very Long Mission Life Cycle**

- Mission Life Cycles can space a career
  - Seven years from concept to launch is not an exaggeration, it is a goal for fast-moving projects
- NASA Gravity Probe Life Cycle
  - Proposed (1959) by MIT Professor George Pugh
  - Proposed and supported by NASA (1961)
  - Funded (1964-1977)
  - NASA changes launch vehicle from Shuttle to Delta-II (1986)
  - Launch (2004) and still flying
  - Preliminary results announced (2007)

“We thank NASA for forty-four years of continued support since issuing the first Research”

http://einstein.stanford.edu/highlights/status1.html

Space Mission Analysis and Design
Mission Evaluation

The Concept Refinement must include evaluation of the candidate mission concepts. This chapter explores Mission Evaluation and the Go or No-Go gate determining if the Concept is acceptable.
Identification of Critical Requirements

- Look at the principal performance requirements
  - Coverage or response time
  - Resolution
  - Sensitivity
  - Mapping Accuracy
  - Transmit Power
  - Orbit Lifetime
  - Survivability
- Look at top level requirements
- Look for hidden requirements
Mission Utility

• “Mission Utility Analysis quantifies mission performance as a function of design, cost, risk and schedule
  – This is an area where a controversy should occur
  • Performance of the design can be subjective
    Cost is analyzed by cost models, and should be accurate to about +/- 30%
    • If there is a cost over-run, it is usually in coincidence with a cost over-run
  • Risk tends to be poorly assessed by Engineers
    – Pressure to conform
    – Highly Subjective
    – All to often in ignorance of history
Mission Analysis

• “Mission analysis is the process of quantizing the system parameters and resulting performance”
  – Document reasons for choices
  – Spread Sheet documentation allows for dynamic analysis and updates
    • Now a common practice
  – Feasibility Assessment
  – Size
  – Point Design
    • Description of the Concept under study
  – Performance Assessment (Parameters)
  – Utility Assessment (How well)
Mission Concept Selection

- Go – No-Go Decisions
  - Does the candidate system meet the overall mission objective?
  - Is the candidate system technically feasible?
  - Is the level of risk acceptable?
  - Are the schedule and budget within established constraints?
  - Do preliminary results show this option to be better than non-space solutions?
    - See next Slide
  - Does the mission meet political objectives?
    - Space Shuttle, Space Station and Dinosaurs
Special Observations

• There have been instances where non-space solutions have been a serious blow to space programs
  – Iridium and Global Star went bankrupt when competing against terrestrial-based cell phone technology
  – Transponder leasing rate fell 10-fold (from $300 per hour to $30 per hour) as a result of undersea fiber optic cables that provided better (clearer, less delay) digital wide band communications previously served by satellite

• Beware of wild ideas for space applications that can be done on Earth
  – Terra Form Venus and Mars when no one wants to Terra Form the Sahara Desert
  – Space Power, when 10,000 square miles of ground solar-thermal or photo-voltaic will meet all domestic power needs
Conclusions and Observations

• The chapter is long on wording but short on objective metrics in Mission Evaluation
  – Mission selection is often more political than logical
  • As recognized by the Chapter authors
• Suggested Alternative
  – Monetize all parameters to achieve a common denominator
  – Evaluate Risk based on Historical Observations like Cost Models use historic cost
  – The design team is probably the worst organization to evaluate Risk, and realism of the Schedule
  • All too often over-optimistic

Let’s explore Advancing Risk Management in the next 5 slides
Current Risk Management Process

- Risk are tracked by Specific Risk on a “Color Grid Chart”
  - According to Likelihood (Red, Yellow and Green)
  - And According to Consequences

- Identify all risks
- Determine probability
- Model outcomes

- Risk Mitigation
- Return to Realism
- Back-Up Plans
Risk Mitigation Plan (Bad Tire)

- Found Split in tire on night of August 2\textsuperscript{nd} at La Verne California en route to Las Vegas Nevada (228 miles)
  - Consequences of High-Speed Blowout Severe
  - No replacement until morning, spare good for only 50 to 100 miles
- Reduce speed from $> 80 \text{MPH}$ to $< 60 \text{MPH}$
- Re-Inspect in Barstow
- Near Range of Spare
- Arrive in Las Vegas
- Replace Tire
- Next Morning

Not in SMAD Book
What’s Wrong With The Process?

• What is wrong with the prior Risk Mitigation Plan?
  – Treats Management like “Comic Book Readers”
  – Very Subjective (both to likelihood and consequences)
• No real Science behind the process
  – No assurance all risks are really and realistically addressed or classified
  – Decisions made from such charts may be far from optimum
  – Risk mitigation strategies may be superficial and unresponsive to real world factors
• A better system is highly desirable, but requires less laziness in implementation and operation

Not in SMAD Book
Alternative Risk Management

- Scientific Characterization of Historic Risks, with statistical values determined from history
- Quantify the likelihood of all risks as a probability function
- Quantify consequences in terms of a common denominator
  - Cost ($)
- Rate risk mitigation on the criteria of lowering the product of the probability of events or occurrences happening and the cost consequences
- Identify every significant risk
- Identify inter-related risks
  - i.e. Cost Risk & Schedule Risk, where a Schedule slip causes a cost overrun
- Integrate and Model (using Computer application) risks
- Track Changes in Risk Make decisions on trends

Not in SMAD Book
Adding Science to the Analysis

• Can we add the Scientific Method to Risk Analysis?
  – Yes, by analyzing the cause of past failed Projects and creating a data base of the problems that caused the failure

• Try This
  – Go to the local Technical Library and look up back issues of AVIATION WEEK or SPACE NEWS over a period of several months, at least 10-years back
    • How many Projects were announced?
    • How many succeeded?
      – Succeeded / Announced \( \rightarrow \) Near Zero or Low
      • Yet the supporters of each one honestly believed at the time that their project was a “Sure-Fire Winner”

Not in SMAD Book
You have enjoyed ATI's preview of

Space Mission Analysis and Design

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