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16.89J / ESD.352J Space Systems Engineering  
Spring 2007

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## 1.0 GENERAL DESCRIPTION – SPACE SYSTEMS ENGINEERING: 16.89

*Note: The following paragraphs are a general description of the 16.89 Space Systems engineering course. Individual projects for 16.89 vary from year to year, and not all the descriptions are completely applicable every year. However, the generic requirements are included here to allow students to appreciate the general context of 16.89 projects.*

Systems Engineering and Architecture (SE&A) tells a story. It is a careful marriage of fact and vision. The story must be self-consistent and factual. At the same time, the result must be visionary either in the way in which it meets the customer needs, advances scientific knowledge, exploits new technology and processes, or reaps return for investors. Good analysis guarantees success but vision sells the concept.

Systems Engineering and Systems Architecting have different definitions for different people. However, each definition contains some common elements. One definition is “the ensemble of coordinated analyses, simulations, and processes which lead to the design of a technical product which best meets the needs of an identified customer.” It is essential that any systems design tell the “whole” story. The whole story consists of why, which, what, how, when and where.

- *Why:* The functional requirements define the customer’s needs and why the mission is worth conducting.

Note: Some requirements might be known at the start, but others might evolve over time.

- *Which:* The trades analysis compares different mission architectures and determines which architecture best meets the requirements and therefore the customer’s needs.
- *What:* The design describes what will actually be built and operated to conduct the mission.
- *How:* The program plan describes the organizational structure, resource allocation, funding profile, and schedule. In essence, it describes how the mission will be deployed.

- *When:* As part of the program plan, the schedule describes when different mission development and deployment stages will occur and how they depend upon each other.
- *Where:* Also as part of the program plan, the hardware flow details where the following are located: component procurement sources, sub-system integration facilities, test and validation sequence as well as checkout and launch facilities.

## **2.0 ORGANIZATIONAL STRUCTURE**

Space Systems Engineering (16.89) is a twelve (12) unit course consisting of four (4) hours of lectures, (2) two hours of “laboratory” (team meetings) and six (6) hours of homework and personal preparation per week. (Note that for this course, there is not necessarily a hard distinction between laboratory and homework.) Lectures and some of the laboratory work will take place Wednesdays and Fridays from 9:00 a.m. to 11:00 a.m., although a few lectures might occur on other days depending on external guest speaker availability. Other laboratory work will be conducted during standard academic hours to be scheduled amongst the students in their respective teams.

## **3.0 SCHEDULE AND WORK BREAKDOWN STRUCTURE**

Good scheduling is key to getting the work done in the time allotted. Formal reviews provide not only an opportunity to present progress on the program but also provides intermediate milestones for making sure that the SE&A story makes sense and that the various parts of that story fit together. If problems are revealed, careful

scheduling (planning) allows the team to understand how the remaining time can be most effectively used to finish the work, while correcting the problems. The course schedule will be posted separately and may change as needed by the various demands that will be placed on the program. However, the final step in the program, the **Critical Design Review (CDR)**, can not be delayed.

### 3.1 Program Schedule

Traditional program planning consists of three formal presentations (milestones): the System Requirements Review (**SRR**); the Preliminary Design Review (**PDR**); and the Critical Design Review (**CDR**). The work toward these milestones is broken into three phases: the Conceptual Design Phase; the Preliminary Design Phase; and the Detailed Design Phase. The documents that support these milestones may exist in hardcopy but must also exist in electronic form accessible to the entire class and controlled when appropriate. These documents and the associated presentations are described in more detail in Section 6.0.

The following description of the traditional design phases is included here for context, as described at the beginning of Section 1.0. Some but not all of these elements will be included in the Spring 2007 project.

The objective of the Conceptual Design Phase is to arrive at one or two mission architectures which meet the needs of the customer in a significantly more effective fashion than other candidate architectures. To this end, several tasks must be completed which are described below. The relevant document is shown in parentheses:

1. *Extract Customer Requirements:* The mission is being designed for a customer. It is essential that the team understand the needs of that customer. These needs must be translated into customer requirements which guide the development of the program. These requirements are stated in the language of the customer. The design should be periodically compared back to these requirements during the program. [SRR]

2. *Functional Requirements:* The functional requirements are created from the customer requirements and mission timelining. The functional requirements explain what must be achieved by the mission design but not how it should be done. The functional requirements are stated in engineering terms. [SRR]
3. *Architectural Options:* All plausible technical options for implementing the various elements of the mission will be listed. The open literature, space mission databases, textbooks, Internet, Engineering Advisors as well as other sources should be used to identify these options. Then, those element options which are compatible with other element options are combined into a systems architecture. If an architecture meets the customer and functional requirements, it is considered a candidate architecture for the mission. [Design Document]
4. *Metric Definition:* Only a formal and quantifiable method for measuring the ability of each candidate architecture to meet or exceed the requirements allows a fair downselection to the architecture to be further developed in subsequent design phases. These metrics should include performance and cost but can also include time, reliability, etc. [Design Document]
5. *Trade Analysis:* Given the metrics, each candidate architecture needs to be studied in some detail in order to quantify how each ranks with respect to the defined metrics. This study requires understanding of some of the functional dependencies between performance and cost and consumed resources such as mass, power, time, etc. [Design Document]
6. *Downselection:* A formal downselection must lead to one or two architectures which merit further study. If a second architecture is carried forward, it should only be retained if it provides an alternative to some very high-risk element in the first architecture, if it represents a descoping, or if it is deemed comparable to the first architecture. [Design Document]

It is important to realize that decisions made during the Conceptual Design Phase, a phase which always consists of the least amount of funding, commits most of the funding that will be spent in subsequent phases. If a decision proves to be poor, it is difficult and

expensive to change in the subsequent design phases. In other words, “Roughly 10% of the resources are used to determine how to commit the remaining 90%.”

The objective of the Preliminary Design Phase is to take a “straw man” mission architectural concept and develop the design in more detail. Functional requirements are flowed down to technical system and sub-system requirements. The design explains how the system achieves its requirements and how the sub-system functions are allocated. The tasks to be completed are listed below:

1. *Respond to SRR Action Items:* A formal presentation such as the SRR allows outside experts to review the design and suggest alternatives, corrections, and solutions. These comments are collected at the end of the review, ranked by priority, and assigned to a representative of the team as “action items.” Action items are completed as soon as possible and formally closed at a team meeting. [Design Document]
2. *Requirements Flowdown:* The customer and functional requirements are flowed down to the sub-system level. At this level, they are stated in technical terms and start to describe how the mission will work at the system and sub-system levels. [SRR]
3. *Interface Refinement:* After the SRR, the organization of the teams might change, and groups of people will form more clearly defined groups around individual disciplines such as environmental control and life support, power, propulsion, etc. A formal definition of the new organizational structure as well as definitions of each group’s interfaces is needed. These interfaces define what each group needs to know in order to do their analysis as well as define the type and format of information that that group will provide to others.
4. *Module Development:* With the team broken down into sub-system disciplinary groups, software modules (probably written in MATLAB code) which relate sub-system performance and cost to sub-system requirements will need to be developed. For example, the power group will need to relate cost, mass, volume, lifetime, and

heat load of the power system to inputs such as peak power, average power, watt-hours, duty cycle, etc. [Appendices to Design Document]

5. *Module Analyses:* With sub-system modules in place, sub-system trades are conducted. For example, the impact of variations in power consumption, hardware mass, number of units, etc. on system cost, performance, reliability, etc. is calculated. This is a highly interactive process and works best if conducted concurrently among the team members. These software modules will enable integrated concurrent engineering sessions.
6. *Budget Development:* The systems group will develop budget tracking methods to monitor the inevitable growth in resource consumption during the semester. Resources such as mass, power, computation, reliability, volume and cost will be tracked. The systems group will hold margins (30% at PDR and 20% at CDR). The systems group will also re-allocate margins between groups in order to balance the difficulty of the design effort. [Design Document]
7. *Detailed Timelining:* The details of the chronology of events also impact the design and warrant further analysis. [Design Document]
8. *PDR Preparation:* Preparing for the review is not simply “viewgraph engineering.” It forces the SE&A story to be coherent and correct. Do not under-estimate the effort associated with this task.

The Preliminary Design Phase is where teamwork is defined. Most design failures can be traced back to poor teamwork. One of the hardest parts of systems engineering is the management of interfaces. There will be times when your work requires input from others in the class. Oftentimes, this input may not be forthcoming for a variety of reasons. Sometimes, it is in the best interest of the project to make assumptions, proceed with your analysis, and present your results to those with whom you need to interface. If you’ve performed the analysis correctly, changing the value of an input should not take too long. “Don’t demand or accuse, help!”

The objective of the Detailed Design Phase is to develop the design such that once the final design review is successfully completed, the program is ready to “cut metal.” This is

actually the definition of a traditional “Critical Design Review” (CDR), but this course will not go to this level of detail. However, detailed block designs of the sub-systems will be required. These must be sufficiently detailed such that they can be simulated to verify that they meet their requirements. Most of the tasks started during the Preliminary Design Phase are continued in more detail during the Detailed Design Phase. The Program Plan details the organization, workforce, schedule, spending profile and other programmatic issues associated with the implementation of the mission beyond CDR. “The Design Document explains what you are going to do while the Program Plan explains how you are going to do it.” The Detailed Design Phase is where underestimates, design errors, and bad interfaces are revealed. Efficiency in the design as well as in how the team works together is critical.

### **3.2 Lecture and Laboratory Schedule**

A draft schedule for the course is provided on the Stellar web site as a separate document. This schedule will be updated as the semester progresses. Unscheduled periods will be used for design work. Periodically, outside visitors may make presentations to the class, followed by an interactive time for questions and answers. Some class periods have no lectures planned. These provide scheduled times when the faculty and staff will be available to assist in the effort.

## 4.0 DELIVERABLES

The deliverables in 16.89 are highlighted on the course schedule:

1. Assignment #1: Existing Designs for Major Astronomical Telescopes
2. Assignment #2: Preliminary Study of Telescope Design Options
3. System Requirements Review (SRR) presentation
4. System Requirements Document
5. Preliminary Design Review (PDR) presentation
6. Preliminary Design Report
7. Critical Design Review (CDR) presentation
8. Final Design Report

All documents will be presented formally by class members. Each class member must take part in at least one formal presentation.

## 5.0 MODULE DEVELOPMENT

*Note: Traditional Space Systems Design projects are usually oriented towards hardware design, in which case the module development described below typically concentrates on modeling subsystems. The Spring 2007 design project will undertake this kind of computer modeling exercise only in the second part of the semester, once the requirements and architectural tradeoffs are complete. The following is a description of the traditional, subsystems-oriented module development.*

During the semester, each student will be responsible for developing and utilizing a software module. This module describes the particular discipline for which that student is responsible and mathematically captures the relationships between that discipline's inputs and outputs. There will be times during the semester when one person will ask another how much that second person's sub-system will change (outputs) in the event that the requirements on that sub-system change (inputs). For example, a power subsystem module might describe how the mass, volume, and reliability change if the required watt-

hours, battery (dis)charge duty cycle, and mission lifetime change. As another example, a systems module might describe how the total cost of the spacecraft changes as required power, mass, mission lifetime, and reliability change. These relationships can be derived from SMAD as well as other reference material.

These modules serve several purposes and may be combined with other modules within that person's group. First, they force the student to understand and codify functional relationships within their discipline. Second, they help to define and clarify interfaces between the different groups and modules. These modules will be codified, grouped with other modules within that group, documented, utilized, and submitted to the Design Document as an appendix.

If codified in Matlab, they can be linked as function calls (subroutines) with their strict definitions of inputs and outputs. During an integrated concurrent engineering exercise, the computer display of key assumptions and system budgets will be projected onto a screen in front of the class. The class will then alter assumptions and view the impact of these changes in realtime on the screen. In this way, design spaces can be explored and compared in fractions of the time conventionally required. Students will be graded on their modules. Remember, the module must be complex enough to capture the important relationships yet simple enough to provide outputs that make sense and code which is available in time to be used in these integrated concurrent engineering exercises. The modules are only useful if their information is correct and they are available on time. The following deliverables are required for each student's module:

1. Definition of interfaces (inputs and outputs) and module content (i.e., module requirements). Be sure to specify units for different variables.
2. Module development: mathematical relationships, software code, and code validation.
3. Contribution to the Concurrent Engineering exercises.
4. Module refinement: list features to be refined, mathematical alterations, software code, and code validation.

5. Final submittal to Design Document appendix: module requirements, mathematical relations, code, validation, and use history.

## 6.0 COMMUNICATIONS

### 6.1 Daily Communications

An email list will be established. It should be used to augment communication between individuals and groups in the class. Faculty will not be on this list.

### 6.2 Weekly Communications

**The instructor staff will meet weekly (time and place TBD) to discuss progress in the class.** Representatives from the class will on occasion be asked to come and talk with the staff at this meeting.

Each student will from time to time give informal progress reports for their team. Report assignments will be made as the semester evolves. The purpose of the reports is to make the other students aware of the progress and needs of that team. These reports will summarize the progress of that student's team, plans for near term work, and solicit and information needed from other teams.

### 6.3 Oral Presentations

High quality presentations are important for communication of what you are doing. Every student is expected to make at least one oral presentation during the term. The oral presentations are listed below. Part of the grade for each student will be on the technical contribution to all formal presentations as well as on the delivery of their portion of presentations. A small group of students will be assigned to coordinate each of these presentations (a different coordinating group for each presentation). These reviews are discussed in more detail below:

1. *System Requirements Review (SRR)*: The primary objective is to present and formally accept the written Requirements Document. This is the guiding document for the development of the telescope architecture options that will comprise the bulk of the

work for the course. It is critical that the class agree early on what requirements the system will have to satisfy. A design effort without clearly stated requirements is doomed to failure.

2. *Preliminary Design Review (PDR)*: The teams will each present the status of their individual design efforts, showing how their selected architectures meet the design requirements.
3. *Critical Design Review (CDR)*: This will be a unified presentation for the entire class. The main content will be the telescope architecture that the class recommends NASA to implement. The process that was followed for arriving at this architecture as well as supporting rationale (calculations ...) must also be included.

## 6.4 Documents

The lasting value of the work done for this course will consist primarily of the two documents which the class will produce. The documents will include sections written at two different levels. The documents must be technically correct and should represent an appropriate level of work for MIT graduate students; however, if the work is to have an impact outside MIT, the documents should include sections addressed to non-technical audiences, people with an interest in space but not a high level of technical expertise (such as the media or congressional staffers).

The following two (2) documents will be prepared, maintained and eventually integrated by the class. Always reference the sources of information and ideas in the documents. These documents must be electronic in nature and accessible to the entire team.

1. *Requirements Document*: defines the “goods and services” that are required of the design. This document constitutes the “contract” between the customer and the systems engineering and architecting team. Sometimes, part of this document is written by the customer. At other times, it results from a study by the systems team to determine the needs of a customer in order to assess the viability of a new product. **For the Spring 2007 design project, the class will determine the design**

**requirements flowing from the NASA Lunar Architecture Study mentioned earlier in this document.**

- Design Document:* captures the specifications for the system. It also captures the rationale that led to these specifications. To this end, the trades analysis, requirements pushback, budgets, system and sub-system designs, analysis tools and simulation results are included. Requirements pushback is the analysis that verifies that the design meets the requirements. This is in contrast to the requirements flowdown, which simply allocates requirements with minimal knowledge of the implications of these allocations. Requirements pushback is essential to determine whether the design meets the requirements and whether one or more part of the overall system is facing particularly stringent requirements while others face more lenient requirements. This allows proper balancing of the allocated requirements.

## **6.5 Web Page**

A web page will be maintained as the electronic repository of the current 16.89/ESD.352 documents. This page will provide all team members access to the current versions of the program documents. In addition, it will enable our engineering advisors to have access to this same information. This will allow them to track the progress of the class and provide comments and suggestions throughout the duration of the semester.

**It is the students' responsibility to check frequently if updates or new materials and announcements have been posted.**

## **7.0 GRADING**

Grading for 16.89/ESD.352 will be based upon the criteria shown in the following table. The percentage weights of each item and a brief description are provided. These grades will be reported to the students in their end-of-term grades as well as at least once during the term.

**Table 7.0: Grading Categories and Weights**

<b>Criteria</b>	<b>Grader</b>	<b>Total Weight</b>	<b>Number</b>
Written documents	Faculty and Staff	20%	2
Oral presentations	Faculty and Staff	20%	5
Presentation View Graphs	Faculty and Staff	15%	5
Colleague reviews	16.89 students	15%	1
Analysis/SW development	Faculty and Staff	20%	1
Class Participation	Faculty and Staff	10%	-

- 1) *Written documents*: Each student will author portions of the two required documents. Their contribution will be clearly indicated using initials.
- 2) *Oral presentations*: Each student is required to participate in at least one of the oral presentations during the semester. The faculty and outside advisors will grade both the students' presentations as well as the quality of the presentation material.
- 3) *Formal presentation View Graphs*: Each formal design review presentation will be accompanied by annotated viewgraphs provided electronically and in written form by the students to the faculty. Each student's contribution to the written presentation will be indicated by their initials.
- 4) *Colleague reviews*: Students will turn in, shortly before Spring break, their evaluations of their student colleagues. These will include discussions of the ways in which each student interacted with other students in the class, the usefulness of these interactions, areas in which the other students excel, and areas in which the other students can improve. If none of the students say that they worked with you, it will reflect poorly on your team working skills. The specific format of this evaluation will be discussed later.
- 5) *Software development*: Each student will be responsible for the development of some software or analysis that contributes to the class design effort. In some cases, contributions other than software may be used instead.
- 6) *Class Participation*: This design project is a team effort. Class attendance and full participation is critical and will be graded.

**Academic Honesty:** The fundamental principle of academic integrity is that you must fairly represent the source of the intellectual content of work that you submit for credit. 16.89 is a design course heavily dependent on teamwork. It is important that individual contributions to the team effort be properly identified.

## 8.0 RESOURCES

### Books:

- 1) Larson, Wiley, and James Wertz, eds. *Space Mission Analysis and Design*. Torrance, CA: Microcosm Press, 1999. ISBN: 9781881883104. [ISBN-10: 1881883108]
- 2) Larson, Wiley, and Linda Pranke. *Human Space Flight: Mission Analysis and Design*. Columbus, OH: McGraw-Hill Companies, 1999. ISBN: 9780072368116. [ISBN-10: 007236811X]
- 3) Eckart, Peter. *The Lunar Base Handbook: An Introduction to Lunar Base Design, Development, and Operations*. Columbus, OH: McGraw-Hill Companies, 2006. ISBN: 9780073294445. [ISBN-10: 0073294446]