Space Systems Engineering
16.83J/12.43J/16.S898 (Spring 2019)
Room: 33-319 on Tue/Thur 2-5 pm

Ocean Worlds Space Mission Analysis: Finding Life in the Solar System

Department of Aeronautics and Astronautics
Department of Earth, Atmospheric, and Planetary Sciences
Massachusetts Institute of Technology

1 CLASS OBJECTIVES

The 16.83J/12.43J Spring 2019 topic is **Ocean Worlds Space Mission Analysis: Finding Life in the Solar System**. The objective of the class is to learn the complete space systems engineering design cycle "CDIO" [Conceive, Design, Implement, Operate] through the development of a project requiring integration of a complex space mission. Mission trajectory analysis, propulsion, power, scientific instrumentation, thermal, environmental control, autonomy, mass and cost estimates, and human-machine operations requirements will be developed. The complete engineering cycle will be **led by the students** guided by faculty and TA mentorship. Students participate in teams, each responsible for requirements, analysis, design and integration at the subsystem level. All students gain experience in project organization, interaction among disciplines, and technical communications. At the end of this course the students will have a fundamental understanding of 1) subsystem design and analysis and 2) scientific instrumentation design for a real aerospace science and technology mission. Communications requirements include: three formal team presentations, individual written progress reports, colleague assessments, and a final integrated team report formatted as a publication.

2 PROJECT DESCRIPTION

2.1 Background and Significance

The Aero/Astro and EAPS 16.83J/12.43J space mission capstone class for academic year 2018-19 will study Ocean Worlds Mission Exploration to search for, find, and identify life in the solar system. The three essential questions for exploration include: **Are we alone? Are there other habitable planets?** and **Is there life elsewhere in the Solar System?** Key to answering if life exists elsewhere are missions to explore ocean worlds – defined as a solar system body with a stable, globe-girdling liquid ocean[1]. Including Earth, we know of a dozen water ocean worlds in the solar system. Earth is the only one with surface oceans, which make it a model for habitable planets around other stars. Three moons, Europa (Jupiter), Enceladus (Saturn), and Titan (Saturn) have known subsurface oceans that hold invaluable knowledge about life in the solar system. Exploring these worlds will likely transform humanity's understanding of life, and our own existence, forever. The engineering and scientific challenges of conducting Ocean World Exploration are formidable, unprecedented and historic. Mandated by Congress, NASA is directed to create and conduct Ocean Worlds Exploration 'to seek out and discover extant life in habitable worlds in the Solar System' using a mix of existing programs within NASA[2].

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[1] Jonathan I. Lunine, Ocean worlds exploration, *Acta Astronautica*, 131 (2017) 123-130. https://doi.org/10.1016/j.actaastro.2016.11.017

[2] The Congressional Commerce, Justice, Science, and Related Agencies Appropriations Bill (CJS) directed NASA to create an Ocean Worlds Exploration program in 2016. https://www.govinfo.gov/content/pkg/CHRG-114hhrg20501/pdf/CHRG-114hhrg20501.pdf

2.2 Mission Statement for 16.83/12.43

Conceive and design an Ocean World Mission, prototype science instruments, demonstrate technologies, and create communications to assure a successful mission to detect life on other worlds.

The project will involve conceiving and designing a mission to the Jovian or Saturnian ocean worlds where trip times can be a decade, power is extremely limited, and science targets are global-scale oceans beneath kilometers of cryogenic ice[3]. Currently, we lack some scientific instrumentation, remote operational-intelligent technologies, sufficient funding and compelling story-telling and outreach to accomplish multiple ocean world missions within the next 5 years.

Lectures and assigned publications and readings introduce students to the overall missions, subsystems, and scientific objectives. Actually building and testing scientific life detection instrumentation is beyond the scope of what can reasonably be accomplished in 16.83, a one-semester capstone course. However, to provide hands-on experience we will work with students to 1) produce initial prototypes of scientific instruments 2) demonstrate technologies for remote operations, and 3) create media to virtually experience an Ocean World Mission.

3 Credit Units and Work

3.1 Credit Units

Space Systems Engineering (16.83) is a twelve (12) unit course consisting of three (3) hours of lecture, three (3) hours of lab, and about six (6) hours of outside classwork per week. These hours will be spent primarily in either individual work studying space systems engineering concepts presented in lectures or in group work to complete the design of the project. It is intended to be the design component of the senior capstone program, although junior-year students are welcome to join the class provided they have taken sufficient Professional Area Subjects so that prior class material can be applied to the space mission design process.

3.2 Journal Article Review

Two Ocean World journal articles are required reading for the first week of class, and are available on the Stellar class website.

B. Sherwood, J. Lunine, C. Sotin, T. Cwik, F. Naderi, "Program options to explore ocean worlds", *Acta Astronautica* 143 (2018) 285–296.

Jonathan I. Lunine, "Ocean worlds exploration", *Acta Astronautica*, 131 (2017) 123-130.

Each student will submit a written journal article review, on an additional article, relevant to the class project. The review will be on a journal article referenced in either the Sherwood *et al*. or the Lunine publications, but which cannot be a non-journal reference. The review should be no more than 2 pages in length, should follow a journal article format, and must summarize the main topics of the selected paper *and clearly demonstrate lessons learned from that paper relevant to the 16.83/12.43 class project*. The intent of this review is to further familiarize you with journal publications and to gain more in-depth knowledge of Ocean World Missions science and technology. It is also part of the communication requirement that 16.83J satisfies. The same

[3] B. Sherwood, J. Lunine, C. Sotin, T. Cwik, F. Naderi, Program options to explore ocean worlds, *Acta Astronautica* 143 (2018) 285–296. https://doi.org/10.1016/j.actaastro.2017.11.047

article may be reviewed by at most two students; an online-sign-up will be made available on a first-come-first-served basis.

3.3 Individual Progress Reports

You are required to write 2 individual progress reports that demonstrate your contributions and subsystem expertise. The objective of the progress reports is to allow the faculty to understand how much each individual has learned during the class and what contributions the student is making towards the class project. Faculty will assess scientific and technical understanding. Complete details and format will be provided during CI lectures.

3.4 Mission Requirements Review (MRR)

This is the first of three reviews that will be carried out as part of the design process. They are designed to introduce students to the type of reviews in which they will participate when working on "real world" projects for NASA or in the aerospace industry.

MRR Objectives: The goal of the MRR is to identify the requirements and current status of the mission design and to detail the plan for accomplishing end-of-semester deliverables. The students will demonstrate a robust knowledge of the current mission design, future plans, and logic behind requirement creation and flow down choices. Furthermore, they will provide a schedule with milestones detailing how they will accomplish their end-of-semester goals. The team will present for two hours total and should be prepared to answer questions during the review.

The **systems engineering and science/payload teams** will present on the mission development path including the following:

- Summary of system level requirements and objectives
- A detailed breakdown of sub-system level objectives and tasks
- System and sub-system level requirements, risks, and unknowns
- Detailed work schedule for the semester

Sample Presentation Content:

- Systems team overview: mission, budget, schedules

Sub-System Presentations (some of the following elements):

- Create story boards for communicating the Ocean Mission
- Requirement flow-down, constraints and interfaces
- Trades (e.g., modeling, simulation, analysis, engineering and science test units & evaluation)
- Risks and mitigation, budget, and schedules
- System risks and mitigation
- Plan for next phase

The presentation will focus on the science requirements, technology development, story-telling and the plan for flowing those down to sub-system requirements. The team will present the mission along with a rough design of how this mission will be accomplished, since the team should have a mature list of requirements that will lay the groundwork for the design of 1) scientific instrument prototypes, 2) technologies for remote operations, and 3) story boards for immersive communications in an Ocean World Mission.

3.5 Preliminary Design Review (PDR)

Objectives: The objective is to arrive at a precise statement of the system's design that will meet the requirements of the mission. Students will respond to any MRR action items. The team review will last 1.5-2 hours. The specific contents are listed below:

Sample Presentation Content:

- Systems and Creative/Comms teams overview
  - Preliminary review of the requirements (mission, virtual mission experience, budgets/costs, schedules) [Note: Some TBDs allowed at this PDR stage]
- Preliminary Media/Comms content for a virtual OW Mission
- Preliminary design of Scientific Instruments
  - System overview
    - Functional requirements
    - Design (drawings, schematics, etc.)
    - Evaluation of ability to meet requirements
  - Subsystems
    - Driving requirements, test objectives, design, operations
  - Budgets and Costs
    - Mass, power, data, costs, schedule, margin
- Prototype(s): plan, preliminary presentation (sketches, sub components, etc.)
- Plan for next phase: end of semester review (CDR).

3.6 Critical Design Review (CDR)

Objectives: The objective is to present a complete design, detailed through each sub-system, which meets all system requirements. Students will respond to any PDR action items and demonstrate the complete sub-system design details, including status, prototyping, and future work needed to be completed. The review will last two (2) hours. The specific requirements for each sub-system team are listed below:

Sample Presentation Content:

- Systems and Creative/Comms teams overview (mission, virtual mission experience, budgets, schedules)
- CDR
  - Detailed Sub-System designs (drawings, schematics, etc.).
    - Including science, functional, and physical requirements
- Technology Development Plan
- Prototype(s): final presentation (scaled drawings, sub components, software/code/algorithms)
  - Fabrication/build plan for prototype units
  - Constraints and interfaces
  - Integration & test plan
  - Detailed budget
    - Scheduling
    - Staffing

3.7 Final Deliverables: Team Journal Articles and Virtual Ocean Mission Experience

The final class deliverables at the end of the spring semester include: 1) a formal journal article-formatted document for all 6 teams. The journal article documents will be a synthesis of all the subsystem team members' relevant work from the semester formatted as a journal article. The document will include an Abstract, Introduction, Ocean World Mission Analysis, Results, Discussion, and Conclusion of the project.

The final deliverables will be evaluated for technical content and communications skills at the team level. This deliverable should combine and synthesize the critical results of all subsystems work. That means that each team will present design and analysis with substantial detail for an aerospace system that accomplishes all given requirements. The final articles must incorporate any prototype results that backup the subsystem analysis and designs. It is recommended, but not required, that students will submit the journal article to be presented at a conference(s) and/or submitted for journal publication in 2019.

3.8 Six (6) Subsystem Teams

Each student will be a contributing member of a subsystem team for the duration of the semester. Teams will be assigned early in the semester based on students' top priorities and desired skill enhancement. More information will be provided the first week of the semester to aid student preferences.

Leadership and Systems Engineering: The systems team will play the crucial role of coordinating subsystem team efforts and ensuring a cohesive final product is delivered. They will maintain a high level understanding of all subsystems and make sure they work together to meet system and mission requirements in a way that can be tracked by figures of merit. The systems team will have the leadership responsibility and final say on the allocation of resources and margins and verify requirements are being met, all within specified mass and budgetary limitations.

Creative Communications and Immersive Virtual Mission Experience: The creative communications team will play the essential role of communicating the Ocean World Mission to class peers and NASA advisors/mentors, and develop a virtual experience for outreach to 'bring the next generation' along on the Ocean World mission. This critical sub-system team is responsible for telling the Ocean World Mission story via story boards, multi-media, social media, and immersion. The team will investigate, develop and create an immersive experience for an OW mission likely based on VR/AR technologies. A final multi-media presentation and written article will be the "blueprint" for a future life detection ocean world mission.

Life Detection and Instrumentation: The science and instrumentation team will determine what measurements and sample types are necessary to realize a successful Ocean World search for life mission. This could potentially include remote sensing, in situ analysis, or sample return. They will define scientific objectives and requirements as well as develop preliminary instrument prototypes that can be tested on Earth.

System Autonomy and Remote Operations: The autonomy team will work to implement and test new algorithms and remote operations strategies with applications to Ocean Worlds exploration. The remoteness and communication delays of any ocean world necessitate advanced autonomous operations for any robotic explorer. New advances in perception, prediction, system-health assessment, and risk-awareness, and decision making are all needed to enable on board decision making. A robotic explorer must leverage advances in sensing, perception, estimation, learning, reasoning, mobility, and manipulation, to perceive and classify terrains, select targets of interest for in situ scientific analysis, assess hazards, plan safe trajectories, reach targets of interest, and improve performance by learning from past experiences.

Spacecraft Bus, Structures, and possible Lander/Rover/Drilling: The spacecraft team will ensure that all system components are integrated effectively into a cohesive spacecraft(s) that can perform its required functions and communicate back to Earth. Designs must consider the unique challenges of Ocean Worlds including long travel times, extreme cryogenic conditions, high radiation environments, mobility in rugged terrain, active geologic processes, and mixed-state (solid, liquid, gas) sampling operations. Each challenge will require critical engineering decision making.

Launch, Navigation, Entry, Descent, and Landing: The LNEDL team is responsible for planning the end-to-end mission dynamics, orbital mechanics, and spacecraft delivery to the Ocean World target. This could include launch vehicle and launch windows, orbital trajectories, in-space propulsion, attitude control, flybys, orbits, and potentially entry, descent, and landing (EDL) technological capabilities.

3.9 Prototypes

Each subsystem team will build or develop a physical/software deliverable. These deliverables will be graded at the subsystem-level team. Each team will need to complete a prototype of their sub-system by the Critical Design Review. The laboratory prototype will demonstrate understanding of the basic functionality of the sub-system by the students, including the ability to perform a sub-set of the actions required for the overall mission. Possible laboratory deliverables include machined or 3D printed scientific instruments, spacecraft hardware prototypes, robust simulations or computer models, robotics and algorithm demonstrations, or VR/AR visualizations. Students are encouraged to propose any hands-on lab work that advances the state of knowledge of Ocean Worlds exploration. Prototypes will not be spaceflight ready final products, but they should demonstrate significant progress towards scientific and technical objectives.

Each subsystem team will submit a brief written proposal for their specific prototype plan by the PDR, and discuss that plan during the PDR presentation. The final laboratory prototype demonstrations will occur after the CDR. The Laboratory Prototype Project Plan consists of the following:

- Objective(s) of the prototype demonstration—What problem did you choose to solve and why?
- Engineering design. What is your current design approach and why was it selected? How will it solve the problem and meet the objectives? How will you go about building or developing your prototype/simulation/model/etc?

- Data Plan (success criteria) – a clear list of the data to be collected in order to demonstrate the objective is met; this includes description of how you intend to collect the different data and subsequent analysis tools required to determine success of the prototype.
- Design-of-Experiments: identify the *parameters* of the test (that you choose to vary), the *constraints* of the test (that cannot be changed) and the *variables* of the test (which you will measure) and select the optimal set of parameter combinations to obtain the most data possible with the minimum number of tests.

The laboratory project plan can evolve as the prototype is developed; any updates should be presented in a final document with the prototype demonstration.

Final prototype demonstrations the last week of class must include a live demonstration of the operational prototype that fulfills the success criteria.

3.10 Peer Review

Students taking this class will be working as part of a whole team, and each student will receive a portion of their grade from their classmates. Emphasis will be placed both on the constructive criticism that they receive, but also on the quality of the constructive criticism they provide to others. Peer Evaluations will take place twice during the semester. Each student will assess several other students in the class, usually members of their own sub-team, as well as themselves.

3.11 Class Participation

A portion of each student's grade will be based on class participation, as the team will suffer if individuals do not attend or provide meaningful effort to advance the project. Therefore, attendance in class is expected and contributes to your grade. The faculty and staff will provide this assessment at the middle and end of the semester.

3.12 Grading Matrix

The grade in 16.83 is composed of both individual performance and team performance. In addition, since 16.83 is a Communication Intensive (CI) course, a significant portion of the grade comes from the student's ability to demonstrate written, oral, and visual communications. Table 1 shows how the grade of each student will be composed.

Table 1 16.83 Spring 2019 Grading Matrix

Assignment	Technical %	Communication %
Journal Article Review	10	5
Individual Progress Reports	15	5
Major Presentations *	15	10
Final Journal Article Documents & Multi-media Presentation	15	5
Design and Laboratory Prototype	10	0
Peer Review	5	0
Class Participation	5	0
Total	**75**	**25**

* **NOTE:** Every student will present in two of the three major presentations: MRR, PDR, and CDR. The grade will be based both on the student's technical content in the presentation and also on their ability to answer questions and challenges on the technical area during the talk.

3.13 Academic Integrity

Because a fundamental principle of academic integrity is that you must fairly represent the source of the intellectual work that you submit for credit, it is important that individual contributions to the team effort be properly identified. The student's initials in the subheading of the sections and/or slides that s/he contributed is sufficient. In addition, all referenced materials must be fully annotated, and a complete bibliography is expected for each written assignment and major presentation. Visual communications (i.e., tables, figures, simulations, visualizations) are highly encouraged. Each student must access, read and certify that they abide by the MIT Academic Integrity Handbook and Conduct for all class assignments (https://integrity.mit.edu).

4 16.83 S19 Lecture Schedule (subject to change)

Week	M	TUE	W	THUR	F
1	02/04 *Reg. Day*	**02/05** Intro. to 16.83J/12.43J [DJN RB] Ocean World (OW) Missions Learning Objectives Syllabus Communications Requirement Grading	02/06 *Lunine, 2017; Sherwood et al., 2018*	**02/07** Focused Lecture: OW Scientific Objectives Sub-Systems Teams Overview [DJN/RB/JdL] 6 Teams: Systems, Virtual Experience, Science, Autonomy/Ops, Spacecraft, LNEDL Article Selected	02/08 *SMAD Ch 3,4*
2	02/11 *Carr, 2017; Astrobiology Primer, 2015*	**02/12** Expert Lecture [invited guests] Life Detection Instruments [Dr. Chris Carr] Content of MRR [JS] Article Review Lecture [JLC] Sub-System Team Selection	02/13 *SMAD Subsystem Team Readings*	**02/14** Expert Lectures [invited guests] Trajectory Analysis: Orbital Mechanics [Prof. Richard Linares] Article Review DUE	02/15 *SMAD Subsystem Team Readings*
3	02/18 *Presidents Day*	**02/19** *No Class (Monday Schedule)*	02/20 *SMAD Subsystem Team Readings*	**02/21** Expert Lecture [invited guest] Propulsion & Power Sub-Systems [Prof. Paulo Lozano] Decision-Making / Conflict Mgt. [JLC] Technical Writing/Graphics [JLC]	02/22 *SMAD Subsystem Team Readings*
4	02/25	**02/26** Expert Lecture [invited guest] Autonomy & Remote Ops [Prof. Brian Williams] Entry, Descent and Landing (EDL) [Steve Sell, JPL]	02/27 *Distrubuted Leadership Reading*	**02/28** Leadership Lessons: Apollo 13 [DJN] D. Ancona, *Distributed Leadership Reading* Progress Reports [JLC]	03/01
5	03/04	**03/05** Spacecraft Sub-Systems, SMAD CH 19-23 Highlights [DJN] Mass and Cost Estimates [JdL] Project Management & Team Skills [JdL] Individual Progress Report #1 DUE	03/06	**03/07** Expert Lectures [invited guests] Finding Life in Earth's Oceans [Prof. Peter Girguis, Harvard]	03/08
6	03/11	**03/12** Dry Run for Mission Requirements Review (MRR);	03/13 *Apollo50 (Kresge)*	**03/14** Mission Requirements Review, MRR	03/15
7	03/18	**03/19** Software, Tools, 3D Printing [JS] Introduction to Design Reviews (PDR, CDR) [JLC] Individual check-ins Peer Review 1 DUE	03/20	**03/21** Expert Lectures [invited guests] Case Study: Psyche Mission [Dr. David Oh, JPL] Laboratory Project Plan due	03/22
8	03/26 *Spring Break*	03/27	03/28	03/29	03/30
9	04/01	**04/02** PDR Preparation Introduction to Final Article Document and Collaborative Writing [JLC]	04/03	**04/04** PDR Preparation Final Article Annotated Outline DUE	04/05
10	04/08	**04/09** Dry run for PDR PDR Debrief	04/10	**04/11** Preliminary Design Review, PDR	04/12
11	04/15 *Patriot's Day*	04/16 *Patriot's Day*	04/17 Peer Review 2 DUE Individual Progress Report #2 DUE	**04/18** Student work day	04/19
12	04/22	**04/23** Student work day	04/24	**04/25** Student work day Draft of Final Article DUE	04/26
13	04/29	**04/30** CDR Preparation Final Article Preparation	05/01	**05/02** Dry Run for CDR Final Article Preparation	05/03
14	05/06	**05/07** Critical Design Review, CDR combined with Prototype Demo Day	05/08	**05/09** Class Debrief	05/10
15	05/13	**05/14** Final Article Preparation	05/15	**05/16** Final Article DUE	05/10

DJN – Prof. Dava Newman Graded Activities

RB – Prof. Rick Binzel
JLC – Dr. Jennifer L. Craig
JdL – Dr. Javier de Luis
JS – Jeremy Stroming

Technical / CI lectures with exercises
Reading assignments **before** class, j. articles, SMAD

5 Text Books

- **Reserved**: Space Mission Engineering: The New SMAD, James R. Wertz, David F. Everett, and Jeffery J. Puschell, eds., Microcosm Press, © 2011, ISBN 978-1-881-883-15-9. This is the "bible" of space system design. Available online or at the Coop. Be sure to read the New SMAD, which is in a larger format than the old editions and has a lot of new material, including on-line resources that will be helpful in class exercises and in design work for the class project.)

6 Communications

General class materials, including this syllabus and lecture materials, will be posted to the Stellar website. **Students will be required to upload all their to-be-graded written materials to the Stellar site, including the design documents, presentations, and background research.**

6.1 Mailing Lists

The following mailing list will be created:

- 16.83–faculty@mit.edu: this list includes all faculty/mentors and the TA.
- 16.83-students@mit.edu: this list includes all registered students

The list will be actively maintained by the 16.83 TA, Jeremy Stroming and by administrative assistant to Prof. Newman, Mr. Quentin Alexander.

Students are allowed, and encouraged, to create their own team mailing lists or utilize workspace group messaging services like Slack as necessary.

6.2 Faculty Communications

Contact information for the faculty is included below. Further, the TA/mentors will schedule fixed office hours at least once a week throughout the semester to enable student contact.

Since leadership is a key skill in engineering design work, students will transition into leadership roles. The faculty and staff will continue to be available throughout this semester as well as subsequent semesters as mentors. As the semester progresses, the class format will transition from faculty/expert lectures to assistance and problem solving sessions.

7 Class & Room Schedule for Spring 2019

The class meets in 33-319 on:

Tue & Thu
14:00-17:00

Each three-hour period of classes will consist of:

- Lectures
- Group Work

During the scheduled group work time, students will break out into separate rooms based upon their sub-team and need. There are a number of breakout rooms and lab spaces available:

- Breakout Rooms
  - 33-218 (available 2:30-5 pm)
  - 33-419 (available 2-5 pm)
- Lab facilities (as needed):
  - Gelb Lab and Machine Shop

8 CONTACT INFORMATION

Person		Role	Office	Phone	Email	TA/Mentor Area of Expertise
Dava Newman	DJN	Professor	37-305	617-258-8799	dnewman@mit.edu	Leadership, Systems, Human Operations
Richard Binzel	RB	Professor	54-426	617-253-6486	rpb@mit.edu	Planetary Missions, Scientific Instruments
Jennifer L. Craig	JLC	CI-mentor	33-320	617-452-3841	jcraig@mit.edu	Oral and Written Communication, Teamwork
Jeremy Stroming	JS	TA	37-155	425-466-7759	stroming@mit.edu	Systems, Course Deliverables
Javier de Luis	JdL	Lecture/Mentor	37-371	617-253-3288	deluis@mit.edu	Systems, Payloads and Flight Ops
Quentin Alexander	QA	Administrator	33-336	617-253-6270	qla@mit.edu	Admin. Support

9 CHANGE LOG

Version	Date	By	E-mail	Change
1	2019-02-05	Dava Newman	dnewman@mit.edu	Initial Syllabus

APPENDIX I - LEARNING OBJECTIVES

At the completion of 16.83, students will be able to:
Key: LO = learning objective, MO = measurable outcomes: how LO's can be graded

LO 1: Summarize the mission requirements and develop a set of system and sub-system requirements that meet the mission requirements
- MO 1.1: Requirements analysis in final journal article
- MO 1.2: Mission Requirements Review

LO 2: Develop a set of Figures of Merit (FOM) that quantitatively characterize the performance of the system to meet the mission requirements.
- MO 2.1: Mission Requirements Review
- MO 2.2: Conceptual Design section for final team Journal Articles

LO 3: Develop a system architecture that provides a "best solution" to meet the mission requirements based on the FOM
- MO 3.1: Conceptual Design section of journal article
- MO 3.2: Conceptual Design Review

LO 4: Based upon the chosen system architecture, design subsystems that are technically sound (i.e., satisfies the laws of nature; is build-able within the time and cost constraints; can be tested to verify that it meets the mission requirements, and is operable in the mission environment).
- MO 4.1: Preliminary Design Review
- MO 4.2: Conceptual and Preliminary Design sections of journal article
- MO 4.3: Report of lessons learned from previous experiences.

LO 5: Complete the detailed mission design with analysis and planning to a level that the work could be continued and implemented in to a real flight mission by someone else
- MO 5.1: Critical Design section of the journal article
- MO 5.2: Critical Design Review

LO 6: Fabricate or acquire sub-systems and assemble subsystem prototypes
- MO 6.1: Test Plan sections of journal article
- MO 6.2: Scientific Instrument Prototype Demonstration

LO 7: Report the outcomes of the subsystem prototype performance and resulting lessons learned
- MO 7.1: Scientific Instrument Prototype Demonstration
- MO 7.2: Critical Design Review and journal article subsections

LO 8: Apply project management methods to execute the project on schedule, with resource constraints, and to deliver the technical performance measured by the FOM
- MO 8.1: Project reviews: MRR, PDR and CDR
- MO 8.2: Risk management

LO 9: Keep records of work done and document progress made to achieve the design project objectives
- MO 9.1: Class notes, notebooks
- MO 9.2: Individual progress reports and oral check-ins

LO 10: Communicate facts, findings, and ideas to peers, supervisors, and mentors
- MO 10.1: Formal Reviews
- MO 10.2: Journal articles
- MO 10.3: Individual progress reports
- MO 10.4: Individual oral check-in

LO 11: Evaluate progress towards team and class goals and improve teamwork and leadership skills.
- MO 11.1: Peer reviews
- MO 11.2: Self-assessments

APPENDIX II - LESSONS LEARNED FROM PAST 16.83/16.831 CLASSES

The following are lessons learned from previous MIT CDIO Capstone Classes. Please read these carefully because they were learned through hard work and experience. By understanding the cause, effect, and solution, this class will be able to work more productively, which leads to a better product and learning experience and possibly less overall work and more efficient use of students' time.

- Students (and faculty) often get into the mindset that they cannot perform their work until they get information from others. This inevitably leads to a drawn out, sequential process that consumes precious time. It is important to search for tasks that can be done concurrently or on a "first pass" using preliminary estimates. Once the needed information becomes available, utilize it to update your calculations and complete your work. Always bias for action.
- Lead through example, not orders. Sometimes the quietest person can be the best leader. The person who identifies and solves problems, and helps others to do the same, is a natural leader.
- Seek multiple views and opinions on questions. Unlike standard homework problems, there is often no one "right answer", since design choices usually have many possibilities. It is often hard for a single individual to think of multiple approaches. This is where the team approach becomes valuable. Always take a moment to consider opposing arguments during discussions. You might even try to argue in favor of an opposing point of view, which will help provide a new perspective and possibly lead to a better design. Avoid rejecting suggestions "out of hand" without pausing to reflect. Often "one thing leads to another", and positively thinking about a suggestion will lead to yet a new idea.
- Designing, building and operating a product requires a working appreciation for hardware fabrication and testing techniques. Acquire this experience as early in the program as possible. A spiral approach is effective, whereby the team goes through a complete cycle, knowing it doesn't yet have the final design or answer, but in the process gaining valuable experience.
- Unlike classes with tests and problem sets that provide weekly updates on performance, this class is more open-ended and representative of the "real world." Learn to self-assess. Develop the skills to recognize when you are doing well and when your performance is sub-par. Do teammates look to you for guidance? Are you on time with deliverables and attend all scheduled meetings, both inside and outside of class? Are you a major contributor during "crunch times?" Has the class started to pass you by?
- Analysis saves time and money. Guessing and building prior to analysis wastes resources.
- For many students, it takes a while to adjust to the fact that the staff is only a resource for guidance and consultation, not the decision makers for this project. This "lack of direction" can be frustrating, but this is representative of "real world" assignments and problem solving. Take initiative, trust your engineering knowledge, defend your thinking, and make the most of this project.
- The largest amount of wasted effort occurs during the first third of the first semester (**NOW!**). Think about what you need to accomplish. Envision the end state. Define deliverables and interfaces with your teammates and other teams. Organize. Get traction.

APPENDIX III - WEBSITE AND SOFTWARE (MATLAB, STK, SOLIDWORKS)

Class Website: The 16.83 Space Systems Engineering class website will be on Stellar (https://stellar.mit.edu/S/course/16/sp19/16.83/index.html).

MATLAB: Student licenses available at: https://ist.mit.edu/matlab/all

SolidWorks: Student licenses available at https://ist.mit.edu/solidworks

STK: Student licenses, procedure below TBC:
Space Systems Laboratory Software License: James Clark

0) STK is currently only available on Windows. (You may be able to run it on other platforms using virtual machines as MIT IS&T has Windows10 VMs).
1) Verify that you meet the system requirements at http://www.agi.com/products/stk/
2) Use your MIT e-mail address to log-in to AGI or to create a new account
3) Download free version: Save the file to your desktop
4) Extract all files
5) Install
6) Follow on-screen prompts to install STK
7) At the end of the installation DO NOT check "obtain licenses" box
8) Open AGI License manager
9) Email the STK SSL software representatives (see above):
    - Host ID
    - Registration ID
    - Operating system
    - Full name
10) The SSL software representatives will e-mail you a license and installation instructions.

GMAT: Available for free download at https://sourceforge.net/projects/gmat/