Space Resources

Degrees Offered

- Graduate Certificate in Space Resources – online
- Master of Science in Space Resources (non-thesis) – online
- Doctor of Philosophy in Space Resources – on campus and online

Program Description

Since the 1990s, Colorado School of Mines has been a leading institution for the study of space resources and their utilization through its *Center for Space Resources*. It has also become a destination for space scientists and engineers, government agencies, aerospace companies, entrepreneurs, the mining and minerals industry, financial and legal experts, and policy makers to discuss all topics related to this field at its annual *Space Resources Roundtable*.

In recent years, growing interest in the identification, extraction, and utilization of space resources by space agencies and the private sector has been driven by an awareness that further exploration and growth of commercial opportunities in space will require extraction of materials, production of propellants, and power generation from extraterrestrial resources for more affordable and flexible transportation, facilities construction, energy production, manufacturing of parts, and life support. The broad topic of space resources brings together many fields in which Mines has a strong presence, including remote sensing, geomechanics, mining, materials/metallurgy, robotics/automation, advanced manufacturing and construction, electrochemistry, solar and nuclear energy, resource economics, and public policy.

In this light, Mines launched a first-of-its-kind multi-disciplinary graduate program in Space Resources in 2017 to offer Post-Baccalaureate Certificate, Master of Science, and Ph.D. degrees for college graduates and professionals interested in this emerging arena. The program focuses on developing core knowledge and gaining design practices in systems for responsible exploration, extraction, use, and stewardship of resources in the Solar System.

Primary Contact

Angel Abbud-Madrid, Director
aabbudma@mines.edu
For more information on the Space Resources program, visit https://space.mines.edu.

Space Resources Program Requirements

The interdisciplinary Space Resources program is targeted to train recent graduates, as well as professionals interested in expanding their knowledge and skills to address the opportunities and challenges in space resource exploration, extraction, and utilization. Space Resources touches on physical sciences, engineering, and the social science fields. Thus, this program engages faculty members from many academic departments at Mines. Graduates from the Space Resources program will be prepared to serve the growing interest of industry, government, and academia to identify, extract, process, and utilize resources beyond Earth. Students will have a broad, multi-disciplinary understanding of the overall flow of activities in the development of extraterrestrial resources, a high-level exposure to the different science, engineering, economics, and business disciplines involved in each phase, and an understanding of the current status in the space resources field across academia, government, and the private sector.

The graduate program for Space Resources includes the following degree options:

- a 12-credit-hour graduate certificate offered online,
- a 31-credit Master of Science Non-Thesis (MS-NT) degree in Space Resources offered online,
- a PhD program in Space Resources requiring a total of 72 credits of combined coursework and research, and a doctoral dissertation. The PhD program can be completed on campus and also online for those students approved to conduct their research remotely by their advisor and dissertation committee.

Mines' Combined Undergraduate/Graduate Degree Program

With approval of the Space Resources Program faculty, students may be allowed to enroll in a combined undergraduate/graduate program in Space Resources. Students approved to enroll in this program may double count up to six credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with "B" or better, not be substitutes for required coursework, and meet all other University, Department, and Program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

Graduate Certificate

The Graduate Certificate is intended to give the student a panoramic view of space resources to understand the role that scientific knowledge, engineering systems, economic analyses, business cases, and legal and policy aspects play in this field. This option requires students to take a minimum of 12 credits online with 3 credits from Space Resources Fundamentals (SPRS501) and 9 credits chosen from other courses. Table 1 lists the courses that will comprise the curriculum for the Graduate Certificate.

Table 1 – Required courses for 12-credit hour Graduate Certificate in Space Resources

SPRS501	SPACE RESOURCES FUNDAMENTALS	3.0
ELECTIVES	SPRS 502 or Elective courses chosen from Table 3	9.0
Total Semester Hrs		**12.0**

Elective courses can be taken from a variety of important topics on space resources, such as: planetary geology, space operations, remote sensing, resource economics, materials extraction, advanced manufacturing, space law and policy, and other topics which continue to be introduced as relevant subjects are identified and new courses developed (see Table 3). Students are also allowed to take courses from other departments and programs with the approval from the Space Resources Program Director in consultation with faculty members of the program.

Master of Science (Non-Thesis)

The Master of Science program is intended to give the degree holder the knowledge and skills to make immediate contributions to any government

agency or company pursuing technical activities related to space resources. The Master of Science degree program is exclusively non-thesis (MS-NT) and online. The MS-NT degree program coursework requires 31 credits as laid out in Table 2, with 13 credits from five courses (SPRS501, SPRS502, SPRS503, SPRS591 and SPRS592) and 18 credits from elective courses. For students coming into the program with previous Master or PhD degrees, up to 9 credits of relevant courses can be transferred after approval from the Space Resources program director in consultation with faculty members of the program.

Table 2 – Required courses for the 31-credit hour online Master of Science Non-Thesis degree in Space Resources

SPRS501	SPACE RESOURCES FUNDAMENTALS	3.0
SPRS502	SPACE SYSTEMS ENGINEERING	3.0
SPRS503	SPACE RESOURCES SEMINAR	1.0
SPRS591	SPACE RESOURCES PROJECT I	3.0
SPRS592	SPACE RESOURCES PROJECT II	3.0
ELECTIVES	Elective courses chosen from Table 3	18.0
Total Semester Hrs		**31.0**

The 6 credits of project courses (SPRS 591 and 592) allow students to develop a design, system, or economic analysis focused on the exploration, extraction, utilization, and responsible stewardship of space resources. The 18 credits of elective courses can be selected from any of the various courses listed in Table 3. These courses provide students with a broad interdisciplinary coverage of critical areas in space resources, such as: Remote Sensing and Resource Assessment; Planetary Geology; Extraction, Processing, and Resource Utilization; Power and Energy; Robotics, Autonomy, and Communications; and Economics, Law, and Policy.

Additionally, new courses continue to be developed and introduced on various relevant subjects. Also, courses from other departments and programs at Mines are allowed as electives after approval from the Space Resources program director in consultation with faculty members of the program.

Table 3 – Current elective courses for all degree options of the Space Resources program (additional topics continue to be introduced as relevant subjects are identified and new courses developed). Other courses at Mines are also allowed after approval from the Space Resources program director in consultation with faculty members of the program.

AMFG501	ADDITIVE MANUFACTURING PROCESSES	3.0
AMFG521	DESIGN FOR ADDITIVE MANUFACTURING	3.0
AMFG522	LEAN MANUFACTURING	3.0
CEEN501	LIFE CYCLE ASSESSMENT	3.0
GEOL557	EARTH RESOURCE DATA SCIENCE 1: FUNDAMENTALS	3.0
GEOL558	EARTH RESOURCE DATA SCIENCE 2: APPLICATIONS AND MACHINE-LEARNING	3.0
MEGN551	ADVANCED FLUID MECHANICS	3.0
MEGN566	COMBUSTION	3.0
MEGN571	ADVANCED HEAT TRANSFER	3.0
SPRS504	ECONOMICS OF SPACE RESOURCES	3.0
SPRS505	SPACE OPERATIONS	3.0
SPRS506	INTERNATIONAL SPACE LAW & POLICY	3.0
SPRS507	ADVANCED PLANETARY GEOLOGY	3.0
SPRS508	REGOLITH PROPERTIES AND PROCESSING	3.0
SPRS509	SPACE ROBOTICS	
NUGN598	SPECIAL TOPICS (Introduction to Space Nuclear Technology)	3.0
SPRS598B	INNOV8X – ENTREPRENEURSHIP AND INNOVATION	3.0
SPRS599	INDEPENDENT STUDY IN SPACE RESOURCES	1-6

PhD in Space Resources

The Doctor of Philosophy (PhD) is intended to provide the degree holders the necessary knowledge and research skills to pursue academic positions or contribute as a space-resources specialist in industry or government agencies. A student who completes a PhD in Space Resources will possess all the training of a Master's degree holder with further specialization in one or more areas within the space resources field. The completed doctoral dissertation will make original contributions to the field.

1) General Requirements

The Doctor of Philosophy (PhD) degree in Space Resources requires 72 total credits, consisting of at least 36 credits of courses beyond the BS and at least 24 research credits. The balance of 12 credits can be either course or research credits. Coursework beyond the MS degree program will not be restricted other than approved by the student's advisor and Dissertation Committee. The PhD degree allows for both on-campus and online options. The latter requires approval by the student advisor, Dissertation Committee, and Program Director who will review and approve if the research project can be conducted remotely. If a student requests to transfer from on-campus to online status (or vice versa) after passing the PhD Qualifying Exam, the Dissertation Committee will also have to approve the change in addition to the advisor.

For students coming into the PhD program with a Master Non-Thesis degree in an engineering, science, economics, or other relevant field, up to 24 credits of courses can be transferred, after approval from the Space Resources Program Director in consultation with the program faculty. These students will still be required to take 13 credits from five courses (SPRS501, SPRS502, SPRS503, SPRS591 and SPRS592) and other elective courses needed to complete the minimum 36 credit course requirement. For students with a previous Master with Thesis or PhD degree, up to 36 credits of relevant courses can be approved for transfer; however, the student will still be required to take the 13 credits from the previously mentioned five courses and other elective courses needed to complete the minimum 36 credit course requirement. For all students starting the PhD program already with a Mines Space Resources Certificate or MS-NT degree (or transferring to the PhD from any of these two programs), all credits taken at the Mines Space Resources program can be transferred to the PhD degree.

Students in the Space Resources PhD degree program must successfully complete a Qualifying Exam, defend a written Dissertation Research Proposal, submit at least one publication to a peer-reviewed journal, deliver conference and program seminar presentations, and write and defend a Doctoral Dissertation, in addition to their course and research work. PhD research is aimed at advancing fundamental knowledge in the Space Resources field. From the beginning of their studies at Mines, students must have an advisor to direct and monitor their academic plan, research, and independent studies. A PhD Dissertation Committee must also be assembled after passing the Qualifying Exam, as outlined below.

2) PhD Qualifying Exam

Students enrolled in the Space Resources PhD program are required to pass a Qualifying Exam. The PhD Qualifying Exam will be administered at specific dates during the year as determined by the Space Resources PhD Qualifying Exam Committee. The Committee will appoint an Exam Chair, who oversees the process and ensures that the Exam is administered fairly. The Qualifying Exam assesses attributes expected of a successful PhD student, including:

- Basic knowledge of the field of space resources represented by the core courses,
- Ability to review, synthesize, and apply fundamental concepts,
- Creative and technical potential to solve open-ended, challenging problems, and
- Verbal and written communication skills.

Students must take the exam at the first opportunity after completing the following requirements:

- Taken a total of 18 credits of course work (not including research thesis credits) with a minimum 3.3 GPA from all courses taken at Mines
- Taken SPRS501, SPRS502, SPRS503, SPRS591, and SPRS592. The latter can be taken concurrently with the exam during the same semester.

Students may petition the Committee for course waivers or deviation from these requirements. If the student fails the exam on the first attempt, he/she must retake the exam at the first opportunity. A maximum of two attempts is permitted.

To sign up for the Qualifying Exam, students must provide to the Exam Chair at a given deadline an updated *Space Resources Course Plan* and a *Statement of Intent* to take the exam at a particular opportunity. In the *Space Resources Course Plan,* the student will list all required five courses and technical electives taken, number of credits, and any waivers for courses requested. In the *Statement of Intent*, the student must explain how the Qualifying Exam Criteria will be met and the rationale for course waivers or deviations from the criteria, if requested. Waiving the five required courses is not encouraged. SPRS501 and SPRS502 can only be waived if a student has completed a substantially similar course. SPRS591 and SPRS592 can only be waived if a student has completed a MS degree with Thesis relevant to space resources or has substantial work experience in the space resources field.

For those students transferring courses (not replacing the required five courses) from previous Master's or PhD degrees, these courses should be listed as Technical Electives in the *Space Resources Course Plan*. The Exam Committee will review the *Course Plan* and *Statement of Intent* by the established deadline and determine if the student is ready to take the Exam.

The Qualifying Exam will consist of a written Research Review paper and an Oral Exam.

a) Research Review Paper. After the Committee has approved the request from the student to take the Qualifying Exam, the student will suggest in writing to the Committee Chair a topic that he/she would like to review for the Research section of the Qualifying Exam. Preferably, this topic should be related to the research the student is intending to pursue for his/her dissertation, but should not describe the student's current or proposed research project in any detail. The Qualifying Exam Committee will make the final decision on the topic assigned to each student. Students will be given at least four weeks to write a critical review of the topic. The review paper is to discuss the relevance of the topic to space resources, its current state in the field, and possible extensions of research in that area to fill current gaps.

b) Oral Exam. Once the Research Review paper has been submitted, an Oral Exam will be conducted by the PhD Exam Committee composed of a minimum of two faculty members and the student's advisor. The Committee will specify the exam format in advance. The Oral Exam is structured as follows:

- It lasts between *90 and 120 minutes*,
- It is conducted in a synchronous video-conference,
- It starts with a 15-20 minute presentation on the Research Paper delivered by the student,
- It continues with 15-20 minutes of questions from faculty regarding the Research Paper, and
- The rest of the time consists of open-ended questions from faculty on any topic in space resources.

Qualifying Exam results of Pass, Conditional Pass, or Fail will be provided to the student in a timely manner by the Exam Chair. A Conditional Pass requires a student to pursue a remedial plan, which must be approved by the Qualifying Exam Committee.

3) PhD Dissertation Committee:

After passing the Qualifying Exam, the PhD student will meet with his/her advisor and select a Dissertation Committee. If the research topic of the student has changed significantly from the one initially intended, the student may select a new advisor (with the help of the original advisor), who will then help the student to select a Dissertation Committee. The Committee must have at least four members, including the advisor; at least two members must be permanent faculty in the Space Resources Program and at least one member must be from outside the program and be a faculty member at Mines. This outside member must chair the Committee. The student's advisor and Dissertation Committee must be approved by the Program Director. An Advisor/Thesis Committee form must then be submitted to the Office of Graduate Studies for its approval. Additional Committee members from outside Mines are allowed with the student's advisor approval.

4) Research Proposal The student should meet with the advisor and Dissertation Committee not long after its selection to discuss the research topic and obtain their feedback before starting the preparation of the Research Proposal, which consists of a document and a presentation. Other meetings prior to the presentation of the Proposal may be scheduled if the student, advisor, or Committee judges that it is needed. The student will then prepare a written Proposal of up to 10 pages (or more with Committee approval). The format is a single-spaced document with one-inch margins and 12-pt font. The document can include images and graphs; references and footnotes should be included in additional pages. The student will formally submit the Proposal to the Committee at least two weeks in advance of the date agreed upon by all for its presentation. The written Research Proposal is expected to achieve the following:

- Demonstrate a thorough familiarity with the background and motivation of the research problem being undertaken as embodied by a review of the relevant literature,
- Enumerate specific aims and/or hypotheses,

- Identify preliminary techniques, analyses, studies, materials, and in the case of experimental work, specific test objectives for the proposed research project,
- Explain clearly the merit ("value added") of the proposed work to the existing body of knowledge,
- Provide a general idea of the timeline for the research program, and
- Specify potential publications and presentations that may arise from the work.

The student and the advisor must convene a 2-hour meeting of the full Dissertation Committee in which the student will provide an oral summary of the written Proposal in a 30-45-minute presentation followed by questions from the Committee. This Proposal gives the Committee an early chance to discuss the research topic, help the student more clearly define the work to be accomplished, and identify the salient aspects of the proposed research. The Research Proposal presentation may be held the semester after successfully passing the Qualifying Exam, but preferably no later than one year after the Exam. The Research Proposal must be completed before admission to PhD candidacy. After passing the Research Proposal, it is highly recommended that the student and advisor keep the Committee informed of the student's work progress.

5) Degree Audit and Admission to Candidacy

PhD students must complete the Degree Audit form and the Admission to Candidacy form by the posted deadlines. For on-campus students, the Admission to Candidacy form must be submitted by the first day of classes of the semester in which they want to be considered eligible for reduced registration. Additionally, full-time PhD students should complete the following requirements within the first three years after enrolling into the PhD program:

- Have a Thesis Committee appointment form on file in the Graduate Office,
- Complete all prerequisite and curriculum course requirements,
- Demonstrate adequate preparation for, and satisfactory ability to conduct doctoral research,
- Be admitted into candidacy for the degree.

6) Reduced Registration

Students become reduced registration eligible once they have

1) earned 72 credit hours (combined coursework and research),
2) paid for 54 credit hours (including transfer of credit if applicable), and
3) achieved candidacy.

7) Required Number of Publications and Presentations

The required and recommended journal publications for PhD students prior to graduation are listed below. Students wanting to defend before meeting these requirements must submit a one-page petition with a reasonable explanation to the student advisor and the Committee.

a) Journal publications **-** Required: One first-author paper accepted or published in a peer-reviewed journal (recognized as high quality in the research field) before the Dissertation Defense. Recommended: Two or more first-author papers accepted or published in peer-reviewed journals. Three or more first-author journal publications are recommended for students interested in academic positions.

b) Presentations **-** Required: One research presentation (poster or podium) at an external technical conference before the Dissertation Defense. Three presentations in seminars within the Space Resources program or at Mines (such as the campus-wide graduate student research conference, online presentations during student research meetings or program seminars, research sponsor meetings, or additional conference presentations) during PhD program. Recommended: Two or more conference presentations (poster or podium) before the Dissertation Defense in which the student is the first author on these presentations. Numerous conference presentations are strongly encouraged to establish a reputation amongst researchers in the field for students interested in academic positions.

8) Dissertation Defense

At the conclusion of the student's PhD program, the student will be required to write a Dissertation and make a formal presentation and Defense of his/her research. This Defense should be scheduled for at least 2 hours to give the student 45 minutes of presentation followed by questions from the general public attending the defense, and finally questions and discussion exclusively with the advisor and Dissertation Committee. A student must pass this Defense to earn a PhD degree, as determined by voting members of the Dissertation Committee. The Dissertation should be submitted to the Dissertation Committee at least two weeks prior to the Defense. The Committee will perform a post-presentation review of the Dissertation, technical contributions, and publications with the student. The Committee may request revisions to the Dissertation and additional work that requires subsequent review by the advisor and the Committee. These revisions should be incorporated to the Dissertation and the document formally submitted to the school after following all the Dissertation requirements and guidelines for its writing and publication.

9) Unsatisfactory Progress

To ensure that a student receives proper feedback if progress toward the Preliminary Defense or the Dissertation Defense is not satisfactory, the Advisor must provide the student and the Committee a brief, written progress evaluation. If the student's progress is unsatisfactory such that the Advisor gives them a PRU grade for research credits, the student will go on academic probation as outlined in the Graduate Catalog. Students must maintain good academic standing as defined by the Office of Graduate Studies. If the student falls out of good standing, Office of Graduate Studies policies to restore good standing must be followed in order to continue in the PhD program.

10) Time Limit

As stipulated by the Mines Graduate School, a candidate for a doctoral degree must complete all requirements for the degree within nine years of the date of admission into the degree program.

SPRS501. SPACE RESOURCES FUNDAMENTALS. 3.0 Semester Hrs. (I,II) This course provides an overview of the space resources field, including the current knowledge of available resources in the Solar System, extraction and utilization systems under development, economic and technical feasibility studies, legal and policy issues, and space exploration architectures that may be enabled by utilizing extraterrestrial resources in the near future. The course will build broad knowledge and develop confidence in problem solving in the space resources field. This is an 8-week online course. Prerequisite: Working knowledge of physical sciences, engineering fields, or economics at an advanced undergraduate level, with basic numerical analysis skills using a programming language or spreadsheet calculations.
Course Learning Outcomes

- 1. Students will demonstrate knowledge of space resource exploration, resource availability, and technologies associated with their recovery, extraction, processing, and utilization
- 2. Students will exhibit understanding of current technological, economic, and policy challenges in space resources
- 3. Students will develop the ability to evaluate quantitatively and design a space-resource technology plan

SPRS502. SPACE SYSTEMS ENGINEERING. 3.0 Semester Hrs.
(I,II) This course conveys the fundamentals of the systems engineering process as applied to large, complex space systems. It is intended for graduate students with various backgrounds. The students will become familiar with full scope of the systems engineering process from requirements definition, system design, system analysis through system verification. The process will be illustrated with real-world examples from current space systems with an emphasis on systems relevant to the development of space resources. This is an 8-week online course. Prerequisite: SPRS501.
Course Learning Outcomes

- 1. Understand the logic steps of the systems engineering process for space systems
- 2. Understand the detailed objectives of each step in the process and become familiar with some of the standard industry tools.
- 3. Understand the wide range and applicability of analysis disciplines in assessing space systems.
- 4. Gain familiarity and develop intuition with the complex interactions among system elements and how proper operation can be verified.

SPRS503. SPACE RESOURCES SEMINAR. 1.0 Semester Hr.
The Space Resources Seminar will engage students in the program with current research and developments related to space resources. Students will assess the importance and relevance to the space resources field in the near-, medium-, or long-term of topics covered in lectures presented by technical experts from a variety of disciplines. They will report and analyze events, news, and research publications and develop scientific, technical, and economic arguments for their impact and relevance to the space resources field, while also responding thoughtfully and critically to other students' contributions. Students will synthesize the information presented during the course in a final report with an analysis of the most important developments in the science, technology, economics and policy of space resources during the course period. This is an 8-week online seminar course.
Course Learning Outcomes

- Gain in-depth exposure to current research and development pertaining to space resource.
- Develop student’s skills at professional communication through giving their own presentation and evaluating those of others.
- Understand professional expectations for technical experts in the space resources field through assessing industry, government, and academic opportunities.

SPRS504. ECONOMICS OF SPACE RESOURCES. 3.0 Semester Hrs.
(I,II) This course provides an overview of economics and business topics that are commonly found in the space industries. Students will build a basic knowledge of economics, finance, and business issues that are relevant to space resource markets and industries. The big picture is to help provide perspective on what investors or the financial officers at companies are investing in and planning for in or around the space industry. Prerequisite: SPRS501.
Course Learning Outcomes

- Interpret and assess basic economic intuition and lingo so that one can contribute to projects on the business side
- Evaluate and critique standard investment analysis techniques
- Describe common market structures for natural resource commodities and theorize its impact on firm behavior
- Name the location of basic data on natural resource price, production, and consumption and demonstrate its evolution over time
- Design a presentation for the business community that provides a clear value proposition
- Execute an "elevator pitch" (concise and persuasive speech to spark interest) about a Space Resource topic

SPRS505. SPACE OPERATIONS. 3.0 Semester Hrs.
(I,II) This course explores the people, events, missions, operations, and basic system principles that have shaped the space industry. It is intended for graduate students with various backgrounds. Students will become familiar with space operations principles through work in orbital mechanics, space environments analysis, as well as mission and spacecraft design. Students will evaluate a broad range of existing missions and architectures from different perspectives through various case studies and discussions and will apply these concepts to the preliminary design of a space mission. Eight-week online course with asynchronous web content and no on-campus lectures, but with two synchronous, one-hour videoconferencing sessions per week. Prerequisite: SPRS501.
Course Learning Outcomes

- 1. Analyze the influence of policy, politics, physics on the history and evolution of the space industry
- 2. Integrate and outline characteristics, operations, and suitability of launch systems and spacecraft missions
- 3. Calculate and estimate preliminary spacecraft subsystem parameters and architecture
- 4. Articulate a space mission motivation and objectives that support space resources
- 5. Apply design principles to iterate and optimize across multiple subsystem interactions and top-level requirements
- 6. Develop an integrated preliminary spacecraft mission and bus design solution that synthesizes learning

SPRS506. INTERNATIONAL SPACE LAW & POLICY. 3.0 Semester Hrs.
(II) This course will familiarize students with the fundamentals of international space law, and train students to think critically about issues of space law and policy as human utilization of space continues to grow and change. Students will be exposed to new ways of thinking-spotting issues and applying what is learned in order to analyze issues of space law. It is intended for graduate students with various backgrounds. This is an 8-week online course. Prerequisite: SPRS501.
Course Learning Outcomes

- 1. Define, classify, and apply international law to the law of outer space, its associated fields, and the applicable rules, regulations, and policies
- 2. Explain the role played by the United Nations in creating and maintaining the Outer Space Treaty regime
- 3. Critically analyze the multilateral agreements between States that make up the main body of international space law

- 4. Articulate the principles and evaluate the policy reasoning as well as ethical considerations underlying the past, present, and future uses of space for civil, military, and commercial development, particularly space resource utilization
- 5. Identify, interpret, and examine problems and gaps in international space law with a view to future problem solving
- 6. Apply space law and learn to develop effective policy recommendations when presented with real world or hypothetical scenarios
- 7. Explain the relationship between international space law and domestic space law

SPRS507. ADVANCED PLANETARY GEOLOGY. 3.0 Semester Hrs.
(I,II) This course provides a detailed look at planetary bodies, from atmosphere to surface to interior. The focus is on the geological processes that have formed then transformed these bodies over time, with special attention paid to the formation of space resources. These processes include accretion and differentiation, impact cratering, tectonics, geodynamics, volcanism, erosion and deposition, and chemical weathering, among others. Schedule Type: Eight-week online course with asynchronous web content and no on-campus lectures, but with two synchronous, one-hour videoconferencing sessions per week. Prerequisite: SPRS501.
Course Learning Outcomes

- Use order of magnitude estimation and/or provided formulas to solve quantitative problems for geologic processes including accretion, differentiation, impact cratering, volcanism, and mass transport.
- Create and interpret visual plots used to convey the composition and physical state of planetary materials, including phase diagrams, Ellingham diagrams, and ternary plots.
- Judge the resource potential of planetary bodies and specific locations on those bodies, in terms of the type, concentration, and distribution.
- Conjecture about counterfactual scenarios related to specific planetary bodies and events in solar system history.
- Construct and interpret map products from planetary datasets using GIS tools.
- Evaluate planned architectures from space mining companies and public statements about space resources on the basis of their geological plausibility, and potential challenges that could be faced based on actual conditions on the ground.

SPRS508. REGOLITH PROPERTIES AND PROCESSING. 3.0 Semester Hrs.
This course provides a detailed look at regolith, the unconsolidated layer of fragmented rock that covers the surface of most terrestrial planetary bodies. The first half of the course focuses on regolith properties, including how regolith forms, its structure and composition on different bodies, and its physical and geotechnical properties. In the latter half, the course explores end-to-end processing methods for regolith including excavation & transport, mineral processing/beneficiation, construction & manufacturing, and oxygen/metal extraction. Prerequisite: Space Resources Fundamentals (SPRS 501); SPRS 507 is recommended but not required; students planning to take both this course and SPRS 507 should take SPRS 507 first.
Course Learning Outcomes

- 1. Develop space resource architectures specific to regolith using knowledge of the source composition and geotechnical properties, and the desired end product(s).
- Critique regolith-focused space resource architectures written by others in terms of their efficiency and realism.
- Evaluate a specific technology's ability to work with regolith in terms of performance and risk.
- Sketch concepts visually or in code to communicate to colleagues and stakeholders.
- Solve quantitative problems related to regolith amounts, resource concentrations, and processing requirements using models and equations.
- Discuss both classic and cutting-edge peer-reviewed research papers by drawing on course materials and outside expertise.

SPRS509. SPACE ROBOTICS. 3.0 Semester Hrs.
This online course introduces students to the design, analysis, and operation of robotic spaceflight missions. By integrating space exploration with robotics, students will explore planetary science questions, develop mission plans, and evaluate the technologies required to achieve mission objectives. Topics include sensor systems, automation trade-offs, and rover mobility. The course prepares students for careers in aerospace and robotics by providing essential technical, analytical, and organizational skills to solve complex challenges in these fields. Prerequisite: SPRS501.
Course Learning Outcomes

- Identify state of the art planetary science questions and technology goals from the 2023 origins, worlds, and life (OWL) planetary science decadal survey.
- Illustrate the evolution of spaceflight technologies for planetary surface robots, specifically around rover mobility and sensing.
- Design an extraplanetary surface robotic mission with a science or technology goal derived from OWL.
- Assess the data signals from sensors necessary to produce the end data product, which is informed by the science or technology goal.
- Plan the mission operations and robot actuators necessary to achieve mission objectives.
- Differentiate operations between robot automation and human teleoperation along the metrics of risk, SWaP, complexity, and timeline.
- Develop a perception framework and path planning strategy informed by mission requirements and a concept of operations.
- Execute basic mobility algorithms constrained by robot capabilities and limitations in Moon environment.

SPRS510. OFF EARTH ADDITIVE MANUFACTURING. 3.0 Semester Hrs.
This course covers the fundamentals of the rapidly developing field of Additive Manufacturing (AM) in Space, on the Moon and Mars. It will consider two basic feedstock approaches for Off-Earth production: (i) AM with Earth-based raw materials in Space and (ii) Off-Earth sourced feedstocks from various celestial bodies (the Moon, Mars, and Asteroids) - an approach that is called Space Resource Utilization (SRU). Major sections of the course will focus on the SRU feedstock approach, discussing specifically regolith (and water), including a summary of their genesis, availability and relevant properties for AM. After briefly introducing/reiterating the seven ISO/ASTM AM process categories, coursework will discuss the impact of gravity, vacuum/low pressure, and temperature on Off-Earth AM in Space, as well as introduce various mitigation approaches to overcome such challenges.
Course Learning Outcomes

- List and describe relevant Off-Earth AM process categories, feedstocks, and fusion mechanisms.
- List and describe different relevant feedstock states such as powder, wire/filaments, liquids, and colloids.
- Ability to analyze how gravity, vacuum/low pressure, and temperature affect AM processes in these environments.
- Convey general knowledge of space resources on different celestial bodies.
- Convey knowledge of current AM techniques using regolith simulants as found in the literature.
- List and describe methods of direct regolith feedstock refining and advanced techniques for the SRU processing of highly refined AM feedstocks.
- List and describe material selection for Off-Earth AM and potential parts plus applications areas.

SPRS591. SPACE RESOURCES PROJECT I. 3.0 Semester Hrs.
This course will provide graduate students in the program with directed team-based project learning by exploring the design, planning, and analysis of missions, processes, systems, science, business, and economics for space resources assessment, extraction, and utilization. The course will meet formally online once a week for one hour and include a discussion on relevant design aspects of space mission, processes, and/or systems. In this regard, it will build on content learned in the Space Resources Fundamentals, Space Systems Engineering, and other courses in the Space Resources Program. Students will collaborate in multi-disciplinary teams and will be advised by a course instructor with significant industrial design experience and supported by faculty affiliated with the Space Resources program from relevant disciplines on campus. For teams with students in space resource economics, detailed economic analyses will be incorporated into those projects. Student teams will prepare a preliminary design, planning and analysis report early in the semester, one interim progress report, and a final report and project presentation. This is a 16-week online course. Prerequisite: SPRS501 and SPRS502.
Course Learning Outcomes

- 1. Learn principles and best practices in space systems design, mission, planning, and resource analysis
- 2. Develop student's confidence through practice at design, planning, and analysis for missions,systems, economics, business, and science related to space resources.
- 3. Gain practice in written and oral presentations of design and analysis of space systems.

SPRS592. SPACE RESOURCES PROJECT II. 3.0 Semester Hrs.
This course will provide graduate students in the Masters and PhD programs in Space Resources with an independent design and analysis project. This project will be guided by the course instructor and a technical advisor, and will enable the student to delve deeply into a particular system related to the prospecting, extraction, processing, and utilization of potential space resources, as well as business and economics cases in this field. As much as possible, projects will be coordinated with industrial or government agency partners who are collaborating with the program. The course will involve weekly online meetings where ideas are exchanged and progress discussed within the context of design and analysis principles learned in the prerequisite courses. Students will be partnered with a faculty member affiliated with the Space Resources Program. The student will prepare a final report and presentation to present to industry collaborators, space resources faculty, and other students in the course. The final report and/or presentation as appropriate will be converted to a journal publication, conference publication and/or research proposal and resources from the program will support student costs for publishing and/or presenting the work. This is a 16-week online course. Prerequisite: SPRS501, SPRS502, SPRS591.
Course Learning Outcomes

- 1. Develop a level of expertise and understanding of a technology opportunity in space resources.
- 2. Raise student's confidence through practice at design, planning, and analysis for missions and systems related to space resources.
- 3. Gain practice in written and oral technical presentations of design and analysis of space systems.

SPRS598. SPECIAL TOPICS IN SPACE RESOURCES. 6.0 Semester Hrs.
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: SPRS501. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

SPRS599. INDEPENDENT STUDY IN SPACE RESOURCES. 0.5-6 Semester Hr.
(I, II, S) Students can do Individual research or special projects supervised by a faculty member. The student and instructor will agree on the subject matter, content, and credit hours. Prerequisite: SPRS501

SPRS707. GRADUATE THESIS / DISSERTATION RESEARCH CREDIT. 1-15 Semester Hr.
(I, II, S) Research credit hours required for completion of Doctoral dissertation. Research must be carried out under the direct supervision of the student's faculty advisor. Variable class and semester hours. Repeatable for credit. Prerequisite: Instructor approval.

CORE FACULTY

Director and Professor of Practice

Angel Abbud-Madrid

Professor of Practice

Christopher Dreyer

George Sowers

Assistant Professor

Frankie Zhu

Additional Information

Adjunct teaching instructors and faculty from several departments at Mines are also affiliated with the program and teach courses, supervise independent and course projects, act as thesis advisors, and conduct research. A list of current adjunct and affiliated faculty members can be found at: https://space.mines.edu/faculty/