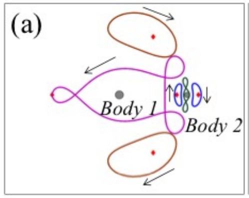
ASEN 6060
ADVANCED ASTRODYNAMICS
Welcome

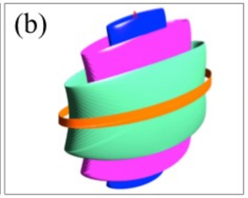
Introduction

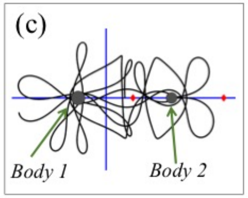
Instructor: Prof. Bosanac (she/her)
Email: natasha.bosanac@colorado.edu

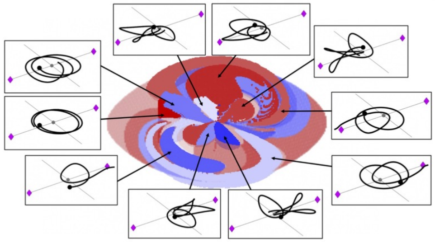
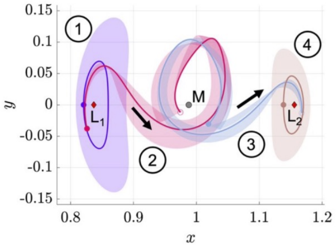
Research interests:

- Develop new strategies for trajectory analysis, design, and prediction in multi-body systems
- Use methods from dynamical systems theory, machine learning, data mining, path-planning
- Applicable to monolithic s/c and formations, large s/c and CubeSats, destinations in solar system or extrasolar systems







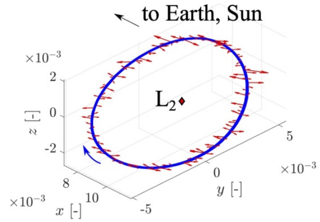


Image credits for last three pictures:

- 4: Bonasera, S; Bosanac, N, November 2021, Vol. 133, No. 51, Celestial Mechanics and Dynamical Astronomy, DOI: 10.1007/s10569-021-10047-3.
- 5: Smith, T.R.; Bosanac, N, September 2023, Vol. 70, No. 34, The Journal of Astronautical Sciences, DOI: 10.1007/s40295-023-00395-7
- 6: Bonasera, S; Bosanac, N; Sullivan, C; Elliott, I; Ahmed, N; McMahon, J, February 2023, Vol. 46, No. 2, Journal of Guidance, Control, and Dynamics, DOI: 10.2514/1.G006783

Introduction

Teaching Assistant:

Austin Bodin (he/him)

Email: austin.bodin@colorado.edu

Office Hours:

- Prof. Bosanac:
  - Wednesdays 4-5pm MT (virtual)
  - Fridays 2-2.50pm MT (hybrid, in AERO N453)
- Austin:
  - Mondays 9am-10am MT (hybrid, in AERO 403, starting 1/27)
  - Tuesdays 11.30am-12.30pm (hybrid in AERO 303)
- Zoom link for virtual and hybrid OH is on Canvas page

Course Format

- **Lectures**: Tuesdays & Thursdays 10am-11.15am in AERO 114

- **Webpage**: canvas.colorado.edu

- **Textbook**: None required.
  - Interesting supplemental readings from resources that are free to CU students are available on the Canvas page.

- **Recommended prerequisites**: ASEN 5050/5052 or equivalent graduate-level orbit mechanics class, or instructor permission.

Course Format

- Lecture periods will include:
  - Traditional lectures
  - Small-group activities / discussions

For lectures:

- Partially filled lectures notes provided day before lecture
- If you encounter any accessibility issues, please let me know

For the in-class small-group activities / discussions:

- Will work in small groups to answer questions that delve further into a concept or method discussed during lectures or application to new problems
- Facilitates deeper understanding of course material and assists you with homework
- Some discussions (particularly later in the semester) will rely on having access to one computer per group

Course Calendar

Calendar available on Canvas page

ASEN 6060 Spring 2025: Course Calendar

	Date	Class Type	Topic	Assessment
Week 1	1/14	Lecture	Introduction; Formulating the circular restricted three-body problem	
	1/16	Lecture		
Week 2	1/21	Lecture	The Jacobi constant and zero velocity surfaces	
	1/23	Discussion		
Week 3	1/28	Lecture	Equilibrium points	HW 1 due
	1/30	Discussion		
Week 4	2/4	Lecture	Periodic orbits	
	2/6	Discussion		
Week 5	2/11	Lecture	Orbital stability and the state transition matrix	HW 2 due
	2/13	Lecture		
Week 6	2/18	Lecture	Numerically correcting periodic orbits	
	2/20	Lecture		

Course Format

- All lectures are recorded whereas discussion sessions will only be partially recorded
  - All students in our class can view recordings
- Students in -001 section attend in-person
  - Please actively participate
- Students in the -002 section participate asynchronously
  - Please watch recorded lecture videos and work through discussion problems in timely manner after they are posted
- Both sections complete assessments with same deadlines

- If I become unwell, unavailable, or have an emergency, I will either pre-record or hold the lecture remotely (will notify you through an announcement if needed)

Course Material Restrictions

- Lecture recordings may not be downloaded, duplicated, or used for any other purpose, consistent with FERPA restrictions.

- Course materials (including but not limited to lecture notes, homework, instructions, videos, etc) may not be distributed publicly or shared with individuals who are not registered in the course this semester without prior instructor consent.

Software

- Numerical computations: please use either MATLAB (preferred), Python, or C++.
  - If you choose to use an alternative language or software, we will likely not be able to provide you with any help
- Higher-fidelity environments in software: GMAT or STK.
  - Neither of these software may be accessible to users of assistive technology. If you use assistive technology to access the course material, please contact me ASAP to discuss.
  - Any use restrictions must be followed by all students
- To participate in office hours virtually: Zoom
- To meet other students, ask technical questions: Slack (optional)
- You are <u>not</u> permitted to use artificial intelligence (AI) or machine learning tools in any assessments in this class

Assessments

- Grading policy:
  - Homework (75% of grade)
  - Final project (25% of grade)

- Homework:
  - Submit electronically in Gradescope
    - Correctly assign each page to each question
    - You are responsible for correctly uploading document
  - Generally due on Tuesday evenings at 9pm MT
  - Involve derivations, implementation of numerical methods, generating and analyzing data, discussions
  - Can collaborate with peers to discuss problem solving, but must have a unique response and write your own scripts

Assessments

- Homework:
  - Graded on 1) accuracy of answers, and 2) accuracy, precision, and completeness of accompanying writeup
  - Submissions require a clear and technically precise discussion, including:
    - Mathematically accurate discussion of theory and details
    - Description of the solution to a problem
    - Mathematical working and/or derivation to solve problem
    - Demonstrating intermediate steps and calculated quantities
    - Description of the results
    - Analysis of the results
    - Justification of the results.
  - Include text of scripts at end of the homework problem
  - Code or code comments alone are not a homework writeup and will not receive full credit

Assessments

- Homework:
  - Extension requests must be sent via email by 10am MT the business day before the deadline, except for emergencies
  - Late homework without an extension/emergency will not be accepted and will receive a zero grade
  - If you believe an error in grading has occurred, regrade requests must be submitted within 1 week of being returned (except at end of semester)
  - I will not provide solutions, but you will receive sufficient feedback to understand how to address the issues and/or ask further questions during office hours.
- Project:
  - Designing a transfer with maneuvers in the Earth-Moon system
  - Due last week of classes
  - Same expectations for writeup as homework

Communication

I will make announcements either via email or the Canvas announcement feature (check that your Canvas settings allow you to receive regular updates)

General, technical, or homework questions: Slack

- Ask each other or us questions about lecture material
- Practice answering questions and explaining concepts
- Meet your colleagues, expand your network
- To maximize understanding and ensure everyone will work through the homework, please do not simply copy code or upload your answers to the discussion board
- Be respectful and inclusive
- Prof. Bosanac & Austin will check and respond when available

Individual questions: email

Course Policies

Please read through the syllabus and note the following sections:

- Honor code
- Accommodations for disabilities, temporary medical conditions, and medical isolations
  - If you require any accommodations, or any course materials are not accessible to you, please reach out ASAP
- Religious observances
  - Please provide schedule conflicts in first week of class
- Preferred student names and pronouns
  - Please update me at any time during the semester
- Classroom behavior
- Sexual misconduct, discrimination, harassment and/or related retaliation
- Mental health and wellness

Additional Comments

- If any logistics need to change unexpectedly during the semester, I will communicate changes with you promptly.
- Please take care of your physical and mental health and well-being, creating boundaries between classes and other time.
- Please be kind and patient with one another.
- Please be patient with receiving graded homework.
- We can only respond to emails during our regular working hours when we are not otherwise occupied; please be patient. For general, technical, or homework questions, use Slack.

Additional Comments

- The material we will cover is challenging, but fascinating
- You will need to implement computational methods and mathematical concepts throughout the semester
  - If you feel uncomfortable with linear algebra, differential equations, programming, implementing numerical methods etc, you may want to consider taking refresher courses first
- As this is an advanced graduate course, I expect that you will be an active learner:
  - Be sure to attend (or watch recorded) lectures, take notes, carefully and regularly review notes, verify derivations, participate in discussions, and ask questions
  - If you get stuck: try reviewing the notes again, doing a literature review of scholarly works, chatting with your classmates, stopping by office hours
  - Be organized

Current Responses to Welcome Survey

Given: 27 of 41 responses
Why are you taking this course? Most common answers:

- Enjoyed 5050/5052 and want to extend further
- Have seen interesting examples of trajectory or mission design in multi-body systems, want to learn about the CR3BP
- Interested in spacecraft operations in cislunar space
- Want to learn more about trajectory design
- To help you with your future research / career (or career change), typically in astrodynamics or mission design
- Initial exposure to CR3BP, but didn't truly understand it before or didn't get to delve into it in too much detail
- Have been looking forward to learning this material for a while!
- Need a 6000-level course for degree/certificate requirements
- + many more…

Current Responses to Welcome Survey

What are you most excited to learn about?

- Understanding the mathematical formulation of the CR3BP
- Implementing numerical methods to generate/study trajectories
- Designing transfers
- Excited to delve deeply into the CR3BP and better understand the interesting solution space
- Using STK/GMAT to approx. recreate solutions
- Understanding, computing, and analyzing periodic orbit families
- How to generate manifolds of periodic orbits
- Generating and analyzing Poincaré maps
- Everything!

Current Responses to Welcome Survey

What are you most concerned about?

- Complexity/challenges of a 6000-level class
- Complexity of this specific topic
- Workload (courses, work, research) and time
- Starting homework early and asking for help
- Really understanding the material and math
- Coding after some time away
- Missing out on discussions in -002 section
- Finding a study group
- Attending office hours as a distance student

Most folks have plans to continue their hobbies, take breaks, and constrain their work to specific hours (but some folks continue to struggle with this) – please be diligent about prioritizing your well-being during the semester!

Course Learning Objectives

By the end of this course, students should be able to:

- Describe the formulation of the circular restricted three-body problem and derive the equations of motion
- Compute, characterize, and analyze equilibrium points and periodic orbits as well as their hyperbolic invariant manifolds
- Implement a numerical corrections procedure and examine the validity of the results
- Construct a Poincaré map to visualize and analyze an array of trajectories
- Design foundational transfers between libration point orbits in the circular restricted three-body problem
- Formulate technically precise and clear discussions of a solution to a problem and critically assess the corresponding results and observations
- Approximately recover solutions in STK or GMAT

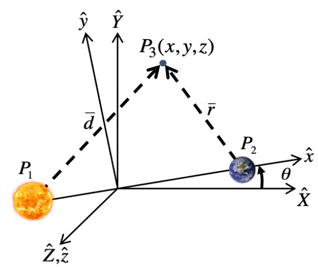
Motivation

Spacecraft are and will continue to be operating in multi-body gravitational environments

- Trajectories cannot be described by exact, generalizable analytical solutions
- Dynamics are chaotic, producing sensitive and complex solution space
- Understanding natural or low-cost controlled transport pathways impacts capacity to find a solution that satisfy constraints and/or objectives while limiting resource requirements

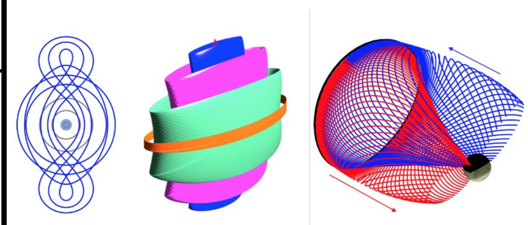
Generating Trajectories in Earth-Moon System

Define low-fidelity model

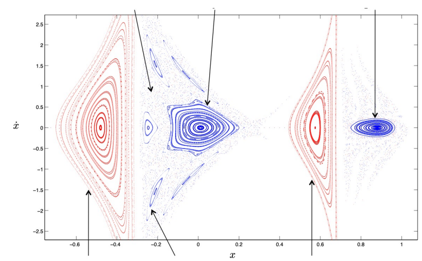


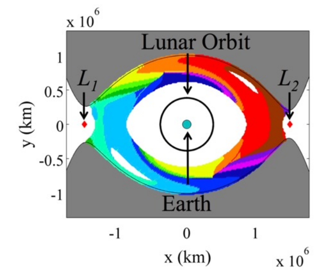
Analyze underlying solution space

Fundamental solutions

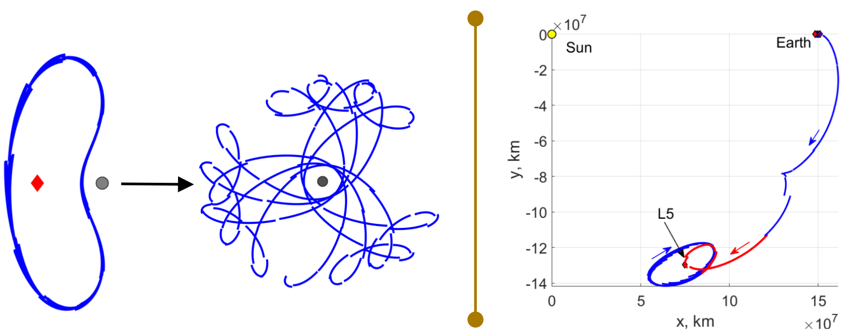


Poincaré map

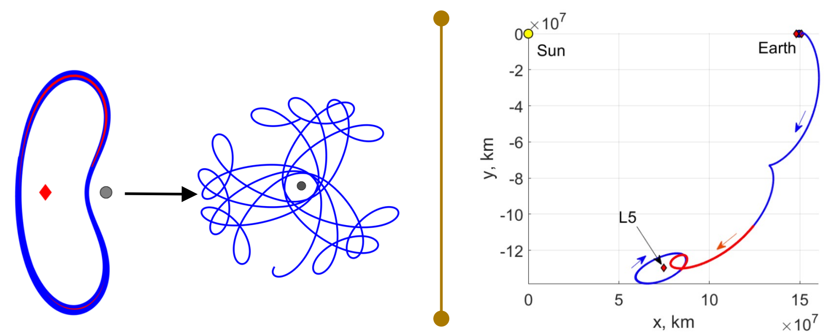




Form initial guess

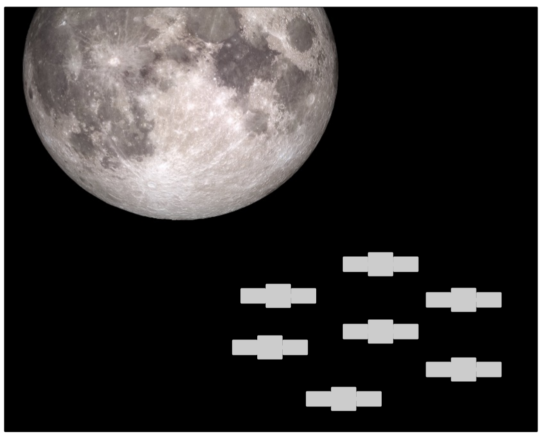


Corrections to recover solution



Motivation

- Expanding exploration, infrastructure, and science in multi-body environments within our solar system
- Increasing presence in cislunar space



Moon image credit: NASA/GSFC/ASU

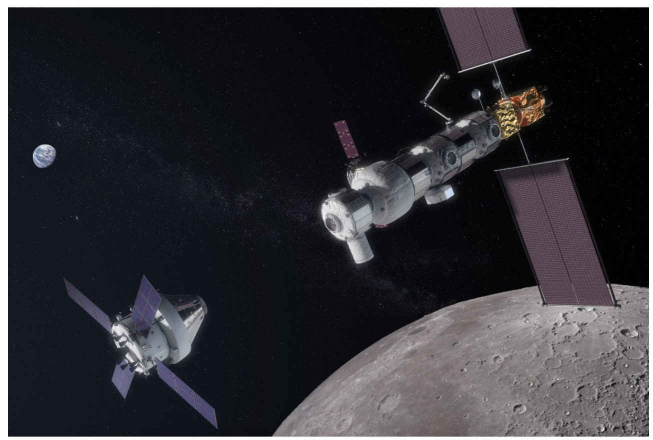
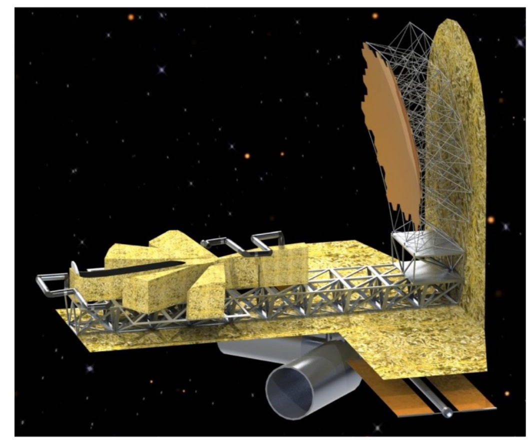


Image credit: NASA



Credit: iSAT ConOps Graphical Storyboard, 2019, Mukherjee, Mick, Naasz, et. al.

Motivation

Deploying small satellites to complete meaningful science, exploration and technology demonstration objectives

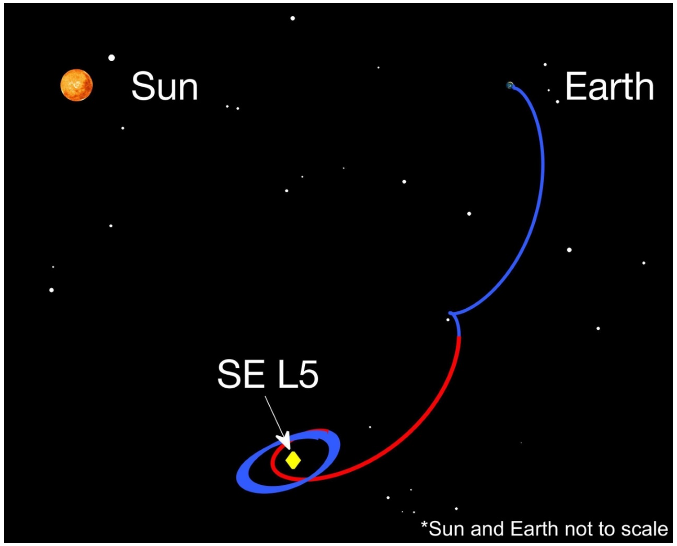


Image credit: Elliott, Sullivan, Bosanac

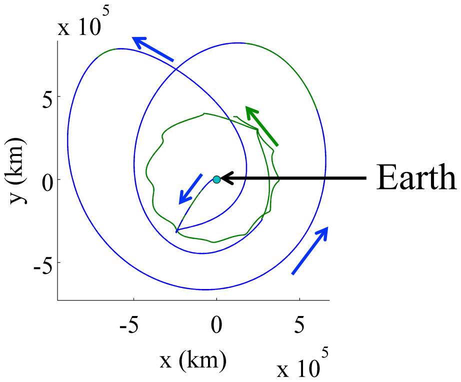


Image credit: Bosanac, Cox, Howell, Folta, 2018.

Image credit: Morehead State University

Motivation

Studying and predicting the natural paths of celestial bodies

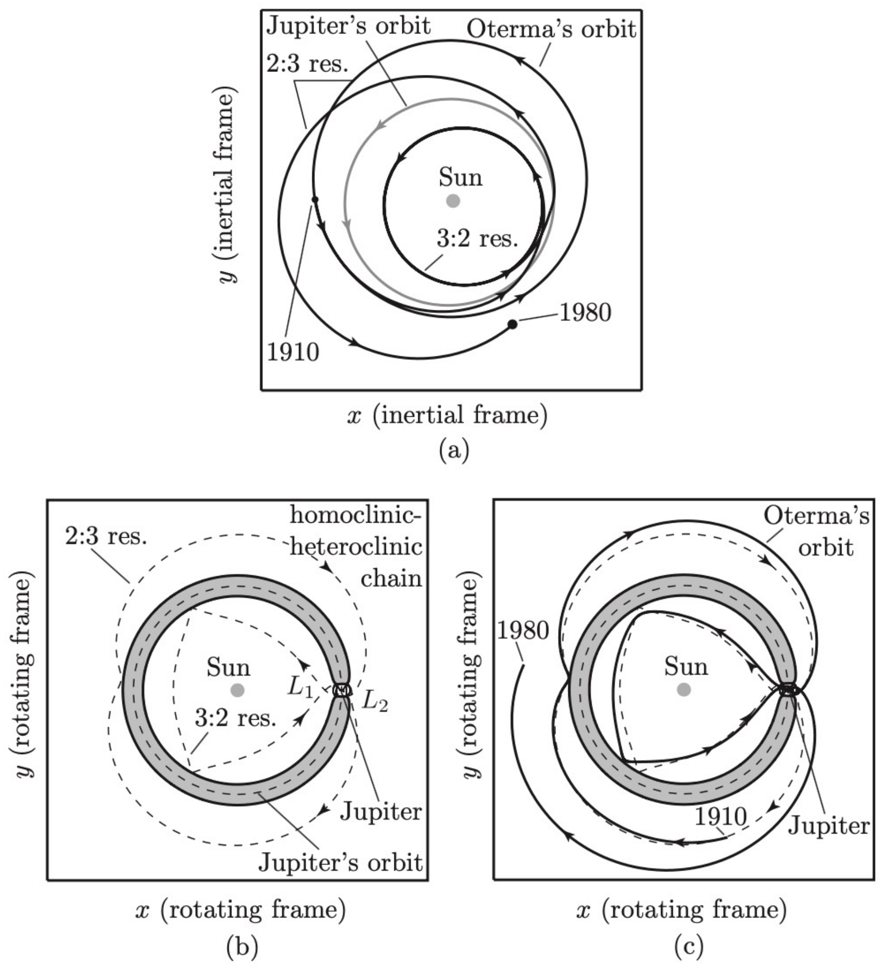


Image credit: Koon, Lo, Marsden, Ross 2011