Space and Trade Spaces
Exploring the Booster Design Problem

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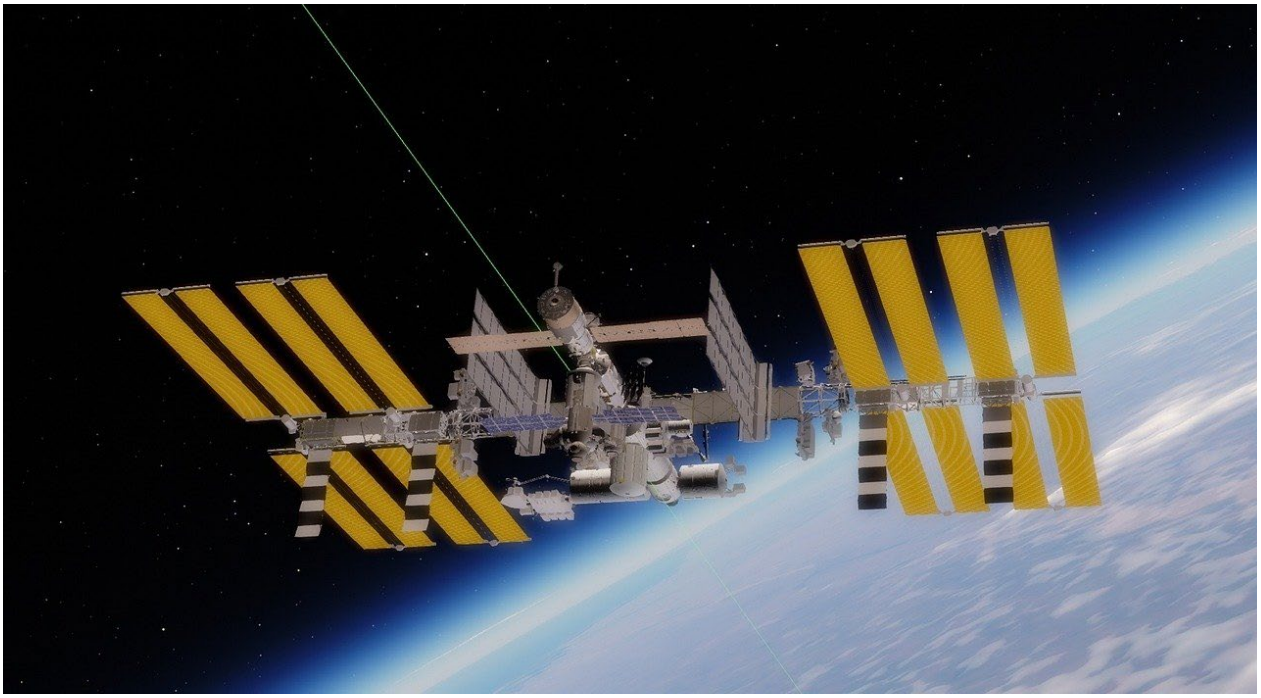
Wahlpflichtmodul – "Seminar 2"



This elective online course is designed to make students aware of design challenges for boosters designed to insert payloads into Earth's orbit. Students will be divided into teams who will compete to deliver the best possible solution to each design challenge. It is an introductory course to booster design for students with no background knowledge of the subject.

The course is structured into 60 to 90-minute online lecture modules combined with group problem assignments. Since only brief problems are possible in a short course, teams will be expected to identify a trade space for each problem rather than delivering a numerical solution.

Prerequisites: Students are expected to have completed courses in differential equations, statics, dynamics, deforms, and material properties before joining this course. Prior experience with a vehicle design process (aircraft or automotive) would be a significant benefit.

The class will be in English and students are expected to have good knowledge of the English language to be able to participate successfully.

The class will be recognized as "Seminar 2" (2 ECTS) for Bachelor students in aerospace engineering. Students need to register for the class in advance and must have completed the prerequisites for "Seminar 2" (all courses for Year 1 of aeronautical engineering incl. *Vorpraxis* must be successfully completed). Students can also not take the class for credit. All students will receive a certificate for successful participation.

Course schedule:

Week 1	Launch Vehicles and The Launch Vehicle Design Process
Week 2	Tyranny of the Rocket Equation and Orbital Mechanics
Week 3	Δv Estimation
Week 4	Rocket Engines and Launch Vehicle Performance and Staging
Week 5	Ascent Trajectory Analysis and Optimization
Week 6	Launch Vehicle Structures and Layout
Week 7	Sizing, Inboard Profile, and Mass Properties and Launch and Flight Loads Analysis
Week 8	Launch Vehicle Stress Analysis and Launch Vehicle Stability and Control

Week 1: Launch Vehicles and The Launch Vehicle Design Process

This module focuses on the history of launch vehicle development since Sputnik was launched by the Soviet Union in 1957. While the first five decades of launch vehicles were developed and flown by nation states, commercial space operations have become more common place over the last decade.

- Evolution of booster systems
- Moon race
- Worldwide launch facilities
- Disruptive impacts of commercial space

This lecture will also include the launch vehicle design process as introduced by Anthony Straw and refined by Don Edberg. The primary steps in the process are:

- Level 1 sizing, mass, propulsion, Con-Ops
- Vehicle geometry: mass, profile, and layout
- Determination of aerodynamic characteristics and loads
- Trajectory performance
- Determination of vehicle mass distribution
- Analysis of vehicle load distributions
- Level 2 vehicle structural design: axial, shear, and moments
- Access vehicle stability and control
- Access vehicle manufacturing, launch facilities, and operations
- Determine vehicle/system costs
- Trade studies

Week 2: Tyranny of the Rocket Equation and Orbital Mechanics

The Tsiolkovsky rocket equation is a mathematical equation which describes the motion of rockets. This equation relates the propellant specific impulse, initial weight, final weight, and burnout velocity.

- Defining specific impulse
- Specific impulse values for common liquid and solid propellants

- Specific impulse and volume specific impulse
- Nozzle optimization: over and under expansion
- Vehicle steps and staging

This lecture will also include a brief review of orbital mechanics. We will discuss the types of Earth orbits and their military and commercial applications as well as Δv considerations related to the latitude of the launch site and the inclination of the desired orbit. Topics include:

- Classic orbital elements
- Kepler's laws
- Useful orbits: polar, sun synchronous, polar, inclined, and geostationary
- Direct ascent versus Hohmann transfer orbital insertions

Week 3: Δv Estimation

Once the Δv requirements and orbital elements for a mission are understood, a first order estimate of the booster's Δv losses must be developed.

- Gravity losses
- Aerodynamic drag losses
- Propulsion losses
- Steering losses
- Launch latitude and inclination losses and gains
- Application to multiple steps

Week 4: Rocket Engines and Launch Vehicle Performance and Staging

The characteristics of solid and liquid-propellant engines will be explored. For solid-propellant engines, the relationship between regression rate, propellant density, and burning area will be explored. Particular attention will be paid to how the time dependent thrust curve of a solid rocket motor can be tailored to address the specific requirements of a mission. For liquid propellant engines, the characteristics and benefits of different engines cycles will be discussed. The module will conclude with a discussion of hybrid and combined cycle engines. Combined cycle, i.e., rocket to ramjet, engines are of particular interest for emerging hypersonic vehicles since they can address the propulsion requirements for both the boost and the cruise phases of flight.

- Solid-propellant engines:
    - Basic configuration
    - Solid Rocket Motor (SRM) types and burn rates
    - Thrust profiles and grain shapes
    - Propellant additives
    - Solid engine performance

- Liquid-propellant engines and cycles:

    - Gas generator cycle
    - Staged combustion cycle
    - Expanded cycle
    - Open expander cycle
    - Pressure-fed cycle
    - Electric pump-fed
    - Liquid engine performance
    - Toxicity considerations

- Hybrid-propellant engines
- Combined cycle engines

Returning to Tsiolkovsky rocket equation, we will start by examining the mass categories which comprise a launch vehicle. Based on this discussion, we will consider the Single-Stage-to-Orbit (SSTO) proposition and identify the fundamental problems preventing its implementation. Returning to the question of multi-stage design, we will discuss:

- Types of staging
- Determining the speed provided by a multi-stage vehicle
- Payload ratio relationships
- Restricted and unrestricted staging
- Tradeoff and Sensitivity derivatives

Week 5: Ascent Trajectory Analysis and Optimization

This two-module topic will discuss how ascent trajectories are determined, identify trades, and build a foundation for the discussion of general launch vehicle motion.

- Vertical flight in gravity without atmosphere
- Gravity losses
- Benefits of coasting
- Inclined flight in gravity without atmosphere
- Vertical flight in the atmosphere with gravity
- Manipulation of the thrust equation
- General flight with gravity and atmospheric effects
- Establishing a coordinate system
- Equations of motion
- Launch vehicle forces and torques due to aerodynamic, thrust, and steering forces
- Launch vehicle lift and drag
- Trajectory shaping
- Gravity turn trajectory

Week 6: Launch Vehicle Structures and Layout

This module will focus on launch vehicle structures based on a discussion of past and current launch vehicle designs.

- Structural examples of selected launch vehicles including layouts, components, and key design trades
- Introduction to launch components: interstages, intertanks, skirts, payload attach fittings, and payload fairings
- Structural materials: metals, composites and their properties, material selection criteria

Week 7: Sizing, Inboard Profile, and Mass Properties and Launch and Flight Loads Analysis

This two-module topic will focus on processes and trades employed to perform detailed vehicle sizing, determine the inboard profile of the vehicle (configuration layout), and determine the launch vehicle's mass properties.

- Inboard profile: where does all of the equipment fit
- Determining the required propellants
- Tanks, tank domes, tank sizing, and volume calculations

- Engine integration and thrust structure
- Intertank structure and loads
- Payload attach fitting and payload fairing
- Mass estimating ratios (MERs)
- Mass properties estimation: mass, center of mass, and moments of inertia

Based on the vehicle geometry determined in the prior two modules, this module will examine the loads that the vehicle experiences while in flight.

- Flight winds
- Maximum dynamic pressure
- Aerodynamic coefficients and flight loads
- Loads due to propellant and structure
- Loads due to engine gimbling
- Axial, bending and shear loads

Week 8: Launch Vehicle Stress Analysis and Launch Vehicle Stability and Control

Launch vehicles are highly mass optimized structures which are exposed to extreme loads. This module will examine and characterize the loads experienced by the vehicle.

- Strength and stress analysis
- Stress determination using external loads
- Allowable stresses based on buckling criteria
- Structural methods to increase critical axial stress
- Effect of internal pressure on stresses
- Determining the overall vehicle stress state

For a launch vehicle to deliver a payload to a defined orbit, it must be stable during atmospheric and exoatmospheric flight and must have an adequate margin to allow for off-axis thrust (thrust vector control) to be employed to steer the vehicle.

- Guidance and navigation versus attitude control
- Stability and control
- Flight control elements
- Controlled vehicle equations of motion
- Control system performance and rules of thumb

Student Evaluation and Grading

Each student will be evaluated based on their individual performance as well as group performance.

- **Individual:** Students will be evaluated in essay form final exam or with a final individual topic assignment.
- **Group:** Groups will be given weekly assignments related to the lecture materials along with feedback for their prior submissions. Grades will be assigned based on team performance.

Individual and group performance will be weighted 2/3^{rds} and 1/3rd to determine each student's final grade.