

Laboratory Instruction in Undergraduate Astronautics

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Introduction

One significant distinction between the “standard” educational programs in aeronautical and astronautical engineering is the extent to which experimental methods are incorporated into the curriculum. The use of wind tunnels and their many variations is firmly established in the aeronautical engineering curricula throughout the United States. In astronautical engineering, however, there do not appear to be any standard experimental facilities in wide use. This is understandable, given the unique environment in which spacecraft operate; however, there are several facilities which could fill this role, some of which are already in place at universities with a strong space emphasis. The purpose of this paper is to describe some of these facilities and their uses in teaching undergraduate astronautics.

We begin by describing the topics in astronautics that are distinct from other topics in aerospace engineering. We then describe a variety of field exercises and laboratories that can be used to enrich the teaching of astronautics. These exercises focus on satellite “observation,” both visually and using amateur radio receivers. Additional laboratories described include a Spacecraft Attitude Dynamics and Control Simulator, and a “design, build, and fly” project to be launched in late 2001.

Topics in Astronautics

Some topics in aerospace engineering, such as structures, are common to both aeronautics and astronautics, so that related laboratories benefit both parts of the curriculum. There are however some space-specific topics that typically have no laboratory component, primarily related to the motion of spacecraft. Satellite motion is a complicated combination of the orbital motion of the satellite around the earth and the attitude, or pointing, motion of the satellite platform. The overall motion is affected by gravity, controlled thrusters, material outgassing, motion of internal components of the satellite, solar radiation pressure, atmospheric drag, and other forces. The study of satellite dynamics and control is typically divided into astrodynamics and attitude dynamics, with additional applied material on spacecraft design.

Kepler (1571–1630) and Newton (1642–1727) laid the foundations for the subject of astrodynamics as it is taught today. Kepler’s three laws were formulated from curve-fitting of the carefully recorded astronomical observations of Tycho Brahe (1546–1601):

1. The orbit of each planet is an ellipse with the Sun at one focus.
2. The line joining the planet to the Sun sweeps out equal areas in equal times.

3. The square of the period of a planet is proportional to the cube of its mean distance to the sun.

Newton subsequently invented the differential and integral calculus and stated the law of gravitation and his three laws of motion, which he used to derive Kepler's laws of planetary motion. Both Kepler's and Newton's laws are included in essentially all textbooks on astrodynamics. The standard presentation includes development of the vector differential equation describing orbital motion, development of the solution to this equation, and detailed study of a variety of applications such as orbit determination, orbit transfers, and interplanetary trajectories. Typical textbooks for this subject include the affordable but out-dated Bate, Mueller, and White¹ and the more recent book by Vallado.²

A fundamental concept in astrodynamics is that an orbit can be described by a set of six *orbital elements*, based on the fact that an orbit is a conic section. One set of six orbital elements includes semimajor axis, eccentricity, inclination, right ascension of the ascending node, argument of periapsis, and time of periapsis passage. Typical exercises in astrodynamics include a variety of numerical problems, such as

- Given the position and velocity of a satellite, determine its orbital elements
- Given a satellite's orbital elements at a particular time (or *epoch*), determine the position and velocity at a later time
- Given a launch site and a desired orbit, determine the correct launch heading and velocity to achieve the orbit

These and other problems can be solved by hand calculations when specifics are given, and they are certainly appropriate for implementation as computer subroutines that can be used in solving more complex problems. These are valuable exercises, but not all students develop a clear understanding of the significance of the calculations or the results. Graphical tools for visualizing orbital motion are helpful, including FreeFlyer,³ Satellite ToolKit,⁴ and WinOrbit.⁵ The latter two have the distinction of being freely available for download off the internet. In addition, we have developed a suite of MatLab⁶ functions that students can use to perform calculations and to visualize orbital motion. A commercial MatLab "toolbox" is also available.⁷

Attitude dynamics is more complicated than astrodynamics in that it involves the rotational motion of reference frames instead of the comparatively simple translational motion of a point. The foundations of this topic were established by Euler (1707–1783), whose Euler angles, Euler axis, and Euler parameters are still standard topics. A standard though advanced reference for the material is the monograph edited by Wertz.⁸ An introductory text exclusively on attitude dynamics is available in Rimrott,⁹ whereas Hughes¹³ provides an advanced treatment of attitude dynamics. More commonly, texts include both astrodynamics and attitude dynamics; *e.g.*, Sidi,¹⁰ Wiesel,¹¹ and Wie.¹²

Typical problems developed in attitude dynamics texts involve kinematics, dynamics, and control. Kinematics problems involve working with rotation matrices and various parameterizations of rotation matrices, including Euler angles and Euler parameters (also known as quaternions). Attitude determination is treated in some texts (notably Refs. 8, 10, and 14), but is typically not covered at all. Rigid body dynamics is central to all attitude dynamics texts, with special attention to Euler's equations of motion and the special solutions for the case of torque-free axisymmetric rigid bodies. Other special cases include the use of thrusters, momentum wheels, or control moment gyros to control the rotational motion of a rigid body. As with astrodynamics, these problems can be studied using hand calculations or by using computer subroutines. The latter are certainly more useful in dealing with more advanced problems. Visualization of attitude motion is an important ability that students need in order to understand attitude dynamics. Satellite ToolKit⁴ has commercial modules that permit the visualization of attitude motion. We have also developed MatLab routines that students can use. A commercial MatLab toolbox is also available,¹⁵ and is compatible with Satellite ToolKit.

Space systems design is typically taught during the senior year. At Virginia Tech, space design is an alternative to aircraft design (a required one-year capstone design course), and is typically chosen by a significant fraction of seniors. This course is usually taken after an astrodynamics course, but often students in space design have not had an attitude dynamics course. Typically, students develop a detailed spacecraft design in response to a Request for Proposal (RFP), written either by the instructor or a participating outside agency. Several textbooks on space design have appeared in the past few years, including Pisacane and Moore,¹⁴ Agrawal,¹⁶ Griffin and French,¹⁷ Fortescue and Stark,¹⁸ and Larson and Wertz.¹⁹ A distinguishing characteristic of the latter text is its emphasis on the relationship between mission requirements and design, with a single non-trivial example mission being used throughout the text to illustrate the design process.

As we have described above, astronautics education typically focuses on applied numerical solutions to specific problems in orbital and attitude dynamics and control, with a capstone spacecraft design course to provide the students with some "practical" experience. In the remainder of the paper we describe some field and laboratory work that can be used to enhance this standard approach.

Visible Satellite Tracking

One way to engage students with the relatively abstract idea of satellites hurtling through outer space at 8 kilometers per second is to get them outside watching the satellites go by. As the astronomer and science fiction author, Sir Frederick Hoyle (1915–) put it,

"Space isn't remote at all. It's only an hour's drive away if your car could go straight upwards."

The relative closeness of "space" means that we should be able to see some of the objects that are up there. Of course, we can see stars and planets and the moon, but with a little planning, we can also see many of the artificial moons in low Earth orbit (300–1000 km altitude). The hobby of satellite-watching is well enough established that there are websites available to tell you when and where

Table 1: Example of GSOC Satellite Visualizations Homepage Output

Visible Pass Details				
Date:	Saturday, 13 March, 1999			
Satellite:	ISS			
Observer's Location:	Blacksburg (37.2327N, 80.4284W)			
Local Time:	Eastern Standard Time (GMT - 5:00)			
Orbit:	389 x 395 km, 51.6 (Epoch 08 Mar)			
Sun elevation at time of maximum pass elevation:	-16.9			
Event	Time	Elevation	Azimuth	Distance(km)
Rises above horizon	19:42:54	0	NW	2,285
Reaches 10 deg elevation	19:44:59	10	NW	1,428
Maximum elevation	19:48:10	67	SW	425
Enters shadow	19:49:08	39	SE	597

to look to see such artificial moons as the Hubble Space Telescope, the Mir Space Station, and the International Space Station. For example, the German Space Operations Center (GSOC) maintains a Satellite Visualizations Homepage²⁰ that allows a user to enter a particular Earth location and bookmark the resulting page for future use. This page provides the user with tables of visibility for specific satellites. For example, on Saturday, March 13, 1999, the International Space Station is visible from Blacksburg, Virginia as described in Table 1. The station rises in the northwest at about 7:43 PM local time and goes into the Earth's shadow in the southeast about 6 minutes later. This example illustrates some important aspects of satellite observing. The satellite must pass over the ground site; normally for low-Earth orbit satellites, the "pass" will last just a few minutes, and will occur relatively infrequently. Additionally, it must be dark at the ground site but the satellite must be in sunlight in order for the observer to see it. Thus satellite observing opportunities are typically just after sunset or just before sunrise.

An entertaining exercise for students in astrodynamics involves finding out when a particular satellite will be visible locally and then going out to see it. This can be combined with an essay-writing assignment on the particular spacecraft. Of course, local weather conditions can interfere with the observing part of this assignment. Furthermore, this exercise requires relatively minimal application of the concepts taught in astrodynamics. An enhanced version requires the student to duplicate the calculations that are performed automatically by the software at the Satellite Visualizations Homepage.²⁰

Calculation of satellite visibility is based on the fundamental concepts taught in astrodynamics, specifically position vectors and orbital elements. There are, however, some additional details that must be covered, including the effects of Earth rotation and Earth oblateness, and the use of range, azimuth, and elevation as coordinates for describing position. These topics are covered in the standard astrodynamics texts. Another topic that is necessary is the interpretation and use of "two-line element sets" or TLEs. The classical orbital elements mentioned above are useful for describing basic orbits, but are inadequate for long-term prediction of future satellite position.

The reason for this inadequacy is that the classical orbital elements are based on several ideal assumptions about the orbital environment that are not strictly valid for Earth-orbiting satellites. These include gravitational perturbations due to the Sun and Moon, the effects of Earth oblateness, and the effects of aerodynamic drag. The TLE is the standard format for communicating the orbital elements as well as information about the perturbations. The format description and an example TLE for the ISS are given in Table 2.

Further information about TLEs is available in Vallado,² and at the CelesTrak website.²¹ The latter is also a useful source for current TLEs for many satellites, and includes links to useful software for working with satellites. Using “fresh” TLEs is important, since the effect of perturbations is to cause the orbital elements to change over time.

Using current TLEs for Earth-orbiting satellites, students can apply the basic algorithms of astrodynamics to determine when these satellites pass over a particular ground site, what the azimuth of the rise and set will be, and how the elevation will vary during the “pass.” Their calculations can be compared with trusted calculations such as those provided by the Satellite Visualizations Homepage.²⁰ Furthermore, packages such as Satellite ToolKit⁴ and WinOrbit⁵ work with TLEs and provide similar information.

A simple MatLab application, `Visible.m`, has been developed at Virginia Tech to compute passes. This application allows a user to select a specific TLE (saved in a text file), a specific date, and specific ground site latitude and longitude, using a graphical user interface. The program then computes all the passes during a 24-hour period and allows the user to view the passes in several different graphical formats. One example is shown in Fig. 1. Note that this application does not take into account lighting conditions at the ground site or at the satellite, so that it is not quite as useful for visual satellite observing as the Satellite Visualizations Homepage²⁰ is.

However, the purpose of `Visible.m` is not really to enable students to “see” satellites, but rather to enable them to predict when satellites will be above the horizon with respect to a particular ground site. This is a slightly more general concept of “visibility,” which we will call “accessibility.” Accessibility is in fact of more practical interest to satellite operators than visibility.

Amateur Satellite Tracking and Telemetry

In practice, the owners and operators of satellites are not usually interested in seeing the satellites as they pass overhead, but are definitely interested in knowing when they are passing overhead so that communications can be established. Thus it is important to be able to predict a satellite pass, even if the viewing conditions (ground site in darkness, satellite in sunlight) are not met, since these conditions are irrelevant for communications with the satellite. Having students determine when particular satellites are accessible from a ground site is straightforward, but would be more interesting if the students could then take the next step and access the satellite in some way other than visual observation. Fortunately there is a relatively large fleet of amateur satellites that permit just such access.

The amateur satellite community is embodied in The Radio Amateur Satellite Corporation (AMSAT).²² Collectively, the organization has designed, constructed, arranged launches for, and op-

Table 2: Two-Line Element Format

Data for each satellite consists of three lines in the following format:

AAAAAAAAAAAAAAAAAAAAAAAAAAAA

```
1 NNNNNNU NNNNNNAAA NNNNNN.NNNNNNNNN +.NNNNNNNNN +NNNNNN-N +NNNNNN-N N NNNNNN
2 NNNNNN NNN.NNNNN NNN.NNNNN NNNNNNNNN NNN.NNNNN NNN.NNNNN NN.NNNNNNNNNNNNNNNNN
```

Line 0 is a twenty-four character name (to be consistent with the name length in the NORAD SATCAT).

Lines 1 and 2 are the standard Two-Line Orbital Element Set Format identical to that used by NORAD and NASA. The format description is:

Line 1

Column	Description
01	Line Number of Element Data
03-07	Satellite Number
08	Classification (U=Unclassified)
10-11	International Designator (Last two digits of launch year)
12-14	International Designator (Launch number of the year)
15-17	International Designator (Piece of the launch)
19-20	Epoch Year (Last two digits of year)
21-32	Epoch (Day of the year and fractional portion of the day)
34-43	First Time Derivative of the Mean Motion
45-52	Second Time Derivative of Mean Motion (decimal point assumed)
54-61	BSTAR drag term (decimal point assumed)
63	Ephemeris type
65-68	Element number
69	Checksum (Modulo 10) (Letters, blanks, periods, plus signs = 0; minus signs = 1)

Line 2

Column	Description
01	Line Number of Element Data
03-07	Satellite Number
09-16	Inclination [Degrees]
18-25	Right Ascension of the Ascending Node [Degrees]
27-33	Eccentricity (decimal point assumed)
35-42	Argument of Perigee [Degrees]
44-51	Mean Anomaly [Degrees]
53-63	Mean Motion [Revs per day]
64-68	Revolution number at epoch [Revs]
69	Checksum (Modulo 10)

All other columns are blank or fixed.

Example:

```
ISS (ZARYA)
1 25544U 98067A 99026.49859894 -.00001822 00000-0 -18018-4 0 2532
2 25544 51.5921 190.3677 0004089 55.0982 305.0443 15.56936406 10496
```

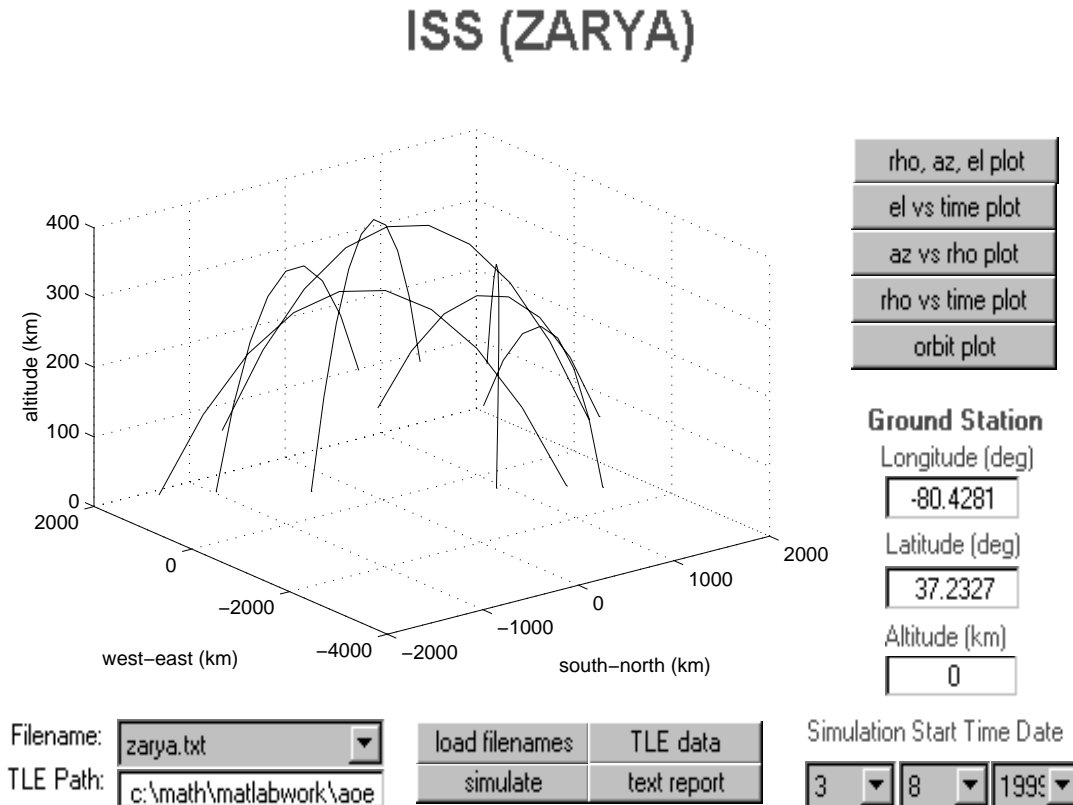


Figure 1: Example using Visible.m to illustrate Zarya visibility from Blacksburg, Virginia.

erated over two dozen satellites since its founding in 1969. The satellites in orbit today are in a variety of different orbits and use a variety of communications and other technologies. Note that these satellites are generally much smaller than the large spacecraft that are visible from Earth. Typical amateur satellites range from 10 to 100 kg in mass, as compared with the 11,600 kg Hubble Space Telescope. Detailed information is available on the AMSAT website, and the handbook by Davidoff²³ provides an excellent introduction to the concepts of operating amateur satellites. A useful collection of articles on amateur satellites has been edited by Roznoy.²⁴ Among the many satellites whose orbital information is available as TLEs on the CelesTrak website²¹ are 27 satellites listed under the category of “Amateur Radio.”

The upshot of the availability of amateur satellites is that there exists a substantial body of literature on how to set up inexpensive ground stations for tracking and communicating with these satellites. The amateurs who work with these satellites generally do not have unlimited budgets and so have developed simple systems solutions to these problems. Stanford University’s Space Systems Development Laboratory has an extensive ground station facility operated in conjunction with their graduate satellite design program.²⁵ The information available on their website should make setting up a ground station relatively painless for interested aerospace engineering professors and students.

We are establishing a Satellite Tracking Laboratory at Virginia Tech to be used primarily in teach-

Table 3: Satellite Tracking Laboratory Components

Item	Price
Yaesu FT-736R Transceiver	\$1,890
Yaesu G-5400B Rotator	549
Landwehr 2M Pre-amplifier	229
Landwehr 435 Pre-amplifier	249
Cushcraft 22XB Antenna	229
Cushcraft 738XB Antenna	179
Rohn 20' tower	500
Kansas City Tracker/Tuner	319
Total	\$4,144

ing undergraduate astronautics. The facility includes the essential components listed in Table 3. In addition to these major components, one or two desktop computers and some small hardware such as coaxial cable and connectors are also required. It is illegal to transmit without an amateur radio license, so the transmit capability of the transceiver is disabled, requiring a key to enable this feature.

With the Satellite Tracking Laboratory, the satellite visibility prediction assignment becomes more meaningful and leads to a significant laboratory exercise for teams of two or three students. A typical laboratory assignment is based on a fresh TLE for a particular amateur satellite. The students must perform basic calculations using the given TLE to determine when potential accessible passes will occur within the near future. These calculations can be checked by comparison with results from programs such as Satellite ToolKit⁴ and WinOrbit.⁵

Using these predictions, the students must schedule use of the Satellite Tracking Laboratory at an appropriate time. Typically this involves selecting one of several upcoming passes based on pass duration and convenience. Once a lab time has been scheduled, the students must arrange for a demonstration of operations of the tracking station. Then the actual pass operations can be carried out by the students. The antenna must be pointed in the direction of the predicted rise of the satellite, and the Kansas City Tracker/Tuner (KCT) must be configured. Then the KCT controls the pointing of the antenna at the spacecraft and the adjustment of the receiver frequency to account for Doppler shift. Students record signal strength, azimuth, and elevation as functions of time, and also download and store the spacecraft telemetry. The telemetry includes spacecraft status and health information such as battery voltages and temperatures, and solar cell currents.

The information gathered by the students during the pass is applicable to astrodynamics, attitude dynamics, and space design, and can be analyzed appropriate for the particular course. Tracking the trajectory itself is an affirmation of the topics covered in astrodynamics. Solar cell currents can be used to provide a coarse determination of the satellite's attitude with respect to the sun. Other telemetry is useful in understanding the performance of specific components used in satellites.

Spacecraft Attitude Dynamics and Control Simulator

Another laboratory being established at Virginia Tech is the Spacecraft Attitude Dynamics and Control Simulator. This laboratory is initially intended to support the author's research in this field. The principal class of problems being investigated involves the large-angle, three-dimensional, rotational maneuvers of rigid and flexible spacecraft, such as those used to point the Hubble Space Telescope. The actuators used to control these rotational maneuvers are typically spinning flywheels, such as momentum wheels and control moment gyros. The reason for using flywheels instead of conventional rocket thrusters is that rocket thrusters expel gases that contaminate the spacecraft's instruments. The modeling and analysis of these problems requires the use of nonlinear differential equations and new approaches to nonlinear control. The centerpiece of the new facility is a Spherical Air Bearing Space Simulator, manufactured by Space Electronics, Inc.²⁶ The air bearing supports an approximately 150 kg payload, and allows the experimental investigation of pointing maneuvers.

With the simulator, we are able to conduct a wide range of large-angle, three-dimensional, rotational maneuver experiments. The initial emphasis of these investigations is on verifying newly developed nonlinear control laws and determining the impact of flexibility on maneuver effectiveness. New space-based telescopes being developed by NASA and the Air Force will require improved approaches to executing maneuvers, and the new facility will allow the experimental validation of potential maneuvers. In addition, the new technology of using flywheels for simultaneous energy storage and attitude control has yet to be experimentally verified for three-dimensional maneuvers.

Once this facility is established, it will be used in undergraduate laboratory exercises in the author's attitude dynamics and control course. Example projects include: system identification of moments of inertia and location of mass center, attitude stabilization using momentum wheels or compressed gas thrusters, and implementation of large-angle rotational maneuvers.

Satellite Design, Build, and Fly

Perhaps the ultimate aerospace engineering educational laboratory is the "design, build, and fly" project. Virginia Tech has extensive experience in student-centered projects of this type for aircraft, and is now involved in designing and building a small satellite. This satellite project, the Virginia Tech Ionospheric Scintillation Measurement Mission²⁷ (VTISMM), is sponsored by the Air Force Research Laboratory, the Defense Advanced Research Projects Agency, and NASA's Goddard Space Flight Center through the University Nanosatellite Program.²⁸ The 10 kg satellite is being designed by undergraduate students in aerospace, computer, and electrical engineering, and will be launched on the shuttle in late 2001. The "HokieSat" will fly in formation with two other university "nanosats" being built by students at Utah State University and the University of Washington. The formation of three satellites is collectively called the Ionosphere Observation Nanosatellite Formation (ION-F). In addition to designing and building the satellites, the students are also designing and building ground stations at Virginia Tech and Utah State University*. These

*We will not have a ground station at the University of Washington because its high latitude means that the satellites will rarely be accessible there.

ground stations will be connected to the internet so that either satellite can be controlled by either university through either ground station.

Although this type of design, build and fly project is an excellent opportunity, it may not be possible to establish such a project in every aerospace engineering program. Other opportunities include NASA's Shuttle Small Payloads Project²⁹ and Reduced Gravity Student Flight Opportunities.³⁰ Both programs provide opportunities for students to build and fly space hardware.

Conclusions

There are many opportunities to enhance the space component of undergraduate aerospace engineering education. Undergraduate education in astronautics, especially spacecraft dynamics and control, typically emphasizes computational exercises. These exercises can easily be enhanced by introducing students to the hobby of satellite-watching, especially if students are required to complete the appropriate calculations rather than using existing software to plan their viewing. For a reasonable investment, a satellite tracking station can be established to permit students to gain significant experience relevant to astrodynamics, attitude dynamics, space design, and satellite operations. A more costly facility can be used to provide hands-on experience with attitude dynamics and control, but such a facility will typically require a research program to provide adequate financial support. Design, build, and fly projects provide challenging opportunities for students to develop and fly significant space experiments.

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The School of Aeronautics and Astronautics undergraduate program normally begins in the second year, after completion of the common First Year Engineering Program. AAE is among the top aerospace engineering programs in the nation and was ranked No. 4 in the 2020 U.S. News and World Report rankings of aerospace undergraduate programs. Some courses in the junior year are available in both aeronautical and astronautical versions, and students choose the version of primary interest. In the senior year, students pursue, in consultation with their academic advisor, a specialization area. This is commonly chosen from the disciplines of Laboratory: introduction to graphics, computation and simulation. ASTE 280 Astronautics and Space Environment I (3, Sp) Solar system, two-body problem, orbits, Hohmann transfer, rocket equation, space environment and its effects on space systems, sun, solar wind, geomagnetic field, atmosphere, ionosphere, magnetosphere. (Duplicates credit in former AME 282.) Prerequisite: MATH 226, PHYS 152 L . ASTE 291 Team Projects I (1, max 4, FaSp) Participation in ASTE undergraduate student team projects. Intended for lower-division students or those with little prior project experience. ASTE 301ab Home > Undergraduate study > Undergraduate courses > Aerospace Engineering, Astronautics & Space Technology MEng/BEng (Hons). Facebook Twitter. Aerospace Engineering, Astronautics & Space Technology MEng/BEng (Hons). Explore. arrow_downward. I am just starting a PhD at Kingston researching rocket propulsion technologies, having graduated with a first in Aerospace Engineering, Astronautics and Space Technology BEng (Hons). My progress into university was through Clearing – a process that can scare people and make them feel unhappy about going to university.