

# ASTE 520    Spacecraft Design



**Fall 2010**

**Mike Gruntman**

**Astronautics and Space Technology  
Viterbi School of Engineering  
University of Southern California  
Los Angeles**

# Spacecraft Design

- **Organization of the class**
- **Content**
- **Schedule**
- **Astronautics Program**
- **Course notes**
- **Other supporting material**
- **Homework**
- **Exams**
- **Distance Education Network DEN**

## Organization of the Class – First Lecture

- Class Notes are essential and mandatory for ASTE 520
- On-campus and remote students: download Class Notes from the class web site at DEN (<http://den.usc.edu> or <http://mapp.usc.edu/>)  
password required (see Slides 34–35)
- Teaching will be done directly from the notes – bring the required materials to the class
- Files for the first class meeting on August 23, 2010:  
[2010\\_Fall\\_MG\\_SCD\\_00\\_part\\_1\\_no\\_pswd.pdf](#)  
[2010\\_Fall\\_MG\\_SCD\\_00\\_part\\_2\\_no\\_pswd.pdf](#) (this presentation)  
[2010\\_Fall\\_MG\\_SCD\\_01.pdf](#) (self study for homework)  
[2010\\_Fall\\_MG\\_SCD\\_02.pdf](#)

**Attention: read this section of Class Notes for rules**

# Contents – ASTE 520

- **Section 00, Part 1 and Part 2**  
**Organization of the Class**
- **Section HW**  
**Homework Problems**
- **Section 01**  
**Brief History**
- **Section 02**  
**Universe, Galaxy, Solar System**
- **Section 03**  
**Space Environment**
- **Section 04**  
**Orbital Mechanics**
- **Section 05**  
**Mission Geometry**
- **Section 06**  
**Spacecraft and Mission Design Overview. Operations. Reliability.**
- **Section 07**  
**Spacecraft Attitude Determination and Control**

# Contents – ASTE 520

- **Section 08**  
**Spacecraft Propulsion**
- **Section 09**  
**Launch Systems**
- **Section 10**  
**Communications**
- **Section 11**  
**Electric Power Systems**
- **Section 12**  
**Thermal Control**
- **Section 13**  
**Structures and Mechanisms**

# Objectives of the Course

- This course is of a survey nature, meant to acquaint the student with key aspects of spacecraft system design.
- The class notes and textbook provide most of the details, and the homework is designed to provide a first-level understanding.
- We will learn the basic nomenclature and vocabulary, so that you can converse with understanding with subsystem specialists.
- No pundit will ever “snow” you.

**Spacecraft design is essentially an interdisciplinary sport that combines science, engineering, and external phenomena. The course provides basics of systems engineering of space systems.**

# Objectives of the Course

- Whenever possible, you will learn the design considerations which come into play in laying out a mission and a preliminary design.
- You will learn some basics. It is assumed, however, that everyone has taken undergraduate physics, mathematics, and some engineering classes.
- You are expected to **remember some *Physics and Mathematics***
- Satellite system design is an essentially interdisciplinary sport that combines engineering, science, and external phenomena.

# Instructor

## Mike Gruntman

Professor of Astronautics

*Department of  
Astronautical Engineering*

Tel. 213-740-5536

Office: RRB-224

mikeg@usc.edu

<http://astronautics.usc.edu>



- detailed biographical sketch in Section 00, Part 1
- communications on the first-name basis most welcome
- URL <http://astronauticsnow.com/MikeGruntman/>  
<http://astronautics.usc.edu>

# Is This Course for You?

- **If you are** a student, engineer, or scientist in astronomy, physics, chemistry, mathematics, Astronautical Engineering (E), Aerospace E, Aeronautical E, Civil E, Electrical E, Mechanical E, Industrial E, Systems E, Nuclear E, Chemical E, Computer E, .....

and/or

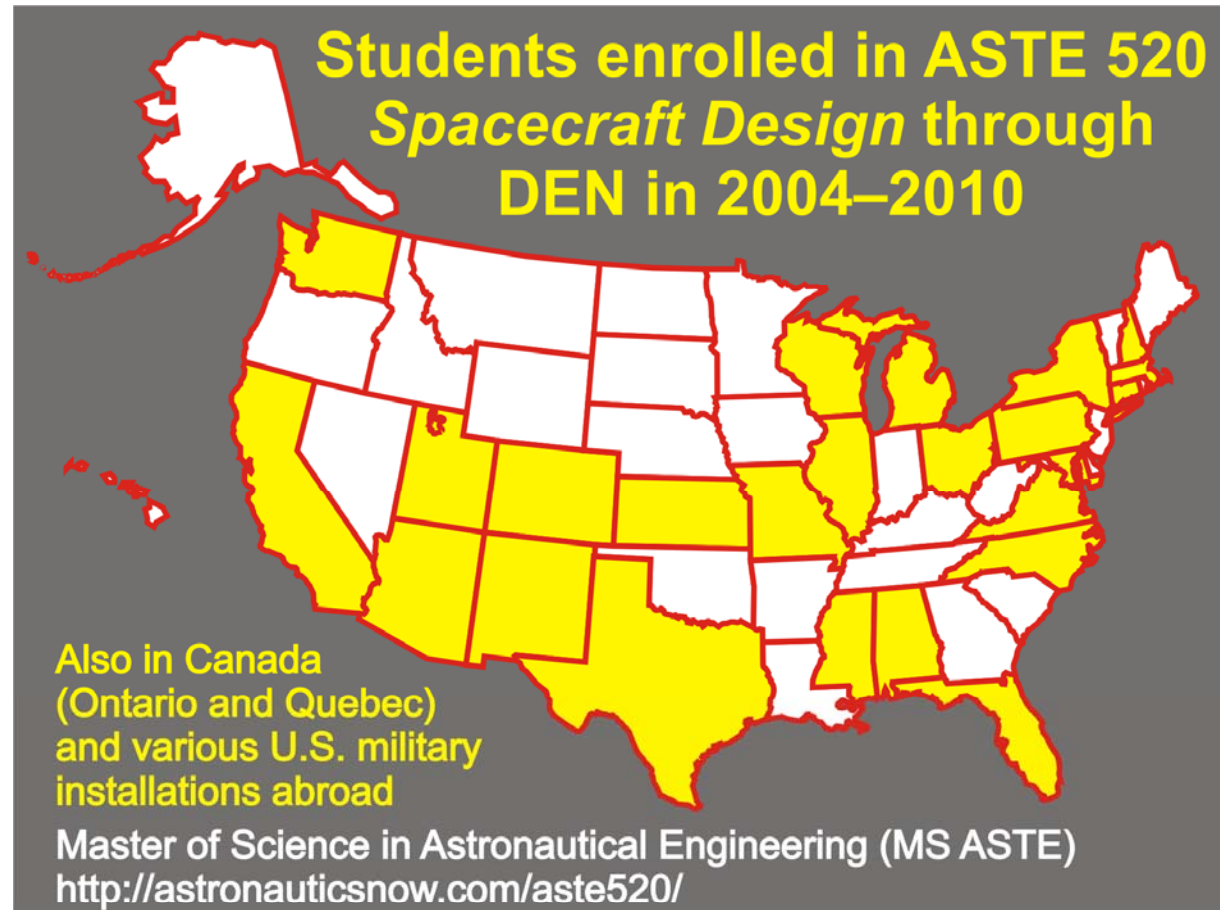
- **If you work or plan (want) to work** in the space or defense industry or in government space research and development centers (NASA, Air Force, IC, DOE, NOAA, ...) or space mission operations and control centers

**This course – ASTE 520 – IS FOR YOU**

In addition to classroom, *ASTE 520 Spacecraft Design* is simultaneously offered through the USC Viterbi's Distance Education Network (DEN) and can be taken by students anywhere in the United States

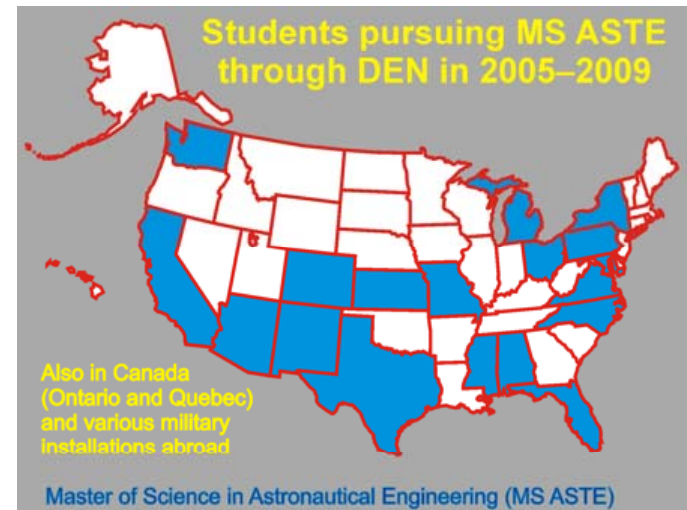
## ASTE 520 Spacecraft Design

ASTE-520  
*Spacecraft Design*  
accessible to  
students anywhere  
in the United States  
through the  
Distance Education  
Network (DEN)



# Astronautics on the West Coast

- **ASTE 520** is a **required core class** for the USC graduate degree program in *astronautical engineering*.
  - Many students in other science and engineering graduate programs take ASTE 520 as technical elective
- USC **Astronautics Program** was established in 1994–1995
- Today, it is a comprehensive program that offers **BS**, **BS Minor**, **MS**, **Engineer**, and **PhD** degrees and **Graduate Certificate** in **Astronautical Engineering**
  - Program history, focus, and organization is at <http://astronauticsnow.com/SpaceEducation/> (includes downloadable papers at AIAA and ASEE conferences)

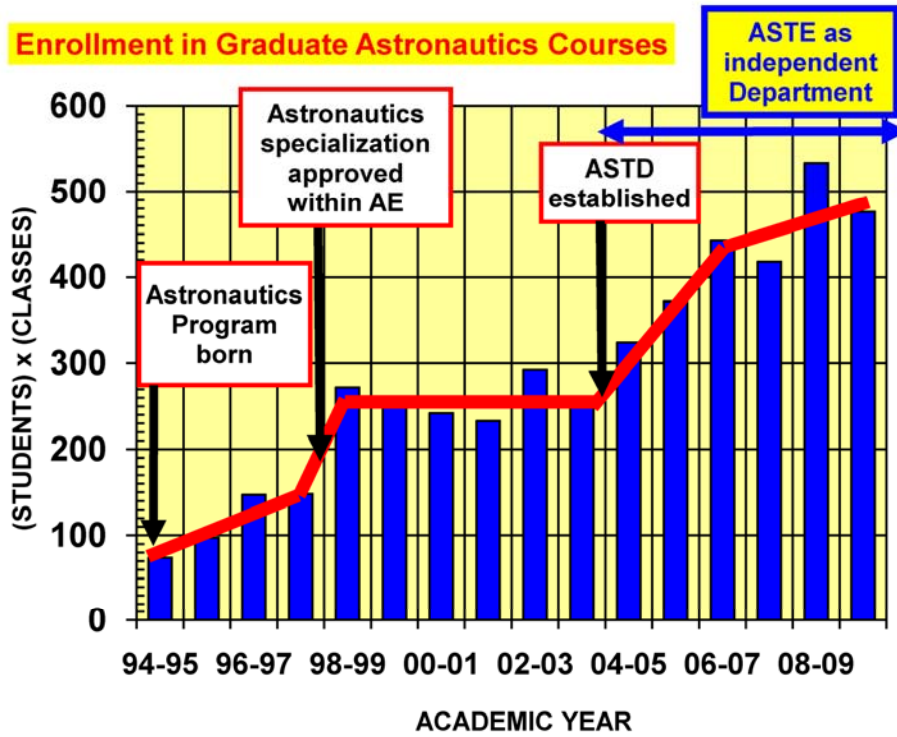


## Department of Astronautical Engineering (ASTE)

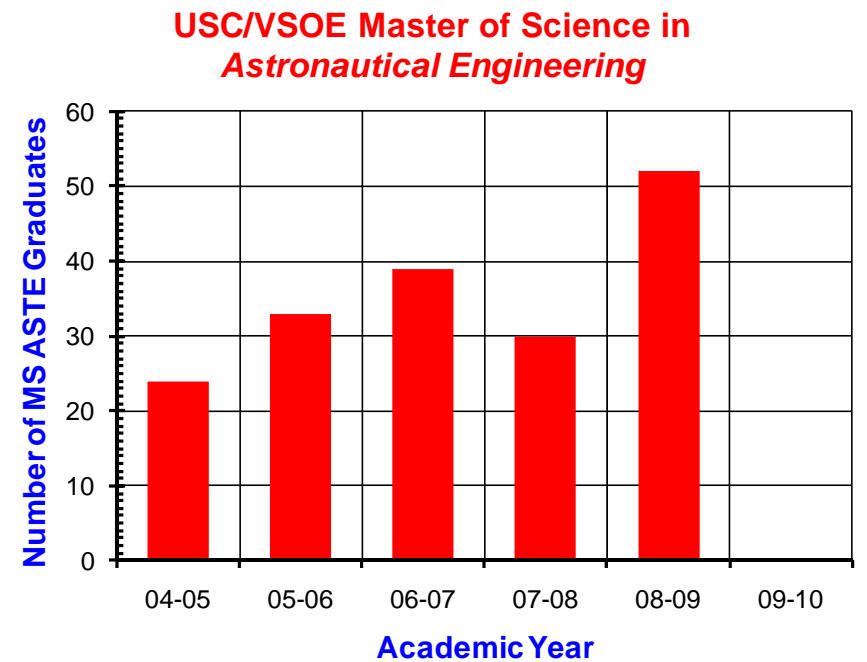
- USC established the **Astronautics and Space Technology Division (ASTD)** in August 2004 “to position the USC Viterbi School of Engineering to take full advantage of rapidly growing opportunities in space”
  - independent academic unit within the USC Viterbi School of Engineering operating as an academic department – assumed charge of all former degree programs and courses in *aerospace engineering (astronautics)*, postcode AEAN
  - USC approved in May 2005 new degree programs in *astronautical engineering* (postcode **ASTE**) and discontinued programs in *aerospace engineering (astronautics)*
  - see program history at <http://astronauticsnow.com/SpaceEducation/>
  - renamed **Division of Astronautical Engineering** in 2009
- Since July 1, 2010, it is the **Department of Astronautical Engineering (ASTE)**  
**ASTE – a unique pure-space-engineering Department in the United States**
- Today, ASTE offers **BS**, **BS Minor**, **MS**, **Engineer**, and **PhD** degrees and **Graduate Certificate** in *astronautical engineering* (postcode **ASTE**)
- ASTE is responsible for programs in astronautics and space technology at USC, concentrating on meeting the educational and research needs of interest to the space and defense industries, government research and development centers, and academia

## Department of Astronautical Engineering

- **Astronautics Program**  
Combines science and engineering fundamentals with highly specialized classes taught by astronautics adjunct faculty and part-time lecturers ([top specialists in the trenches](#))
- **ASTE web site** — <http://astronautics.usc.edu>
- **Web site *Frequently Asked Questions FAQ MS ASTE***  
<http://astronauticsnow.com/MSASTE/>
- **Long-term class schedule** — <http://astronauticsnow.com/MSASTE/>
- Always check with ASTE Student Affairs for updated class schedule



Some statistics



## ASTE 520 – Spacecraft Design

- **Prerequisite**

Graduate standing in engineering or science

- **Class Notes**

Class Notes are essential and mandatory for the course. Download Notes from the class web site at DEN (<http://den.usc.edu> or <http://mapp.usc.edu>).

- **Class Procedure**

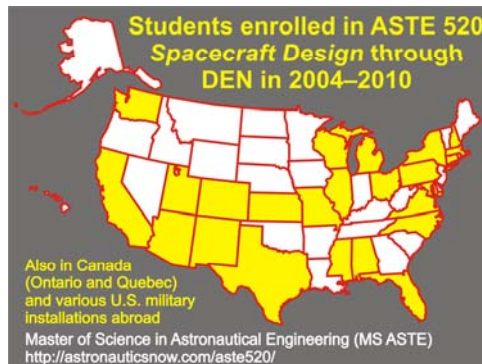
Teaching will be done directly from the notes. It is advisable to bring appropriate materials to class.

## ASTE 520 Spacecraft Design

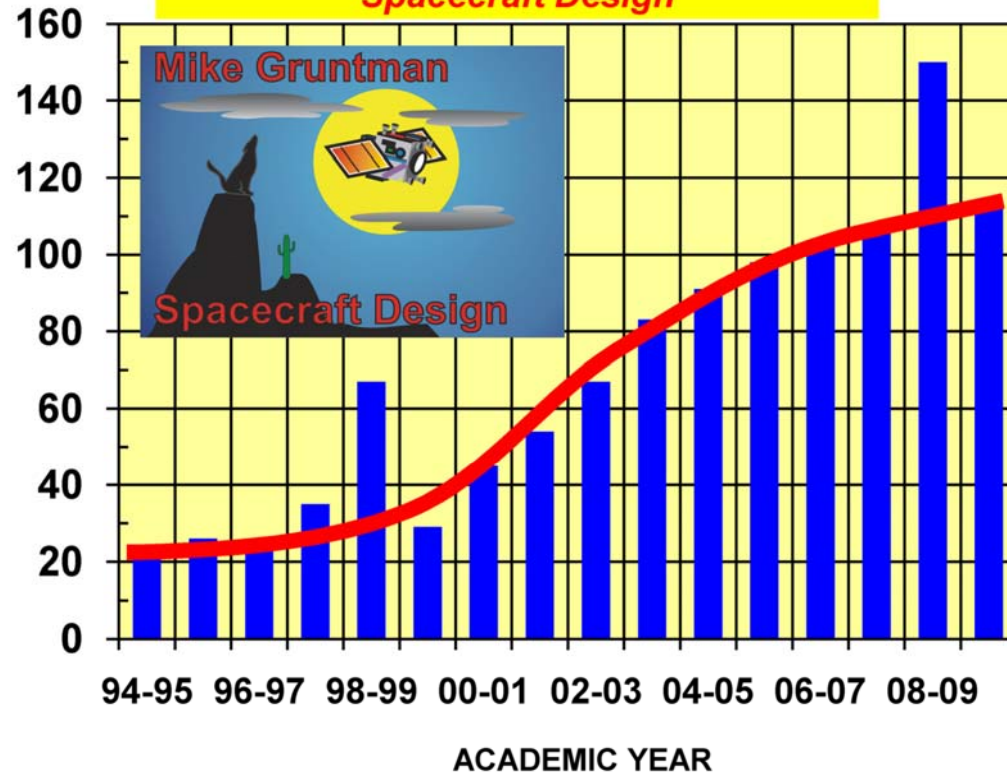
## Popular Course – Enrollment Dynamics

### ASTE 520

Each year, students  
hail from 10–14  
States of the Union



Enrollment in Mike Gruntman's ASTE 520  
Spacecraft Design



About one half of enrolled students pursue degrees in *Astronautical Engineering*. Other students pursue various engineering degrees (electrical, mechanical, system, aerospace, civil, computer, etc.). Most students pursue MS; 5–10% pursue PhD.

# Typical Grade Distribution

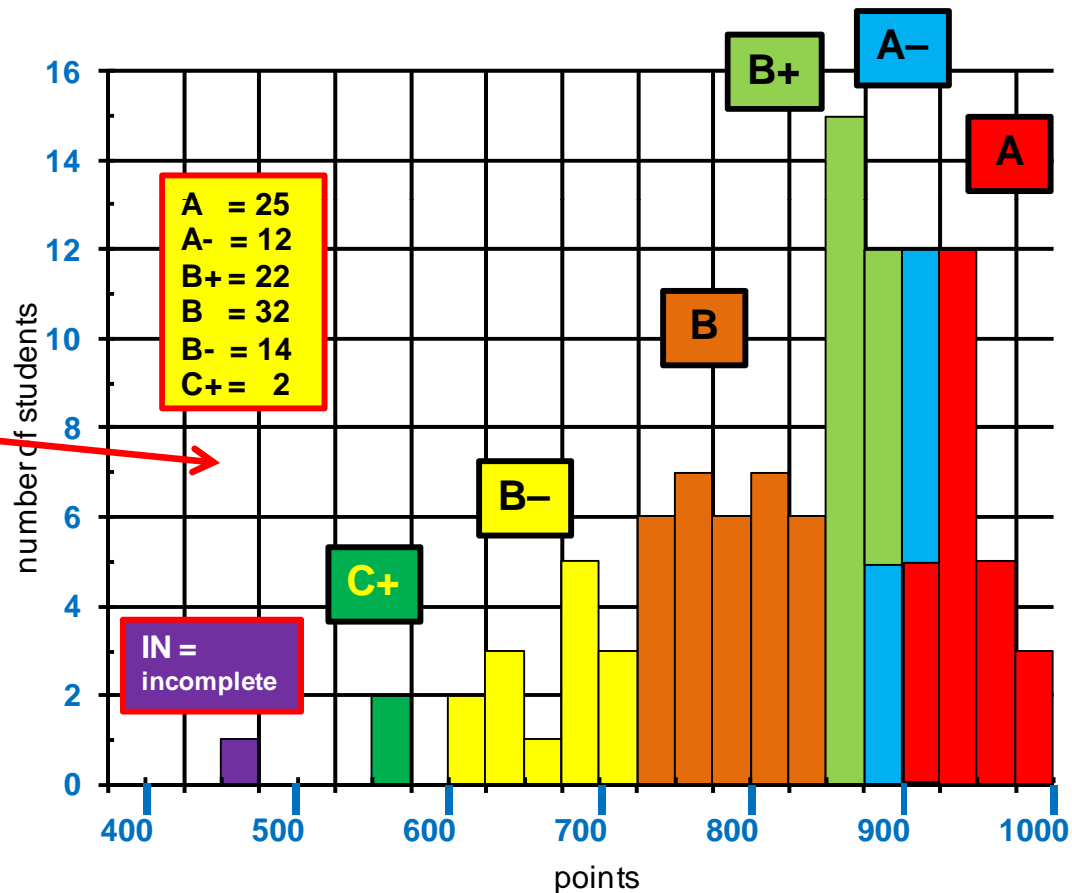
Important question by enrolled students:

What is a typical grade distribution in the class?

Example

**ASTE 520  
Spacecraft Design  
Fall 2007  
Grade Distribution  
(108 students)**

**ASTE 520 Spacecraft Design  
Fall 2007 - Total Scores - December 2007**



# Homework

- **First HW assignments (1,2) due in one week on August 30, 2010.**
- There are **32** homework assignments. Due as **scheduled** (submission schedule is in Section 00, Part 1).
- **Late homework** may be submitted **within two weeks** after the due date but not later ( $\equiv$  must be received by TAs) than **November 22, 2010** (inclusive).  
Late homework will be graded; the grade will be reduced by **50%**.  
No late homework submissions after 22 November. (“No” means “No.”)
- No “make up” (home)work is possible. No special “deals” on homework submission, **regardless of the cause**, are possible.  
**“No” means “No.” “Regardless” means “Regardless.”**
- Homework assignments are posted at the class web site at DEN (<http://den.usc.edu> or <http://mapp.usc.edu>).
- Solutions will be posted, usually a few days after the due date, at the class web site at DEN (<http://den.usc.edu> or <http://mapp.usc.edu>).

## Exams and Grading

- **Midterm Exam**  
**18 October (Monday)**  
**7:00 – 9:00 p.m. (120 min), in class**  
Instructor and TA will be available at 6:30 p.m.  
DEN will arrange proctoring for remote students
- **Final Exam**  
**13 December (Monday)**  
**7:00 – 8:30 p.m. (90 min) , in class**  
Instructor and TA will be available at 6:30 p.m.  
DEN will arrange proctoring for remote students
- **DEN rule:** remote students from the Greater Los Angeles area must take exam on campus. Contact DEN directly if you have questions.

### Grading ASTE 520

<b>Homework</b>	<b>20%</b>
<b>Midterm Exam</b>	<b>40%</b>
<b>Final Exam</b>	<b>40%</b>

**Exams are usually open-book, -notes, -..... No laptops.**

# Organization of the Class

- Syllabus and schedule – flexible guidelines
- Class begins at 6:30 p.m. We have one 10–15 minute break during class.
- **Grading:** Teaching Assistant and Graders: TBA
- **Questions and Complaints about grading**
  - to be directed to TA
  - **only** if arbitration is necessary, contact the instructor
- **Communications with the instructor and TA**
  - office hours
  - telephone and e-mail
    - email to TA **or** instructor; add a copy to the other, **only** if necessary
  - Do not hesitate to call or see TA with questions about the class material, homework, etc.

**Contact Teaching Assistant (TA)! TA is here to be bothered!**

# Office Hours

- **Teaching Assistant's office hours**  
**to be announced (TBA)**

- **Instructor's office hours**

**Monday**                      **3:00 p.m. – 4:30 p.m.**

**Thursday**                      **4:30 p.m. – 6:00 p.m.**

# Organization of the Class

- **Class Attendance:**      **Free walk in / walk out**
  - If sleep, do not snore (on-campus rule only)
  - No food (on campus – DEN's rule)
  - Cell phones and pagers off (be nice)
- **Religious Holy Days**
  - Discuss with instructor in advance conflicting schedules.
- **Questions**
  - Any aspect of astronautics and space exploration may be discussed
  - FEAR NOT! Questions are welcome.
- **Academic Integrity**

See the statement in the Notes ([Section 00, Part 1](#)) and familiarize yourself with the Academic Integrity guidelines in the USC student handbook.

  - **Bottom line**

Homework, exams, etc. are **individual effort**

# Class Notes and Textbook

- **Course Notes (>800 pages)**

**Mike Gruntman, *Spacecraft Design, ASTE-520 Notes, Fall 2010***

**For your personal use only. Copyright protected.**

- **Required text**

***Space Mission Analysis and Design*, ed. W. J. Larson and J. R. Wertz**, Kluwer Academic Publishers and Microcosm, 2nd or 3rd editions.

In addition to the USC bookstore and on-line booksellers (Amazon, B&N, etc.), this book (softcover ~\$50–60) can be purchased **directly and conveniently** from the publisher – <http://astrobooks.com> .

# Spacecraft Design – Class Notes

- Class notes are **mandatory and essential** for the class
- Download class notes from the class web site at DEN (<http://den.usc.edu> or <http://mapp.usc.edu>).  
**Password required (see slides 34–35).**
- Teaching will be done directly from the notes – bring the required materials to the class.
- Homework assignments are in the Class Notes
- Class schedule and Homework submission schedule are in Section 00, Part 1
- **Print the entire set of notes**
  - Total number of pages > 800
  - Many students choose to print **two slides/pages per sheet** of paper
  - You can later print selected pages one page per sheet

# Other Sources of Information

- Several (course-related) video clips – free download and links at <http://astronauticsnow.com/vp/> (also on YouTube in low-resolution)
- A large number of books can be recommended for this class – check the list of recommended books at <http://astronauticsnow.com/AstroBooks/>
- Publications of professional societies (journals, conference proceedings, etc)
- Trade pubs – usually good; mainstream media – often embarrassment
- World Wide Web (WWW)
  - Caution – a lot of unprofessional and inaccurate information (including pure, unmitigated garbage) out there

## Class websites

**Class web site at DEN:** <http://den.usc.edu>

**Public (permanent) class web site:** <http://astronauticsnow.com/aste520/>

Also, frequently asked questions: <http://astronauticsnow.com/msaste/>

## Selected/Recommended Books

- *AIAA Aerospace Design Engineers Guide*, AIAA, 1993..
- B. N. Agrawal, *Design of Geosynchronous Spacecraft*, Prentice Hall, 1986.
- R. R. Bate, D. D. Mueller, and J.E.White, *Fundamentals of Astrodynamics*, Dover, 1971.
- C. D. Brown, *Spacecraft Mission Design*, AIAA, 1992.
- V. A. Chobotov, *Orbital Mechanics*, AIAA, 1991.
- P. Fortesque and J.Stark, *Spacecraft Systems Engineering*, John Wiley and Sons, 1995. (3rd ed. in 2003)
- M. D. Griffin and J. R. French, *Space Vehicle Design*, AIAA. (2nd ed. in 2004)
- M. Gruntman, *Blazing the Trail: The Early History of Spacecraft and Rocketry*, AIAA, 2004.
- S. J. Isakowitz, *International Reference Guide to Space Launch Systems*, AIAA, 1991.
- A. S. Jursa, ed., *Handbook of Geophysics and the Space Environment*, Air Force Geophysics Laboratory, Hanscom AFB, 1985.
- M. H. Kaplan, *Modern Spacecraft Dynamics and Control*, John Wiley and Sons, 1976.

## Selected/Recommended Books (cont.)

- V. L. Pisacane and R. C. Moore, *Fundamentals of Space Systems*, Oxford University Press, 1994.
- V.L. Pisacane, *The Space Environment and its Effects on Space Systems*, AIAA, 2008.
- D. Roddy, *Satellite Communications*, McGraw-Hill, 1996.
- G. P. Sutton, *Rocket Propulsion Elements*, John Wiley and Sons, 1986.
- T. Tascione, *Introduction to the Space Environment*, Orbit Book Co., 1988.
- A. Tribble, *The Space Environment*, Princeton University Press, 1995.
- *TRW Space Data*, TRW Space and Technology Group, 1992.
- D.A. Vallado, *Fundamental of Astrodynamics and Applications*, Microcosm Press and Kluwer academic Publishers, 2001.
- J. R. Wertz, ed., *Spacecraft Attitude and Determination Control*, Kluwer, 1978.

Many, many, many other books – see instructor's web site  
<http://astronauticsnow.com/AstroBooks/>

# Professional Societies and Groups

- It is highly advisable to become a member of professional societies and groups
- Membership helps professional growth, networking, etc.
- *Primary society* for space engineers is  
**American Institute of Aeronautics and Astronautics (AIAA)**  
<http://www.aiaa.org>
- Many other professional societies for scientists and engineers working in various fields related to space exploration and space technology  
AAS, AGU, APS, IEEE, OSA, SPIE, .... , ....

**Professional networking group on LinkedIn**

[http://astronauticsnow.com/astrousc\\_linkedin/](http://astronauticsnow.com/astrousc_linkedin/)

**USC Astronautics Alumni, Students, Faculty, and Friends**

**USC  
Astronautics**

## USC Astronautics Alumni, Students, Faculty, and Friends

[LinkedIn Group](#)

### USC Astronautics Alumni, Students, Faculty, and Friends

The network of the **alumni, students, faculty, and friends** of the **USC Astronautics**, a rapidly growing program offering degrees in astronautical engineering. Hundreds of our alumni work in the leading American space companies and government research and development centers.

We welcome not only our **current and former students** with the degrees in **Astronautical Engineering** (or the old degree **Aerospace Engineering, Astronautics**), but also **all current and former USC students who took our space classes** and are part of the great space enterprise. USC Astronautics began as a space engineering specialization in the **Viterbi School of Engineering** of the **University of Southern California**. Today, it is an **independent space-focused academic unit** in the Viterbi School, operating as an academic department. ([Astronautics program history, focus, dynamics.](#))

The true story ... Now it can be told



In addition, we welcome **program friends, all those space professionals (space/defense industry, national labs, government, academia, space advocates) who are interested in and support our program.**

Connect with your fellow Astro-Trojans. Ad Astra!

USC Astronautics  
networking group  
launched on 11  
April 2009

>160 members  
(as of May 2010)

[http://astronauticsnow.com/astrousc\\_linkedin/](http://astronauticsnow.com/astrousc_linkedin/)

# ASTE 520 on DEN

- **Lecture webcasts**

All lectures are available through Distance Education Network DEN for all students enrolled in class during the entire semester

- **PC or Mac**

DEN streams course videos using Microsoft Windows media encoders and servers. While streaming windows media files are supported by both the latest Mac and PC operating systems, using a Windows based system will usually provide a better experience. Additionally, DEN has recently added video download capabilities using Microsoft's Digital Rights Management supporting Windows operating systems.

# On-Campus and DEN Instructions

- On all homework pages, put your name and course number ASTE-520
- On-campus (non-DEN) students **must** submit their homework in class; they will receive graded homework **also in class**
  - **non-negotiable rule**
- On-campus students must set up access to DEN webcasts. If you are going to be absent from a USC class, you can watch the class at the convenient time through webcast.
- Final and Midterm exams are held on campus for students in the Los Angeles area (no exceptions). Outside this area, the exams are arranged at remote sites (contact DEN).
- If you absolutely have to be on a business trip during the exam – **contact the instructor in advance**.

# All Students – Homework

- **No homework can be submitted to the instructor's e-mail address or fax (unless specifically directed by the instructor).**
- **Do not copy (to the instructor) your submissions to DEN.**

# Contact MAPP/DEN

- DEN web site <http://den.usc.edu> or <http://mapp.usc.edu>
- Instructions on homework submissions are at <http://den.usc.edu> or <http://mapp.usc.edu>
- The list of MAPP/DEN contacts is at <http://mapp.usc.edu>
  - print the page with the names and telephone numbers of DEN contact persons
  - Use it! Do not be shy!
  - **Call them!**
  - **E-mail them!**
  - **They are here to help!**
  - **They will be delighted to hear from you – trust me**



# Survey and Password

- E-mail the survey (next slide) to the instructor (mikeg@usc.edu) **from August 11, 2010** as a **plain text in your message** (do not attach as an MS Word or PDF file) with the subject line **ASTE520 Survey**. (Note that the instructor has a heavy biz travel schedule in August 2010 – expect delays, particularly during the week August 15–21, with his response.)
  - Survey is important for communications with students
  - **In response to your survey, the instructor will e-mail you the password to the class notes and homework solutions (posted on the class web site at DEN)**
  - **Do not email the survey earlier than instructed above. If emailed earlier, it will be deleted and disregarded.**

# Survey – e-mail to Instructor

(as plain text in your e-mail message)

1. Name (**no SSN or student ID, please!!!**)
2. Degrees attained: university and field (e.g., AstronauticalE, AerospaceE, ME, EE, SystemE, Physics, ...)
3. Degree sought (MS, PhD, Certificate, BS, Progressive 4+1, ...) and field (AstroE, EE, ME, CompE, AE, CivilE, ChE, Phys, Chem, ...)
4. Are you a full-time student? Or, do you work full time and study part time?  
  
If you work – tell me where (e.g., NASA–JPL, Aerospace Corp, NASA–JSC, SMC–LAAFB, Boeing–EI Segundo, Orbital, VeryCoolRockets.com, etc., ...)
5. Your (place of work) location (city, state)
6. Telephone
7. E-mail
8. Student status (regular admitted, limited status, ..., undergrad)

The information in this survey is for your instructor only. It is in your interest to provide me with the ways to reach you if and when needed. I will also compile class statistics. You will thus know who (statistically) your peers are.

# Units and Constants

<b>1 inch</b>	<b>=</b>	<b>2.540 cm</b>		
<b>1 mil</b>	<b>=</b>	<b><math>10^{-3}</math> inch</b>	<b>=</b>	<b>25.4 <math>\mu\text{m}</math></b>
<b>1 foot</b>	<b>=</b>	<b>30.48 cm</b>		
<b>1 statute mile</b>	<b>=</b>	<b>1609 m</b>	<b>=</b>	<b>1.609 km</b>
<b>1 nautical mile</b>	<b>=</b>	<b>1852 m</b>	<b>=</b>	<b>1.852 km</b>
<b>1 ounce</b>	<b>=</b>	<b>28.35 g</b>		
<b>1 lb (pound)</b>	<b>=</b>	<b>0.4536 kg</b>		
<b>1 lbf</b>	<b>=</b>	<b>4.448 N</b>		
<b>1 slug</b>	<b>=</b>	<b><math>1.459 \times 10^4</math> g</b>	<b>=</b>	<b>14.59 kg</b>
<b>1 atm</b>	<b>=</b>	<b><math>1.01325 \times 10^5</math> N/m<sup>2</sup></b>	<b>=</b>	<b>1.01325 bar</b>
<b>1 psi</b>	<b>=</b>	<b><math>6.89476 \times 10^3</math> N/m<sup>2</sup></b>	<b>=</b>	<b><math>6.805 \times 10^{-2}</math> atm</b>

# Units and Constants

<b>Electron charge (e)</b>	<b>=</b>	<b><math>1.6022 \times 10^{-19} \text{ C}</math></b>
<b>Electron-volt (eV)</b>	<b>=</b>	<b><math>1.6022 \times 10^{-19} \text{ J}</math></b>
<b>Atomic mass unit</b>	<b>=</b>	<b><math>1.6605 \times 10^{-27} \text{ kg}</math></b>
<b>Astronomical Unit (AU)</b>	<b>=</b>	<b><math>1.496 \times 10^{11} \text{ m}</math></b>
<b>Earth equatorial radius</b>	<b>=</b>	<b>6 378.14 km</b>
<b>Gravitational constant (G)</b>	<b>=</b>	<b><math>6.6726 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}</math></b>
<b>Free fall acceleration (g)</b>	<b>=</b>	<b>9.80665 m/sec<sup>2</sup></b>
<b><math>\mu_{\text{EARTH}}</math></b>	<b>=</b>	<b><math>3.9860 \times 10^{14} \text{ m}^3/\text{sec}^2</math></b>
<b><math>\mu_{\text{SUN}}</math></b>	<b>=</b>	<b><math>1.3271 \times 10^{20} \text{ m}^3/\text{sec}^2</math></b>

# Units and Constants

You must be confident in juggling units: *meter, mile, nautical mile, astronomical unit, pound, foot, ton, Newton, radian, ....*

Conversion coefficients can be found in many publications (e.g., *AIAA Aerospace Design Engineers Guidebook, etc*).

A guide to the use of the [metric] International System of Units (SI) can be found at the *National Institute of Standards and Technology* (NIST) web site

<http://physics.nist.gov/Pubs/SP811/sp811.html>

Make a copy of the pages with the conversion coefficients, or prepare such a list yourself, and attach it to your notes. Such a list will be exceptionally useful (and time-saving) for working on the homework assignments and exams.

# Units and Constants

- Prefixes  
kilo, nano, deka, femto, Giga, ....
- Physical constants  
 $G, c, h, k, \dots$
- Compile a separate list of physical constants as the class progresses (will be useful!).
- Many physical constants can be found at the NIST web site

<http://physics.nist.gov/cuu/Constants/index.html>

### Greek alphabet

$\alpha$	A	alpha	$\iota$	I	iota	$\rho$	P	rho
$\beta$	B	beta	$\kappa$	K	kappa	$\sigma$	$\Sigma$	sigma
$\gamma$	$\Gamma$	gamma	$\lambda$	$\Lambda$	lambda	$\tau$	T	tau
$\delta$	$\Delta$	delta	$\mu$	M	mu	$\upsilon$	$\Upsilon$	upsilon
$\epsilon$	E	epsilon	$\nu$	N	nu	$\phi$	$\Phi$	phi
$\zeta$	Z	zeta	$\xi$	$\Xi$	xi	$\chi$	$\chi$	chi
$\eta$	H	eta	$\omicron$	O	omicron	$\psi$	$\Psi$	psi
$\theta$	$\Theta$	theta	$\pi$	$\Pi$	pi	$\omega$	$\Omega$	omega
			$\varpi$	—	“curly pi,” an alternative form of $\pi$			
			$\varsigma$	—	an alternative form of $\sigma$			