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Advanced degrees in astronautical engineering for the space industry

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ABSTRACT

Ten years ago in the summer of 2004, the University of Southern California established a new unique academic unit focused on space engineering. Initially known as the Astronautics and Space Technology Division, the unit operated from day one as an independent academic department, successfully introduced the full set of degrees in Astronautical Engineering, and was formally renamed the Department of Astronautical Engineering in 2010. The largest component of Department's educational programs has been and continues to be its flagship Master of Science program, specifically focused on meeting engineering workforce development needs of the space industry and government space research and development centers. The program successfully grew from a specialization in astronautics developed in mid-1990s and expanded into a large nationally-visible program. In addition to on-campus full-time students, it reaches many working students on-line through distance education. This article reviews the origins of the Master's degree program and its current status and accomplishments; outlines the program structure, academic focus, student composition, and enrollment dynamics; and discusses lessons learned and future challenges.

1. Introduction

Ten years ago in June 2004, the University of Southern California (USC) announced establishment of a new unique academic unit focused on space engineering [1]. Initially known as the Astronautics and Space Technology Division (ASTD), the unit operated from day one as an independent academic department and successfully introduced the full set of degrees (Bachelor, Bachelor Minor, Master, Engineer, Ph.D., and Graduate Certificate) in Astronautical Engineering. (This article author had the privilege to serve the founding chairman of ASTD from 2004–2007.) The Division was formally renamed the Department of Astronautical Engineering in the USC's Viterbi School of Engineering (VSOE) in 2010.

In the United States, space engineering education was traditionally part of a significantly broader aerospace curriculum, historically anchored in aeronautics and dominated by fluids-focused engineering and sciences. Aerospace degrees are usually offered by departments of aerospace engineering or by departments combining aerospace with other engineering disciplines, particularly with mechanical engineering.

In contrast, USC established a unique separate pure-space-focused academic department to address specific challenges in space engineering education. The largest component of the Department of Astronautical Engineering has been and continues to be its flagship Master of Science in Astronautical Engineering (M.S. ASTE) program, specifically focused on meeting needs of the American space industry and government space research and development

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centers. This program successfully grew from a specialization in astronautics developed in mid-1990s and expanded into a large nationally-visible program [1].

The tenth anniversary of the establishment of the independent Department is a propitious time to review the program status; to summarize its accomplishments, impact, and challenges; and to look into the future. We specifically focus here on the Department's industry-oriented M.S. ASTE program, with other degree programs being outside the scope of this article. First, the rational for creating independent astronautical engineering departments is discussed followed by specifics of program development at USC. Then, we describe the M.S. ASTE structure, coursework, program students, and the role of distance education. The article concludes by putting the program into a broader perspective of trends in the global space enterprise.

2. Rational for independent astronautics departments

Gruntman [1] discussed in detail the rational for establishing an independent department in astronautical engineering. Briefly, following the beginning of the space age in late 1950s, space engineering education found a home in existing aeronautical engineering departments [2], which changed their names to "Aerospace" or some variant of "Aeronautics and Astronautics." However, the curriculum remained concentrated in fluid sciences and engineering and aeronautical applications, with some coursework added in space-related topics, primarily in orbital mechanics and rocket propulsion [3–5]. At the same time, the American space effort greatly expanded in space exploration and national security.

In 1970s and early 1980s, advocates of space education had been arguing for establishing of a curriculum in "pure" astronautics leading to a Bachelor of Science (B.S.) and higher degrees in astronautical engineering [3,4]. They hoped that such development would give "astronautics" equal status with "aeronautics" in aerospace engineering departments and thus advance space education.

Many important changes have occurred in the ensuing years. The Accreditation Board for Engineering and Technology (ABET) recognizes astronautical engineering as a separate from aerospace degree. (ABET awards accreditation to qualified Bachelor of Science engineering degrees. Master of Science degrees do not require accreditation with the exception, for historical reasons, of those offered by two military institutions [1,6].) Many aerospace departments and aerospace programs in combined (such as aerospace and mechanical engineering) departments in American universities offer space-related courses to undergraduate and graduate students.

One could argue that astronautical engineering has thus been accepted. A more precise characterization of the situation would rather be that aerospace departments "tolerate" space engineering to varying degrees [1]. Fluid sciences with aeronautical applications and astronautics are certainly not of equal status in many present-day aerospace programs. Reflecting this reality, the American Society for Engineering Education (ASEE) does not list astronautical engineering as a separate discipline category [7] and includes the degree into generic "aerospace engineering" which combines aeronautical, astronautical, and aerospace degrees. A quick look at job advertising in academe in *Aerospace America*, a monthly journal published by the American Institute of Astronautics and Aeronautics (AIAA), does not suggest forthcoming changes in emphasis or transformation of aerospace programs.

At major American research universities, the faculty members largely determine the fields of their concentration and change in the areas of faculty interests does not come easily. It takes decades for dead branches of the evolutionary tree to fall off and for new directions to replace them in the existing academic structures. Outside the universities, the space technology world is highly dynamic, does not enjoy the luxury of undergoing slow evolution, and continues to expand. Teller once noted [8] "that the substance with the greatest inertia known to man is the human brain, and that the only substance more inert is the collection of human brains found in a large organization such as military service or the faculty of a university."

The realities of academe force faculty to vigorously defend their turf and to favor hiring new faculty in the areas of their own research interests. A change in department directions requires determined effort by visionary and powerful administrators. Many aerospace programs actually broadened their scope during the last 10–15 years by hiring new faculty in emerging and cross-disciplinary areas, such as, for example, mechatronics and nanotechnology, rather than in traditional space fields as spacecraft attitude dynamics or satellite thermal control and power systems. The vision of equal status of "astronautics" and "aeronautics" in aerospace departments has not materialized. The space curriculum in many universities is limited, and the old question "Is there any space in aerospace?" [9] remains.

Consequently, the establishment – in some universities – of separate academic space departments offering degrees in astronautical engineering to better meet the needs of the space industry and government centers was called for in [1]. It was argued that such a step would logically advance the earlier efforts of 1970s and 1980s to recognize astronautical engineering as a separate degree. Importantly, separate astronautical engineering departments could shift the existing competition (which is rarely fair) from among groups of faculty within aerospace departments to a (much more even-leveled) competition among aerospace, astronautical, and aeronautical departments of various universities.

It was specifically emphasized [1] that creation of astronautical engineering departments was a *practical* approach to achieve desired flexibility within *constraints of realities* of the glacially-changing academe. The resulting competition among the departments and universities would force a balanced mix of the offered programs, determined by national educational needs and better respond to the engineering workforce development challenges of the space enterprise.

3. Astronautical engineering at USC

Aerospace engineering at USC was rather typical for the country. Most of the aerospace engineering faculty have been traditionally focused on fluid dynamics research since the founding of the Aerospace Engineering Department in 1964. (Aerospace engineering option in mechanical engineering dated back to late 1950s.) The first chairman of the department had been former chief of the fluid physics section at the Jet Propulsion Laboratory prior to joining the USC [10]. Only a few courses in space technology were offered in 1980s to graduate students by adjunct faculty [1,9,11]. A general observation about aerospace faculty in the country that "… most [faculty] are well established in research and devoted to aeronautics and thus have little incentive to take an interest in space technology" [3] did apply to USC.

On a historical note, the first man on the moon, Neil Armstrong, was among most renowned USC aerospace graduates of those times. He had studied part time while being stationed at the Edwards Air Force Base in California as a test pilot [10]. Armstrong had completed all required coursework, except the seminar, towards Master's degree when he joined NASA in early 1960s and transferred to Houston in Texas. In January 1970, Armstrong gave a one-hour seminar on the technical aspects of landing Apollo's lunar module *Eagle* on the surface of the Moon in 1969 and received – immediately after the seminar – his Master of Science degree in Aerospace Engineering from USC.

The faculty composition of the Aerospace Engineering Department had somewhat changed by early 1990s, however, when several tenure-track faculty had been added in modern areas of research such as hypersonic flight, physical kinetics, space science, and space instrumentation. This group formed the nucleus of the Astronautics Program within the Department. (The Aerospace Engineering Department merged with the Mechanical Engineering Department in 1998–1999, forming the Department of Aerospace and Mechanical Engineering [12].)

The attitude of many USC aerospace faculty toward space technology was not much different from other engineering schools in the country. The history of the department [12] published in 2004 by its former chairman highlighted the challenges faced by astronautics programs within a broader aerospace area at universities. The history only once casually mentioned the existence of the astronautics specialization in the department at the time when courses offered by this pure-space-focused program accounted for 80% of graduate students enrolled in aerospace courses, with non-space aerospace courses drawing the remaining 20% of the students. In addition, the recently established astronautics undergraduate specialization was also approaching one half of the total enrollment in the aerospace program [1,11].

The USC aerospace engineering program was also rather typical for American universities [13] in other respects: after rapid growth and large enrollments, the undergraduate and graduate student populations had dropped by late-1990s, following the end of the Cold War, by factors of five and two, respectively, from their peaks [10,12].

The response of the astronautics-oriented faculty to the prevailing doom-and-gloom atmosphere of mid-1990s was to found the Astronautics and Space Technology Program (Astronautics Program) taking advantages of some obvious opportunities [1,11]. First, we specifically focused on providing engineering degrees in the area of spacecraft technology for the space industry and government research and development centers. The University is strategically located in Los Angeles in the heart of the American space industry in Southern California. In early 2000s, California accounted for roughly one half of the revenues of the U.S. space enterprise and dominated ($\sim$80%) the satellite segment of the market [14]. California remains the home of a major space effort to this day.

Second, we initially concentrated on the Master of Science program. Three-four decades ago engineers with Bachelor's degrees could have rewarding and fulfilling technical careers. Today, changes in industry have made Master's degrees desirable (sometimes called "the terminal degree") for a successful technical career in the United States. Consequently, many leading industrial companies and government centers now hire young graduating engineers with Bachelor's degrees and support their pursuit of M.S. degrees part-time while working full-time. In fact, tuition coverage for such studies has become part of standard compensation packages in defense and aerospace industries.

Third, we leveraged the existing VSOE distance education capabilities (discussed below) to reach students across the country. Distance education plays an increasingly important role in pursuits of Master's degrees in engineering.

Last but not the least, the traditional diversity of arrangements in U.S. higher education made it easier and possible to experiment with new approaches. The University of Southern California, the oldest and largest private university on the West Coast, has a long tradition of working with the aerospace and defense industries. Consequently, the USC Viterbi School of Engineering was a natural home for an initiative in space technology.

So, in the mid-1990s, the astronautics faculty of the Aerospace Engineering Department began expanding coursework of interest to the space industry and government research and development centers in Southern California [1,11]. Starting with only a few space-related courses taught by regular and adjunct faculty, the curriculum steadily grew. The M.S. degree program with emphasis in astronautics was first recognized as a specialization in 1997. The University formally approved it in 1998 and assigned a separate independent postcode. The approval of the Graduate Certificate and the Bachelor of Science degree specializations followed [1].

Student interest in a certain program can be characterized by an annual enrollment in program classes, N_S, during an academic year. Fig. 1 shows the annual student enrollment in classes offered by the Master's astronautics program since its inception in 1990s. At USC, the academic year begins with the fall semester and includes the spring and summer semesters of the next calendar year. (For example, the academic year 08–09 includes semesters in the fall 2008 and spring and summer of 2009.) VSOE offers few classes during summers when most students take a break from studies. The number N_S directly reflects tuition revenues brought by the program. USC is a private university without generous subsidies enjoyed by many competing state institutions of higher learning which

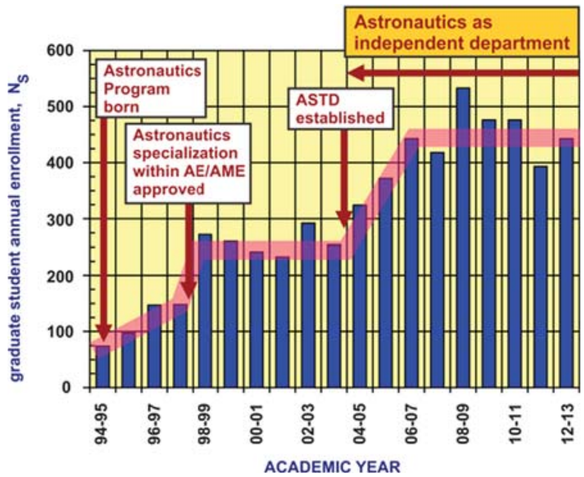

Fig. 1. Annual (academic year) student enrollment in classes, N_S, offered by the USC Master's astronautics program since its inception. AE/AME – Aerospace Engineering and Aerospace and Mechanical Engineering Departments; ASTD – Astronautics and Space Technology Division.

makes financial soundness of our programs particularly important.

Fig. 1 also reveals the importance of program clear self-identification for its growth. A separate program usually appeals to motivated students seeking education in a certain area of engineering. The approval of the independent Astronautics specialization in 1997–1998 increased student enrollment in program classes by 60% in one year. The separation from the Department of Aerospace and Mechanical Engineering (AME) in 2004 and establishment of an independent academic unit, the Astronautics and Space Technology Division, with distinct degrees in astronautical engineering led to another surge in student interest. Here, graduate student enrollment in classes increased by 80% within 3 years. This increase has proved the timeliness and benefits of the establishment of an independent space engineering department.

Some smaller year-to-year changes in the number of students enrolled in program classes are caused by various factors such as sabbatical leaves of faculty; changes in tuition reimbursement policies in major space companies; state of the national economy and industry; and even loss or award of a particular major government contract by a certain company. Despite such variations, Fig. 1 clearly shows the trends.

Following the creation of the new Department of Astronautical Engineering in 2004, it took one year to establish the full set of degrees in astronautical engineering and more than two years to achieve smooth operations of the academic unit. Parenthetically, building a new academic department is a prodigious task. Since it does not happen often in universities, many arrangements have to be re-invented. The sheer number of administrative loose ends that need to be tied up is staggering.

In addition to M.S. ASTE, the Department offers other degrees, but their discussion is outside the scope of this article. We note here that the new Ph.D. program in astronautical engineering took off to a good start, with 11 Ph.D. degrees awarded during the last two academic years alone. Concentrations of studies of Ph.D. students are aligned with expertise and research interests of the faculty. The B.S. program in astronautical engineering enrolls 10–20 new students each year, with the size of the freshman class capped by the VSOE. The new B.S. program received the ABET accreditation in 2011–2012. (ABET requires assessment of a couple cohorts of graduating students who enrolled into a new program as freshmen and accreditation thus takes 6–8 years.) The Department actively creates opportunities for student team projects such as designing and building sounding rockets as well as space-related systems; the latter in collaboration with the VSOE's Information Sciences Institute (ISI) [15,16].

In 2003, then Dean of the Viterbi School Prof. Max Nikias (who became President of USC in 2010), Dr. Simon "Pete" Worden (then at the Space and Missiles Systems Center, and now director of NASA's Ames Research Center), and then President of the Aerospace Corporation Dr. William F. Ballhaus, Jr. challenged the USC astronautics faculty and ISI scientists to advance science and engineering (creating a "Bell Labs of Space") of cost-effective microsatellites systems. ISI's Drs. Joe Sullivan and Peter Will and the author of this article led this major initiative, with Stan Dubyn (co-founder of Spectrum Astro, Inc. and founder of Millennium Space Systems), and Dave Barnhart (then Vice President of Millennium Space Systems) also playing particularly important roles.

This initial effort from 2003 to 2007 had developed programs that expanded into other areas of specialized technology and engineering workforce development and laid the foundation for the subsequent creation of the VSOE's Space Engineering Research Center (SERC) in 2007–2008. After 2007, activities of SERC and ISI significantly changed the focus of the initiative away from the initial objectives and toward student-centric projects [16]. Astronautics students have been involved in development of microsatellites at SERC, with two cubesats in orbit.

4. Master of Science in Astronautical Engineering

The Master of Science in Astronautical Engineering is among many advanced degrees offered by the Viterbi School of Engineering. For many years, VSOE's Distance Education Network (DEN) has been playing an important role in offering Master's programs, cementing traditionally strong ties to the industry. In addition to full-time on-campus students, working full-time engineers enroll in the distance education program as part-time students. In 2011–2012 academic year, the Viterbi School awarded 1661 M.S. degrees in engineering (1224 degrees excluding computer science), more than any other engineering school in the United States [7]. Distance education students earned 301, or 18%, of these degrees.

Three practical considerations focused our initial effort on development of the space engineering specialization on the Master's level. (This article author has been directing the Master's degree program since its inception to this day.) First, there was clear interest by working full-time students in the space industry, particularly in Southern

California. Here, School's DEN provided a powerful tool to conveniently reach such students in California and beyond.

The second contributing factor was seemingly unending and especially strong resistance in academe to separate undergraduate programs in astronautics. Even today, there are only three B.S. degree programs in astronautical engineering in existence nationally [1].

The last consideration was a possibility to rely on adjunct faculty and part-time lecturers for teaching highly-specialized graduate classes, in contrast to undergraduate courses usually taught by full-time faculty. External lecturers provided flexibility for the initial program build-up without the complications of hiring new tenure-track faculty.

4.1. Program structure and coursework

The M.S. ASTE degree program is open to qualified students with B.S. degrees in engineering, mathematics, or hard science from regionally accredited universities. In contrast to many other aerospace programs, we do not require a Bachelor's degree in astronautical or aerospace engineering, and also admit students with educational background in other areas of engineering and science. Typical undergraduate courses in physics, chemistry, and mathematics taken by engineering students provide the basis for successful studies in the program.

The M.S. ASTE coursework consists of nine courses (27 units), with typical semester-long graduate classes being 3 units each. The program usually offers 8–10 graduate astronautics classes each semester. Practically all our graduate classes are available not only to on-campus students but also to remote on-line students through DEN. Writing a Master's thesis is an option but not a requirement. The thesis earns credit of 4 units, usually complemented by 2 units of directed research. Most students prefer coursework; a few however choose writing theses, which requires a major effort.

A typical full-time student studies on campus, taking three courses per semester, and completes the entire program in three semesters or one year and a half. A full-time working student studies part-time and usually takes one course each semester or sometimes two. (Workload at the main job, which varies widely and depends on individual circumstances, determines the number of courses for part-time students.) Therefore, it takes on average 4 years for a working student to achieve the degree.

To earn the M.S. ASTE degree, students must take four *required courses* (12 units); two *core elective courses* (6 units) chosen from a list of core elective courses; two *technical elective courses* (6 units); and one course (3 units) in engineering mathematics chosen from a list of four different courses. The required courses include three broad overview courses in (i) spacecraft system design, (ii) spacecraft propulsion, and (iii) space environment and spacecraft interactions. The fourth required course is in orbital mechanics.

A typical 3-unit course consists of 12–13 weekly three-hour lectures and two exams (mid-term exam and final exam) complemented by weekly homework assignments and sometimes term papers and projects. The program's flagship spacecraft system design course (taught by the author of this article) provides a broad overview of fundamental science and engineering topics essential for understanding satellites and their launch systems as well as operations and applications. It introduces main concepts and nomenclature, emphasizes interplay among various satellite subsystems and design decisions, and puts into perspective various areas of space technology. After introductory lectures on space environment and orbital mechanics students analyze various subsystems of spacecraft, with roughly one week or slightly more devoted to a particular subsystem. Many follow-on elective courses explore these particular subsystems in depth and detail.

The required spacecraft system design course also serves as an entrance gateway both for students with non-astronautical and non-aerospace engineering undergraduate degrees and for those who have been some years out of school. Some students in the latter category have been promoted to positions of engineering management of technical projects and this course helps them to return to technical studies. The course is also popular among students pursuing degrees in other areas of engineering and planning careers in the space industry. More than 1100 graduate students have enrolled in this spacecraft system design course during the last ten years.

Core elective courses cover satellite subsystems, specialized propulsion, advanced orbital mechanics, attitude dynamics, and subjects of space mission and system design. The Astronautics program objective is to offer overview courses on space systems, orbital mechanics, and space environment and supplement them by coursework focused on satellite subsystems, key applications, and emerging technologies. While we cover many satellite subsystems at this time, there are a few areas where we would like to bring new courses. Introduction of new coursework is limited by two main factors, attracting qualified instructors actively working in areas of interest and constraints of the allocated budgets and distance education infrastructure. Even maintaining the current offering of more than twenty courses presents an administrative challenge since occasionally our external instructors have scheduling conflicts or relocate to other parts of the country.

There are several areas in which we plan to bring new coursework. In 2014–2015 academic year, for example, three new courses are being introduced, in human spaceflight, launch vehicle design, and plasma dynamics. Among our development priorities are courses on space systems (reliability of space systems; space debris), subsystems and new technologies (ground control segment; space software; entry, descent, and landing; space cryogenic technology, including superconductivity; small satellites, including cubesats), and applications (global navigational systems; communications satellites; space solar power systems).

Most course lectures involve little interaction with students because many take courses through DEN (as discussed below in Section 4.3). The exception in our program is the Space Studio Architecting course. Each year this studio addresses a specific topic, such as, for example, design of a lunar base, exploration facilities on Mars, future human spaceflight, or planetary defense. A student in the studio chooses a component that fits into the topic and focuses on its design. Student presentations during the semester and especially during the mid-term and final exams involve major interactions and discussions. We limit the course enrollment to ten students, one half on campus and one half through DEN. At this time, the studio usually uses WebEx for presentations and discussions. As technology evolves, we may be able to improve the format.

The Astronautics Program never limits the choice of technical electives to coursework offered by the home department but rather emphasizes importance of choosing courses which best contribute to achieving students' educational objectives. Most graduate non-astronautics science and engineering courses are approved as technical electives. (We only limit coursework in topics outside classical engineering and science such as, for example, management of engineering programs.) Many students find the space-focused core elective courses so attractive that they choose all their technical electives from this list.

Table 1 shows astronautics courses presently offered for graduate credit. We continuously work on addition of new courses, subject to availability of qualified instructors, distance education studio slots, and programmatic needs.

The M.S. ASTE program usually offers 8–10 courses each semester, out of two dozen Astronautics courses. All required courses are offered at least once each year and some twice a year. Students can take many popular core elective courses (for example, Advanced Spacecraft Propulsion, Spacecraft Power Systems, and Orbital Mechanics II) also every year, while other highly specialized courses are available every other year. The latter scheduling allows us to use the same number of precious distance-education studio slots to make a larger number of different courses available to students. Since it takes four years for many full-time working students to complete their studies, careful planning of their coursework usually allows them to take all the desired courses.

Table 1
Astronautics courses offered for graduate credit.

Required courses
Spacecraft System Design
Spacecraft Propulsion
Space Environment and Spacecraft Interactions
Orbital Mechanics I
Core elective and elective courses
Orbital Mechanics II
Space Navigation: Principles and Practice
Advanced Spacecraft Navigation
Liquid Rocket Propulsion
Advanced Spacecraft Propulsion
Space Launch Vehicle Design (to be introduced in 2015)
Physical Gas Dynamics I, II
Plasma Dynamics (to be introduced in 2014)
Design of Low Cost Space Missions
Space Studio Architecting
Human Spaceflight (to be introduced in 2014)
Safety of Space Systems and Missions
Spacecraft Attitude Dynamics
Spacecraft Attitude Control
Spacecraft Structural Dynamics
Spacecraft Structural Materials
Spacecraft Power Systems
Spacecraft Thermal Control
Systems for Remote Sensing from Space
Spacecraft Sensors

Although many students prefer to begin their studies with the overview spacecraft system design and space environment courses, the program does not require a specific sequence of courses. There are a few exceptions, however. For example a course in space navigation requires introductory orbital mechanics as prerequisite and courses in liquid and advanced propulsion require prior coursework in spacecraft propulsion. Some students, particularly with aerospace degrees, have been exposed to subjects covered by some required courses, such as propulsion and orbital mechanics, during their undergraduate studies. In these cases, the required course is waived, with a student taking one additional technical elective instead.

The M.S. ASTE program provides an important educational foundation for getting into systems engineering of major space systems. A traditional path for these highly-sought positions in the space industry required first excelling in a particular engineering area. Consequently, we see interest in our program among accomplished engineers with non-astronautical background. Some already have Master's degrees in mechanical, electrical, computer, and other areas of engineering and successfully work in their specializations. They enroll in the M.S. ASTE to gain better understanding of other aspects of space systems. A degree in astronautical engineering is a natural path for them to achieve technical and managerial leadership positions in space programs.

It is important to note the difference of the M.S. ASTE program from two other areas of studies.

First, the focus of the program is not in systems engineering while we recognize its particular importance for development and operations of space systems. The M.S. ASTE program concentrates on traditional areas of science and engineering as they applied to space systems. Students may take a technical elective course or two in systems engineering or architecting offered by other engineering departments. A student with strong interest in such studies is usually advised to switch to dedicated systems engineering or systems architecting programs.

The other field of studies distinctly different from the M.S. ASTE program is often called “space studies” in contrast to “space engineering.” Space studies usually combine some science and engineering classes with coursework dealing with space policy; legal, management, communications, and entrepreneurial aspects; and program development. The University of North Dakota in the United States, the International Space University in Strasbourg, France, and the University of Delft in the Netherlands [17] are among well known educational institutions in this field. In contrast, the USC program in astronautical engineering focuses on specific technical areas of importance for research, development, designing, building, and operating space systems.

4.2. Program faculty and lecturers

Adjunct faculty and part-time lecturers play an especially important role in the M.S. ASTE program. Graduate engineering programs in the United States traditionally aligned with academic pursuits in the areas in which doctoral degrees are normally granted. Some areas of space engineering are not directly compatible with doctoral study. For example, spacecraft design is not usually considered an academic area because the knowledge base required to be an expert designer is broad rather than deep. Interestingly, this particular area attracts a large number of inquiries about possibilities of pursuing doctoral degrees.

In addition, many areas of critical importance to the space industry are sufficiently specialized and rapidly evolving that no university faculty member would likely have expertise in them unless he or she had spent years working in industry. Ironically, in the latter case, such a specialist would unlikely qualify for tenure in a research university because of the overriding requirement of superb scholarly achievements, including publications in academically recognized peer-reviewed journals. Examples of such specialized areas are spacecraft power systems and spacecraft thermal control. The need of covering a large number of highly specialized areas makes it impossible to provide comprehensive astronautics degree programs responsive to the needs of the space industry with instruction given only by regular university-based faculty.

Consequently, our solution to program development was a combination of regular tenure-track faculty and adjunct faculty and part-time lecturers. The regular faculty primarily focus on basic science and technology such as dynamics, gases and plasmas, space science, and fundamentals of spacecraft design, orbital mechanics, propulsion, and space environment. The adjunct faculty, who are leading experts typically full-time employed in the space industry and government research and development centers, cover the highly specialized and rapidly changing areas of space technology. They also bring the real-world experience, a vital component of a high-quality engineering education program.

The adjunct faculty and part-time lecturers are the pride and a great strength of our program. They work at various space companies and centers, large and small, including Boeing, Lockheed-Martin, Raytheon, Aerojet-Rocketdyne, Microcosm, Space Environment Technologies, NASA Jet Propulsion Laboratory, and The Aerospace Corporation. The access to the unmatched wealth of first-rate specialists in the Los Angeles area allows us to offer a wide breadth of courses in space technology and launch new courses as needed. These courses contain current space-industry practice of particular interest to many our M.S. ASTE students. Some adjunct faculty also play active roles in advising Ph.D. students.

4.3. Role of distance education

The opportunities offered by the VSOE's Distance Education Network played an enabling role in launching the USC Astronautics Program. DEN is among the largest engineering distance education programs in the United States, with 301 Master's degrees awarded in the 2011–2012 academic year. Astronautics distance education students accounted for about one-tenth of these degrees.

The USC School of Engineering initiated a pioneering effort in distance education, then first called the Instructional Television Network (ITV), in 1968. One year later the Federal Communications Commission approved putting television transmitters at Mount Lee in the hills above Hollywood, with broadcasts reaching the Los Angeles basin and the San Fernando Valley. With the grant from the Olin Foundation the School built technical facilities and commenced televised classes in 1972 [10].

ITV provided interactive one-way video and two-way audio broadcasts, with remote classrooms set up at local aerospace companies such as Hughes, McDonnell Douglas, Rockwell, TRW, Burroughs, Jet Propulsion Laboratory, The Aerospace Corporation, and many others. The system had limitations, however, and was costly. It required the affiliated companies to maintain special distance education centers and arrange reception of USC television broadcasts.

The ITV coverage was also limited to the Los Angeles area. A USC courier drove daily to collect homework and deliver to the remote sites graded homework, new assignments, and course handouts. Examinations were held on campus. In 1990s ITV began renting transponders on geostationary satellites to extend reach to students outside Southern California (Fig. 2).

In the late 1990s, VSOE reorganized ITV into the Distance Education Network. Course delivery has transitioned to "webcasting," streaming compressed video and audio over the Internet. Standard high-speed Internet connection allows viewing lectures from home or office or a hotel room anywhere in the world. The high-quality webcasting opened a way for small companies and individuals to enroll in DEN on-line programs. The new web technology has had a profound impact on distance education: it dramatically expanded reach and brought competition to once static programs. Continuous education on-line have become the way of life for many engineers in industry.

The full-time students attend class meetings in special DEN-equipped studios on-campus with lectures being simultaneously webcast to on-line students. Distant students can view lectures in real time over the Internet and they can call using special toll-free telephone lines to ask questions. The interaction with students in the classroom is usually limited to

Fig. 2. Antennas of the Distance Education Network in 2004.

responses to questions raised in the classroom. While distance students watching lectures in real time can call in it does not happen often. This is because many do not watch lectures in real time and also for those who do such a question sometimes involves a delay of dialing and connecting through the control room as the lecture moves on. Because of distance students, many instructors do not encourage exchanges with students in the classroom. The exception is few courses which essentially rely on interaction with the instructor and among students. Such arrangements present technical challenges at this time. We offer one such course as discussed in Section 4.1 above. In general, distance education courses, especially those with large student enrollment, have significantly reduced interaction during lectures. One possible remedy could be online chat-rooms, moderated by teaching assistants and with some participation of instructors during designated hours.

After class meetings, lectures are stored on the VSOE servers and students can access them as many times as they want during the entire semester. Such asynchronous access is especially important for working professionals who balance demanding schedules of their jobs, business-related travel, families, and studies. In addition, asynchronous viewing is convenient for many students who reside in time zones different from that of Los Angeles. Consequently, some on-line students do not watch class lectures in real time unless classes require interaction.

In the studio classroom, instructors could speak to the facing them camera or show the prepared presentations in preferred format and software (such as Microsoft PowerPoint, Adobe Acrobat, specialized scientific and engineering software) from desktop computers or their laptops. Some instructors choose to use preprinted course notes, with the overhead camera zooming in on the page. The instructor can then write additional equations or add a sketch or circle some content while discussing this particular page in order to emphasize specific content and thus augment the printed material. The camera can also zoom in on a special notepad where the instructor writes and, for example, derives equations or sketches diagrams by a pen. (Special pens with somewhat thicker than conventional lines are used for better writing visibility.) Finally, the camera can show the instructor utilizing a traditional large whiteboard or electronic board. It is customary for students to download, print, and bring to class meetings instructor's course notes, adding their own notes on the printouts during lectures.

Fig. 3 shows a typical DEN studio where one can see the instructor's desk with three large monitors behind on the wall continuously displaying to students attending the lecture in class the feeds from cameras, computers, and the webcast stream. A permanent desktop computer supports each studio although many instructors prefer bringing their own laptops and connect them to the projection and webcast system. In each studio, a specially trained student operator supports the lecture and follows instructor directions for switching between cameras, zooming in on papers on the instructor's desk, or switching to the feed from the laptop.

Asynchronous viewing of lectures stored on the servers offers convenient features. Fig. 4 shows an example of a computer screenshot of a typical lecture webcast viewed asynchronously after the lecture has been delivered and stored on the DEN server. The direct real-time feed (in the top-left area) may show either a camera view of an instructor at the desk or next to the whiteboard or a camera view of materials on the desk or a direct feed from a computer. The streaming material (shown in the top-left of the computer screenshot) can also be downloaded as a video file and watched on the full computer screen.

Fig. 3. Typical VSOE's Distance Education Network studio with the instructor's desk and three large monitors behind showing camera feeds and lecture webcast. Full-time on-campus students attend lectures in such studios.

Astronautics students studying through DEN reside in many geographical areas with rocket and space activities, installations, test and operations sites, space companies, and government centers (Fig. 5). In addition, some students live and work in Canada. We also always have students who serve in the armed forces and are stationed at various locations scattered across the globe.

DEN staff interacts with distance students electronically, with class notes, homework assignments, and handouts downloaded from special secure servers. Students in the Greater Los Angeles area take exams on campus. At distant sites, DEN contracts local community colleges to proctor exams. Working students are sometimes sent on business-related travel during the time of exams. In such cases DEN arranges proctoring of exams locally wherever the student might be.

Some exams are closed book and some are open book, the latter allowing use of course notes, textbooks, and old homework assignments and solutions. Calculators are usually required. The calculators become increasingly powerful, with the distinction from laptop computers blurring. Some instructors thus allow laptop computers at the exams, usually requiring turning off wireless internet connection. Exam proctoring centers enforce identical exam rules for distance students.

4.4. Program students

The Master of Science program in astronautical engineering attracts both full-time on-campus students and students who work full-time and study part-time while earning their degrees. The latter category accounts for about three-quarters of the awarded Master's degrees in astronautics. Their fraction among enrolled students is even higher because it takes longer for them to earn the

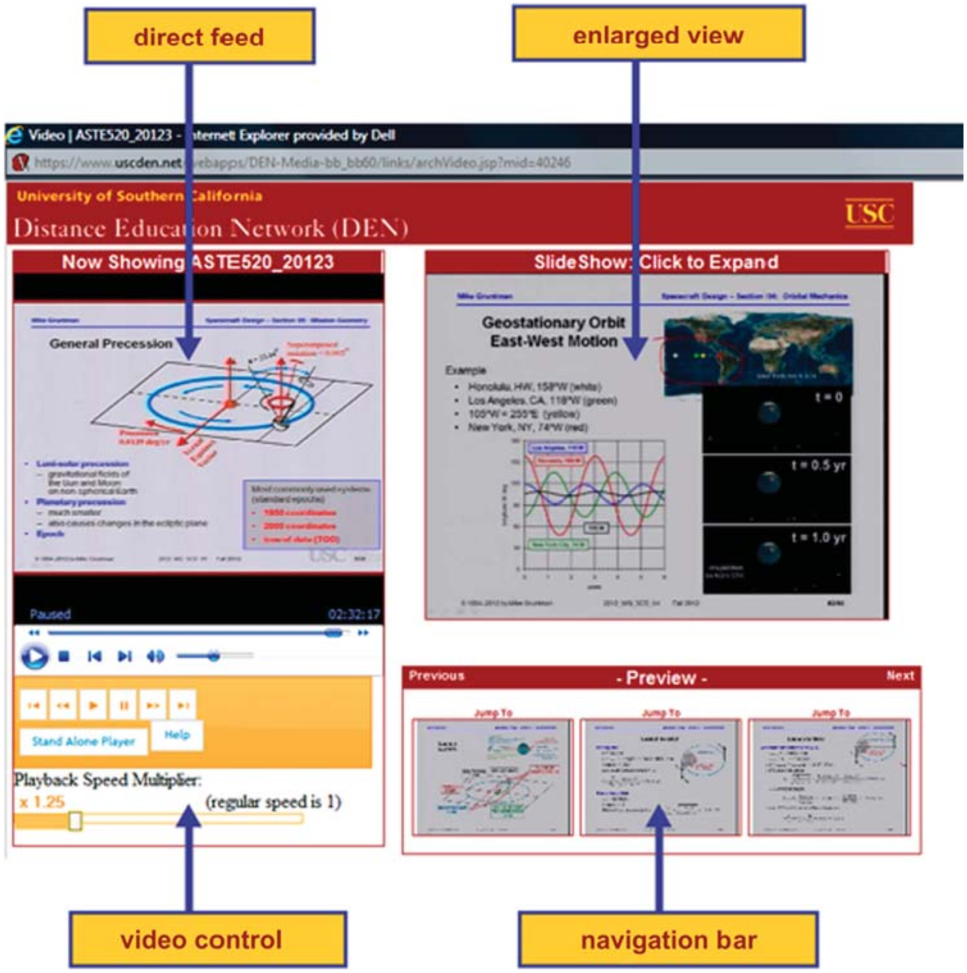

Fig. 4. Four distinct areas on the computer screenshot of a typical asynchronously viewed captured lecture webcast. The top-left area shows the captured direct real-time feed of the lecture. It could be a face camera view of the speaking instructor or a notepad or other printed materials on the desk in front of the instructor or a feed from a desktop or instructor's laptop computer (as in this figure). This captured live feed can also be downloaded as a video file and played on the full screen of the computer. The top-right area shows selected images of the feed (on the left) periodically captured in high resolution. Bottom parts of the screen show a video control panel (left) and a navigation bar (right) for selection of captured high-resolution images for display in the top-right area above.

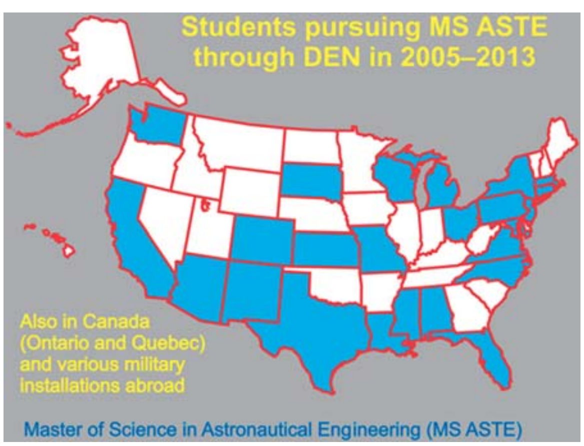

Fig. 5. Students pursuing Master of Science in Astronautical Engineering (M.S. ASTE) degrees through distance education reside in many states of the United States as well as in Canada and stationed at military installations across the globe.

degree compared to full-time on-campus students. About one quarter of our students (those who study full-time) achieve their degrees in 1.5 years while almost three-quarters (DEN students) obtain their degrees in 4–5 years, with a few distance students graduating faster in 2.5–3.5 years and very few in 6–7 years (if they have to temporarily interrupt studies for some reason).

A typical full-time graduate student usually earns the degree in one year and a half or three semesters. It may take longer, however, to complete the degree requirements if they start working, initially part-time, in industry. Some research-oriented students also decide, if qualified, to continue their studies towards PhD degrees after completion their Master's program. Here, the critical issue is identifying a faculty advisor to guide the student.

Full-time working students are employed by the space industry and government research and development centers. Many students work for large space companies such as Boeing, Northrop-Grumman, and Raytheon or large government centers. In recent years we noticed an increase in students who work in smaller companies. Most full-time working students take courses through DEN, even if they live within a driving distance from the campus. The typical time of studies to complete the degree ranges from two and half to five years depending on the course load. Many distance education students today earn their degree without the need of ever visiting the campus. Some would fly to Los Angeles to attend the festive official Commencement ceremony at USC and formally receive their diplomas.

As a matter of policy, VSOE treats all students – on-campus and on-line – equally, with the identical requirements toward the degrees and standards in student admission and in evaluating student performance. Although distance students watch their lectures remotely from the comfort of their home or office, they are held to the same high standards as all USC students and are expected to show the same dedication toward their education.

All on-campus students also have access to lecture webcasts of classes in which they are enrolled. As a result, some full-time students also choose to sometimes watch lectures from their homes at convenient times instead of attending them in classroom studios. At the same time, some distance education students from the Greater Los Angeles or travelling to Los Angeles on business come to some lectures on campus.

The faculty advisor helps graduate students to select courses that best fit their educational goals. Typically students desire to get in-depth knowledge in technical areas of their present job. Another category of students, however, concentrates on the areas of technology where they would like to transfer to in their companies. Selecting coursework in the desired areas often facilitates such internal moves after earning the degree.

The background of our students is truly diverse. The majority of students admitted to the M.S. ASTE program have Bachelor's degrees in engineering or science. Some students already have their Master's degrees in other areas of engineering and successfully work in the space industry. They often are promoted to leading technical positions and the objectives of their studies focus on gaining better understanding of entire space systems. In addition, we have students with doctorates in other fields of science or engineering. Almost each year, a medical doctor also enrolls into the program. A few students, often with M.S. or Ph.D. degrees, join the program in order to improve their chances to be selected for astronaut training.

The USC Astronautics Program has earned a solid reputation. It is highly visible in the space industry and reaches students across the country. The group of program alumni, students, and supporters on the professional network, LinkedIn, includes more than 500 members. As a result, the word-of-mouth plays today a most important role in program promotion bringing new students who first heard about it from satisfied alumni.

National statistics in the United States do not distinguish between aeronautical, astronautical, and aerospace degrees and combine all of them in one group. There are 67 institution of higher learning in the United States that

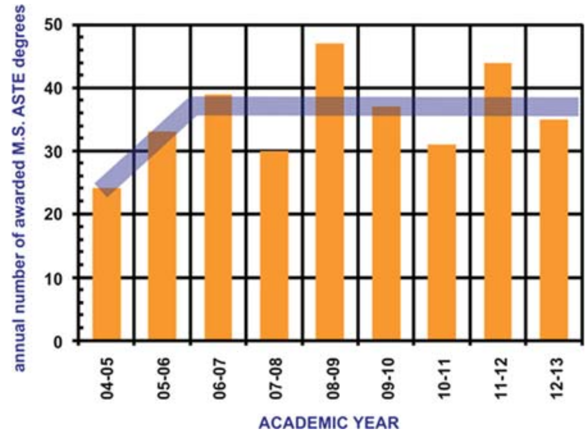

Fig. 6. Annual number of the awarded M.S. ASTE degrees, with the average 37 degrees (the straight line to guide the eye) during the last 8 academic years. This is approximately 3% of the M.S. degrees awarded in the United States in the broad area of astronautical, aeronautical, and aerospace engineering.

award today Master's degrees in this broad aerospace group [7].

During the last 8 academic years, our program awarded 296 Master of Science degrees in Astronautical Engineering, or on average 37 degrees annually (Fig. 6). The full-time students accounted for 72 degrees (or 24%) and distance education students for 224 degrees (76%). This breakdown between full-time on-campus and working and enrolled through DEN graduating students remained practically unchanged during the last 8 years. Correspondingly, the same ratio of 3-to-1 of DEN to on-campus students is typical in specialized Astronautics classes taken primarily by students pursuing the M.S. ASTE degree. The only exception in our program is the Spacecraft System Design course which attracts a number of on-campus students (and some DEN students) pursuing engineering degrees in other areas. A fraction of distance students in this class is usually smaller, about 60%.

Our M.S. ASTE degrees constituted more than 3% of the Master's degrees awarded to the broad group of aeronautical, astronautical, and aerospace engineers in the United States in 2005–2012 which was more than twice the average for the 67 programs. In fact, in 2011–2012, the last academic year for which national statistics were available, we awarded 44 degrees. Only 8 other institutions of higher learning in the country awarded more aerospace M.S. degrees [7].

The number of foreign students in the M.S. ASTE program is smaller than in many other engineering programs in VSOE. During the last 8 years, about two dozen international students (or about 8% of the total number of students) earned their Master's degree. This smaller fraction is explained in part by the fact that three-quarters of our M.S. degrees were awarded to domestic students who worked full time at leading space companies and government centers and who thus were either U.S. citizens or permanent residents. Among our full-time on-campus students about one-third was international. Foreign students are also usually aware of restrictions of the export control International Traffic in Arms Regulations (ITAR) and many decide to enroll in engineering programs in other fields.

All university classes, including in astronautics, are open to students without restrictions of their nationality. Outside coursework, participation in research projects funded by external government agencies and industry may have ITAR restrictions, however, requiring involved students to be U.S. persons (in the language of the regulations). In addition, it is harder, but not impossible, for international students to find internships and later, after graduation, employment.

In spite of the ITAR effect, the M.S. ASTE program awarded degrees to students from at least 16 countries since the formation of the separate department in 2004. These countries included (alphabetically): Canada, China (both the People's Republic of China and Republic of China, Taiwan), Columbia, India, Iran, Italy, Japan, Malawi, Myanmar, Nepal, Pakistan, South Africa, South Korea (Republic of Korea), Spain, and Sweden. Many students continued studies to pursue their Ph.D.s, either at USC or elsewhere, after earning their Master's degrees. To the best of my knowledge, one European student returned to his home country after graduation where he received a prestigious post-doctoral fellowship. In addition a couple students pursued their degrees through fellowships supported by their governments and were obliged to go back. All other graduated international students stayed in the United States.

ITAR effectively limits foreign student participation in civilian commercial projects and in research and development in some areas of space science and space technology. Many industrial leaders and university administrators have been arguing for some time in favor of relaxation of these export control restrictions viewed as counterproductive and for facilitating the path for graduating foreign nationals to obtain permanent residency status and to stay in the United States. The current ITAR arrangements emerged, in part, as a result of the unanimous bipartisan report ("Cox Report") on technology export incidents by the select committee of the U.S. Congress [18]. Continuing violations of ITAR by major defense and aerospace companies [1] weaken such arguments and make it harder for Congress to enact consequential changes in the law. Academe also contributed to violations with one university professor convicted to a jail term in 2009. These realities, often ignored rather than addressed head-on by advocates of relaxation, make the meaningful ITAR reform even more complex and politically controversial.

5. Looking into future

Space exploration and space applications have been continuously expanding for decades. Many countries are now engaged in space activities or operate purchased commercial satellites. Global space expenditures have been steadily growing for the last ten years. They increased from $178B in 2005 to more than $300B in 2012, with annual increases of 7–8% during the last four years [19]. Commercial space is now at least twice as large as government-funded space programs worldwide. Annual insurance premiums for launch and operations of space systems reached about $1B in a clear indication of maturing commercial space. While significant expansion in space expenditures relies on many fields of engineering such as, for example, communications, computer sciences, and ground stations, the core expertise in space engineering remains the indispensable anchor that glues together and enables further advancing of this expansion.

The United States still leads the world in space. The last years of the administration of President Dwight D. Eisenhower more than half a century ago had shaped the structure of the American government space programs, which essentially survived in its main features until the present day [20]. The American economy, infrastructure, and national security depend on space more than those of any other country, which brings numerous advantages as well as vulnerabilities. It was noted ten years ago [21] that the United States had been spending on government space programs four to six times more in terms of the fraction of the gross domestic product (GDP) than Western European countries and Japan. (The only exception was France, spending more than other European countries as the fraction of the GDP.) The latest Space Report [19] shows that this substantially smaller commitment by the peoples and governments of these countries remains unchanged. Even self-inflicted loss of direction and vision by the U.S. civilian NASA program during the last five years has not altered this ratio.

What had changed, however, during the last ten years was a rapid advance of space programs, both in exploration and applications, by the People's Republic of China and India. The Chinese program in particular showed major progress and developed capabilities in human spaceflight and military space. In addition, the highly space capable Russia recently stepped up government spending in space activities, particularly in national security, and is building up its space assets.

Commercial space outgrew government programs ten–fifteen years ago. It is now dominated by direct-to-home satellite television broadcasts and communications [19]. Fig. 7 illustrates progress of satellite engineering in this area by highlighting the astounding increase in capabilities of geostationary spacecraft, using as an example one family of communications satellites built by Hughes, now part of the Boeing Company. Other new emerging areas of commercial space, such as space tourism for example, may mature and expand in a similar spectacular way in the future.

The steady increase of the role of space is also reflected indirectly in American academia. Perhaps the best indicator is the growing number of ABET-accredited B.S. programs in aerospace, astronautical, and aeronautical engineering in the United States (Fig. 8; based on ABET data, http://abet.org; cited December 13, 2013). One can see that 13 such new programs had earned accreditation during the time period since 1990 that was characterized by initially significant drawdown of the aerospace enterprise after the end of the Cold War. This increase means that universities have been establishing new aerospace departments or upgrading aerospace options in other degrees (such as mechanical engineering) into full-fledged aerospace degree programs although more along

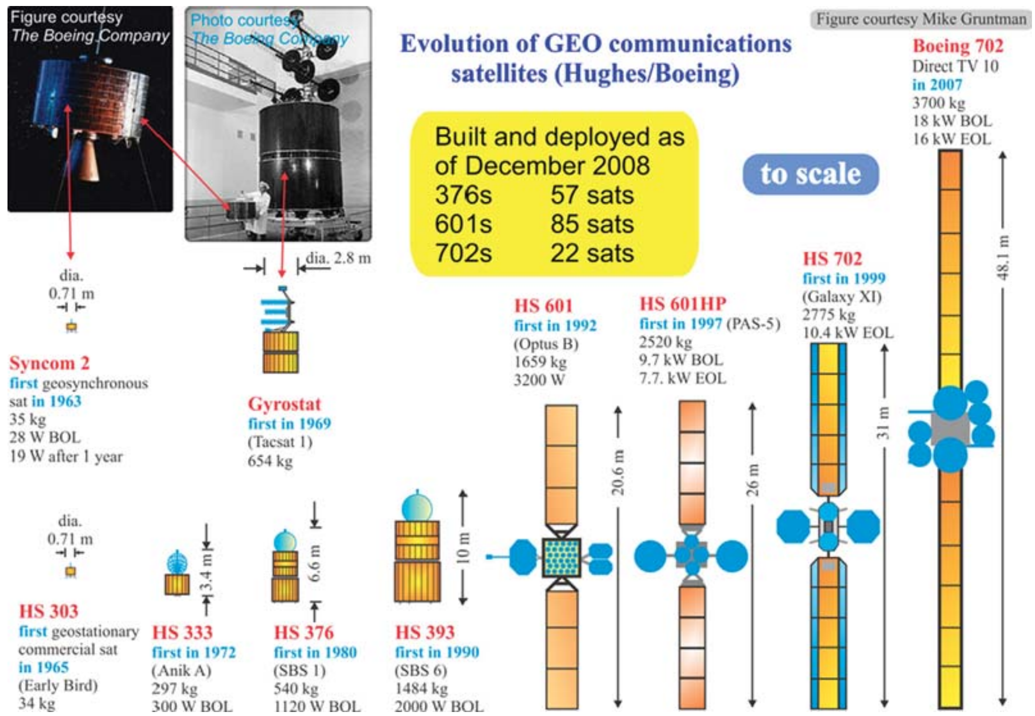

Fig. 7. Spectacular growth of communications satellite capabilities: example of geostationary satellites developed by Hughes/Boeing; BOL – beginning of life; EOL – end of life (M. Gruntman, Space System Fundamentals, Course Notes, 2008; also [20]).

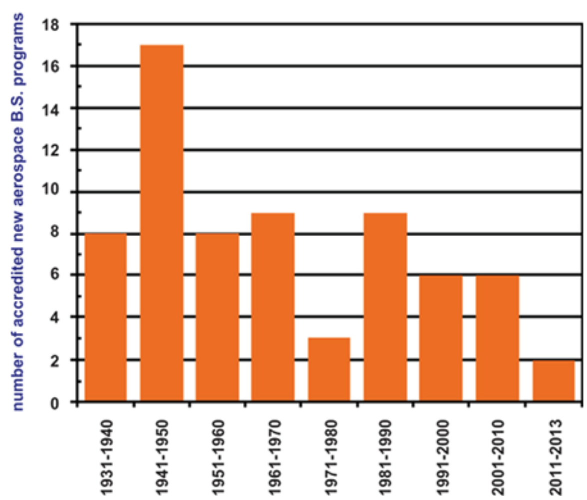

Fig. 8. The number of new bachelor of science degree programs in the broad area of aerospace, astronautical, and aeronautical engineering accredited by ABET in the United States during 10-year time intervals.

traditional aerospace lines and not necessarily focused on space.

Alarming warnings of the forthcoming shortfalls in the aging aerospace engineering workforce have become common during the last twenty years in the United States [1]. The sky has not fallen however, and the space segment of the industry has been growing. These trends suggest that the importance of space will increase with various careers available for engineers with degrees in astronautics.

Today, there are the total of 68 ABET-accredited Bachelor of Science degrees in the areas of aeronautical, astronautical, and aerospace engineering in the United States (http://abet.org; cited December 13, 2013). Six universities offer degrees in aeronautical engineering and 59 in aerospace engineering (called at a few universities "aeronautical and astronautical engineering").

Forty years ago there was only one B.S. degree program in astronautical engineering in the country at the U.S. Air Force Academy, accredited in 1973. Today, there are three such accredited programs with the addition of our program at USC and the other in the Capitol College in Maryland.

In 2007, there were only three institutions offering Master of Science degree in astronautical engineering in the United States [1]. Two such degrees were offered by graduate institutions of the Military Services, the Air Force Institute of Technology (AFIT) and the Naval Postgraduate School (NPS). Our program at USC became the third to offer the M.S. ASTE degree, the first by an American civilian university. The Capitol College also recently joined this group offering its Master's degree.

Many spacefaring nations across the world established extensive educational programs in space science and engineering. Their approaches naturally differ from those in the United States and they are beyond the scope of this article. We briefly mention here that perhaps the most important example is the highly space capable Soviet Union of the past which poured enormous resources into ballistic missiles and space. The People's Republic of China largely copied the Soviet system in 1950s and developed its engineering education along similar lines.

Both countries established separate institutions of higher technical learning in particular engineering areas (railroads, aviation, metallurgy, mining, etc.) as well as polytechnic institutions combining multiple engineering fields. Only few engineering schools were within universities.

The Soviet Union created a number of colleges (faculties) focused on training scientists and engineers for ballistic missile and space programs, following the government decree of 1946 [22]. These specialized faculties were usually hosted by leading institutions of higher technical learning located near major rocket and space design bureaus and production plants (Moscow, Leningrad, Kuybyshev, Krasnoyarsk, Omsk, Dnepropetrovsk, etc.). The faculties produced many thousands of engineers educated specifically in the areas of rocketry and space technology. (Based on coursework and duration of studies, degrees of Engineer in the Soviet Union roughly corresponded to a Master's degree in the United States.)

For example, the space engineering faculty of the Moscow Aviation Institute (MAI), one of the space education institutions in Moscow, had been graduating more than 500 space engineers each year by early 1990s; it employed more than 170 full-time faculty members [23]. In Ukraine, the Physical-Technical Faculty of the Dnepropetrovsk State University (supporting the Yuzhnoe Design Bureau and the Yuzhmash rocket plant) trained 20 thousand space and rocket engineers in the 50 years since 1952 [24,25]. Space educational programs in Russia and Ukraine are currently evolving, e.g., [25,26], to adjust to changing conditions. A number of universities and technical institutions in the People's Republic of China award degrees in space engineering.

Numerous specialized graduate programs in space engineering have emerged in Europe, Asia, and South America. In an interesting experiment, six universities from six European countries – Cranfield University in England; Czech Technical University in Prague, Czech Republic; Helsinki University of Technology in Finland; University of Wurzburg in Germany; Luleå University of Technology in Sweden; and Université Paul Sabatier in Toulouse, France – combined their efforts to establish a degree program in space engineering. This Joint European Master in Space Science and Technology has expanded to include additional universities in Europe, Asia, and North America. Some European universities, e.g., [17,27], experiment with specialized space systems engineering programs in cooperation with industry.

At USC, we plan to further grow the M.S. ASTE program, extending its reach to students across the United States and abroad and offering relevant coursework. We have identified a number of new courses, listed in Section 4.1 above, that could supplement and expand the existing program. As the scope and balance of government and commercial space activities shift, it is essential to adjust our offerings. While we stay focused on the program core of satellite systems and their subsystems, the role of courses related to commercial space will expand reflecting national and international trends. In addition, we clearly see the importance of complementing the existing program by bringing attention of students to major emerging issues such as space debris as well as focusing on the most important applications such as communications and navigational systems. As the long-term strategic U.S. national goals in space exploration eventually settle, it will be essential to offer the coursework specifically supporting such programs.

6. Conclusions

Today, space affects government, business, and culture [20]. Many countries project military power, commercial interests, and national image through space missions. It is a truly high-technology frontier, expensive and government-controlled or government-regulated. Space has become an integral part of everyday lives of people. The worldwide trend of growing expenditures in space exploration and applications, both government and commercial, does not show saturation. This will surely require core space engineering workforce for the space industry and government centers.

Universities contribute to expanding space activities by providing engineering education to the worldwide space enterprise. The establishment of a separate independent space-focused Department of Astronautical Engineering at USC in 2004 was a practical approach to achieve the desired flexibility within the constraints of the American academe. Highly motivated engineers who work full-time in the space industry and government centers and pursue Master's degrees part-time can freely choose among numerous available high-quality programs in the United States. Many enroll in the USC M.S. ASTE program. The program growth in this competitive environment and the number of awarded degrees validate the value of specialized astronautical engineering education and degrees for the industry. The M.S. ASTE program helps engineers to grow professionally within a highly competitive area. Providing coursework highly relevant to the needs of working professionals is the main challenge for the program and the key for attracting new students.

Our experience at USC also unambiguously shows that academic and administrative independence of the space engineering program is essential for its success. Does it suggest that each traditional aerospace department should branch off its space-focused groups of faculty? The answer is negative. It does mean however that there are circumstances when departments offering degrees in astronautical engineering could be the answer to educational challenges. Coexistence of traditional aerospace departments with the pure-space-focused astronautical engineering departments and purely aeronautical engineering programs will bring the needed diversity of options in meeting national and international educational goals. The resulting competition will force the balanced self-adjusting mix of engineering education and degrees determined by the realities of the evolving space enterprise.

The experience of the USC Department of Astronautical Engineering shows that separate pure-space-focused space engineering departments will be successful; will significantly contribute to space engineering education; and will play an important role in meeting the challenges of space engineering workforce development of the future.

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The views expressed in this article are those of the author.

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The Time for Academic Departments in Astronautical Engineering

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Alarming warnings of the forthcoming shortfalls in aerospace engineering workforce have become common. At the same time, the space segment of the industry continues to grow. The space industry is critically important for national security and for economic competitiveness. Non-space faculty traditionally dominate aerospace engineering departments in universities, with changes in their focus coming at a glacial pace. The time has come for separate academic departments in astronautical engineering. To meet the industrial demand, the University of Southern California established such a new academic unit – Astronautics and Space Technology Division – three years ago in the Viterbi School of Engineering. The current status of the Division, its accomplishments and challenges are reviewed.

I. Twenty Years After

"Practitioners in the field of astronautics (space engineering) believe that spacecraft design is now a mature endeavor, and the design of space stations is fast approaching the same degree of maturity. Yet, we find that educational resources, other than on-the-job training, available to the many student engineers who yearn for a career in space have not kept pace. The academic world is almost devoid with experience in the space industry … A just published National Research Council study on NASA-university relationships …. notes that 'interest in space-related disciplines is burgeoning among undergraduates, but the universities are ill-prepared to capitalize on the opportunity.'"

Does the above quote look familiar? Is it an excerpt from a recently published alarming report on workforce development requested by Congress or industry? No. It appeared in an article[1] in "Engineering Education" more than 22 years ago. The article's author, Professor Robert F. Brodsky, argued that the time had come for establishing curriculum in "pure" astronautical engineering leading to a Bachelor of Science (B.S.) degree in astronautical engineering. He hoped that this move would give "astronautics" equal status with "aeronautics" in aerospace engineering departments.

Many important changes have occurred in the ensuing twenty plus years. The Accreditation Board for Engineering and Technology (ABET) now recognizes *astronautical engineering* as a separate degree. Many aerospace departments across the country offer space-related courses to undergraduate and graduate students. One could argue that astronautical engineering has thus been accepted. A more precise characterization would rather be that aerospace engineering departments "tolerate" space engineering to varying degrees. Aeronautics and astronautics are certainly not of equal status in most present day aerospace engineering departments.

The American Society for Engineering Education (ASEE) does not list astronautical engineering as a separate engineering discipline category[2] and includes the degree into generic "aerospace engineering." With a very few notable exceptions, the degrees are offered in "aerospace engineering" or "aeronautics and astronautics" or in some other similar mix of terms of aeronautics and astronautics. Traditional aeronautics-centered courses still dominate the curricula (though more diverse than in the past) of many aerospace departments, with pure-space-focused programs practically nonexistent. Job opportunities in academe, as manifest by advertising in AIAA's *Aerospace America*, do not suggest forthcoming changes in emphasis or transformation of aerospace departments.

Does the current status of space engineering education – twenty years after – fully meet the needs of the space industry and government research and development centers in space technology? The answer is no. *The time has come for separate academic space departments offering degrees in astronautical engineering* to better respond to the workforce development challenges of the American space enterprise.

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II. Educational Programs and Industrial Needs

Twenty years ago there was only one B.S. degree program in astronautical engineering in the country. Today, ABET lists this program at the U.S. Air Force Academy as the only accredited pure astronautics B.S. degree program (http://abet.org [cited 31 May 2007]). (ABET groups all aerospace, aeronautical, astronautical, and possible combinations thereof in one "aerospace engineering" category.)

To the best of my knowledge, only two other B.S. degree programs in astronautical engineering exist today: one in the Capitol College in Maryland and the other in the University of Southern California (USC) in Los Angeles. Capitol College is located a few miles from NASA's Goddard Space Flight Center. Its astronautics Bachelor's degree requirements – in addition to several space engineering courses – are substantially loaded with the electrical engineering curriculum, including courses in circuit design, digital electronics, microprocessors, and communications (http://www.capitol-college.edu [cited 23 July 2007]). The program focuses on space operations; the web site promotes it as a path to "joining NASA's team." ABET does not list this degree as an accredited aerospace degree program. The University of Southern California approved the full set of degrees (see Section V below) in astronautical engineering two years ago and its Bachelor's degree in astronautical engineering is ABET-ready and will undergo accreditation after graduation of a few cohorts of undergraduates.

So, twenty years after Prof. Brodsky's call to arms, only three programs in the United States offer pure-space-focused B.S. degrees in astronautical engineering. At the same time, ABET lists 56 accredited aerospace engineering degrees and five aeronautical engineering degrees (http://abet.org [cited 31 May 2007]). The ASEE database for 2005–2006 academic year (private communications, Michael T. Gibbons, ASEE, 2007) shows only three pure-space-focused Master of Science (M.S.) degrees in astronautical engineering. Two degrees are offered by graduate institutions of the Services, the Air Force Institute of Technology (AFIT) and the Naval Postgraduate School (NPS). (In contrast to universities, the M.S. degrees offered by AFIT and NPS are also accredited by ABET – see text box below.) USC offers the third Master's degree program: it seems to be the only pure-space-focused graduate degree program in astronautical engineering offered by American universities. Students (reflecting the needs of the industry that employs them) show strong interest in the M.S. degree in astronautical engineering which caused remarkable growth of the USC program – see Section VI below.

The focus of the American aerospace academe is not exactly on space. At the same time, the economy, infrastructure, and national security of the United States depend on space more than those of any other country in the world. Our country leads the world in space exploration and space applications. Only France (and the Soviet Union in the past) approaches the U.S. space expenditures in terms of the fraction of the gross domestic product (GDP). Most other industrialized countries in Europe and Japan spend in space, as fraction of GDP, four to six times less than the United States.[3]

ABET Accreditation of M.S. degrees

The ABET list of accredited aerospace programs includes only four Master of Science programs: two in aeronautical engineering and two in astronautical engineering. Graduate schools of the Services offer these programs, the Air Force Institute of Technology (AFIT) at White-Patterson Air Force Base in Ohio and the Naval Postgraduate School (NPS) in Monterey, California. Why do military institutions of higher learning undergo accreditation of their graduate degrees? Peter J. Torvik of AFIT explains,[4]

> The Department of Defense submitted to the Bureau of Budget in 1952 and in 1953 proposed legislation authorizing the award of master's and doctor's degrees to students in the Resident College [of AFIT]. But there were difficulties. The regional accrediting agency (North Central) was reluctant to support the granting of undergraduate degrees by institutions that were primarily technical or scientific. It initially recommended that USAFIT concentrate its effort on the graduate programs rather than seeking authority to grant undergraduate degrees. The U.S. Office of Education was unconvinced that government-supported schools should grant degrees at all, and there were those in the Office of the Secretary of Defense who did not feel that the Air Force should be conducting 'schools of higher education.' But on August 30, 1954, President Dwight Eisenhower signed Public Law 733 of the 83rd Congress, giving degree granting authority for programs completed in the Resident College of the United States Air Force Institute of Technology, subject to accreditation by a nationally recognized accreditation association or authority.
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> Arrangements for an accreditation visit were made, and in October of 1955, [the ABET predecessor the Engineers Council for Professional Development] ECPD granted accreditation for both curricula.

NASA primarily focuses on astronautics, with only 3.2% of its 2008 fiscal year budget allocated to aeronautics. Space exploration enjoys enthusiastic support of many Americans. National security space has expanded beyond the national assets addressing strategic objectives: space has become an integral part of military operations, directly supporting warfighter on the ground. The concepts of responsive space and tactical space assets are gradually moving into implementation. Satellites contribute to the maturing missile defense system. Satellite capabilities enable new commercial applications. The Space Foundation reports that worldwide space industry revenues reached $180 billion in 2005, including $110 billion in commercial activities.[5] The importance of space and its role in national security and national economy will continue to grow. The U.S. space industry is strong, with exciting careers for astronautical engineers readily available.

Clearly, the importance of space will increase and the opportunities for engineers with degrees in astronautics are abundant. A degree in astronautical engineering is a natural path to becoming with time a systems engineer in the space industry and then to technical and managerial leadership positions in space programs. At the same time, the vision of equal status of "astronautics" and "aeronautics" in aerospace departments has not materialized. The space curriculum in many universities is limited, and the old question[6] "is there any space in aerospace" remains.

Americans Support Space Exploration

A majority of Americans – 63% – believe humans will establish a permanent colony on the moon someday, with 39% holding the belief it will come within 50 years…

[66% of Americans] are interested in space exploration.

… Four in five [of Americans] said that it's important to America's international prestige to have a space program, and 71% oppose any cut to NASA's budget …

While 80% of Americans see a space program as vital to America's international prestige, a lower 75% believe a *manned* program is necessary to this purpose.

Zogby poll press release, 3 May 2007
Zogby International, http://www.zogby.com
[cited 9 May 2007]

Space Education

While recognizing that the U.S. system of higher education is unique, we note approaches to space engineering education in other spacefaring nations. The most important example is obviously the highly space capable Soviet Union of the past which poured enormous state resources into ballistic missiles and space. (It is reasonable to assume that the People's Republic of China copied the Soviet system in 1950s and developed its space education along analogous lines, reflecting fundamental similarities of communist totalitarian states.)

Following the government decree of 1946,[7] the Soviet Union created a number of engineering departments (faculties) focused on training scientists and engineers for ballistic missile and space programs. These specialized faculties were usually hosted by leading universities and other technical institutions of higher learning located near major rocket and space design bureaus and production plants (Moscow, Leningrad, Kuybyshev, Krasnoyarsk, Omsk, Dnepropetrovsk, etc.). These faculties produced thousands of engineers educated specifically in the areas of rocketry and space technology. (Based on coursework and duration of studies, the degree of engineer in the Soviet Union roughly corresponded to a Master's degree in the United States.) For example, the Physical-Technical Faculty of the Dnepropetrovsk State University (supporting Yuzhnoe Design Bureau and Yuzhmash plant) in Ukraine trained 20,000 space and rocket engineers in the 50 years since 1952.[8] The space engineering faculty of the Moscow Aviation Institute (MAI), one of several space education institutions in Moscow, graduated each year more than 500 space engineers by early 1990s; it employed more than 170 full-time faculty members.[9] Today, MAI enrolls annually more than 300 freshmen in its space engineering program (private communications, Prof. Oleg M. Alifanov, 2006).

Several specialized graduate education programs in space engineering have emerged in Europe. The International Space University in Strasbourg, France, offers a one-year Master's program. The joint space department, located in Kiruna, of Umeå University and Luleå University of Technology offers a Master's program in Space Engineering in Sweden. Six universities from six European countries – Cranfield University in England; Czech Technical University in Prague, Czech Republic; Helsinki University of Technology in Finland; University of Wurzburg in Germany; Luleå University of Technology in Sweden; and Université Paul Sabatier in Toulouse, France – combined their efforts to establish a two-year degree program Joint European Master in Space Science and Technology, with students taking courses in any of the participating universities.

Aerospace Engineering Departments

The final major influence on education in aeronautics and astronautics came in the '50's with the launching of the space age. After Russia shocked the world on October 4, 1957 with the launching of Sputnik, the West hurried to catch up and duplicate their feat. Many of the engineers attempting to do this were aeronautical engineers who knew little about rocket propulsion, orbital mechanics and such. The academic community hurried to fill this void and most of this effort was done within the existing departments of aeronautical engineering. It was a natural transition then to find that these departments, beginning around 1957 to about 1965, changed their names to reflect activities in astronautics. Those that adopted something like "Aeronautics and Astronautics" were realistic. The term "Aerospace Engineer" immediately brings to mind, to the man on the street, a "rocket scientist." There are still many of us who would rather be called "aeronautical engineers" but that went out of fashion in the first half of the 60's.

Barnes W. McCormick, 2004[10]

Diversity of arrangements and flexibility to experiment remain a vital strength of the American system of higher education. In 2004, the USC Viterbi School of Engineering (VSOE) created a new pure-space-focused academic unit, Astronautics and Space Technology Division (ASTD), in order to take advantage of rapidly growing opportunities in space.[11] The division operates as an independent academic department, offering a full set of university-approved degrees (Bachelor of Science, Bachelor of Science Minor; Master of Science, Engineer, PhD) in astronautical engineering. It is anticipated that the division will formally assume the name of a department in a few years. Student interest and enrollment in degree programs in astronautical engineering are rapidly growing. Academic and administrative independence of the division has enabled success of this experiment (see Section VI below).

ASTD experience shows that independent academic units focused exclusively on space engineering can significantly contribute to meeting the existing educational needs of the space industry. Realities of academe are such that university departments do not change their focus easily. It takes decades for dead branches of the evolutionary tree to fall off and for new directions to replace them in the existing academic structures. Outside the universities, the space technology world is highly dynamic, does not enjoy the luxury of undergoing slow evolution, and expands.

Does the disconnection between existing educational programs and industrial needs mean that each traditional aerospace department should branch off its space-focused groups of faculty? No, not necessarily. It does mean however that there are circumstances when the pure-space-oriented departments offering degrees in astronautical engineering are *the answer* to the educational challenges and they will prosper. Co-existence of traditional aerospace and pure-space-focused astronautical departments will bring the needed diversity and competition in meeting national educational needs. Similarly, purely aeronautical engineering programs, as they are offered today by at least four universities, complement the mix of available options. (The accredited Bachelor's degrees in *aeronautical engineering* are offered by the University of California in Davis, Clarkson University, Rensselaer Polytechnic Institute, Western Michigan University, and also by the United States Air Force Academy; AFIT and NPS offer accredited Master's degrees in *aeronautical engineering*.)

Establishment of independent academic departments in astronautical engineering will shift the existing competition (which is rarely fair) from between the groups of faculty within aerospace departments to a (much more even-leveled) competition between aerospace, astronautical, and aeronautical departments. *This is a practical approach to achieve flexibility within constraints of realities of the academe. The competition among the departments of various universities will force the balanced mix of the offered programs, determined by national educational needs. The American space enterprise and the American student will win.*

The time has come for independent academic space departments offering degrees in astronautical engineering to meet the educational needs of the space and defense industries and government research and development centers in space technology. What follows below describes the motivation and the focus of a pure-space-focused academic unit established at USC, its current status, accomplishments and challenges.

III. National Space Workforce Challenges

Alarming warnings of the forthcoming shortfalls in aerospace engineering workforce have become common during the last ten years. At the same time, the space segment of the industry continues to grow. Space technology and applications are critically important for national security and for economic competitiveness. Many government and industrial leaders point at the acute need to improve space-related education as a major challenge for the American space enterprise.

More than thirty five years has passed since the great advances in space technology of the 1960s. Much of the expertise in the space industry and government research and development centers is held today by engineers nearing or past retirement age. The report (2002) of the *Commission on the Future of the United States Aerospace Industry*, chaired by former congressman Robert S. Walker, noted[12] that “the industry is confronted with a graying workforce in science, engineering and manufacturing, with an estimated 26 percent available for retirement within the next five years.” The Commission recommended[13] that “the nation immediately reverse the decline in, and promote the growth of, a scientifically and technologically trained U.S. aerospace workforce.” In 2003, NASA’s Associate Administrator for Education described the situation as a national crisis[14]: “this year [2003], [NASA] potentially may have 200 to 300 engineers and scientists exit the workforce because they will be retirement-eligible. Also, in the next three to five years, roughly 25 to 30% of that skill set also will be retiring, and that’s a national crisis.”

This challenge was recognized already in mid-1990s. A magazine of the space industry sounded an alarm[15] in 1997: “There is a growing shortage of engineers available to space-oriented businesses in the U.S. and Canada. The shortage, because of industry predictions of rapid and sustained growth in commercial space activities and low student enrollment rates at engineering schools, is likely to adversely affect the industry for a decade or more.” In another chilling observation, an editorial in AIAA’s *Aerospace America* noted[16] that “80% [of aerospace workers] said that they would not recommend aerospace careers for their own children.”

Very recently, *Aviation Week and Space Technology* emphasized the workforce problems in the cover story,[17] “aerospace companies aren’t attracting nearly enough engineers to replace the wave of baby boomers nearing retirement. The gap could have a profound effect on the future of the [aerospace] industry – and the nation.” The presented dynamics of the evolution of the aerospace workforce unmistakably points at the particularly significant increase of the older workers and decline in the middle age group:[17]

Age group	35 yr and younger	35–44 yrs	45 yrs and older
1998	22%	39%	39%
2005	18%	27%	55%

In addition, my personal observation based on anecdotal evidence points to another consequential trend of transferring high-performing and most technically-capable engineers into management positions. This trend calls for stepping up training and education, including pursuit of advanced degrees, of the engineering workforce. Fortunately, many leading space companies and government centers recognize the need and include coverage of tuition towards Master’s degrees as part of standard compensation packages.

Note that undergraduate and graduate engineering education is part of a broader challenge facing the United States today. The Walker Commission emphasized[13] that “the nation must address the failure of the math, science and technology education of Americans. The breakdown of America’s intellectual and industrial capacity is a threat to national security and our capability to continue as a world leader.” (As part of a research university, Astronautics Program at USC concentrates its effort on the undergraduate and graduate engineering components of the educational challenge.)

The immediate consequences of the growing older aerospace workforce were complicated, and perhaps partly mitigated, by deep impact of the end of the Cold War which caused substantial shrinking of the defense industry. Total aerospace-related employment in the United States decreased[16] by 45%, from 1,280,000 to 700,000 workers, between 1987 and to 2002, and stabilized afterwards.

Enrollment in nation’s engineering schools declined in 1990s. In the mid-1990s, the space side of the aerospace sector of the economy began to grow again. The commercial space business expanded, while the national security programs stabilized. By 1999, commercial satellites and satellite services accounted for twice as much revenue as the military and government space share of the market.[18] The number of commercial launches from Cape Canaveral Air Force Station outnumbered military and civilian government launches in 2000.[19] While the grand vision of communication satellite constellations has not materialized, commercial space applications steadily expand. Satellite systems have limited lifetime and need to be periodically reconstituted. Therefore, even maintaining existing national security space capabilities would keep the space industry busy. In addition, NASA’s space exploration programs enjoy solid support of the Americans and will continue.

This turnaround in fortunes of the space and defense industries also shows in aerospace engineering enrollment statistics in undergraduate and Master’s programs between 1999 and 2006 (Table 1). While the total engineering enrollments (presented here as a reference for comparison) edged up by 10–15%, enrollment in aerospace programs increased by 60%. Note that “aerospace” here includes aerospace, aeronautics, and astronautics.

A large fraction of engineering students in the United States are foreign nationals, which presents a special challenge for the space industry and government research and development center. In 2006, about 5.1% of enrolled undergraduate engineering students (all majors) were in this category; the fraction was much higher in Master’s

Table 1. Aerospace and Total Undergraduate and Master's Enrollment (based on Ref. 2).

	1999	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Undergrad Enrollment								
Aerospace Engineering	**7,962**	**8,842**	**9,756**	**9,772**	**11,310**	**12,145**	**16,470**	**16,599**
Total	364,858	373,073	389,993	397,878	408,766	409,778	397,437	404,504
Master's Enrollment								
Aerospace Engineering	**1,495**	**1,755**	**1,741**	**1,631**	**1,984**	**2,162**	**2,428**	**2,385**
Total	70,752	75,368	78,947	89,442	91,665	87,194	82,991	83,515

Note that ASEE has changed the way it collected data between 2004 (enrollment at the department level) and 2005 (enrollment at the degree program level). In particular, "some aerospace data was grouped with mechanical data prior to 2005 because mechanical engineering departments often award aerospace degrees. Consequently, the aerospace total is much larger in 2005."[2] While the 36% jump in undergraduate enrollment in 2004–2005 is partly an artifact, the trend is obvious – the undergraduate enrollment in aerospace programs increased by at least 60% between 1999 and 2006. The effect of change in data collection is much smaller in Master's enrollment. "Aerospace" includes enrollment in aerospace, aeronautics, and astronautics.

(36.3%) and especially doctoral (54.1%) programs.[2] In the aerospace field, foreign nationals accounted for 5.5% of Bachelor's degrees awarded in academic year 2005–2006; at the same time 24.5% of Master's degrees went to foreign nationals (private communications, Michael T. Gibbons, ASEE, 2007).

In physics (a traditionally important field for the space industry), according to the American Institute of Physics, first-year foreign graduate students for the first time outnumbered U.S. nationals in 1998–2002. In 2003 and 2004, U.S. citizens had edged up back into majority. In 2004, the most numerous groups of foreign students came from the People's Republic of China (33%), India (12%), and Eastern Europe (11%). In the time period from 1999 to 2004, the fraction of students from China increased from 26% to 33%, the fraction of students from India doubled from 6% to 12%, and the fraction of students from Eastern Europe dropped from 21% to 11%.

Not only are graduating foreign nationals largely ineligible for defense contractor employment and the military services, but the International Traffic in Arms Regulations (ITAR) effectively limit their participation in civilian commercial projects. Foreign students are also excluded from research and development in many areas of space science and space technology. Many industrial leaders and university administrators have been arguing for relaxation of ITAR restrictions and for facilitating the path for graduating foreign nationals to obtain permanent residency status and stay in the United States permanently. It does not make much economic sense to educate foreign students and then send them back to their home countries which sometimes are openly hostile to the values of the free world and to the United States. One does not have to be a rocket scientist to realize that such practice helps those adversarial states in building capabilities in the areas of critical importance to U.S. national security and economic competitiveness.

The issue is a complex one, however. During last several years, major federal civil penalties were assessed for ITAR-related and other similar violations[20] to a number of major space and defense contractors, including Space Systems Loral, Inc. ($14.0M in 2002); Hughes Electronics Corp and Boeing Satellite Systems ($12.0M in 2003); EDO Corporation ($3.0M in 2004); ITT Corporation ($3.0M in 2004); General Motors Corporation ($8.0M in 2004); Orbit Advanced Technologies Inc. ($0.5M in 2005); The Boeing Company ($15.0M in 2006); Goodrich Corporation ($1.25M in 2006); and L-3 Communications ($2.0M in 2006). In March of 2007, ITT pleaded guilty and was fined $100M for transfer of night vision technology to the People's Republic of China. The continuing ITAR violations will certainly weaken arguments for relaxing ITAR restrictions and the recent ITT case in particular may actually lead to strengthening their enforcement.

Accommodating ITAR-restricted research and development programs on campuses, with numerous foreign students and open class enrollments, presents a challenge to university administrators. Supporting ITAR-restricted programs is especially important for maintaining excellence in the areas of space science and space technology. Accommodating classified research in space technology poses even a greater challenge to universities. While some faculty and administrators, particularly from disciplines other than science and engineering, may argue against classified work, restrictions on classified research infringe on academic freedom. Faculty members who are willing, capable, and qualified for such work should be given the opportunity to conduct it.

Whether the alarming government, Congressional, and industrial findings and reports on the state of the U.S. space workforce collect dust on library shelves or translate into changes depend on a concerted effort by all stakeholders of the American space enterprise, including the space industry, civilian and national security elements of the government, academe, and professional societies, especially AIAA.

The Air Force's Space Command recently made major steps in addressing challenges of space workforce development. The Space Professional Development Program seeks to provide education and training in space technology and operations to the Air Force officers.[21] The Space Command identified more than 7000 personnel (Credentialed Space Professionals) that constituted the "space cadre." To better appreciate the magnitude of the challenge, one only needs to note that most of the cadets graduating from the Air Force Academy major in the fields other than science and engineering. Many of these officers will later operate complex national security space missions and manage acquisition of space systems.

The Space Command created a space education and training organization by activating on 18 October 2004 the National Security Space Institute (NSSI) as the Department of Defense's single focal point for space education and training. NSSI complements existing space education programs at the Air University, Naval Postgraduate School, and Air Force Institute of Technology. Some space fans may call NSSI the beginning of the "Starfleet Academy." The Space Command also established the Space Education Consortium (coordinated by the University of Colorado in Colorado Springs, Co., and including a dozen of universities) as the primary source for civilian space-related educational programs.

Whether NASA, industry, and academe match this Air Force initiative in national security space remains to be seen.

The universities can and should contribute to meeting the educational challenges and reversing alarming trends in the nation's space workforce by determined and focused actions. We report below how establishing an independent academic unit focused exclusively on astronautics and space technology have made a difference in one particular university, the University of Southern California.[11,22–25]

IV. Challenges in Academe and Astronautics at USC

At major research universities, the faculty members largely determine the fields of their concentration and change in the areas of faculty interests does not come easily. Edward Teller once noted[26] "that the substance with the greatest inertia known to man is the human brain, and that the only substance more inert is the collection of human brains found in a large organization such as military service or the faculty of a university." The realities of academe force faculty to vigorously defend their turf and to favor hiring new faculty in the areas of their own research interests. A change in course requires determined effort by visionary and powerful administrators.

Aerospace engineering at USC was rather typical for the country. Most of the aerospace engineering faculty have been traditionally focused on incompressible fluid dynamics research since the Department's founding in 1964. Only a very few courses in space technology were offered in 1980s to graduate students by adjunct faculty. By early 1990s, however, several tenure-track faculty had been added in modern areas of research

The Trouble in Academia

Although astronautical engineering logically could be adopted by mechanical engineering (structures, heat transfer, controls), electrical engineering (power, communications, controls), or aerospace engineering (structures, aerodynamics, controls, orbital mechanics), it appears almost by default to have become the neglected offspring of the aerospace departments. It gives the faculties of most aerospace engineering departments great comfort to believe that since their curriculum teaches "basics," their proffered education already "covers" the field of astronautics. This is not surprising since profiles of the faculties of the 50-odd departments giving some kind of an aerospace degree show that only a handful have worked in the space industry for any significant time, and that few consult with industry. Moreover, most are well-established in research and devoted to aeronautics and thus have little incentive to take an interest in space technology. It is easy for them to rationalize their arguments, since they don't know what an astronautical engineer needs to know.

Robert F. Brodsky, 1984[28]

such as hypersonic flight, physical kinetics, space science, and space instrumentation. This group formed the nucleus of the Astronautics Program within the Aerospace Engineering Department. (The Aerospace Engineering Department merged with the Mechanical Engineering Department in 1998–1999, forming Department of Aerospace and Mechanical Engineering.[27])

The attitude of many USC aerospace faculty toward space technology was not much different from other engineering schools in the country. The history of the department penned by its former chairman only once casually mentions the Astronautics Program,[27] though already at the time of his writing the courses offered by this pure-space-focused program accounted for 80% of the total of graduate students enrolled in aerospace courses, with non-space aerospace courses drawing the remaining 20% of the students. In addition, the recently established astronautics undergraduate specialization was rapidly growing and approaching half of the total enrollment in the aerospace program. (When this rendition of history by the former department chairman was mentioned in our another publication[11] the reviewer rhetorically asked in his comments, "what is special here?" This is exactly the problem: many "mainstream" senior aerospace faculty focus on fluid mechanics and aeronautics, tolerate some elements of astronautics, and consider it "normal." We cannot provide the space engineering education without challenging and changing this attitude.)

The USC aerospace engineering program was also rather typical for American universities[29] in other respects: after program rapid growth in 1980s, the undergraduate student population dropped in mid-1990s, following the end of the Cold War, by a factor of five from its peak.[27]

There were some obvious opportunities, however. USC, the oldest and largest private university on the West Coast, is strategically positioned in the heart of the American space industry in Southern California. California accounts for roughly one half of the revenues of the U.S. space enterprise and California dominates (~80%) the satellite segment of the market.[30] The university is located in Los Angeles and USC's Viterbi School of Engineering has broad expertise and long tradition of working with the aerospace and defense industries. (During the last several years, *U.S. News and World Report* consistently ranked the Viterbi School among top ten engineering schools in the United States.) As part of a private research university, the Viterbi School is dynamic, innovative, and entrepreneurial. Clearly, the *University of Southern California was a natural home for an initiative in space technology*.

So, our response to the doom-and-gloom atmosphere of mid-1990s was to found the Astronautics and Space Technology Program (Astronautics Program) focused on providing engineering degrees in the area of spacecraft technology for the space industry and government research and development centers.

We described the early history of the program in some detail elsewhere.[11,22–25] Briefly, in the mid-1990s, the astronautics faculty of the Aerospace Engineering Department began introducing coursework designed to support the space industry and government research and development centers in Southern California. In addition to the core faculty of the Astronautics Program, the program faculty included several USC faculty from the Aerospace and Mechanical Engineering, Electrical Engineering, and Physics and Astronomy Departments as well as part-time lecturers and adjunct faculty. We started with only a few selected space-related courses taught by regular and adjunct faculty and steadily expanded the curriculum. The Master's degree program with emphasis in astronautics was introduced first as a specialization in 1997 and was formally approved by the University as a degree program in *Aerospace Engineering (Astronautics)* with a separate postcode in 1998. The approval of the Graduate Certificate and the Bachelor of Science degree in Aerospace Engineering (Astronautics) followed. This astronautics specialization degree went with flying colors through ABET accreditation as part of the aerospace program.

This step-by-step development of the program in space engineering laid the foundation to what would follow in 2004.

V. Astronautics and Space Technology Division at USC

Following the initial success of the USC Astronautics Program, the University has taken a major step in further program development. In order to position the USC Viterbi School of Engineering to take full advantage of rapidly growing opportunities in space, Dean of Engineering Professor Max Nikias announced in August 2004 the creation of a new pure-space-focused academic unit, the Astronautics and Space Technology Division. (Prof. Nikias was appointed Provost of USC in 2005.) ASTD, the reorganized Astronautics program, is an independent academic unit within the Viterbi School of Engineering and functions in a manner similar to an academic department. I was privileged to be appointed the first (founding) chairman of ASTD for the three-year term 2004–2007. Two aerospace engineering professors, Daniel A. Erwin and Joseph A. Kunc, became other founding faculty of ASTD. The University approved the new academic title, *Professor of Astronautics*, for the Division faculty.

ASTD assumed immediate charge of all degree programs in aerospace engineering (astronautics) and astronautics-related courses. The Division is responsible for programs in astronautics and space technology in the Viterbi School. In 2005, ASTD obtained University approvals of the full set of new degrees in *astronautical engineering*: Bachelor of Science, Bachelor of Science Minor, Master of Science, Engineer, and PhD. In addition, the University approved the Graduate Certificate in astronautical engineering. It is anticipated that the Division will assume the name of a "department" after graduating a few cohorts of undergraduates.

(Parenthetically, building a new academic unit is a prodigious task. It does not happen often in universities, so many arrangements have to be re-invented. In addition, a sheer number of administrative loose ends that need to be tied up is staggering. Naturally, not every faculty member outside the new unit is happy with the changes and thus particularly collegial and helpful. It took more than two years to achieve the state of a smoothly operating academic unit.)

Today, ASTD offers the full set of degrees in *astronautical engineering* and also manages old degrees in *aerospace engineering (astronautics)* that are being phased out. Freshmen enrollment varies between 10 and 20 students, being capped by the University. The typical undergraduate student takes classes full-time and completes the degree work in four years or eight semesters, taking four to six courses per semester. In addition to the courses required of all undergraduate engineering students (mathematics, physics, chemistry, and humanities), specialized undergraduate courses cover the following astronautics areas: orbital mechanics; space environment; compressible, rarefied, and molecular gas dynamics; spacecraft attitude dynamics; rocket propulsion; and spacecraft design. The Bachelor's degree program in astronautical engineering is ABET-ready – it is based on the astronautics specialization in aerospace engineering that was ABET-reviewed during earlier accreditation of the aerospace program.

The underlying basic science and engineering courses, along with engineering design and laboratories, are for the most part the same as taken by aerospace and mechanical engineering undergraduates. A notable exception and significant difference are in the thermo-fluids course sequence that emphasizes modern statistical concepts, compressible gasdynamics, and rarefied gases and plasmas. Space communications is another important technical area which is outside of the scope of a traditional aerospace curriculum but required for program ABET accreditation. Astronautics students are exposed to various aspects of space communications in several courses: orbital mechanics classes address orbital features and ground coverage; space environment lectures deal with wave propagation in the ionosphere; and the spacecraft design course covers communications link budgets, communications subsystems, and constraints and effects on other spacecraft subsystems.[11]

Creating opportunities for exiting team projects designing and building space-related systems and components is of particular importance in engineering education. Astronautics undergraduates are involved in student projects, including sounding rockets and microsatellites. ASTD works jointly with VSOE's Information Sciences Institute (ISI) in bringing new opportunities for astronautics undergraduates in hands-on experience in space technology.[31]

A few astronautics students pursue doctoral degrees and the Division graduated the first PhD in astronautical engineering earlier this year. ASTD faculty presently includes three full-time tenured senior faculty, two research faculty, two adjunct professors, and a number of part-time lecturers. Several engineering and physics faculty hold joint appointments in ASTD. A search for new tenure-track faculty members is under way.

The Master of Science program in astronautical engineering grew up significantly and it remains the flagship of the Astronautics Program. The program played the key role in development of astronautical engineering at USC and it has achieved national recognition. *Its successful record also strongly argues in favor of establishing pure-space-focused degrees and academic units nationwide.* We review the program in some detail in the next section.

VI. Master of Science in Astronautical Engineering

The USC Viterbi School of Engineering has traditionally strong ties to the defense industry. For many years, VSOE's Distance Education Network (DEN) offered Master's degree programs in various areas of engineering. Working full-time engineers enroll in the program as part-time students. In 2005–2006 academic year, the Viterbi School awarded 1190 Master of Science degrees in engineering, more than any other engineering school in the United States.[2]

A. Initial Focus on Master's Degree

There were several reasons for our initial focus in early 1990s on the Master of Science program. It was practical to begin development of the space engineering specialization with the Master's degree because of interest by students from the industry in Southern California. DEN provided a powerful tool to conveniently reach these students.

Another contributing factor was seemingly unending and especially strong resistance in academe to separate undergraduate programs in astronautics. Even today, there are only three B.S. and three M.S. degrees in astronautical engineering in existence nationally. The last but not the least reason for the focus on the Master's program was its reliance on adjunct faculty and part-time lecturers. Bringing new highly-specialized classes was thus practical and possible without hiring new tenure-track faculty.

Distance Learning at USC

Around 1970, the USC School of Engineering initiated a pioneering effort in distance education called the Instructional Television Network (ITV). Remote classrooms were set up at local aerospace companies such as Hughes, McDonnell Douglas, Rockwell, TRW, the Aerospace Corporation, and many others. ITV was an extensive interactive one-way video, two-way audio broadcast system.

ITV was very successful and cemented close ties between USC and the local companies. However, the system had limitations and was costly, with the affiliated companies maintaining special distance education centers and arranging reception of USC broadcasts. ITV had eight F.C.C.-licensed digital television channels transmitted from two mountain top locations in the Los Angeles area. The system coverage was limited to the Los Angeles and Orange Counties. A USC courier daily collected homework and delivered to the remote sites graded homework, new assignments, and course handouts. Examinations were held on campus and required that students traveled to USC.

In the late 1990s, ITV was reorganized into the Distance Education Network (DEN). Since that time, courses are broadcast over the Internet, or "webcast," using streaming compressed video and audio over the web. Standard high-speed Internet connection allows viewing lectures from home or office anywhere in the world. Consequently, new technology has expanded the program reach. The webcasting opened a way for small companies and even individuals to enroll in our DEN programs. The password-protected lectures could be viewed, asynchronously, at any time during or after the actual lectures during the entire semester. Class notes, homework assignments, and handouts are transmitted to students electronically. Exams are taken on campus by students in the greater Los Angeles area. At distant sites, the exams are typically proctored at local community colleges.

B. Adjunct Faculty and Part-Time Lecturers

Adjunct faculty and part-time lecturers play an important role in the M.S. program. Graduate engineering programs in the United States are traditionally oriented along academic lines in the areas in which doctoral degrees are normally granted. Some areas of space technology are not directly compatible with doctoral study. For example, spacecraft design is not usually considered an academic area because the knowledge base required to be an expert designer is broad rather than deep. Interestingly, spacecraft design attracts a large number of inquiries by students and engineers about the possibility of pursuing doctoral degrees.

Moreover, many areas critical to the space industry are sufficiently specialized and rapidly evolving that no university faculty member would be likely to possess a real command of them unless he or she had spent years working in industry. Ironically, in the latter case, such a person would unlikely qualify for tenure in a research university because of the overriding requirement of superb academic achievements, including publications in academically recognized peer-reviewed journals. Examples of such specialized areas are spacecraft power systems and spacecraft thermal control.

The need of covering a large number of highly specialized areas makes it impossible to provide comprehensive astronautics degree programs responsive to the needs of the space industry with instruction given only by regular university-based faculty. The field is progressing so rapidly that degree programs offered by a relatively static full-time tenure-track faculty would not keep up with industrial developments.

Consequently, our solution to program development was a combination of regular tenure-track faculty and adjunct faculty and part-time lecturers. The regular faculty primarily focus on basic science and technology such as dynamics, gases and plasmas, space science, engineering mathematics, and fundamentals of spacecraft design, orbital mechanics, propulsion, and space environment. The adjunct faculty, who are typically have full-time positions in the space industry and NASA field centers, primarily cover the highly specialized and rapidly changing areas of space technology.

The adjunct faculty and part-time lecturers are a great strength of our program. The access to the unmatched wealth of first-rate experts in space technology in the greater Los Angeles area allows us to launch new courses as needed. The courses taught by lecturers are primarily aimed at students in the Master's degree program and contain much more current space-industry practice than could be offered by a regular university faculty.

C. Program Students

The Master of Science program in astronautical engineering focuses on students who work full-time while earning their degrees. These students (about 80% of the total number) are employed by the space industry and government research and development centers and take their classes through DEN. The remaining 20% of our students are full-time on-campus students. A full-time graduate student not engaged in research could complete the degree in one year of two semesters. In practice, full-time graduate students are also engaged in some research projects and complete the degree requirements in three or four semesters. Some students decide to continue their studies towards the PhD degree after completion their Master's program. Here, the critical issue is identifying a faculty advisor to guide the student.

Most of the students working full time take one or occasionally two courses every semester. The students are highly motivated and their workload at the main job determines the possible load. Consequently, their typical time of studies ranges from two and half to four years. Many distance education students today earn their degree without the need of ever visiting the campus.

Astronautics program graduate advisors help the students to select sets of courses that best fit their educational goals. Usually students desire to get in-depth knowledge in the technical area of their present job. There is another category of students, however, that concentrates on the areas of technology where they would like to transfer to in their companies. Specializing in the desired areas often facilitates such internal moves.

Graduate degrees in astronautical engineering, whether obtained through on-campus study or remotely through the distance education program, are bona fide university degrees. There is a significant difference between a university degree program and short courses in specialized areas such as those offered by UCLA's Extension Program, AIAA, LaunchSpace, or Applied Technology Institute which do not grant degrees. A degree program emphasizes fundamentals and basic science and engineering and their role and applications in specialized topics, whereas a typical short course emphasizes specific applications. The semester-long courses taken towards advanced degrees last three-four months and provide much deeper penetration into the topic through extensive homework, term papers, and other course-related projects. In addition, the feedback and corrections through graded course assignments and continuous contact – live and/or electronic – with the instructors and teaching assistants offer much more than can be usually obtained in even the best-taught short course.

As a matter of policy, VSOE treats all students – on-campus and remote – equally, with the identical requirements toward the degrees and standards in student admission and in evaluating student performance. Although distance students watch their lectures remotely from the comfort of their home or office, they are held to the same high standards as all USC students and are expected to show the same dedication toward their education. This policy is an effective mechanism of quality control.

Access to webcast courses is also open to on-campus students enrolled in those classes. As a result, some full-time students choose to watch classes from their homes instead of attending the lectures in classrooms. At the sane time, some local distance education students prefer attending some lectures on campus.

D. Enrollment Dynamics

Figure 1 shows the dynamics of graduate student enrollment in astronautics courses. We started the program in 1994 by packaging few available astronautics courses in an informal specialization within the Aerospace Engineering Department and began introducing new coursework. Initially, only two astronautics-related courses were available each semester. Today, we offer half a dozen astronautics courses each semester. (This number does not include the required engineering mathematics courses.) By 1998, graduate students enrolled in astronautics courses of the Aerospace Engineering Department outnumbered by a factor of 4 students enrolled in other (non-astronautics) aerospace classes. This ratio remained roughly the same in the next several years.

The Astronautics Program attracted significant student interest and generated positive feedback from the space industry. It became clear that administrative and academic independence of the program was indispensable for further growth. In the summer of 2005, Dean of Engineering Prof. Max Nikias and the University administration established ASTD as an independent academic unit. In the ensuing three years, the program showed remarkable growth, on average about 20% per year (80% growth in three years), in the number of students enrolling in its courses. The growth was achieved at the time of accomplishing numerous academic and administrative tasks of creating the new academic unit, such as approval of new degrees in curriculum committees, creating new entries in catalogs, establishing student admission and advising systems, enrolling first cohorts of freshmen into the new program and guiding them, developing an innovative internship program jointly with VSOE's ISI, and completing numerous administrative tasks of new mail codes, financial accounts, web sites, listings, etc.

The remarkable growth of the Astronautics Program at USC convincingly confirms the wisdom and timeliness of establishing a new independent academic unit in astronautical engineering.

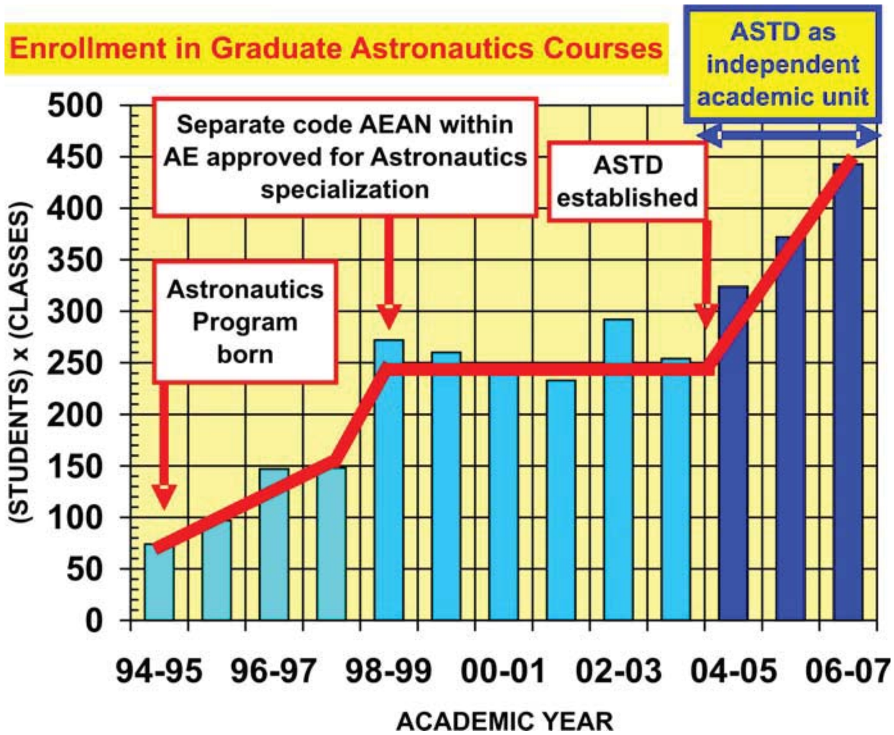

Figure 1. Enrollment dynamics of graduate students in astronautics classes at USC. The program began in 1994. In 1998–1999 academic year the university approved an astronautical specialization *aerospace engineering (astronautics)* with a separate postcode AEAN within the aerospace engineering program.

Today, almost 160 graduate students are enrolled in our Master's program in astronautical engineering: this is about 6–7% of the national enrollment in the broadly defined area of aerospace/astronautical/aeronautical engineering. One quarter of the aerospace/astronautical/aeronautical students nationwide study part-time and work full time. In this latter category, our share is about 20% of national enrollment.

The required introductory course of the Astronautics Program is *Spacecraft System Design*. This is the perhaps the largest graduate course in spacecraft design in the country; Figure 2 shows the dynamics of enrollment in the course. Many astronautics students take this course in the beginning of their studies. (Establishing the individual sequence of courses of study is usually up to a student, with the help of a graduate advisor.) Those astronautics students who take the Spacecraft System Design class will continue their studies in our program and take a number of specialized courses in space technology. Therefore, the enrollment in this class serves as a reliable indicator of the program state during the next two years. The dynamics of enrollment (Fig.1 and Fig. 2) suggest further program growth in the near future.

We graduated 34 students with the degrees *M.S. in astronautical engineering* in 2005-2006 academic year. In this period, we thus accounted for about 3% of M.S. degrees awarded nationally in the broadly defined area of aerospace/astronautical/aeronautical engineering. In astronautical engineering, for comparison, AFIT granted 12 M.S. degrees in 2005–2006 (private communications, Michael T. Gibbons, ASEE, 2007). In 2006–2007 we graduated 37 students. Because part-time students are significant majority in our program and it takes about four years for them to complete studies and graduate, the annual number of our graduates will significantly increase in the next two-three years.

E. Program Reach

I personally teach the required course in the program, Spacecraft System Design (Fig. 2). In addition to astronautics students, this class is also taken by many engineering students with other specializations who work or plan to work in the space industry. Student surveys in the class provide useful statistics on program reach.

Today, about one half of students enrolled in the spacecraft design class pursue the space-focused degree in *astronautical engineering*. This fraction of pure-space-focused students was significantly smaller five–ten years ago. The enrollment to the astronautical program began to grow especially rapidly after establishing of independent ASTD. The program has earned the solid reputation and is highly visible in the space industry; the students are satisfied; and the word-of-mouth plays today perhaps the most important role in the program promotion.

The other half of the students in the class pursues various degrees in engineering. The most numerous group – about 20% – are from the M.S. program in Systems Architecting and Engineering. Electrical Engineering students account for about 12–15% and Mechanical Engineering students and Aerospace Engineering students contribute about 8–10% each. Sometimes we have a few civil engineering, computer engineering, and physics students as well as engineering students from the "undecided" category. (VSOE DEN allows qualified students to begin their studies without being formally admitted to the Master's program. Up to four courses taken as such "limited status" students are later credited toward the degree. This is a convenient way for students to begin studies immediately while having their applications for admission to degree programs being processed.)

Webcasting opened the program to students "from sea to shining sea" across the United States. During the last three years, about 20% of the students in the class were located outside California. Astronautics program at USC has become a truly national program. Each year, the students in the Spacecraft System Design class hail from 10–14 States of the Union.

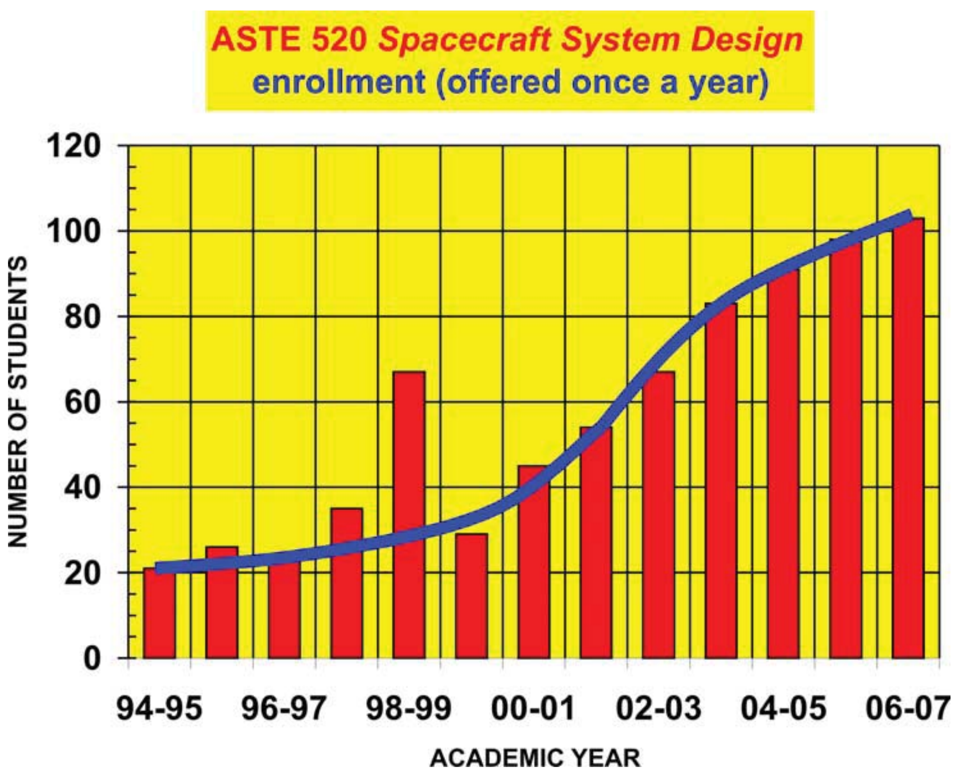

Figure 2. Annual enrollment is the required course Spacecraft System Design since 1994–1995 academic year. A significant expansion by a major company in Southern California caused an enrollment spike in 1998–1999. Many students enrolled in this class would continue studies towards the M.S. degree in astronautical engineering by taking specialized courses. The class enrollment is a reliable indicator for the total student enrollment in astronautics courses during two years in the future.

Many our students work for leading space companies. The list includes many branches of Boeing and Northrop-Grumman. The students also come from Lockheed-Martin, United Space Alliance, Raytheon, Aerojet, Orbital Sciences, ATK, RAND, BAE, Rockwell Collins, Goodrich, Scitor, Sparta, Swales, Microcosm, Stellar Solutions, Honeybee Robotics, and many others. Many students work at NASA centers, especially in JPL in Pasadena and JSC in Houston. A number of students are from the Aerospace Corporation and Air Force's Space and Missile Systems Center (SMC). Several officers (Air Force, Army, Navy, Marine Corps) on active duty stationed elsewhere in the country and overseas are enrolled in our program.

F. Program Coursework

The required coursework for the Master's degree in astronautical engineering consists of nine courses (27 units), with all regular graduate classes being 3 units. In addition to the required mathematics classes, a half a dozen graduate astronautics classes are offered to students every semester. Many specialized courses are taught by our adjunct faculty and part-time lecturers who are leading specialists working in the space industry and government centers. These specialists bring the real-world experience, a vital component of a high-quality program.

To earn the Master's degree, students must take two required core overview courses (6 units) in spacecraft design and space environment and spacecraft interactions; two required courses (6 units) in engineering mathematics; one core elective course (3 units) chosen from a list of core elective classes; and four technical elective courses (12 units). While most of graduate non-astronautics science and engineering courses can be approved as technical electives, many students, however, find the diverse offering of core electives so attractive that they choose all or almost all their technical electives from this list.

Table 2. ASTD courses offered for graduate credit.

Available through DEN	Offered each year	Offered every other year	Course
*	*		Spacecraft System Design (required)
*	*		Space Environment & Spacecraft Interaction (required)
*		*	Design of Low Cost Space Missions
*	*		Spacecraft Propulsion
*		*	Advanced Spacecraft Propulsion
*		*	Liquid Rocket Propulsion
		*	Physical Gas Dynamics I
		*	Physical Gas Dynamics II
*		*	Near Space Flight (first time offered in spring 2008)
*	*		Orbital Mechanics I
	*		Orbital Mechanics II
*	*		Space Navigation: Principles and Practice
*		*	Spacecraft Attitude Control
*		*	Spacecraft Attitude Dynamics
*		*	Spacecraft Structural Dynamics
*		*	Systems for Remote Sensing from Space
*		*	Spacecraft Sensors
*		*	Spacecraft Power Systems
*		*	Spacecraft Thermal Control
	*		Space Studio Architecting

The two required classes, Spacecraft System Design and Space Environment and Spacecraft Interactions, are broad survey-type courses. The Spacecraft Design course also serves as an entrance gateway both for students with non-aerospace engineering undergraduate majors and for those who have been some years out of school. Students of the latter category have often been promoted into management of technical projects and for them this course program is a return to direct involvement with technical study. (Robert F. Brodsky introduced perhaps the first spacecraft design course in the United States at the Iowa State University in 1972; he began teaching this course at USC – as an adjunct professor – in 1982.[32])

ASTD-offered courses cover a wide range of topics in astronautics and space technology. Most of the courses are webcast by DEN. All required courses offered every year as well as a few elective courses, such as orbital mechanics. Many highly specialized courses offered every other year. The latter arrangement allows us to use the same number of precious DEN slots for a larger number of available courses. Demand accumulates for elective classes during the off semesters, resulting in a larger number of students enrolled in these classes. The program is thus fiscally sound, which allows to gradually build the program up, experimenting with new courses. Since it takes about four years for most full-time-working students to complete their studies, careful planning of their coursework usually allows them to take all the desired courses.

Table 2 shows ASTD courses presently offered for graduate credit. We anticipate addition of several new courses in the future, subject to availability of qualified instructors, DEN slots, and programmatic needs. Among possible additions are courses in reliability of space systems, space launch systems, manned spaceflight, constellation design, responsive space systems, space communications, and space science.

VII. Ad Astra!

The workforce development for the American space industry and government research and development centers is a major national challenge. We, at USC, have built a comprehensive educational program in space engineering. The University demonstrated the vision and established a new independent academic unit, Astronautics and Space Technology Division, which offers a full set of degrees in astronautical engineering. ASTD is highly successful and has achieved national recognition; it rapidly grows.

The story of Astronautics at USC clearly shows that the space industry needs the pure-space-focused education. It also shows that *academic and administrative independence of the program is indispensable* for its success. *The time has come for separate academic space departments offering degrees in astronautical engineering* to better respond to the workforce development challenges of the American space enterprise.

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