Good Morning – Thank you all for being here on such a beautiful morning, and thank you to Brian Cantwell and the symposium organizers for inviting me to participate. I am honored and truly humbled to have been selected from among such an awe-inspiring group of national and international leaders.

My good fortune at having the opportunity to be a graduate student at Stanford has certainly changed me and the course of my life. At Stanford I got to take classes from the true Masters – John Breakwell, Dan DeBra, Steven Boyd, Art Bryson, Bob Cannon. I was engaged in research in many aspects of GPS guided by the unchallenged “father” of the field, Brad Parkinson. I had the opportunity to work and study among a truly multidisciplinary group of students and researchers including Jeremy Kasdin, Mark Lewis, Jeff Crier, Clark Cohen, Todd Walter, Xinhua Chen, Hsing Tung Chu, Changdon Kee, and others on the GP-B project. Along the way I also met a remarkable man who would eventually become my husband, Tim Perley.

What sticks with me the most about being in graduate school at Stanford is a sense of being in a place where technical challenges came to be solved and a whole community of smart people was there saying – bring them on. As an advisor, Brad had a knack for swinging by his students’ offices and somehow conveying to you two things - first that he understood how difficult a challenge you faced and second, that he had complete confidence that you'd figure it out – and that was that.

When Brian Cantwell asked me what I would like to speak about – I had to pause. My usual talks about GPS research would be just a little too much preaching to the choir here at Stanford. This is not a group that I could entertain with stories about getting up in the middle of the night to run experiments when the GPS satellite geometry was good, or impress with the accuracy of my latest GPS bistatic radar altimeter results. Too many people already heard the story of how I got Brad to climb up the catwalks of the highbay of HEPL to see where I’d mounted the GPS antennas on the roof. There is one early GPS experiment at Stanford that will always stand out in my mind. When I first started, Kevin Fitzgibbon and I were both working on algorithms for positioning with early Trimble 19” rack–mount surveying equipment. We were running some dynamic tests using his rather late model Fiat, trying to drive at a fairly constant, low speed along Sand Hill Road. This irritated the other (newer) cars who were used to zipping along this road. After an hour or so of this, we finally figured out how to cut down on the honking and nasty looks – and I don’t remember whose idea this was, but we drew up a sign for the back window of the car saying “Caution – radio-wave experiments in progress” Given the proximity to SLAC and the radioactive symbol we attempted to include, this must have seemed like a dangerous enough proposition, that people backed off ….

So, what to talk about if not GPS. As a faculty member for 16 years at the University of Colorado at Boulder, and dept chair for the past academic year, I have been immersed in aerospace engineering education for quite some time. So I thought I would share some of what I’ve read and experienced, and some ideas about the future of this endeavor that actually is what brings us all together here for this wonderful 50th anniversary event.

I’ll give you a little background on my educational experiences so you get a sense for where I’m coming from. After graduating from Stanford I worked in Santa Clara at Stanford Telecom. I was invited back initially to teach Advanced Space Mechanics by Professor Breakwell and then also taught a quarter of the radio and inertial navigation course. In 1992 I came to the AES department at CU, Boulder. We are fairly large for an Aero department with 28 faculty (now) about 400 undergraduates and about 160 graduate students (evenly split between MS and PhD). As a state university our student population and constituency is a bit different from that at Stanford, but we do share, I think many challenges and opportunities. At CU I’ve taught at all undergraduate and grad levels, graduated 14 PhD students, most of whom are now at JPL, and been a partner in curriculum development for and outreach to various K-12 groups. Our department undertook a major revision of the undergraduate curriculum in the late 1990’s,
largely to better integrate our required subjects and to infuse hands-on learning and professional skill
development into every one of our core classes. We are now in the 2nd year of a substantial revision of our
graduate program aimed at enhancing research experiences and technical preparation for our MS as well as
PhD students. At the campus level I serve as affiliate of the Faculty Teaching Excellence program which
provides peer-to-peer training and support to improve the quality of teaching on the CU Boulder campus.
For the past few years I’ve also served on the visiting committee for the Aero/Astro dept at MIT, where I
did my undergrad and grad work. So, educationally, I’ve been around, so to speak.

INTRO

Engineering education is not what it used to be.

Students are lacking in math skills and there is not enough emphasis on the fundamentals.

Is this a new idea? Yes and no. I have a very distinct memory of hearing these words when I was an
undergraduate at MIT in 1984. They were spoken by the renowned astrodynamist, Richard Battin, one of
the best professors I’ve ever had, who was lamenting the fact that hypergeometric functions and continued
fractions were (apparently quite shockingly), no longer taught in the standard high school curriculum. Fast
forward to 2008 - I still hear the same sentiments echoing in the engineering hallways today.

Lack of emphasis on fundamentals is also a time honored complaint of faculty members (equally heard
from those just out of school themselves and those most senior in the department. Students should be able
to derive things from first principles. Even at a recent meeting of the college advisory board at CU the
industry panel members’ #1 concern was with what they perceived to be a declining emphasis on
fundamentals.

It is hard to disagree that a strong understanding of fundamentals, especially mathematics, is essential to
being an effective engineer. The hard part is on narrowing down exactly what are the engineering
fundamentals these days. There are the classic ones - Physics, Chemistry, Calculus plus Fluid Mechanics,
Thermodynamics, Structural Mechanics, Dynamics and Controls. How about materials science? Biology?
Computational methods? Visualization? Probability and statistics, electronics, and telecommunications?
The list of fundamentals is getting awfully long.

Other departments like mechanical and electrical engineering are beginning to come to grips with the
multidisciplinary challenges that aero/astro departments have long faced. That is, the challenge of
determining how, as a department, do we balance requirements for breadth and depth, theory and practical
application. How do we as educators, researchers, and practitioners, best educate the students of today to be
the engineers, scientists, researchers, and leaders of the field in the future?

So, what I’d like to do this morning is tell you what I know about the faculty and students in aerospace
programs, how we go about teaching and learning these days, some of the challenges we face and the
opportunities that abound for us to make an impact.

1. Who are the faculty and what are the performance metrics?
2. Who are the students and what do they expect
3. Why is Aerospace Engineering relevant - What should we be teaching? What do students need to
   learn to be successful in today’s “flat earth”

Who are the faculty and what are the performance metrics?

Aerospace faculty are largely educated at the top ranked programs in the US and internationally. Many of
us are foreign born or first generation American, (and largely democrats according to recent media
reports’). Many aerospace faculty do not have degrees from aero/astro programs – in fact it is quite
common to find electrical and mechanical engineers on aerospace faculty – at CU we even have 2 civils,

two oceanographers, and a geophysicist. What draws us together in aerospace programs are the complex challenges of flight and of the exploration of space.

For now, aerospace faculty are fairly unique in the extent of their involvement in multidisciplinary projects, experimental work, practical applications of engineering and science, and systems engineering. That is not to say that departments of electrical, mechanical, and chemical don’t do these things. In fact they do – and the trend is for them to do more multidisciplinary work as complex applications arise that absolutely require engineers with the wide variety of skills that aerospace projects have needed all along.

Industry, the national academies, deans, and university presidents are all in agreement about the growing importance of multidisciplinary work to tackle today’s most challenging problems – they tout the need to break down traditional barriers and stovepipes. We see new departments, programs, and institutes springing up to foster such collaborations. This is all good.

A challenge for aerospace faculty and departments is that these collaborative projects, perhaps at the boundaries of traditional disciplines, often don’t fit standard models of academic success. The significant contributions of aerospace engineers have indeed in the past been highly valued and recognized. Despite the fact that we represent a small fraction of all engineers, the National Academy of Engineering has 222 members in its Aerospace Section – about 1/10 of the total membership. Incidentally, 14 of the current and emeriti faculty associated with Stanford’s Aero/Astro Department are members of the NAE.

There is, I think, a fairly new tendency in universities to establish metrics and norms (the faculty equivalent of standardized testing) to allow comparisons of faculty performance across departments. Things like numbers of students supervised, publication rates in high impact journals and productivity rates are being considered by well-meaning deans and chairs as a way of improving quality and providing fair comparisons. While this might seem like a laudable goal, there are several real dangers to faculty and departments in this pursuit – first of all, it pushes us to an ever increasing state of busy-ness – in accounting (and bean-counting) more is always better than less. Second, it leads us to hire and favor faculty who tend to science, perhaps engineering science, over engineering and especially over multidisciplinary engineering. Essential engineering endeavors like system engineering, design, system testing and validation, don’t lend themselves to journal publications in the same way as scientific discoveries. BUT, they are at the core of what aerospace engineers really do.

Here is a challenge and opportunity for aerospace faculty and departments and our very important partners in government and industry, to take a lead in re-defining the faculty score card. The strength of a department lies in its ability to contribute as a whole to advancing research, to provide quality education to students, and to create and support a vibrant academic community. Let us explore how faculty can best contribute to these endeavors and how we can assess in a flexible and broad way their contributions.

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Who are the students?

Back in the “good old days”….engineering students were nerdy young men and a few determined and thick skinned young women who had grown up tinkering with mechanical things, maybe blowing things up, but certainly taking things apart and making various attempts to put them back together. Aerospace students differ a bit from the general engineering pool in their fascination with flight – either airplanes or space. I think this makes us a bit more adventurous than the more mild mannered flavors of engineer (without naming names…). Aero students want to hurl things away from the earth at the highest speeds possible. Aero students like “the view from 30,000 ft” - both literally and figuratively. They look for the big-picture, and appreciate the interplay between disciplines that makes this possible. Sure we have specialists in controls and fluids and GPS, but in general, our students expect to gain a breadth of technical subjects, at least at the undergraduate level, and they know that their work will not be that of a solitary working toiling away undisturbed by others. In this sense, students who gravitate to aerospace engineering have a leg up on others in the collaborative teamwork environment practiced in all engineering disciplines nowadays.

Students who choose aerospace engineering today are not slouches. Those coming into universities like Stanford and CU have received high grades in HS. They have lots of AP credit, know how to study long...
hours, score exceptionally well on exams, and get by on little sleep afforded by their involvements in
numerous sports, community service activities, honor clubs, etc. They are more adept at Googling, texting,
and multitasking than their parents and teachers.

Who are aerospace students? The students are typically sons and sometimes daughters of educated parents.
Minority students are only 15% of undergrad populations and less than 3% in graduate programs. Even the
number of women entering aerospace has stagnated at 15% nationwide.

(Just as a side-note - In the 10 year period from 1995-2005 Stanford graduated more PhDs in aerospace
than any other school in the country. CU’s claim to fame is that we have 25% female graduate students
and the highest percentage of US citizens and PR receiving PhD’s in aerospace except for the Air Force
Institute of Technology.)

There are efforts ongoing at most schools to address female and under-represented minority enrollments
and graduation rates. The question is what works most effectively. Programs that engage with students in
middle school provide the best lever to college. Both kids and their parents need to be focused on college
admission in course selections and be aware of extracurricular and financial aid opportunities. Once they
are in school, programs that create community experiences for students work very effectively in retention
and pursuit of graduate school. Efforts like minority engineering programs, summer research programs,
and individual participation of undergraduate students in research labs, working side by side with graduate
students, do work, but they require sustained commitment and progress overall is slow.

Pre-collegiate hs programs that focus on Science Technology Engineering and Math (STEM) can be very
effective. The Denver HS of Science and Technology, for example, is a public charter school focused on
engineering and science. Their mission is nothing less than the following2: “DSST will increase the
number of underrepresented students (women, minorities and economically disadvantaged) who attain
college science and liberal arts degrees. DSST graduates will be responsible, engaged citizens who are
prepared to be leaders of the future.” Currently DSST’s enrollment is 40% low income and 63 % URM.
This May the first class of 79 students are graduating - ALL have been accepted to 4 year colleges,3
including two who are planning to go to Stanford.

These successes have not and do not come easily for the students or the community. Denver Tech was
founded by a remarkable group of educators and citizens. These founders wrote and won numerous grants
to support their work. Volunteers from local industry participate in projects both inside and outside the
classroom. CU faculty and graduate students teach pre-engineering courses there.4 To make it work,
parents, teachers, and students are focused on success and are committed to do what it takes to get there.

Beyond the diversity of students entering engineering, American society faces a broader issue of declining
or perhaps continued low interest in STEM fields by the population at large. I think Barbie said it best
some years ago - “Math is hard”, unfortunately many kids and adults think that hard is to be avoided. It’s
clear that all of us here today do not.

Some K-12 educators over the past 10 years have been eager to shower students with praise in the interest
of insuring their positive self-image. While this is a well-meaning response to negative messages like girls
can’t do math, or racially biased negative advice, students who become addicted to encouragement that is
not based on actual accomplishment don’t develop the tenacity to deal with set backs and push through a
rough patch to find an answer. At the college level we are now often facing young adults who have never
been told that their ideas are incomplete, poorly reasoned, or flat out wrong. Our challenge is to
reinvigorate the notion that one must study, struggle, fail and succeed in difficult tasks in order to build a
sense of self worth that is not hollow and easily damaged. Students must understand how to learn from
mistakes and criticism and then legitimately feel the lightbulb pop when they gain new insights.

2 http://www.scienceandtech.org/
3 http://www.scienceandtech.org/news.html
4 http://itll.colorado.edu/ITLL/index.cfm?fuseaction=NSFGK-12Program
Here is a real Aerospace opportunity. Flight and the exploration of space continue to capture the imagination. Will everyone who is intrigued by flight or by space become an aerospace engineer? Certainly not, but there’s no reason that we shouldn’t set the hook early and deep and draw them in toward science, technology, and engineering.

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**Why is there a need for aerospace education?**

So why is Aerospace Engineering relevant – What should we be teaching and how? What do students need to learn to be successful in today’s “flat earth”

Many engineers who work in the aerospace industry do come from electrical, mechanical, and computer engineering programs. So why are aerospace programs so important and so popular? When universities started offering general engineering degrees, students studied mechanics, electrical, thermo, drafting...all the “fundamentals” What happened as the fields progressed is that the quantity of technical information mushroomed, specialization was required just to keep up. This led directly to the departmental structure that dominates our engineering colleges today. An alternative solution to the skill overload was the emergence of application-centric departments that brought together disciplines critical for subjects like aeronautics, nuclear and ocean engineering, astronautics, and most recently biological engineering. The advantage of colleges that support both discipline-specific and application-specific departments is that students and faculty can self-select according to their primary motivation. For example, in my field GPS, it is perfectly reasonable for researchers who are interested in GPS to be rostered in an electrical engineering department (because of the emphasis on signal processing or RF/digital design) or geophysics (if they are primarily interested in applications to study of the earth) or geomatics engineering (with land applications in mind) or as is the case at Stanford and Colorado, in aerospace engineering because of the ties with satellites, orbits, and aircraft applications. The fact that different universities “realize” GNSS programs differently is a good thing – it leads to interactions among different types of colleagues and enhances the education of students in different and sometimes surprising ways.

I believe that a heterogeneous mix of faculty and student groupings in departments or centers or institutes provides the right, albeit a bit messy, structure for both education and research. The classic aerospace company matrix structure, in which people are aligned with disciplines on one axis and projects on another, actually applies well to the educational environment. The key idea, I think, is that departments can and should be able to be organized along either axis (or maybe a diagonal?) not forced to all be project/application based or discipline-based. A sense of community, shared values in education and visions for research directions make for a collegial and productive faculty. The challenge to engineering deans will be how to evaluate the apples, oranges, and kiwis.

What is the role of government and industry in aerospace education?

To be competitive in the global economy the US needs to take seriously investment in STEM and I would argue specifically in aerospace programs. This is just not happening in a real way - despite calls for funding and change, there has not been substantial action. Furthermore, budget imbalance at NASA has cut many important technology and science programs and the heavy science/engineering science -bias at NSF keeps this door largely closed to aerospace research. The DoD does have some opportunities, but ITAR restrictions which limit participation of students who are not US citizens in much space and aircraft research, ties the hands of university researchers. Initiatives taken by China, Europe, India will advance aerospace education and technology for their own scientific, commercial, and national security interests. The US cannot afford to be left behind without dramatically compromising our own commercial opportunities, scientific leadership, and national security. Having led the development of space assets to enhance commerce and defense, we are now strongly dependent on these resources in our daily lives. We – universities, government, and industry must invest in future workforce and creative research so that we don’t lose this important resource.

So, what should we teach and how?

1) Problem solving skills and practical approaches
2) Fundamental technical skills in each sub-discipline: mechanical, electrical, computational, materials, systems engineering
3) Key professional skills – technical writing, speaking, experimentation, collaboration

In the old days, teachers were not expected to “motivate” students. People went into engineering to provide a good job that would provide stable income. Students came to college and trusted that the faculty would guide them to enlightenment. Take math and science, follow the path set before you. Today’s generation expects to have choices – click on the link you are interested in. Tell me where you want to go. Choose from one of hundreds of channels – you decide.

This has pro’s and con’s – first the cons (easier for a curmudgeon…) students don’t know yet what they don’t know. Having too many choices can lead to inaction. Constant questioning (as anyone who has ever had a 4-year-old, knows) will drive you batty. It’s as if you are going for the first time ever on a vacation to a place that you’ve never been where you don’t speak the language. At one extreme you take a bus tour where the tour guide explains all to you from the air-conditioned comfort of your coach. At the other extreme you arrive at the airport with no plans, no guide or guidebook, or reservations. I think that the undergraduate experience should be like a multisport guided tour. We take students to interesting places, explain what they are about, show them how to use the tools and gear, and then provide ever-widening opportunities to gain experience and explore on their own. As students their education will be grounded in the experience of others. As teachers we will learn much from their questions and the new paths that they discover.

A new challenge

Today we really do face a new challenge and opportunity afforded by the instantaneous availability of information on the web. Until very recently students and researchers regularly tackled problems through discovery and derivation, frankly because it was often harder to find out what other people had done than it was to figure it out yourself. Even in the 1980’s and early 1990’s “finding an answer” as a student or researcher was limited by library hours or the knowledge base of your roommates and colleagues. So, we had to work hard on solving problems alone or in small, localized groups. We were forced to make assumptions about the task at hand, work through the missing steps, make connections to previous experiences. The dearth of information led to a lot of “inefficient” struggling and creative solutions.

The internet has made it far easier to find an answer than to figure out an answer. It’s like having an answer key to everything at your fingertips: 24-7. And, like an answer key, the solutions are notoriously not always right!

Cleverness is evolving into figuring out what to “google” to find a site that has what you want. This really is so convenient and so helpful that we all do it. I was pretty surprised when a student told me that I give an assignment in my intro GPS class, the first thing that most students do is google to see if they can find an existing solution! The fact of the matter is that they usually can find it. Is this cheating? I don’t really know. I do know that by short cutting to an answer students nowadays are missing out on the painful task of developing problem solving skills.

To play devil’s advocate - so what? – isn’t it better to use what others have done to help. In today’s world isn’t this a perhaps more valuable approach? In many cases, the answer might be yes. But as is the case when one works backwards from the answer to the question, jumping on other peoples’ solutions doesn’t teach you how to set up problems and think about sanity checks along the way. The lure of internet really makes it more difficult for students to learn problem solving methods. What’s worse is that I think ther is a real danger that we’ll start believing that finding an answer is equivalent to understanding it.

How should we teach

So how can we educate students effectively (note that I didn’t say efficiently – teaching, like parenting, is inherently inefficient – to do it well, requires time, meaningful engagement, and low teacher-student ratios). Here are some tools:
Education research has found that the deepest learning occurs when it is “inquiry-based”\(^5\). The constructivist view is that students/learners construct understanding by connecting new information to their existing knowledge. The concept is that as learners, each of us has a mental scaffolding that we use for support as to build up new understandings. This view is in stark contrast to the now old-fashion image of students as empty receptacles into which a wise instructor pours knowledge. To be effective in educating students we have to expose or understand the scaffolding to insure that the base upon which students construct their understanding is sound. This is a more difficult and messy task than standing in front of a lecture hall and presenting to 300 students, assigning problems from the book.

Physics education researchers, including Carl Weiman and his colleagues\(^6\), have been working on technologies and resources to help faculty teach and assess learning in a way that stimulates creativity and fosters understanding. They emphasize the importance of clear statements of learning goals, careful design of multiple choice questions that get at the heart of the concept and the misconceptions (trick questions) – and the use of technology namely RF clickers to get instant student feedback in class. They also promote the development and use of simulation tools to allow students to readily explore concepts in a self-directed manner. I think these methods can be quite effective and should be employed to some degree, but, I also think that we need to make sure that we’re not pre-packaging things so carefully that students can avoid taking ownership for the hard work of learning.

What other tools do we have –

**Labs** – experiments with clear instructions that work as planned and involve filling in a few numbers are nice demonstrations that students like and gives some of them more sense of understanding than straight textbook learning. Even more valuable are experiments and design projects are ones that turn out to have substantial errors or are not so carefully defined. These are more time consuming and more frustrating for students, but they offer truly outstanding learning opportunities, provided that the students have experts to go to with questions. When students have spent 2-3 hours in the lab, talking with their team members to decide what to do, asking someone for advice about how to do it, figuring out what might have gone wrong, and then writing up their explanations, they are going to come to lecture the next day a lot more interested in paying attention to the theory that might help explain what happened in lab. The equations or derivations presented at this point, are fundamentally more meaningful than if we first show the theory and then run an experiment that just confirms the theory. The challenge is that it is very difficult to construct experiments that are just vague and sloppy “enough” to generate questions and interest without being overwhelmingly frustrating. This approach really does build theoretical understanding and develop engineering thinking skills.

**Collaborations** – students working together who either have common or diverse backgrounds builds skills and understanding. In my department we do a lot of group work in the lab throughout the curriculum and we try out different student partnering. We try to set up situations so that each student has the opportunity to be a leader and a follower, the recorder and the person fussing with the hardware. Students think (at least initially) that random lab assignments are the most fair. We do that sometimes, but we also make groups of student based on exam performance, C students do far better in lab when there is not an A student telling them what to do all the time. We form groups of all female students. We form groups that involve students from different departments and groups that mix graduate and undergraduate students. The opportunity to work often and intensely in diverse groupings helps students to develop both professional communication skills and technical skills.

**Projects/customer-based courses** – Project based courses\(^7\), can have a tremendous impact on student learning for students at all achievement levels. These have long been a part of the curriculum at the senior or capstone project level, but over the last 10-15 years project courses have migrated to first year

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\(^5\) National Research Council Reports including Bransford, et al., 2005, *How Students Learn*


\(^7\)For example: http://www.colorado.edu/ASEN/SrProjects/
experiences, graduate projects, and multi-level projects. Projects that have external constituencies, for example competitions like the national design-build-fly aircraft competition, the DARPA challenges, underwater vehicles, and even the autonomous lawnmower competition, excite students, while strengthening significantly their system engineering and discipline-specific technical skills. Industry sponsorships of capstone and graduate projects are also a fantastic opportunity. These customers provide project ideas and requirements to which student teams, mentored by faculty members, follow a design process from requirements definition, preliminary and critical design reviews, manufacturing, testing, and analysis.

So what are the challenges and opportunities in Aerospace education?
1) We, that is today’s engineers and scientists, must foster a well-prepared and motivated student population – this means that we have to get involved in engaging students and developing STEM skills in K-12 students and teachers.

2) At the university level, faculty must develop and apply methods to engage students in active problem solving and discovery. We must also find ways of identifying and measuring our diverse educational and research contributions.

3) The nation needs increase investment in higher education. To get this done, engineering faculty need to do a better job explaining what we do to the public. The discovery channel helps. Industry can help a lot more by investing in graduate / MS student scholarships, faculty fellowships, project support. Universities and companies need to advocate with the government for increased support and a reduction of restrictions on basic research. These will have tangible benefits to workforce development, new markets, and new technologies.

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Thomas Mallon is an essayist and novelist who spoke recently at CU on “Space and the Literary Imagination” I went to hear him speak in one of the humanities buildings that I, in 16 years at the university, had never stepped inside before.

Dr. Mallon’s theme for this talk was that the scientific discoveries and flights of imagination enabled by human and robotic space travel should not be underestimated. He fears that in the decades since the beginning of the space race, we as a nation have lost our confidence. We are no longer bold and brave in our thinking. We stick to the safe and the known. We regret past mistakes, and agonize so as to not repeat them. We end up looking backward far more than forward. And we treat risk in exploration as something to be carefully avoided – at a very high cost.

Aeronautics and Space flight are about leaving earth – to explore what is beyond, and to better appreciate what is here. We take for granted now how our world is enhanced by the satellites that orbit – they link our calls, keep us from getting lost, and thank goodness fill our airways with reality tv. What other opportunities lie ahead as we study the earth from above, travel to the moons of Saturn, discover how birds use the magnetic field of the earth to navigate, and build telescopes to peer off into the universe for other planets? I myself, don’t know. But, if we do our job well, the aerospace students of today and tomorrow will be the ones providing the answers.