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AERONAUTICS & ASTRONAUTICS 2008

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State of the Field

AERONAUTICS & ASTRONAUTICS

When the Department of Aeronautics and Astronautics was established in 1958 it was the first department at Stanford to be dedicated to interdisciplinary research. By that time high-speed flight and access to space had developed into two of the most important forces shaping modern culture. It was recognized that to effectively impact the development of aircraft and space vehicles a new department was needed where the research would span the disciplines of fluids, structures, control and navigation. In the five decades since, the faculty of the department have made major contributions to all of these fields, particularly in the areas of precision navigation, aerodynamic design, flow simulation, composite structures, robotic systems and control of complex systems.

On the occasion of the half-centenary of the department in 2008 it is an appropriate time to reflect on our field and ourselves. The purpose of this document is to make our best attempt to peer into the future while noting the accomplishments of the past, and to define a strategic plan that will ensure the future strength and leadership of the Department.

Today, modern flight systems and space systems continue to be two of the most important technology pillars that support a worldwide aerospace enterprise that fuels economic growth, brings together people and cultures, strengthens national security, enables the study of the whole Earth and supports the exploration of distant worlds. The U.S. aerospace industry generates almost $200 billion in annual sales. The industry is by far the largest U.S. exporter, generating more than $50 billion of trade surplus in the year 2006. The trade surplus has doubled since 2003 when it was about $25 billion. In fact, the trade surplus of this enormous industry is roughly equal to that of all other manufacturing industries with a positive trade surplus put together.

Department mission *Box 1*

The mission of the Department of Aeronautics and Astronautics at Stanford is to sustain worldwide leadership in research, to further the nation's aerospace enterprise and to educate students to be lifetime learners and leaders in industry, academia and government.

Because of the complexity of air and space systems and the constant demand for more capability and lower weight at lower cost, aerospace engineers invariably find themselves needing the latest, most advanced and most sophisticated engineering tools at the earliest possible time. Thus the field always sits at the leading edge of scientific and engineering inquiry, often as the first user of new research results.

Future vision

Aerospace transportation is a key underpinning of the world economy and it is undergoing rapid change. Twenty five years from now air and space travel will be completely different from today. The nations of the developed and developing world will be increasingly connected and heavily dependent upon the air transport of people and goods between them. There will be more than twice as many subsonic commercial airliners sharing the airspace with large numbers of small aircraft operating at a wide range of altitudes and speeds. Fleets of UAVs will be patrolling borders and autonomous freighters will carry goods and material across the world. New kinds of vehicles will be moving passengers and payloads in increasing numbers to and from space for commerce, research and exploration. Overlaid on this will be the requirement for security and safety at all levels.

This worldwide air and space network must operate seamlessly, efficiently and robustly in order to sustain a stable, growing world economy, to minimize environmental impact, and to ensure the safety of passengers and property. This is an enormous challenge as well as a source of new opportunities. To achieve this future vision, key advances are needed in aerospace design, space systems, position technology, decentralized control, engineering simulation, optimization, propulsion, high speed flow and aerospace materials.

Research in aerospace cuts a wide swath across department lines requiring disciplines from Aeronautics and Astronautics, ME, EE, Materials Science, Computer Science, Management Science and Applied Math. As a consequence, our faculty engage in a wide variety of collaborations across the School of Engineering as well as with Applied Physics and Physics.

The Department of Aeronautics and Astronautics *Box 2*

The Department of Aeronautics and Astronautics at Stanford comprises 13 active faculty and 7 emeriti who are recalled to active duty. The department is graduate only, offering the M.S., Engineering and Ph.D. degrees. Undergraduates in AA follow an interdisciplinary program in the School of Engineering leading to a major in Aeronautics and Astronautics. The department matriculates 55 to 65 new Masters students and 5 to 10 new Ph.D. students each year. In any given year there are approximately 120 students working toward the Masters, 105 Ph.D. students, and a few Engineering degree students and undergraduates. The department graduates an average of 20 Ph.D. students per year. The fundamental goals of the department are to fulfill its mission (Box 1), to maintain a high level of excellence, to provide aerospace leadership and to achieve a diverse faculty and student body.

Peer departments. Our peer departments include MIT, Caltech, Michigan, Georgia Tech, Purdue, Princeton and Cornell. Despite its relatively small size, the Stanford Aeronautics and Astronautics department is consistently ranked in the top three out of approximately 55 departments nationally in both NRC and US News and World Report surveys.

Faculty distinctions and honors. Among the 13 active faculty there are 7 Fellows of the AIAA, several fellows of RAS, IEEE and APS and 6 members of the NAE. Of the 7 recalled emeriti 6 are members of the NAE. Recent faculty awards include the Dryden Medal (2003), Eckman Award (2003), Ramo Prize (2003), Guggenheim Medal (2003), Draper Prize (2003), Goddard Award (2006), Reed Award (2006), MacArthur Prize (2006), Axelby Award (2007) and Sperry Award (2007).

FIVE YEAR PLAN

We are fortunate to get many of the best graduate students in the nation and our faculty are widely recognized for their accomplishments. We constantly strive to increase the diversity of our faculty and student body to better reflect the diversity of the nation. We are an extremely productive department with many students and a broad variety of well funded research programs directed at important problems. These key elements are necessary if we are to maintain our standing among the best Aerospace departments in the country despite our small size.

But they are not sufficient. In the last ten years there has been immense growth in the size and diversity of certain sectors of the aerospace field and there are enormous technical challenges that face the nation as we go forward. At the same time these challenges bring great opportunities. Many of our competitor departments have recognized this and have been able to grow accordingly. However Stanford has been stagnant and if anything the department has diminished in size and breadth over the last two decades. As a result, certain critical needs are becoming apparent.

(i) We have a world-recognized satellite design program but the entire effort is heavily supported by department funds. Important new space technologies are emerging and our department must be positioned to lead this area. Therefore it is essential to broaden our activities to the larger field of astronautics and to make this a core activity of the department.

(ii) It is widely recognized that position technology is still in its infancy and that advances in this area will have a major impact on the whole world. In addition, new kinds of signals including space radar and hyper-spectral sensing will be available to provide an integrated, dynamic approach to remote sensing of a changing environment. We must add strength in this area to insure that we continue to lead and to help realize the full promise of this important field.

(iii) A few years ago we had four active faculty in the area of structures. Today we have only one and this is not enough to take advantage of the opportunities that exist at a time when new aircraft are vastly increasing the use of composite structures. In the future a whole new class of nano-engineered materials will begin to have important applications to a new generation of aircraft, spacecraft and propulsion systems and we need to be in a position to lead this area.

(iv) Future air and space systems will be cyber-physical systems, with the information sensing and processing integrally connected from initial design onwards. New developments are needed in autonomous and embedded systems, network design and analysis, machine learning and AI, and real-time software methodologies. Progress in these areas must be made in the context of real, safety-critical aerospace systems.

Aerospace is advancing much more rapidly than just a few years ago with immense challenges and exciting opportunities. It is essential that AA continues to lead this important field that has such a huge impact on our culture. The proposed new faculty described in Box 3 are the positions that we believe must be filled over the next five years to achieve this goal.

Proposed new faculty *Box 3*

Listed below is a series of new positions that we propose to fill in the next five years. Each is designed to address emerging opportunities and meet an important area of need in the department. Each is essential if we are to maintain the excellence of our faculty. In striving to achieve this goal we will actively seek to increase the number of women and under-represented minorities on our faculty.

Astronautics. *(Tenure track, full time AA)*
The space industry is at a crossroads and there is a huge opportunity for university based research to have a major impact. We propose to search for a faculty member in the field of Astronautics encompassing satellite design, communications, space systems and launch systems. This person would be expected to develop new experimental programs in space research and develop collaborations with faculty in ME, EE and Applied Physics. Exciting opportunities include new space entrepreneurship (page 20), new micro-satellite designs (page 21), space-borne experiments (page 25), distributed satellite systems and global space infrastructure.

Advanced Navigation and Remote Sensing. *(Tenure track, 1/2 AA, 1/2 EE)*
The next generation of position technology is fast approaching. An expected area of major new growth is the use of satellite-born hyper-spectral and radar sensors for security as well as environmental and climate studies of the Earth. Together these technologies will have an immense impact on the world, comparable to the advent of GPS (page 10). This person would be jointly appointed between AA and EE and would be expected to collaborate with faculty in CEE and the Woods Institute.

Aerospace materials and structures. *(Tenure track, 1/2 AA, 1/2 Materials Science and Engineering)*
The promise of failure-free structures based on the development of new multifunctional materials with built-in sensors and intelligence will become one of the most important drivers of future aerospace systems (page 15). Advanced high temperature materials will continue to improve the performance of new propulsion systems with reduced environmental impact (pages 11 and 13). This person would be jointly appointed between Materials Science and AA and would be expected to collaborate with faculty at Stanford working on nano-technology to develop new programs in advanced materials with application to aerospace systems.

Design for aerospace systems. *(Tenure track, full time AA)*
This billet is targeted at researchers with experience in the design of safety-critical large-scale systems. Potential candidates would have experience in one or more of the following areas: air-traffic infrastructure (page 8), autonomous and embedded systems (page 17), real-time software design (page 18), machine learning and AI applied to aerospace (page 17), innovative ways to deal with unknown environments, system specification and verification, high-confidence design, and cyber-physical systems.

THE AIR TRANSPORT CHALLENGE

The principle of *safety first* was the foundation upon which commercial air travel was created out of the risky barnstorming adventures that marked the early days of flight. The advent of high speed commercial jets in the 1950s ushered in a new era of both safety and reliability but also brought concerns about airport noise and aircraft emissions. For the last half century the goals of commercial aviation have been to achieve better aircraft safety, reliability and performance, better engine efficiency, lower emissions and lower noise. The fact that a commercial air ticket today costs roughly the same in nominal dollars as it did in the 1960s is a tribute to the remarkable success of commercial aircraft and engine manufacturers at attaining those goals.

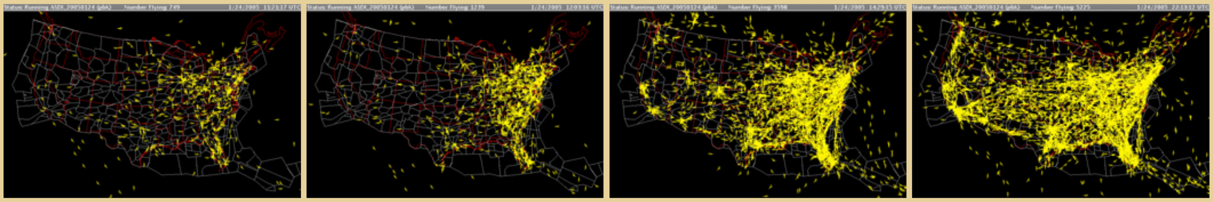
Today the aerospace field faces constraints from an extraordinarily diverse range of factors. Rapid growth in the aerospace infrastructure such as the air traffic system and more stringent environmental constraints on noise and emissions have come to dominate decisions on future investment by industry. With the events of 9/11, safety has taken on a new dimension as it has become much more tightly intertwined with the problem of security.

The air traffic system

The world air traffic system is approaching a crisis. According to Boeing's 2006 outlook on the aerospace market, there are approximately 18,000 commercial jets of all sizes in use today. Between 2006 and 2026 about 10,000 of these will be retired. During that same time period an astonishing 28,600 new commercial jets are expected to be sold with a value of $2.6 trillion, doubling the

Air traffic control

Box 4



A day of U.S. air traffic from February 2006. Credit: NASA Ames.

The current air traffic control system cannot handle the existing traffic demands: ground holds and airborne delays have become so common that airlines automatically pad their estimated flight times. The current structure of air traffic control often compounds the delays due to bad weather, aircraft failure, and runway or airport closure, leading to repercussions throughout the country. Stanford is leading a multiple university effort to address the design of the *Next Generation Air Transportation System*. Supported by NASA and the FAA, Stanford researchers are designing new positioning systems with greater levels of accuracy and integrity than ever before, novel automatic collision avoidance schemes for aircraft, and optimization schemes for easing air traffic congestion while increasing the capacity of the system.

size of the worldwide fleet. In addition, there are signs of a strong emerging market in very light jets and a renewed interest in supersonic flight driven by a potential market for high speed business jets.

There is great concern about the future safety and integrity of the global air transportation system. There is an extremely urgent need for a more flexible and efficient air traffic system that will allow for much higher volume as well as heterogeneous use, from large commercial jets to regional air taxis, and that will support the use of unpiloted aircraft.

The demand for air transportation is outpacing our ability to increase capacity at airports and to manage the in-flight traffic (see Box 4). Record delays of the type seen in the New York metropolitan area in 2007 are likely to be seen in other large metropolitan areas in the U.S., Europe and Asia as the capacity of the air traffic system is reached. This problem has been recognized for some time and has prompted the FAA to undertake a twenty year program to modernize the nation's Air Traffic Control (ATC) system. The goal is to reduce reliance on current technologies such as radar, VHF Omni-directional Range (VOR) navigation systems and non-directional beacons and move to satellite-based navigation. However a great deal of fundamental and applied research will be needed as the new system moves toward full-scale development.

The air traffic problem is one of the major areas of research emphasis in the department. Hybrid systems theory is being used to develop provably safe algorithms for collision avoidance (see Box 5). Hybrid systems are those that exhibit both continuous and discrete dynamics such as an aircraft switching flight modes on landing approach. The methods are very general and can be applied over a diverse range of fields. For example, AA and medical school faculty together are using these methods to help advance the new field of systems biology.

Unmanned Air Vehicles (UAVs) *Box 5*

DragonFly UAV. Credit: C. Tomlin.

The Stanford DragonFly UAVs have a 3 m wingspan, on-board automatic control, sensing, and communications, and fly at 150 m altitude. The aircraft have been developed as a testbed for automatic collision avoidance systems. Successful tests in 2004 led to the demonstration of Stanford's collision avoidance algorithms on Boeing F-15 and T-33 aircraft. Current development of the STARMAC quad-rotor UAV is targeting environmental sensing as a testbed for multiple vehicle control policies.

An important related area of research in the department is the complex and extraordinarily difficult problem of controlling and coordinating multiple aerospace systems, each of which only has

Stanford Center for Position, Navigation and Time (SCPNT) *Box 6*

GPS Satellite. Credit: NASA.

The new Stanford Center for Position, Navigation and Time (SCPNT) has the objective of developing positioning technology that operates in environments that are difficult for current GPS systems, such as space, urban canyons, mountainous terrain, foliage, underwater and underground. Substantial challenges are presented by the requirement that the technology should be low-cost, compact, easy-to-integrate, authenticated, secure, low power, and be resistant to electromagnetic interference and jamming.

limited information about the others. The need for decentralized control occurs in a wide variety of aerospace applications from formation flying of several aircraft or spacecraft to the vast complexity of the worldwide air traffic system.

Position and navigation

Navigation technology is undergoing a revolution that began in 1973 with the advent of the Global Positioning System (GPS). The ability to locate oneself on the Earth's surface by triangulating signals broadcast by multiple satellites 20,000 kilometers away in space was made real over the last three decades with key leadership provided by AA faculty.

The Wide Area Augmentation System (WAAS) recently implemented by the FAA grew out of early research in the 1990s by AA faculty and students. Funding from the FAA was used to develop the concept, including setting up a trial network over the Western U.S. with a master station at Stanford. The system became operational over the U.S. in 2004. More recently it has been extended to include Canada and Mexico. WAAS has enabled approach minimums to be lowered from around 600 ft to 250 ft, and this will soon go down to 200 ft. This system enables precision approaches at most of the 5000 airports in the U.S. with no equipment required at the airport. Previously precision approaches were only available at airports with an Instrument Landing System (ILS) installed, which cost a few million dollars per airport.

More recently AA researchers came up with a novel way to use very inexpensive inertial components, combined with ordinary GPS, to determine the attitude of an aircraft. That research has translated into a product that is now part of the avionics suite that is included in many new private aviation aircraft used by the general public.

In the coming decades, breakthroughs in technology for position, navigation and time will impact the world in many significant ways, benefiting billions of people. GPS is used in millions of cars, trucks, motorcycles and boats. It is used in private and commercial aircraft, robotic vehicles, ships, communication networks, energy transmission grids, security systems, and seismic sensor networks. New location based services are emerging world-wide. The location revolution wrought by the GPS system is just beginning and the department is well positioned to play a leadership role in the future as improved accuracy and better signal availability support the development of hundreds of new applications.

The future military and civilian air traffic system will have to accommodate large numbers of unmanned aerial vehicles (UAVs) with aerial refueling. These systems will have to operate with a high degree of autonomy in a decentralized control environment. Position accuracy is of the utmost importance along with provably safe collision avoidance algorithms. To avoid mishaps, the navigation signal will have to be available with an extraordinary level of integrity and resistance to jamming. Uses include protecting borders, performing long, repetitive missions such as reconnaissance, and undertaking highly dangerous missions.

The Department of Aeronautics and Astronautics has substantial ongoing research in position and navigation technology, and our aim is for Stanford to be the premier academic and research institution for this technology in the world. The new Stanford Center for Position, Navigation and Time (see Box 6) focuses on major projects in this area, with high potential payoffs for society. This research blends theory and experiment, and enables multi-disciplinary work between the departments of AA, EE, ME, CS and Physics. It provides a new level of interaction between Stanford researchers, government, and industry.

Aircraft propulsion

Of all the advances in commercial flight that have occurred over the last century the most important was the transition from propellers to faster, lighter, more efficient jets in the 1950s. Constant improvements to the workhorse gas turbine engine have kept costs down, reliability up and helped sustain the worldwide system of air travel that we enjoy today.

New materials and cooling technologies have enabled modern engines to reach remarkable levels of efficiency with reduced emissions. One particularly key area has been the development of improved cooling schemes and lightweight ceramic coatings to protect the high temperature end of the turbine. In a modern engine the hottest section of the turbine may operate at temperatures that exceed the melting point of the metal by over five hundred degrees Celsius. Under these extreme conditions modern commercial jet engines are expected to operate for up to 30,000 hours without a major overhaul.

The development of improved high temperature materials will remain a strong driver of innovation in a whole range of aerospace applications including propulsion, thermal protection systems for re-entry and hypersonic flight and systems for power generation.

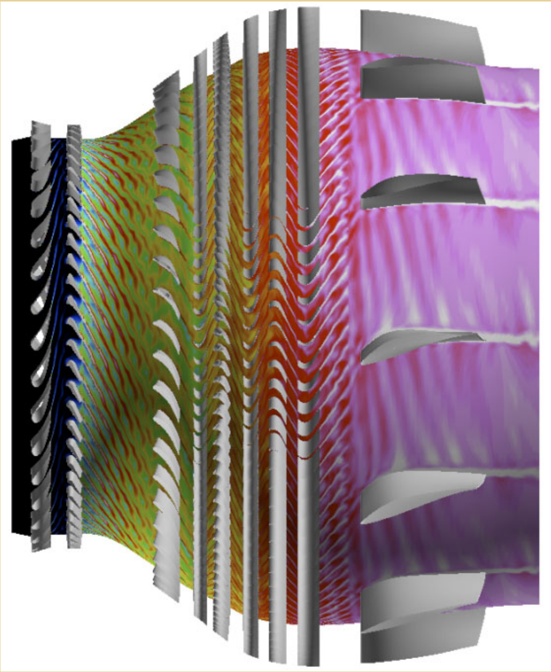
Computational design

Improved capabilities in numerical simulation and more sophisticated analytical tools for design and optimization promise new opportunities for improved systems. Beginning with the first Transonic Flow Symposium held at Aachen in 1962, the art of aircraft design has been revolutionized by the rapid improvement of powerful computers that use numerical methods to compute the flow over complex aerodynamic shapes. AA faculty have played a major leadership role in this revolution. Computer codes and algorithms developed by our faculty have been utilized in the design of nearly every modern commercial airliner we fly in today as well as a number of military aircraft.

Computational research by AA faculty has pushed the frontier of our understanding of flight at hypersonic speeds where air begins to undergo chemical reactions. New advances in supersonic combustion ramjet (scramjet) design by NASA and the Air Force have produced the forerunners of a new class of hypersonic vehicles capable of speeds in the atmosphere exceeding Mach 8. At these speeds the vehicle performance becomes extremely sensitive to the inlet flow field. Researchers are looking at ways of manipulating the electric currents in the inlet flow so as to reduce losses and improve inlet stability. AA faculty have pioneered new computational tools that enable the simulation of such complex reacting flow fields including the effects of magnetic and electric fields.

Computational methods have enabled the development of more efficient fans, compressors, combustors and turbines. Faculty in AA in collaboration with ME are developing methods that will enable the computation of the coupled flow through an entire turbofan engine (see Box 7). The next step will to be to include the interaction of the flow with the engine structure to address the problem of fatigue and to extend engine life. Powerful engineering simulation tools such as these will play a growing role in the development of next-generation aircraft propulsion systems.

Turbofan engine simulation *Box 7*



Turbine simulation. Credit: Stanford ASCI project.

Through the ASCI program and in partnership with ME, AA faculty have been pioneering the development of computational tools that will allow the simulation of the flow through an entire turbofan engine, enabling engine manufacturers to reach the next level of improvements in performance and efficiency.

Future research will aim toward the further development of multi-physics, multi-disciplinary computational tools for the virtual engineering of complex air and space vehicles. New methods for multidisciplinary design optimization promise to replace traditional engineering analysis with a holistic approach to new system design that optimizes performance as well as cost and environmental impact (see Boxes 8 and 9).

Aircraft and the environment

Modern commercial aircraft are up to 70% more efficient than they were 40 years ago and emissions have been reduced by comparable amounts. The new GEnx engine being developed by General Electric will produce 30% less NO_x and be 15% more efficient than current engines. The new 787 aircraft being designed by Boeing will be mainly constructed of composites instead of aluminum, leading to an aircraft that will burn 20% less fuel than its predecessor. Engine and airframe makers have delivered a nearly constant rate of 1 to 2% improvement in aircraft efficiency per year for decades. Radically new designs such as the blended-wing-body aircraft (see Box 8) promise even larger improvements in efficiency and reductions in emissions.

Despite this progress, air travel as a fraction of the worldwide production of greenhouse gases which is about 2 to 3% today could increase to as much as 12% in the next two decades. There are strong signs that airlines and aircraft manufacturers are beginning to recognize this and increasingly aerospace leaders are pushing for new initiatives to reduce the production of greenhouse gases, including continuous descent landing trajectories and more efficient use of the airspace.

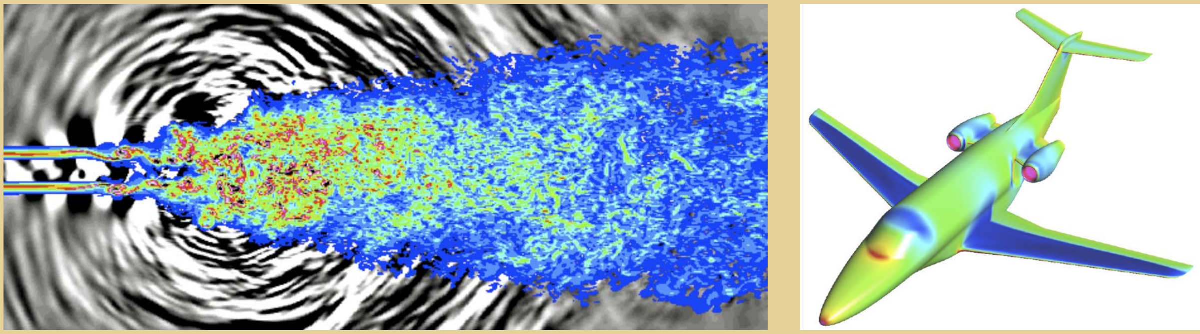
Substantial improvements can be made by using multidisciplinary design optimization, where noise and environmental constraints are introduced at the beginning of the design process. Recently AA faculty have developed design tools to enable this to be done at the preliminary design stage of a new aircraft. The results show significant noise reductions and also define the design trade-offs that must be made between noise and emissions constraints.

New concepts for green aircraft *Box 8*

Boeing X-48B blended wing body. Credit: NASA.

While great improvements in efficiency and noise reduction have been obtained with conventional aircraft designs, dramatically larger gains could be achieved by using radically different aircraft configurations. One concept that is being studied by AA faculty is the Blended Wing Body shown above. By generating lift from the entire body, such designs promise substantial fuel savings and greatly reduced noise impact.

Reduced-noise aircraft designs *Box 9*

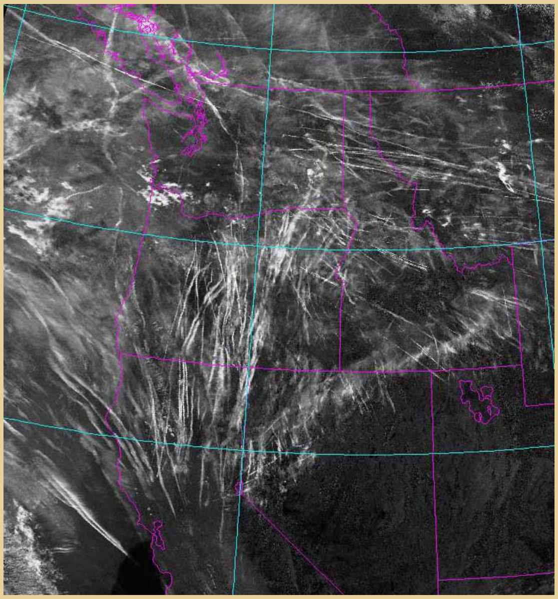

Turbulent jet acoustic field and pressure field over an aircraft. Credit: S. Lele and A. Jameson.

Computational aerodynamics research by AA faculty is focused on reducing drag and optimizing aircraft performance. In addition, numerical simulation of basic flows is leading to new understanding of flow generated noise. This research is enabling a new generation of high performance aircraft that will reduce the noise pollution around airports, even as air traffic volumes continue to grow.

Commercial aircraft will continue to use fuels derived from oil through the first half of this century, but at some point the world's oil reserves will begin to play out. Bio-derived fuels and synthetic fuels such as those manufactured using the Fischer-Tropsch process may extend the use of hydrocarbon fuels for a time but by the latter half of the 21st century aircraft will have to consider the use of hydrogen. This will require an entirely new approach to accommodate the high energy density but very low mass density of hydrogen, requiring much larger volumes for storage. The large amounts of water vapor produced by such aircraft may also be problematic since water vapor acts as a greenhouse gas at altitudes above 30,000 feet. This will be a major challenge to the future of air travel.

One of the key environmental challenges that has long faced the aeronautical designer is that of reducing aircraft and engine generated noise. Local noise rules have forced aircraft manufacturers to put enormous resources into this area. The manufacturer that can demonstrate the quietest aircraft enjoys a huge competitive advantage. The central importance of jet noise has led to the creation of the relatively new field of computational aeroacoustics. Highly accurate computational methods developed by AA faculty are being used to better understand the nature of noise sources in high speed jet flows (see Box 9). The challenge is to resolve the minute pressure fluctuations associated with noise that are many orders of magnitude smaller than the pressure variations that drive the overall flow.

Contrail formation *Box 10*



Contrails over the Northwest U.S. Credit: NOAA.

Contrails are formed by the condensation and freezing of water vapor around aerosols in aircraft exhaust. They make a significant contribution to cirrus cloud cover and thus directly impact climate. Faculty in AA are developing methods for simulating such cloud processes, which are one of the greatest areas of uncertainty in current climate models.

Structural health monitoring

We are about to enter the next great era of aircraft design; this is the era of the mostly-composite aircraft. Composite materials have been one of the greatest successes of material science in the late 20th century. There are many advantages of composite materials, ranging from decreased weight with increased strength to improved shaping capabilities in manufacturing. Carbon composite materials have been used to reduce weight in aircraft structures for many years but these uses have almost always been limited to secondary structures such as flaps and rudders. New generation aircraft are heavily reliant on composites for primary aircraft structure such as the wings and fuselage, as seen in the military F-35 (35% by weight) and civilian Boeing 787 (50% by weight). Both Boeing and Airbus are investing billions in new composite technology but in some respects they are leaping into uncharted waters. It is not clear how an all composite aircraft will absorb lightning strikes without installing a metal mesh in the skin that would take away some of the benefits of the lighter material. It is hard to drill holes in composite material without causing damage and the fatigue life and wear resistance of bolted joints is still poorly understood. The life issues of adhesive joints is an especially important research area. Finally, composites are carbon-based and it is not clear how to dispose of discarded aircraft without environmental impact.

A key research area in aerospace structures is structural health monitoring. Research in AA is focused on developing techniques for embedding arrays of minute sensors and actuators in composite materials to detect defects. When pulsed the actuators produce propagating waves in the material. The waves are scattered by defects and the associated attenuation can be measured by the sensors. The signals from the array of sensors can be inverted to determine the location and size of the defect. A major challenge is implementation of the approach in structures with complex curvature (see Box 11).

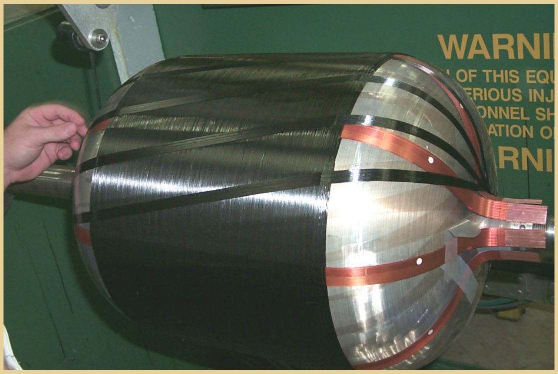
By far the most complex aircraft ever developed is the Joint Strike Fighter (JSF), now called the F-35

Lightning II. Designed for short take-off and vertical landing and with the capability of supersonic flight, this single engine aircraft is viewed as the replacement for both the British Harrier and the venerable F-16. It is the largest government procurement program ever undertaken and over the thirty year life of the program as many as 5000 aircraft may be sold with a value exceeding $300 billion. The JSF incorporates a wide range of advanced technologies in the propulsion, avionics, and airframe design. One of the most interesting features of the JSF is that it employs a revolutionary autonomic logistics support system. This system employs a large number of sensors distributed throughout the aircraft and propulsion system. The output from these sensors will be continuously analyzed so as to anticipate maintenance and repair needs. When a fault is found a decision will be made whether or not to abort the mission and the system will find the nearest source of a spare part, order it, and alert the repair facility that the part is on the way. This is a new paradigm for maintenance and repair. The needed signal analysis and decision making algorithms are still under development and will require advances in computational science and high fidelity modeling that capture details of system operation at the deepest level.

The next generation of innovative structural materials may involve nanoscale manufacturing to obtain radically new material properties and behaviors. The possibilities include dramatic improvements in strength and stiffness for a given weight, novel electromagnetic properties, better wear and damage resistance, and truly pervasive embedded sensors to constantly report the integrity of the structure.

Structural health monitoring

Box 11



Embedded and surface sensors. Credit: F.-K. Chang.

New aircraft are made increasingly of composite materials (over 50% of the Boeing 787), so detecting incipient failure in composites is of great importance. This is difficult because impact damage to composites is typically not visible on the outer surface, even though it has caused large amounts of damage internally. AA faculty are working on Structural Health Monitoring systems using networks of embedded sensors to detect hidden damage in structures with complex curvature such as the pressure vessel shown above.

The vision is that of failure-free air and space craft where light, high strength structures will maintain a history of their stress-strain environment and this information will be used to provide a warning when and where a failure might occur. These technologies will play a key role in the future development of safe air and space travel.

TOWARD A MORE SECURE WORLD

The modern world presents many dangers we must protect against, ranging from environmental catastrophes such as hurricanes and earthquakes, to threats from both conventional and non-conventional military attacks. The effects of global climate change may cause fragile nations to collapse due to shortages of food, water and arable land causing increased human suffering and producing areas of political instability. This will put great pressure on relief logistics and may also bring new military threats. Recently a military panel deemed climate change effects to be a growing national security challenge. Aerospace has historically played a central role in these areas and future aerospace developments are critical to ensuring safety and security in an ever-changing world.

Autonomous vehicles

Unmanned aircraft systems of all sizes and categories have made significant operational and technological progress worldwide over the past decade, with increased roles and responsibilities placed upon such systems for a wide variety of applications. Not only are unmanned aircraft called into action to provide the military with better intelligence, surveillance, and reconnaissance, they are now being used to better monitor the environment, to provide support and information to natural disaster managers, as well as for low cost research and commercial missions. Significant scientific challenges accompany the flexible flight of unmanned aircraft through any air transportation system: the vehicles must be able to respond to directives of air traffic control, but must also be able to detect and avoid other aircraft in the system. To reap the full benefits of multiple coordinating teams of unmanned systems, new algorithms for automatic safe and efficient unmanned aircraft coordination have to be developed (see Box 5).

Sensing and perception

Real-time sensing and perception is an integral part of any autonomous vehicle system. While on-board GPS and inertial measurement units can now be used to reliably determine information pertinent to each vehicle, such as its position and velocity, the capability of a vehicle to reliably sense and interpret its environment continues to be an unsolved problem (see Box 12). For example, a group of unmanned aircraft may be tasked with looking for interesting events, such as unidentified people or vehicles entering restricted areas, using sensors such as cameras, and laser and sonic range finders. Designing a system to quickly recognize when such an event has occurred without providing many false alarms is a major challenge.

Mobile sensor networks

The design, management, and use of large networks of distributed mobile sensors is one of the most exciting current and future areas of research and technology development. Challenges abound, from managing power consumption in the network with severe limitations at each sensor, to efficient methods of information processing at each sensor, to finding optimal strategies for communicating information between sensors.

Solutions to these problems demand expertise from a broad range of disciplines, such as sensor design, power, wireless communication, control, and algorithm design. Many different applications are driving this research, including scientific discovery in atmospheric, underwater and ground-based environments, monitoring of structural health, and inventory control.

Real-time software

A central feature of all modern aerospace systems is that they are increasingly dependent on software. Indeed, software related issues are the Achilles' heel of modern aviation system development. Traditional systems software development is characterized by low level programming, ad hoc approaches, standalone and static implementations, custom systems, and little code reuse. This results in prolonged design schedules, excessive cost, limits in functionality, and difficulty in maintenance, upgrades, and retrofits. New approaches in software design and analysis are required. Current research in the verification and validation of embedded software generally does not consider safety critical aspects, interaction with humans, and non-deterministic code, all essential features of aerospace software. Success would be a significant economic and opportunity stimulant. This issue is recognized by many organizations but real progress has been slow.

Space radar

Radar, which is unaffected by cloud cover and can operate at night, has been used to study the Earth from space for many years in a wide variety of applications, including the use of ground penetrating radar to identify ancient trade routes. Perhaps one of the most remarkable achievements of the Space Shuttle program was the Shuttle Radar Topography Mission, an international research project, that flew on the Shuttle Endeavour in February 2000 (STS-99). The project used a

Automated carrier landings *Box 12*

F/A-18F carrier landing. Credit: U.S. Navy.

Landing on an aircraft carrier is one of the most demanding tasks facing a pilot and is a key obstacle for flying UAVs from carriers. Ship-relative GPS enables fully automated carrier landings, but reliance on this technology means that it must be extremely reliable in a wide variety of environments. Improvements in availability and jamming resistance are active research topics that must still be solved before the danger of carrier landings can become a thing of the past.

method known as Interferometric Synthetic Aperture Radar to produce the most complete digital topographic map of the Earth to date.

Now on the horizon is a new initiative to place in orbit a constellation of satellites that will carry electronically steered synthetic aperture radar systems that will have unprecedented resolution and the ability to track small moving objects. The system is primarily intended for military and intelligence operations. However those who are proposing the system believe that Space Radar could be the next space-based utility with substantial commercial and private uses as well. The belief is that it could follow the same world-changing path as GPS.

If Space Radar were to become a reality its capabilities would complement and strengthen the technologies being developed by the Stanford Center for Position, Navigation and Time, vastly expanding the range of applications. It could become a key enabling technology for decentralized control of fleets of aircraft or ground vehicles by providing enhanced tracking information over the whole collective under any weather conditions. Users would have access to position and radar image data for large numbers of related objects such as traffic in a city. Shipping and the movement of containers between ships and trucks could be monitored. One could study the activities of various types of farm equipment and relate it to crop yields. Market analysts could study traffic between neighborhoods and shopping districts. One could even use the radar to track animal herds or study the migration of birds over long distances. Flocks of birds near airports could be better monitored to prevent bird strikes on aircraft.

NEW FRONTIERS

ACCESS to space has provided us with instant worldwide communications, constant positioning data, and remote sensing for weather prediction and environmental monitoring. It has also provided scientific data not only for our own planet but also for the solar system and the universe beyond.

Despite the crucial importance of space access, the business side of the traditional space industry is not nearly as healthy as the aeronautics side. The high cost of a launch and the high risk of failure have not changed significantly in a quarter century. Over this period propulsion failures of both solid and liquid rockets have occurred in about 1.5% of launches, a failure rate that is not tolerated in any other industry. As much as 15 to 20% of the cost of a satellite is for the insurance to cover the risk of launch failure. This makes the business of building and launching large satellites barely sustainable. The problem is illustrated by the recent formation of the United Launch Alliance (ULA) by Boeing and Lockheed. Under this agreement, recently approved by the Air Force, the two companies will split the business of launching DoD satellites. This is essentially an agreement not to compete for DoD business. The Air Force agreed to the program and even encouraged the agreement because it recognized that the DoD business was not profitable enough to sustain the two companies.

New space

One of the most exciting new developments in space access is the emerging growth of privately funded space ventures. A variety of small companies are investing money to develop everything from low cost launch vehicles to habitats for lengthy stays in space. These efforts are referred to collectively as ”new space”. Probably the most prominent of these is the effort by SpaceX to develop a family of low cost launch vehicles for putting satellites in orbit. Bigelow Aerospace is developing low-cost inflatable structures that can be placed in orbit to be used by astronauts engaged in commercial activities. The first sub-scale module, Genesis I, was placed in orbit and inflated in July of 2006.

There is a growing interest in sub-orbital flight which came into sharp focus with the flight of Space Ship One on October 4, 2004. This was the first privately funded, manned spacecraft to exceed an altitude of 100 km twice within a two week period, thus claiming the $10 million Ansari X-prize. This event marked the beginning of a new sub-orbital space tourism industry. In the next few years a larger vehicle will begin to carry passengers to an altitude of 100 km where they will see the curvature of the earth and experience several minutes of weightlessness. What makes space tourism interesting and potentially very important is the fact that it is the first instance of a mass market for space travel. As such it marks a watershed in the history of human space flight. Numerous market studies have shown that sub-orbital space tourism has the potential to become a multi-billion dollar industry. Remarkably, the space tourism market is presently regarded as the most quantifiable market in the space field. A robust market for space tourism will drive private investment in the technologies required for safe, cost effective space access.

If a competitive ”new space” industry materializes as expected then there will be a major impact across the whole spectrum of space activities including communications, earth sensing, and exploration that will benefit everyone. But commercial space flight will never develop if the cost is too great or if the risk to life and limb is too high. The founding principle must be *safety first* just as it was at the dawn of the age of flight.

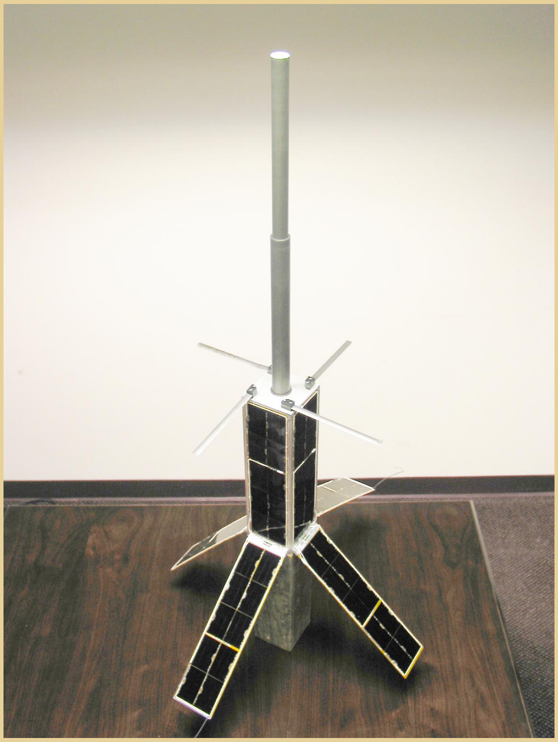
Small satellites

A large number of private and academic research groups are working on mission applications that can be carried out by very small satellites. There is an explosion of innovation and excitement in this area being driven by the opportunity to bring miniaturization and low cost, off-the-shelf components to the design of systems that can be put into orbit. Faculty of the AA department have been at the forefront of this revolution. The CubeSat concept developed at Stanford has become a de facto worldwide standard for microsatellite design as more and more research groups have adopted its basic bus architecture (see Box 13). There are currently six satellites in orbit today that were designed and built by AA faculty and students. The number of research groups working on small satellites is continuing to grow rapidly and a whole series of private ventures are pursuing plans to launch small payloads to orbit.

A very exciting innovation being supported by DARPA is the concept of fractionated satellites. The basic idea is to split a satellite into a set of independent subsystems. Once in space the subsystems may simply fly in formation or they may organize themselves into a single large satellite. The satellite system would make use of new space infrastructure that would supply wireless communications and wireless transfer of power.

Today large satellites are designed with a fifteen year lifetime by a few large companies. The fractionated concept is a paradigm shift toward a

QuakeSat nano-satellites *Box 13*



QuakeSat. Credit: QuakeFinder, Inc.

The QuakeSat satellite built with the help of AA faculty is exploring the use of sensed radio waves as earthquake precursors. QuakeSat is based on the standard 10 cm on a side CubeSat platform pioneered at Stanford and Cal Poly. CubeSat has become a worldwide standard and is enabling novel space-based science at a fraction of the cost of traditional missions.

larger number of small launches to reduce risk to the overall mission, to enable the technology carried by a given satellite to be upgraded on a much shorter time scale, to rapidly respond to damage or degradation of subsystems, and to promote new, much more flexible satellite architectures. One of the most important aspects of this approach is that it will lower the economic barrier for non-traditional vendors of spacecraft technology. This is an entirely new approach to satellite design and Stanford AA is well positioned to play a significant role in this area.

Earth observation

There is a growing consensus that, in the near future, we will see a substantial expansion of our dependency on Earth observations for a wide variety of applications including border security, global warming studies, forest management, forest fire tracking, precision agriculture, water resources management and regional climate change.

Regional climate change is an especially critical area where flexible, small satellite architectures can play a key role. In the coming decades state and local municipalities will be investing billions in new infrastructure in response to local changes in climate. It is critical to support these investment decisions with accurate data that quantifies the effects of climate change over the area in question. These systems will be based on new satellite architectures and will use a variety of new sensing approaches including radar and hyper-spectral sensors as well as high-speed data transfer rates. In addition, new software tools will make imagery and data from different instruments and platforms compatible so that climatologists and other users will have access to data that is seamlessly integrated. This a completely new approach to Earth observation that will make it much easier to understand the complex interplay of phenomena responsible for climate change.

By far the biggest roadblock to the realization of these new uses of space is the sheer cost of launching satellites. At present NASA is actually scaling back its support for Earth observation missions precisely because of budgetary issues. This is happening at a time when the rest of the world is recognizing more clearly than ever the crucial importance of the data derived from these missions.

Space solar power

There is now a renewed interest in the 40 year old concept of Space Solar Power (SSP). The basic idea is to collect renewable power from the Sun and beam it to Earth using microwaves or laser beams.

The DOE with support from NASA carried out a major study of the concept in the 1970s concluding with a reference design in 1979 that would have cost $100 billion and would require major new engineering technologies not available at the time. During 1996-97 NASA took a ”fresh look” and re-examined the concept in the light of technology progress since the 1970s. NASA studied three system architectures in depth; a sun-synchronous low earth orbit design, a middle Earth variable-inclination orbit concept and a geostationary design. It was concluded that while SSP deserved continued study it was not economically viable without the development of key new technologies especially low cost launch systems. Nevertheless SSP was seen as a technology that might emerge again as a serious option for meeting the energy needs of the 21st century.

Interestingly, SSP is once more under consideration and the impetus is not just energy but also global security and climate change. In addition, the needed technologies have advanced considerably. Solar cell efficiency is closing in on 50% through research funded under DARPA's very-high-efficiency cell program. The efficiency of the solid state amplifiers needed to transmit power from space has increased from about 20% to 80%. Beam steering would be done electronically instead of mechanically. Modular or fractionated design together with advanced robotics would make assembly in space easier.

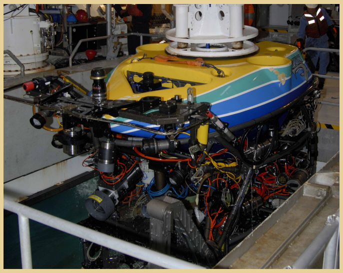
Launch cost is still a major issue but there may be niche markets where the SSP on a modest scale could be used to bring power to remote or newly developing regions of the world.

Aerospace robotics

AA faculty have made major contributions to the field of aerospace robotics since the founding of the Aerospace Robotics Laboratory in the early 1980s. Robotic systems have not only revolutionized the manufacturing sector of our economy, they have also extended our reach into environments that are either too dangerous or too remote for a human presence. Robot dexterity, vision, autonomous operation, operation in a weightless environment, dynamic path planning and distributed systems are recurring themes of the research and will remain so well into the future. AA faculty have played a major role in bringing robotic exploration to the study of the oceans.

Autonomous underwater archeology

Box 14



USS Macon in 1933, Tiberon robot, and Sparrowhawk wrecks. Credit: U.S. Navy, MBARI, and Stanford ARL.

The USS Macon was a 239 m long dirigible from which five Sparrowhawk aircraft could be launched and recovered. It crashed and sank off Point Sur, California in 1935. During a NOAA expedition to the site in September 2006, a Stanford-developed vision system was used to control a robotic underwater vehicle to fly over the two debris fields of the Macon, producing a mosaic of the site from over 14,000 image tiles.

Traditional exploration of the ocean by humans in deep submersibles is now complimented by robots that can execute many of the same tasks, especially in situations where long endurance is required. Recently a vision system developed by AA faculty was used to map the wreckage of the USS Macon off the California coast (see Box 14).

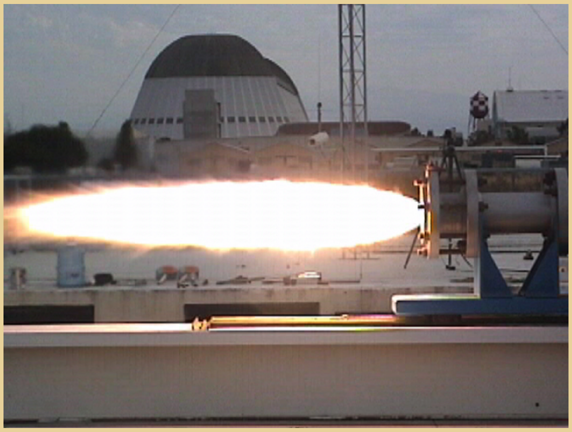
On a fundamental level the same methods and principles used to explore the oceans can also be used in other remote environments as well as in space. A number of increasingly ambitious programs for the robotic exploration of the solar system are being envisioned by NASA and AA is well positioned to play a major role in these efforts.

Hybrid propulsion

A promising alternative to conventional solid and bi-propellant liquid rockets is the hybrid where a liquid oxidizer is burned with a solid fuel. The hybrid concept has been around for more than fifty years. In the hybrid design, the fuel is contained within the rocket combustion chamber in the form of a cylinder with one or more channels called ports hollowed out along its axis. Combustion takes place between vaporized oxidizer flowing through the ports and fuel evaporating from the solid surface. The hot gases are expelled through a nozzle to produce thrust. Compared to a liquid engine, the hybrid is mechanically much simpler. Compared to a solid motor the hybrid uses higher performance, environmentally friendly propellants and can be throttled, stopped and restarted. In contrast to both systems the hybrid presents a design that is much less susceptible to chemical explosion. Despite the obvious advantages, large hybrids have never been successfully commercialized despite several attempts to do so. The reason has to do with the diffusive nature of the combustion process which leads to very low burning rates. The low burn rate leads to a bulky, impractical system with poor performance. Recent advances in the develop-

Hybrid rockets

Box 15



Test-firing of a hybrid rocket. Credit: B. Cantwell.

Recently Stanford researchers have developed a class of paraffin-based fuels that burn at surface regression rates that are three to four times that of conventional, polymeric fuels. The flow of hot gas in the port causes these materials to form a thin liquid film on the melting surface of the fuel. The viscosity of the liquid is low enough so that droplets are lifted from the liquid-gas interface producing a spray that substantially increases the rate of mass transfer. These fuels promise to make large hybrids practical for the first time.

ment of fast burning fuels for hybrids promise to remove this obstacle to hybrid development (see Box 15). A fully mature hybrid propulsion technology could fundamentally change the safety, reliability and cost of space access.

Space-based science experiments

The Stanford Gravity Probe B mission (see Box 16) is just one example of the tremendously fruitful interdisciplinary research being conducted by AA and Applied Physics faculty under the auspices of the Hansen Experimental Physics Laboratory (HEPL). In April of 2007 the first preliminary results of this remarkable forty six year project were reported to the physics community. The AA department has lead the development of several new technologies needed to make possible the exquisite measurements required for GP-B. The drag-free satellite capabilities and ultra-precise gyroscopes achieved for GP-B are eight to ten orders of magnitude ahead of all others, giving Stanford a huge opportunity to lead future space-physics missions and to develop new gravity-based Earth sensing technologies.

An exciting example of gravity-based Earth sensing is the Gravity Recovery and Climate Experiment (GRACE) currently being conducted by NASA, the German DLR and the University of Texas aerospace department. The experiment consists of twin satellites 220 km apart equipped with precise positioning technology. Changes in distance between the satellites can be used to determine an extremely accurate time-dependent map of the Earth's gravitational field. This has recently permitted the direct measurement of the change in ice mass of both Antarctica and Greenland over the last four years. The ability to accurately measure continent-wide changes in geophysical variables will have a profound impact on our understanding of climate change, water distribution and many other key variables of the Earth's ecosystem.

We intend to strengthen our connection with the Stanford physics community and space-based experiments so that AA students can continue to be involved with experimental research that leads to innovative new measurement technologies while pushing the limits of the possible.

Ultra-precise space physics *Box 16*

GP-B gyroscope. Credit: Stanford GP-B Project.

The Gravity Probe B (GP-B) satellite is a Stanford-led project to directly measure the relativistic geodetic and frame-dragging effects. After more than forty years, preliminary results were announced in April 2007 and work is ongoing to provide new bounds on the accuracy of general relativity and possibly point the way to new and unknown physics.

CONCLUDING REMARKS

The Stanford AA department was formed at the dawn of the space age and within a few years rose to national prominence. Today, after a half century, air and space systems continue to deepen their profound impact on the world and our department has been at the center of many of the most important advances that have shaped the field.

In this document we have attempted to describe our vision of future air and space systems and to summarize some of the most important technologies that we believe will impact this vision in the next few decades. Almost every important aerospace technology area will see increased emphasis on information technology, the environment, energy, new materials and computation all of which have close connections to Stanford's School of Engineering Strategic Initiatives.

The new faculty positions described in Box 3 are designed to support this vision and are essential to insure that the AA department is well positioned to remain faithful to its mission and to maintain Stanford's continued presence as a world leader in aerospace.