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AEROSPACE
Assuring Space Mission Success

Crosslink

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From the Editors

The U.S. government has increasingly come to recognize climate change as a threat to national security. Military and intelligence services now consider the impacts of climate change in their strategic planning activities, and various branches of the military have begun to assess new missions that could arise in a climate-altered world—some of which could require support from space assets. For example, climate models predict that within a decade or so, Arctic sea ice will melt enough during the summer months to allow commercial shipping and mineral exploitation. Accordingly, the Navy issued new policy guidance and structural plans to address the challenges posed by increased activity in the region. Similarly, military planners are anticipating an increase in the need for disaster relief and humanitarian aid as a result of changing weather patterns.

Anticipating future mandates in this area, The Aerospace Corporation has been conducting environmental and climate-related research using internal funds. Efforts so far have established Aerospace as a clearinghouse for information on climate trends and impacts, specifically with regard to future military and national security space requirements. Some of these research initiatives are detailed in this issue of *Crosslink*.

For example, Aerospace has been applying its expertise in modeling and simulation to explore how different parts of the globe might respond to shifts in the distribution of natural resources brought about by climate change. Also, in light of recent data-sharing agreements between the strategic and civil science communities, Aerospace has been investigating how spectral imaging technology initially developed for military applications can provide a paradigm for systems to address a variety of environmental monitoring applications. Another intriguing study assessed the feasibility of using space systems to detect the clandestine release of aerosols into the atmosphere to alter Earth's albedo and cool the planet.

The current emphasis on developing a commercial launch and space tourism industry could lead to higher launch rates in the near future. Aerospace research has anticipated concerns over soot emissions from rocket plumes and the push for "green" alternatives to traditional propulsion technologies, including hybrid rocket engines. Similarly, Aerospace has been applying its expertise in constellation management and collision avoidance to predict the effects of increasing levels of atmospheric greenhouse gases, which—counterintuitively—decrease the density of the upper atmosphere and thus extend the orbital lifetimes of satellites and space debris alike. Continuing a long tradition of applying space-system engineering to terrestrial energy production, Aerospace has also put its hyperspectral imaging systems to work assessing the potential for geothermal power plants near the Salton Sea in Southern California.

Some of these efforts have been presented in academic journals and industry conferences around the world—but this issue of *Crosslink* represents the first time they've been showcased collectively. Although it is by no means comprehensive, this issue provides an intriguing glimpse into the corporation's exciting and forward-looking work in this increasingly vital domain.

In Defense of the Planet

Earth has been struck by asteroids numerous times in its history—sometimes with devastating effects. Is another major collision overdue? The International Academy of Astronautics held a conference in May 2011 to explore the potential of an asteroid collision and the prospects for avoiding such disasters. William Ailor, principal scientist in the Vehicle Systems Division, cochaired the conference.

The good news: observers find no near-term future threats of a one-kilometer or larger "planet killer." However, smaller asteroids do pose a threat. "A small asteroid roughly 30 meters in size is big enough to take out a large city," said Ailor. "There is a growing realization that we need to increase our efforts to find these small asteroids well before they might impact. But they are hard to see until they are fairly close to Earth, so the warning time may be very short."

The world community is considering ways to prevent such collisions. One option would be to crash something into an asteroid, changing its velocity. This could be accomplished by a nuclear explosion, or by hitting the asteroid with a fast moving "bullet." Another approach would use the tiny gravitational attraction between an asteroid and a spacecraft parked nearby to slowly pull the asteroid into a nonthreatening orbit.

The 2011 Planetary Defense conference was held in Bucharest, Romania. Aerospace has chaired or cochaired this conference since its inception in 2004, and this year's was the fourth in the series. For more on potential collision risks, visit NASA's Near Earth Object Program at http://neo.jpl.nasa.gov/risk/.

End of an Era

Space shuttle Discovery launched for the final time (STS-133) from Kennedy Space Center on February 24, 2011. The NASA shuttle and its six-person crew traveled to the International Space Station to deliver a new storage module, an equipment platform, and the first humanlike robot in space. Aerospace supported this last scheduled launch of Discovery.

"We performed studies to assess the risk of damage to the orbiter from foam debris, which became a potential issue when a seven-inch crack on the surface of the external tank was discovered during its first launch attempt. Our findings were used to quantify the risk to the shuttle, and helped clear it for flight to conduct its mission safely," said Randall Williams, systems director, Civil and Commercial Launch Projects.

This launch marked the 39th flight for Discovery, which first flew in 1984. During its service life, Discovery made two return-to-flight missions and several satellite repair missions and launched the Hubble Space Telescope and Ulysses solar probe. It visited the International Space Station 13 times and spent 365 days in space. Discovery landed at Kennedy Space Center on March 9, 2011. Now retired, it will be displayed at the Smithsonian Institution in Washington, DC. NASA has announced where the other two shuttles will retire: Endeavour will go to the California Science Center, Los Angeles, and Atlantis to Kennedy Space Center, Florida.

Courtesy of NASA

Space shuttle Discovery's final launch from Cape Canaveral.

Aerospace Nanosatellite Launched on Atlantis

The latest in a series of nanosatellites built by Aerospace was integrated onto the space shuttle Atlantis for the STS-135 mission which launched in July. David Hinkley of the Mechanics Research Department is the project manager. The Miniature Tracking Vehicle (MTV) is designed to serve as an orbiting reference for ground tracking systems. It will "demonstrate three-axis attitude control, solid rocket propulsion for orbit modification, adaptive communications, active solar-cell performance monitoring, and radio-occultation tomography in a nanosatellite platform," said Siegfried Janson, senior scientist, Mechanics Research Department. MTV weighs just 4 kilograms and measures 5 × 5 × 10 inches; it was ejected shortly before shuttle reentry into a 340-kilometer orbit with an expected orbital lifetime of three to nine months, depending on solar activity, said Janson.

The nanosatellite will be controlled using a primary ground station at Aerospace and an Internet-based ground station network consisting of two additional antennas in U.S. territories. Two onboard GPS receivers will provide accurate time and position information to facilitate analyses of tracking errors. Multiple megapixel cameras took pictures of Atlantis as MTV left, thus supplying the last on-orbit photos of NASA's workhorse space transportation system. MTV is the 12th Aerospace miniature spacecraft launched.

Aerospace Algorithm Finds Broad Application

The airline industry could reap big benefits from an Aerospace program developed to streamline the design, reconfiguration, and replenishment of satellite constellations. The Genetic Resources for Innovation and Problem Solving (GRIPS) program is a decision-support process that uses evolutionary algorithms, efficient parallel processing on thousands of compute cores, and advanced high-dimensional visualization to solve complex problems, explained Matthew Ferringer, a project leader in the Aerospace Architecture and Design Subdivision. It offers the ability to understand and communicate the key architectural tradeoffs in system-of-system designs, he said.

The technology was recently licensed to Apptimation LLC, a startup company that develops and markets decision-support and business applications for the travel and transportation, energy, logistics, and finance industries. Aerospace and Apptimation have demonstrated that by using solutions generated by GRIPS, a small airline could save as much as $1 million a day by streamlining its flight schedule. The Apptimation GRIPS product, called NetXellerate, is also used for short- and long-term strategic planning.

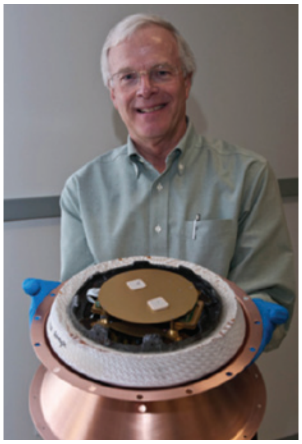
GRIPS was developed by Aerospace with researchers from Penn State University, who participated through the Aerospace Corporate University Affiliates Program. Nearly a decade of research went into its development. The Aerospace inventors, including Matthew Ferringer, Ronald Clifton, Timothy Thompson, and Marc DiPrinzio, were honored in February 2011 with the Aerospace Howard Katzman Innovation Award for their work with GRIPS.


(Left to right) Andrew Quintero, Matthew Ferringer, and Howard Katzman at the 2011 Aerospace Inventors' Day celebration. Ferringer accepted the innovation award for the GRIPS team.

REBR Records Rocket Reentry

When the Japanese launch vehicle HTV2 reentered Earth's atmosphere on March 29, 2011, it managed to send detailed information about its temperature, accelerations, and rotational rates as it disintegrated and burned up. That is because it carried a small device known as a reentry breakup recorder (REBR) designed and built by Aerospace. According to William Ailor, principal scientist in the Vehicle Systems Division and director of Aerospace's Center for Orbital and Reentry Debris Studies, this event marked the first time that such data was collected during the planned breakup of a space object. "Prior to REBRs, there was no data to determine how spacecraft behave during reentry breakup," said Ailor. "Now we will be able to predict more accurately which parts of the satellite will impact the surface as well as hazards posed by the surviving debris." The data can aid in the design of space hardware that poses less of a hazard on reentry, he explained.

The HTV2 rocket launched in January 2011, and made its way to the International Space Station. It carried two REBRs; one remained attached to the HTV2, while the second was attached to the ATV2, a European spacecraft. As HTV2 reentered Earth's atmosphere, the REBR attached to it broke away as designed, and at approximately 60,000 feet, transmitted data to receiving stations before crashing into the southern Pacific Ocean. The recorder was not designed to survive impact, but contained a GPS device to alert scientists to its location. Analysis of the data was expected to take six to eight weeks. The REBR launch and reentry test was coordinated by the Department of Defense's Space Test Program.


William Ailor shows the REBR instrument package nestled within its protective heat shield.

Rockets, Soot, and the Stratosphere

For 20 years, Marty Ross has been investigating the effects of rocket exhaust on the atmosphere. Though his work has sometimes met with resistance, it has nonetheless fostered a healthy scientific debate.

Donna Born

Could rocket launches be regulated in the future because rocket engines emit soot into the stratosphere? That is the question Marty Ross and fellow scientists are striving to answer with their research into rocket emissions and climate, research that has caused a stir in the aerospace and space tourism industry. Many have interpreted their widely published research to mean that scientists want to regulate rocket launches, but Ross said that's not how science works. And in fact, in this case, the opposite is true—if anything, Ross and his colleagues want to reduce the risk of unnecessary regulation.

"Ultimately, I'm a space cadet," Ross said. "I want to see daily launches. What worries me is that the vision of daily launches is put at risk if we don't pay attention to emissions and the possibility of regulations. So, that's why we want to do this—to look at this work as risk reduction. That's a big part of what we do at The Aerospace Corporation—risk analysis. The idea is to gather the data and the understanding so that when the regulator comes knocking at the door, we can say we know exactly what our emissions do to the atmosphere—and they are relatively small. The failure mode is that rockets unnecessarily get swept up in global regulation."

How Science Works

Ross, a senior project engineer and scientist in Aerospace Civil and Commercial Launch Projects, joined The Aerospace Corporation in 1988. Since then he has published more than 50 papers on a variety of space and atmospheric science and engineering subjects. His recent work has involved studying black-carbon particles, or soot, released by rockets into the stratosphere. (See his article in this *Crosslink* issue.) "We made some reasonable assumptions that are neither crazy speculation nor overly conservative — just middle-of-the-road assumptions. We drop these assumptions into models of the atmosphere and pull out a single number—the amount of increased heating in the atmosphere. And at first glance it seems significant, kind of an important result. The details and uncertainties will have to be explored later on with direct measurements of soot emissions from rockets."

He believes that their research is often misunderstood, that people interpret their conclusions as saying they are predicting exactly what's going to happen. "We're not saying that at all. We don't know exactly what is being emitted because of a lack of data and models so we'll make reasonable guesses about soot and carbon dioxide and water vapor. When you do, you derive a range of numbers regarding the atmospheric effects of rockets—and some of that range falls above a level where the effects become significant. So clearly, we need to look a little more closely and reduce the uncertainties so we can reduce the risk of unwarranted regulation."

To get at the real numbers, researchers must obtain funding, then gather instruments to measure the size and shape of the soot particles, carbon dioxide, water vapor, and other gases emitted by rockets. They will put the instruments on a high-altitude research aircraft and fly through the stratospheric plumes of various hydrocarbon-fueled rockets and actually make the measurements. Ross thinks the required plume and modeling data could be collected in a few years.

Into the Plume

This is not his first research using high-altitude planes. Ross and other scientists in the early 1990s worked with NASA and used the agency's WB-57F to get measurements inside the plume of an Air Force Titan IV solid-rocket motor. The collaboration produced measurements that showed it unlikely that rockets constitute a serious threat to global stratospheric ozone. The effort, funded by the Titan IV program, helped demonstrate the scientific value of the WB-57F, which has since become one of the key aircraft for NASA airborne science. "We saw a lot of interesting data, enough to say that solid-rocket motors were not the threat that some were speculating about before they collected actual data. We clearly saw significant ozone loss, but it wasn't catastrophic," Ross said.

That research was the beginning of the RISO (Rocket Impacts on Stratospheric Ozone) program that Aerospace established at the request of the Air Force to collect data regarding the effects of solid-rocket-motor emissions on the atmosphere. In 1999, RISO joined forces with NASA, the National Oceanic and Atmospheric Administration, and the National Center for Atmospheric Research to form ACCENT (Atmospheric Chemistry of Combustion Emissions Near the Tropopause). ACCENT provided a common set of atmospheric measurements from shared payloads on the high-altitude aircraft to serve the interests of both NASA and the Air Force. (See "Rockets and the Ozone Layer," by Ross and Paul Zittel in *Crosslink*, Vol. 1, No. 2.)

Looking Forward

Ross is concerned about the lack of an institutional connection between the rocket business and science community. An established ongoing mechanism for the aircraft engineers to interact with the atmospheric scientists provides much information about how airplanes affect the atmosphere. "But that connection doesn't exist for rockets. The rocket engineers—the propulsion people—don't really have an appreciation for the science, and the scientists don't realize what rocket engines can do." He regards his own role as working to see this connection grow.

Most recently, he suggested that Aerospace should import an established climate model—a three-dimensional computer representation of Earth's atmosphere from the surface to the outermost layer so that Aerospace could begin to directly contribute to climate research and apply the model to long-term customer needs. For example, the upper atmosphere may cool and shrink as the surface warms in coming years, causing the density of the air at orbital altitudes to decrease, possibly resulting in less drag and a longer stay in orbit for spacecraft, spent hardware, and debris. Climate change could affect Air Force future requirements for meteorological sensors. And rocket emissions affect more than just climate and ozone—for example, they influence GPS signals. "A researcher in Japan recently was able to track a foreign missile by using GPS receivers because the signals were affected by holes created by the missile exhaust. He was able to track the trajectory by looking at GPS signals," Ross said. "This is something we need to be expert about."

Acquiring a climate model would not be out of the ordinary for Aerospace but would require an initial push internally, Ross said. "Within the company, Aerospace is quite entrepreneurial. If you do good work—even for research that is maybe fringe, not mainstream—if it's objective and technically sound, that gets rewarded. And if you demonstrate credibility, you can carve out a niche. You see different levels of support over the years for that kind of activity, but in the long run, Aerospace is a pretty neat company. We look forward while keeping an eye on the past."

Space Scientist

Ross first learned about The Aerospace Corporation at the University of Michigan, where he earned his B.S. in aerospace engineering. "When we were all graduating, doing interviews with companies, if you could snag an interview with Aerospace, well, that was the cream of the crop. Nobody knew much about it. What exactly did they do? So coming aboard Aerospace after grad school was incredible for me." His M.S. and Ph.D. degrees in planetary and space physics are from UCLA.

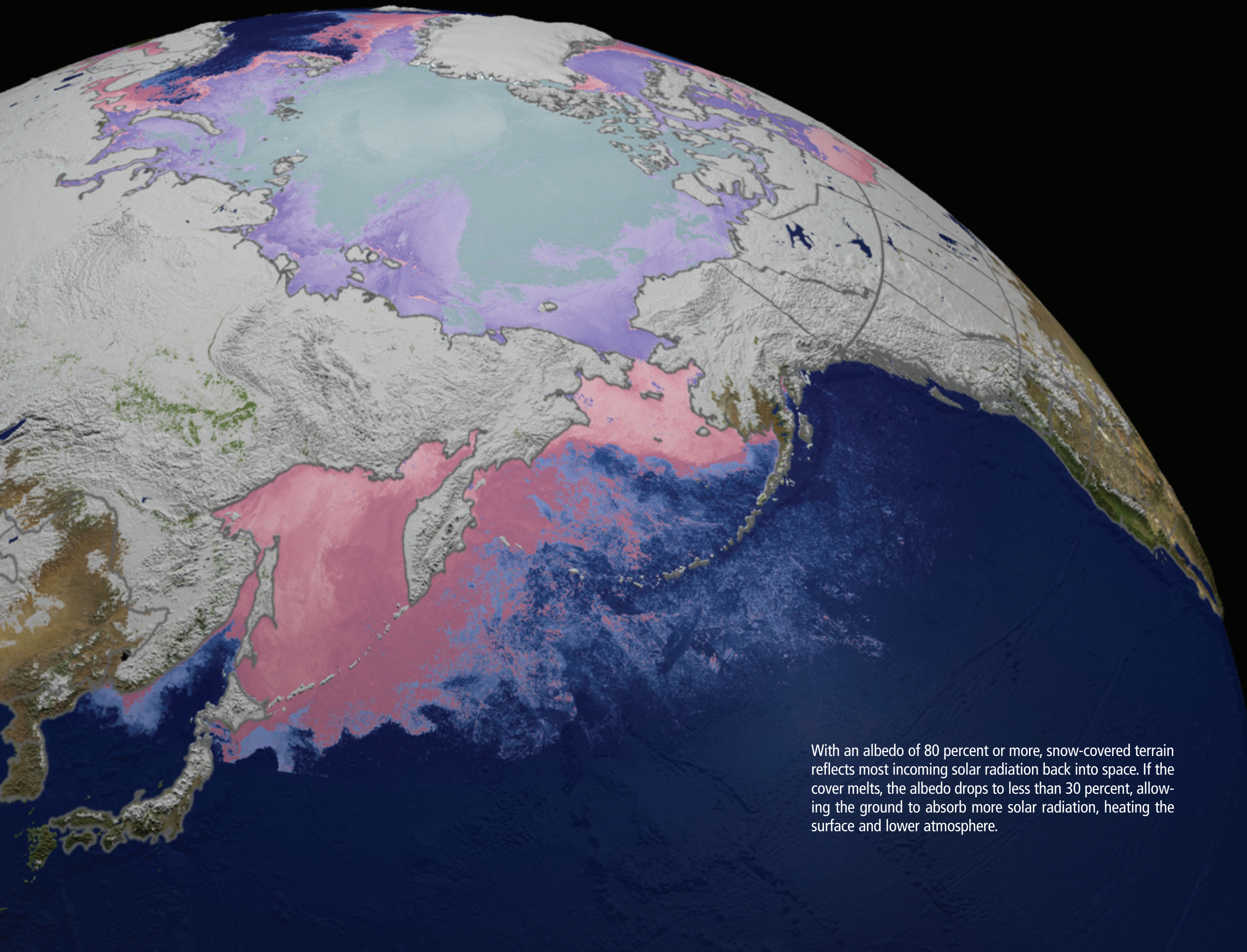
"I'm not so smart that I can give advice to young engineers, but I would tell them—based on my 30 years of experience as a student, researcher, and professor—load up on mathematics, learn it as a language. Once you've got a language telling you how the universe works, everything else can be made to seem simple. I've been studying *The Road to Reality*, a book by Roger Penrose, an English physicist. He starts with the most elementary mathematics and works up to quantum mechanics and cosmology. Every day, I read a few pages of Penrose and try to get through it—not just skip over the rough stuff—to really understand what's going on. And I realized that if you know the mathematics, everything else follows along."

Ross has been interested in science and astronomy since a child. "My earliest memory is crawling up in a big recliner with my dad and he would read *You Will Go to the Moon*. I had my first telescope at 7, and at 16, I delivered newspapers to put up an observatory in our backyard. I built a concrete platform and a structure and shelter for a 12-inch telescope because it was too big to move. There was no question that I was going to do the space thing. And I still just kind of poke around the edges and try to look around where people just haven't looked yet."

Climate Change and National Security: Implications for Space Systems

The effects of climate change constitute an unprecedented threat to global security and military readiness. What, if anything, can the space community do to prepare?

James A. Vedda



With an albedo of 80 percent or more, snow-covered terrain reflects most incoming solar radiation back into space. If the cover melts, the albedo drops to less than 30 percent, allowing the ground to absorb more solar radiation, heating the surface and lower atmosphere.

The United States has spent the last several decades configuring its security establishment to confront ideological foes with large standing armies and modern tools of war. In the future, the most dangerous challenges may well come from the forces of nature, as global climate change brings about extreme weather conditions, changes in global resource distribution, mass migrations of disrupted peoples, and insurgencies fueled in part by the unmet needs of unstable societies. All of this is set to take place at a time when Earth is more densely populated and has a greater capacity for generating human casualties, property damage, and environmental harm than in previous centuries.

Efforts to adapt the security system to this new threat environment must recognize that climate change threats are different from those usually associated with military confrontation, and must be viewed in a longer time frame. Among the variables to be considered are temperature changes, both average and extreme; increasing or decreasing precipitation; frequency and severity of storms; and sea level rise, which has multiple consequences, including encroachment on land, inundation of fresh water supplies, and amplification of storm surge effects.

The expected effects of climate change have consequences that can include crop failures, flooding, loss of fresh water supplies, and the spread of diseases, as well as loss of productivity due to property damage and transportation disruptions. Worldwide, such crises can contribute to political instability, especially within weak or failed states, and to international conflict stemming from resource scarcity and cross-border human migration. Even if direct effects on the U.S. homeland are manageable, the resulting global repercussions will be detrimental to U.S. interests and are likely to require substantial humanitarian and military intervention. At the same time, U.S. forces around the world will need to contend with changing environmental conditions affecting their facilities and areas of responsibility.

As a threat multiplier… climate change could degrade security at overseas ground stations, or even force them to close.

Numerous government and think-tank reports have identified threats and advocated urgent attention. These have focused on the likelihood that climate change will be a threat multiplier, exacerbating problems in parts of the world already suffering from political and economic instability. Although these studies have considered operational problems and possible solutions for U.S. forces overseas—primarily related to logistical requirements such as fuel supplies—they have not directly addressed threats to space operations. Nonetheless, these studies have direct implications for the way space systems are conceived, deployed, and maintained.

Implications for Space Systems

Satellites fly far above terrestrial weather, which makes them excellent observers but doesn't make them immune to climate concerns. They need support from the ground—launch sites to provide them with access to space, and facilities around the world to monitor and control them and put their capabilities to use. Given these conditions, there are two major roles for the space community in addressing climate change. The first is identification of direct threats to the ability to employ space assets, leading to mitigation and adaptation efforts. The second is development of space systems for science and applications that contribute to prevention, mitigation, and adaptation, thereby helping to minimize destabilizing effects.

Threats to Space Assets

An obvious example of a potential threat to space systems is sea level rise and its possible effects on coastal areas that are home to space support facilities. Current estimates project a sea level rise of 0.5 to 1.2 meters by 2100, with the possibility of several more meters beyond that time. The amount predicted for this century may not seem like much, but a 1-meter rise would put 640 square kilometers of U.S. territory under water and 2223 square kilometers worldwide, according to the most recent assessment of the Intergovernmental Panel on Climate Change. This is not going to cause launchpads to sink below the waves any time soon, but there are other detrimental effects to be considered. The rate of coastal erosion will accelerate, and storm surges will be more damaging as they become more frequent and more severe. Under these circumstances, schedule disruptions would become more likely and may require more costly and time-consuming repairs.

Sites around the world may have to deal with more than disrupted schedules and higher operating costs. As a threat multiplier for political and social instability or a motivation for mass migration, climate change could degrade security at overseas ground stations, or even force them to close.

A climate threat assessment of space facilities would need to employ a multifaceted approach that would encompass a diverse array of possible threats from the forces of nature and the failure of technologies and institutions. The assessment should not be limited to obvious targets like coastal launchpads and their associated support facilities. Other vital and vulnerable components of the space enterprise include locations that perform functions such as the design, development, and manufacture of space systems; tracking, telemetry, and control of spacecraft during launch and operation; recovery operations for returning spacecraft; and space situational awareness.

Many facilities that perform these functions are not on U.S. territory, and some are in areas highly vulnerable to climate change effects. For example, the island of Diego

Courtesy of NASA


Courtesy of US Air Force

The Ground-Based Electro-Optical Deep Space Surveillance System (GEODSS) facility at Diego Garcia. The average height of the atoll is only about one meter above sea level.

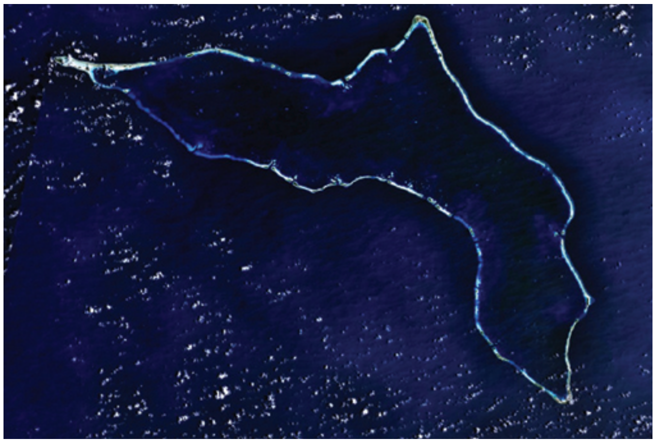

Courtesy of NASA

Even a small rise in sea level would affect islands such as Diego Garcia, which would potentially become more prone to damage from severe storm surges.

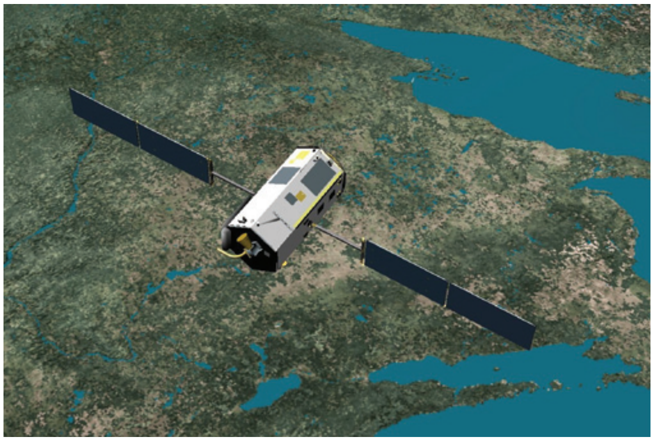
Garcia in the Indian Ocean is a critical logistics hub for U.S. and British forces in the Middle East. It also hosts a Ground-Based Electro-Optical Deep Space Surveillance (GEODSS) facility, the only one in that part of the world, which contributes to the U.S. Space Surveillance Network. The Air Force Satellite Control Network also uses equipment on Diego Garcia to control the GPS constellation.

Diego Garcia is threatened by the effects of climate change because its average height above sea level is just over one meter. Another site that may be threatened is the Kwajalein atoll in the Pacific Ocean, where a U.S. Army facility conducts near-Earth and deep space surveillance, as well as missile test functions, on land that has a maximum elevation of eight meters above sea level.

The National Defense Authorization Act for Fiscal Year 2008 included an amendment to Title 10 of the U.S. Code requiring consideration of the effects of climate change on defense facilities, capabilities, and missions. The Obama administration has begun to address climate change effects in national security planning documents and now must follow through with action plans for all sectors of the national security community. This would include integration of climate change into the operational planning of regional combatant commands. Users of space services should be aware of the short- and long-term threats to those services so they can make contingency plans. The planning effort should prioritize "no-regrets" policies and solutions—improved practices and technologies that yield benefits in reliability, capacity, and cost even in the absence of disruptions caused by climate change. Examples include protection of coastal areas, which are subjected to severe storms and flooding even in the absence of climate change, and cost-effective military-to-military environmental security initiatives like those that already have yielded a variety of benefits in the Persian Gulf and Central Asia. Some adaptive actions will save money, others will have significant costs—but ultimately, these costs will be less than the costs imposed by climate change damages that could be averted.


Courtesy of NASA

The Kwajalein atoll, shown here using nighttime satellite imaging, has a long history of serving U.S. military needs. The atoll is one of many considered threatened by the effects of climate change.


Courtesy of NASA/JPL

NASA's Orbiting Carbon Observatory was lost in a launch failure in 2009. A new version is scheduled for launch in 2013.

Environmental Sensing

For prevention and mitigation efforts, space systems will continue performing the functions they have been doing for many years: identifying and monitoring weather and climate changes, attempting to determine the extent and rate of specific changes, and providing data to improve computer models. These are important functions—scientists would know far less about weather and climate change today in the absence of space systems, possibly missing key variations, patterns, and the clues to their causes. Fortunately, highly capable U.S. space systems are complemented by strong and growing programs in Europe and Asia, as well as Canada and Brazil, facilitated by organizational mechanisms for applying the data to global research efforts.

A prime example of growing international activity is the Global Monitoring for Environment and Security (GMES) program, led by the European Commission and the European Space Agency (ESA). The 10-year program, initiated in 2008, aims to launch 15 electro-optical and radar satellites to study the land, oceans, and atmosphere for both scientific investigations and ongoing operations.

In the medium to long term, space systems can play a role in mitigating climate change, but this will be more challenging due to technical, institutional, and political hurdles. Initially, this will be done by systems much like those in operation today. For example, electro-optical and thermal sensors could be used to help enforce carbon caps or other regulatory restrictions. This has already started to a limited extent. Japan's Ibuki satellite, launched in January 2009, and the U.S. Orbiting Carbon Observatory 2, scheduled for launch in 2013, are designed to look for carbon dioxide sources and sinks, taking a first step toward treaty monitoring applications. Satellite systems eventually could become a tool for monitoring and enforcing domestic and international laws and agreements relevant to a variety of environmental concerns; however, the space community is still a long way from reaching this point. Long-term continuity is required in monitoring an array of key climate variables, and research satellites are not designed to provide this. Commitments to operational satellite systems are necessary, analogous to the nation's commitments to operational early warning, surveillance, and reconnaissance systems. Like the national security community, the climate research and environmental monitoring communities need to achieve what their defense counterparts have termed "persistent surveillance."

Satellite systems can also play a role in the tracking and exploitation of shifting global resources. For example, Arctic ice is thinning, and the extent of ice coverage is shrinking. If current rates continue, by midcentury the Arctic Ocean may be ice-free in the summer months. This will increase shipping traffic and exploration for resources, especially oil and natural gas. Inevitably, demand will increase for security patrols—and for the space systems to support them—to provide rescue services and guard against conflicting resource claims by Arctic nations. Those nations and NATO are already engaging in dialogues aimed at preventing such conflict. This attention comes none too soon, as the first potentially exploitable oil discovery off the coast of Greenland was announced in September 2010 by a Scottish energy company.

Multinational Monitoring

The global proliferation of remote sensing satellite systems is allowing space to contribute more than ever to climate and disaster monitoring. The growing capabilities and numbers of such satellites are providing tangible benefits that will increase as climate change effects are felt. Two examples of how these contributions are being coordinated include:

> The Group on Earth Observations (GEO), which includes participation by 85 nations (including the United States), the European Commission, and 61 organizations (as of October 2010). Its objective is to establish a Global Earth Observation System of Systems that coordinates system planning, data sharing, and research collaboration worldwide.
>
> The Charter on Cooperation to Achieve the Coordinated Use of Space Facilities in the Event of Natural or Technological Disasters (Space & Major Disasters Charter), which was created in 2000 to provide emergency response. Its 19 members, consisting of government space agencies and nongovernment space system operators, supply data and services when disasters strike anywhere in the world. From February 2002 through January 2011, the charter was activated 273 times. This is an example of a "no-regrets" program—one that serves a clear need even in the absence of climate change effects.

Integrating the Climate Change Threat

National security agencies routinely plan for a wide range of contingencies, including worst-case scenarios. National policy recognizes that space capabilities are a vital national interest and that space-based communications and navigation are part of the nation's critical infrastructure. Therefore, in facing environmental and climate threats capable of causing damage and instability on a global scale, the nation should be preparing to safeguard its space system operations against these threats with the same determination used to defend terrestrial assets against attack.

Some analysts see a need for more comprehensive studies than those done so far. For example, the National Intelligence Council conducted an assessment in 2008 on the implications of climate change to help the intelligence community anticipate changes in the status of individual nations and regions of interest. In general, the assessment found insufficient resolution and specificity in climate change models, particularly those dealing with hydrological patterns and changes in the frequency and intensity of extreme weather events. Similarly, a 2007 report published by the Center for Strategic & International Studies noted that "studies of potential sea level rise impacts have not been conducted for most parts of the globe, and those that have been typically examine only one aspect of sea level impacts, such as beach erosion or storm surge height" while ignoring other consequences such as inundation of fresh water supplies, damage to infrastructure and agriculture, and temporary or permanent population displacement.

Response to climate change is complicated by the fact that it does not simply produce a single consequence (e.g., a rise in average temperature) that prompts an easily defined response (e.g., increased use of air-conditioning). It is not limited to one or a few locations, all experiencing the same effects; rather, an array of effects will be felt worldwide to varying degrees. Incorporating such circumstances into strategic planning across many affected agencies is a formidable challenge, but delay could make the search for solutions more difficult over time.

Courtesy of National Snow and Ice Data Center

The maximum extent of arctic sea ice in 2011 was below the median for the two decades from 1979 through 2000. By mid century, the Arctic Ocean may be ice-free in the summer months, enabling commercial traffic and increasing the demand for space-system support.

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The Climate Change Threat: How Does It Differ from Conventional Threats?

- It is not coming from a conventional (human) adversary. As a result, it cannot be deterred or fought by conventional means, such as building weapons, installing traditional early warning systems, or employing diplomacy. Rather, deterrence requires technological breakthroughs coupled with alteration of societal practices and individual human behaviors worldwide.
- It is happening slowly, spanning many years or decades. The rate and duration of change are not precisely known, nor is it known whether a tipping point will be reached that causes abrupt change. The slow, unpredictable pace and multiplicity of probable causes prompt skeptical observers to conclude that the changes are not threatening or cannot be affected by the actions of humans.
- Technological society has never experienced abrupt climate change, so the failure modes of societal coping mechanisms are not known. Even if climate change progresses gradually, the ultimate magnitude of the threat is unknown and response options are complicated by the fact that it is occurring all over the world at the same time. The exact locations and manifestations of climate effects can only be estimated based on imperfect models, so for much of the world the effects will be known for certain only after they occur.

A Call to Action

Severe weather and worsening environmental conditions will be detrimental to the performance and readiness of military operations at home and abroad. Additionally, the effects of climate change will be felt simultaneously by allies, potential adversaries, and unstable governments around the globe. Deployed U.S. forces could find that their capabilities are degraded at precisely the time that they are required to be more engaged in stability operations. With this in mind, a military advisory board of 11 retired generals and admirals from the U.S. armed services led a 2007 study at CNA Corporation (Alexandria, Virginia) to consider possible scenarios and recommend appropriate courses of action. Although the report does not speak directly to the role of the space sector, all five of its recommendations convey applicable guidance for the requirements and operations of space systems:

1. The national security consequences of climate change should be fully integrated into national security and national defense strategies.
2. The United States should commit to a stronger national and international role to help stabilize climate change at levels that will avoid significant disruption to global security and stability.
3. The United States should commit to global partnerships that help less developed nations build the capacity and resiliency to better manage the effects of climate change.
4. The Department of Defense should enhance its operational capability by accelerating the adoption of improved business processes and innovative technologies that result in improved U.S. combat power through energy efficiency.
5. The Department of Defense should conduct an assessment of the impact on U.S. military installations worldwide of rising sea levels, extreme weather events, and other projected climate change effects over the next 30 to 40 years.

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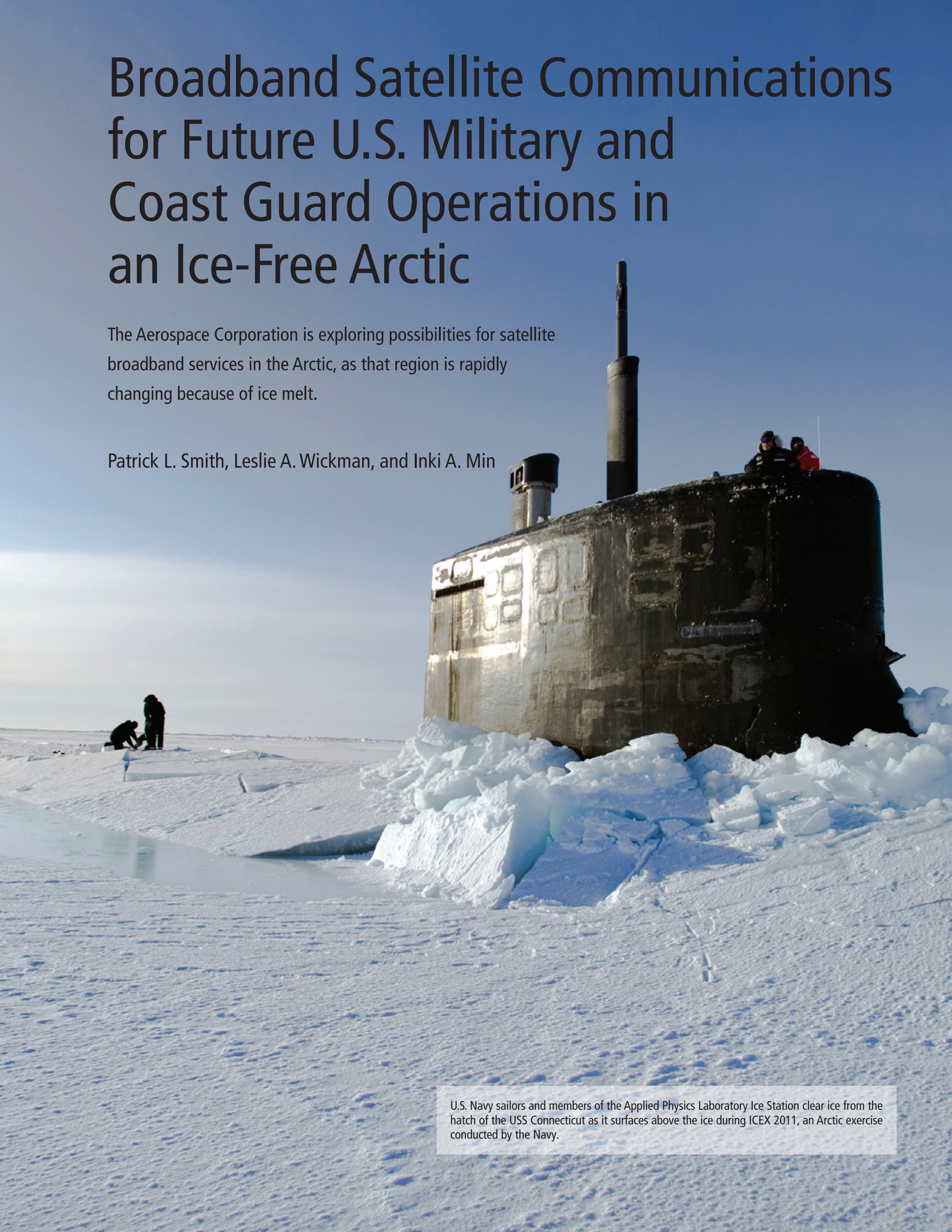
Broadband Satellite Communications for Future U.S. Military and Coast Guard Operations in an Ice-Free Arctic

The Aerospace Corporation is exploring possibilities for satellite broadband services in the Arctic, as that region is rapidly changing because of ice melt.

Patrick L. Smith, Leslie A. Wickman, and Inki A. Min



U.S. Navy sailors and members of the Applied Physics Laboratory Ice Station clear ice from the hatch of the USS Connecticut as it surfaces above the ice during ICEX 2011, an Arctic exercise conducted by the Navy.

During the past 23 years, 41 percent of the perennial Arctic ice has melted. Between 2004 and 2005 alone, 14 percent was lost. The volume of ice at the peak of the 2009 annual freeze was the lowest on record, (until March 2011) and of that, only 30 percent was thick, slow-melting multiyear ice. The Northwest Passage briefly opened in 2007, and could soon become a busy navigation route, cutting about 7000 kilometers from the shipping routes between Asia and Europe.

At the same time, a U.S. Geological Survey report suggests that the Arctic seabed may hold as much as 25 percent of the world's undiscovered oil and natural gas reserves. Sovereign rights to energy resources in the Arctic seabed remain largely undetermined under international law. The U.N. Convention of the Law of the Sea provides a general legal framework to govern the use of the world's oceans and resources, and the major players in the region are scrambling for evidence to bolster their claims under the treaty (which has not yet been ratified by the United States).

The U.S. Navy, Coast Guard, and other military services have begun planning for increased operations in the Arctic, which is predicted to become essentially ice-free in summers as early as 2025. To assist the military's efforts, The Aerospace Corporation began a study in 2007 to determine the impacts of climate change on future national security space requirements, including manufacturing and launch operations—with a particular focus on the need for broadband satellite communications in the Arctic to support increased U.S. fleet and Coast Guard operations.

Satellite Coverage of the Arctic Region

The Arctic is very different from lower latitudes in regard to space system constraints and capabilities. Weather and imaging satellites have excellent coverage because their inclined sun-synchronous orbits put them in view on every pass. On the other hand, passive imagery for ice monitoring and other types of surveillance is hampered by persistent cloud cover and seasonal darkness. GPS is available, but the lower elevation angles to the satellites and increased ionospheric effects somewhat reduce positioning accuracy.

Communications in the Arctic region are quite limited. Dedicated U.S. military communication satellites typically fly in equatorial geostationary orbits (GEO), which are below the 10-degree elevation constraint on most terminals within the Arctic region and therefore not accessible. Options for 24/7 Arctic coverage include three satellites in 90 degree inclined geosynchronous orbits; four satellites in medium altitude elliptical (or "magic") orbits; three satellites in "tundra" elliptical 63.4 degrees inclined geosynchronous orbits; or two satellites in highly elliptical molniya orbits.

The most efficient constellation for dedicated Arctic communications is a phased two-satellite molniya constellation. However, molniya satellites have different payload and antenna designs, ground-station connectivity, and user terminals than GEO satellites. Terminal antennas must continuously track satellites in molniya orbits and switch between them as they move in and out of view. Also, because it is too costly to maintain a spare satellite in each orbital plane, a satellite failure in a molniya constellation will result in a periodic gap in coverage, which would probably take many months to remedy through the launch of a replacement satellite, whereas in GEO, a spare satellite is easily shifted to take a failed satellite's place.

There are established U.S. military requirements for communications support for submarines, aircraft, and other platforms and forces operating in the high northern latitudes (as in all other theaters), but these requirements do not take into account increased military and Coast Guard operations in the region as a result of accelerated Arctic melting. At lower latitudes, there are several ways to surge military communications capacity, such as repositioning geosynchronous satellites, leasing commercial satellite transponders, and linking to fiber networks. None of these options is feasible in the Arctic region.

The current Interim Polar System (IPS) and follow-on Enhanced Polar System (EPS) are strategic communications payloads hosted on other satellites. The IPS program was established in 1995 after the original plan to place Milstar satellites in inclined geosynchronous orbits was scrapped (IPS packages are basically low-data-rate Milstar payloads).

Courtesy of NASA Goddard Space Flight Center

Researchers from NASA, the National Snow and Ice Data Center, and others using satellite data detected a significant loss in Arctic sea ice in 2005. Satellites have made continual observations of Arctic sea ice extent since 1978, and the 2005 data showed the extent had dropped to 2.05 million square miles, the lowest levels yet recorded.

Courtesy of U.S. Navy

Courtesy of USGS

The Canadian Coast Guard ship Louis S. St. Laurent (left) and U.S. Coast Guard Cutter Healy (right) on the Arctic Ocean. The ships came together to learn the operations of one another during a scientific expedition to map the Arctic seafloor in 2008.

EPS is an upgrade based on Advanced Extremely High Frequency technology and the eXtended Data Rate waveform and will provide connectivity to Global Information Grid gateways. EPS terminals are being procured by each service under separate contracts, and the mission control segment will be part of the AEHF mission control segment.

Iridium Satellite LLC provides the only commercial satellite communications service available in the Arctic region. The Iridium constellation provides 2.4-kilobyte-per-second channels for voice and data. U.S. government users comprise about 25 percent of the 100,000 or so subscribers under a long-term service contract signed in 2000. Military uses of Iridium continue to evolve. For example, the U.S. Air Force is reportedly deploying more than 280 meteorological data terminals that relay data to a processing center via Iridium. The U.S. government has its own Iridium gateway for secure access to the system.

Russian communication satellites in molniya orbits provide communications to their military forces (molniya orbits were first used by the USSR). Reportedly, there are 16 operational molniya satellites carrying the Russian Orbita Television network as well as commercial, government, and military communications traffic.

Future Options for Arctic Broadband

More-capable alternatives to the IPS and EPS hosted payloads have been studied by the Air Force. A 2004 study considered a dedicated molniya constellation crosslinked to the then-planned TSAT constellation. A 2008 study considered a constellation of small satellites. But free-flyer alternatives cost more than hosted payloads, which have remained the preferred options for military strategic communications in the Arctic up to now.

The range of options for future military broadband satellite communications in the Arctic region include hosted payloads (as with IPS and EPS), a dedicated molniya constellation, a combined all-latitudes constellation (such as the inclined 24-hour synchronous orbits originally considered for Milstar), a shared or joint program with allies, and leased commercial transponders (if a commercial broadband system becomes available in the future). Steps toward acquiring a dedicated military broadband system will need to start with a formal set of requirements followed by preliminary design studies and cost estimates for a range of development options. The final set of requirements and development budget would have to be negotiated and approved by all parties, including Congress.

Aerospace has studied orbital coverage options and preliminary satellite concepts for the region. A typical example is a commercial-class molniya system providing up to 2 gigabytes per second of bandwidth capacity, which is estimated to cost approximately $1 billion plus the costs of user terminals and ground operations. Higher levels of protection and survivability would cost more. Smaller satellites would cost less but provide significantly less bandwidth because of the less-efficient payload-mass fraction.

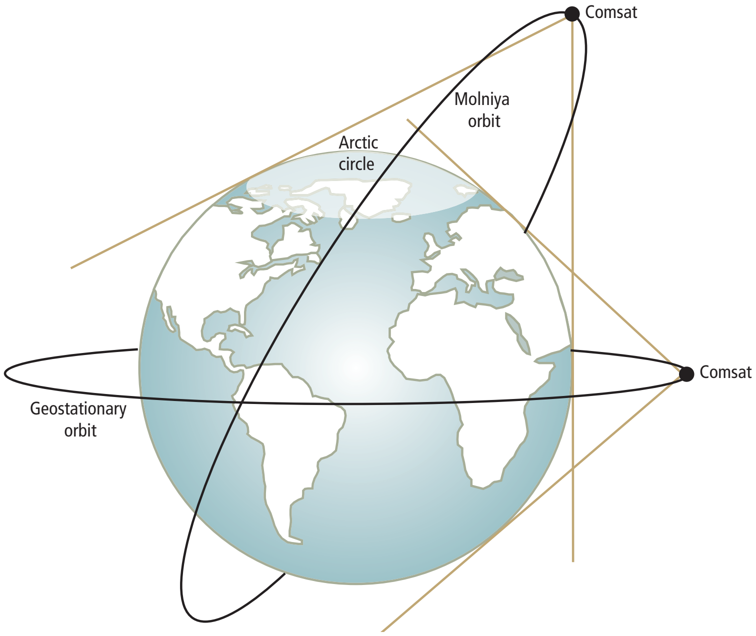
Given the uncertain pace of future Arctic melting, it is premature to recommend a dedicated program for military broadband service in the Arctic region. An all-latitude system (as originally planned for Milstar) may turn out to be the best long-term solution. An attractive option in the near term might be a joint program with U.S. allies or a commercial operator. Possibilities include:

Iridium Next

Iridium reportedly has partners and financing for the follow-on Iridium Next system (current Iridium satellites are already well beyond their design lifetimes). Iridium Next plans to offer Internet Protocol broadband channels with rates of up to 10 megabytes per second, which would provide a modest level of broadband communications as early as 2016 if development goes as planned; however, the available bandwidth would not support the most capable unmanned aerial vehicles, and there may be other limitations on U.S. military use as well, given the foreign ownership of Iridium Next.

Polar Communications and Weather

The Polar Communications and Weather (PCW) system being developed by the Canadian Space Agency and Environment Canada consists of two multimission spacecraft in molniya orbits. One of the proposed payloads is a Ka-band communications package with a capacity similar to Iridium Next. The PCW system may offer a partnership opportunity that might provide some level of broadband service to U.S. military users. The U.S. currently has Radarsat-2 data-sharing agreements, for example, which could serve as a model. Canadian developers have reportedly had discussions with Finland, Norway, Russia, and the United States. One concern, however, is that the multimission PCW initiative is primarily a remote sensing program, and if cost or weight-growth issues arise, the secondary communications package might be downsized or dropped altogether. As with Iridium, foreign partners might also restrict the U.S. military's use of the system's communications package.



An assessment of polar broadband communications options.

Russian Programs

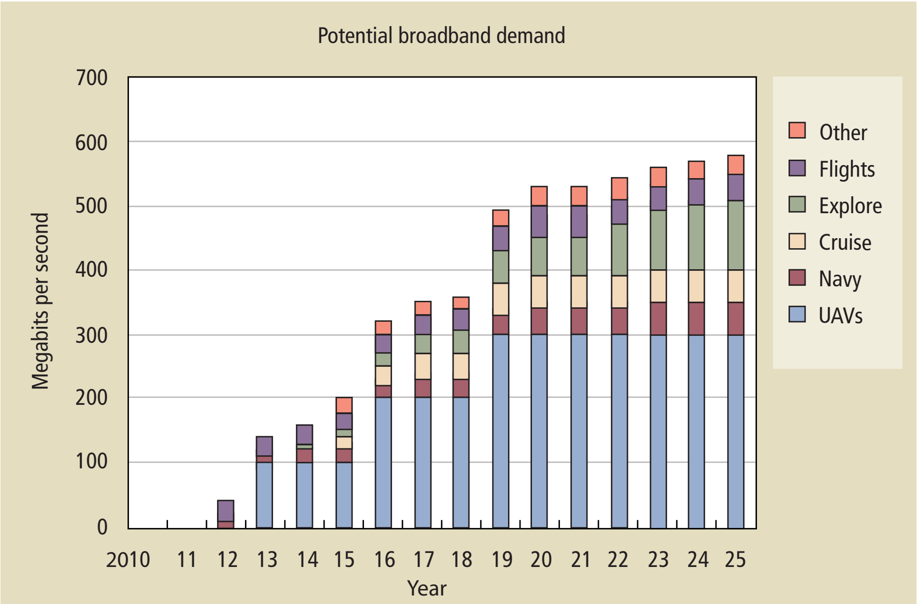
Russia already provides various communications services in the Arctic region with its molniya systems. In 2010, Russia announced plans to develop a molniya satellite cluster called "Arktika" for weather and ice monitoring, broadcast communications, and data relay from Arctic buoys and automated weather stations. The Arktika-M spacecraft is designed to measure polar winds, cloud cover, precipitation, and ice parameters. The Arktika-R spacecraft will have synthetic-aperture radar, and the Arktika-MS spacecraft will provide telephone communications, relay television, and FM radio broadcasts to aircraft and ships. Russia has also announced plans for a molniya version of its Express series of GEO communications satellites based on the 8–12 kilowatt Express-4000 bus. The Express-RV is designed to provide

Assessment Criteria	Hosted	Dedicated	Combined	Shared	Leased
Cost (space segment, user segment, operations)	🟩	🟥	🟥	🟩	🟦
Levels of satisfaction of various users' needs	🟥	🟦	🟦	🟩	🟩
User segment requirements and constraints	🟥	🟦	🟦	🟩	🟩
Auxiliary mission capacity (e.g., secondary payloads)	🟥	🟩	🟩	🟩	🟥
Schedule (time required to develop and deploy)	🟩	🟥	🟥	🟥	⬜
Interoperability (e.g., connection to Global Information Grid)	🟩	🟦	🟦	🟩	🟥
Flexibility (e.g., adaptable to changes in need or technology)	🟥	🟩	🟥	🟩	🟥
Sustainability (e.g., replenishment constraints)	🟥	🟦	🟦	🟩	🟩
Availability (e.g., hosted payloads are secondary)	🟥	🟦	🟦	🟦	🟥
Security (e.g., jamming, tamper resistance)	🟩	🟦	🟦	🟩	🟥
International participation (e.g., cost sharing)	🟥	🟩	🟩	🟦	🟦
Leveraging commercial systems (e.g., Iridium)	🟥	🟥	🟥	🟥	🟦
Risks (e.g., technical, cost, schedule)	🟩	🟩	🟥	🟩	⬜

🟦 Excellent 🟩 Moderate 🟥 Poor ⬜ Uncertain

Assessment criteria for polar broadband communications options.

Internet access and broadcast service.



The potential growth of bandwidth requirements in the Arctic region over the next 15 years.

Some European nations, including NATO members, have reportedly expressed interest in partnering with Russia in the development of these systems, which could potentially meet certain U.S. military and Coast Guard needs as well, such as communications for search and rescue and disaster response.

Commercial Broadband

Providing broadband and other communication services for oil exploration, air travel, shipping, tourism, and other activities may offer future business opportunities; however, the hurdle for closing the business case for a commercial Arctic molniya system will be higher than for a typical GEO system. Two satellites are needed for continuous coverage, and the satellites require extra radiation hardening. Demand and spot lease revenue will be highly seasonal. Private investors will want higher expected returns to compensate for risks of uncertain demand growth, unresolved treaty issues, and non-GEO satellite development and operations.

The European Space Agency is exploring potential future demand for communication services in the Arctic to identify possible development opportunities for the European industry. Potential markets include search and rescue, vessel traffic systems, maritime highways, in situ sensor data collection and dissemination, and surveillance and military activities.

The broadband market in the Arctic will eventually be substantial, but at this point, it is impossible to predict how fast demand will grow. Thus, it is unlikely a commercial business case can close in the near term without the Department of Defense as a partner in development or as a long-term anchor tenant.

Summary

National security space planners should start anticipating new military support requirements arising from increased military and Coast Guard operations in the Arctic. U.S. military satellite communications are limited at high latitudes, and there is no ability to surge capabilities by rephasing

Launch Vehicles Class	LEO Performance[2] western range (kg)	Molniya Performance[2] (kg)	Spacecraft Wet Mass (kg)	Spacecraft On-orbit Mass (kg)	Comm Capacity (Mbps)	Launch Vehicle Cost[1] ($M)	Launch Vehicle	Spacecraft Cost[1] ($M)	Spacecraft	Total Cost [3] ($M)	Dual Launch
EELV Med, M+	N/A	3000 +	3500	3500	~1000	$150	2	$350	2	$1000	No
EELV Med, M+	7000 +	N/A	3500	1500	~300	$150	1	$200	2	$550	Yes
Delta II/Taurus II Class	3500	N/A	3500	1500	~300	$80	2	$200	2	$560	No
Delta II/Taurus II Class	3500	N/A	1900	700	~100	$80	1	$100	2	$320	Yes

[1] Costs are rough order of magnitude, for relative comparison only
[2] Performance numbers are approximate, for the class of vehicles
[3] Does not include ground terminal or network costs

Typical bandwidth capacities and the costs associated with a Molniya constellation.

satellite orbits or leasing commercial transponders. The lack of broadband communication in the Arctic will constrain the use of unmanned aerial vehicles and other military operations when nations in the region are jockeying for influence and control. Developing a dedicated military broadband molniya system cannot be justified in the near term, so the Department of Defense should work with potential international and commercial partners to explore opportunities for jointly developing a broadband system. Assured access to foreign and commercial synthetic-aperture radar imagery for ice surveillance should also be a priority.

Acknowledgments

The authors acknowledge and appreciate the contributions of our colleagues at The Aerospace Corporation, including Thomas Lang for his analyses of satellite constellation geographic coverage options, Thanh Hoang for his contributions on communication satellite capabilities and costs, and Andrew Izaguirre for his research on currently operational polar satellites.

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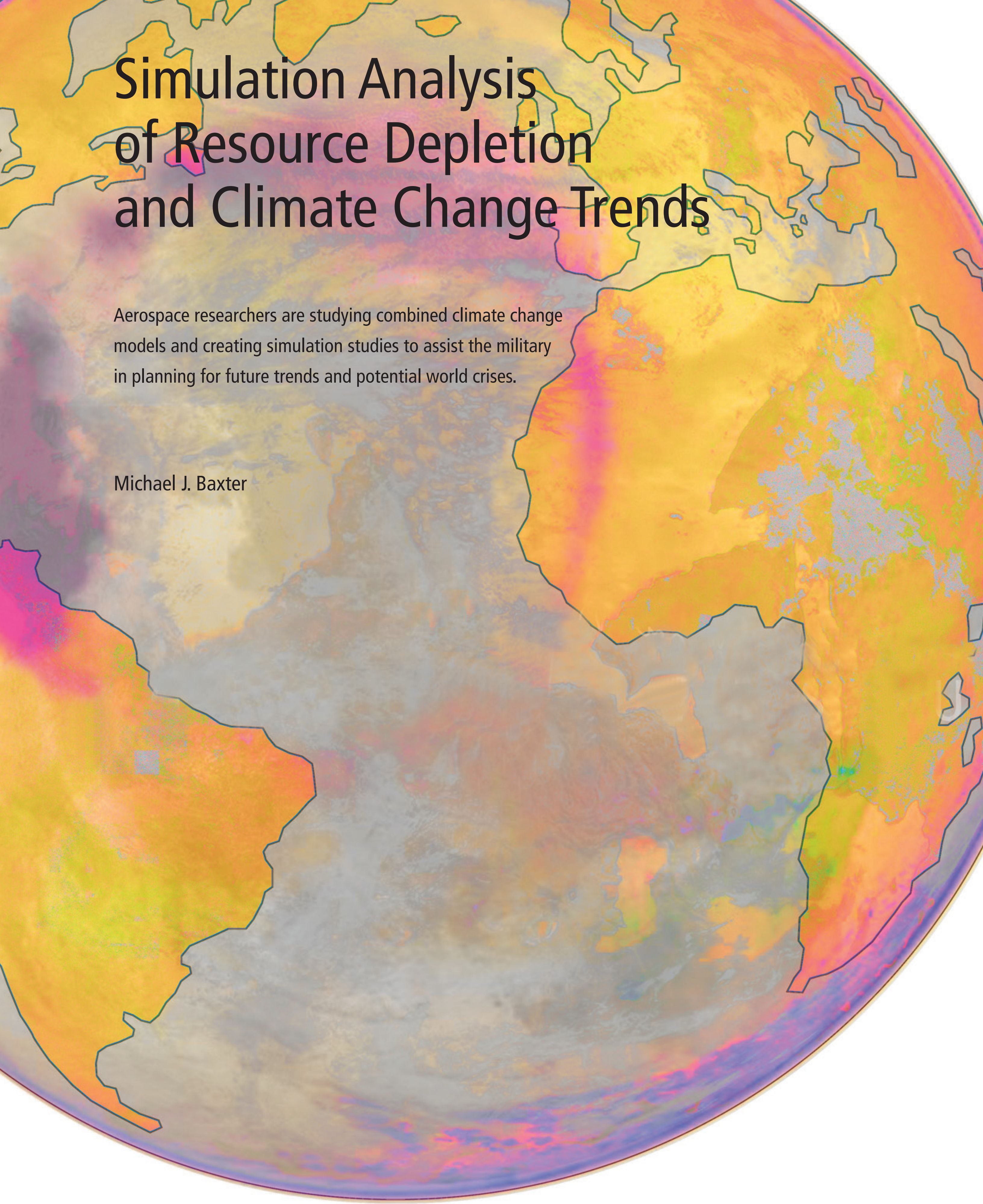
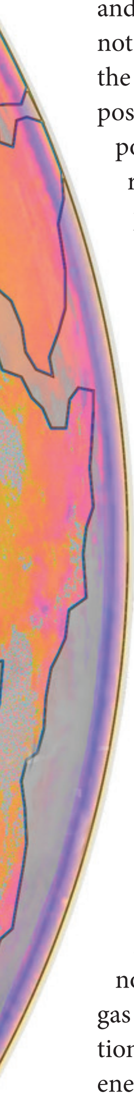


Simulation Analysis of Resource Depletion and Climate Change Trends

Aerospace researchers are studying combined climate change models and creating simulation studies to assist the military in planning for future trends and potential world crises.

Michael J. Baxter



U.S. national security is increasingly being threatened by a number of global trends. These include climate change, pollution, resource depletion, global financial imbalances, and forced migration. Researchers at The Aerospace Corporation have combined models of climate change, resources, economics, and population dynamics in a simulation to help the military better anticipate these trends and prepare for potential world crises. Human responses are not necessarily predictable, but the simulation indicates that the synergistic effects of such trends pose significant and possibly dire threats. The ability of the United States to postpone and mitigate these effects is limited and diminishing rapidly—hence the effort to better understand and anticipate them.

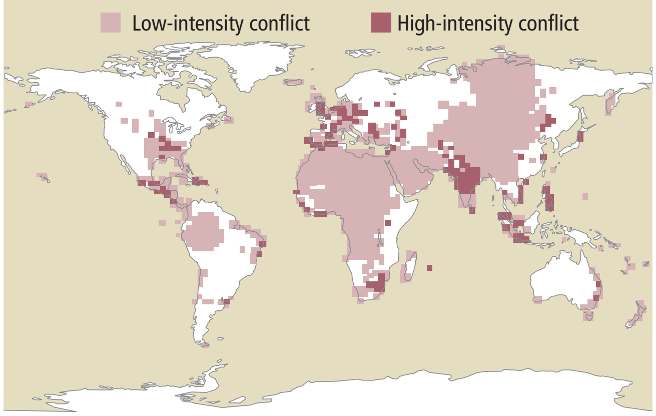
Systems Modeling

Climate models generally consist of systems of differential equations based on physical laws that calculate atmospheric and oceanic attributes such as wind, heat transfer, humidity, and chemistry. These calculations are mapped into three-dimensional grids encompassing Earth's surface and atmosphere. Researchers at Princeton University generated some of the first long-term climate models in 1969. Those evolving models correlate well with both current and paleontological observations, although they tend to predict less dramatic effects than were actually recorded or found.

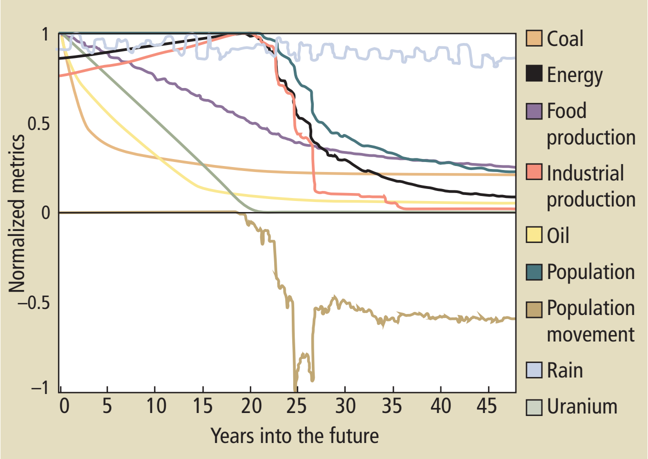
The modeling of global systems involving the dynamic behavior of human beings and the physical world can be traced to *Industrial Dynamics*, written in 1961. Such models generally involve the use of nodes (sources, sinks, stores, and transfer nodes) and flows of energy and materials. Applications for these models include the U.S. energy transition, energy technology, and policy options aimed at mitigating greenhouse gas emissions; urban policy and environments; transportation and electric utilities; and the interactions between the energy sector and the economy.

In the Aerospace simulation, a dynamic node-and-flow model was superimposed upon a cellular map of the globe. Each cell is a two-degree-latitude by three-degree-longitude area on Earth's surface. A cell possesses a number of attributes, including the amount of resources that can be extracted from it. Production then determines the energy and materials available to support local populations, water and energy needs, and food and industrial product needs.

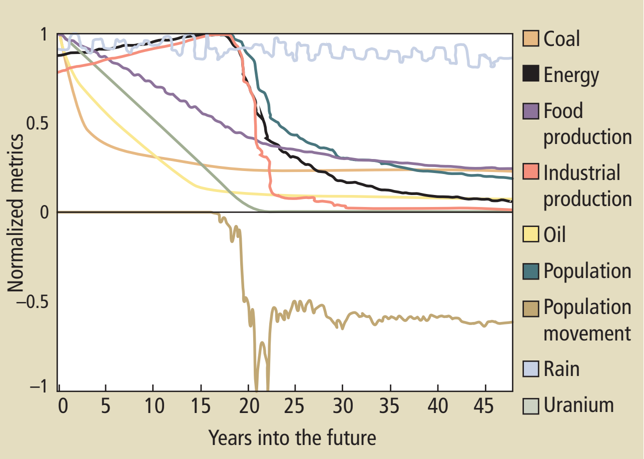
Exchanges of material and energy between cells occur during each interval of time as the model is propagated. As the simulation cycles, shortages may be resolved through trading. When a population does not have the option to trade materials or goods, the unsupportable part of the



These figures show the results of two simulated scenarios. The first (expected conditions) was specified as a 6°C increase in global average temperature occurring over 100 years using the resource base. The second scenario had the same temperature rise, but energy resources were increased by 75 percent. The top figure shows the resulting conflict map after 25 years using the first scenario.



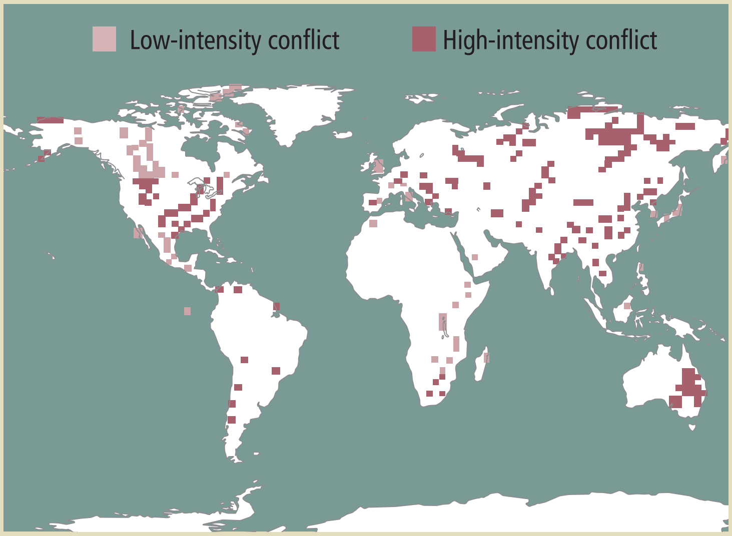
This figure shows total population, population movement, total energy produced, and total rainfall for the next 50 years using the first scenario. The remaining coal, oil, and uranium resources, as well as food and industrial production curves, are also shown.



This figure shows the same data using the second scenario. The 75 percent increase in energy resources postponed the population decline by roughly four years. The final stable population is roughly the same in both scenarios, as local limits on available resources are only temporarily overcome by trading between cells.

An Aerospace Simulation Scenario

The Aerospace simulation uses initial resource deposits as estimated by British Petroleum (BP). Total initial deposits were 1.3×10^{12} tons of coal, 1.2×10^{12} barrels of oil, and 3.3×10^{6} tons of uranium ore at the end of 2006. When the simulation is run, shortages of essential resources develop in some areas from changing rainfall patterns or the depletion of energy sources. These shortages may be met by exchanges of food or industrial production, or by shifting water and energy resources to food production. Where shortages cannot be mitigated, the portion of the population affected is flagged as either migrating or in conflict. If the population moves to a new cell but still does not have sufficient resources, it decreases to the minimally supportable number of individuals. The simulation records the difference between the population growth and decrease on a monthly basis. Cell populations suffering from resource shortages have the option of migrating to a neighboring cell if it has sufficient food and water (the simulation assumes that such cells will accept refugees), or randomly competing with either the population within its cell or a neighboring cell. Competition with another cell involves migrating into a target cell without sufficient resources to support the new combined population. In cases where spreading shortages occur with energy in short supply, the area is labeled as a low-intensity conflict. In areas of water or food shortages, where energy resources and production are not in short supply, the area is labeled as a high-intensity conflict.



population may migrate to a surrounding area with sufficient resources to absorb it, decline in place, or migrate to an area with insufficient resources and decline there. Temperature increase is modeled as a function of global atmospheric carbon dioxide concentration that results from energy and resource consumption (primarily oil and coal, but also to a lesser extent operations that support production such as mining and construction). The economic system is modeled as demand and trade of resources and production.

A seasonal hemispheric average temperature variation between 8.1°C during the winter and 22.4°C during the summer, and the corresponding fluctuations in the global rain bands, is the basis for the climate change model. Increased global temperature then drives an increase in the seasonal variation. As the global average temperature increases, the rainfall distributions are distorted. This distortion consists of the narrowing of the equatorial band and movement of the nonequatorial bands toward the poles.

As might be expected, the simulation showed increased conflict in areas already dealing with large and impoverished populations, such as India and Pakistan, and areas that might be directly affected by rising sea levels, such as Indonesia, Northern Europe, and Central America. Perhaps more surprisingly, the simulation also showed conflict within the United States, particularly in the coal-producing states and populations along the Mississippi delta. The simulation also showed a precipitous drop in global energy production with a corresponding drop in total population and a significant shift in migration patterns.

Conclusion

A number of implications can be inferred from the results of the simulation. These include a future environment where conflict may be much more widespread than is currently the norm, industrial production and energy for supporting military systems may be increasingly constrained, and migration may become a significant source of conflict and concern. Most of the modeled trends—such as population growth, resource exploitation, and climate changes—follow S-shaped curves in which growth approaches nearly exponential rates until some limiting factor kicks in (sometimes gradually, sometimes abruptly—especially where human ingenuity is involved). The analysis suggests that any solutions or preventive measures for countering the threats would have to be much more fundamental and extensive than those now being applied, and the window of opportunity is much smaller than is generally recognized, because of the nearly exponential nature of the identified trends.

Earth's climatic system is complex, and significant uncertainty exists in the scientific understanding of it. Continuing research into climatic positive feedback processes and data collection, as well as evaluation of potential interactions with other systems, tends to display greater perturbations than what has been predicted by climate models alone. The integration of climate and global systems models increasingly illustrate the significant national security threats posed by climate change. These models also show the synergistic effects of a number of global trends, including climate change, resource depletion, pollution, and economic imbalances.

Space Support For Disaster Relief

The U.S. military humanitarian responses to Pakistan's flooded regions in 2010 and Japan's quake- and tsunami-stricken northeast in 2011 are indications of how worldwide natural disasters are affecting U.S. national security priorities. Currently, environmental and disaster relief organizations rely primarily on civilian and commercial space systems for humanitarian operations. Iridium phones, for example, are valuable in situations where local telephone and cell phone service is disrupted, providing first responders with continuous connectivity from their staging areas to arrival on the scene. But U.S. national security space systems are also starting to play more of a role in these events. For example, the Defense Information Systems Agency (DISA) recently started the Transnational Information Sharing Cooperation project (TISC) to link nongovernmental organizations (NGOs) with U.S. military units in relief areas. With TISC in place, DISA was able to use channels on the Defense Satellite Communications System (DSCS) to communicate with NGOs supporting relief efforts in Haiti on the day after the earthquake in January 2010.

The response to the earthquake in Haiti provides an example of the innovative use of national security space programs. Hours after the Haiti earthquake struck, a volunteer Web site was set up to receive victim-supplied damage reports via the Internet and cell phones. Commercial satellite imagery and "crowd-sourcing" software were combined in a Web-based application to keep track of damage reports. Coordinating through the Internet, Haitian volunteers in the United States translated the Creole text messages into English within minutes of receipt. Reports with GPS coordinates were then automatically overlaid on Digital Globe high-resolution imagery, providing a near-real-time picture of the unfolding disaster. This self-organized "everyone-as-informant" Web site quickly became a main source for directing efforts of rescue workers and military assistance in the region.

The 2010 Quadrennial Defense Review calls for increasing the military's capabilities to rapidly respond to natural disasters to avoid destabilization and conflict in volatile regions of the world. But if major hurricanes, floods, heat waves, and drought become increasingly common because of climate change, then responding to humanitarian emergencies could "significantly tax U.S. military transportation and support force structures, possibly resulting in a strained readiness posture and decreased strategic depth for combat operations," according to the 2009 Annual Threat Assessment published by the U.S. Office of the Director of National Intelligence.

The Navy, Air Force, and Army (especially the Army National Guard) have begun incorporating the demands of future foreign disaster relief operations in their force planning activities, especially for logistics and communications. Increased priority for disaster relief could eventually have implications for military space budgets. Next-generation space programs will enter service at a time when climate scientists are predicting intensifying storms and exacerbated drought and water scarcity. With disaster relief becoming a core military mission, national security space planners should begin exploring how future military space systems can enhance disaster relief capabilities. The Haitian experience suggests that proactive planning and innovative thinking—especially with regard to interfacing with NGOs, local authorities, and the Internet—can have a big payoff.

—Patrick L. Smith

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Green Propulsion: Trends and Perspectives

Environmentally friendly alternatives could reduce the risk and cost of propulsion systems. Aerospace has been investigating possible candidates for national security space systems.

John D. DeSain

The Swedish Prisma satellite mission successfully tested a monopropellant thruster developed by ECAPS based on ammonium dinitramide (ADN).

Courtesy US Air Force and Steven Son, Purdue University

The Air Force Office of Scientific Research and NASA launched the first test rocket fueled by an aluminum-ice (ALICE) propellant in 2009. The vehicle accelerated to a speed of 330 kilometers per hour and reached an altitude of nearly 400 meters.

The propellants used in space programs pose environmental concerns in four main areas: ground-based impacts, atmospheric impacts, space-based impacts, and biological impacts. Ground-based impacts range from groundwater contamination to explosions caused by mishandling of propellants. Atmospheric impacts generally come from the interaction of propellant exhaust with the atmosphere. Space-based impacts generally focus on debris and effects on spacecraft. Biological impacts tend to focus on the toxicology and corrosiveness of propellants.

Space system developers have long sought to mitigate these impacts, because doing so could potentially reduce both cost and risk—especially the costs and risks associated with propellant transport and storage, cleanup of accidental releases, human exposure to toxic substances, infrastructure requirements for handling hazardous propellants, and orbital debris. The continued use of highly toxic propellants that generate environmental pollutants keeps program costs high—but the cost of developing and qualifying green alternatives also tends to be high. This has traditionally slowed development even when a green propellant provides potential performance benefits.

Also, the term “green propellant” is often confusing, as many assume a green propellant has no environmental impact. Such a propellant is generally beyond the realm of physical possibility. All propellants affect the environment in some way. For instance, all launch vehicles produce exhaust. The components of this exhaust can include soot, carbon dioxide, alumina, inorganic chlorine, water vapor, sulfates, and nitrogen oxides. All of these have an environmental impact, and may contribute to climate change, ozone destruction, or upper atmospheric contrails, depending on the atmospheric layer in which they are deposited; however, the severity and duration of the impact can vary greatly. Given this fact, a green propellant is more correctly viewed as one that seeks to minimize or eliminate a critical environmental impact in one or more of the four main areas. A green propellant is likely to have its own environmental impacts, which may be equal to the current technology in certain areas. For example, many green propellants seek to eliminate hydrazine because of its biologic impact, but they still present atmospheric or space-based effects.

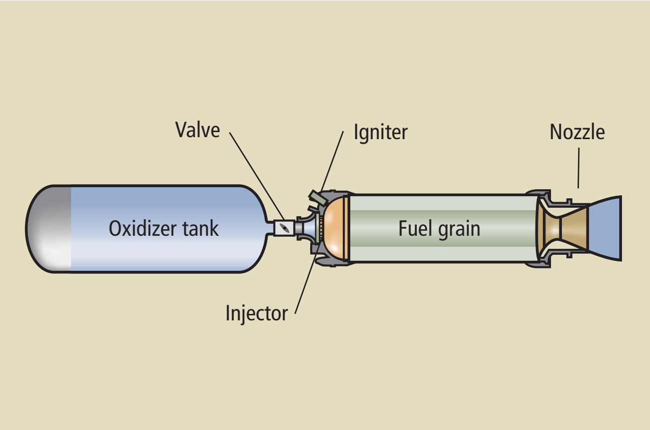
The Aerospace Corporation has been investigating the potential for green propulsion systems with an eye toward helping space system designers minimize environmental impacts while improving overall efficiency and economy.

Ammonium Perchlorate Replacements

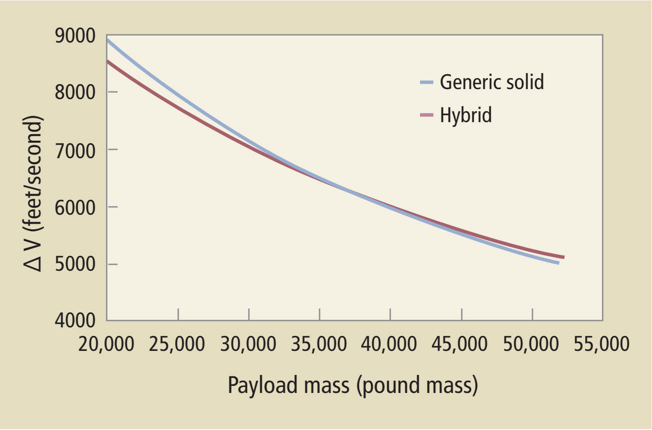
Hydrocarbon-based solid fuels have been used as rocket propellants in combination with the solid oxidizer ammonium perchlorate for several decades. Solid rocket motors are commonly used in launch-on-demand systems, boost-phase launch-assist systems, and small-lift launch vehicles. Unfortunately, much of the environmental impact (both ground and atmospheric) from the launch vehicle fleet comes from the ammonium perchlorate in solid rocket motors. Perchlorate leaching from discarded motors and from manufacturing operations can diffuse into groundwater, which can pose a health hazard for humans. The hydrogen chloride and chlorine produced during launch can destroy stratospheric ozone. Many of the exhaust components (soot, carbon dioxide, alumina, inorganic chlorine, stratospheric water vapor, and nitrogen oxide) can also contribute to climate change, either directly or through their reactions with other atmospheric species. In addition, perchlorate-based solid motors present safety challenges because they cannot be shut down once ignited.

Several green propellants are being developed as replacements for ammonium perchlorate in solid rocket motors. One potential candidate that has been gaining in popularity is ALICE (aluminum-ice). It combines the fuel, composed of nanoparticles of aluminum, with the oxidizer, oxygen, stored as water. The mixture is maintained below the water’s freezing point, so that it behaves like a solid propellant. ALICE has a higher theoretical specific impulse than conventional perchlorate-based solids. In 2009, NASA and the Air Force Office of Scientific Research launched a small suborbital demonstration vehicle powered by ALICE. The propellant has also been proposed for use on interplanetary return missions, as both water and aluminum could potentially be produced in situ on many interplanetary landing sites. ALICE produces hydrogen and alumina as its main exhaust; while these are generally billed as environmentally friendly, stratospheric alumina has the potential to reduce ozone concentrations. ALICE does present some risk of explosion (as all propellants that combine fuel and oxidizers do), but

Courtesy of Swedish Space Corporation



Conceptual diagram of a standard hybrid rocket motor with a liquid oxidizer tank and a solid fuel grain.



Performance comparison for a conventional solid rocket motor and a hybrid motor with the same propellant mass.

this risk has been shown to be relatively low. Alone, neither aluminum nor water is hazardous.

Several energetic salts have also been proposed as replacements for ammonium perchlorate. Solid motors based on ammonium dinitramide (ADN) could potentially have a 4-percent-higher specific impulse than perchlorate-based systems without producing hydrogen chloride exhaust. However, ADN is more prone to detonation under high temperatures and shock. Also, its density is about 8 percent less than that of ammonium perchlorate, so its performance is lower than a one-to-one comparison would suggest. In the late 1990s, ATK produced a solid ADN propellant that was thermally stable—but autoignition still occurred at about 110 kelvin less than that of comparable ammonium perchlorate propellants. NASA has been developing a solid motor based on ADN and has been working with the Swedish Defense Research Agency to investigate a solid fuel that would overcome the limitations of current formulations. Hydroxylammonium nitrate (HAN) is another energetic salt that has been proposed as an ammonium perchlorate replacement. In 2007, Raytheon and Aerojet demonstrated a 150-pound thruster based on HAN.

Hybrid rockets have also been investigated as a green alternative to perchlorate-based solid rockets. Hybrid propulsion systems use a solid hydrocarbon fuel (typically a polymer) and a liquid oxidizer. They have several advantages over conventional perchlorate-based solids in that they are nontoxic and nonhazardous, they can be shipped as freight cargo, and they can be shut down in case of an on-pad anomaly. They also have better performance attributes—they can be throttled for thrust control, they can potentially be restarted on demand, and they have higher achievable specific impulse. The disadvantage of hybrid motors is that many of the oxidizers would need a propellant management system, which often adds mass and cost to the vehicle—although some proposed self-pressurizing oxidizers could eliminate this as a liability. Hybrids produce exhaust products similar to those of conventional liquid motors, with carbon dioxide, soot, water vapor, and nitrogen oxides as potential components. Soot levels may be similar to those of conventional solids that also use solid hydrocarbons as binders. Because the solid fuel and liquid oxidizer are not mixed initially, they have a lower explosion risk than conventional solid motors. Scaled Composites has produced a hybrid launch vehicle, SpaceshipTwo. The vehicle, designed to perform only suborbital human space flights, is being tested, and commercial passenger flights are expected to start in 2011.

Hydrazine Replacements

Hydrazine is a multipurpose propellant that can be used as a hypergolic bipropellant with nitrogen tetroxide or in a monopropellant thruster with a catalyst. Hydrazine derivatives are still used as bipropellant fuels in launch vehicles in several countries. The United States no longer flies rockets based on bipropellant hydrazine derivatives, but small hydra-

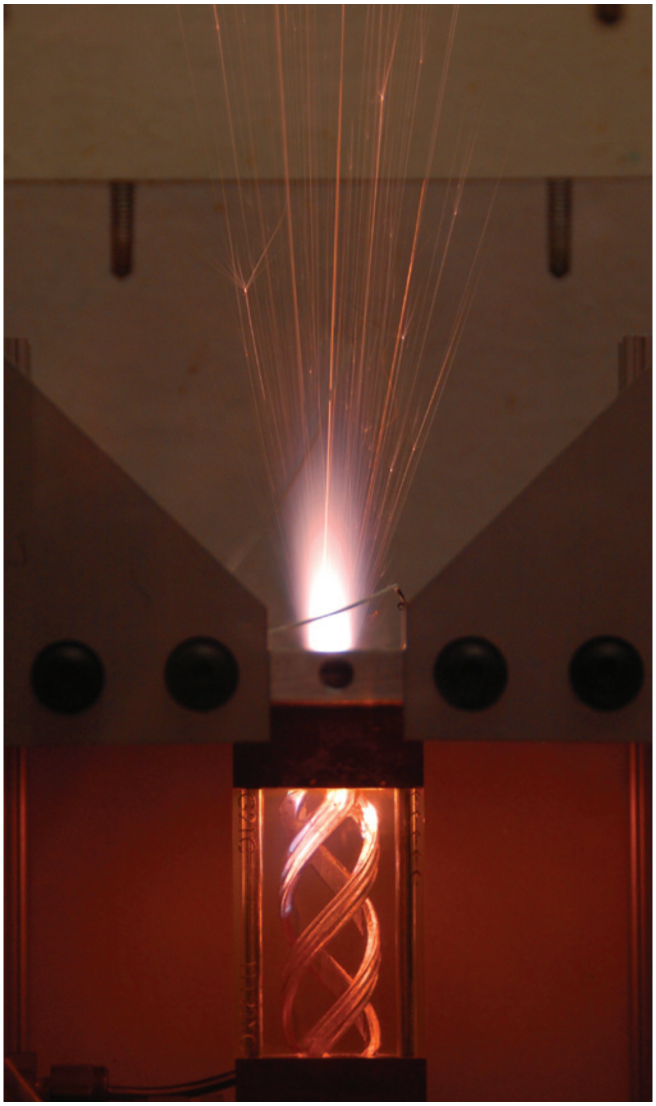
Kevin Dorman and John DeSain testing green propellant.

zine monopropellant thrusters are often used by spacecraft—and these are the applications that are typically targeted for green replacements. Hydrazine storage is a concern on the ground. Because of its toxicology, it is costly to handle. The atmospheric impact is not a large driver in hydrazine research, but the space environment is a cause for concern. Hydrazine is naturally unstable, and unvented hydrazine tanks have been known to rupture in space, posing a debris risk at the end of mission life.

The Swedish company ECAPS produced a satellite thruster based on an aqueous ADN solution that produced higher specific impulse than monopropellant hydrazine. It was used on the formation-flying Prisma satellites. Thus, ADN is a potential replacement not only for perchlorate, but for hydrazine monopropellant as well. Similarly, HAN can potentially be used in aqueous solution as an alternative to hydrazine.

Electric propulsion offers another potential green alternative. Electric thrusters encompass a wide range of designs, including arcjets, resistojets, ion thrusters, and Hall thrusters. They use a magnetic field to trap injected electrons that are used to ionize an injected gas—usually xenon. Electric thrusters have the advantage of high specific impulse (compared to chemical thrusters), and they can potentially use much less propellant than a hydrazine vehicle to achieve the same maneuver. The main disadvantages are that they require an electric power source and generally offer only low thrust, which means they take longer to deliver a satellite to orbit. Many satellites have appropriate power generators onboard for other applications, so electrical thrusters need not add mass—but the longer delivery time can make them unattractive for certain missions. Thus, many satellites that use electric thrusters still must have hydrazine onboard for certain maneuvers. The xenon released from electric propulsion is generally not an environmental hazard, although the ionic plume can affect the space environment. Electric propulsion has been used by Russian satellites for a long time and is gaining acceptance in the United States; the technology is flying or will fly in many major U.S. Air Force programs and has helped lower the amount of hydrazine needed for these missions.

Several potential bipropellant formulations that use liquid oxygen (LOX) are being produced as potential hydrazine replacements. In general, these propellants are much less toxic than hydrazine derivatives; however, the cryogenic (< 91 kelvin) nature of liquid oxygen makes it hazardous to produce and difficult to store for long periods. Some of the first launch vehicles ever developed used LOX formulations, and kerosene/LOX and hydrogen/LOX engines are still in use today. LOX-based formulations are less popular for spacecraft propulsion because they require bulky tanks and feed lines and need large amounts of energy for refrigeration. Still, LOX/hydrocarbon fuels offer higher specific impulse than hydrazine monopropellant. Specific impulse is a way to describe the efficiency of rocket and jet engines. It is the ratio of the thrust produced by an engine to the rate of fuel consumption: it has units of time and is the length of time that one unit weight of propellant would last if used to produce one unit of thrust continuously. Thus an engine with a higher impulse would be more efficient because it would produce more thrust for the same amount of fuel used. Several different designs of LOX/hydrocarbon fuels have been demonstrated recently. For example, an 870-pound LOX/ethanol reaction-control thruster was developed and test-fired by Northrop Grumman in 2003, and Aerojet has also tested a LOX/ethanol reaction-control thruster. In 2007, XCOR and ATK test-fired a 7500-pound motor based on LOX and methane; the pressure-fed engine was sponsored in part by NASA's Advanced Development LOX/Methane Engine program. In 2008, the Pratt & Whitney Rocketdyne RS-18 monopropellant thruster was modified to use LOX/methane and was tested by NASA at White Sands, New Mexico. Methane engines have performance close to that of


Testing of a hybrid motor with a built-in swirl pattern created via stereolithography.

The National Environmental Policy Act

The National Environmental Policy Act (NEPA), signed into law on January 1, 1970, requires federal agencies to study and document the effects of their actions on the environment. Potential impacts on human health and safety; air, soil, and water quality; ecosystems; cultural and historical resources; land use; and socioeconomics resulting from the proposed action (and all viable alternatives) must be considered in an environmental assessment conducted by qualified experts. The assessment involves comprehensive analyses and documentation that is made available to the public during a 30-day review period. If impacts are determined to be significant, efforts must be made to minimize them. If this is not possible, an environmental impact statement must be prepared. The impact statement requires a 45-day public review along with public hearings and meetings with regulatory agencies, public officials, and affected groups. NEPA not only involves issues that are currently regulated by the federal government, but also extends to unforeseen impacts that a federal agency could prohibit or regulate.

Air Force space-related activities subject to NEPA requirements include the processing and launching of spacecraft and launch vehicles, construction and operation of ground systems, and the disposal of spacecraft, launch vehicles, and associated equipment. Aerospace assists the Air Force in fulfilling these requirements by quantifying the environmental impacts of satellite and missile launches, interpreting regulations to help ensure final documents and proposed actions are within applicable requirements, and assessing potential impacts from ground-based activities.

Ground-based activities that could affect the environment include the installation and operation of new antenna systems, terminals, and associated infrastructure. Detailed knowledge of planned construction, demolition, transportation, and operation of a proposed ground system is required to determine potential impacts to the ecosystem as well as to the health and safety of humans and wildlife. Cumulative effects—that is, the total impact of the proposed action considered together with other past, present, and reasonably foreseeable future actions—must be assessed. Many factors can combine to complicate the analysis. For example, the assessment of cumulative health and safety impacts of nonionizing radiation produced by a new ground antenna must include the nonionizing radiation emitted by all other antennas in the region of influence. Effects of pollutants that could potentially reach local water supplies and aquifers must be studied from chemical, biological, and engineering perspectives.

Proposed launch and ground station activities can have significant effects on endangered species. Many launch facilities and ground systems are located in remote coastal regions and on islands, which tend to contain sensitive habitats such as wetlands and coral reefs. Noise caused by construction, launch, and daily operations must also be considered. NEPA also requires that impacts from reentering spacecraft be studied.

NEPA also covers atmospheric effects, which have been a primary focus for many years. Short-term pollution from construction must be estimated, as well as long-term emissions from space system operations, to assess compliance with applicable air quality regulations. Launch vehicles can affect the atmosphere in many ways. For example, Aerospace has quantified global ozone depletion caused by the release of chlorine into the stratosphere from perchlorate-based solid-fueled rockets. Launch vehicles also release a large quantity of greenhouse gases and other species (in this case, nongaseous products of the exhaust such as black carbon soot and metal particulates) that can interact with existing atmospheric gases. Because these gases are released in all layers of the atmosphere, they can have dramatically different effects as compared with gases released on the ground. Aerospace calculates the amount of carbon dioxide generated by Air Force space launches and can also evaluate the effects of other pollutants that may soon be regulated.

Launch activities also can produce sonic booms that can affect the surrounding environment. Sonic booms can occur not only from launch operations but also from spacecraft and debris reentering the atmosphere from space. Sonic booms over the ocean penetrate below the surface and can affect the deep ocean environment as well. The process is not well understood, and the effect on biological systems has not been quantified. Aerospace is studying these impacts.

Many of the propellants used in launch vehicles and spacecraft—such as ammonium perchlorate, nitrogen tetroxide, and hydrazine and its derivatives—are toxic or corrosive. Others contain cryogenic materials. A small number of spacecraft also use radioactive material in orbit. NEPA requires that the environmental and human health risks from the routine handling, storage, and use of these materials be considered as well as the effects of unintentional release into the environment. Because launch operations are not always successful, appropriate mitigation and verification methods must be identified and documented in an environmental assessment or impact statement.

Summary

NEPA documentation addresses an extensive set of considerations that encompass nearly the entire sphere of proposed Air Force space activities. Aerospace is actively involved in supporting the Air Force with NEPA compliance in all areas of potential concern, including anticipation of future requirements and related mitigation planning and implementation.

—Mary Ellen Vojtek, Charles Griffice, John DeSain, and Brian Brady traditional LOX/kerosene engines, but generally have lower fuel density. An advantage of methane over kerosene is the possibility to use a fuel-rich gas generator without soot formation; it also features a high cooling efficiency. Methane is injected in a gaseous state, thus lowering the risk of combustion instabilities. One reason for the renewed interest in LOX for spacecraft is the potential for in situ resource use during planetary missions.

High-test hydrogen peroxide has always been attractive as a monopropellant, as its decomposition products are water and oxygen. It can also be used as part of a bipropellant. In the past, hydrogen peroxide was used for satellite propulsion, but fell out of use as good catalysts for hydrazine thrusters became available. One major drawback of hydrogen peroxide is that storage becomes more difficult as the purity increases. A purity of at least 67 percent is needed to generate sufficient energy from a thruster. Several submarine accidents have resulted from unintended explosions of hydrogen peroxide propellants used in torpedoes. Still, hydrogen peroxide has been safely used by Russian Soyuz launch vehicles (82 percent purity) for more than 40 years to drive the main turbine pump in the gas generator and in the reaction-control-system thrusters used for the descent phase. Hydrogen peroxide was also used as the oxidizer in the British Black Arrow launch vehicle. As a monopropellant, hydrogen peroxide has a performance about 20 percent lower than hydrazine. The volume specific impulse achievable with 90 percent hydrogen peroxide is higher than for most other green propellants because of its high density. The most significant technological challenge for creating hydrogen peroxide monopropellant thrusters has always been the development of effective, reliable, long-lived catalytic beds. Also, alternative decomposition techniques are still needed to fully exploit the higher performance offered by 98 percent hydrogen peroxide. Current research is generally focused on microthrusters for small satellites. Lawrence Livermore National Laboratory developed a microthruster that uses 85 percent hydrogen peroxide; it flew on a 25-kilogram satellite. For the last decade, General Kinetics has offered 3-, 6-, and 25-pound force monopropellant and bipropellant thrusters and gas generators based on hydrogen peroxide.

Nitrous oxide is similar to hydrogen peroxide in its usability as an oxidizer in a bipropellant or as a monopropellant. Nitrous oxide offers potentially 80 percent of the specific impulse of hydrazine. Unlike other nitrogen oxides, it is nontoxic, noncorrosive, and stable under ordinary conditions; however, like most monopropellants, it can explode under certain conditions, so handling and shipping are a concern. Nitrous oxide is easily liquefied under pressure and is often stored as a liquid. High vapor pressure (50 atmospheres at room temperature) enables self-pressurization of the propellant tank, which can save weight. The reaction products—nitrogen and oxygen—are not hazardous. Catalysts are generally used to accelerate the decomposition of nitrous oxide because the decomposition temperature tends to be high. Developing space-qualified monopropellant catalysts are an issue with nitrous oxide, although some progress has been made on small resistojet thrusters for microsatellites. A monopropellant based on nitrous oxide is being developed by Firestar Engineering with support from NASA and DARPA (Aerospace has been involved in reviewing the safety testing program). It has higher performance than hydrazine, and may soon fly on the International Space Station. Much of the current investigation has focused on the use of nitrous oxide as the oxidizer in hybrid bipropellants—although in this application, ozone destruction from the nitrogen oxides in the exhaust would have to be considered.

Another hydrazine alternative, cold-gas thrusters, has been used on satellites for many years, both for maneuvering and for attitude control. They are suitable for applications that require very low total impulse. Cold-gas thrusters offer a wide range of chemical propellants because the gas need not be a combustible to provide thrust. Nitrogen has been used in many designs and has a specific impulse of 68 seconds. The main disadvantage of cold-gas thrusters is their low performance; however, for nanosatellites (where space is limited), their simplicity is an important advantage. Low-thrust propulsion engines using cold-gas thrusters are commercially available from various sources.

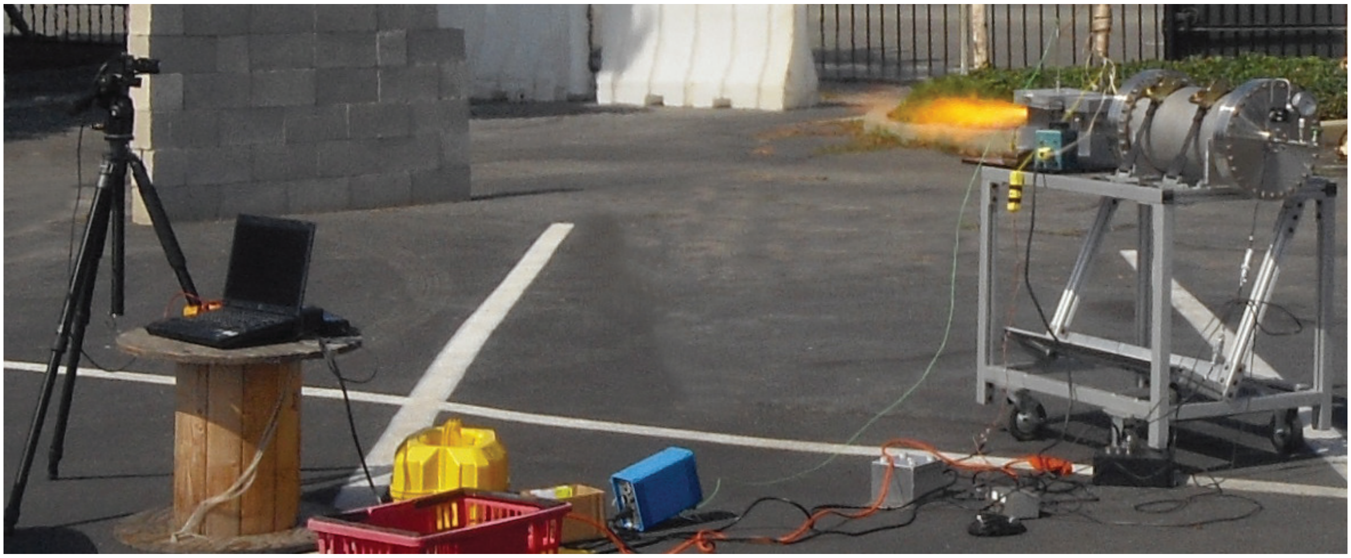
Examples of Aerospace Research

Aerospace has a long history of investigating electric propulsion systems. Early programs focused on hydrazine arcjets, ion engines, and Hall-efffect thrusters. More recent work has complemented the corporation's expertise in small satellites.

For example, a recent study verified the feasibility of a two-stage air-breathing Hall thruster. The system would be used to compensate for the increased orbital drag acting on a satellite at lower altitudes. A small, responsive satellite flying at lower altitudes could achieve better optical performance or present simpler design constraints. A key aspect of the thruster design was an ionization stage based on electron cyclotron resonance.

For many years, Aerospace scientists have been working with cold-gas microthrusters manufactured from photosensitive glass-ceramic materials. The technology would be suitable for a miniature spacecraft. The material has also been investigated for use in arrays of one-shot microthrusters that could be individually activated on orbit. More recent work geared toward the propulsion needs of CubeSats has focused on the use of a UV laser to activate a solid polymer and produce usable exhaust; the use of a laser to permit the combustion of solid propellants at pressures that would otherwise be too low; the use of ADN monopropellant; and electrolysis of water—essentially a fuel cell—to generate hydrogen gas as propellant.

Another intriguing study examined the introduction of a liquid hydrocarbon (*n*-heptane) and a gaseous oxidizer in



The Aerospace Corporation has developed a paraffin wax fuel grain that can be hypergolically ignited. Hypergolic propellants spontaneously ignite when they come into contact and thus do not need a separate ignitor. The photograph shows the 2010 test firing of a hypergolic paraffin wax/gaseous oxygen motor at The Aerospace Corporation hybrid rocket test stand.

a modified shock tube to create a pure gas-phase fuel and oxidizer mixture. Also, plans for new research facilities at Aerospace include the capability of studying liquid-oxygen/liquid-hydrogen thrusters.

Aerospace has developed a hybrid motor sizing code to answer fundamental questions such as: What is the performance gain or loss that will result from using hybrids instead of conventional perchlorate solids or liquids? What materials and design techniques could be used to increase payload-to-orbit capability? What is the estimated cost, and how does that compare with a conventional launch vehicle?

The sizing code shows that as payload weight increases, hybrids become more competitive with conventional solids. The LOX and helium tanks (used as a pressurant) are the primary reason that hybrids have a larger inert mass than solid rockets. Future systems that use self-pressurizing oxidizers or composite oxidizer tanks would significantly improve hybrid system performance.

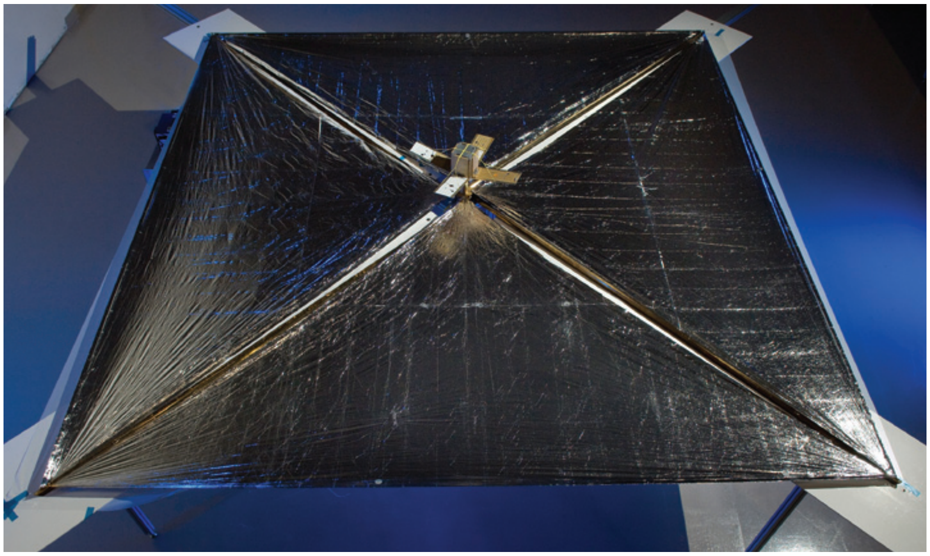
Enhancing the burn rate of the solid propellant would also boost hybrid motor performance. With this in mind, Aerospace has been examining the use of fuel additives to create novel fuel grains. These additives may increase burn rates and overall performance and could also enable a restart capability. Currently, hybrid rocket motors are ignited by explosive squibs or gas flames. The squib systems can only be restarted if the squib is replaced, which is not possible for upper stages already in flight. External flame sources are possible on upper stages, but these add weight. Hypergolic fuel grains, which ignite spontaneously upon contact with the oxidizer, provide the simplest and most reliable form to start and restart a motor. Studies at Aerospace have demonstrated that the addition of lithium aluminum hydride ($LiAlH_4$) to paraffin wax produces a fuel grain that ignites upon contact with several different chemicals. A 50-pound-thrust paraffin wax/gaseous oxygen motor was constructed and tested at Aerospace, demonstrating the feasibility of hybrid motors that use $LiAlH_4$ doped paraffin wax and nitric acid as a hypergolic ignition system.

Hypergolic propellants are extremely useful on orbit, where conventional solids are rarely used. Aerospace has been researching a novel approach to fabricating fuel grains that could be used to create hybrid motors for CubeSats. In this approach, a fuel grain is built up using a form of rapid prototyping called stereolithography, in which patterns in successive layers of a liquid photopolymer are cured to produce a three-dimensional structure. Complete control of the three-dimensional grain shape allows the design of a hybrid motor that is highly filled and where the ports are not limited to straight, axially constant shapes, as is the case for motors produced by typical casting methods. Aerospace has fabricated and tested several fuel grains using gaseous oxygen. A novel deposition apparatus has been set up that will allow printing of paraffin wax motors as well. Positive results have been shown, and the technology is at Technology Readiness Level 3.

Future Technology

Some proposed technologies would eliminate propellants entirely. These tend to be far-reaching and have generally been demonstrated only in small-scale ground tests, if at all. They include concepts such as space elevators, laser propulsion, nuclear propulsion, and kinetic rail guns. Aerospace scientists have even proposed the ejection of microminiature spacecraft, instead of chemical exhaust products, to provide thrust; the satellites could even be programmed to return to the host craft, enabling long-term reuse. Though intriguing, these proposals do not appear likely to affect the space industry in the near future.

One exception is the solar sail. Originally proposed almost 50 years ago, solar sails use pressure from the solar wind and solar radiation to propel the spacecraft. Current technology uses ultrathin mirrors, and future crafts could potentially use a sail that acts both as a solar panel and as a propulsion device. Solar sails are generally not practical for Earth orbits, where atmospheric drag would overcome the forces produced, although solar sails that rotate with the craft could possibly make them suitable for some orbital use. The Japanese IKAROS satellite launched in 2010 uses a solar sail as its primary mode of propulsion; it will travel to Venus and then to the far side of the sun. Several other solar sail projects are currently in the works and may soon fly.


Courtesy of NASA/MSFC/D. Higginbotham

Solar sails such as this one use pressure from the solar wind to propel spacecraft through interplanetary space.

Summary

Ultimately, the fate of green propulsion will depend on its ability to satisfy the two main drivers for its development—higher performance and lower costs. U.S. space agencies have already begun the move toward green propellants with the acceptance of LOX/hydrogen and LOX/kerosene launch vehicles and greater use of electric propulsion for spacecraft. Currently, the atmospheric impact from launch vehicles remains low, but only because launch rates remain low. Limiting environmental impacts is a key part of achieving the high launch rates that would be needed to pursue ambitious space architectures, as doing so would help achieve the cost efficiency needed to make rapid launches financially possible. Green technology could also make interplanetary missions more efficient and sample-return missions from distant bodies more feasible. Green technologies aren't just a future possibility—they are already a part of the space architecture, and further growth seems highly likely.

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The Adaptation of Tactical Imaging Spectrometry to Applications in Earth Science

Long-wave infrared imagery is being applied to Earth observation activities in anticipation of future needs to assess climate change impacts around the globe and assist the national security community in defining future observational requirements.

David M. Tratt and George J. Scherer

Aerospace engineers conduct laboratory testing on the new Mako instrument. (L-R) David Gutierrez, Shaun Stoller, and Nery Moreno.

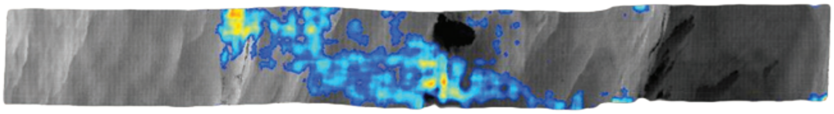
There is increasing awareness within the U.S. government that climate change has the potential for considerable and unpredictable disruption around the globe. In 2007, Congress called for a national intelligence estimate on how climate change might affect national security and consequent U.S. force projections. In 2008, the intelligence community completed this analysis; the findings pointed to important and extensive implications for U.S. national security interests within the next 20 years. The impacts are expected to exacerbate existing problems abroad in many countries struggling with poverty, social tensions, environmental degradation, ineffective leadership, and weak political institutions.

The convergence of Department of Defense climate concerns with related activities that have traditionally been pursued within the civil sector prompted The Aerospace Corporation to initiate a pilot program of Earth remote sensing observations. Aerospace has been developing the theory and practice of high-resolution spectral imaging at long-wave infrared (LWIR) wavelengths (7–14 microns) for more than two decades. The instruments developed have been applied almost exclusively to tactical applications; however, since 2008, these technologies have demonstrated their applicability to a variety of diverse topics in Earth science, such as the detection and tracking of trace atmospheric gas plumes, the mapping of surface composition and geological structure, and the characterization of geothermal activity.

Although LWIR imagery has a long history in Earth observation, the number of spectral bands employed is typically small: ten channels for MODIS (Moderate Resolution Imaging Spectroradiometer) and five for ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), two instruments currently flying on satellites as part of NASA's Earth Observing System constellation, and only one channel for the Enhanced Thematic Mapper Plus aboard Landsat. Even the most advanced plan for a next-generation LWIR imager (the Hyperspectral Infrared Imager, or HyspIRI) calls for just seven channels, whereas considerably more knowledge could be gained by even a moderately higher resolution imager. Although remote LWIR thermometry has a long heritage and can be carried out to reasonable accuracy with very few channels, more fully resolving the thermal radiation distribution enables researchers to discern residual spectral structure, which can then be correlated against known spectral signatures to test for a variety of chemical constituents in a scene.

Natural and Anthropogenic Methane Emission

The climate science community has predominantly focused on understanding the global distribution of atmospheric carbon dioxide, which is the most prominent marker of industrial activity; however, methane is receiving growing attention because the current warming trend threatens to dramatically increase methane fluxes into the atmosphere from solid reservoirs (in the form of methane hydrates) in Earth's oceans and permafrost regions. While carbon dioxide is significantly more abundant and remains in the atmosphere much longer, the relative potency of methane as a greenhouse agent is approximately 100 times that of carbon dioxide on decadal timescales. With methane being this much more effective at retaining heat in the atmosphere, the potential for major climate change from rising atmospheric methane levels is therefore a serious long-term issue.


LWIR grayscale radiance field over part of the Trilogy Seep, Santa Barbara, California, with false-color methane overlay. The dark patch adjacent to the methane cloud marks the position of cold-water upwelling from one of the sea-floor seep locations. The methane cloud itself obscures a second seep site.

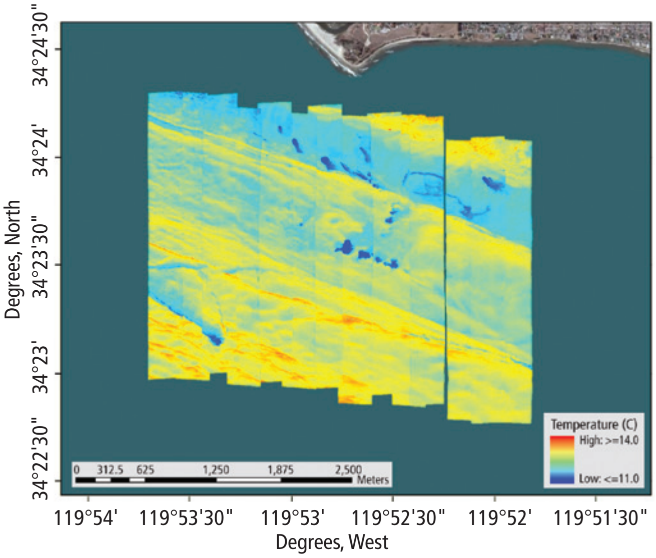

LWIR grayscale radiance map over the La Brea Tar Pits, Los Angeles, with color overlay showing methane emission from a nearby vent pipe at the bottom edge of the frame.

The marine oil seeps in the Santa Barbara Channel off Goleta, California, are among the most productive natural methane emission sites in the world (~100 cubic meters per day). The methane, along with other liquid and gaseous hydrocarbons, is contained in geological reservoirs formed by anticlinal folding in the strata that make up the ocean floor. Breaching of the anticline crests by erosion releases these trapped hydrocarbons—a trend that has persisted for at least the last few centuries, as attested by early European explorers and the indigenous cultures of the region. As more of the submarine hydrocarbon load has been captured by petroleum production operations throughout the twentieth century, the observed levels of seepage have declined considerably. Nevertheless, atmospheric hydrocarbons originating from the Santa Barbara Channel seeps far exceeds that from all highway traffic in Santa Barbara County on an annually averaged basis.

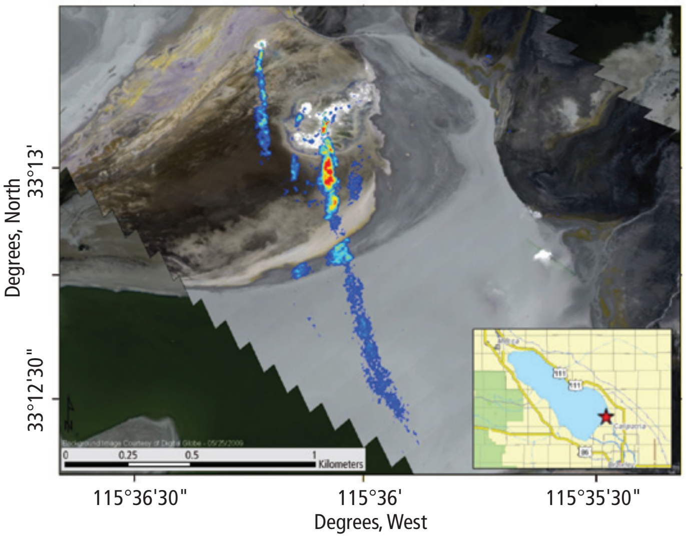
Aerospace's SEBASS (Spatially Enhanced Broadband Array Spectrograph System) instrument was flown over this location, focusing on an area that encompasses the most vigorously emitting seeps, the so-called Trilogy Seep. The primary objective was to assess the suitability of LWIR imaging spectroscopy for detecting methane in the atmosphere.

A number of methane haze features were detected in the data. Another interesting finding was the rich structure evident in the retrieved ocean surface temperature field. This complexity results from a combination of current interactions, cold-water upwelling, and surfactant-driven emissivity modulation arising from capillary wave suppression by surface oil films.

A pronounced methane emission was also observed near the La Brea Tar Pits in Los Angeles, though not from the tar pits themselves. The emission was localized and initially thought to be a remnant of tar eruption reported a few days earlier. However, further investigation uncovered the fact that in the late 1990s a vent pipe was erected at this location



Brightness temperature map of the Santa Barbara Channel field survey area, centered on Trilogy Seep. Cooler features correspond to the mapped locations of major hydrocarbon seepages.



LWIR radiance imagery of a segment of the Calipatria Fault as it crosses the southeastern shore of the Salton Sea. The false-color features denote ammonia plumes emitted from an active fumarole group exposed on a sandbar at the shoreline.

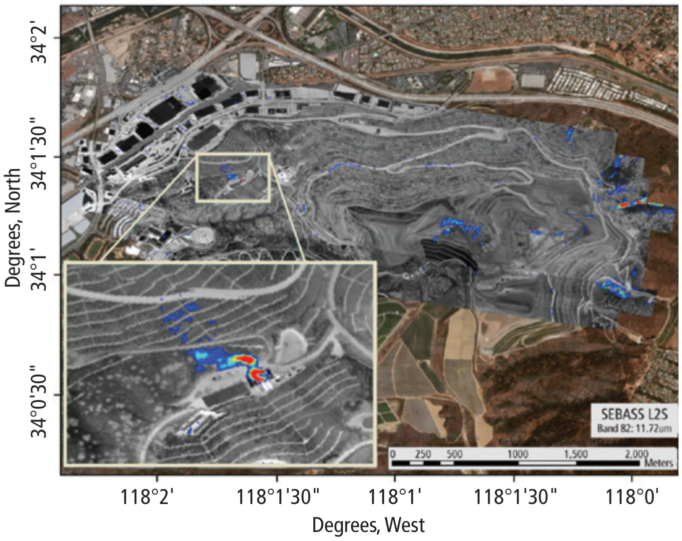
Aerospace personnel confer with the airplane pilots before departure to the Salton Sea field site. From left: Brian Kasper (Imaging Spectroscopy Dept.), Jeff Hall (ISD), Bill Clark (Twin Otter International, Ltd.), Jim McCormick (Twin Otter International, Ltd.), Mike Martino (Advanced Sensor Engineering Dept.).

to allow gas to escape from an especially prolific subterranean methane pocket, which is consistent with the observation of a highly localized source of gas with a distinctive plume morphology suggestive of a point source emission.

Another significant source of methane is the decomposition of organic matter in fetid water bodies, marshes, and landfills. According to the Environmental Protection Agency, landfills accounted for roughly 23 percent of total U.S. methane emissions in 2007. The SEBASS instrument was also flown over an active landfill in Los Angeles, and was successful in detecting fugitive methane emissions.

Geothermal Observations in an Active Seismic Zone

The Salton Trough, located in Southern California's Imperial Valley, represents a major structural feature in Earth's crust because it contains the northern portion of the transition zone between the San Andreas and Imperial Faults, which themselves demarcate the interface between the North American and Pacific tectonic plates. The transition zone is marked by a latticework of minor faults that in places provides conduits to the surface for hydrothermal fluids generated by an underlying magma chamber. In prehistoric times (15,000–20,000 years ago), this resulted in significant surface volcanism (forming the Salton Buttes, a line of quiescent vents along the southeast edge of the Salton Sea), but the only remnant of this activity is a proliferation of hydrothermal vents that are variously described as fumaroles, mud pots, or mud volcanoes. The area is currently being tapped by a number of geothermal power plants.



LWIR grayscale radiance imagery from a nighttime overflight of an active landfill. Fugitive methane emissions are depicted in false color. The inset highlights an on-site methane reclamation facility.

The Salton Sea occupies the lowest reaches of the Salton Trough. Although a freshwater lake has existed here at various points in history, the present lake was created inadvertently in the early twentieth century when an irrigation project went awry and the Salton Trough, at that time dry, filled with water from the Colorado River. This created a peculiar environment, because the lake had no outlets. The subsequent cycle of evaporation and continued inflow resulted in hypersaline conditions, with the water being further polluted by high levels of agricultural runoff from adjacent terrain.

This area was selected to evaluate the suitability of the Aerospace airborne LWIR imagers for making high-resolution observations of surface geothermal activity. A flight line was established along the presumed surface track of the Calipatria Fault, one of the most consistently geothermally active areas in the Salton Sea geothermal complex. The 1-meter-resolution LWIR imagery revealed numerous prominent thermal sources associated with an active fumarole group that has been exposed in recent years by the declining water level of the Salton Sea. In addition, a pronounced thermal hot spot is apparent in the shallows a short distance to the northwest of the landward cluster of fumaroles. The center of this particular fumarole was measured at almost 80°C. This was one of many fumaroles that emit vapor plumes, most of which were shown by spectral analysis to contain ammonia. It is presumed that this ammonia arises from geothermal pyrolytic decomposition of the nitrogen-rich agricultural runoff that permeates the lake water and sediments. These measurements are the first indication that geothermal activity contributes to the atmospheric ammonia content in this area.

With sufficient knowledge of the prevailing meteorological conditions, it is possible to estimate quantified emission fluxes. When this was done for six of the most clearly defined plumes, their combined ammonia output was calculated to be 30–90 kilograms per hour. The range in values expresses the total aggregate uncertainty attaching to the LWIR-derived quantities and local meteorological parameters for this particular data collection.

Ammonia is one of many atmospheric pollutants that environmental agencies monitor because it creates airborne particulates that not only influence climate through their effects on the terrestrial radiation balance, but also present health risks to humans. Large-scale maps of ammonia distribution across the United States are currently compiled from data gathered by a sparse network of surface-based in situ sensors that are then processed by mesoscale atmospheric transport models to estimate ammonia concentrations over broader areas. These operational products are subject to inaccuracies from incomplete sensor coverage and performance uncertainties associated with the transport models. The measurements described here, in combination with recent advances in satellite retrieval approaches, point toward a means for more thorough characterization of atmospheric ammonia burdens on regional to global scales.

Conclusion

The research findings described in this article have borne out the original premise that hyperspectral LWIR equipment and techniques developed for the tactical realm are readily adaptable to a diverse range of Earth and environmental science applications. The principal limitation of such systems concerns the modest areal coverage rate, and this issue is being addressed through the development of two new LWIR imaging instruments being built with support from Aerospace and NASA. The Aerospace research plan was conceived at the outset to be synergistic with the latter program, while the investigations themselves were chosen based on the likelihood of hyperspectral LWIR imagery to uncover new or unique knowledge relating to natural phenomena. The greatly expanded areal coverage rate of these new sensors will enable considerably more comprehensive studies to be undertaken over much larger areas than has been possible with the previous generation of instrumentation.

Acknowledgments

The work described in this article was supported by The Aerospace Corporation's IR&D and Civil and Commercial Operations program offices and involved staff from several different departments within the corporation, including Imaging Spectroscopy, Remote Sensing, Advanced Sensor Engineering, Sensor Exploitation, and the Commercial, International and Homeland Security Programs office. Data processing and visualization for this article were provided by Kerry Buckland, Stephen Young, and Patrick Johnson. Mission planning was carried out by Brian Kasper, David Lynch, Jeffry Padin, and Mark Polak, while instrument preparation and support to field operations involved David Gutierrez, Jeffrey Hall, Eric Keim, Michael Martino, Luis Ortega, Jun Qian, Shaun Stoller, Adam Vore, and Karl Westberg.

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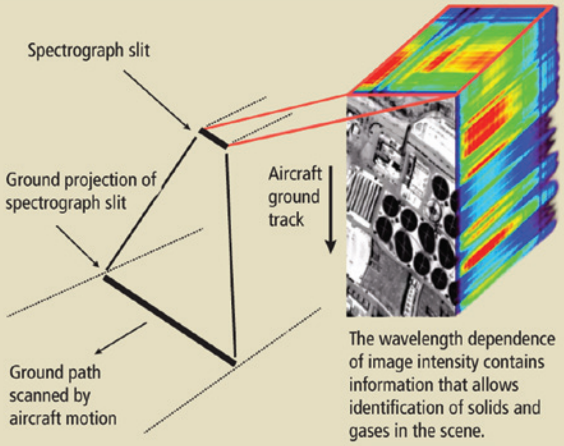
Fundamentals of Spectral Imaging

Spectral imaging is an umbrella term that encompasses all techniques whereby the electromagnetic radiation recorded from a given scene is resolved according to wavelength. Historically, the number of channels into which the light is divided has determined the nomenclature. Hence, systems with less than 100 spectral channels are termed multispectral, those with between 100 and 1000 channels are hyperspectral, and those with more than 1000 channels are ultraspectral. Most of the systems used at Aerospace fall into the hyperspectral range, but it is worth noting that modern parlance is tending away from these arbitrary divisions in favor of the more inclusive terminologies, "spectral imager" and "imaging spectrometer."

The vast majority of imaging spectrometers operate in the visible-through-shortwave-infrared (VSWIR) spectral region, which is dominated by reflected and scattered solar radiation. In contrast, the thermal infrared region, comprising the midwave infrared (MWIR) and LWIR, not only offers technical challenges distinct from those of the VSWIR, but also accesses an entirely different range of phenomenologies because at these wavelengths the solar contribution is negligible and measurements depend on thermal emission originating from the scene itself.

There is considerable overlap between the possible applications for each type of imager, but the reliance on dissimilar phenomenologies (and the fact that VSWIR systems are only operable in daylight, while thermal infrared systems can operate throughout the diurnal cycle) means that the two classes of instrument are essentially complementary. Because these imagers can resolve the spectral content of the radiance from a scene, it becomes possible to carry out sophisticated analysis of the resulting data stream to infer physical and chemical properties of the observed surface and the intervening atmosphere. Airborne and space-based spectral imagers are of primary importance in surface compositional mapping, land use and ecology, and atmospheric trace gas distribution.

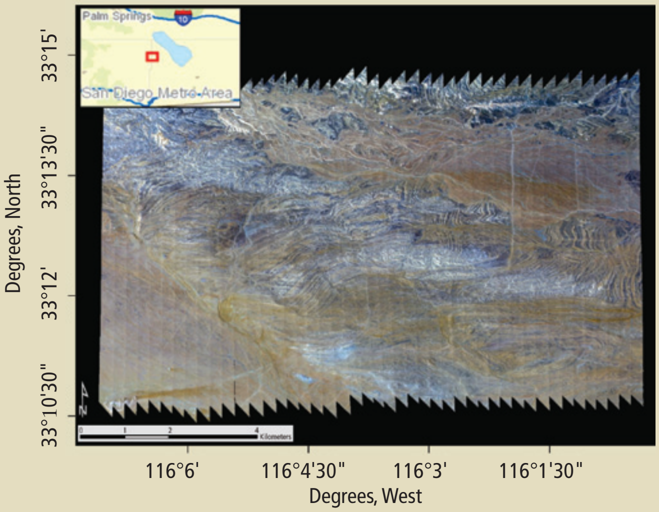
Aerospace's emphasis on hyperspectral thermal infrared imagery recognizes that full exploitation of such sensors lags well behind VSWIR, for which many commercial imaging services are now offered.



In the pushbroom spectral imager, each cross-track spatial pixel (1, …, N) is dispersed perpendicular to the platform motion vector so that individual wavelength bins can be separately resolved by the M pixels of the N × M focal plane array.

Aerospace LWIR Instrumentation

The research described in this article was possible in part by airborne deployments of the Spatially Enhanced Broadband Array Spectrograph System (SEBASS). First commissioned in 1995, SEBASS is a nadir-viewing, roll-compensated, pushbroom hyperspectral imager comprising two spectrographs, one operating in the midwave infrared (MWIR) region at 2.9–5.2 microns, and the other in the LWIR region at 7.8–13.4 microns. Each uses a single cooled focal-plane array with 128 spatial pixels and 128 spectral pixels. While SEBASS is a thoroughly field-proven system, its narrow field-of-regard (125-meter swath from an altitude of 3000 feet) limits the area that can be covered during a typical flight and thus constrains the scope of the studies it can support. Future investigations will alleviate this shortcoming by employing a wide-swath, three-axis-stabilized, whiskbroom hyperspectral LWIR instrument (named Mako) that concluded its inaugural airborne trials in September 2010. Built under an Aerospace corporate research initiative, Mako will offer up to 15 times the SEBASS areal coverage rate while matching its radiometric performance and spatial resolution.



False-color LWIR radiance image mosaic acquired by Mako in a single 4-minute pass over an area of exposed complex geological structure in California's Imperial Valley. To cover the equivalent area with SEBASS would require 45 passes and more than 3 hours of flight time.

Aerospace is also completing a NASA-funded effort to develop a 32-channel LWIR imager optimized for retrieving surface composition and atmospheric trace gas content. The instrument, named MAGI (Mineral and Gas Identifier), will have three-axis-stabilized whiskbroom scanning ability for wide-swath performance suited to Earth science applications. Both Mako and MAGI feature novel compact spectrometer designs that can operate at low f-number with low optical distortion. Each is intended for use in fundamental science investigations and to function as test beds to assist in the definition of future space-based instrument concepts.

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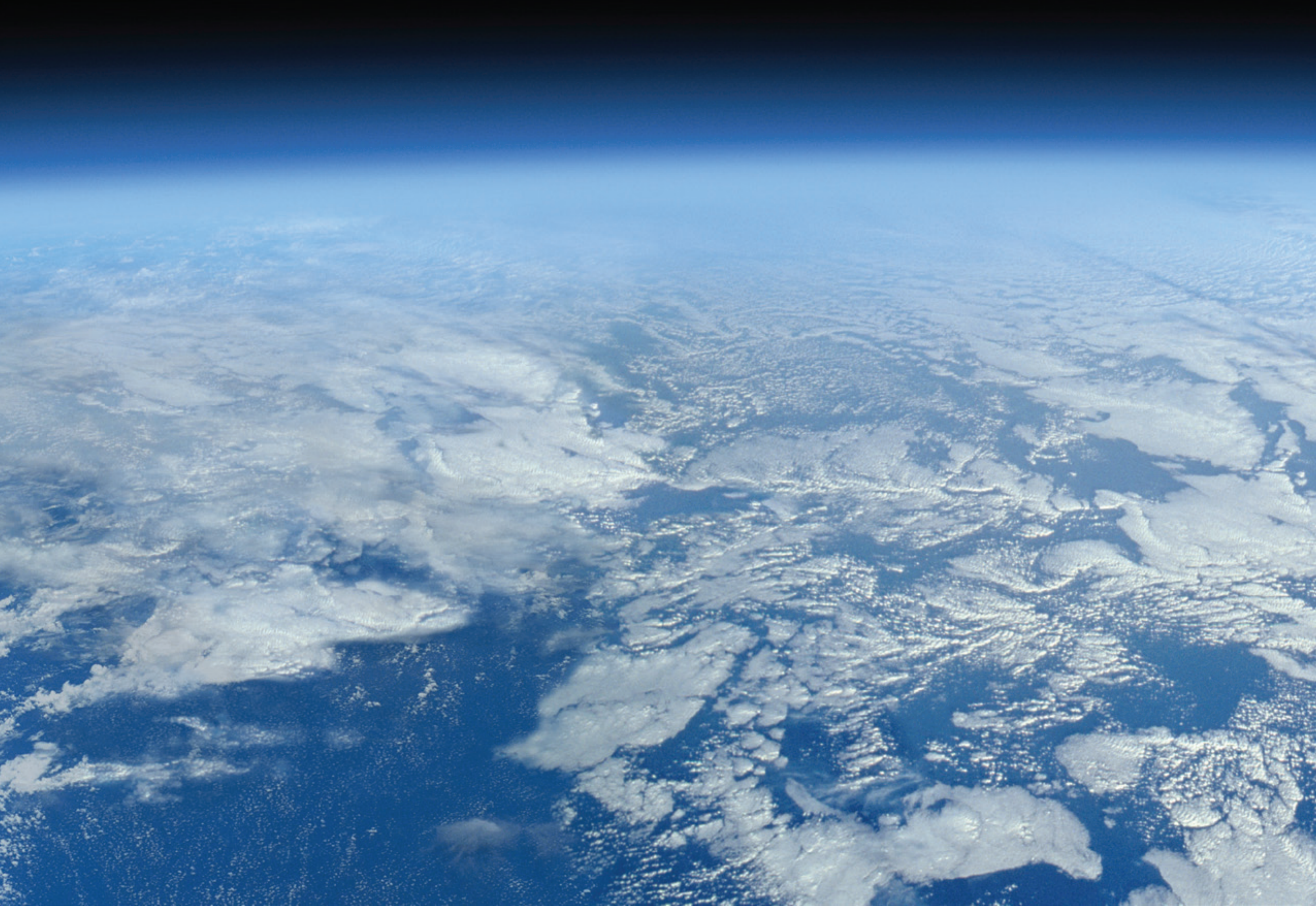
Rocket Soot Emissions and Climate Change

Scientists at The Aerospace Corporation have been studying the effects of rocket launch emissions on the atmosphere in anticipation of growing trends in space launch activities.

Martin Ross



Photos courtesy of NASA

If the space transport industry grows significantly in coming years, whether by tourists traveling to space or crew and cargo heading to the International Space Station or beyond, emissions of black carbon (soot) from increased rocket launches could contribute to global climate change, according to a recent study by scientists at The Aerospace Corporation. Black carbon particles efficiently absorb the sun's visible light and so can increase solar heating in the atmosphere, similar to the way carbon dioxide and other greenhouse gases increase heating by absorbing Earth's infrared light. Additional thermal energy from particles heated by the sun can change the overall circulation of the atmosphere and cause regional changes in temperature, ozone, and other atmospheric parameters from the surface to the top of the atmosphere.

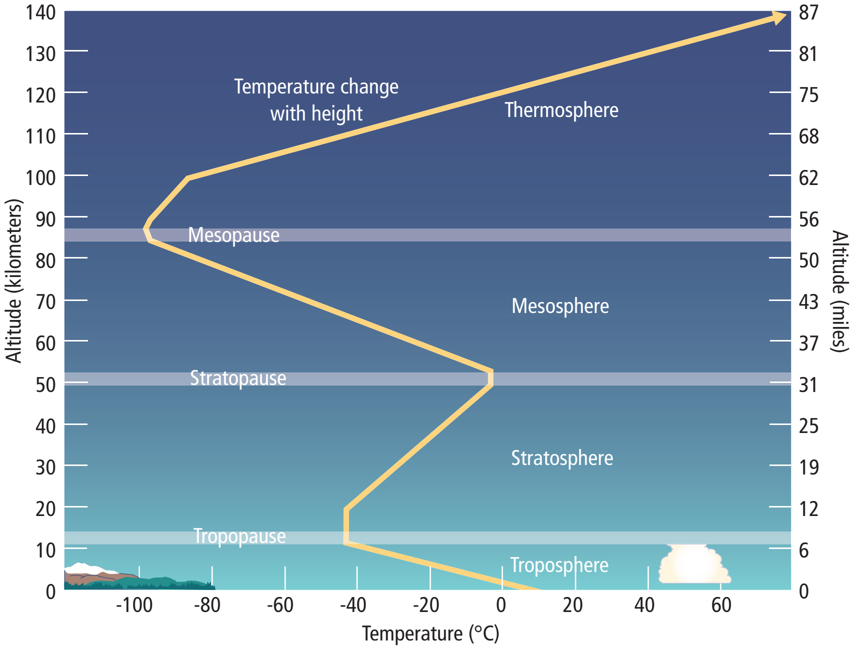
Black Carbon

Black carbon particles from all global sources play an important part in global change, likely second only to carbon dioxide in adding heat to the atmosphere. It may come to pass that regulation of black carbon—rather than carbon dioxide—will be the first path that the global community takes as it tries to deal with ongoing climate change. It is prudent then that the space industry understands exactly how much black carbon rockets emit and what unique effects these rocket emissions have on the Earth climate system.

The Aerospace study has shown that black carbon particles emitted by hydrocarbon-fueled rockets could play a role in climate change in coming decades. Funded by the Aerospace Research and Program Development Office and other agencies, it is the first study of the effects that rocket exhaust could have on the climate system. Black-carbon particles produced by hydrocarbon-fueled rockets could be significant because rocket exhaust is the only direct source of human-produced compounds in the atmosphere above approximately 20 kilometers (12 miles). Rockets also emit carbon dioxide, water vapor, and other compounds that absorb thermal energy, but soot particles have possibly the greatest potential—on a kilogram-for-kilogram basis—to promote climate change. This is the fundamental point of the work.

The authors of the study believe that a fast-growing suborbital launch market could develop over the next decade, with perhaps as many as 1000 suborbital rocket flights per year. This scenario is based on business and government plans and analysis for suborbital commercial space flights, which suggest that such a high launch rate market could be established in approximately a decade. While it is difficult to predict exactly what the space transport sector will look like in 2020, the emission scenario assumed for this climate study is a plausible extrapolation of current efforts and plans. The calculations are based on one of the world's most respected global climate models, the Whole Atmosphere Community Climate Model (known as WACCM), maintained by the National Center for Atmospheric Research in Boulder, Colorado.

Stratospheric Changes



The envelope of gas surrounding Earth changes from the ground up. Distinct layers are identified in the graph, each of which is bounded by a "pause," where the greatest changes in thermal characteristics, chemical composition, movement, and density occur.

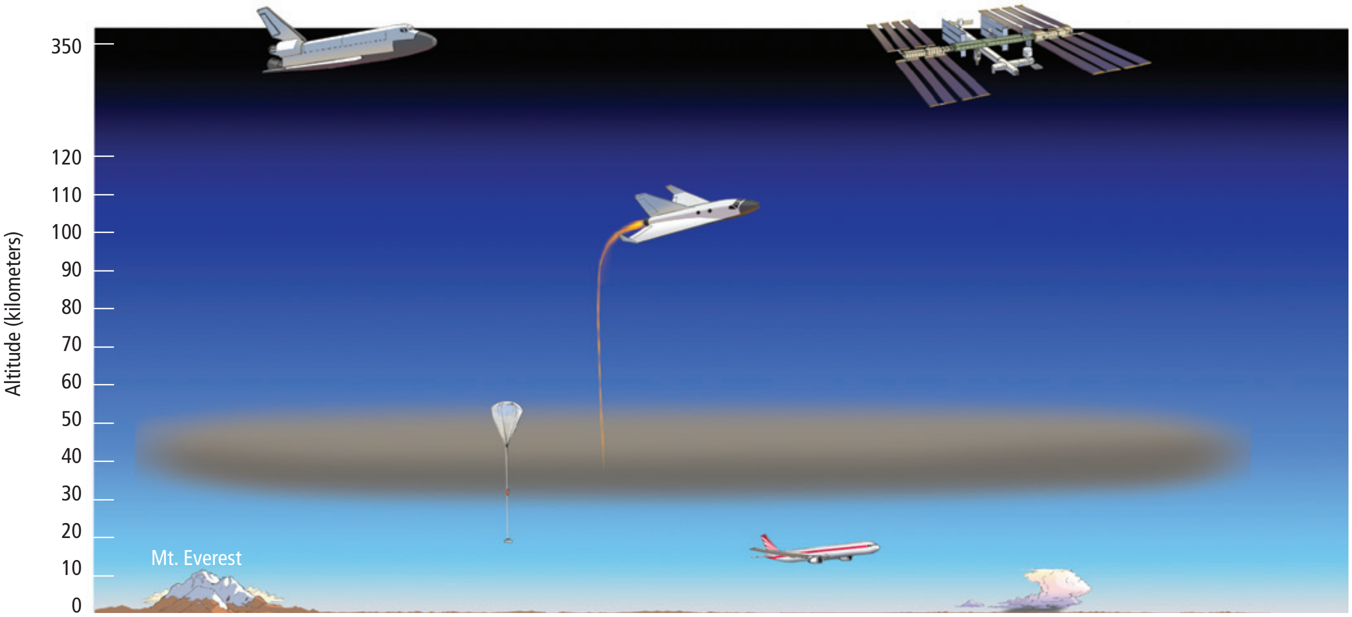
Two main characteristics of black carbon particles emitted by rockets combine to create the potential for significant—and possibly surprising—changes in the atmosphere. First, small particles emitted directly into the stratosphere have lifetimes of years, so soot from many launches will accumulate in the stratosphere to absorb sunlight that would otherwise reach Earth's surface. The soot from about four years of launches from suborbital rockets is estimated to gather into a thin cloud about 40 kilometers (24 miles) above the surface, an altitude three times higher than where typical airline traffic travels. Second, while rockets burn much less fuel than airliners, rockets emit up to one thousand times more soot per amount of fuel burned than aircraft. Coupled with the much longer lifetime of rocket soot, the potential effect of rocket exhaust is amplified and could cause larger changes in atmospheric heating than the soot emitted by jet aircraft across the globe. Even though the amount of propellant burned by rockets—and so, too, their carbon dioxide emissions—is small compared to the fuel burned each year by the aviation industry, the accumulation of stratospheric soot could represent a net additional heating, or radiative forcing, on the atmosphere comparable to all of aviation.

One key point of the study is that the particles emitted by rockets into the stratosphere, which have been overlooked in other accounting of climate effects, have a far greater impact on direct radiative forcing than rocket emissions of carbon dioxide. Radiative forcing is a metric used by scientists to compare how different emissions and Earth system changes can affect climate. Radiative forcing measures how much extra energy Earth and its atmosphere absorb after being modified by human-caused or naturally occurring changes. The Aerospace study shows that the radiative forcing of soot from a given hydrocarbon rocket scenario is as much as 100,000 times that of the carbon dioxide from the rockets. (In comparison, the radiative forcing of soot emitted by jet aircraft is less than one-tenth of the forcing from its carbon dioxide.) Because rocket soot has such an outsized radiative forcing compared with that of rocket carbon dioxide, an assessment of the climate impact of hydrocarbon rockets must account for the soot, or the assessment will have not accounted for most (> 99.9 percent) of the impact.

Complex Patterns

The idea that rocket soot accumulates in the stratosphere, absorbs sunlight, and adds thermal energy to Earth's atmosphere in a sensitive region—the middle stratosphere—is not much in doubt. Predicting how Earth's atmosphere responds to this added heating is the difficult part. The WACCM model predicts a subtle, but global in scope, change in the circulation of the atmosphere. While the overall result is that more solar radiation is absorbed by the atmosphere, the temperature response is a complicated pattern with warming in some regions of the planet and cooling in others. Earth's surface in the midlatitude regions tends to cool by about one degree Fahrenheit; the polar regions can warm or cool by up to five degrees, depending on the season. This complicated pattern does not sound like "global warming," but the rocket soot has caused a "global change" in the atmosphere. Some areas will cool and some will warm, varying seasonally, but the overall net effect is to add a little more solar heating to the atmosphere that would not otherwise be there.

The same idea applies to ozone as well, through feedback effects between ozone and the overall circulation. Some atmospheric regions gain ozone, and others lose ozone—so some areas on Earth will experience a slight thinning of the ozone layer, and others a slight thickening. As a whole, however, circulation changes caused by the black carbon heating only moves ozone around, changing its distribution, but does not significantly change the total amount of ozone in Earth's atmosphere. Thus, black carbon will not deplete ozone in the global sense like the long banned chlorofluorocarbons, but the soot-induced changes in circulation will cause a slight redistribution of existing ozone. Since Earth's climate balance depends partly on ozone, the ozone redistribution can also affect climate in a complex feedback loop.



A cloud of rocket soot may accumulate at about 25 miles over the Northern Hemisphere.

The essential point of the study is that soot emissions from the space launch industry could become, under some growth scenarios, a significant component of the total climate forcing associated with the transportation sector of the global economy. This conclusion follows from the output of a highly credible global climate model and inputs from future launch and emissions scenarios. The model predictions are large enough for climate scientists to consider soot from rockets a potentially important future impact, something to keep an eye on and understand better.

Current launches of hydrocarbon-fueled orbital rockets—including the Atlas V, Soyuz, Falcon, Zenit, and others—emit less than one-tenth the mass of black carbon particles into the stratosphere than is implicit in the fast-growth suborbital scenario, so the practical concern is small for now. Still, many scientists believe that rapid growth is inevitable for commercial rockets, and because many of these new rockets rely on hydrocarbon fuel, this growth would substantially add to stratospheric soot emissions. Significant investments are being made across the commercial, civil, and military sectors in hydrocarbon rocket engines without a full understanding of their impact on the global atmosphere. While there are currently no regulations that control injection of radiatively active particles into the stratosphere, whether on purpose (e.g. so-called geoengineering) or as a by-product of space transport, this groundbreaking study clearly indicates that a full understanding of their effect is prudent because unnecessary or overly restrictive regulations often result when policy makers have inadequate information.

The Path Forward

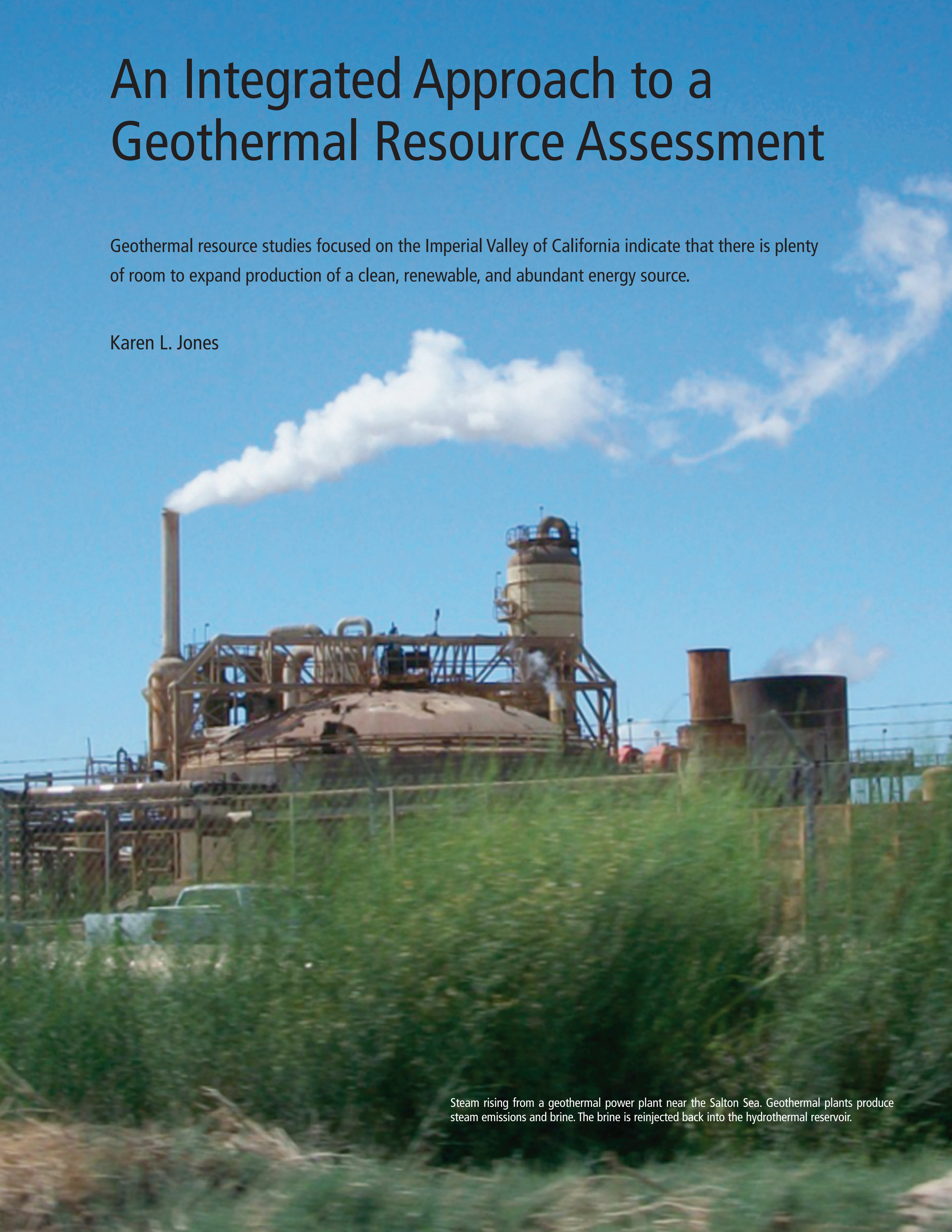
The questions raised by this study are many. How much soot do the various hydrocarbon engines actually emit? How does the emission vary from rocket to rocket? How accurately do the global models predict the accumulation of the rocket soot? What is the impact of rocket soot–induced changes on important atmospheric parameters? Could there be other types of particles injected into the stratosphere by rockets—alumina from solid rocket motors, for example—that also have a significant effect, akin to that of the soot particles?

The study employed a respected computer model of Earth's atmosphere and made reasonable assumptions about inadequately known rocket emissions. Measurements of actual rocket emissions and ensemble runs of many different climate models must be performed before definitive conclusions can be drawn about the relationship between soot particles emitted by rocket engines and climate change. Scientists at Aerospace, in collaboration with those from other institutions, will continue to work and improve our understanding of this complex problem for many reasons. Scientifically, we need to better understand all of the emissions and atmospheric processes that together determine Earth's climate and its variability. More directly, we must understand how space transportation fits into the overall picture of global climate change to ensure sustainable space industrial development in the twenty-first century.

An Integrated Approach to a Geothermal Resource Assessment

Geothermal resource studies focused on the Imperial Valley of California indicate that there is plenty of room to expand production of a clean, renewable, and abundant energy source.

Karen L. Jones



Steam rising from a geothermal power plant near the Salton Sea. Geothermal plants produce steam emissions and brine. The brine is reinjected back into the hydrothermal reservoir.

Global energy use during the past 20 years has increased 70 percent and is expected to climb as developing countries continue to grow and industrialize. Such increasing demand and high consumption rates can threaten U.S. access to energy and raw materials, with potential implications for national security. Developing renewable energy from natural sources within the United States can reduce that risk.

In California, interest in geothermal resources has been growing because of the state's mandate to generate 33 percent of its power from renewable sources by the end of 2020 and the availability of federal funds for energy sector renewable infrastructure. As a result, the Imperial Valley of Southern California has become the focus of investigation for renewable energy and the target of numerous solar and geothermal energy projects.

The hot and arid Imperial Valley produces more than $1 billion in crops annually. These crops are fed by the Colorado River, which is routed to the valley through the All American Canal. In 1936, after discovering the potential for low-cost hydroelectric energy from the canal's five waterfalls, the Imperial Irrigation District joined the power industry, becoming the sixth largest utility in California.

Seeking to expand its service and capacity, the Imperial Irrigation District asked The Aerospace Corporation to provide an assessment of its lands near geothermal areas of interest. The goal was to help establish a cost-effective development strategy for locating and tapping sources of geothermal energy. Working from multiple sources, Aerospace compiled information on surface and subsurface geology and organized the geospatial data into a Geographic Information System, which the district now uses as the basis for its exploration and land-management strategy.

Geothermal Energy

Since the early twentieth century, geothermal heat has been exploited to produce energy. Geothermal power plants operate in nine states: Alaska, California, Hawaii, Idaho, Nevada, Utah, New Mexico, Oregon, and Wyoming, and produce approximately 3,102 megawatts—or enough energy to power 2.4 million homes. A recent U. S. Geological Survey assessment of the nation's geothermal resources found that:

- The mean estimated power from undiscovered geothermal resources could provide an additional 30,033 megawatts.
- Another 517,800 megawatts could be generated from enhanced geothermal systems by fracturing and stimulating hydrothermal reservoirs.

Typically, geothermal prospectors seek three critical elements—heat, a heat-transfer medium (usually water), and a permeable reservoir that can produce hot water. Earth's temperature increases with depth from the surface, and the change in temperature per unit distance is called the geothermal gradient. When the geothermal gradient is high and there is sufficient water to transfer the heat, energy can be generated by drilling and producing hot water.

Marvin Glotfelty, a hydrogeologist with Clear Creek Associates, examines a mud volcano near Wister, California.

This water is usually brine, having high concentrations of total dissolved solids. The hot brines can be brought to the surface, where they flash (burst into steam) and drive a turbine to generate electricity—this is called a flash steam plant. If the brine is insufficiently hot, the heat can be transferred to a secondary liquid that can flash at a lower temperature—this is known as a binary plant. The brine can be reinjected into the reservoir to ensure that the resource is sustainable and that surface water, aquifers, and soils are not contaminated.

The Salton Trough

The Imperial Valley lies within an area known as the Salton Trough, a topographic and structural feature that extends from southeastern California into Mexico. The area is located in a complex tectonic environment where the North American plate transitions from a transform boundary (an area where Earth's plates slide in opposite directions—e.g., the San Andreas fault) to an extensional boundary (an area where Earth's plates spread apart from each other, allowing new crust to form between them, e.g., the East Pacific Rise in the Gulf of California).

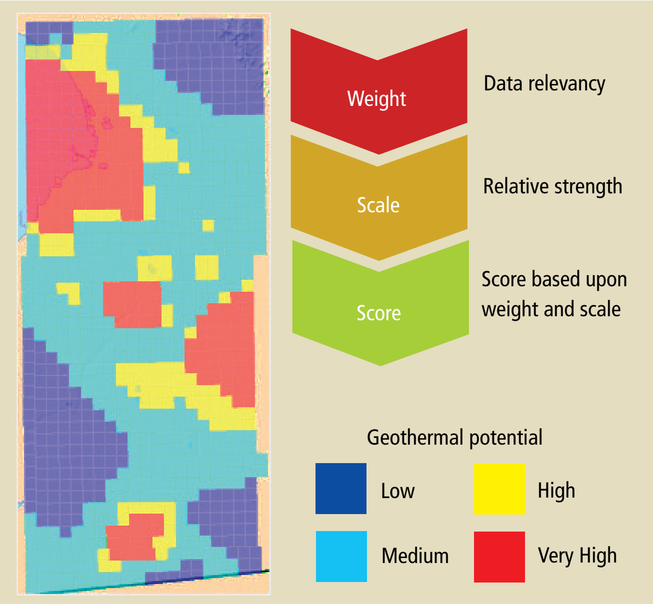
The Salton Trough, which is about 130 miles long and up to 70 miles wide, is a landward extension of the Gulf of California, which began forming by seafloor spreading approximately four million years ago. In fact, the trough was once part of the Gulf of California. The Salton Sea now occupies the lowest part of the trough, which sits more than 200 feet below sea level.

Within the Salton Trough, several geothermal fields (designated as known geothermal resource areas) situated over local zones of extension allow magmas from Earth's mantle to intrude and heat up the sedimentary strata. Reservoir temperatures within these zones are often greater than 260°C (500°F).

Why Geothermal Energy?

Four main factors make geothermal energy appealing: geothermal kilowatt hours are generally cost competitive with conventional sources of energy; the production of geothermal energy is not associated with significant release of greenhouse gases or waste generation; unlike solar and wind power, geothermal power is predictable and typically supplies uninterrupted energy; and the United States and the world have significant unexploited geothermal resources.

Geothermal energy is one of the least land-intensive energy production options available, second only to nuclear energy. By contrast, other energy sources are often characterized by extensive aboveground infrastructure (such as hydroelectric dams and nuclear plants) that are exposed, more vulnerable, and capable of creating significant impact to surrounding land use.



A geographic information system-based prioritization matrix was developed, based upon a myriad of relevant information. Red and orange areas are highly prospective for geothermal resources.

Although some geothermal exploration occurred between 1927 and 1954, the actual emergence of geothermal energy within the Imperial Valley began in the 1960s and 1970s with the drilling of several wells leading to private generating plants in the early 1980s. The first commercial geothermal well was commissioned on January 1, 1964, near Niland, California.

Twenty geothermal energy plants from five geothermal fields currently produce hot brine, which flows to the surface and powers electrical generators. As a result, the Imperial Valley receives more than 617 megawatts of geothermal electricity—enough energy to power more than 600,000 homes.

Aerospace and the Imperial Irrigation District

Working closely with the Imperial Irrigation District, Aerospace formed an assessment team with Clear Creek Associates, a groundwater consulting firm based in Scottsdale, Arizona. The team's ability to assimilate surface and subsurface data from multiple sources and generate a three-dimensional interpretation of the hydrothermal system provided the basis for the district's geothermal energy exploration strategy.

Each township (6 × 6 miles) was divided into 36 cells, with each cell covering a square mile. The cells were ranked on a scale of 2 to 31, with the higher scores having the greatest geothermal potential. The scores were based on four criteria, arranged according to priority: surface manifestations (garnered from satellite and airborne remote sensing data and field observations), Bouguer gravity data, geothermal gradients, and presence within a known geothermal resource area. Resistivity data were also considered in the scoring.

Surface Data—Airborne and Satellite Imagery

A linear string of mud pots and mud volcanoes on the southeastern coast of the Salton Sea displays evidence for a southern extension of the San Andreas Fault that runs through the Salton Sea. The mud volcanoes are cones of mud built up by viscous hot mud that bubbles up through vents. Mud pots occur in the same area as mud volcanoes, but they are enclosed basins and appear as depressions with bubbling hot muddy water. Both geothermal features result when water and gas are forced upward through sediments. These features are strongly associated with volcanic and seismic activity, active plate boundaries, and hot spots—key indicators for subsurface hydrothermal systems.

Other visible signs of active hydrothermal systems are the fumaroles or gas vents throughout the Salton Trough area. These fumaroles are the result of hot gases (primarily carbon dioxide) migrating to the surface by way of active faults and fractures. A series of small fumaroles are also located near the eastern edge of the Salton Sea—a marsh area that has become a bird sanctuary. These fumaroles were observed in the field as continuous bubbles emerging from the shallow waters of the marsh. Many similar geothermal indicators lie under the shallow waters of the Salton Sea and are thus surveyed only with difficulty; however, airborne hyperspectral thermal-infrared imagery provides a means for readily locating and monitoring such features.

Aerospace provided airborne hyperspectral data and analysis over a portion of the district's area of interest using the SEBASS (Spatially Enhanced Broadband Array Spectrograph System) hyperspectral sensor. Aerospace captured evidence of a large fumarole field within the Mullet Island

Mud pot with actively bubbling CO_2. Mud volcanoes are in the background. The location is in the Wister unit of the Imperial Wildlife Area, California.

Utility-Scale Geothermal Production at Military Bases

Geothermal energy has a significant role to play at many military bases. The U.S. Navy, for instance, currently produces 250 megawatts from its Coso geothermal field near Ridgecrest, California—enough energy to serve approximately 190,000 homes. Not only does the Navy generate free electricity for the base, it produces over $380 million per year in revenue by selling excess energy to the grid.

The U.S. Air Force has an energy plan that calls for it to develop and use renewable and alternative energy to reduce greenhouse gases. The plan states that there are strategic and security implications for generating energy on-site "to enhance operational efficiencies and insulate operations from grid disruptions."

As the Air Force seeks ways to generate renewable energy, Aerospace's approach to geothermal resource assessments can provide insight and a basis for a land management and drilling strategy. Certain Air Force properties offer excellent potential to generate carbon-free electricity. Nellis Air Force Base in Nevada, which is adjacent to the Nevada Test Site, shows evidence of past and present geothermal activity and is on par with established geothermal resource areas. Other high-potential renewable energy Air Force bases include Hill Air Force Base, Utah; Kingsley Field Air National Guard Base, Oregon; Gowen Field Air National Guard Base, Idaho; and Luke and Davis-Monthan Air Force Bases, Arizona.

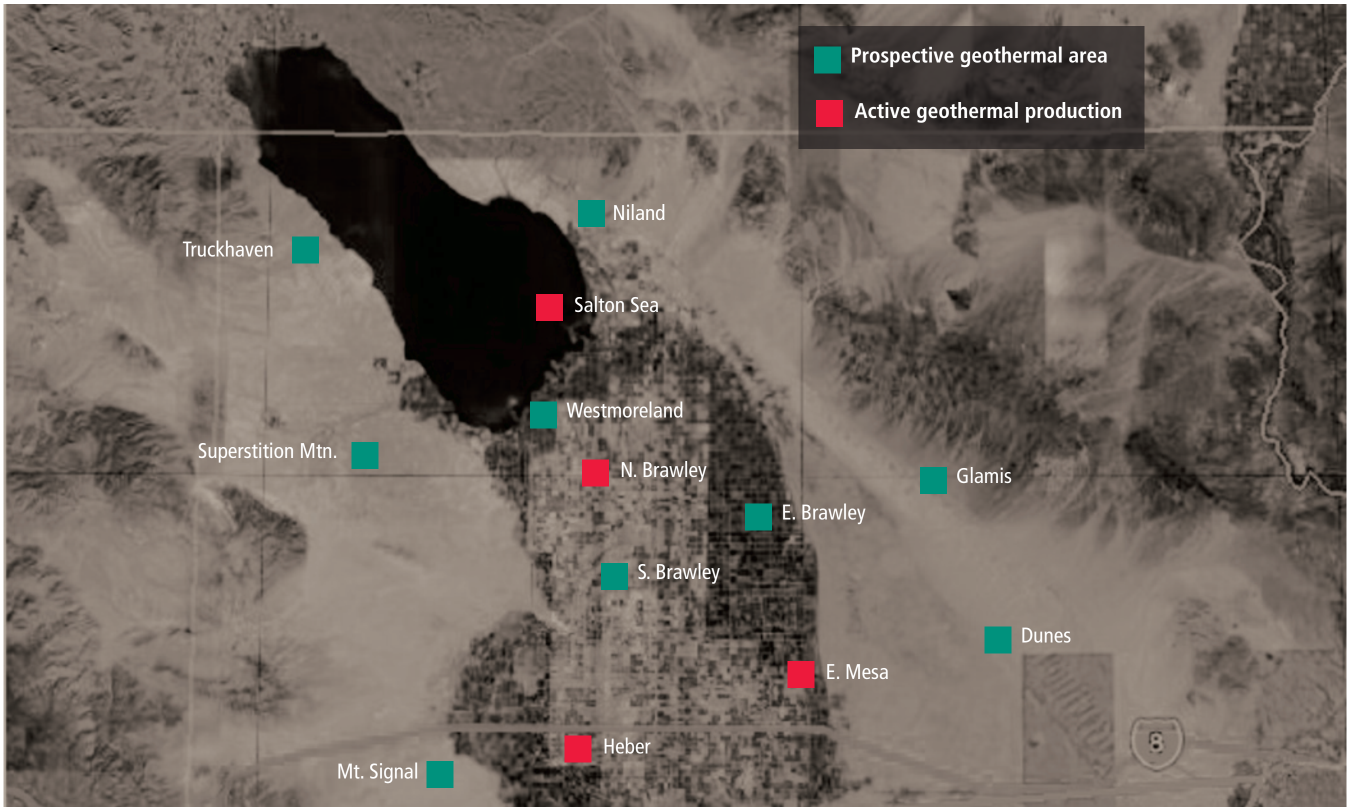
Thermal Anomaly at the edge of the Salton Sea. Some of these fumaroles exhibited core temperatures of more than 60°C and were well resolved by the SEBASS sensor. The team also assembled available imagery from ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), an instrument aboard a satellite in NASA's Earth Observing System. ASTER is a multispectral system and captures imagery in 14 bands from visible to thermal infrared wavelengths. In general, the ASTER thermal maps indicate that surface temperatures reflect general land-use patterns. Further investigation is needed over areas with little human interference to determine the utility of ASTER data for detecting thermal anomalies associated with subsurface hydrothermal systems.

Aerospace also used the SEBASS hyperspectral data to identify minerals, which could indicate previous geothermal activity; however, most of the minerals seem to be associated with human-made features—for example, roads, berms, and agricultural tracts. Moreover, surface drainage and shallow sea deposits influence the distribution of minerals. Because of these significant and natural surface-level disturbances, garnering as much information as possible from subsurface indicators is critical.

Subsurface Data—Bouguer Gravity, Geothermal Gradients, and Resistivity

Clear Creek Associates compiled data using available reports, files, maps, well logs, and other geologic and hydrogeologic information to evaluate geothermal potentials of land owned by the district. Bouguer gravity data were obtained from Shawn Biehler at the University of California-Riverside. High Bouguer gravity values have been shown to be associated with geothermal resources in the Salton Trough and may be related to upwelling of denser materials from Earth's mantle; low values are associated with thicker crust that does not allow for heat transfer. Clear Creek Associates noted that the lower land elevations in the Salton trough and the thinner crust is indicative of dense, oceanic style crust—perhaps associated with mantle upwelling and emplacement of intrusive rocks. Such movement was consistent with the tectonic setting of the Salton Trough as an area with both rifting (pulling apart) and transform (moving horizontally) faulting.

Geothermal gradients for approximately 200 wells in the areas were calculated using data from the California Department of Conservation. The relative thermal gradients were recorded, scored, and arranged according to priority within a matrix to evaluate the geothermal resource potential of the area. Typically throughout Earth, the geothermal gradient is 25–30°C per kilometer of depth; however, the Salton Sea is characterized by unusually high geothermal gradients, in excess of 200°C per kilometer. For the matrix scoring, the team gave greater weight to high geothermal gradients.



Twenty geothermal plants from five geothermal fields currently produce 617 megawatts of energy. Over the next several years, more prospective geothermal areas within the Salton Trough in California will start producing energy. It is estimated that the Salton Trough is capable of producing 2488 megawatts of renewable energy—enough to power approximately 1.9 million homes.

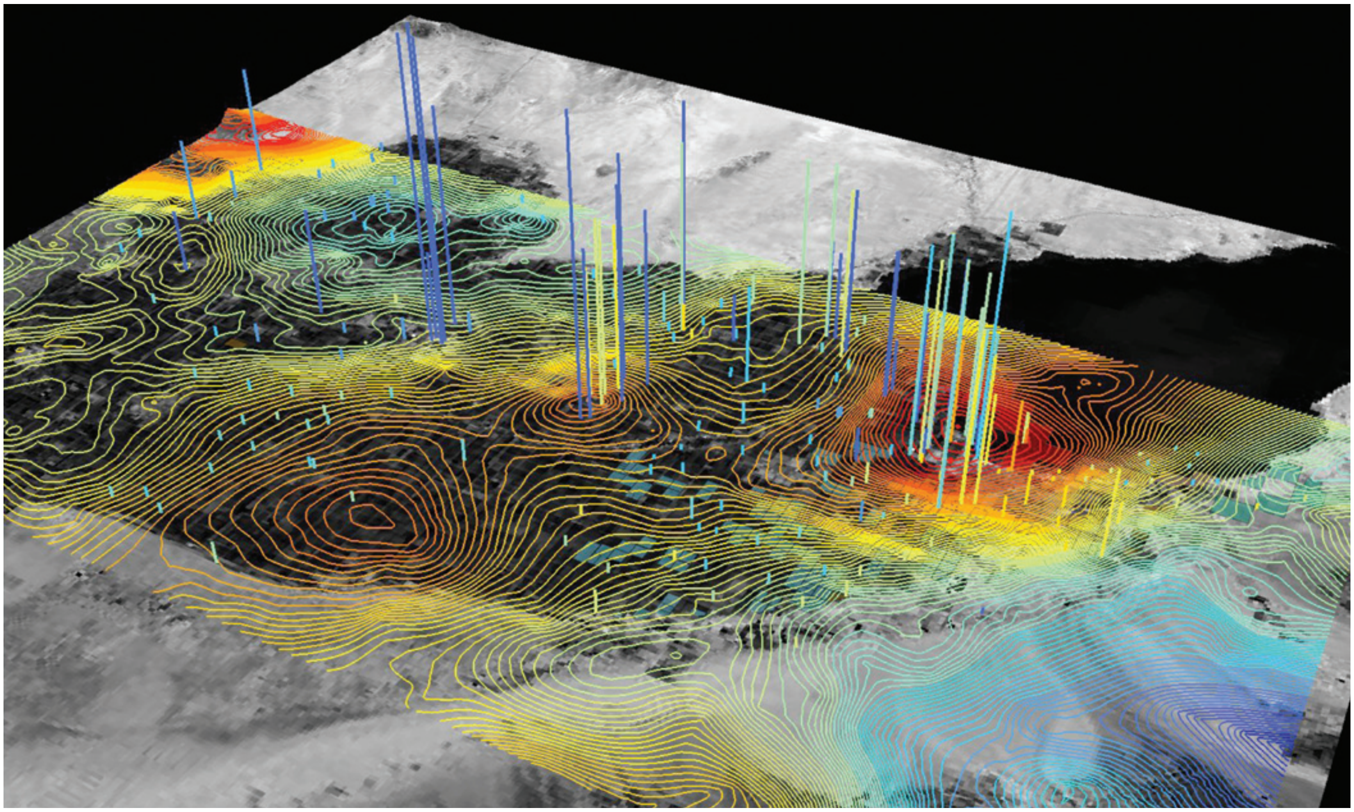
The geothermal assessment team also acquired and incorporated resistivity survey data, which became critical input for the delineation of geothermal resource areas. Resistivity surveys have been the traditional method of exploring for geothermal resources in other areas, but this method has been secondary to gravity surveys in the Salton Trough. The resistivity survey is a geophysical measurement to locate subsurface features by mapping the way Earth conducts an electrical current. The principle is that resistivity of solution-saturated rocks will decrease as the salinity of the solution increases. Salinity generally increases with temperature, so resistivity generally decreases (or conductivity increases) as temperature rises. A particular type of resistivity survey, natural source magnetotelluric survey, has been successful in identifying hot, briny water that is more conductive than the background water. Schlumberger Ltd., an oilfield services company, conducted a magnetotelluric survey in 2009 and completed four resistivity lines over the area of interest on behalf of the California Energy Commission. The resistivity survey found that the upper three kilometers consisted of three layers: a thin (300–600 meters) surface cap of approximately 1 ohm meter (i.e., cap rock); a low-resistance layer that is extremely conductive at approximately 0.2–1.0 ohm meter (i.e., hot brine reservoir); and a relatively resistive basement at greater than 1.0 ohm meter (i.e., dense deep basement rock).

The conductive second layer appears to be the reservoir rock for supersaline thermal fluids, while the thin upper layer is composed of surficial trough sediments. The resistivity data further helped define the depth and geometry of the hot supersaline reservoir.

Geographic Information System Integration

The geothermal assessment team integrated the multimodal geospatial information (satellite, airborne, resistivity, and gravity data as well as field observations and thermal gradients) into the Geographic Information System. The team created a matrix that arranged in priority the weighted values for surface and subsurface survey data. The weighted values were assigned based upon the relevancy and accuracy of the data. This priority-coded matrix has become the basis for the Imperial Irrigation District's land management and geothermal exploration and drilling strategy.

The team also worked with the district to develop a priority matrix that provided weighted factors for various data inputs and cumulative scores. The district was then able to rank its land parcels and develop land management and drilling strategies as part of its geothermal exploration plan. For instance, high scores could indicate a drillable prospect, and low scores would indicate areas that the district might want to lease or farm out.



A Bouguer gravity anomaly contour map was compared to geothermal gradients from wells at various depths. High geothermal gradient wells generally coincide with gravity anomalies. Wells with lower geothermal anomalies, however, might not be relevant because of the cooling effects of circulating drilling muds for those wells, which were not shut in for sufficiently long periods of time. In general, for the Salton Trough region, gravity data seems to provide the most reliable indicator for geothermal resources.

Conclusion

The Aerospace Corporation is in a unique position to apply its natural-resource-assessment technologies and expertise to evaluate the feasibility and value of geothermal energy resources. Beyond the priority matrix and geothermal assessment of the Imperial Irrigation District's lands, this project demonstrated the effectiveness of developing a geological understanding of a region by compiling independent surface and subsurface data from a variety of sources. Multiple layers of geospatial data in a geographic information system can be integrated, analyzed, and prioritized to provide actionable information to decision makers. Aerospace maps and priority matrices were integrated with existing data to allow the district to continue to manage, analyze, and work with the information in the future.

Acknowledgment

The author would like to thank Clear Creek Associates; Patrick Johnson, Stephen Young, and David Tratt of Aerospace; Shawn Biehler; The California Division of Oil and Gas and Geothermal Resources; and Schlumberger.

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Feasibility of Space-Based Monitoring for Governance of Solar Radiation Management

Preliminary analysis at Aerospace suggests that detecting tests of particle injection schemes from space will be quite challenging, especially for unannounced small-scale, localized trials with short-term observable effects.

Patrick L. Smith, Leslie A. Wickman, Inki A. Min, and Steven M. Beck

Climate researchers and theorists have suggested that industrialized nations could combat global warming by injecting aerosols—sulfur dioxide, aluminum oxide, or manufactured nanostructured particles—into the stratosphere to actively manage the amount of solar radiation that filters through. Proposed means for lofting these aerosols into the stratosphere include large-caliber guns, rockets, balloons, tethered hoses, aircraft, and even via photophoresis (the process whereby small particles suspended in gas or liquid move away from a sufficiently intense light source).

As promising as this might appear at first glance, there are many potential downsides. The influence of aerosols and clouds is the largest source of uncertainty in climate models and forecasts, and the uncertainties and risks involved in particle injection are significant. Ideally, any experimentation with solar radiation management would be based on a global consensus regarding what strategy to pursue and how to pursue it. In reality, a single state might unilaterally attempt action. One reasonable fear is that a country may begin experimenting with solar radiation management, even at the risk of adversely affecting neighboring nations or the planet as a whole.

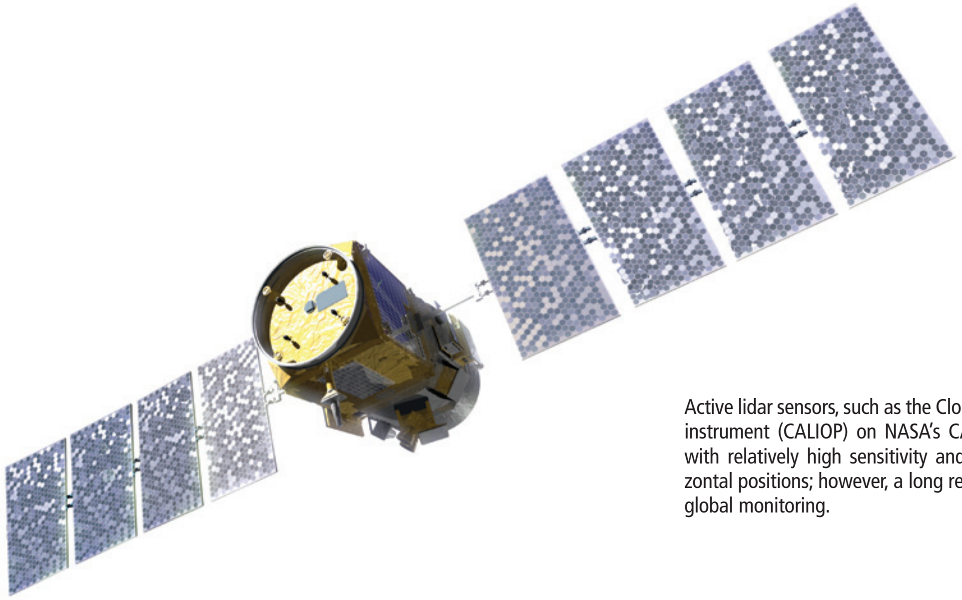
The Aerospace Corporation has been investigating how space-based sensors could be used to detect and track injected particles to help enforce any future international agreements concerning climate engineering and solar radiation management. Initial findings suggest that any effort to do so will be difficult.

A Postulated Scenario

A country or organization developing a particle-injection capability would need to conduct extensive developmental testing. Initial tests with natural particles like sulfur dioxide or aluminum oxide might be used to evaluate various injection methods and to quantify factors such as particle aggregation, dispersion, and persistence. These early experiments would lead to larger experiments and eventually to a full-scale test deploying a huge quantity of particles. Such a full-scale test would be easy to detect—but by then, it would be too late to do anything about it. The ability to detect small precursor tests would provide the international community with more options for intervening or possibly deterring unsanctioned activities altogether.

Developing a system to detect such activities presents an enormous challenge because of the wide range of unknowns—for example, the type of material released, particle size, amount released, altitude of release, release mechanism, and area of dispersion (initial density). In addition, the process of dispersion itself is highly variable: estimates of eddy diffusivity in the stratosphere can vary by more than an order of magnitude. Requirements for data access and dissemination, redundant verification, reliability, and operational control would be similar to current systems for monitoring arms control agreements. Geopolitical constraints and possible funding mechanisms would also be important considerations.

To determine the requirements for a space-based monitoring capability, Aerospace considered, as a typical scenario, a small clandestine test involving an aircraft release of 1 to 10 metric tons of precursor gases or engineered particles. Detecting this type of unannounced test (which could be conducted anywhere in the globe) would require nearly continuous global monitoring. The aerosol cloud would not stay together more than a few hours at detectable levels, and the detection threshold would vary greatly depending on background and sensor technique. The maximum size of the cloud at detectable levels might be on the order of a few kilometers. The high wind speeds and shear prevalent in the stratosphere would transport the cloud hundreds of kilometers downwind while shredding it into filaments. As a rough quantitative example, 1 metric ton of sulfur released over an initial volume of 10^7 cubic meters is estimated to have a mean particle density of 1000 particles per cubic



Active lidar sensors, such as the Cloud-Aerosol Lidar with Orthogonal Polarization instrument (CALIOP) on NASA's CALIPSO spacecraft, can detect aerosol layers with relatively high sensitivity and provide accurate aerosol heights and horizontal positions; however, a long revisit rate limits their suitability for continuous global monitoring.

Images courtesy of NASA

Aerospace Support to Global Climate Research

In addition to its primary mission to support defense and intelligence space system development, The Aerospace Corporation supports civil and commercial space activities, many of which involve global climate research. Most notable is the U.S. Geological Survey (USGS) Landsat program. Initially launched in 1972, the first Landsat missions were technology demonstrators that collected imagery and for the first time allowed global monitoring of the environment. Since then, Landsat satellites have continuously observed Earth.

In 1992, the Land Remote Sensing Act directed the federal government to begin Landsat 7 as a multiagency effort that involved the Air Force, NASA, NOAA (National Oceanic and Atmospheric Administration), and the USGS, among others. Aerospace first supported USGS with the Landsat 7 development project and with monitoring flight operations for the Landsat 5 mission. Today, it continues to provide daily support to USGS for these missions, and technical advice and leadership for the ongoing acquisition of the Landsat 8 data continuity mission. Aerospace is also participating in the USGS preformulation of a Landsat 9 acquisition project. Aerospace has been a major contributor to the lasting success and impact of the Landsat program, supporting flight operations management, investigating subsystem anomalies, and coordinating the numerous international ground stations that receive Landsat data on a daily basis.

At NASA, Aerospace has supported systems acquisition for missions such as ICESat (Ice, Cloud, and Land Elevation Satellite), which measured Earth's ice thickness and cloud property before its mission ended in 2010. Aerospace also supported NASA's Distributed Active Archive Centers, ground-based systems that process, archive, document, and distribute data from NASA's past and current research satellites and field programs. Aerospace's architecture studies and support of major system acquisitions led to faster delivery of more accurately calibrated products to atmospheric and land scientists around the world. Aerospace also supports systems acquisition for NOAA's weather and environmental satellites GOES (Geostationary Operational Environmental Satellite) and POES (Polar Operational Environmental Satellite). NASA is developing and plans to launch the NPOESS (National Polar Orbiting Environmental Satellite System) preparatory mission in 2011. Aerospace is supporting this mission, particularly in the areas of integration, testing, calibration, and validation for the sensors. The joint NOAA/Air Force NPOESS has been restructured into two separate missions with NOAA responsible for the Joint Polar Satellite System and the DOD responsible for the Defense Weather Satellite System. Aerospace will assist in the development of both of these systems.

The NASA Soil Moisture Active Passive (SMAP) mission developed by the Jet Propulsion Laboratory with assistance from Aerospace is scheduled to launch in 2011. This mission will measure Earth's soil moisture and freeze/thaw parameters with much higher accuracy than ever before and thus aid the hydrology, climate, meteorological, and environmental communities.

Looking to the future, Aerospace will continue to support NASA's Earth Science Technology Office as it seeks new technologies to sense, monitor, and process Earth science data that will one day help define and improve the models that describe Earth's processes and any anthropogenic impacts. Aerospace technical experts annually review more than 100 technology projects in this arena, and evaluate a corresponding number of new proposals dedicated to improving Earth sensing instruments and information technologies.

—Frank Donivan and Steve Covington

centimeter after 1 hour and 100 particles per cubic centimeter after 10 hours. This calculation assumes an eddy diffusivity value of 100 square meters per second horizontally and 0.1 square meters per second vertically. These concentration values would change greatly depending on the parameters and the modeling technique assumed.

System Requirements

The purpose of the clandestine tests would be to assess injection techniques and better understand the effectiveness of the particles in changing the albedo. Objectives would include demonstration of the delivery mechanism, observation of aerosol formation and growth rates, observation of particle dispersion characteristics, observation of vertical spreading and motion, observation of evolving particle size distribution and location, observation of particle attitude (where relevant), measurement of albedo levels, and validation of associated models.

In terms of space sensor requirements, these goals translate to an ability to quantify aerosol optical depth or extinction coefficients in the stratosphere as a function of wavelength, enabling an estimate of particle density and size distribution. Spectral information would also be used to discern particle composition. Specialized algorithms would have to be developed (most likely from ground-based reference test data) to differentiate particle shapes, orientations, and makeup. Quite a bit of uncertainty surrounds the derivation of these parameters from the directly observed radiance and backscatter measurements, so a significant research program would be needed to substantiate the baseline science and establish confidence in the retrieval methodologies.

Spacecraft	Sponsor	Purpose	Instrument	Sensor Type
POES	NOAA	stratospheric aerosols	AVHRR	advanced very high-resolution radiometer
CALIPSO	NASA-CNES	stratospheric aerosols	CALIOP	cloud-aerosol lidar with orthogonal polarization
CloudSat	NASA	stratospheric aerosols	CPR	cloud-profiling radar
Earthprobe	NASA	tropospheric aerosols, volcanic SO_2, AI	TOMS	total ozone mapping spectrometer (UV)
EnviSat	ESA	SO_2, tropospheric and stratospheric trace gases	SCIAMACHY	scanning imaging absorption spectrometer for atmospheric cartography
EOS-Aqua	NASA	atmospheric temperature, moisture, trace gases, SO_2	AIRS	atmospheric infrared sounder (spectrometer)
EOS-Aura	NASA	AOT, SSA, SO_2, O_3	OMI (ozone monitoring instrument)	hyperspectral UV-visible spectrometer
EOS-Terra	NASA	atmospheric, volcanology, AOT, AE, SSA, ASD, ASP	MISR	multiangle imaging spectroradiometer
GLORY	NASA	distinguish natural from man-made aerosols in atmosphere	APS	aerosol polarimetry sensor
GOES	NOAA/NASA	weather and atmosphere, stratospheric aerosols	VISSR	visible infrared spin scan radiometer
ICESat	NASA	PBALH, AOT, AEC, BC	GLAS	geoscience laser altimeter system
Meteosat Second Generation (MSG)	ESA	SO_2, ice	SEVIRI	spin-enhanced visible and infrared (rapid-scan, multispectral) imager
Odin	Sweden/CSA	NO_2, aerosols	OSIRIS (optical spectrograph and infrared imaging system)	infrared limb scanner
SeaStar	NASA	AOT, AC	SeaWiFS	Sea-viewing wide-FOV sensor
UARS	NASA	atmospheric concentration profiles of various chemicals such as HCl and SO_2	MLS	microwave (atmospheric) limb sounder

A number of atmospheric monitoring spacecraft are equipped with aerosol sensors. Key: AC: angstrom coefficient; AE: angstrom exponent; AEC: aerosol extinction cross section; AI: aerosol index; AOT: aerosol optical thickness; ASD: aerosol size distribution; ASP: aerosol size parameter; BC: backscatter cross section; PBALH: planetary boundary and aerosol layer heights; SSA: single scatter albedo.

The ability to accurately determine the altitude of an aerosol layer would be critical for determining its origin—but not sufficient in itself. For example, with the exception of volcanic aerosols and some phenomena associated with specific polar regions and seasons, natural clouds generally do not extend into the stratosphere. Thus, an aerosol cloud in the stratosphere could be a good indication of human intervention. However, at higher latitudes, jet aircraft do fly above the tropopause—so in these regions, it may be difficult to distinguish normal jet contrails and cirrus clouds from a particle injection test. Also, because observed instantaneous aerosol optical depth values can change by a factor of two or more from day to day, only very large spikes in sensor measurements would indicate intentional particle injections.

The required sensor revisit rate, spatial resolution, and measurement accuracy all depend upon the type of sensor, the dispersal rate, and other characteristics of the aerosol tests, especially during the first minutes to hours after injection. Other critical parameters to monitor (in addition to ambient conditions) are particle size distribution and spatial distribution as the plume spreads out.

System Architecture

The types of space-based sensors that would be most effective in detecting intentionally injected aerosols are passive multispectral imagers, both reflective and emissive, and active laser-based sensors or lidars. These two types of sensors have complementary advantages and deficiencies and would need to be used in combination to be most effective.

For sensors with nadir-viewing geometry, such as NASA's Moderate Resolution Imaging Spectroradiometer (MODIS),

Pros and Cons of Solar Radiation Management

Pros

- Stabilize global temperatures
- Reduce/reverse sea ice melting
- Reduce/reverse ice sheet melting
- Reduce/reverse sea level rise
- Potentially increase plant productivity
- Potentially increase terrestrial carbon dioxide uptake
- More colorful (red/yellow) sunsets (?)

Cons

- Unknown and unexpected consequences
- Potential for human error
- Continued ocean acidification
- Worsened ozone depletion
- Less sun for solar power
- Environmental impact of implementation (noise, emissions, pollution, debris, etc.)
- Rapid warming probable if discontinued
- Cannot stop effects immediately
- White instead of blue skies
- Commercial control issues (regulation, profit, benevolence, etc.)
- Potential for military use of technology
- Who decides the "correct" temperature?
- Ruins terrestrial optical astronomy
- Ruins much of satellite remote sensing
- Impacts on respiratory health
- Disruption of monsoons
- Changes/reductions in global precipitation
- Full-scale testing is all but required to understand how solar radiation management will or won't work (including the side effects), but full-scale testing will probably have negative side effects.
- More acid deposition
- Potentially greater tropospheric (heat-absorbing) cirrus cloud formation
- Hundreds-of-millions to tens-of-billions of dollars spent per year
- Moral hazard: the prospect of it working reduces incentive for mitigation
- Moral authority: do we have the right to do this?

the combination of background clutter and relatively short column depth makes it difficult to detect and characterize aerosol concentrations with low optical depths (i.e., less than or equal to 0.1–0.3). Even thin high cirrus clouds, consisting of rather large ice crystals, are difficult to detect or measure with these instruments.

Solar occultation sensors (which view the atmosphere tangentially against the backdrop of the sun as it sets or rises) are significantly more sensitive to small aerosol concentrations as a result of very long viewing paths and related factors; however, viewing is limited to times and regions correlating to occultation events, resulting in spotty coverage for any given orbital pass. In addition, the sensing geometry results in poor horizontal resolution and geolocation capability.

Active lidar sensors, such as the Cloud-Aerosol Lidar with Orthogonal Polarization instrument (CALIOP) on NASA's Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) spacecraft, can detect aerosol layers with higher sensitivity than the nadir-looking passive sensors and provide accurate aerosol heights and horizontal positions. In particular, the low background density in the stratosphere (less than 10 particles per cubic centimeter at 20 kilometers) means that even fairly diffuse particles can be detected with lidar.

One of the challenges in detecting injection tests lies in distinguishing intentionally injected particles from naturally occurring particles. There may be some peculiarities with regard to spectral region, polarization, or geometrical behavior that would allow for their differentiation. For instance, nonspherical particles tend to depolarize the scattered photons from a polarized light source. Thus, if the scattered signals are resolved polarimetrically, lidar sensors can provide some information regarding the shape of the aerosols.

Courtesy of NASA

This view of Earth's limb from space shows the various layers of the atmosphere. The pinkish-white layer constitutes the stratosphere, the region where an aerosol injection test would probably occur.

The main disadvantages of using lidar sensors are the small field-of-view and relatively high-power requirements. For example, CALIOP's ground swath is only 100 meters wide, resulting in a 16-day revisit time—far too long for a single spacecraft to accomplish an effective monitoring mission.

Increasing the footprint of an orbiting lidar sensor would probably entail an increase in laser power, allowing the beam to be either spread out or split into multiple spots while maintaining sufficient power density for high sensitivity. While high-power solid-state and fiber lasers have been demonstrated on the ground, considerable development will be required to qualify any of these to meet the challenging requirements for use in space.

In light of these considerations, an appropriate suite of sensors might include visible and thermal multispectral imagers; a long-wave (5–12 micron) hyperspectral imager for chemical resolution and detection; a passive solar-occultation spectrograph; and a multiwavelength, polarization-sensitive, wide-swath (about 10 × 0.5 kilometer) lidar system.

Detection of a particle injection test would require extensive analysis of the temporally and spatially colocated passive multispectral sensor data and lidar data. However, even with advanced spacecraft-based sensor systems, detection of the small tests would be difficult, given the background noise and infrequent revisit rate of a single spacecraft. A large constellation of spacecraft would reduce the revisit time, but the huge cost of such a system weighed against the benefit of quickly detecting a small particle-injection test would make it impractical. Given the high level of uncertainty and the lack of a background reference data set, the job of detecting, identifying, and monitoring such tests for treaty purposes will need to be shared and cross-checked by numerous assets.

Conclusion

Deterrence of unsanctioned and clandestine solar radiation management activities will require monitoring systems that can reliably detect early test phases involving relatively small amounts of particles. Doing so from space will be very challenging. Indeed, future treaty negotiations may need to consider alternative methods of monitoring such activities. As with monitoring nuclear tests, detecting clandestine particle-injection experiments and development activities will require a combination of techniques on the ground and in space. Still, given the strong need for improved understanding of the role of aerosols in the stratosphere, as well as the need to monitor volcano dust for airline safety, the impetus may exist for the development of a multifunction system of space-based sensors.

Acknowledgments

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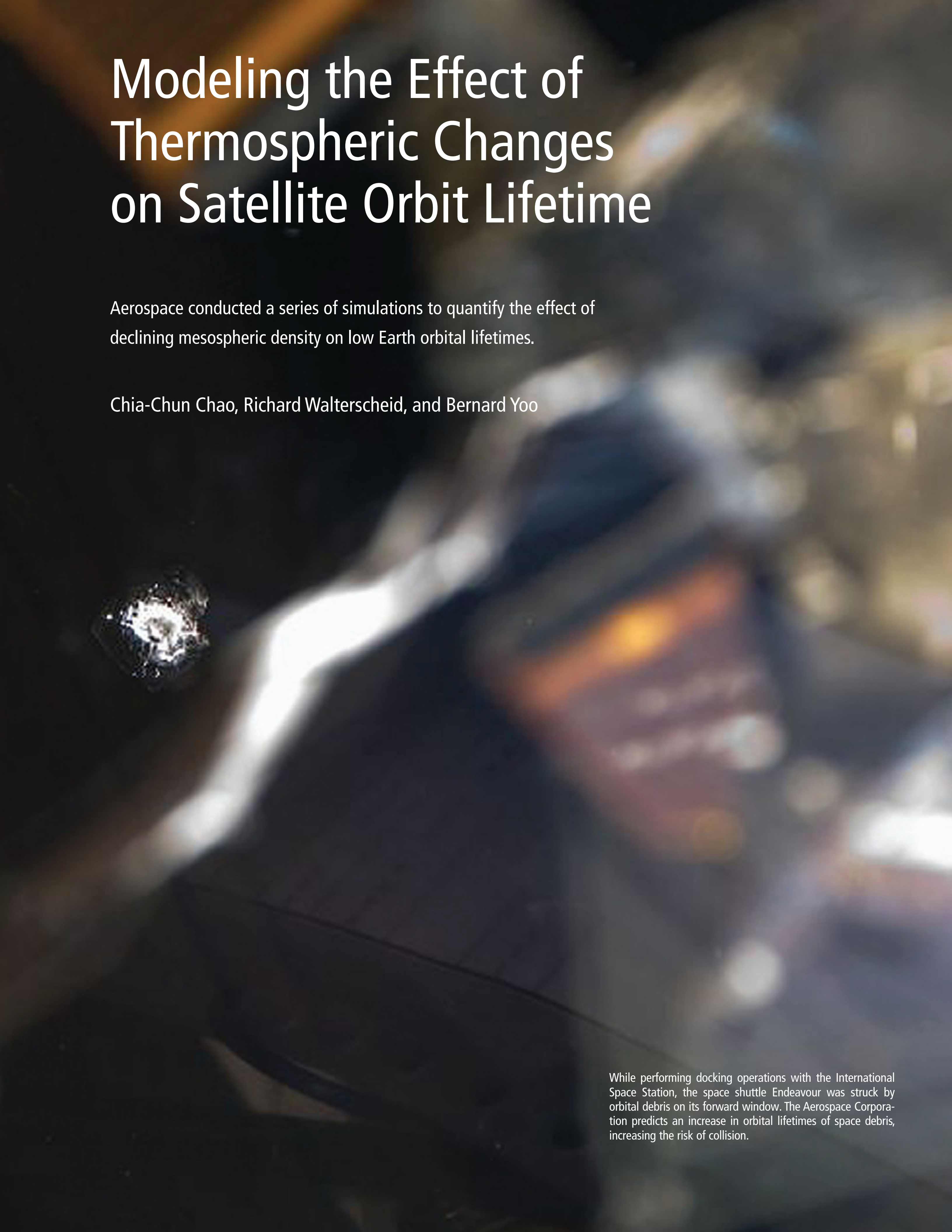
Modeling the Effect of Thermospheric Changes on Satellite Orbit Lifetime

Aerospace conducted a series of simulations to quantify the effect of declining mesospheric density on low Earth orbital lifetimes.

Chia-Chun Chao, Richard Walterscheid, and Bernard Yoo



While performing docking operations with the International Space Station, the space shuttle Endeavour was struck by orbital debris on its forward window. The Aerospace Corporation predicts an increase in orbital lifetimes of space debris, increasing the risk of collision.

During the past 35 years, atmospheric carbon dioxide has increased 4.3 percent per decade. As a result, the density of the thermosphere 90–1000 kilometers above Earth has been decreasing. This trend presents important implications for space mission design, reentry planning, and debris hazard forecasting.

For satellites whose useful mission lifetime is limited by stationkeeping fuel allocation, the decreased density will result in increased orbital lifetimes with the same fuel allocation, or reduced fuel allocation (and spacecraft mass) for the same orbital lifetime.

On the other hand, orbital lifetimes will also increase for debris, increasing the risk of collision. One way to mitigate the increased debris hazard is to plan for collision avoidance maneuvering. This requires additional fuel allocation, which will offset any gains from decreased stationkeeping fuel requirements. It also requires accurate prediction of impending collision and effective operational maneuvers for avoidance. Increased satellite lifetimes will also increase the fuel requirement for end-of-life disposal to ensure reentry within 25 years, as recommended by the Inter-Agency Space Debris Coordination Committee.

The Aerospace Corporation has been reviewing the available data and conducting a series of simulations to quantify the effects of increased orbital lifetimes and the implications for national security space systems.

Theoretical Basis

Thermospheric temperature reflects the net effect of heating and cooling through a number of processes. The most important are heating caused by the absorption of very short wavelength solar radiation, and cooling caused by molecular diffusion and infrared radiation. Infrared radiation has a cooling effect because the kinetic energy of the gas at the molecular level is transferred to the radiation field and lost to space. Energy is radiated away (escapes) because the emitting gases are tenuous (optically thin), and little radiation is absorbed and reradiated back to where it was emitted; moreover, greenhouse gases that do absorb radiation reemit before they can transfer the absorbed radiation to kinetic energy through collisions. The more infrared emitters (greenhouse gases) there are, the greater the amount of radiation lost—and the greater the cooling. The most important greenhouse gas in the thermosphere is carbon dioxide.

By contrast the troposphere is optically thick. Radiation emitted from the surface is absorbed and reradiated before it can escape. The absorbed radiation is reradiated both upward and downward. The downward radiation warms the lower layers of the atmosphere. The more greenhouse gases there are, the greater the downward flux of radiation—and the greater the warming. The most important greenhouse gas in the troposphere is water vapor, followed by carbon dioxide. The greenhouse effect near Earth's surface is huge; without it, Earth would be several tens of degrees (Celsius) cooler (this is the total effect, not the incremental effect due to human activity).

Unlike the troposphere, where there is a complicated system of feedback, the thermosphere is a comparatively simple system, and there is general agreement on the magnitude of the effect of increasing levels of greenhouse gases (which causes the thermosphere to cool down).

The resulting cooling of the thermosphere causes it to contract. The expected effect on satellites is to decrease the atmospheric drag—and in fact, this has been observed for a number of space objects that have been studied since 1961. Aerospace has applied the results derived from observations of those space objects to model the future decrease in density and explore the ramifications for spacecraft lifetimes.

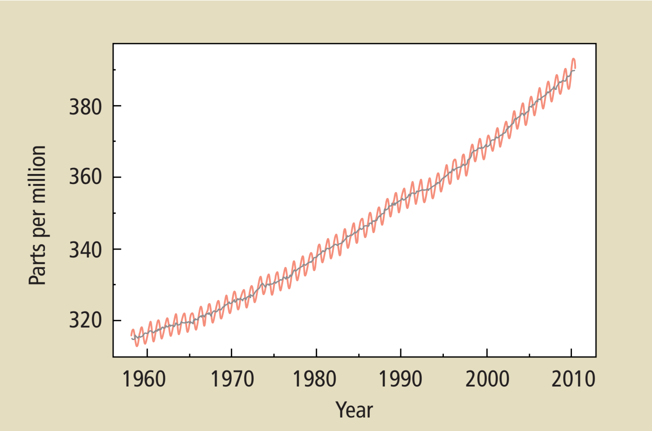
Model Assumptions

The ability to project the future state from available data is complicated by several factors. For example, the increase in carbon dioxide has been fairly linear in the recent decade, but the longer-term trend has been for an accelerating increase. On the other hand, it is also possible that future controls on emissions might substantially decrease the annual rate of increase. Moreover, as greenhouse gases build up, self-absorption effects become increasingly important—clearly, the thermosphere will not disappear in the future, so eventually, self-limiting processes will act to decrease the sensitivity to increases in greenhouse gas concentrations.

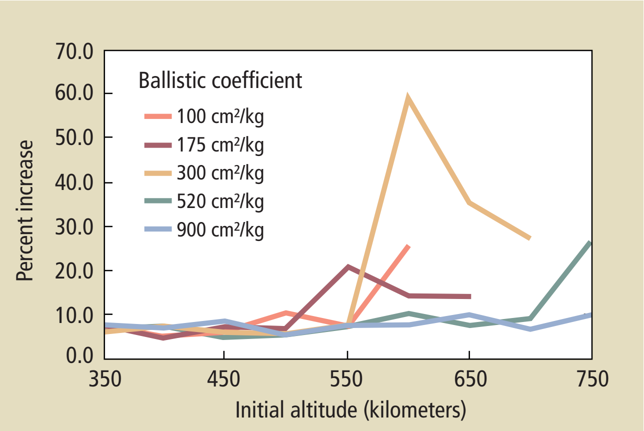
A model of the future must also account for the aging of model data prior to the present. The Aerospace study applied NASA's Mass-Spectrometer-Incoherent-Scatter (MSIS) model, which includes atmospheric data generated over the course of several decades. A precise accounting of data aging is difficult, but an adequate estimate of a reference year would be the midpoint of the years spanned since the earliest data taken to the latest. The earliest data used in the MSIS model is from 1961, so a reasonable midpoint year for the model released in 2000 (MSIS00) is 1980. Thus, January 1, 1980, was selected as the starting point.

From there, the change in thermospheric density was modeled as a linear decrease of 2 percent per decade at 200 kilometers, increasing to 4 percent per decade at 750 kilometers, changing linearly between those limits.

The model was incorporated into the LIFETIME semianalytic orbit propagation program. Developed at Aerospace, LIFETIME is a software tool designed for the prediction of satellite decay/reentry and orbit-sustenance fuel requirements. It is especially useful for performing long-term orbit propagations of low Earth orbits, accounting for forces such as Earth gravity harmonics, atmospheric drag, sun and moon perturbations, and solar radiation pressure. Recent numerical tests of the latest version of LIFETIME show close agreement (less than 0.7 percent difference in orbit lifetime computation) with the high-precision orbit determination program, TRACE. The atmospheric density scale factor



The past five decades have seen a steady increase in the amount of atmospheric carbon dioxide. (Data courtesy of NOAA/Scripps Institution of Oceanography).



This chart shows the percent increase in orbital lifetime, as a result of thermospheric contraction, for a satellite launched in 2010.

adjustment was applied to the density value returned by the MSIS00 atmospheric model function.

A large population of the low Earth orbit satellites (such as DMSP, POES, and TOPEX) reside in sun-synchronous orbits. Therefore, a sun-synchronous, circular orbit with a 6 a.m. local time at ascending node was selected as the reference orbit.

Initial altitudes of 350 to 850 kilometers, in increments of 50 kilometers, were selected. The lower limit is representative of the minimum altitude needed for basic satellite operation, and includes the orbit of the International Space Station; the upper limit is representative of sun-synchronous weather satellites.

The selected orbits were simulated for launches taking place in 2010, 2020, and 2030. The first is representative of satellites (and debris) presently in orbit, the second is representative of space missions presently in development, and the third is a future projection.

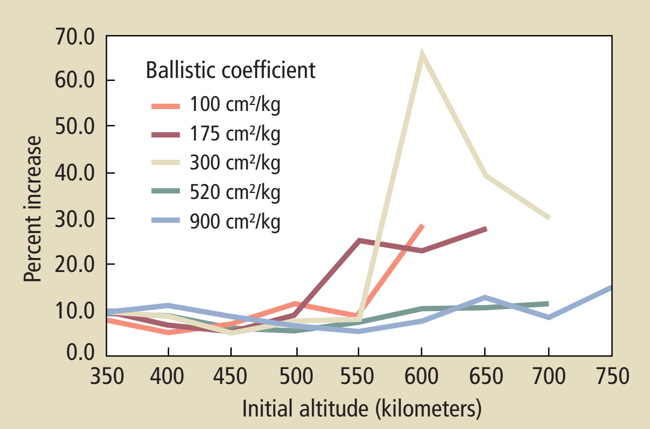
Five ballistic coefficient values were used: 100, 175, 300, 520, and 900 square centimeters per kilogram (cm^2/kg). This range of values is representative of many operational and nonoperational human-made space objects. The lowest value, 100 cm^2/kg, is representative of the International Space Station, while 300 cm^2/kg is representative of many low Earth orbit weather satellites. A higher value implies a higher ratio of surface area to satellite mass.

Every combination of epoch, initial orbit altitude, and ballistic coefficient was simulated in LIFETIME, with and without the modeled reduction in mesosphere density. The simulations were run with a propagation limit of 50 years because the linear model for the carbon-dioxide growth rate may not be valid beyond 50 years from now.

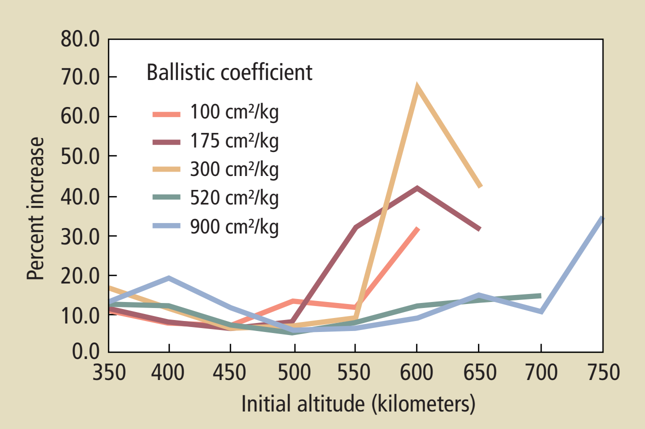
Results

The simulations show a modest increase in orbital lifetimes—increasing with time—for all initial altitudes up to 500 kilometers. More dramatic lifetime increases are seen from 550 to 750 kilometers for certain combinations of initial altitude and ballistic coefficient. Comparisons above 750 kilometers (and some at even lower altitudes) were not possible because the increased orbital lifetimes exceeded the study's 50-year propagation limit (there is no arbitrary propagation time limit in the LIFETIME program).

For initial altitudes up to 500 kilometers, the simulations show a steady, linear increase in the duration of orbital lifetime caused by thinning of the upper atmosphere. For a 2010



This chart shows the percent increase in orbital lifetime, as a result of thermospheric contraction, for a satellite launched in 2020.



This chart shows the percent increase in orbital lifetime, as a result of thermospheric contraction, for a satellite launched in 2030.

Ballistic coefficient (cm^2/kg)	Initial altitude (km)	Lifetime for 2010 launch without greenhouse gas modeling (years)	Lifetime for 2010 launch with greenhouse gas modeling (years)	Percent increase	Lifetime for 2020 launch without greenhouse gas modeling (years)	Lifetime for 2020 launch with greenhouse gas modeling (years)	Percent increase	Lifetime for 2030 launch without greenhouse gas modeling (years)	Lifetime for 2030 launch with greenhouse gas modeling (years)	Percent increase
100	350	0.61	0.65	6.6	0.95	1.02	7.4	1.23	1.36	10.6
	400	1.22	1.29	5.7	1.84	1.94	5.4	2.48	2.66	7.3
	450	2.23	2.37	6.3	2.92	3.14	7.5	3.68	3.94	7.1
	500	4.08	4.51	10.5	4.81	5.37	11.6	5.56	6.31	13.5
	550	13.61	14.56	7.0	14.3	15.63	9.3	15.07	16.8	11.5
	600	28.14	35.32	25.5	28.7	36.87	28.5	29.32	38.63	31.8
	650	>50	>50	0.0	>50	>50	0.0	>50	>50	0.0
300	350	0.23	0.24	4.3	0.36	0.4	11.1	0.43	0.5	16.3
	400	0.58	0.62	6.9	0.96	1.04	8.3	1.3	1.45	11.5
	450	1.07	1.13	5.6	1.72	1.81	5.2	2.36	2.52	6.8
	500	1.82	1.93	6.0	2.52	2.71	7.5	3.26	3.49	7.1
	550	3.04	3.28	7.9	3.8	4.13	8.7	4.57	5	9.4
	600	7.19	11.41	58.7	7.6	12.56	65.3	8.18	13.7	67.5
	650	17.39	23.59	35.7	17.87	24.9	39.3	18.46	26.25	42.2
	700	36.56	46.57	27.4	37.27	48.59	30.4	38.03	>50	32.5
	750	>50	>50	0.0	>50	>50	0.0	>50	>50	0.0
900	350	0.09	0.09	0.0	0.14	0.15	7.1	0.15	0.17	13.3
	400	0.22	0.24	9.1	0.38	0.42	10.5	0.47	0.56	19.1
	450	0.50	0.54	8.0	0.92	0.99	7.6	1.28	1.43	11.7
	500	0.90	0.96	6.7	1.55	1.66	7.1	2.22	2.34	5.4
	550	1.44	1.55	7.6	2.18	2.3	5.5	2.93	3.11	6.1
	600	2.30	2.48	7.8	3.05	3.29	7.9	3.83	4.16	8.6
	650	3.75	4.13	10.1	4.47	5.04	12.8	5.25	6	14.3
	700	12.46	13.31	6.8	13.22	14.36	8.6	13.98	15.49	10.8
	750	23.67	26.08	10.2	24.35	28.04	15.2	25.13	33.93	35.0
	800	43.91	>50	14.7	44.25	>50	13.9	44.27	>50.38	13.8

The effects of greenhouse gases on thermospheric density contribute to an increase in orbital lifetimes. The effects are most pronounced for altitudes higher than 600 kilometers; in many cases, the simulations show that orbital lifetimes could double within the next 20 years even without the greenhouse effects. This is due to near the peak of the 11-year solar cycle. Note that ballistic coefficients 175 and 520 cm^2/kg have been omitted for brevity, but follow the same trend.

launch, the increase in orbital lifetime is 5.2–10.5 percent. This rises to 5.3–11.6 percent for a 2020 launch. By 2030, the increase is 5.0–16.6 percent. At this altitude range, the original orbit lifetime is relatively short, less than 10 years, and the accumulated effect on lifetime due to slow density decrease is small.

At 550 kilometers and higher, the lifetime increases are much more dramatic for certain combinations of initial altitude and ballistic coefficient. For a 2010 launch, the orbital lifetimes increase by 6.8–58.7 percent. For a 2020 launch, the increase is 6.9–65.2 percent. For a 2030 launch, the increase is 6.2–67.5 percent.

The magnitude and altitude of maximum effect vary with ballistic coefficient. Higher ballistic coefficients tend to produce the maximum effect at higher initial altitudes; however, this is not a monotonic trend.

From 550 to 750 kilometers, ballistic coefficients of 100 to 300 cm^2/kg have the greatest effect. The largest lifetime increases (58.7–67.5 percent) occur with a ballistic coefficient of 300 cm^2/kg at an initial altitude of 600 kilometers.

At 550 kilometers, a ballistic coefficient of 175 cm^2/kg has the greatest effect for all epochs, starting at 20.9 percent for a 2010 launch and increasing to 31.9 percent for a 2030 launch.

At 750 kilometers, the largest ballistic coefficient of 900 cm^2/kg produces the largest lifetime increases at later epochs. For a 2030 launch, the 900 cm^2/kg case produced a 35.0 percent increase in orbital lifetime. The response is flatter in earlier epochs, with a 15.1 percent increase for a 2020 launch and a 10.2 percent increase for 2010.

Beyond these observations, it is difficult to draw conclusions for altitudes above 650 kilometers and ballistic coefficients less than 100 cm^2/kg because many orbits in these ranges exceeded the study's 50-year propagation limit. For example, all cases starting at 600 kilometers and below reentered within 50 years, but none of the 850-kilometer cases did. Between these limits, reentry within 50 years varied according to ballistic coefficient. At a ballistic coefficient of 100 cm^2/kg, the results and conclusions are valid up to an initial altitude of 600 kilometers. At 300 cm^2/kg, the results are valid up to 700 kilometers initial altitude. At 900 cm^2/kg, the results are valid up to 750 kilometers.

The lack of valid results for the orbital lifetimes exceeding 50 years does not imply that the effect of mesospheric thinning is not significant. Indeed, the effect may be even greater for orbits that naturally have longer lifetimes. Such effects were not quantified in the Aerospace simulations, but merit further study, especially for long-term debris hazard studies. The importance of atmospheric thinning above 650 kilometers should not be dismissed for lack of valid results from this study.

Conclusion

The change in orbit lifetimes has important and interrelated implications for mission design, fuel allocation, space operations, and debris hazard assessment. The increased orbit lifetimes present the possibility of longer satellite operational lifetimes, at the cost of increasing debris hazard. Aerospace continues to study the available data to support guidelines and recommendations for future system design.

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Lasers Probe Atmosphere for Aerosol Characterization

Aerosols are the fine particulates suspended in the air that produce hazy conditions. These small particles play a critical role in climate and weather, and directly affect how much solar energy is retained or reflected by Earth's atmosphere. Their primary influence is through scattering of solar radiation, but they also can absorb a significant amount of energy, depending their composition. Aerosols also play a secondary role as the nuclei for condensation of water and other atmospheric species to form fog and clouds.

While the critical role of aerosols in climate and weather is acknowledged, their exact contribution is poorly understood, said Pavel Ionov of Aerospace's Photonics Technology Department. In fact, he explained, aerosols represent one of the largest sources of uncertainty in climate models because they are incredibly complex and diverse, as are the mechanisms of their creation, transformation, and removal from the atmosphere. In addition, their relatively short lifetimes of one to two weeks lead to incomplete mixing and very complex spatial (especially vertical) distributions.

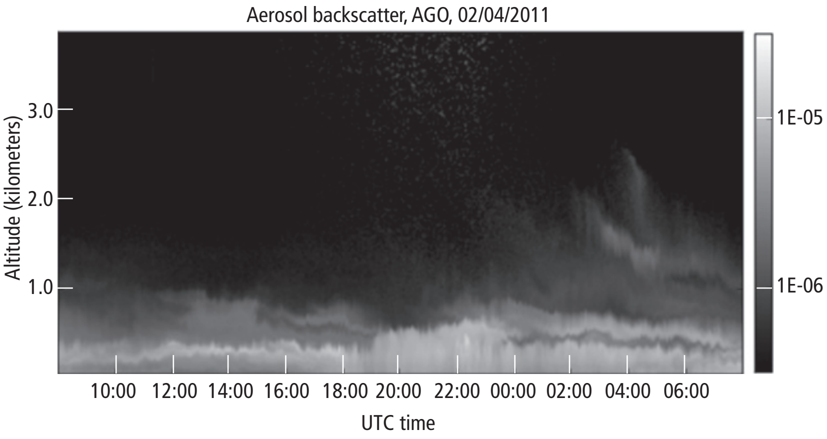
"Aerosol effects are not limited to weather and climate," Ionov said. "For instance, they play an important role in atmospheric chemistry and public health. Also of interest to Aerospace's primary customers is the role aerosols play in degrading space-based imaging—especially hyperspectral—as well as affecting laser propagation through the atmosphere."

The Photonics Technology Department has been developing laser-based remote sensing of atmospheric aerosols. This technique, known as a lidar, probes the vertical distribution of aerosols in the atmosphere. The system sends a short pulse of laser light vertically into the atmosphere, and some of the laser light scatters back off of the aerosols and air molecules. The time of arrival of the scattered light provides distance information, and the intensity of the backscattered signal reveals how much aerosol is present.

The primary focus of the Aerospace aerosol lidar program has been calibration and validation of satellite sensors. Ionov, together with Steven Beck of the Electronics and Photonics Laboratory, Leslie Belsma of Environmental Satellite Systems, and Christopher Woods of Radar and Signal Systems, have been working on a research project to improve aerosol optical thickness measurements from space using lidar ground truth data. "Because of our poor understanding of aerosol mechanisms, direct monitoring from space is the only viable way to assess their global weather and climate effects," explained Beck, who has been working with lidar since its inception.

The MODIS (Moderate Resolution Imaging Spectroradiometer) sensor onboard NASA's Aqua and Terra satellites provides optical thickness data, and a new VIIRS (Visible/Infrared Imager Radiometer Suite) instrument is planned for future National Oceanic and Atmospheric Administration Joint Polar Satellite System and Air Force Defense Weather Satellite System missions. "Despite the great need for global coverage, passive remote sensing of aerosols from space is fraught with uncertainties," Ionov said. "An unknown Earth surface albedo presents the greatest challenge. Thus, ground-based active and passive remote sensing is critical to orbital sensor calibration."

All Earth-sensing satellite instruments require ground-truth validation once on orbit—satellite data must be compared with known and verifiable data taken at the same time and location by ground or aircraft based sensors. The primary goal of the Aerospace aerosol program is to develop reliable remote sensing techniques that provide such calibration standard while providing as much information about the aerosols as possible. One approach is to use multiple instruments for greater accuracy and the complementary information that they can provide. The Aerospace project also operates a collocated sun photometer. This instrument derives height-integrated aerosol parameters from solar and sky radiance measurements. This combination of active and passive aerosol instruments creates a more reliable and more comprehensive data set than any one of



Time evolution of aerosol vertical distribution measured with Aerospace aerosol lidar. The measured backscatter coefficient in units of $m^{-1}*sr^{-1}$ is a measure of aerosol abundance. Lighter shaded areas indicate higher aerosol concentrations.

the instruments can provide. The combined data is continuously collected, checked for consistency, and archived. It is then further compared with the aerosol data products of space-based sensors such as MODIS.

In addition to the lidar and sun photometer data, other meteorological data is combined into a comprehensive database. This database serves as a unique resource for exploring the relationships between aerosols and local meteorological conditions. The research team is hoping that this will provide insight into aerosol production and transport mechanisms. This knowledge will also improve accuracy of space-based remote sensing of aerosols. Because of the complexity and variety of aerosols and because satellite measurements of them are indirect, analysis of satellite data is complex and relies on assumptions about likely aerosol compositions. Improving the scientific understanding of aerosol mechanisms will improve these assumptions and the algorithm accuracy of space-based sensors such as MODIS and VIIRS.

A unique feature of lidar is its remarkable spatial and temporal resolution. The lidar data shown in the accompanying graphic reveals complex local atmospheric dynamics. "It is the study of the mechanisms underlying the aerosol dynamics that is of interest to the research community," said Beck. The research team is hoping that their measurements will find application in areas that go beyond space sensor calibration. For example, aerosols serve as a convenient marker to visualize atmospheric boundary layer dynamics, which, in turn, is critical for accurate weather modeling and in study of pollution transport.

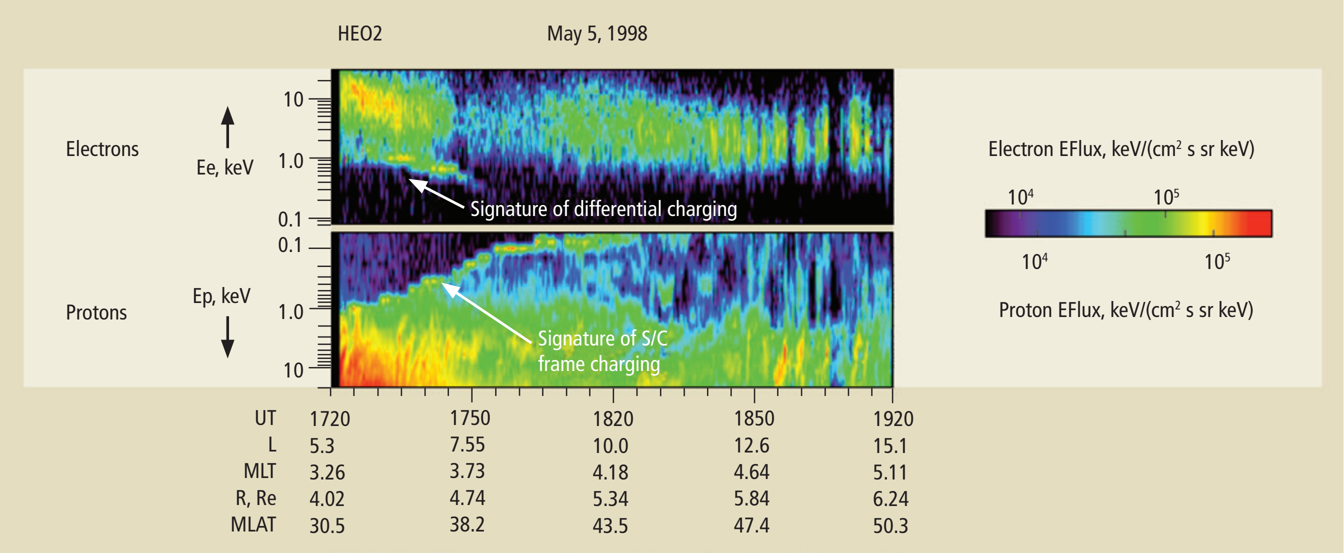
Building Plasma Specifications for Highly Elliptical Orbits

Space plasma contributes to two distinct spacecraft hazards: surface charging and surface dose. All satellites, in all orbits, have surfaces that charge in response to the space plasma environment. Because differential charging carries an associated discharge risk, satellites must mitigate surface charging. In addition, sensitive satellite surfaces can degrade as a result of the dose accumulated from that same space plasma environment. The environment responsible for surface charging and dose is only well observed near geosynchronous Earth orbit (GEO).

A team of Aerospace scientists, led by Timothy Guild of the Space Science Department, is working to broaden the knowledge of this space plasma environment beyond GEO by using unique instruments in highly elliptical orbits (HEO). The team will develop two plasma specifications specifically tailored to HEO. One will characterize space plasmas that contribute to surface dose, while the other will determine the plasma environment most conducive to surface charging. "These specifications will feed directly into ongoing spacecraft development efforts and aid in evaluating on-orbit anomalies related to surface charging," Guild said.

Surface Charging

The electrostatic potential of spacecraft surfaces is a complex function of the net current to those surfaces from the space environment. Low-energy ions and electrons impact the



An interval of surface charging measured from an Aerospace plasma analyzer in HEO. The charging signatures are the annotated bright lines in the electron and ion spectrograms. The energies represented by these lines with time correspond to the potential of a nearby surface to the spacecraft frame (electron line) and of the spacecraft frame (proton line) relative to the space plasma.

Tedlar, a white fluoropolymer film, before (left) and after exposure to the equivalent of 1 year (middle) or 3 years (right) of the GEO space environment.

surface and impart their charge, or, depending on the surface and incident species, eject one or more secondary electrons. Ultraviolet photons on the sunlit side remove charge through photoionization. Any surface that charges to a large potential relative to neighboring surfaces poses a potential discharge risk, and requires mitigation.

"One shortcoming of existing surface charging specifications is that they were largely derived from measurements at GEO," Guild said. "The process of surface charging can be highly localized, even within a few hours of local time at GEO. Previous HEO observations of charging intervals show a strong radial, local time, and geomagnetic activity dependence to the charging likelihood."

Guild and other members of the team—Joseph Fennell, James Roeder, James Clemmons, and Margaret Chen, also from the Space Science Department—are using these plasma observations in HEO, as well as observations from the Aerospace-developed surface-charging monitors on the NASA TWINS (Two Wide-angle Imaging Neutral-atom Spectrometers) mission to investigate charging intervals in HEO. The charged particle motion in space allows these HEO observations to be mapped along magnetic field lines to other orbits, contributing to charging specifications for orbits from medium Earth orbit out beyond GEO.

Surface Dose

The impinging ions and electrons deposit all their energy in the first few mils (1 mil = 0.001 inch) of the spacecraft surface, causing intense radiation damage to thin films and coatings. The surface radiation dose caused by the low-energy plasma dominates for thicknesses below about 1 mil.

"Existing satellite specifications for surface dose are also largely GEO-centric," Guild said. "In our project, we are developing a surface dose specification for vehicles that traverse HEO magnetic field lines, sometimes flying through a very different plasma environment." Guild noted that previous Aerospace research showed order-of-magnitude differences between the average omnidirectional hydrogen flux between GEO and GPS orbits. "By combining these three specialized HEO plasma datasets, we will drastically improve our knowledge of the environment in time and space, leading to a more robust and more widely applicable plasma specification for surface dose," he said.

Current understanding of surface dose and charging, as well as the state-of-the-art specifications of these hazards, have been contributed by The Aerospace Corporation, NASA, and Los Alamos National Laboratory, among other institutions. Aerospace personnel are widely recognized in the fields of spacecraft surface dose and surface charging, and have contributed many of the plasma and surface charging specifications used for spacecraft design.

"Aerospace has designed, built, and operates three plasma analyzers in HEO uniquely suited to providing plasma and surface charging specifications," Guild said. "Aerospace personnel have the expertise to appropriately interpret these observations and their differences with other empirical models. After developing the plasma and surface charging specifications, Aerospace is also well positioned to include these results into the next-generation radiation specification models and effectively communicate the results to relevant customers via our close involvement with many national space programs," Guild said.

BOOKMARKS Recent Publications, Papers, and Patents by the Technical Staff

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Rocket boosters typically use a nozzle with an outlet pressure selected to optimize average performance during launch. This is not the most efficient setup because these nozzles typically overexpand the exhaust gases at liftoff and then underexpand them at high altitudes. Better performance could be obtained by continuously varying the outlet pressure during ascent. This invention allows a bell-shaped rocket nozzle to do so. The interior of the nozzle is lined with a thin layer of combustible material, which is ignited by the rocket engine exhaust. The gases produced travel down the nozzle and create an outgassing pressure plane inside the nozzle approximately equal to the external atmospheric pressure. The matched exhaust pressure from the nozzle to atmosphere over a large range of altitudes increases the lift performance of a rocket engine without additional mechanical parts. The combustible material is relatively inexpensive and does not add significant weight. The material thickness, position, and taper can be selected to optimize the lift capability of the rocket.

Y. Chan, J. Camparo, S. Karuza, et al., "Precision Frequency Change Detector," U.S. Patent No. 7,847,597, Dec. 2010.

GPS satellites use atomic frequency standards to generate signals with precise frequencies. Atomic frequency standards are known for their precision and stability; however, they can suffer frequency jumps caused by their environment and external/internal clock physics perturbation. This fractional error can cause a much larger user error, especially if undetected and allowed to compound. Currently, frequency change detectors are located on the ground. This patent describes a change detector that can be installed onboard to autonomously and continuously monitor and solve frequency jumps or changes in frequency standard. The device operates by splitting a frequency standard into two replica signals. One replica signal is maintained, while the other is delayed by a predetermined amount. The two replica signals are then mixed together to form a mixed-frequency signal, which is filtered and amplified. The output detection signal indicates any change in the frequency.

CONTRIBUTORS

Climate Change and National Security: Implications for Space Systems

James A. Vedda, Senior Policy Analyst, Center for Space Policy and Strategy, has been performing research and analyses on national security, civil, and commercial space issues at Aerospace since 2004. Previously, he spent several years assigned to the Office of the Secretary of Defense working on space policy and homeland defense issues. He was also an associate professor in the Department of Space Studies at the University of North Dakota, where he taught graduate courses on civil, commercial, and military space policy. He has an M.S. in science and technology policy from George Washington University and a Ph.D. in political science from the University of Florida. He is the author of *Choice, Not Fate: Shaping a Sustainable Future in the Space Age* (Xlibris, Bloomington, IN, 2009).

Green Propulsion: Trends and Perspectives

John D. DeSain, Research Scientist, Chemical Propulsion and Environmental Sciences Division, has more than 16 years of experience working in the field of infrared kinetic spectroscopy. His research focuses on the kinetics, thermochemistry, and reaction mechanisms of species involved in propulsion systems related to the space environment. His work includes environmental assessments of the use of common propulsion systems that include ground impacts, potential for space debris, ozone destruction, and global warming impact. DeSain joined Aerospace in 2003. He has a Ph.D. in physical chemistry from Rice University.

Simulation Analysis of Resource Depletion and Climate Change Trends

Michael J. Baxter, Director, Modeling and Simulation Department, is responsible for the development of simulations and analyses covering military utility, system-of-systems, and large-scale system effectiveness and performance. Prior to joining Aerospace in 1986, Baxter was a naval reserve officer, having served with the Naval Air Weapons Center and Strike Force Squadron. He has an M.S. in aeronautical and astronautical engineering from Purdue University and a Ph.D. in industrial and systems engineering from the University of Southern California.

Feasibility of Space-Based Monitoring for Governance of Solar Radiation Management

Patrick L. Smith (not pictured) joined Aerospace in 1968. His early technical work focused on missile guidance and tracking systems and phase-conjugation beam-forming techniques. Later, he supported efforts to integrate space systems into tactical air operations in Europe and Korea. Since retiring in 2007, he has coauthored two AIAA papers on the effects of climate change on national security space programs. He has a Ph.D. in engineering from UCLA.

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Leslie A. Wickman (center), Senior Engineering Specialist, Space Architecture Department, is also director of the Center for Research in Science at Azusa Pacific University. Her current projects include research on global climate change and national security issues, assessment of current and future space mission technologies and their applications, and sustainable water reclamation systems. Before joining Aerospace, she supported NASA's Hubble Space Telescope and International Space Station programs. She has a B.A. in political science from Willamette University, an M.S. in aeronautical and astronautical engineering, and a Ph.D. in human factors and biomechanics, both from Stanford University.

Inki A. Min (right), Principal Engineering Specialist, Architecture and Design Subdivision, leads and performs system-level analyses of various Air Force, NASA, and NRO projects. He joined Aerospace in 1987. He has a Ph.D. in aeronautics from Caltech.

Patrick L. Smith, Leslie A. Wickman, and Inki A. Min also authored the article, "Broadband Satellite Communications for Future U.S. Military and Coast Guard Operations in an Ice-Free Arctic."

Rocket Soot Emissions and Climate Change

Martin Ross, Senior Project Engineer, Commercial Launch Projects, leads research concerning the effects of space systems emissions on the stratosphere. Ross has provided technical leadership and management for many large programs associated with the NASA WB-57F aircraft, including successfully developing and managing four large multiyear WB-57F-based science campaigns for NASA. He is developing new interagency strategies to better understand the scientific, economic, and political implications of the impact of space systems on stratospheric ozone and climate change. He has authored more than 50 papers on space and atmospheric science, engineering, and policy. Ross has a B.S. in aerospace engineering from the University of Michigan and a Ph.D. in planetary and space physics from UCLA.

An Integrated Approach to a Geothermal Resource Assessment

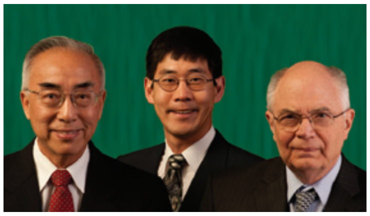
Karen L. Jones, Senior Project Engineer, Civil and Commercial Operations, develops and manages projects involving natural resource assessments, remote sensing, and renewable energy. Her current focus is on technology strategy and commercialization, renewable energy, and natural resource policy and economics. She has a B.S. in geology from Louisiana State University and an M.B.A. from the Yale School of Management. She joined Aerospace in 2004.

The Adaptation of Tactical Imaging Spectrometry to Applications in Earth Science

David M. Tratt (left), Senior Project Engineer, Imaging Spectroscopy Department, joined Aerospace in 2006. He currently works developing Earth observation applications using imaging spectrometry and laser remote sensing techniques. He supported NASA's Earth Science Technology Office, overseeing the laser technology R&D program targeted toward future space-based Earth science measurement needs. He is the founding chair of the Space Technology Alliance's Laser/Optical Technologies Working Group and is a fellow of the Institute of Physics and the Royal Meteorological Society. He is a member of IEEE, the American Geophysical Union, the American Meteorological Society, and the European Geosciences Union. He has a Ph.D. in physics from Heriot-Watt University in Edinburgh, Scotland.

George J. Scherer (right), Director, Imaging Spectroscopy Department, develops passive infrared remote sensing instruments and techniques, with a particular focus on infrared laser spectroscopy for detecting ultralow levels of gases. He has also led the development of operating and analysis software for Fourier transform spectrometers deployed from vehicles, helicopters, and fixed-wing aircraft. Scherer joined Aerospace in 1985. He has a B.S. from Wake Forest University and a Ph.D. in physical chemistry from Harvard University.

Modeling the Effect of Thermospheric Changes on Satellite Orbit Lifetime



Chia-Chun (George) Chao (left), joined Aerospace in 1978. He has more than 40 years of experience in the areas of orbit perturbation, stationkeeping, satellite navigation, formation flying, and troposphere refraction calibration methods. Chao designed and tested the PC-based software tool LIFETIME, which has supported a wide range of DOD and civil and commercial programs. He is the author of *Applied Orbit Perturbation and Maintenance* (The Aerospace Press/AIAA, El Segundo, CA, 2005) and also teaches orbital mechanics at the UCLA Extension and USC Viterbi School of Engineering. He has a Ph.D. in astrodynamics from UCLA and is an associate fellow of AIAA.

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Richard Walterscheid (right), Distinguished Scientist, Space Sciences Application Laboratory, joined Aerospace in 1979. He works in the areas of atmospheric dynamics and physics, with a focus on the upper atmosphere. He received the Aerospace President's Achievement Award in 1992 for contributions in atmospheric science with applications to space systems. Walterscheid has served as a visiting professor at UCLA. He has published more than 130 papers in peer-reviewed journals. He has a Ph.D. in atmospheric sciences from UCLA.

THE BACK PAGE

Future Military and Coast Guard Activities in the Arctic

Patrick L. Smith

A member of the USS Texas inspects the deck of the fast-attack submarine in October 2009. The USS Texas was the first submarine of its kind to conduct operations in the Arctic.

Unlike Antarctica, the Arctic has no ban on weapons, and nations surrounding the region have started increasing their military presence there. Canada, Russia, and the United States have begun deploying surveillance assets and conducting Arctic military exercises, flights, and exploration missions using icebreakers. As yet, however, no country has clear legal authority to conduct maritime interdictions, ensure safe transit of commercial shippers, or conduct routine surveillance of maritime traffic.

Opening Arctic sea routes may complicate relations among nations that want to exploit oil and gas reserves in the region. Strategic choke points such as the Bering Strait, the Queen Elizabeth Islands in the Northwest Passage, and the Severnaya Zemlya and New Siberian Islands in the Northeast Passage are subject to control or even blockade. If melting of the permafrost damages roads or pipelines, freedom of maritime shipping will become critical.

The United States has several interests in the region, including approximately 1000 miles of Alaskan coastline. A 2007 National Security Presidential Directive calls on the Secretaries of State, Defense, and Homeland Security to "develop greater capabilities and capacity, as necessary, to protect United States air, land, and sea borders in the Arctic region." According to Rear Admiral David Gove, the U.S. Navy will soon be called upon to monitor activities related to early warning/missile defense, maritime presence and security, and freedom of navigation and overflight. Admiral Thad Allen has recommended establishing forward operating bases to support search and rescue, pollution response, and security operations in the region.

Actual military conflict over access to shipping lanes or resources appears unlikely, at least for the foreseeable future. The vast majority of accessible oil and gas reserves lie in territorial waters, and the working conditions in the region, even during summer months, are so harsh and unpredictable that cooperation for mutual safety and economic advantage appears to be in everyone's best interest.

The U.S. Coast Guard's immediate concern is lack of resources for rescue operations and response to environmental disasters. More and more cruise ships are operating in regions far away from Coast Guard services (there have already been accidents that required rescuing passengers in dangerous conditions). An oil spill in the Arctic would be catastrophic because there are few resources in the region for containment and cleanup, and the cold-water temperatures would inhibit evaporation.

U.S. Navy and Coast Guard ships require timely and detailed information on icepack composition and drift. Naval vessels operating within the icepack can make use of precise information on the distribution and age of ice and on pack motion to avoid high-pressure ridges and identify navigable leads. At the 2008 First Workshop on Satellite Imaging of the Arctic (Copenhagen, Denmark), requirements for improved ice monitoring in support of shipping and activities in the Arctic were discussed, and a recent U.S. Coast Guard report defined specific requirements for satellite-based imagery for tracking ice floes. Basically, the extent of ice surveillance must be sufficient to cover several days' passage and resolution to delineate routes permitting safe and efficient navigation.

Images courtesy of U.S. Navy

Top: U.S. Navy personnel confer about cold weather safety gear at the Applied Physics Laboratory Ice Station camp in the Arctic Ocean in March 2009.

Middle: The USS Annapolis breaks through three feet of Arctic ice during ICEX 2009.

Bottom: The crew of the USS Hampton after surfacing in the polar ice cap region during ICEX 2004, a joint exercise between the U.S. and British submarine forces in 2004.

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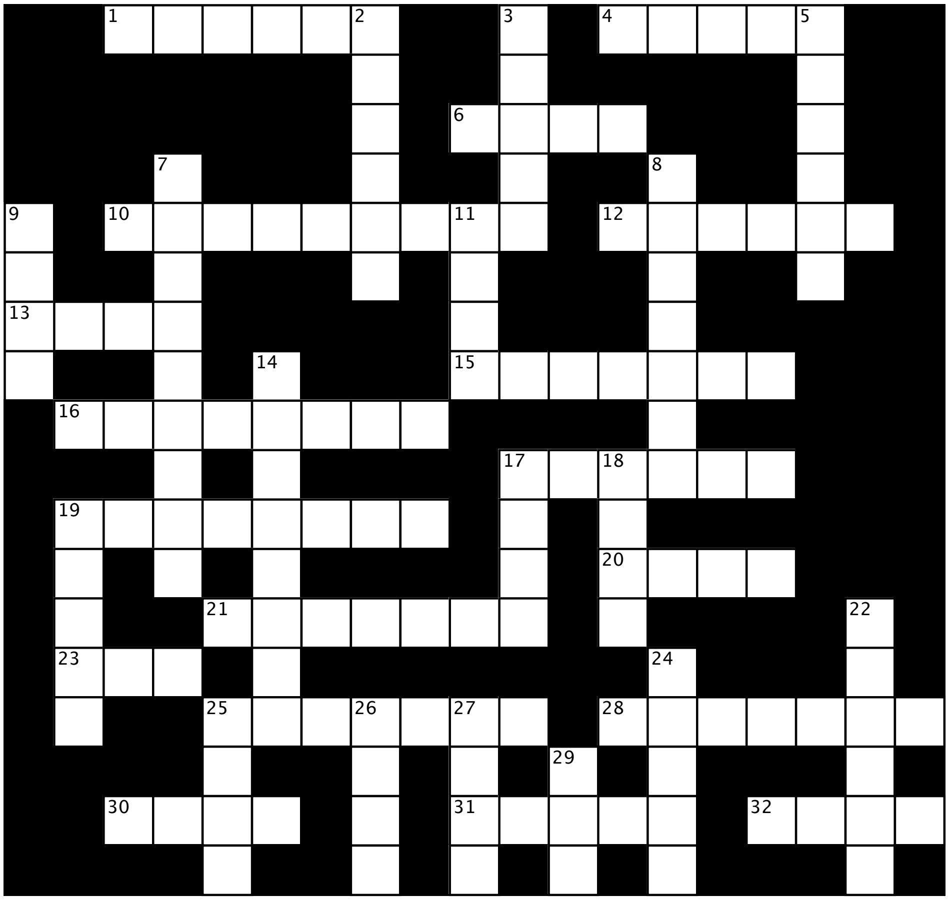

Across

1. Barnyard buffet table
4. An illuminating attachment
6. To sun without sunblock?
10. Yeti evidence
12. Rubbish
13. Nautical wind-catcher
15. Run out of
16. Garbage grinder
17. Antiquated kind of copy
19. Euclid's specialty
20. An amoeba has one
21. Voice to avoid
23. Popsicle, perhaps
25. People per square mile
28. Lava leaker
30. A must for cooking
31. Celeb's rep
32. Tuna______

Down

2. Links sand trap
3. Pizza base
5. Genetic blend
7. Fender bender, e.g.
8. Bother
9. Midnight service
11. Network crossroads
14. Insurance policy scope
17. Magic bullet
18. Accompanies roll
19. Pattern in cherry or walnut
22. Cloak
24. Warsaw natives
25. Like, it's a disappointment
26. Send (a package)
27. ______Lizzy, '70s rockers
29. Trail guide

Most puzzle words and clues are from articles in this issue. The solution is on the Crosslink Web site: http://www.aero.org/publications/crosslink/.