Crosslink
The Aerospace Corporation magazine of advances in aerospace technology

Flying into the rocket plume
Aerospace takes lidar to new heights
IR eyes high in the sky
Photography and launch-cloud prediction
Weather and warfare

Observing and measuring the atmosphere

The Aerospace Corporation celebrates 40 years
Space technology and atmospheric science are related in many ways. Space provides a unique vantage point for observing weather systems, and with the ever-increasing frequency of satellite launches, the effect of rocket exhaust on the environment has become a concern. In this issue, Crosslink explores the contributions made by Aerospace in the areas of weather forecasting and atmospheric analysis.

This year marks the 40th anniversary of The Aerospace Corporation. In its trusted role as space systems engineer for the Air Force, the National Reconnaissance Office, and other government agencies, the corporation has made lasting contributions to the nation’s space programs. In celebration of the accomplishments of the last 40 years, Crosslink introduces a series of historical articles on Aerospace’s involvement in various military and civil programs during those years. The series begins with an article on the Defense Support Program.

Crosslink presents this historical series to commemorate the contributions of all those who have worked on these programs through the years. These past accomplishments are noted as well for their significance as foundations for the important work ahead to meet the space-technology needs of our government and commercial partners in the complex environment of the future.
Water-Vapor Lidar Extends to the Tropopause

John Wessel (right), Photonics Technology Department, supports DMSP in the areas of meteorological lidar and microwave remote sensing and has conducted research in molecular, atomic, semiconductor, and surface spectroscopies. He holds a Ph.D. in chemical physics from the University of Chicago and has been with Aerospace since 1974 (john.e.wessel@aero.org). Robert W. Farley (left), Photonics Technology Department, is responsible for the development and operation of a mobile lidar system that supports satellite programs. He holds a Ph.D. in chemical physics from the University of Colorado and has been with Aerospace since August 1997 (u21670@paros.aero.org).

The Defense Support Program

Fred Simmons (left), consultant to the Space Based Infrared Systems program, has been the coordinator of various studies for SMC, BMDO, and DARPA. He holds a Ph.D. in aerospace science from the University of Michigan and has been with Aerospace since 1971 (frederick.s.simmons@aero.org). Jim Creswell (right), with 35 years of experience in space-based warning satellite development and operations, has been working as a consultant on satellite-related tasks since his retirement in 1994 from full-time employment at Aerospace. Among various appointments during his Aerospace career, he was director of the Mission Support Office of the Defense Support Program. Creswell holds an M.S. in systems engineering from the University of California at Los Angeles and has been with Aerospace since 1965 (james.c.creswell@aero.org).

Aerospace Photos Capture Launch Clouds

Robert N. Abernathy, Surveillance Technology Department, has been responsible for quantitative image processing in support of the Atmospheric Model Validation and the Rocket Impact on Stratospheric Ozone programs since 1995. He holds a Ph.D. in analytical chemistry from Pennsylvania State University and has been with Aerospace since 1980 (robert.n.abernathy@aero.org).

Cloud Cover Over Kosovo

John S. Bohlson (left), Systems Director, Sensors and Display Systems for DMSP, supports both DMSP and the National Polar Operational Environmental Satellite System in the areas of remote sensing, data exploitation, and user requirements. He holds an M.S. in meteorology from the University of Wisconsin and has been with Aerospace since 1988 (john.s.bohlson@aero.org). Leslie O. Belsma (right), Weather and Navigation Division, manages unique quality-control tasks for the Cloud Depiction and Forecast System II. A retired Air Force Weather officer with an M.S. in aeronomy from the University of Michigan, she joined Aerospace in September 1999 (leslie.o.belsma@aero.org). Bruce H. Thomas (center) is senior project leader for the DMSP Environmental Applications Center, Aerospace Omaha field office, at Offutt Air Force Base Nebraska. Thomas established an additional location of the Aerospace field office at the Air Force Weather Agency, extending the DMSP program office into the user community. He holds an M.S. in atmospheric science from Creighton University and has been with Aerospace since 1990 (bruce.h.thomas@aero.org).
First Launch of the Century

The launch of an Atlas IIA from Cape Canaveral on February 7, 2000, marked the first government launch of the century. It placed into orbit a DSCS III (Defense Satellite Communications System) B8 SLEP (Service Life Enhancement Program), an improved military communications satellite, the seventh DSCS launched since 1992. The B8 SLEP is the first of four improved satellites that will increase tactical communication. The payload included new electronics that add more power per channel so that ground forces, ships, aircraft, and submarines can use smaller antennas when communicating. The satellite replaces the A1, launched in 1982, in the primary DSCS Western Pacific Theater constellation. Aerospace provided a launch support team at the Cape and supported the launch remotely from locations in Colorado and California. The successful SLEP program has been in operation for four years.

TIMED to Probe Distant Regions

A remote-sensing spacecraft carrying a payload developed with the help of Aerospace will travel 40 to 110 miles above Earth this year to a little-explored region of the atmosphere. The two-year mission, TIMED (Thermosphere, Ionosphere, Mesosphere, Energetics, and Dynamics), will begin with a launch from Vandenberg Air Force Base. Its purpose is to study how humans and the sun influence the mesosphere and lower thermosphere and ionosphere. Those regions absorb X-rays and extreme ultraviolet radiation. TIMED will carry the Global Ultraviolet Imager (GUVI), a joint effort between Aerospace and the Applied Physics Laboratory at Johns Hopkins University. Aerospace handled the design, fabrication, and operation of the instrument and was also involved in the software and electronics for the GUVI payload. GUVI will measure profiles of the region’s composition and temperature as well as high-latitude auroral energy input.

GPS for the Military and Civilians

The fourth in a series of U.S. Global Positioning System (GPS) replacement satellites, GPS IIR4, was launched aboard a Delta II from Cape Canaveral May 10, 2000. Aerospace reviewed the hardware, software, and procedures, and verified that the vehicle was ready for launch. Aerospace developed the fundamental concept of GPS for the Air Force in 1963. Today, GPS, a constellation of 28 navigational satellites that orbit 11,000 miles above Earth, is used increasingly by civilians. Civilian owners of GPS receivers found their systems significantly more accurate as of May 2, 2000. That day, President Clinton ordered an end to the intentional degradation of GPS satellite signals by the military. The military will, however, retain its right to selectively deny the GPS signals over any given region.

Clothing That Computes

Soon soldiers in the battlefield may be able to shed some of their 70 pounds of gear and don a lightweight wearable computer that could send and receive life-saving information. For example, a soldier whose vehicle has broken down could be wearing the repair manual. Sound like science fiction? It isn’t. Michael Gorlick (in photo), project engineer in the Computer Systems Research Department, constructed suspenders that have electrical conductors woven directly into the fabric. Developed as part of a joint research project between Aerospace and The MITRE Corporation, the suspenders act as a bus and data network for wearable digital devices. Civilian use of wearable computers is also on the horizon. Emergency search and rescue and disaster response teams could be equipped with them. The computers may eventually be carried in pockets, worn on belts, attached to wrists, or worn as brooches and rings. Hardhats and eyeglass frames could also house data networks. Imagine those involved in the meticulous work of satellite assembly having essential information right before their eyes.
Amazing MEMS

Microelectromechanical systems (MEMS), machines so tiny they cannot be seen with the naked eye, are quickly gaining notoriety for their capability and versatility in a variety of areas. MEMS can be used to detect environmental pollutants, monitor the health of a premature newborn, sense an impending car crash and deploy the air bag, and be “woven” into the clothes of soldiers on the battlefield (where the sensors would warn against an attack by chemical or biological weapons). A more aggressive use of MEMS is the potential for manufacturing mass-producible, 1-kilogram-class nanosatellites with microelectronics-processing technology.

More than 30 Aerospace scientists are involved in MEMS research, including Henry Helvajian of the Aerospace Center for Microtechnology and the editor of Microengineering Aerospace Systems (see sidebar). Aerospace researchers sent aloft a MEMS experimental testbed on the space shuttle Columbia last year. Data from 30 of the devices were analyzed to see how the various MEMS performed during launch, orbit, and reentry, compared with their performance in preflight tests. One device, designed and built by Aerospace, contains 15 microthrusters, which act like 15 individual solid rocket motors. The usefulness of MEMS in space has yet to be fully realized, and the analysis by Aerospace was the first systematic testing of MEMS in that capacity. Another experimental MEMS test mission, planned for 2001, will involve the International Space Station.

Miniature Satellites Launched

The tiniest operational satellites ever placed in orbit were launched aboard a new Air Force booster for light satellites January 26, 2000, from Vandenberg Air Force Base. Each satellite weighs less than one-half pound and is slightly larger than a deck of cards. In a project for the Defense Advanced Research Projects Agency (DARPA), Aerospace conceived the mission, designed and built the “picosats,” tested their components, and handled flight operations. The primary mission was to demonstrate the use of miniature satellites in testing DARPA microelectromechanical systems (MEMS). The two picosats were positioned in a low Earth orbit after they were released February 6, 2000, from the Orbiting Picosatellite Automated Launcher (OPAL), a satellite built by Stanford University students. The satellites were joined by a tether, which kept them in range of each other for crosslink purposes as they simulated formation flying. Thin strands of gold wire in the tether allowed the U.S. Space Command’s Space Surveillance Network to use radar to locate and track the picosats. The mission, concluded on February 10, 2000, was the first of a series of missions designed to validate MEMS technology.
Rockets and the Ozone Layer

Martin N. Ross and Paul F. Zittel
Rocket engine exhaust contains chemical compounds that react with ozone in the stratosphere. A new measurement program suggests that current space transportation activities only minimally affect Earth’s protective ozone layer.

Protecting Earth’s ozone layer remains an important environmental issue. Without this shielding layer, ultraviolet (UV) radiation would harm life on Earth. We hear alarming statistics on increasing incidences of skin cancer and other disorders that may be linked to a thinning of Earth’s ozone layer. We know that the presence of chlorofluorocarbons (CFC)—chemicals used as solvents and refrigerants—and other industrial gases in the atmosphere is the major cause of ozone depletion. But what about exhaust from launch vehicles? Can the cumulative effect of emissions from rockets launched every three or four days from various launch sites around the globe significantly alter Earth’s delicately balanced, natural sunscreen?

Space transportation, once dominated by government, has become an important part of our commercial economy, and the business of launching payloads into orbit is expected to nearly double in the next decade. Each time a rocket is launched, combustion products are emitted into the stratosphere. CFCs and other chemicals banned by international agreement are thought to have reduced the total amount of stratospheric ozone by about 4 percent. In comparison, recent predictions about the effect on the ozone layer of solid rocket motor (SRM) emissions suggest that they reduce the total amount of stratospheric ozone by only about 0.04 percent.

Even though emissions from liquid-fueled rocket engines were not included in these predictions, it is likely that rockets do not constitute a serious threat to global stratospheric ozone at the present time. Even so, further research and testing needs to be done on emissions from rockets of all sizes and fuel system combinations to more completely understand how space transportation activities are affecting the ozone layer today and to predict how they will affect it in the future.

The Ozone Umbrella

Ozone, composed of three oxygen atoms, is the result of the action of UV radiation on oxygen molecules, composed of two oxygen atoms. In the upper regions of the atmosphere, UV light breaks apart oxygen molecules into two oxygen atoms, one of which then combines with a second oxygen molecule to form ozone. Born of UV light, ozone is also a powerful absorber of UV light, accounting for its protective role. Most of the ozone that protects Earth’s surface is concentrated in the atmospheric region called the stratosphere, usually taken as the region between about 14 and 50 kilometers altitude. The term “ozone layer” refers to the portion of the stratosphere between about 15 and 30 kilometers altitude, where the bulk of the ozone is concentrated.

Compared with the mass of all the gas in the stratosphere, the mass of combustion emissions from even the largest rocket is miniscule, so it’s easy to conclude that the effect of all rocket launches on the ozone layer must be inconsequential. The ozone layer, however, is maintained by a delicate balance of the production, transport, and destruction of ozone molecules. Relatively small amounts of sufficiently active chemical compounds can upset this balance and cause important changes in the amount and distribution of ozone. Rocket engines produce small amounts of such active compounds.

Early in the past decade, Aerospace conducted research for the Air Force Space and Missile Systems Center (SMC) Environmental Management Branch on how SRM exhaust affects stratospheric ozone. These studies, which raised several environmental concerns, were limited to laboratory and modeling simulations of rocket-plume chemistry. By the middle of the decade, it had become obvious that a complete understanding of rocket-exhaust
effects required moving beyond the theoretical investigations to actual measurements. In 1995, responding to the concerns raised by the earlier studies, SMC requested that Aerospace establish a practical, quick-to-implement program to collect actual data from SRM plumes in the stratosphere. The program, named Rocket Impacts on Stratospheric Ozone (RISO), and led by the Aerospace Environmental Systems Directorate, initially focused on the stratospheric impacts of the heavy-lift Titan IVA. RISO has subsequently been expanded to include responsibility for investigating the impact of all current U.S. Air Force launch vehicles. The Air Force Office of Scientific Research joined with SMC during the RISO planning phase and supported several investigators on the RISO team. The initial pioneering RISO plume measurement campaigns began in 1996.

**Ozone-Destroying Radicals**

Complicated chemical and physical processes, only partially understood by atmospheric scientists, affect both the amount and distribution of ozone in the stratosphere. In general, ozone is formed in the equatorial stratosphere at altitudes above 30 kilometers. Large-scale winds continuously transport the ozone to lower altitudes and toward Earth’s poles to form a layer about 10 kilometers thick, centered at about 22 kilometers altitude. The concentration of ozone is determined by the rate of ozone transport into the layer versus the rate of ozone loss by reaction with ozone-destroying radicals such as the chlorine atom (Cl), nitric oxide (NO), and the hydroxyl radical (OH). Because each radical is able to regenerate after destroying an ozone molecule (called a catalytic cycle), radical molecules exert a major influence on ozone even at the small quantities found in the stratosphere. This means that small changes in stratospheric composition caused by industrial activity, including rocket exhaust, might cause relatively large changes in the ozone layer.

**The Composition of Rocket Emissions**

Both solid and liquid rocket-propulsion systems emit a variety of gases and particles directly into the stratosphere. A large percentage of these emissions are inert chemicals such as carbon dioxide that do not directly affect ozone levels. Emissions of other gases, such as hydrogen chloride and water vapor, though not highly reactive, indirectly affect ozone levels by participating in chemical reactions that determine the concentrations of the ozone-destroying radicals in the global stratosphere. A small percentage of rocket-engine emissions, however, are highly reactive radical compounds that immediately attack and deplete ozone in the...
Before the RISO field campaigns, relatively little was known with certainty about the highly reactive components of rocket-engine emissions or the intensity of ozone destruction in the plume wake. In 1995, managers and researchers from the Air Force and the National Aeronautics and Space Administration (NASA) met to review rocket emissions and identify critical knowledge needs. The meeting participants concluded that airborne measurements inside actual stratospheric rocket plumes should be a priority for further research, and the RISO program was designed with those conclusions in mind.

The Role of Chlorine Radicals

Researchers have long been aware that hydrogen chloride (HCl) is a component of SRM exhaust. It had been assumed that HCl, which is relatively unreactive, would contribute to ozone depletion globally over the long term by slightly increasing radical chlorine levels in the stratosphere but would not alter ozone levels in the plume-wake region immediately after launch. Atmospheric scientists began to wonder, however, if unreactive HCl could be converted into highly reactive chlorine radicals in plume combustion processes, resulting in an immediate and possibly deep ozone loss in and around SRM plume wakes. Such a short-term loss could conceivably influence the intensity of the sun’s harmful UV light on the ground near launch sites.

To find an answer, Aerospace researchers modified existing computer models of secondary combustion in SRM plumes by incorporating a more complete representation of the chemistry of chlorine compounds. Secondary combustion, also called “afterburning,” refers to the intense chemical processing that takes place in rocket plumes after the hot gases have left the engine nozzle until they cool to the temperature of the surrounding atmosphere. These new afterburning models predicted that a significant amount of HCl in SRM exhaust would indeed be converted into chlorine radical in the hot plume. Given the inevitable, and important, implication of deep ozone loss, the reactive chlorine emission index (EI) of SRMs needed to be verified.

An EI provides a standardized way of expressing how much of a particular exhaust component is emitted into the atmosphere by a rocket engine. The EI is

![Graph showing the distribution of chlorine radicals in a rocket plume wake.](image)

Most chlorine emerges from solid-propellant rocket motors as hydrogen chloride (HCl). Some of the HCl is converted into reactive chlorine atom (Cl) and molecule (Cl₂) by downstream chemical processes called “afterburning.” Computer models are used to predict how much of the chlorine is in the reactive form as a function of distance away from the motor nozzle. Here, a model predicts that about one-third of the HCl leaving the nozzle is converted into Cl and Cl₂ in the plume of an Athena II rocket as it flies through the ozone layer.
and the plume has expanded bustion process has occurred position after the secondary com- and burned (in kilograms). For rocket engines, the EI refers to the exhaust plume con- grams) by the total mass of propellant par- calculated by dividing the total mass of a particular component in the plume (in grams) by the total mass of propellant burned (in kilograms). For rocket engines, the EI refers to the exhaust plume com- position after the secondary com- bustion process has occurred and the plume has expanded.

The true extent of the immediate stratospheric response to the putative reactive chlorine emissions was not well understood; the results of various models were not in agreement. For example, predictions of the duration of the short-term ozone loss in the wake of a Titan IV-class vehicle varied from a few minutes to a few hours from model to model. Without actual plume data, it was impossible to evaluate the accuracy of the various models, and the resulting uncertainty allowed the possibility that the actual ozone loss exceeded all predictions. The behavior of ozone in SRM plume wakes needed to be measured, and the plume-wake models needed to be evaluated.

A third uncertainty concerned the alu- mina particles in SRM exhaust. These tiny particles (most are less than one-thou- sandth of a millimeter in diameter) have the same chemical makeup as sapphire (Al₂O₃). Some laboratory measurements had suggested that heterogeneous chemi- cal reactions on the surface of alumina particles might contribute to ozone loss by converting chlorine from inactive to active forms. The potential importance of this effect is critically determined by the exact sizes of the alumina grains in the exhaust. The largest grains fall out of the strato- sphere within several days, and so their surfaces do not have time to promote sig- nificant chemistry in the global sense. The smallest grains may remain aloft for several years, however, possibly promoting ozone-harmful reactions throughout the stratosphere. To resolve this question, alumina particles in SRM plume wakes needed to be collected and the EI of the smallest of them measured.

In-Situ Plume Experiments
At its inception, RISO conducted three independent data-collection experiments. Two of these, both completed in 1998, used remote-sensing devices based at Cape Canaveral Air Force Station. First, a network of sensors measured the influence of stratospheric plumes on the intensity of harmful solar UV light on the ground near the launch site. Second, a multiple-wave- length lidar (light detection and ranging) system successfully illuminated plumes with laser beams to measure the optical properties of plumes over Cape Canaveral and provide insight into how plume exhaust mixes into the stratospheric background air. These two efforts conclusively demon- strated that even though radicals in rocket exhaust cause immediate loss of UV-absorbing ozone in individual plumes, rocket plumes disperse in a way that makes it highly unlikely that the intensity of UV light on the ground near launch sites would measurably increase following launches of even the largest rockets.

RISO’s main focus, however, has been to develop a detailed under- standing of rocket emission chem- istry by directly measuring the composition of stratospheric air inside plume wakes during the criti- cal time from several minutes to sev- eral hours after launch. RISO chose the NASA WB-57F aircraft to carry instruments into lower-stratospheric rocket plumes at an altitude of about 19 kilometers. During a typical mis- sion, the WB-57F enters a plume about five minutes after launch and then executes figure-8 maneuvers around the launch-vehicle trajectory, encountering the plume wake about every 10 minutes for up to two hours after launch. The air- craft travels at about 200 meters per sec- ond and spends between 2 and 60 seconds in the plume during each encounter meas- uring composition.

Beginning in 1996, a variety of exhaust plumes were sampled by the instrumented WB-57F aircraft, including the space shuttle, Titan IVA, Delta II, Atlas IIAS, and Athena II. Three instruments carried dur- ing the 1996 missions proved the scientific value of the RISO concept. The instru- ments have steadily improved since the first missions. Seventeen state-of-the-art instruments carried during the 1999 mis- sions collected a wide variety of gas and particulate data that will allow a more comprehensive characterization of plume- wake chemistry.

Highlights from Early Missions
On April 14, 1996, the WB-57F carried into a Titan IVA plume a Neutral Mass Spectrometer developed by the Air Force Research Laboratory at Hanscom Air Force Base. Analysis of data from the spectrometer unambiguously demonstrat- ed that the plume contained significant.
amounts of reactive chlorine molecule, a gas not found in the natural stratosphere. The RISO team concluded that the estimated chlorine molecule EI of the Titan IVA SRMs was generally consistent with predictions based on the Aerospace computer models of chlorine afterburning chemistry.

RISO WB-57F missions have carried up to four instruments to observe the extent and duration of immediate ozone loss in the plume wake. Data from each plume encounter allow investigators to quantify how much ozone is destroyed in the plume over time. Measurements from Titan IVA and space shuttle plumes show that the amount of ozone destruction does not increase without limit. RISO researchers have shown that ozone loss slows about one hour after launch, suggesting that the most ozone-destructive emissions have been deactivated by reactions with various gases in the surrounding air. This important observation has eased concerns that the short-term ozone loss in rocket plumes might be much greater than in the model predictions.

Surprisingly, data obtained from within the plumes of several different rockets show that launch vehicles with greatly differing SRM emission rates cause about the same amount of ozone loss between 30 and 60 minutes after launch. Ozone loss in the plumes of Delta II and Atlas IIAS rockets was about the same as the loss in the plumes of the much larger Titan IVA and space shuttle. Existing plume-wake models that include only SRM chlorine gas emissions have not predicted this result; why this discrepancy exists is not yet known. It may be that SRM emissions interact with the stratosphere in a fashion not yet accounted for in plume models, or perhaps the liquid-oxygen/kerosene core engines of the Atlas IIAS and Delta II produce reactive gases that act alone or with SRM emissions to cause some additional ozone loss. Further data collection and measurement of the actual radical EIs for the various systems, and the development of detailed models of plume-wake chemistry, are needed to solve this puzzle.

Interagency ACCENT Program
Thiokol Propulsion, the company that manufactures the SRMs used on the space shuttle and Atlas IIAS, and Alliant Techsystems, the company that produces the Delta II SRM, joined RISO in 1998 as contributing partners. In 1999, RISO joined forces with NASA, the National Oceanic and Atmospheric Administration, and the National Center for Atmospheric Research as part of the Atmospheric Chemistry of Combustion Emissions Near the Tropopause (ACCENT) mission, a multiagency-sponsored effort to study the effects of aircraft and rocket-engine exhaust on the upper troposphere and lower stratosphere.

ACCENT brings together RISO and ongoing efforts of the NASA Atmospheric Effects of Aviation Program (AEAP). The
influence that rocket emissions have on Earth’s ozone layer. The advances coming out of RISO are making the Air Force and the entire space-launch community confident that ozone loss from both individual and collective launches does not constitute a significant environmental hazard. RISO has proved that a low-cost program of ongoing plume-wake intercepts using appropriate instrumentation can help resolve the scientific problems surrounding the issue. RISO has also shown how joining forces with other agencies and industry increases the scientific return on investment for all interested parties.

The data and conclusions from the RISO program reinforce a presumption that rocket emissions do not seriously threaten the ozone layer at the present time. However, as the space transportation industry grows, as new launch systems are introduced, and as the ozone layer recovers from past damage caused by now-banned substances, the effect of rocket emissions on stratospheric ozone is likely to become a more visible issue. The space transportation community should continue to support scientific research efforts to fully understand the impact of rocket-propulsion systems on the composition of Earth’s natural umbrella, the ozone layer.

Looking Ahead
RISO represents but one component of ongoing Aerospace activities to provide the Air Force with cutting-edge research and technical guidance on a wide range of environmental issues—from solvent chemistry to toxic ground clouds and ozone depletion. For its part, the RISO team allows SMC to claim world-class scientific expertise with regard to the

Ozone concentration measured across the plume wakes of four different launch vehicles, all obtained about one hour after the different launches. Red represents data obtained while the WB-57F aircraft was inside the exhaust plume. The total amounts of chlorine emitted by the Titan IVA, Atlas IIAS, space shuttle, and Delta II SRMs at the altitude of these measurements are about 2.0, 0.2, 4, and 0.3 tons per kilometer of altitude. Despite such large differences in chlorine emission rates among the four rocket types, the ozone losses in the plumes are comparable. The data were obtained by J. Benbrook and W. Sheldon of the University of Houston.

Further Reading
The question of whether Earth is dangerously heating up has become a subject of debate in our time. But is global warming fact or fiction? One thing is certain: The surface temperature of Earth has increased 0.45 to 0.6 degrees Kelvin in the past century. A recent study supported by The National Science Foundation predicts our planet will warm by 2 degrees Kelvin in the 21st century. Recent research conducted by The Aerospace Corporation to validate Defense Meteorological Satellite Program (DMSP) measurements could shed some light on global warming issues.

Aerospace recently made significant advances in the ability to measure the distribution of water vapor in the upper troposphere (upper portion of the lower atmosphere). Using a ground-based lidar (light detection and ranging) system, “greenhouse gases” (so called because these atmospheric constituents produce a “greenhouse effect” over Earth) contribute to this warming. Water is the most influential component of the greenhouse gas mixture: Water vapor absorbs infrared radiation emitted from Earth’s surface and lower atmosphere more than any other constituent, thereby trapping heat best. Accurate knowledge of the amount of atmospheric water must be obtained to improve and test global-warming models.

A radiosonde is an instrument package carried by a balloon that ascends to altitudes of 20 to 30 kilometers. It measures temperature, humidity, and pressure in the atmosphere and broadcasts the information back to a ground station. The Global Positioning System is used to record the trajectory during ascent to determine wind speed and direction.

**Water-Vapor Lidar Extends to the Tropopause**

Lidar’s role in obtaining accurate measurements of water vapor in the upper troposphere is becoming increasingly important as the issue of global warming heats up.
measure humidity, temperature, and air pressure. First, radiosondes do not operate correctly at the low temperatures typically encountered above an altitude of 8 kilometers. Second, they are one-shot attempts at measuring atmospheric conditions, and they take one hour to reach their zenith.

The lidar system measures water vapor continuously over the entire altitude range. This is important because the lidar can capture data from a satellite as the satellite moves overhead, and satellites are only in view for five minutes. During this brief time, the “ground footprint” of the satellite must be in line with the lidar. The lidar then calibrates the data derived from the satellite. Essentially, it verifies whether or not a satellite is measuring water vapor properly. (See sidebar “How Lidar Works,” pages 14 and 15)

Finally, water-vapor data can now be derived from multiple satellites that measure water vapor all over the world. Before the advent of satellites, data were derived from radiosondes routinely launched over land by national weather services.

### Improving Computer Models

Combining accurate ground-based lidar measurements with high-quality imagery obtained by satellites promises to improve both global-climate and weather-forecast modeling. One way to determine the causes (and the only way to predict the future extent) of global warming is to have accurate models, which presupposes having accurate knowledge of the initial atmospheric conditions.

Global-climate-change studies rely heavily on computer-generated models that predict the future state of the atmosphere based on initial data retrieved from ground- and satellite-based weather measurements. Although these models are largely based on thoroughly tested principles of physics, a number of simplifica-

### Microwave Sounders vs. Radiosondes

DMSP recognized in 1979 the need for accurate data to feed numerical (computer) global-weather-prediction models and pio-

### Lidar vs. Weather Balloons

The combined use of lidar and satellites provides many advantages over conventional balloon-borne radiosondes, which operate much like radar, the researchers discovered significantly more water content in the upper reaches of the troposphere than was previously thought to exist. This capability was developed to improve calibration of U.S. Air Force meteorological satellites.

Setting up the Aerospace mobile lidar are Steven Beck, Yat Chan, and Jerry Gelbwachs. It was first used for satellite calibration at Kauai, Hawaii. The container was equipped with wheels and towed to the final site. The structure on the left front of the container is the elevator that raises the beam director periscope (located on top of the container). The beam director is stored below the roof line so the container can fit inside an aircraft.
neered a microwave-sounding instrument, the SSM/T-1 (Special Sensor Microwave/ Temperature), to measure temperature in the atmosphere. Until then, radiosondes alone were relied upon to gather data about atmospheric temperatures.

Microwave sounders are passive devices, radio receivers that listen for emissions at various frequencies. Water vapor emits microwaves, the intensity of which is used to estimate water content in the atmosphere, particularly over oceans, where conventional methods of obtaining measurements are in short supply. (Radiosondes, which provide a more direct means of measuring atmospheric properties, are in widespread use over land.)

In 1991, DMSP launched the SSM/T-2, which measures water vapor. SSM/T-1 and SSM/T-2 now serve as eyes on worldwide weather, providing the data needed to initialize the computer models. Although the SSM/T-1 temperature sounder has a long history of success, the SSM/T-2 is newer and has had limited development.

Because water vapor is highly variable in the atmosphere, measurements of it are generally neglected in computer-generated forecast models. This is unfortunate because water provides the principal means of energy transport in the troposphere and plays a critical role in global warming. Additionally, water vapor induces cloud formation and violent weather events, determines atmospheric visibility, causes icing, and influences aircraft contrail formation.

In processing water-vapor data derived from SSM/T-2 measurements, serious discrepancies were observed between microwave and radiosonde water-vapor data. The problem was traced to radiosonde humidity transducers. Errors show up in the water-vapor data derived from lidar is useful in measuring the constituents of the atmosphere.

Raman lidar was initially developed at NASA’s Goddard Space Flight Center. Aerospace confirmed its feasibility for use in DMSP applications in experiments performed during 1993 at the Air Force Malabar facility. Plans were then made to develop a mobile lidar system capable of calibrating satellites from a variety of remote locations, and Aerospace designed and constructed the system in-house. This mobile lidar is housed in a surplus Air Force transportable radar container.

**Experimentation on Kauai**

The new Raman lidar system was first put to use during the calibration and validation of the DMSP F-14 satellite. A sea-level island location with an airport and controlled air space, clear dark sky, and, of course, a moist atmosphere were required for the demonstration. The Navy’s Pacific Missile Range Facility on the Hawaiian island of Kauai was chosen. The Hawaii Air National Guard provided transportation.

Calibration was highly successful and showed significant improvement over radiosonde calibration. During a two-week period, 10 lidar measurements were taken that closely matched measurements gathered by the SSM/T-2. However, the radiosonde measurements suggested considerable instrument error. Aerospace concluded that radiosonde water-vapor measurements taken above 8 kilometers altitude are incorrect most of the time because the water-vapor transducers carried by radiosondes become unresponsive at the low temperatures encountered at high altitudes.

**High-Altitude Water Vapor**

High-altitude water-vapor measurement is a key element in modeling global warming because water has a much greater influence on Earth’s tropospheric energy balance than trace gases such as carbon dioxide. However, water vapor is not accurately monitored, and little is known about its influence on global climatic change. Aerospace learned from the Kauai experiment that the lidar’s high-altitude accuracy needed to be improved to accurately validate SSM/T-2 for upper-tropospheric water-vapor measurement. A new high-altitude detector system was incorporated into the lidar, which allowed measurements above 10 kilometers. When this new system was used at the U.S. Navy’s Pacific
The picture of upper-tropospheric water vapor observed from San Nicolas Island was much different than expected based on prior NASA satellite measurements. The lidar measurements indicated that, on average, four times more water vapor than expected lies in thin layers near the tropopause (top of the troposphere).

Missile Range Facility at San Nicolas Island, off the coast of California, SSM/T-2 upper-atmosphere water-vapor measurements were validated.

The lidar measurements indicated that, on average, four times more water vapor than expected lies in thin layers near the tropopause (top of the troposphere).

How Lidar Works

Lidar has proved to be an improvement over ground-based methods of measuring water vapor in the atmosphere.

A lidar consists of a laser transmitter, a receiver telescope, photodetectors, and range-resolving detection electronics (not shown). The Raman lidar shifts the laser frequency from the infrared range into the ultraviolet range using harmonic generator crystals. The ultraviolet is expanded in a collimator telescope to make the output eye-safe and to improve the divergence of the beam.

The operating principles of lidar are similar to those of radar. The laser transmits a short pulse of light in a specific direction. The light interacts with molecules in the air, and the molecules send a small fraction of the light back to the receiver telescope.
A second set of data acquired in 1999 from the NASA Jet Propulsion Laboratory Smithsonian Table Mountain Observatory site, located at 2,300 meters in elevation at Wrightwood, California, confirms this figure. The high location provided very clear skies and reduced the range to the tropopause, thereby improving measurements. Data from the two sites were similar, confirming that the data represent weather in the vicinity of the local tropopause.

If the results of these experiments are broadly descriptive of the midlatitude atmosphere, they may add to our understanding of global warming. Before now, few high-altitude measurements had been taken at those latitudes using precise methods.

**Atmospheric Circulation and Hadley Cells**

The combination of lidar data, wind data, and SSM/T-2 upper-atmosphere water-vapor imagery provided information that supports the current scientific understanding of general atmospheric circulation. Global atmospheric circulation is caused by the uneven heating of Earth’s surface. Lower latitudes receive more radiation...
June 30, 1998

October 7, 1998

Brightness-temperature mappings recorded in the SSM/T-2 upper tropospheric channel for satellite overpasses, made during San Nicolas Island lidar measurements. Blue corresponds to low-brightness temperature, which indicates the presence of moisture and signifies that emissions are primarily from the cold upper troposphere. Red corresponds to high-brightness temperature. High-brightness temperatures occur when microwave emissions originate from low altitudes, which are normally warmer, and the middle and upper troposphere are dry. Otherwise, the microwave emissions would be absorbed by high-altitude water vapor. In these images, San Nicolas Island, indicated by a small white triangle, lies near the boundary between moist and dry upper layers.

Brightness temperature (kelvin)

275

235

275

235

San Nicolas Island

San Nicolas Island

To understand atmospheric circulation, various models have been developed. One such model is the Hadley circulation model. The sun shines approximately overhead at the equator. This heats surface regions, causing air to rise and cool. The cool air loses moisture in the process. Once cool, it moves north and south, descending toward midlatitudes and then returns at low levels back to the equator where it gets reheated.

SSM/T-2 routinely identifies large mid-latitude regions, including locations such as San Nicolas Island, that have very dry upper air. Dry regions are surrounded by moist high-altitude regions. The dry air presumably came from very high altitudes near the equator and subsided to a lower altitude upon reaching midlatitudes. The lidar and radiosonde data can be used to estimate how long ago this subsidence occurred. Thin moist layers are usually observed by lidar in regions that characteristically have dry air.

In the case of San Nicolas Island, we hypothesized that wind shear carries moisture from moist regions into neighboring dry areas. When we combined the wind-shear velocities with the distance between the lidar location and the surrounding moist region, we estimated that the air subsided within 2 to 20 hours of our measurements. The overall picture of dry high-altitude equatorial air moving north and subsiding at our midlatitude is consistent with the Hadley circulation model, which predicts that equatorial air moves toward the poles.

Applying Our Knowledge

Future research will extend water-vapor measurements over regions representative of the global atmosphere, and the capability of measuring temperature will be added to the lidar. The new DMSP Special Sensor Microwave Imager Sounder (SSMIS) instrument will measure temperatures up to 80 kilometers altitude, which will require a new validation method. This instrument is being developed by Aerojet-Gencorp and is scheduled for launch in November 2000. It combines the features of the current-generation SSM/T-1, SSM/T-2, and SSM/I (SSM/Imager) instruments with increased horizontal resolution and the capability of measuring temperatures at high altitudes.

Some researchers use Rayleigh lidar to measure temperature up to 80 kilometers altitude. We currently measure temperature from the sun than do higher ones. To understand atmospheric circulation, various models have been developed.
In 1735, George Hadley, a British physicist (1685–1768), formulated a model to explain the general pattern of global atmospheric circulation. The Hadley model describes, in the simplest form, a large-scale circulation in Earth’s atmosphere, with a rising motion of air over the equatorial regions and a descending motion northward and southward toward the midlatitudes.

Massive convection in the equatorial Pacific lofts air from the surface to altitudes above the tropopause. The tropopause is coldest in equatorial regions, and water precipitates in the form of rain and ice from the convected air masses. This injects very dry air into the region of the tropopause and above. The air moves generally toward the poles and descends in the process, accounting for our observations of exceedingly dry air layers at midlatitudes. Frequently, moist layers occur above the dry regions. Wind shear causes this by transporting thin layers from nearby moist regions.

In general, lidar is an excellent method for calibrating satellite microwave sensors. It accurately depicts the atmosphere those sensors view. Enhancing lidar’s capabilities will contribute to our increasing understanding of the atmosphere, which may one day in the near future lead us to solving the puzzle of why Earth is getting hotter.

Further Reading


Early in the morning on a day in August 1972, all satellites in the constellation that would alert the United States of a missile attack suddenly lost their warning capability. The detectors and circuitry, according to the status data, had been hit by a strong source of ionizing radiation. This appeared to be an ominous event to operators at the ground stations, where the initial interpretation was that the Russians had detonated a nuclear warhead in space, possibly as a precursor to a ballistic missile attack.

Prompt analysis of the sensor outputs by an Aerospace expert in nuclear and space physics on duty at one of the sites provided the actual cause: The satellites had been hit with a massive proton flux from an extraordiarily intense solar flare. An unwise reaction by the government was averted. The Aerospace Corporation subsequently worked with the U.S. Air Force and the system contractor to provide fixes to assure uninterrupted operation through such events. Aerospace has often provided invaluable assistance to the Air Force, playing a key role in the development, operation, and success of this national asset—the Defense Support Program (DSP).

Deployed 40,000 kilometers above Earth in the equatorial plane, a constellation of satellites equipped with infrared sensors (“IR eyes”) looks for ballistic missiles aimed at the United States or its allies. The period of their orbits is 24 hours, so the satellites remain at constant longitudes, that is, in geostationary orbits, guarding against an attack on the United States or its allies from anywhere in the world. The system has been in operation continuously since it went on line in 1971. Fortunately, the United States has never experienced a missile attack; of course, the
extent to which DSP has served as a deterrent to such an attack cannot be known. In addition to performing their primary mission, DSP sensors have produced a wealth of information on a variety of sources, military and otherwise, that has served many other purposes. Certain civilian uses of these surveillance satellites are described in the premier issue (January 2000) of Crosslink. Those particular applications of course are peripheral to the principal mission of DSP.

**Early Development**

The U.S. national early warning program had its beginnings in the early 1960s, when it became evident that the United States was vulnerable to attack by the intercontinental ballistic missiles (ICBM) then under development in the Soviet Union. By the mid-sixties, ICBMs appeared in test flights, and the United States adopted the MAD (mutual assured destruction) strategy as its national defense posture.

Early warning became critical to the survival of U.S. retaliatory forces, and launch detection by space-based sensors was essential. Aerospace was called upon at the start to perform trade studies and prepare technical specifications for an operational system. It provided the general system engineering and technical direction for the development of the program.

The ballistic missile defense studies as a whole had been initiated earlier. As part of its Project Defender, the Advanced Research Projects Agency (ARPA) of the Department of Defense in the late 1950s explored concepts for early warning based on the detection of the infrared emission from rocket exhaust plumes by sensors stationed in space. The ARPA program consisted mainly of system studies and various measurement programs to characterize the infrared properties of ballistic missiles and the backgrounds against which they would have to be observed.

Concurrent with much of that work, the Air Force, aided by Aerospace, began development of its own Missile Defense Alarm System (MIDAS). That system, had it been implemented, would have employed a constellation of many satellites in low Earth orbits.

A space experiment designated as Program 461, the final element of the MIDAS program, provided the proof of principle to support the development of a system with far greater capabilities. Although the exhaust plume from a rocket emits a great deal of infrared radiation, so do many other sources that might appear in the background. To discriminate the rocket from the background sources, the sensors must operate in specific regions of the spectrum. In their characteristic molecular bands between two and three microns, water vapor and carbon dioxide in the atmosphere greatly suppress emissions from fires and other hot terrestrial sources and solar reflections from the ground and low clouds.

Because water vapor and carbon dioxide are the principal products of rocket-propellant combustion, the hot exhaust plume from the missile appears as a very bright source moving against the background in those same spectral bands. Consequently, as a missile rises through the atmosphere and absorption diminishes, the apparent intensity of the plume rapidly increases. Accordingly, the sensors are
Sensor Design

In the design of a sensor for missile detection, a basic engineering decision involves a choice between two approaches. A sensor can be designed to have relatively few detectors that scan the field of view, or it can be designed to have a very large number of detectors staring at the scene to detect targets by their motion through the field of view. The technology of the 1960s enabled only the former approach, which was incorporated in Program 461 and subsequently, DSP. In either case, a basic design tradeoff is the optimization of the spectral filter: The wider the bandpass, the more target intensity is collected, but also the greater the amount of highly variable background. The early target and background measurement programs provided sufficient information, mostly with airborne instruments, for the design of the Program 461 sensors; the results of that program provided the basis for further optimization of the sensors in the DSP system that followed.

Program 461 satellites, built by Lockheed Missiles and Space Company, observed many launches of missiles and space launch vehicles from Cape Canaveral and Vandenberg Air Force Base, as well as from different sites in the Soviet Union. After processing the signals received at the ground stations, the target intensities were reported as radiant intensities in the system bandpass as functions of time for the particular viewing aspect and other parameters of the observation. Extraction of such signatures from the raw data was a formidable task in view of the relatively coarse pointing system of these satellites by today’s standards; Aerospace provided much of the analysis for that purpose.

Such data were obtained from observations of three SS-9 missiles in test flights from the Tyuratam facility near the Aral Sea to the Kamchatka peninsula in the Sea of Japan. At the time, this liquid-propellant ICBM was the largest missile in the USSR inventory and the principal threat to the United States. Among other observations in the Eastern hemisphere, a particular sighting of significance was that of a single-stage missile launched in a test flight from Kapustin Yar on February 3, 1967. The relatively short burn of that missile afforded observations in only three scans between cloud break and thrust termination. That missile was later identified as an SSN-6 medium-range submarine-launched ballistic missile (SLBM), the smallest missile of a direct threat to the continental United States.

During 1966 and 1967, Program 461 collected data on many of the ballistic missiles and space launch vehicles in the Soviet and U.S. arsenals, totaling dozens of test launches. In the course of those observations, Program 461 sensors produced a substantial database on the clutter created by the scanning of the Earth-cloud backgrounds, information also needed for the optimization of the DSP sensors, the development of which was commencing at that time. Thus were provided the proof of principle for space-based surveillance and a valuable database for the design of the sensors in the national early warning system to follow.

DSP Sensors

In the late-1960s, the design of the sensors for the DSP system to some extent followed the concept for MIDAS. A linear array of passively cooled infrared detectors, with spectral filters providing a bandpass in the center of an atmospheric absorption band, was positioned in the focal plane of a telescope mounted in a satellite rotating at six revolutions per minute. The idea of a constellation of many satellites in a low Earth orbit was abandoned in favor of a few satellites in geostationary orbits positioned at longitudes affording views of the launch sites of concern. Accordingly, a sensor with a

![Diagram](image-url)
DSP Flight 1 satellite prior to shipment to Cape Canaveral (1970). Note the offset of the telescope from the vehicle axis. The two small telescopes pointing normal to the axis of rotation are the star sensors that provide the data necessary to determine the precise pointing of the primary telescope. The main body of the satellite contains a reaction wheel to control the spinning rate, propulsion units for station keeping, and electronic components for data processing and transmission. Solar cells covering the body and four paddles provide power. The radiator, used for passive cooling of the detectors, is located near the base of the telescope.

much more powerful telescope and many more detectors was designed by Aerojet for installation in a satellite built by TRW Inc. The DSP development effort was originally known as Program 266, then 949, and later 647. The system became DSP when it achieved full functional capability.

DSP sensors incorporated many features representative of an advanced technology for that time. The design included a larger array of detectors (2000 initially, 6000 eventually), spectral filters, electrical circuitry for optimizing discrimination of targets from a cluttered background, and improvements in data processing onboard and at the ground station. A key feature of the DSP design (insisted upon by the Aerospace advisors to the Air Force), was the absence of moving elements in the sensor optics, elements that enormously simplified the bore sighting and precise attitude determination. The optical axis of the telescope was offset from the axis of rotation of the satellite; the field of view of the detector array extended from near the nadir to slightly above the horizon. Thus, the rotation of the satellite provided a scan of most of a hemisphere every 10 seconds. Two ground stations were initially built, one located near Denver, Colorado, and the other deep in the outback of Australia.

The initial satellite, Flight 1, was launched in November 1970 by a Titan IIIC launch vehicle with a Transtage third stage. Unfortunately, it didn’t quite reach a geosynchronous orbit, and the subpoint circled Earth every five days. The orbit was high enough, however, to allow checkout of the ground data-processing sites and the mission software and to provide nominal Earth-pointing and sensor operation. Aerospace advisors at the ground sites and the Air Force Satellite Control Facility provided the leadership for debugging and modifying the software with “field-fixes” and configuring the satellite for collecting data. The anomalous orbit was fortuitous because it provided the opportunity to observe launches from both the United States and the Soviet Union. The functioning of the system was proved, and data from a considerable number of observations were collected.

In May 1971, Flight 2 was successfully launched, and after on-orbit testing (accomplished in a very short time), it was turned over to the Air Force Systems Command. The satellite was stationed over the Indian Ocean to view the major launch sites of the Eurasian continent. For Flight 2 to effectively perform the warning mission, it had to recognize and report ICBM launches and reject all infrared phenomena.
from other sources. This required templates (intensities vs. time) for threat missiles to compare with the data as it was transmitted to the ground. Analysis to that end by other organizations would have taken months.

Aerospace and the sensor contractor, working closely with personnel at the site, produced templates in a few weeks and continually upgraded them as the data from missile sightings were accumulated. This analysis also facilitated some necessary modifications of the system software by Aerospace and contractor personnel assigned to the ground site. Transition of Flight 2 to a fully operational status, consequently, was greatly accelerated.

The sensor met the requirements and rapidly created a database of all the ballistic missiles and space launches of the time. In later years, additional satellites were deployed to maintain a constellation with satellites in the East to report ICBM launches and in the West to cover the ocean areas from which SLBMs could be launched. Later, a larger constellation of satellites, stationed over a range of longitudes, provided multisensor viewing of areas of particular concern.

The sensors have been upgraded and improved in several respects throughout the life of the program. One significant improvement was the addition to Flight 6 and subsequent sensors of an array of sensors to view targets above the horizon. For such fields of view, it was not necessary to restrict the spectral bandpass to suppress terrestrial sources. That addition and other changes in the detectors and electrical circuitry provided a substantial improvement in sensitivity, which was needed to detect and track upper stages. The average orbit lifetime of a sensor has been five years, with considerable variation. To date, 19 satellites have been built. All but one were launched with Titan vehicles, those since 1989 with Inertial Upper Stages. The exception was Flight 16, deployed from the shuttle into a low Earth orbit for subsequent boost by an Inertial Upper Stage motor to a geostationary altitude.

The research test series that preceded the development of DSP provided no effective means for establishing the precise pointing of the sensors. Aerospace realized that a foolproof backup needed to be added to DSP for determining the precise attitude of the infrared sensors. (In retrospect, the use of an Earth sensor for pointing and star sensors for instantaneous, precise attitude determination proved to be effective.) Aerospace concluded that a ground-based laser operating in the infrared band of the sensor—alogous to a beacon or transponder in the field of view of a radar—could serve that purpose. The idea was vigorously pursued, and a DSP satellite was successfully illuminated within a year of the first satellite launch. Aerospace developed and provided hydrogen-fluoride chemical lasers for that use.

Although the lasers were rarely needed for precise attitude determination of DSP satellites, they were used as a beacon for functional checkout of the overall system.

Apparent motion of target in the satellite field of view over the Atlantic Ocean (left), with time increasing upward to the left, and over the western Pacific Ocean (right), where the launch site was beyond the horizon and the target appeared after rising above the Earth limb. Green indicates target positions of maximum intensity per scan in the main array; blue indicates positions reported by the more sensitive cells in the above-the-horizon array. Note the increasing spread as the vehicle accelerates.
Also, they were used for determining sensor resolution and bore sighting, new software validation and evaluation of stray light properties, and assessing system sensitivity to uncooperative laser illumination and developing means for its mitigation. Incidentally, after two star sensors on Flight 8 failed, lasers were used in their originally intended applications—beacons in the sensor field of view as the primary means of determining the precise attitude.

Target data downlinked from the satellites to the ground include the intensities of the detected source above a prescribed threshold, the identification of the responding detectors, and the universal time, the latter two providing the instantaneous target position in satellite coordinates: elevation and azimuth. By appropriate processing, including a comparison with stored templates of intensity versus time based on prior sightings, the target can be identified and its heading established. The principal product of the DSP system in near real time is a warning message from the ground station relaying that information to the national command authority. **DSP satellites have fulfilled their primary mission by reporting thousands of missile launches over three decades.**

**Data for Off-Line Analysis**

The data from those DSP sightings have also been provided to various centers for off-line analysis, when appropriate, and for archiving in a comprehensive database maintained by Aerospace. The database contains the reports on all ballistic missile sightings, as well as on a vast number of other events, military in nature and otherwise (for example, space launch vehicles). The data listings include not only themaximum intensities in a given scan, but also the lower intensities of the target distributed in the vicinity. For such analysis, data from the satellites can be displayed in a variety of forms.

**DSP Support of Theater Operations**

DSP took on a more direct and proactive role in its missile-warning mission during Desert Storm operations in 1991. In that conflict, Iraq launched a large number of Scud missiles at targets located in Saudi Arabia and Israel. Specifically, the DSP satellites stationed in the Eastern Hemisphere detected and tracked the missiles during the boost period and reported their headings to the appropriate Patriot missile batteries fielded by the U.S. Army in those areas. The information was provided by telephone communication links, some of which were staffed by Aerospace personnel, allowing the Patriots to intercept the incoming Scuds. **Although the effectiveness of the Patriots in destroying the warheads can be questioned, the interceptions did take place, establishing the feasibility of defense against theater missiles.**

Largely because of their success in Desert Storm, DSP satellites currently play the key role in the Air Force’s Attack and Early Reporting to Theater (ALERT) system, an operational function of the 11th Space Warning Squadron of the 21st Space Wing. Aerospace provided invaluable assistance to the Air Force in the procurement of that system by generating specifications and providing support with the contractor selection process. For the ALERT system, data from the entire DSP constellation and other sources are integrated and processed at one facility located at Schriever Air Force Base in Colorado. The detection reports, considerably improved in accuracy, are transmitted rapidly to commanders in the theaters through space-based communication links. **DSP satellites provide worldwide coverage so that the ALERT system can monitor all major regional conflicts and areas of concern simultaneously, and provide threat-missile descriptors, such as launch point, heading, position, velocity, and predicted impact location.**

**Observations of Other Sources**

The database contains hundreds of sightings of other sources that appear in the fields of view of the sensors; many are assigned descriptors that characterize the nature and time variation of their movement across the monitor screen. In no instance has analysis failed to identify the sources of those sightings. (Contrary to some assertions in the popular press, there have been no sightings of alien spacecraft.)
Among the objects of current interest are the occasional meteors of significant size. Earth is constantly bombarded by small meteors, most the size of a grain of sand. Their numbers, and intensities due to atmospheric drag, appear to vary inversely with mass. Large meteors of potentially catastrophic size are rare. Nevertheless, during the last 30 years, DSP has observed some very sizable meteors. For example, in 1972 an exceptionally large meteor was observed in a grazing trajectory that came within an astronomical whisker of hitting Salt Lake City. Analysis by Aerospace led to the conclusion that the object was of sufficient mass that a slightly deeper penetration of the atmosphere would have resulted in an impact equal to the explosive force of the atomic bombs that destroyed Hiroshima and Nagasaki in World War II.

In addition to such moving objects, very intense stationary thermal sources on the ground can be seen in spite of the background suppression afforded by the spectral filters and electronic circuitry. Such sources include fires, gas flare-offs from oil refineries, volcanic eruptions, nuclear explosions, and solar scatter and reflections. The observation of such events is of course facilitated by very low humidity, which minimizes absorption in the path to space.

Some particularly mysterious sightings occurred in the early 1970s. Extremely bright stationary sources suddenly appeared in the area adjacent to the Caspian Sea, with apparent intensities of nearly a megawatt per steradian lasting for several minutes. Certain analysts elsewhere attached a sinister interpretation to those events. However, analysis at Aerospace solved the mystery simply by noting that these sources all appeared precisely along a pipeline to Moscow from the natural gas fields in the area. Clearly, the sources were burning gas, presumably flared off for maintenance of the pipeline, a conclusion later confirmed by other information. Gas flares from oil refineries are also routinely observed, particularly in dry regions such as Southern California and the Near East. Likewise, volcanoes are frequently observed at various locations throughout the world, sometimes by the emission from the lava flow, but more often by reflected sunlight from the ash plume rising high in the atmosphere.

Observations of many other infrared sources, both stationary and moving, have been routinely observed, reported, and processed at Aerospace for inclusion in the database, archived at the Ballistic Missile Defense Organization Advanced Missile Signature Center, Air Force Arnold Engineering and Development Center, Tullahoma, Tennessee, which is accessible to qualified users. Over the years, there have been innumerable reports analyzing the data to fulfill the needs of various Space and Missile Systems Center program offices and other government agencies. The results of most of those analyses are in the classified literature.

The database contains an extensive collection of events, the observations of which were not even thought of when the system was originally conceived. Among other uses, that collection provides the fundamental basis for evaluating the effect of such events on the performance of the Space Based Infrared Systems (SBIRS) that will replace DSP in a few years. It is axiomatic in the field of infrared phenomenology that when more sensitive sensors are deployed in space, unexpected observations and other surprises are invariably produced. This is true of the DSP sensors, not only in their original configuration, but especially in the improved versions. The new system will feature many improvements in the sensors and advances in overall capability, and will be assigned additional missions. SBIRS will quite likely bring many surprises when it is deployed.
Fred Simmons

Rocket Exhaust Plume Phenomenology is an introductory treatment of the multidisciplinary subject of plume phenomenology as it relates to the development of space-based defense systems. The text covers the elementary principles of rocketry, basics of rocket-propellant combustion, gas dynamics of supersonic exhaust plumes, infrared radiation processes, theoretical plume models, physical properties of exhaust constituents, diagnostic measurement techniques, and other related topics. More specifically, this work is primarily concerned with the phenomenology of rocket exhaust plumes as the targets of space-based surveillance systems; however, the spectral, temporal, and spatial distributions of the infrared emission from rocket-powered vehicles are also required for the design and optimization of sensors for various other defense-related missions. It is written at a level intended to bridge the gap between space systems engineers and scientists involved in detailed studies of plume observables.

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Aerospace Photos
Capture Launch Clouds
Robert Abernathy
During countdown to the launch, the U.S. Air Force Range Safety uses an onsite computer model known as the Rocket Exhaust Effluent Dispersion Model (REEDM) to predict the rise and dispersion of the expected ground cloud. REEDM relies on meteorological data such as wind, cloud cover, solar angle, and weather-front conditions to predict the extent of the toxic hazard corridor, the downwind area where ground concentrations of chemicals may exceed allowable public exposure limits. When REEDM predicts the launch may cause exposure to unsafe levels of toxic gases, the launch is delayed until meteorological conditions improve.

When REEDM was being developed during the 1960s and 1970s, several cloud-transport parameters were not well known, so the model was deliberately designed to be conservative. Over the years, the level of toxic compounds considered acceptable for public exposure has been lowered, increasing the likelihood of a launch delay. By 1994, toxic hazard corridor predictions were beginning to reduce launch availability at both Air Force launch ranges, the Eastern Range at Cape Canaveral Air Force Station and the Western Range at Vandenberg Air Force Base.

The high cost of launch delays, up to $1 million a day, and the continued concern for public welfare prompted development of the Air Force Atmospheric Dispersion Model Validation Program (MVP) to test and improve REEDM’s accuracy. The Aerospace Corporation developed this validation program and provides technical management.

An Aerospace method of monitoring exhaust clouds using photographic imagery showed that REEDM consistently underestimated the ground-cloud stabilization height and overestimated the extent of the toxic hazard corridor. With subsequent Aerospace modifications, REEDM predictions have improved launch-range availability, preventing unnecessary launch holds and saving the government millions of dollars while protecting the public safety.

**Monitoring Ground Clouds**

Ground clouds are difficult to monitor. Within the first few minutes after a launch, they grow to dimensions of 1–2 kilometers and rise to similar heights. Also, although the optimal wind for a launch carries the ground cloud out to sea, such a wind direction does not allow for the use of ground-based launch-cloud sampling systems.

Aircraft instrumented to sample and measure ground-cloud concentrations of toxic compounds have been used during launches of the space shuttle, but aircraft sampling is expensive and doesn’t provide an instantaneous three-dimensional extent for the cloud. Additionally, this method of measurement typically relies on the pilot’s ability to fly into the center of the visible cloud, which precludes accurate nighttime sampling. Without visible feedback, the pilot doesn’t know the aircraft’s location relative to the center of the cloud, so concentration measurements are extracted from unknown regions.

Aerospace proposed an alternative approach to monitoring the rise and expansion of exhaust clouds, and in 1994 it developed the technology to track ground clouds using multiple cameras that capture images simultaneously from various locations surrounding the launch pad. Because a ground cloud rises and stabilizes quickly, the cloud needs to be tracked for only a few minutes following launch. The images captured during the tracking complement measurements garnered from aircraft sampling.

Day and night images of the launch cloud were needed to test REEDM under all launch conditions. Visible and infrared imagery would be captured, using visible charge-coupled-device cameras and thermal infrared scanners. In daytime, the visible cameras “see” the scattering of sunlight caused by aerosols from the solid-rocket motors. Throughout the day and night, the infrared scanners observe the temperature difference between the warm launch cloud (vapors) and the cooler background sky.

Launch of a Titan IVB rocket from Cape Canaveral Air Force Station.
Cameras provide better-resolution images than infrared scanners, but the quality of camera imagery is subject to adequate lighting, which depends upon the relative positions of the sun, cloud, and camera. The camera can also provide clearer cloud-edge-detection imagery of a low-elevation cloud on a hot sticky day because atmospheric humidity and cloud elevation affect the quality of the infrared imagery.

Because the two imaging systems complement each other, Aerospace designed and built four visible and infrared imaging systems (VIRIS) in which the visible camera and the infrared scanner are mounted on a single tripod. The camera and infrared scanner are “coaligned,” meaning the center pixel of each camera simultaneously views the same distant object. The four systems were shipped alternately to Cape Canaveral and Vandenberg for use during Titan IV launches from both launch ranges.

### Calibrating VIRIS

Aerospace designed custom tripod heads that accurately encode, or digitize, the viewing direction (azimuth and elevation) as VIRIS tracks a cloud. Optimal camera locations depend upon wind direction, so they cannot be selected until a few hours before launch. The challenge is to quickly calibrate the systems, aligning a known pixel with true north for zero azimuth and level for zero elevation.

Calibrating the angle encoders of the tripods requires the camera crew to identify large landmarks that can be observed by both the cameras and the infrared scanners. Before the imagery systems are deployed, a survey provides accurate position information on the observable landmarks, using either a differentially corrected Global Positioning System (GPS) receiver or accurate maps of the launch range. Once the camera is set up, the GPS receiver provides the camera-site location.

The camera crew calculates the azimuth and elevation from the camera to the landmark. Once the center pixel is aligned with the landmark, it is a simple matter to set the correct azimuth and elevation readout from the tripod. The field of view is calibrated by scanning the landmark horizontally and vertically while recording the change in encoded azimuth and elevation.

Typically, camera crews can set up and calibrate to 0.1 degree of accuracy within 45 minutes. Each calibrated imagery system provides a real-time display of the azimuth and elevation to the ground cloud from each camera’s perspective. Hence, the ground cloud’s approximate position can be triangulated in real time using the pointing angles to the cloud from all sites.

### Triangulating Cloud Position

Aerospace developed PLMTRACK software to triangulate the position and extent of a ground cloud with imagery captured simultaneously from any two sites. Once an image is calibrated, each pixel represents a ray into space from the camera’s position. PLMTRACK converts a selected pixel in one image (the top of the cloud, for example) into an azimuth and elevation from that image’s camera location. It then projects that ray across the simultaneous image from the other site. The analyst identifies the same feature (top of the cloud) in the sister image using the projected ray for perspective, and the same feature is thereby seen from two perspectives. PLMTRACK converts this information into a ray from each site that passes through the same feature and calculates the closest approach of the two rays, which represents the position of the selected feature in three-dimensional space. This approach works well when an object or feature can be observed from two perspectives.

Triangulating the top and bottom of a cloud at low elevations is easy because both top and bottom are observable from multiple perspectives. But how is the horizontal extent of the cloud determined when the same sides cannot be seen from both perspectives? Where is the “middle” of the cloud? PLMTRACK allows the analyst to use a rectangle to define the top, bottom, left, and right extremes of the cloud from each camera’s perspective, and the projection of these rays provides an estimate of the extent for the cloud. The middle of the rectangle provides the ray through the middle of the cloud from each site, and the nearest approach of these middle rays represents the position of the cloud.

### Validating Multicamera Imagery

Neither the camera nor the infrared scanner directly detects the toxic hydrochloric acid in rocket exhaust. For this reason, it is important to document not only that the cameras and infrared scanners see the same extent (angular size) of the ground cloud, but also that the observable (seen by VIRIS) extent contains the toxic acid that might pose a hazard.

Aerospace images obtained from the coaligned camera and infrared scanner have consistently shown the same angular extent for the Titan IV ground clouds, verifying that both image-capturing methods are similarly useful when applied to tracking ground clouds. However, these observations do not prove that hazardous levels of toxic chemicals do not extend beyond the observable extent of the cloud.
Aircraft sampling of hydrochloric acid within four Titan IV exhaust clouds provided the complementary data needed to validate the coaligned multicamera imagery. An aircraft was fitted with a Geomet hydrochloric-acid monitor to obtain concentration profiles during four launches between May 1995 and December 1996—two each from Cape Canaveral and Vandenberg. Comparison of the aircraft data and imagery showed that the observable extent contained the measurable acid (in the form of both vapor and aerosol). These observations are consistent with the mechanism of atmospheric dispersion: Atmospheric eddies mix vapors (seen in the infrared) and aerosols (seen in the visible) equally well. These results show that VIRIS provided the cloud’s extent for Titan IV day and night launches, and that the extent includes the hazardous levels of hydrochloric acid.

### Predicting Ground-Cloud Stabilization Height

Because it is initially warmer than the surrounding air, the ground cloud rises. As it does, it entrains the ambient air, which causes it to cool and lose buoyancy. Within three to four minutes, the cloud reaches its “stabilization height,” where it attains thermal equilibrium with the surrounding air and stops rising. The 1995 version of REEDM was used to predict the height of the ground cloud prior to the May 14, 1995, launch of a Titan IV. The REEDM prediction underestimated the stabilization height of the cloud by half, which corresponds to overestimating the ground-level concentration by a factor of eight. During the next three years, the Aerospace Titan IV ground-cloud imagery consistently showed a difference between the observed and predicted stabilization heights for 13 launches from both launch ranges.

Because the stabilization heights derived from the images consistently remained much higher than REEDM’s predictions, the REEDM code was reviewed, revealing several errors. Yet even after these errors were corrected, predictions of stabilization height remained too low. Speculating that the values of two volumetric parameters in the cloud-rise algorithm might be wrong, Aerospace focused its image-analysis efforts on the accurate measurement of the cloud’s volume immediately after launch and during the cloud’s rise. The desired volumetric parameters, which are simply the initial radius of the ground cloud and the rate of increase in radius with altitude (the air entrainment coefficient), would come directly from these measurements.

### Reconstructing the Cloud

Aerospace developed PLMVOL, a software application based on a second analysis algorithm, which reconstructs the three-dimensional cloud from the two-dimensional imagery collected simultaneously at multiple locations. First, the simultaneous imagery from all available locations is digitized and imported with the calibration information into PLMVOL.
Then the analyst traces the outline of the exhaust cloud within each image. Next, PLMVOL converts the pixels within these outlines into rays projected into space from each camera’s location. The exhaust cloud is located at the intersection of these rays. To derive the points where the rays intercept, PLMVOL divides space into small cubes and marks them as occupied by the ground cloud only when intercepted by rays from all available perspectives. It maps the three-dimensional extent of the ground cloud as the Cartesian locations \((x,y,z)\) of all the occupied volume elements. Since the volume elements are adjacent (stacked cubes), summing all occupied volume elements yields the imagery-derived volume of the ground cloud.

Finally, the sphere-equivalent radius, used by REEDM, is calculated from the imagery-derived cloud volume by determining the radius of a sphere with an equivalent volume. Typically, the Titan IV ground cloud is not spherical in shape, but the sphere-equivalent radius is a convenient unit for comparison. The accuracy of PLMVOL estimates depends upon the relative position of the camera sites to the ground cloud’s position. PLMVOL can’t provide an accurate cloud volume if cameras do not see the ground cloud from complementary perspectives, for example along-wind and crosswind perspectives, simultaneously.

Aerospace used PLMVOL to extract cloud-volume data for only 6 of 13 imaged Titan IV ground clouds. Several factors led to this low yield of volumetric data. For example, the cloud didn’t always travel in the predicted direction, Vandenberg restricted access to camera sites to the east and south of the launch pad, and low atmospheric clouds blocked visibility from one or more of the sites. In sum, the available camera locations and visibility did not always provide the complementary perspectives needed to accurately map the cloud volume.

**Analyzing Amateur Imagery**

REEDM also predicts toxic exposure from a low-altitude launch-vehicle abort. In the event of an abort, the launch vehicle would be destroyed in an explosion that releases a hypergolic mixture of liquid fuel and oxidizer. If the abort occurs several hundred feet above ground, REEDM may predict a larger toxic hazard corridor for the unburned oxidizer than for the ground cloud.

Aerospace proved that normal launch-cloud data could be applied to the abort-cloud scenario. It measured the behavior (rise, growth, and stabilization) of normal launch clouds during launches from 1994 and 1997. Abort clouds weren’t measured...
because no Titan IVs failed during deployment. Without abort-cloud data, the accuracy of REEDM predictions for an abort situation could not be validated nor could the ground cloud’s entrainment data be shown to apply to the abort cloud.

The few options for obtaining the necessary data were considered in 1997. One possibility was to use an explosive release of oxidizer to simulate the abort cloud because the most toxic component of the abort cloud is unburned oxidizer. Safety concerns, however, limited test sites to desert locations that did not match the terrain or the meteorological conditions of the launch ranges. Two other options were to continue imaging Titan IV launches on the chance of a failure or search for imagery of earlier aborts hoping to interpret that imagery quantitatively. We chose the latter.

A worst-case abort scenario was inadvertently tested on April 18, 1986, when a defect in a Titan 34D-9 solid rocket motor caused the rocket to explode at an elevation of 830 feet at Vandenberg. Aerospace reviewed the videotapes from the three range-tracking cameras. Unfortunately, the camera operators at two locations did not keep the abort cloud completely within the field of view. To obtain a cloud’s volume, which involves analyzing the abort-cloud imagery from the third range camera, a second, complementary perspective of the abort cloud had to be available. Without abort-cloud imagery from a second camera, the abort-cloud imagery from the third range camera could not be interpreted quantitatively (as cloud position and volume).

Luckily, an amateur photographer videotaped the launch and its abort cloud with a handheld camcorder. This photograph provided the necessary second, nearly perpendicular, perspective. Interpretation of the abort-cloud imagery was complicated because both cameras were panned and zoomed several times during the three minutes the images were captured. Neither camera was mounted on an

The REEDM-predicted and Aerospace-imagery-derived cloud-height curves for a May 14, 1995, Titan IV launch. The imagery-derived rise curve for the ground cloud revealed a factor-of-two discrepancy between measured and predicted stabilization height. Subsequent MVP deployments documented that REEDM systematically underestimated the stabilization heights for all 13 Titan IV ground clouds at both ranges under a variety of launch conditions.

Aerospace imagery-derived air-entrainment rates for normal Titan IV ground clouds and for the Titan 34D-9 abort cloud. The values are substantially lower than the default value used in REEDM calculations during the past 30 years. Legend: A—solid rocket motor; B—upgraded solid rocket motor; C—Cape Canaveral Air Force Station; V—Vandenberg Air Force Base.
Calibrating Amateur Abort-Cloud Imagery

An amateur video of the 1986 Titan 34D-9 aborted launch provided the second perspective necessary to measure the volume of the abort cloud. In 1998, an analyst used the launch facilities shown in a frame of the video to provide the known landmarks needed to calibrate the field of view and the pointing angle of the camera for the image. The analyst also chose various unknown landmarks (such as patches of sand on the hillside) and measured their pixel locations in x, y coordinates (shown in parentheses). Once the image was calibrated, each pixel could be converted to a specific azimuth and elevation from the camera site. As the camera was panned and zoomed, these landmarks provided the calibration for subsequent unknown features (tertiary calibration points) as they moved into the field of view. This method of transferring the calibration to subsequent imagery was used by Aerospace to interpret quantitatively the amateur photography of the abort cloud.

The simultaneous images collected at surf (amateur video) and program sites reveal the shape and size of the red abort cloud from almost right-angle perspectives. The map shows the position of the launch pad and the abort-cloud images taken at each identified camera site. The colored lines on the map show that the right and left edges of the images correspond to the angular field of view of the cameras and that the cameras are pointing at the abort cloud above the launch pad. A pixel (+ sign at the top of the abort cloud) in the image from the surf site's perspective (northeast of the abort cloud) is projected by PLMTRACK as a ray (red line) into the simultaneous image from the program site's perspective (southeast of the abort cloud). The fact that the projected ray touches the top of the abort angle-encoding tripod, nobody intentionally calibrated the field of view of the cameras, and the camera operators did not realize that abort clouds would later be of more interest than burning ground debris. Fortunately, Aerospace was able to calibrate much of the abort-cloud imagery and used PLMVOL to quantify the position and volume of the abort cloud during its rise.

Improving Model Predictions

Aerospace imagery-derived air entrainment rates for the Titan 34D-9 abort cloud measured at Vandenberg and for normal Titan IV ground clouds measured at both Cape Canaveral and Vandenberg were substantially lower than the default value used in REEDM calculations during the past 30 years. These values indicate that REEDM-based predictions of ground-cloud stabilization height have been consistently too low and toxic-hazard predictions too high. The imagery-derived results also show that the air entrainment coefficient and the initial cloud size are constants for the Titan IV normal launch cloud and have the same value for both launch ranges and for both sets of solid rocket motors. The coefficient is the same for the 34D-9 abort cloud, which indicates similar behavior for both normal and abort clouds.

The current version of REEDM (7.09) provides improved stabilization height predictions through the use of Aerospace imagery-derived values for both the air entrainment coefficient and the initial radius. The new REEDM predictions, which are in closer agreement with the observed launch-cloud stabilization heights, have improved launch-range availability by preventing unnecessary launch holds.

In addition, a Titan IV database now establishes the margin of safety for current and future dispersion models. The MVP database includes quantitative analysis of imagery from nine Titan IV launches at Cape Canaveral and four at Vandenberg between 1994 and 1997. MVP deployments involved collecting meteorological data, necessary for running REEDM or improved future dispersion models.

Aircraft samples were taken from two Cape Canaveral and two Vandenberg Titan IV launches during MVP. Aerospace analysis of these aircraft data revealed that both the visible and the infrared imagery “see” the full extent of the cloud containing hydrochloric acid during the first few minutes after launch. This means that the observable aerosol and vapor disperse at the same rate as the unobservable acid, which is consistent with the behavior of aerosols and the mechanism of turbulent dispersion in the atmosphere.

Tracking Tracer Gas

The Aerospace imagery of the Titan IV launches provided useful cloud rise and stabilization data under favorable meteorological conditions, that is, when winds
carried the ground cloud out to sea or over unpopulated areas. Aerospace imagery crews at Cape Canaveral and Vandenberg supported four two-week-long elevated-tracer-gas releases that provided complementary dispersion data, including winds that carried the innocuous tracer toward populated areas. During these MVP efforts, Aerospace established the usefulness of quantitative imagery for measuring the near-field (2–5 kilometers) dispersion of tracer gases.

A blimp released an invisible inert tracer gas at various heights when the wind was blowing inland. This allowed for dispersion measurements over the complex inland terrain of both ranges. Analysis of the infrared imagery provided the cross-wind and along-wind expansion rates in the near field at the release altitude. During these elevated-tracer-release experiments, aircraft and van sampling provided trajectory and dispersion information further afield. These tracer data complement the Titan IV launch-cloud data.

**Predicting Ground Clouds in the Future**

The ability of Aerospace to capture and process quantitative imagery of Titan ground clouds has provided, at a low cost to the consumer, the rise and dispersion data necessary to tune REEDM for more accurate prediction of ground-cloud toxic hazard corridors. Such accurate prediction also reduces the launch costs because it leads to fewer launch holds. A similar measurement program could be used to tune current and future dispersion models for the other heavy launch vehicles, such as the space shuttle today and the Evolved Expendable Launch Vehicle in the future. In addition, routine imagery of launch clouds could provide real-time range-safety information, not only for normal launch clouds but also for the more toxic abort cloud.

**Further Reading**


The Aerospace surveillance technology crew in front of a mobile laboratory. These mobile laboratories, equipped with visible and infrared imagery systems, support remote detection and tracking of chemicals, such as those in launch abort clouds, bomb detonations, and tracer release experiments. They are deployed at launch and test ranges throughout the continental United States. Shown in the photo from left to right, beginning with the back row (in doorway): Bruce A. Rockie, Luis J. Ortega, Michael A. Rocha; left center row: Gary N. Harper, Brian P. Kasper, Karl R. Westberg, Jess T. Valero; right center row: Robert N. Abernathy, Kenneth C. Herr, Jeffrey L. Hall, Donald K. Stone; front row: Mark L. Polak, Andrew D. Shearon, J. Thomas Knudtson, Naomi J. Rose, George J. Scherer, Roberta S. Precious, Karen L. Foster.
Earth’s cloud cover frequently affects the outcome of modern combat because sophisticated aircraft (and weaponry such as laser-guided missiles and night vision sights) do not operate reliably in the presence of clouds. Knowing the state of the cloud cover can determine the success of reconnaissance missions, and it is the most critical factor in the accuracy of humanitarian airdrops. To be of value, cloud data must be current and accurate, but such data can be difficult to obtain, especially in areas where access is limited by military or political restrictions.

Brig. Gen. Fred Lewis, director of Air Force Weather, recognized in 1998 a need for improved cloud data to support military operations in the Balkans. Gen. Lewis wanted a cloud-analysis model that could do a better job at analyzing and forecasting clouds than either the Air Force Weather Agency (AFWA) model then in use or even the extensive upgrade under development at the time.

The Aerospace Corporation stepped in to develop a prototype system that leapfrogged over the planned AFWA cloud model upgrade to deliver automated cloud-analysis products (such as amount of cloud cover or cloud classification) at a much higher resolution. This prototype became the basis for a cloud-analysis system that was then put into operation in less than 60 days in the spring of 1999 to improve weather support for the war in Kosovo. The improved resolution allowed forecasters to provide more accurate cloud-cover predictions to the battlespace planners and pilots.

Cloud-Analysis Model

The Air Force Weather Agency, at Offutt Air Force Base, Omaha, Nebraska, has used automated cloud-analysis models to generate quantitative information on clouds since 1970. The earliest AFWA three-dimensional cloud-analysis model, the 3-D Neph, used space-based cloud-cover imagery from Defense Meteorological Satellite Program (DMSP) satellites. The current model, RealTime Nephanalysis, known as RTNeph, combines ground-based observations with data from DMSP and the Television and Infrared Observation Satellite (TIROS) of the National Oceanic and Atmospheric Administration to produce worldwide cloud analyses at a 48-kilometer resolution. It computes the number of cloud layers, the percentage of cloud coverage, and the height of the base and top of each layer on a 48-kilometer grid. A cloud-forecast model uses the analyses to produce cloud forecasts at this same grid resolution.

The grid is an array of points superimposed on a map of Earth’s surface. Observations of clouds are not taken at grid points, but at irregularly spaced points. Nephanalysis is the process that interpolates cloud data observations to the points on the grid. The distance between adjacent grid points on the AFWA polar stereographic whole-mesh reference grid is 381 kilometers at 60 degrees latitude. All finer-
resolution grids are defined relative to this whole-mesh reference grid. For example, the distance between points on an 8th-mesh grid is 48 kilometers; on a 16th-mesh grid, 24 kilometers; and on a 64th-mesh grid, only 6 kilometers.

Because cloud cover data at 64th mesh presents much finer detail than data at 8th mesh, data at 64th-mesh is called fine-grid data. Data from a lower-resolution grid, such as that based on an 8th mesh, is called coarse-grid data.

Weather and Warfare

The war in Kosovo demonstrated dramatically that weather affects every aspect of battle. The impact of weather on war has long been recognized. In *The Art of War*, circa 500 B.C., Sun Tzu advised, “Know the ground, know the weather; your victory will then be total.” Vice Adm. Scott A. Fry echoed these words 2,500 years later when he told reporters during a briefing on Operation Allied Force that the Serbs had two main allies—geography and weather.

- In 480 B.C., storms at sea broke up the “bridge of boats” across the Hellespont, turning back the army of Xerxes, the emperor of Persia, from its march to invade Greece.
- In 1588 storms off the coasts of Scotland and Ireland wrecked many ships of the Spanish Armada as they retreated after Spain’s failed invasion of the British Isles.
- In June 1812, Napoleon invaded Russia with 500,000 men, only to withdraw five months later in snow and bitter cold with fewer than 10,000 surviving troops.
- During World War II, storms forced Gen. Dwight D. Eisenhower to delay the Normandy invasion one day.
Improved Resolution Enhances Forecasting

The Air Force Space and Missile Systems Center is developing the upgrade to AFWA’s current cloud-detection and forecast system. The new system, known as CDFSII, will increase the resolution of the AFWA cloud analyses and forecasts from an 8th mesh (48-kilometer) grid to a 16th mesh (24-kilometer) grid. Also, by combining data from multiple weather satellites, it will improve cloud detection in stressing conditions such as low clouds and fog, thin cirrus clouds, and tropical clouds.

When completed in December of this year, the new CDFSII system will

- provide a multiple-satellite data-acquisition system that combines the high spatial resolution of DMSP imagery with multispectral data from TIROS
- merge the global coverage of these polar-orbiting systems with the frequent refresh available from an international constellation of geostationary weather satellites
- perform multiple-satellite-specific cloud detection using science algorithms from SERCAA (Support of Environmental Requirements for Cloud Analysis and Archives)
- use clustering techniques to accomplish cloud layering and typing and then combine these independent satellite cloud data records using an optimal interpolation scheme
- feed the cloud analyses into a single-cloud forecast model to deliver short-term (12-hour) and long-term (48-hour) forecasts

Battlespace Weather Forecasting

Although CDFSII will improve forecasting beyond that provided by the current system at AFWA, Gen. Lewis decided that an even finer-scale automated cloud-analysis and forecasting system was needed to support operations, specifically the “weather function,” in the Balkans.

Under a new centralized support concept, an Operational Weather Squadron was activated in Germany. The Weather Squadron performs the weather function continuously during the intelligence preparation of battlespace in a series of steps that converts weather data into intelligence and communicates it to users. The weather officer collates weather information collected throughout the battlespace, combines it with weather data received from weather flight observers and forecasters and from higher headquarters, and then generates the weather forecasts.

The Aerospace Prototype

In response to Gen. Lewis’s call for high-resolution cloud analyses to better support the Weather Squadron, Aerospace developed a prototype cloud-analysis model at a fine-scale grid, increasing the resolution to 6 kilometers (64th mesh) from the 24 kilometers planned for the CDFSII system.

Aerospace developed the prototype by modifying the CDFSII SERCAA algorithms to improve computing speed. Faster processing enabled use of DMSP “fine mode” data, which is higher resolution than the DMSP “smooth mode” data used in CDFSII.

The Aerospace cloud-analysis prototype represents the first quantitative use of DMSP fine-mode data in a meteorological model. Fine data is not available worldwide, so the prototype model produces the 64th-mesh fine grid regionally using the fine data and then combines it with a worldwide analysis at the coarser CDFSII grid using DMSP smooth-mode data.

The new model began generating cloud analyses as a prototype in January 1999 at the Aerospace Environmental Application Center facility at AFWA. The Kosovo conflict prompted the Air Force to issue a request to put this prototype system, along with high-resolution forecasting capability, into operation within 60 days. Within two weeks of the Air Force request, Aerospace wrote code to post fine-grid cloud data over Kosovo from the prototype system as images on the Air Force Weather Information network, which provides data to weather forecasters in Europe. Color-coding was added to highlight aspects of the cloud mask.

From Laboratory to Battlespace

Aerospace, AFWA, Atmospheric Environmental Research, and Sterling Software (the CDFSII contractor) worked together to develop an operational system based on the Aerospace prototype. The prototype
had to be ported from the laboratory environment to a 24-hour-a-day operational capability, expanded to include multispectral TIROS algorithms, and combined with the forecast model. A capability to “tune” the algorithms on a regional basis to produce a better cloud analysis was added.

Tuning is not as critical for the TIROS algorithms because additional channels allow for more cloud-discrimination tests, but because DMSP has one visible and one infrared channel, a single-test cloud-detection algorithm that is very sensitive to threshold settings is used. Aerospace found that using the same thresholds in the DMSP algorithms for each satellite was inadequate because of differences in DMSP smooth- and fine-mode calibration. Fine data typically exhibits a 5-degree Kelvin cold bias, so a bias term was added to the fine-mode infrared threshold values that greatly improved the fine-grid (64th-mesh) results.

A major task in the transition of the prototype to an operational forecast system involved modifying the CDFSII coarse-grid cloud-forecast model to run at the higher resolution (6 kilometers). Code was written to overwrite the coarse-grid values with fine grid for all grid points touched by one satellite swath of DMSP fine data, which is typically an eighth or less of an orbit. The forecast model then advected the resulting fine-grid cloud analysis with high-resolution winds from an operational mesoscale model to produce the cloud forecast.

The team completed the system in less than 60 days, and Gen. Lewis specifically commended Aerospace for this support to the nation’s warfighters. The operational implementation of the Aerospace prototype cloud model improved weather forecasting for operations across the Balkans by providing more accurate cloud-cover data to the air tasking, order-planning, and execution processes. This system is still in use to support regional high-resolution cloud forecasting.

Further Reading


DMSP Cloud Data

Defense Meteorological Satellite Program (DMSP) satellites have been providing worldwide cloud imagery for national programs since 1966. The Air Force Weather Agency uses data from three-dimensional cloud analyses in developing computer cloud-forecast models for the military. Data from DMSP satellites formed the cornerstone of the Aerospace prototype cloud model.

The U.S. Air Force has launched more than 30 DMSP satellites. The constellation includes at least two sun-synchronous polar-orbiting satellites flying at about 800 kilometers above Earth, with one satellite orbiting in early, and the other in late, morning.

Unlike other meteorological satellites, DMSP provides imagery at the edge of its 3000-kilometer swath that nearly matches the quality of imagery directly below the satellite. The primary sensor, the operational line scan, collects cloud imagery in a visible and a long-wave-infrared band. The operational line scan calibrates, indexes, and stores the data for transmission. During daylight, the fine-mode resolution of the visible-band data is 0.62 kilometers, and the resolution of the infrared-wavelength data is 2.8 kilometers. Fine data is collected on a regional basis up to a quarter orbit. On-board smoothing is used to decrease the data rate (and therefore resolution) to provide data for the entire orbit. The operational line scan also has a unique capability that allows it to gather visible-light data at night at a 3.5-kilometer resolution with as little as one-quarter-moon illumination. Additional satellite sensors measure atmospheric vertical profiles of moisture and temperature and a variety of space environmental parameters.

DMSP has proved to be a valuable tool in scheduling and protecting military operations. The last of the Block 5D-2 series of satellites was launched April 4, 1997. The Block 5D-3 series, the first of which was launched in December 1999, accommodate larger sensor payloads and feature a larger power supply, more on-board memory, and increased battery power that will extend the life of the satellites from the current four years to five.


October 3–5, 2000

19th Aerospace Testing Seminar: Balancing the Forces of “Faster, Better, Cheaper in Aerospace Testing”

Sponsored by The Aerospace Corporation and the Institute of Environmental Sciences and Technology

The forum will include presentations from industry leaders in testing, instrumentation, and program planning. Also offered will be tutorials and a special panel discussion featuring members of the ongoing Broad Area Review commissioned by the U.S. Air Force.

Topics include
• Lessons Learned
• Industry Test Practices, Standards, and Processes
• Testing Methodologies, Innovations, and Challenges
• Risk Management
• Integration for “Best Practices”

Preseminar tutorials (October 2) are
• Handbook for Dynamic Environmental Criteria
• Integration and Test Systems Engineering
• Data Validity Requirements for Your Test Data
• Vacuum Physics and Vacuum Techniques
• Signal Processing
• Satellite Structural Testing
• Thermal Balance and Thermal Vacuum Testing
• Introduction to Modal Analysis and Testing

The seminar will be held at the Manhattan Beach Marriott, 1400 Parkview Ave., Manhattan Beach, CA 90266.
For more information visit www.aero.org/conferences/ats/.

October 22–25, 2000

MILCOM 2000: 21st-Century Military Communications—Architectures and Technologies for Information Superiority

Hosted by The Aerospace Corporation and TRW, Inc.

Sponsored by Institute of Electrical and Electronics Engineers, Inc., IEEE Communications Society, and Armed Forces Communications and Electronics Association

The Military Communications International Symposium offers a diverse program of both classified and unclassified sessions, guest speakers, panels, and tutorials.

Topics of the unclassified sessions include
• 21st-Century Communications Architectures
• Advanced Commercial Systems for Military Application
• Advanced Communications Networks
• Advanced Communications Techniques
• Advanced Communications Standards and Protocols
• Advanced Communications Technologies

Topics of the classified sessions are
• Milsatcom to Support Joint Vision 2010
• Strategic and Tactical Communications Architectures
• Advanced Techniques and Technologies for Information
• Information Warfare, Security, Superiority

Unclassified sessions will be held at the Los Angeles Airport Marriott, 5855 W. Century Blvd., Los Angeles, CA 90045.
Classified sessions will be held at The Aerospace Corporation in El Segundo.
For more information visit www.milcom2000.org.

November 28–December 1, 2000

Risk Management 2000: Lessons for the Millennium

Sponsored by The Aerospace Corporation and the Air Force Space and Missile Systems Center

The goal of this third annual symposium is to stimulate broader interest in risk management at the national level. A tutorial, Earned Value Risk Management, will be offered the first day.

Discussion topics include
• Effective Risk Management Practices
• Application of Tools and Methodologies
• Lessons Learned
• Comprehensive Areas of Interest (launch vehicles, spacecraft, ground systems)

The Conference will be held at the Hilton McLean Tysons Corner, 7920 Jones Branch Dr., McLean, VA 22102.
For more information visit www.aero.org/conferences/risk/.
Communication satellites represent one of the most significant applications of space technology. Almost every year since the early 1960s, a new communication system has launched its first satellite. Today, applications reach more than 100 countries, providing a variety of communication services to both large and small terminals on land, ships, and aircraft.

During these four decades, advances in electronics and satellite technology and an expanding market for communication satellite services have generated changes in communication satellite design.

Two aspects of this broad scope of change—increase in weight and in design life—are shown in the graphs, which are based on data from Communication Satellites, fourth edition. Points on the graphs represent all satellite programs described in the book—whether experimental or operational, civil or military, commercial or noncommercial—from all manufacturers except those in Russia and China. The points are positioned on the graphs to show the date of the program’s first launch. Blue triangles represent satellites in geostationary orbits; magenta squares, satellites in lower orbits.

Satellite weight is usually stated as dry weight without fuel or weight with fuel at the beginning of the satellite’s life in orbit. The latter weight is shown on the first graph. The growth in satellite weight accommodates more communications equipment, thereby increasing satellite capacity to respond to the growing market for satellite services. Also, the mission effectiveness of any given weight has been increased by technological improvements. These improvements, occurring in small increments over the decades, include lighter materials and higher-efficiency solar cells and propulsion.

The weight of most nongeostationary satellites has been restrained by very limited budgets. Only since 1997 have larger nongeostationary satellites been launched for programs that provide voice communications to handheld user terminals.

Satellite life is limited by three factors: random failures, exhaustion of consumables, and component wear-out. Design life is a requirement related to consumables, such as propellant, and to components subject to wear-out, such as rotating mechanical devices.

For those programs that have announced a design or mission life, the increase in satellite life, shown on the second graph, is a result of improved technology; lessons learned in the manufacturing, testing, and operation of satellites; and the ability to build and launch larger satellites. Horizontal lines of triangles show the increase in common communication satellite design lives from 5 to 7 to 10 to 12 to 15 years.
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