Atmospheric Observations and Earth Imaging

Earth is a dynamic, living oasis in the desolation of space. The land, oceans, and air interact in complex ways to give our planet a unique set of life-supporting environmental resources not yet found in any other part of our solar system. By understanding our planet, we can protect vital aspects, especially those that protect life and affect weather patterns. The shuttle played an integral role in this process. In the mid 1980s, NASA developed a systems-based approach to studying the Earth and called it "Earth System Science" to advance the knowledge of Earth as a planet. Space-based observations, measurements, monitoring, and modeling were major focuses for this approach. The Space Shuttle was an important part of this agency-wide effort and made many unique contributions.

The shuttle provided a platform for the measurement of solar irradiance. By flying well above the atmosphere, its instruments could make observations without atmospheric interference. Scientists' ability to calibrate instruments before flight, make measurements during missions, and return instruments to the laboratory after flight meant that measurements could be used to help calibrate solar-measuring instruments aboard free-flying satellites, which degrade over their time in space. The Atmospheric Laboratory for Applications and Science payload, which flew three times on the shuttle in the early 1990s, had four such instruments—two measuring total solar irradiance and two measuring solar spectral irradiance. The Shuttle Solar Backscatter Ultraviolet Instrument, which flew numerous times, also made solar spectral irradiance measurements as part of its ozone measurements.

The shuttle's low-light-level payload bay video imaging led to the discovery of upper-atmosphere phenomena of transient luminous events of electrical storms called "Elves." NASA pointed the first laser to the Earth's atmosphere from the shuttle for the purpose of probing the particulate composition of our air. The agency used the shuttle's many capabilities to image Earth's surface and chronicle the rapidly changing land uses and their impact on our ecosystems.

"Every shuttle mission is a mission to planet Earth" was a commonly heard sentiment from scientists involved in Earth imaging. In addition to working with many Earth observing payloads during the course of the Space Shuttle Program, "Earth-Smart" astronauts conducted scientific observations of the Earth systems. Thus, the shuttle provided an extraordinary opportunity to look back at our own habitat from low-Earth orbit and discover our own home, one mission at a time.

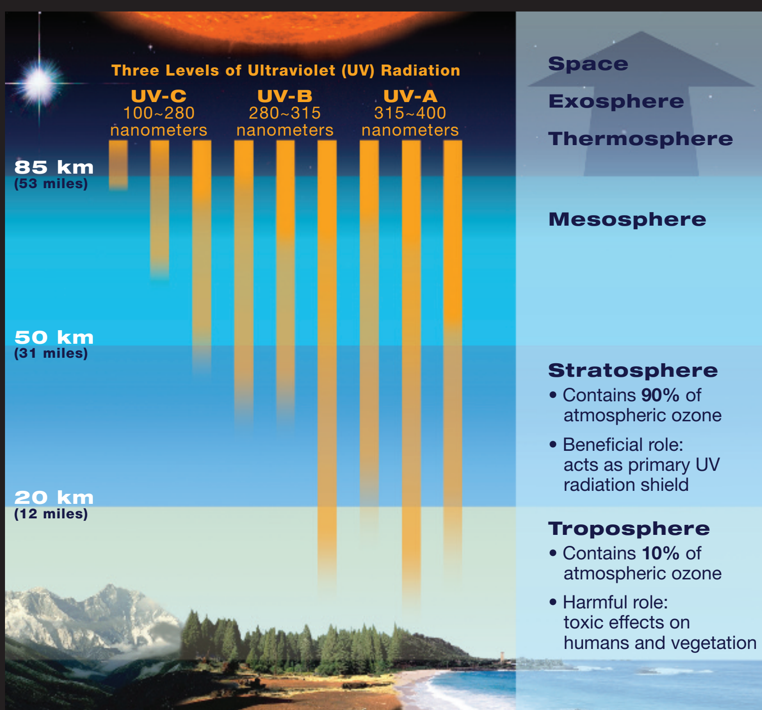
The Space Shuttle as a Laboratory for Instrumentation and Calibration

Global environmental issues such as ozone depletion were well known in the 1970s and 1980s. The ability of human by-products to reach the stratosphere and catalytically destroy ozone posed a serious threat to the environment and life on Earth. NASA and the National Oceanic and Atmospheric Administration (NOAA) assumed responsibility for monitoring the stratospheric ozone. A national program was put into place to carefully monitor ground levels of chlorofluorocarbon and stratospheric ozone, and the shuttle experiments became part of the overall space program to monitor ozone on a global scale. The NASA team successfully developed and demonstrated ozone-measuring methods. NOAA later took responsibility for routinely measuring ozone profiles using the Solar Backscatter Ultraviolet 2 instrument, while NASA continued to map ozone with a series of Total Ozone Mapping Satellite instruments.

Some examples of multiple roles of the Space Shuttle: orbiting laboratory, engineering test bed, Earth imaging, and launch platform for several major Earth-observing systems.

Ozone Depletion and Its Impact—Why Research Is Important

The Earth's ozone layer provides protection from the sun's harmful radiation. The atmosphere's lower region, called the troposphere (about 20 km [12 miles]), is the sphere of almost all human activities. The next layer is the stratosphere (20 to 50 km [12 to 31 miles]), where ozone is found. The occurrence of ozone is very rare, but it plays an important role in absorbing the ultraviolet portion of the sun's radiation. Ultraviolet radiation is harmful to all forms of life. Thus, depletion in the ozone layer is a global environmental issue. Space-based measurements of ozone are crucial in understanding and mitigating this problem.



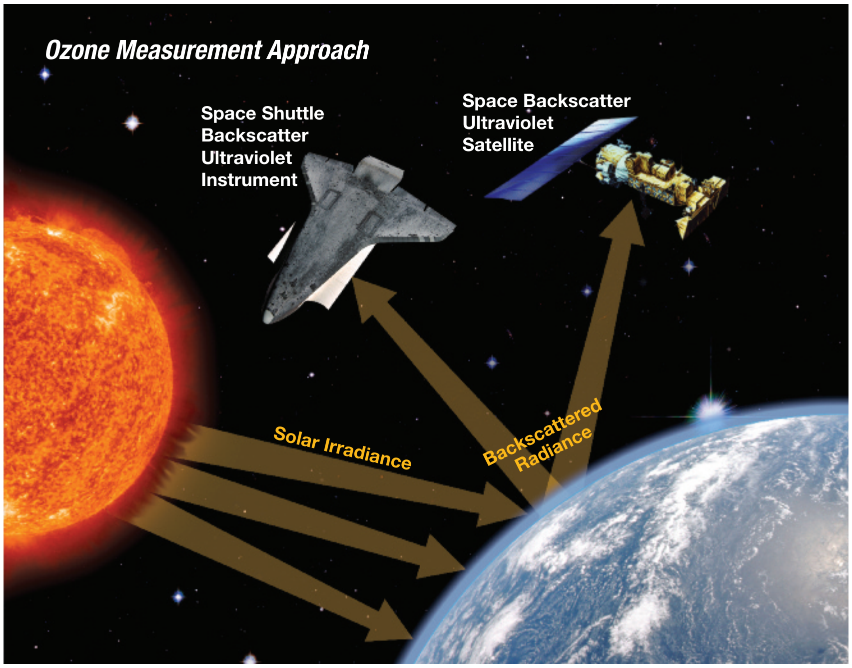
"This most excellent canopy, the air,…" wrote William Shakespeare in Hamlet *long ago. The layers depicted here show the distribution of ozone. Astronauts who have viewed the layers from orbit describe it as a delicate "skin" protecting our planetary "body."*

A Unique "Frequent Flyer" for Ozone Measurements

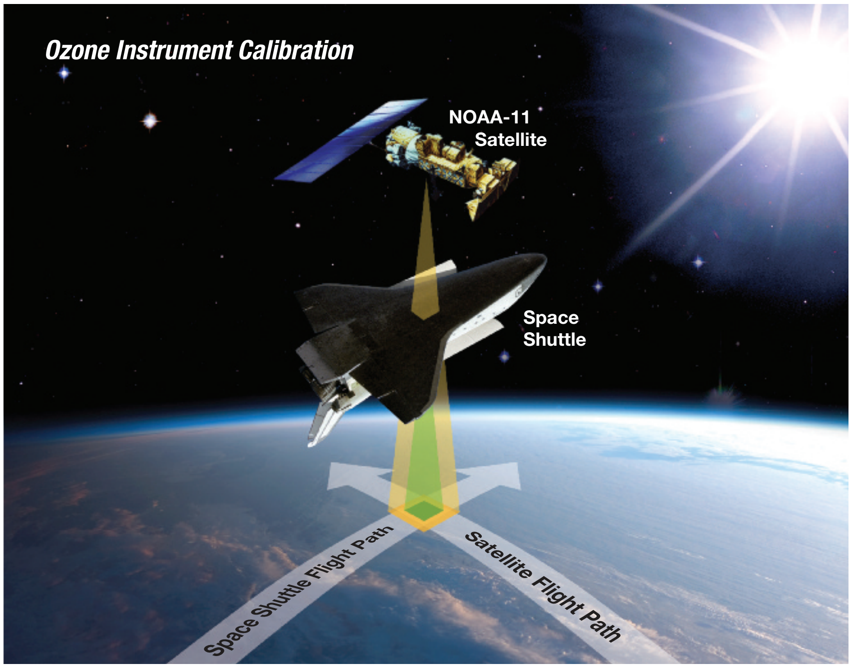
The Shuttle Solar Backscatter Ultraviolet experiment was dubbed "NASA's frequent flyer" since it flew eight times over a 7-year period (1989 to 1996)—an unprecedented opportunity for a shuttle science. Its primary mission was to provide a calibration or benchmark for concurrent ozone-monitoring instruments (Solar Backscatter Ultraviolet 2) flying on the NOAA operational polar orbiting crewless weather satellite. The NOAA satellite monitored stratospheric ozone and provided data for weather forecasts. Other satellites, such as NASA's Upper Atmosphere Research Satellite, Aura satellite, and the series of Stratospheric Aerosol and Gas Experiment and Total Ozone Mapping Spectrometer missions, measured ozone as well. Comparison of these ozone data was a high priority to achieve the most accurate ozone record needed for determining the success of internationally agreed-upon regulatory policy.

How Did Shuttle Solar Backscatter Ultraviolet Work?

Repeated shuttle flights provided the opportunity to check the calibration of NOAA instruments with those of the Shuttle Solar Backscatter Ultraviolet instrument by comparing their observations. The shuttle instrument was carefully calibrated in the laboratory at Goddard Space Flight Center before and after each of flight.



The sun is the source of radiation reaching the atmosphere. A spacecraft carrying an ozone-measuring instrument receives the backscattered radiation. Ozone is derived from the ratio of the observed backscattered radiance to the solar irradiance in the ultraviolet region.



The National Oceanic and Atmospheric Administration (NOAA) satellite carries an ozone instrument similar to the one that flew in the shuttle payload bay. The shuttle-based instrument was carefully calibrated at Goddard Space Flight Center. The shuttle's orbital path and satellite flight pass overlapped over the same Earth location within a 1-hour window during which the measurements took place and were later analyzed by scientists.

The sun's output in the ultraviolet varies much more than the total solar irradiance, which undergoes cycles of about 11 years. Changes in ozone had to be attributed accurately from solar changes and human sources. The Shuttle Solar Backscatter Ultraviolet instrument flew along with other solar irradiance monitors manifested on Space Transportation System (STS)-45 (1992), STS-56 (1993), and STS-66 (1994). Measurements from these three Atmospheric Laboratory for Applications and Science missions were intercompared and reprocessed, resulting in an accurate ultraviolet solar spectrum that became the standard for contemporary chemistry/climate models. This spectrum was also used to correct the continuous solar measurements taken by Solar Backscatter Ultraviolet 2 on the NOAA satellite.

Ozone Instrument Calibrations—Success Stories

- Comparisons with NOAA-11 satellite measurements over a period of about 5 years were within 3%—a remarkable result. The key to Shuttle Solar Backscatter Ultraviolet success was the careful calibration techniques, based on National Institute of Standards developed by the NASA team at Goddard Space Flight Center. These techniques were also applied to the NOAA instruments. The shuttle was the only space platform that could provide this opportunity.

- Although the instrument flew intermittently, it independently helped confirm ozone depletion at 45 km (28 miles), where chlorine chemistry is most active. Measurements made in October 1989 were compared with the satellite Nimbus-7 Solar Backscatter Ultraviolet measurements made in October 1980, an instrument that was also known to have an accurate calibration. Detected ozone loss of about 7% was close to predictions of the best photochemical models at that time.
- Calibration techniques were applied to all international satellites flying similar instruments—from the European Space Agency, European Meteorological Satellite, and the Chinese National Satellite Meteorological Center—thus providing a common baseline for ozone observations from space.

More Good News

An international environmental treaty designed to protect the ozone layer by phasing out the production of a number of chemicals linked to ozone depletion was ratified in 1989 by 196 countries and became known as the Montreal Protocol. This protocol and its amendments banned the production and use of chlorofluorocarbons. Once the ban was in place, chlorofluorocarbons at ground level and their by-products in the stratosphere began going down. The latest observations from satellites and ground-based measurements indicate ozone depletion has likely ended, with good signs that ozone levels are recovering.

Ellen Ochoa, PhD
Astronaut on STS-56 (1993), STS-66 (1994), STS-96 (1999), and STS-110 (2002).

Atmospheric Observations and Ozone Assessments

"The three Atmospheric Laboratory for Applications and Science missions in the early 1990s illustrated the collaborative role that the shuttle could play with unmanned science satellites. While the satellites had the advantage of staying in orbit for years at a time, providing a long-term set of measurements of ozone and chemicals related to the creation and destruction of ozone, their optics degraded over time due to interaction with ultraviolet light. The Space Shuttle carried up freshly calibrated instruments of the same design and took simultaneous measurements over a period of 9 or 10 days; the resulting data comparison provided correction factors that improved the accuracy of the satellite data and greatly increased their scientific value.

"One of the fortunate requirements of the mission was to videotape each sunrise and sunset for use by the principal investigator of the Fourier transform spectrometer, an instrument that used the sunlight peeking through the atmosphere as a light source in collecting chemical information. Thus, one of the crew members needed to be on the flight deck to start and stop the recordings, a job we loved as it gave us the opportunity to view the incredible change from night to day and back again. I would usually pick up our pair of gyro-stabilized binoculars and watch, fascinated, as the layers of the atmosphere changed in number and color in an incredible spectacle that repeated itself every 45 minutes as we orbited the Earth at 28,200 km per hour (17,500 miles per hour)."

Advancing a New Ozone Measurement Approach

From the calibration experiments conducted on five flights from 1989 to 1994, NASA expanded research on ozone elements.

The Total Ozone Mapping Spectrometer (satellite) and Solar Backscatter Ultraviolet instruments measured ozone using nadir viewing spectrometers. This approach was good for determining the spatial distribution (i.e., mapping the ozone depletion) but did a poor job of determining the vertical distribution of ozone. A spectrometer that measures light scattered from the limb of the Earth could be used for measuring how ozone varies with altitude; however, a test was needed to show that this approach would work.

While early models predicted that the largest changes in ozone as a result of the introduction of chlorofluorocarbons into the atmosphere would be observed in the upper stratosphere—in the 40- to 45-km (25- to 28-mile) region—the discovery of the ozone hole demonstrated that large changes were occurring in the lower stratosphere as a result of heterogeneous chemistry. The Solar Backscatter Ultraviolet instruments flown by NASA and NOAA were well designed to measure ozone change in the upper stratosphere.

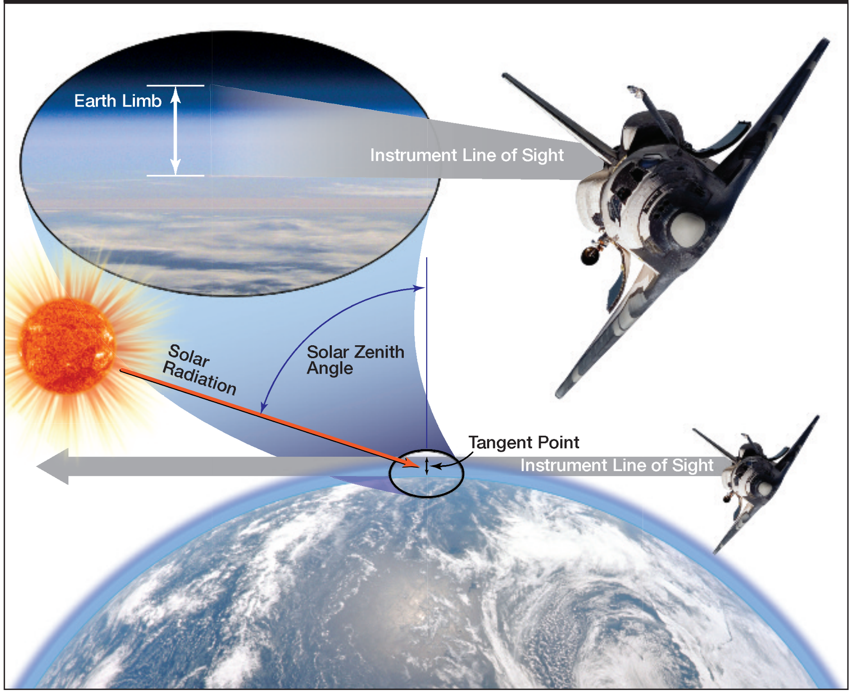
For changes occurring below 25 km (16 miles), Solar Backscatter Ultraviolet offered little information about the altitude at which the change was occurring. Occultation instruments, such as the Stratospheric Aerosol and Gas Experiment, were capable of retrieving ozone profiles from the troposphere to nearly 60 km (37 miles) with approximately 1-km (0.6-mile) vertical resolution, but they could measure only at sunrise and sunset. Thus, the sampling limitations of occultation instruments limited the accuracy of the ozone trends derived for the lower stratosphere while the poor vertical resolution of the Solar Backscatter Ultraviolet instruments severely limited their ability to determine the altitude dependence of these trends. An instrument was needed with vertical resolution comparable to that of an occultation instrument but with coverage similar to that of a backscatter ultraviolet instrument.

The measurement of limb scattered sunlight offered the possibility of combining the best features of these two measurement approaches. The Shuttle Ozone Limb Sounding Experiment was a test of this concept.

How Did the Shuttle Ozone Limb Sounding Experiment and the Limb Ozone Retrieval Experiment Work?

To measure ozone in the upper stratosphere, scientists needed the large ozone cross sections available in the ultraviolet. To measure ozone at lower altitudes, scientists needed to use wavelengths near 600 nanometers (nm). The Shuttle Ozone Limb Sounding Experiment mission addressed these needs through the use of two

Shuttle Ozone Limb Sounding Experiment Concept



Light scattered from the limb of the Earth is measured to determine how ozone varies with the altitude.

instruments—the Shuttle Ozone Limb Sounding Experiment and the Limb Ozone Retrieval Experiment—flown as a single payload on STS-87 (1997).

The Shuttle Ozone Limb Sounding Experiment instrument measured ozone in the 30- to 50-km (19- to 31-mile) region. This ultraviolet imaging spectrometer produced a high-quality image of the limb of the Earth while minimizing internal scattered light.

The Limb Ozone Retrieval Experiment measured ozone in the 15- to 35-km (9- to 22-mile) region. This multi-filter imaging photometer featured bands in the visible and near infrared, and included a linear diode array detector. The 600-nm channel was the ozone-sensitive channel, the 525- and 675-nm channels were used for background aerosol subtraction, a 1,000-nm channel was used to detect aerosols, and a 345-nm channel gave overlap with the instrument and was used to determine the pointing.

New Ozone Measurement Approach Proven Successful

Comparisons with other satellite data showed that the calibration of Shuttle Ozone Limb Sounding Experiment instrument was consistent to within 10%, demonstrating the potential of limb scattering for ozone monitoring.

This approach compared the limb ozone measurements with data from ground observations and showed that this new approach indeed worked.

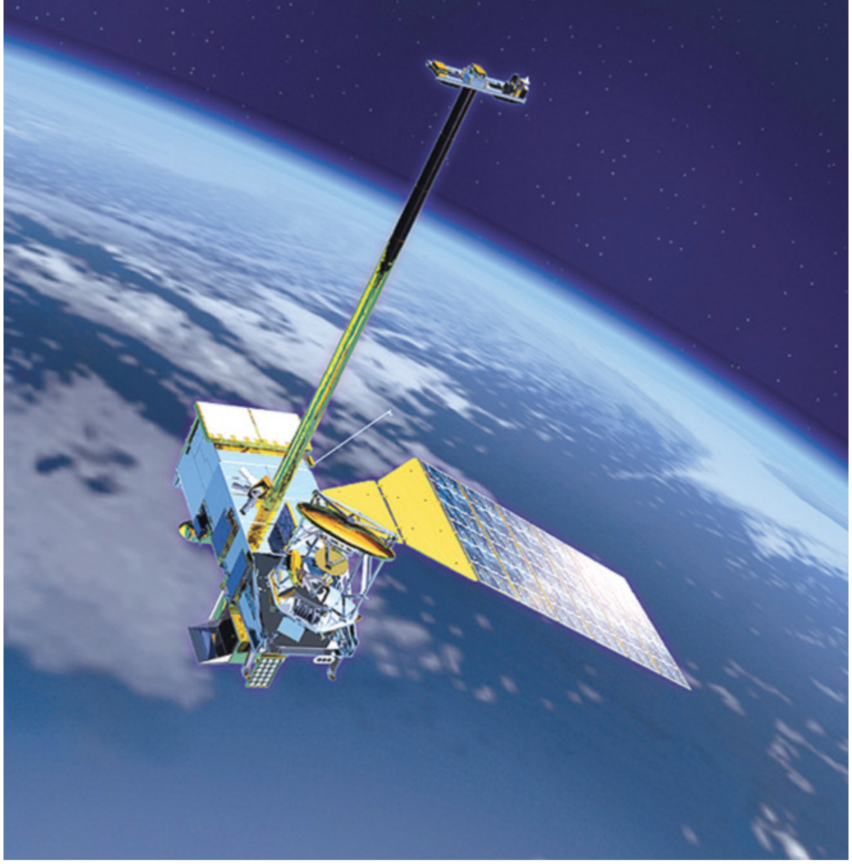
Space Shuttle Columbia's Final Contributions—Ozone Experiments

The loss of Columbia on re-entry was a heartbreaking event for NASA and for the nation. It was a small consolation that at least some data were spared. The ozone experiments were re-flown on STS-107 (2003) to obtain limb scatter data over a wider range of latitudes and solar zenith angles with different wavelengths. For this mission, Shuttle Ozone Limb Sounding Experiment was configured to cover the wavelength range from 535 to 874 nm. Seventy percent of the data was sent to the ground during the mission. In 2003, NASA identified an excellent coincidence between Columbia (STS-107) ozone measurement and data from an uncrewed satellite.

Summary of Ozone Calibration Research

In all, the Space Shuttle experiments showed that limb scattering is a viable technique for monitoring the vertical distribution of ozone. On the basis of these experiments, a

Legacy of Shuttle Ozone Experiments



An ozone limb scatter instrument designed on the basis of successful Shuttle Ozone Limb Sounding Experiment measurements will be included in the uncrewed National Polar-orbiting Operational Environmental Satellite System. This interagency satellite system will monitor global environmental conditions and collect and disseminate data related to weather, atmosphere, oceans, land, and near-space environment.

limb scatter instrument on a newly designed, uncrewed National Polar-orbiting Operational Environmental Satellite System has been included. This is an outstanding example of the successful legacy of these shuttle science flights.

"The Space Shuttle is the only space platform that could provide an opportunity to calibrate the ozone monitoring instruments on orbiting satellites in order to measure ozone depletion in stratosphere. This role of Space Shuttle in ozone research has been invaluable."

– NASA Ozone Processing Team

Understanding the Chemistry of the Air

Atmospheric Trace Molecule Spectroscopy Experiments

The Atmospheric Trace Molecule Spectroscopy experiments investigated the chemistry and composition of the middle atmosphere using a modified interferometer. The interferometer obtained high-resolution infrared solar spectra every 2 seconds during orbital sunsets and sunrises, making use of the solar occultation technique in which the instrument looks through the atmosphere at the setting or rising sun. The availability of a bright source (i.e., the sun), a long atmospheric path length, the self-calibrating nature of the observation, and the high spectral and temporal resolution all combined to make the Atmospheric Trace Molecule Spectroscope one of the most sensitive atmospheric chemistry instruments to ever fly in space. The instrument was first flown on the Spacelab 3 (STS-51B) mission in April 1985 and then re-flown as part of the Atmospheric Laboratory for Applications and Science (ATLAS) series of payloads. The solar occultation nature of the observations provided limited latitude ranges for each mission, but the combination of shuttle orbit characteristics (e.g., launch time) and the occultation viewing geometry provided unique opportunities. For example, the flight in 1993 (STS-56) made sunrise observations at high Northern latitudes to best observe the atmospheric concentrations of "reservoir species" relevant to polar ozone depletion. The flight in 1994 (STS-66) provided the first opportunity to acquire comprehensive space-based atmospheric composition measurements on the state of large-scale, persistent polar cyclonic conditions. These allowed comparisons of photochemical conditions inside and outside the region of maximum ozone loss.

The results of these observations included several first detections of critical atmospheric species in addition to the 30 or more constituents for which profiles were derived at altitudes between 10 and 150 km (6 and 93 miles). These measurements, widely used to test the photochemical models of the stratosphere, have been important in addressing the vertical distribution of halogen- and nitrogen-containing molecules in the troposphere and stratosphere as well as in characterizing the isotopic composition of atmospheric water vapor. Atmospheric Trace Molecule Spectroscopy observations served as important validation information for instruments that flew aboard NASA's Upper Atmosphere Research Satellite on STS-48 (1991). Through its high-resolution infrared observations, the spectroscope also left an important legacy leading to observations aboard the Earth Observing System's Aura satellite, launched in 2004. Aura's instruments studied the atmosphere's chemistry and dynamics and enabled scientists to investigate questions about ozone trends and air quality changes and their linkage to climate change.

The measurements also provided accurate data for predictive models and useful information for local and national agency decision support systems. Shuttle's efforts provided the impetus for the Canadian Atmospheric Chemistry Experiment satellite, launched in 2003.

Aerosols in the Atmosphere—Tiny Particles, Big Influence

Aerosols play an important role in our planet's dynamic atmosphere and globally impacted our climate. For example, aerosols interact with clouds and influence their rain production, which could affect the health of oceanic life and coral reefs as they carry minerals. Scientists have documented that Africa's Saharan dust particles (aerosols) travel all the way to South America to nourish the Amazonian rain forest. The Space Shuttle was well suited to facilitate research on these tiny particles that exert such a big influence on our atmosphere.

The vantage point of space has proven essential for understanding the global distribution of atmospheric aerosols, including horizontal and vertical distribution, chemical

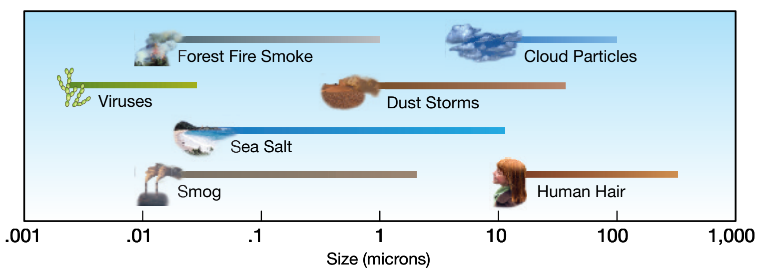
Aerosols—A Mystery Revealed

Have you ever wondered why sunsets appear redder on some days? Or why the Earth becomes cooler after a volcanic eruption? The reason is aerosols.

Aerosols are minute particles suspended in the atmosphere (e.g., dust, sea salt, viruses, and smog). When these particles are sufficiently large, their presence is noticeable as they scatter and absorb sunlight. Their scattering of sunlight can reduce visibility (haze) and redden sunrises and sunsets. Aerosols affect our daily weather and have implications for transportation, among other impacts.

Aerosols interact both directly and indirectly with the Earth's climate. As a direct effect, aerosols scatter sunlight directly back into space. As an indirect effect, aerosols in the lower atmosphere can modify the size of cloud particles, changing how the clouds reflect and absorb sunlight, thereby affecting the Earth's energy budget and climatic patterns.

Sizes of Different Aerosols



and optical properties, and interaction with the atmospheric environment. The diversity of aerosol characteristics makes it important to use a variety of remote sensing approaches. Satellite instruments have added dramatically to our body of knowledge. The Mediterranean Israeli Dust Experiment that flew on board STS-107 in 2003 complemented these observations due to its viewing geometry (the inclined orbit of the shuttle provided data at a range of local times, unlike the other instruments in polar sun-synchronous orbits that only provided data at specific times of the day) and its range of wavelengths (from ultraviolet through visible into near-infrared).

The Space Shuttle Columbia and Israeli Dust Experiment

Space Shuttle Columbia's final flight carried the Mediterranean Israeli Dust Experiment by Tel Aviv University and the Israeli Space Agency.

The primary objective of this experiment was the investigation of desert aerosol physical properties and transportation, and its effect on the energy balance and chemistry of the ambient atmosphere with possible applications to weather prediction and climate change. The main region of interest for the experiment was the Mediterranean Sea and its immediate surroundings.

How Do We Know the Distribution of Dust Particles?

The experiment included instruments for remote as well as in-situ measurements of light scattering by desert aerosol particles in six light wavelengths starting from the ultraviolet region to the near-infrared. The supporting ground-based and airborne measurements included optical observations as well as direct sampling. Airborne measurements were conducted above dust storms under the shuttle orbit ground-track during the passage of the shuttle over the target area. The collocation and simultaneity of shuttle, aircraft, and ground-based correlated data were aimed to help validate the remote spaceborne observations from Columbia and other space platforms.

Since most data from this experiment were transmitted to the ground for backup, the experiment's data were saved almost entirely and, after years of analysis, yielded a wealth of scientific data.

Insights From the Mediterranean Dust Experiment

Over 30% of the dust particles that pass over the Mediterranean Sea are coated with sulfate or sea salt. These particles play a crucial role in the development of clouds and precipitation as they often act as giant cloud condensation nuclei and enhance the development of rain. On January 28, 2003, a dust storm that interacted with a cold front, which produced heavy rain and flooding, was studied during this experiment. This is an example of how dust aerosols influence the local climate.

Observing Transient Luminous Events

In addition to measuring the dust particle distribution, the other major objective of the Israeli Dust Experiment was to use the same instruments at night to study electrical phenomena in the atmosphere. Scientists have known that large thunderstorms produce these electrical phenomena called "transient luminous events."

These events occur in upper atmospheric regions of the stratosphere, mesosphere, or ionosphere. The most common events include Sprites and Elves. It is interesting to note that Elves were discovered in 1992 by video camera in the payload bay of the Space Shuttle.

Sprites and Elves—
Phenomenal Flashes of Light

So what are transient luminous events? They can best be defined as short-lived electrical phenomena generated as a result of enormous thunderstorms, and are categorized into Sprites and Elves.

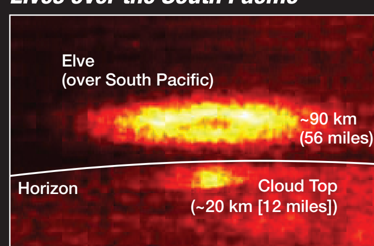
Sprites are jellyfish-shaped, red, large, weak flashes of light reaching up to 80 km (50 miles) above the cloud tops. They last only a few tens of microseconds. Seen at night, Sprites can be imaged by cameras and only rarely seen by human eyes.

Elves are disk-shaped regions of glowing light that can expand rapidly to large distances up to 483 km (300 miles) across. They last fewer than thousandths of a second. Space Shuttle low-light video cameras were the first to record the occurrence of Elves.

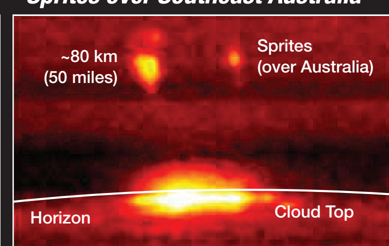
Record-setting Measurements from Columbia (STS-107 [2003])

The experiment succeeded in a spectacular fashion as almost all data on Sprites and Elves were saved, thereby yielding the first calibrated measurements of their spectral luminosity, first detection of Sprite emission in the near-infrared, and clear indication for the generation of Elves by intra-cloud lightning flashes. The global observations of transient luminous events enabled calculation of their global occurrence rate. These shuttle-based results are considered a benchmark for satellite observations.

Elves over the South Pacific



Sprites over Southeast Australia



Short-lived electrical phenomena in upper atmosphere in disk-shaped regions (termed Elves) were imaged over the South Pacific. This was the first calibrated measurement of their spectral luminosity from space.

The Space Shuttle as an Engineering Test Bed

The Lidar In-space Technology Experiment

Scientists need the inventory of clouds and aerosols to understand how much energy is transmitted and lost in the atmosphere and how much escapes to space. To gain insight into these important questions, NASA explored the potential of lidar technology using the Space Shuttle as a test bed. Why lidar? Lidar's ability to locate and measure aerosols, water droplets, and ice particles in clouds gave scientists a useful tool for scientific insights.

Why Use the Space Shuttle as a Test Bed for Earth-observing Payloads?

The Space Shuttle could carry a large payload into low-Earth orbit, thereby allowing Earth-observing payloads an opportunity for orbital flight. Similarly, science goals might have required a suite of instruments to provide its measurements and, taken together, the instruments would have exceeded the possible spacecraft resources. Further, the shuttle provided a platform for showing a proof of concept when the technology was not mature enough for a long-duration, uncrewed mission. All of the above applied to the Lidar In-space Technology Experiment.

Laser technology was not at a point where the laser efficiencies and lifetime requirements for a long-duration mission were feasible; however, the shuttle could fly the experiment with its over 1,800-kg (4,000-pound), 4-kilowatt requirements.

The Lidar In-space Technology Experiment, which was the primary payload on Space Transportation System (STS)-64 (1994), orbited the Earth for 11 days and ushered in a new era of remote sensing from space. It was the first time a laser-based remote sensing atmospheric experiment had been flown in low-Earth orbit.

Of Lasers and Lidar: What is Laser? What is Lidar?

You have heard about use of lasers in eye surgery or laser printer for your computer or laser bar code readers in stores. So, what is a laser? Laser is short for Light Amplification by Stimulated Emission of Radiation. Unlike ordinary light composed of different wavelengths, laser light is one wavelength. All of its energy is focused in one narrow beam that can produce a small point of intense energy. Lasers are used in "radar-like" applications and are known as Lidars.

What is a lidar? It stands for Light Detection and Ranging and is an optical technology that uses pulsed lasers. It measures properties of scattered light to find range and/or other information of a distant target. As with similar radar technology, which uses radio waves, with a lidar the range to an object is determined by measuring the time delay between transmission of a pulse and detection of the reflected signal. Lidar technology has application in many Earth Science disciplines.

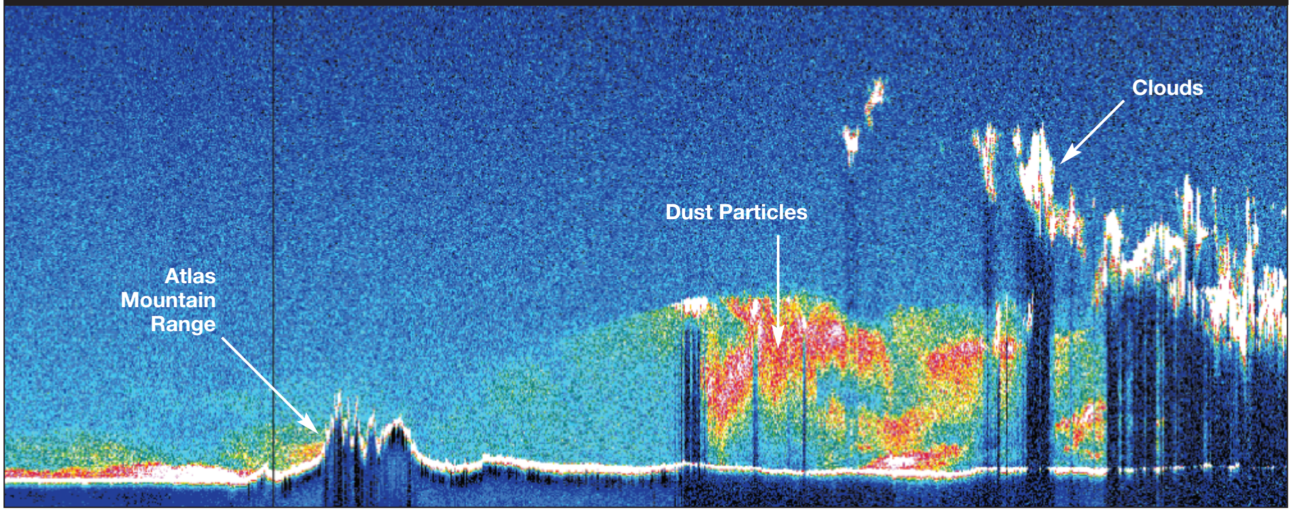
How Did Lidar Work in Space?

A spaceborne lidar can produce vertical profile measurements of clouds and aerosols in the Earth's atmosphere by accurately measuring the range and amount of laser light backscattered to the telescope. Using more than one laser color or wavelength produces information on the type of particle and/or cloud that is scattering the laser light from each altitude below.

The Lidar In-space Technology Experiment employed a three-wavelength laser transmitter. The lidar return signals were amplified, digitized, stored on tape on board the shuttle, and simultaneously telemetered to the ground for most of the mission using a high-speed data link.

The Lidar In-space Technology Experiment took data during ten 4½-hour data-taking sequences and five 15-minute "snapshots" over specific target sites. The experiment made measurements of desert dust layers, biomass burning, pollution outflow off continents, stratospheric

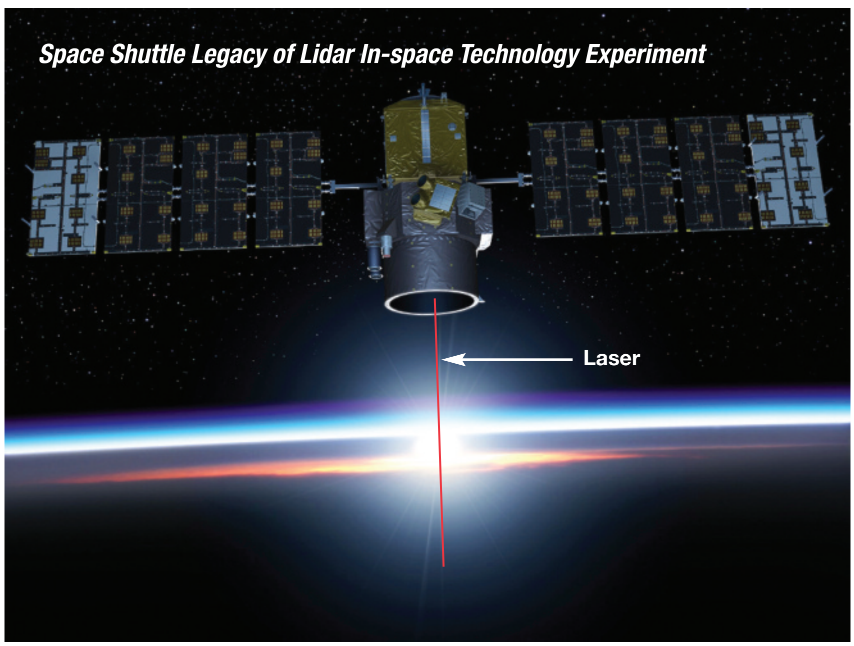
Lidar Maps Saharan Dust Transport



Lidar data during STS-64 (1994) depict widespread transport of dust aerosols over the African Sahara. The Atlas Mountain range appears to separate a more optically thick aerosol air mass to the Southeast from a relatively cleaner air mass to the Northwest. Over the desert interior, the aerosol plume extends in altitude to about 5 km (3 miles) with complex aerosol structures embedded within the mixed layer.

volcanic aerosols, and storm systems. It observed complex cloud structures over the intertropical convergence zone, with lasers penetrating the uppermost layer to four and five layers below.

Six aircraft, carrying a number of up- and down-looking lidars, performed validation measurements by flying along the shuttle footprint. NASA also coordinated ground-based lidar and other validation measurements—e.g., balloon-borne dustsondes—with the experiment's overflights. Photography took place from the shuttle during daylight portions of the orbits. A camera, fixed and bore sighted to the Lidar In-space Technology Experiment, took pictures as did the astronauts using two Hasselblad cameras and one camcorder to support the experiment's measurements.



The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations satellite was launched in 2006 on a delta rocket to provide new information about the effects of clouds and aerosols on changes in the Earth's climate. The major instrument is a three-channel lidar.

Lidars in Space—A New Tool for Earth Observations

The Lidar In-space Technology Experiment mission proved exceedingly successful. It worked flawlessly during its 11-day mission. Data were used to show the efficacy of measuring multiple-layered cloud systems, desert dust, volcanic aerosols, pollution episodes, gravity waves, hurricane characterization, forest fires, agricultural burning, and retrieving winds near the ocean's surface. All measurements were done near-globally with a vertical resolution of 15 m (49 ft), which was unheard of using previous remote sensors from space. The Lidar In-space Technology Experiment even showed its utility in measuring land and water surface reflectivity as well as surface topography.

- It showed that space lidars could penetrate to altitudes of within 2 km (1.2 miles) of the surface 80% of the time and reach the surface 60% of the time, regardless of cloud cover. It appeared that clouds with optical depths as high as 5 to 10 km (3 to 6 miles) could be studied with lidars. The comparison of shuttle lidar data and lidar data acquired on board the aircraft was remarkable, with each showing nearly identical cloud layering and lower tropospheric aerosol distributions.
- The mission introduced a new technology capable of a global data set critical for understanding many atmospheric phenomena, such as global warming and predicting future climates.
- It provided a benefit in developing long-duration lidars for uncrewed satellite missions. Simulations using the experiment's characteristics and data have been carried out by groups all over the world in developing the feasibility of various lidar concepts for space application. This effort manifested itself, for example, in the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations experiment—a joint US/French mission flying a lidar as its centerpiece experiment.

A National Treasure—Space Shuttle-based Earth Imagery

Have you ever imagined gazing through the Space Shuttle windows at our own magnificent planet? Have you wondered what an ultimate field trip experience that could be?

Space Shuttle astronauts have experienced this and captured their observations using a wide variety of cameras. To these astronauts, each

This image of Kuwait and the Persian Gulf was taken from STS-37 (1991) after oil wells were set on fire by Iraqi forces in February 1991. Black smoke plumes are prominently seen. Kuwait City is located on the south side of Kuwait Bay.

Shuttle Imagery Captures Earth's Dynamic Processes

Lake Chad 1968* 1982* 1992* 2000*

Astronauts photographed many sites of ecological importance from their missions over the 30 years of the Space Shuttle Program. These images yielded unprecedented insights into the changes occurring on Earth's surface.

One such site repeatedly imaged by shuttle crews was Lake Chad. This vast, shallow, freshwater lake in Central Africa straddles the borders of Chad, Niger, Nigeria, and Cameroon. Once the size of Lake Erie in the United States some 40 years ago, the shrinking of this lake was recorded on shuttle Earth imagery. First photographed by Apollo 7 astronauts in 1968—when the lake was at its peak—the decline in water levels is clearly seen from a small sampling of time series from shuttle flights in 1982, 1992, and 2000. While estimates of decline vary due to seasonal fluctuations, experts confirm that less than 25% of the water remains in the southern basin.

What has caused the shrinking of this life-supporting source of water for millions of people in Central Africa? Researchers point to a combination of factors—natural climatic changes ushering in drier climate, deforestation, aquatic weed proliferation, overgrazing in the region, and water use for agriculture and other irrigation projects.

Images not rectified to scale

shuttle mission offered a window to planet Earth in addition to whatever else the mission involved.

Astronauts have used handheld cameras to photograph the Earth since the dawn of human spaceflight programs. Beginning with the Mercury missions in the early 1960s, astronauts have taken more than 800,000 photographs of Earth. During the Space Shuttle Program, astronauts captured over 400,000 images using handheld cameras alone.

Making Astronauts "Earth Smart"

Shuttle astronauts were trained in scientific observation of geological, oceanographic, environmental, and meteorological phenomena as well as in the use of photographic equipment and techniques. Scientists on the ground selected and periodically updated a series of areas to be photographed as part of the crew Earth observations. Flight notes were routinely sent to the shuttle crew members, listing the best opportunities for photographing target site areas. The sites included major deltas in South and East Asia, coral reefs, major cities, smog over industrial regions, areas that typically experience floods or droughts triggered by El Niño cycles, alpine glaciers, long-term ecological research sites, tectonic structures, and features on Earth—such as impact craters—that are analogous to structures on Mars.

Scientific and Educational Uses of Astronaut Earth Imagery

Shuttle Earth imagery filled a niche between aerial photography and imagery from satellite sensors and complemented these two formats with additional information. Near real-time information exchange between the crew and scientists expedited the recording of dynamic events of scientific importance.

Critical environmental monitoring sites are photographed repeatedly over time; some have photographic records dating back to the Gemini and Skylab missions. Images are used to develop change-detection maps. Earth limb pictures taken at sunrise and sunset document changes in the Earth's atmospheric layering and record such phenomena as auroras and noctilucent clouds. Shuttle photographs of hurricanes, thunderstorms, squall lines, island cloud wakes, and the jet stream supplement satellite images. Other observations of Earth made by flight crews are used not only as scientific data but also to educate students and the general public about the Earth's ever-changing and dynamic systems. Over 3,000,000 images are downloaded, globally, each month by the public (*http://eol.jsc.nasa.gov/*). Educators, museums, science centers, and universities routinely use the imagery in their educational pursuits.

This imagery, archived at NASA, is a national treasure that captures the unique views of our own habitat acquired by human observers on orbit.

A mighty volcanic eruption of Mount St. Helens in 1980 and a large earthquake altered the landscape of this serene region in a blink of an eye. Landslides and rivers of rocks rushed downhill, causing havoc. Volcanic ash traveled more than 322 km (200 miles). This shuttle image from STS-64 (1994) captures the impact of these dynamic events in the US Pacific Northwest.

Jack Kaye, PhD
Associate director for research at NASA Headquarters Earth Science Division.

The Role of the Space Shuttle in Earth System Science

"The Space Shuttle played a significant role in the advancement of Earth System Science. It launched major satellites that helped revolutionize our study of the Earth. Its on-board experiments provided discoveries and new climatologies never before available, such as the tropospheric carbon monoxide distributions measured by the Measurement of Air Pollution from Satellite experiment, the stratospheric vertical profiles of many halogen-containing species important in ozone depletion measured by the Atmospheric Trace Molecule Spectroscopy instrument, and the high-resolution surface topography measurements made by the Shuttle Radar Topography Mission. It provided for multiple flight opportunities for highly calibrated instruments used to help verify results from operational and research satellites, most notably the eight flights of the Shuttle Solar Backscatter Ultraviolet instrument. Shuttle flights provided for on-orbit demonstration of techniques that helped pave the way for subsequent instruments and satellites. For example, the Lidar In-space Technology Experiment, with its demonstration of space-based lidar to study aerosols and clouds, paved the way for the US-French Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation satellite. Similarly, the Shuttle Ozone Limb Sounding Experiment and Limb Ozone Retrieval Experiment provided demonstrations of the experimental technique to be used by the Ozone Mapping and Profiling Suite's limb sensor aboard the National Polar-orbiting Operational Environmental Satellite System Preparatory Project. The shuttle enabled international cooperation, including the multinational Atmospheric Laboratory for Applications and Science payload that included instruments with principal investigators from Germany, France, and Belgium among its six instruments, as well as deployment of the German Cryogenic Infrared Spectrometers & Telescopes for the Atmosphere-Shuttle Palette Satellite. The shuttle provided launch capability for Earth Science-related experiments to the International Space Station, such as the launch of the French Solar Spectrum Measurement instrument. Finally, the shuttle provided outstanding education and outreach opportunities."

Summary

The Space Shuttle played a significant role in NASA's missions to study, understand, and monitor Earth system processes. The shuttle was an integral component of the agency's missions for understanding and protecting our home planet. In the end, Space Shuttle missions for Earth observations were not only about science or instruments or images—these missions were also about humanity's journey into space to get a glimpse of our planet from a new perspective and rediscover our own home.