The SAGE Legacy's Next Chapter: SAGE III on the International Space Station

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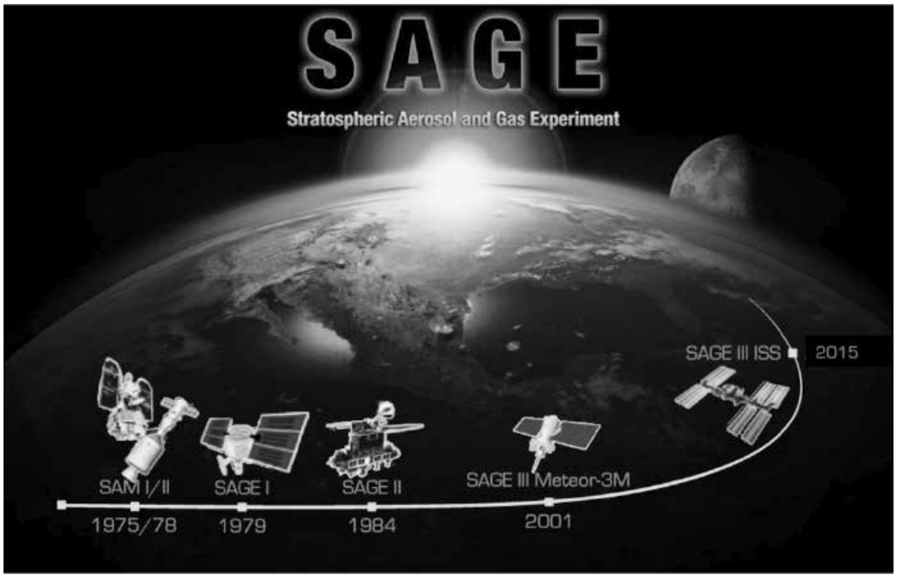
Historic Observations: SAM I and II

Tiny solid or liquid particles suspended in Earth's atmosphere, known as *aerosols*, and atmospheric ozone affect all of Earth's inhabitants. The Stratospheric Aerosol and Gas Experiment (SAGE) family of instruments has long measured stratospheric aerosol and ozone concentrations—see *Observing Ozone Through the Years* on the next page—also enhancing our understanding of the distribution and roles of atmospheric water vapor and other trace gases.

Before the first SAGE mission in 1979, however, there were two Stratospheric Aerosol Measurement (SAM) missions—SAM I and SAM II. Consisting of only a single-channel sunphotometer—used to measure the Sun's intensity—and a camera, SAM I flew on an Apollo spacecraft during the Apollo–Soyuz Test Project in July 1975. The mission proved that the concept of making observations of stratospheric aerosol from space was viable. During the nine-day mission, solar photographs were taken and measurements were recorded by the sunphotometer. A balloonborne aerosol counter and a ground-based laser system later verified those Sam I observations.



A timeline showing the SAGE legacy, beginning with SAM I and continuing to the upcoming SAGE III on ISS mission. **Image credit:** NASA

Success with the SAM I experiment led to the launch of SAM II, which flew on the Nimbus-7 spacecraft from 1978 until 1993, and provided vertical profiles of aerosols over both the Arctic and Antarctic polar regions. Designed to develop a stratospheric aerosol database for the polar regions, data from SAM II allowed scientists to study changes in aerosol concentrations as a function of seasonal and short-term meteorological variations, atmospheric chemistry, cloud microphysics, volcanic activity, and other disruptions. SAM II was a spectrometer that used *solar occultation* as its measurement technique: The instrument pointed toward the Sun as its light source and scanned the limb, or thin profile, of Earth's atmosphere. The SAM experiments demonstrated that solar-occultation measurements by photometer and camera could be used to determine the vertical distribution of stratospheric aerosols. With this now-proven method, scientists and engineers began developing the first SAGE instrument.

Observing Ozone Through the Years

Ozone (O_3) is a highly reactive molecule made up of three atoms of oxygen. It is created and destroyed naturally, a process mediated by sunlight. Although it represents a tiny fraction of the atmosphere (0.02 – 0.1 parts per million (ppm) based on volume, O_3 is vital for life on Earth. O_3 is found mostly in the stratosphere—a layer of the atmosphere between 10 and 31 miles (~16 to 50 km) above the surface. The so-called *ozone layer* acts as Earth's sunscreen, protecting the biosphere from receiving too much of the Sun's ultraviolet (UV) radiation, and is therefore vital for life on Earth—see **Figure 1**.

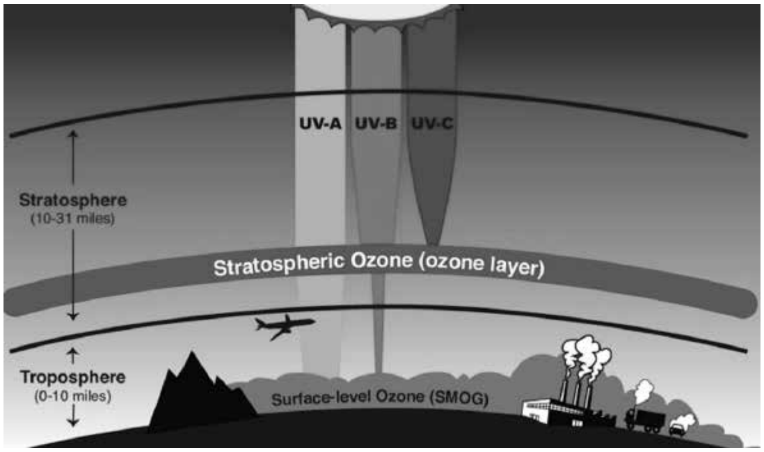


Figure 1. The graphic shows how the stratospheric ozone layer functions as Earth's "sunscreen" and blocks the majority of the Sun's UV radiation (i.e., most UV-B and all UV-C) from reaching the planet's surface. It also shows ozone in the troposphere, which is closer to Earth. Surface-level ozone is called *smog* and is a pollutant. While SAGE focuses on stratospheric ozone, NASA has other instruments that study such tropospheric ozone—e.g., the Ozone Monitoring Instrument (OMI) on the Aura satellite. **Image credit**: NASA

Without the ozone layer, the Sun's intense UV radiation would sterilize Earth's surface. A decrease in the concentration of O_3 at this level could lead to more-intense UV-B and UV-A radiation exposure at Earth's surface, which could subsequently lead to higher risks of contracting sunburn, more cases of skin cancer, increased incidence of cataracts, and reduced crop yields.

In the early 1980s scientists discovered that when human-made chlorofluorocarbons (CFCs)—used for many years as refrigerants and in aerosol spray cans—break down, they release atomic chlorine (Cl), which greatly accelerates ozone destruction (**Figure 2**). By 1985 ozone levels around the world had continued to drop and scientists discovered thinning of the ozone layer particularly over polar regions in the spring months—and coined the phrase *ozone hole* to describe this phenomenon. This was the impetus for international efforts to further study stratospheric ozone. As a result, scientists and policy makers negotiated the Montreal Protocol. Signed in 1987, the treaty limited the production of CFCs and other ozone-depleting substances.

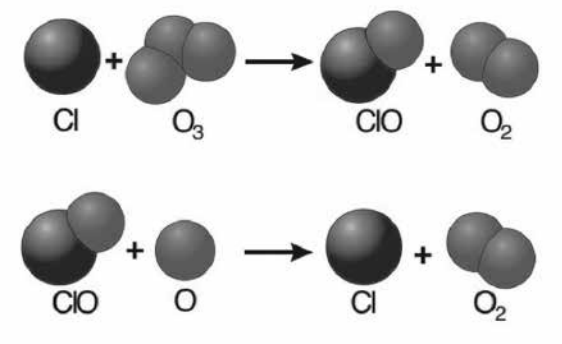


Figure 2. Stratospheric ozone is created and destroyed through reactions with chlorine (Cl), mediated by sunlight. **Image credit:** NASA

The Stratospheric Aerosol and Gas Experiment (SAGE) mission was launched in 1979; in 1990 the U.S. Clean Air Act mandated that NASA continue to monitor ozone. As a result, the SAGE family of instruments observed ozone concentrations, along with water vapor, aerosols, and trace gases, from 1979 to 2006. A second SAGE III instrument—planned for launch in 2015—will continue this legacy of accurate measurements—this time from the International Space Station (ISS). A third and final SAGE III instrument awaits a future flight of opportunity.

Global Aerosol and Ozone Observations: SAGE I and II

The first SAGE mission, SAGE I, was launched February 18, 1979 on the Applications Explorer Mission-B (AEM-B) satellite; it collected valuable data for nearly three years until the satellite's power system failed. Measurements from SAGE I allowed the scientific community to develop a global map of the distribution of aerosols and important trace constituents necessary to understanding global, seasonal, and interannual variability in stratospheric ozone concentrations. Data from SAGE I were used to develop a database of global stratospheric concentrations of ozone, aerosols, and nitrogen dioxide (NO_2). These data are still used to study trends, atmospheric dynamics and transport, and potential climatic effects of these species. In the early 1980s a second-generation instrument was built to continue generation of SAGE's unique datasets.

SAGE II launched on the Earth Radiation Budget Satellite (ERBS) in October 1984; it observed stratospheric ozone from 1984 until 2005. This long-term, stable dataset has proven invaluable in determining trends in ozone distribution and amount. Data from SAGE II, in conjunction with data from SAM II and SAGE I, can be used to estimate long-term constituent trends and identify responses to episodic events such as volcanic eruptions. Major results from SAGE II include the stratospheric impact of the 1991 Mount Pinatubo eruption, identification of a negative global trend in lower-stratospheric ozone levels during the 1980s, and quantitative verification of positive water-vapor feedback in current climate models. Data from SAGE II were integral in confirming human-driven changes to ozone concentrations in the stratosphere, and thus influenced the decisions to negotiate the Montreal Protocol in 1987. Later, observations from SAGE II showed that ozone in the stratosphere stopped decreasing in response to the actions agreed to in the treaty. Building on previous successes, a third-generation instrument was developed to ensure continuous measurements and to generate new data products.

The multidecadal ozone and aerosol datasets from SAGE instruments have undergone intense scrutiny, becoming the international standard for accuracy and stability as a result.

SAGE III Times Three

When SAGE III was developed, three identical instruments were built: one launched on the Russian Meteor-3M spacecraft on December 10, 2001; one was built specifically to fly on the International Space Station (ISS); and the other is planned for a future flight of opportunity. The first two of these will be discussed here.

SAGE III Meteor-3M

Launched in 2001, SAGE III Meteor-3M was a crucial element in NASA's Earth Observing System (EOS). Data from the mission enhanced scientists' understanding of natural and human-derived atmospheric processes. Observations from SAGE III Meteor-3M—that began with data from SAGE I and II—provided the basis for identifying five of the nine critical constituents called out in the U.S. National Plan for Stratospheric Monitoring, including profiles of aerosols, O_3, NO_2, water vapor, and air density (using O_2 as a reporting species).

The multidecadal ozone and aerosol datasets from SAGE instruments have undergone intense scrutiny, becoming the international standard for accuracy and stability as a result—see **Figure 3,** next page. Aerosol data from SAGE are recognized as necessary for understanding ozone trends and predicting climate change. The SAGE ozone product is accurate to better than 1%, and has a vertical resolution of 1 km (~3280 ft) or better.

The SAGE III Meteor-3M mission ended on March 6, 2006, due to a power supply system failure, resulting in loss of communication with the satellite; this left a gap in valuable SAGE data. Two additional copies of SAGE III remained, and as the ISS neared completion in the mid-2000s, plans were developed to fly one of them on that platform.

SAGE III on ISS

Because no active SAGE instrument had been available since 2006, the international scientific community started requesting new (additional) data. The decision to fly a

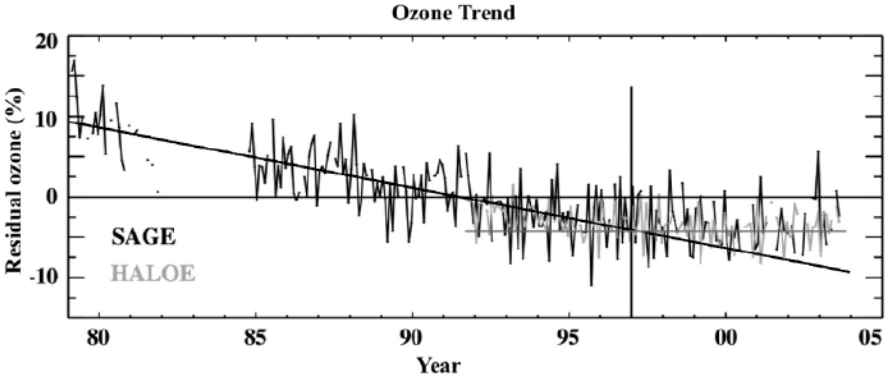


Figure 3. This graph combines data from the first three SAGE instruments, with data from the Halogen Occultation Experiment (HALOE), which flew on the Upper Atmospheric Research Satellite (UARS) and launched from the Space Shuttle *Discovery* in 1991 and operated until 2005. It depicts the decline of ozone with a trend of -7.47% (± 1.04%) per decade between 1979 and 1996. Ozone concentrations stabilized around the time of the Montreal Protocol and have since started to show signs of recovery. **Image credit**: Originally appeared in *The 2006 WMO/UNEP Assessment, Scientific Assessment of Ozone Depletion*.

copy of SAGE III on the ISS came in 2010 with the fiscal year 2011 NASA budget; in 2011 scientists and engineers began preparing SAGE for the ISS. *SAGE III on ISS* will be among the first continuously Earth-observing instruments on the Space Station[1], and among the first NASA Earth-science payloads to be launched on a commercial space vehicle—scheduled to launch on a SpaceX Falcon 9 in early 2015. The instrument, built by Ball Aerospace and Technology Corporation, was refurbished and is being tested at NASA's Langley Research Center (LaRC) in Hampton, VA.

The ISS was designed to allow Earth-observing experiments. Its midinclination orbit allows for a large range in latitude sampling, and it offers scientists and engineers near-continuous communications with payloads. The ISS orbit allows SAGE III to observe ozone during all seasons and globally—including over polar regions. Using the moon as a light source, SAGE III on ISS will detect ozone during the darkness of polar winter. SAGE III on ISS will also measure ozone concentrations deeper into the atmosphere than ever before, reaching into the troposphere—up to where planes fly and down to where people live.

Scientists and engineers have had to come up with innovative solutions to fly SAGE III on the ISS and on the vehicles available to transport it there. To make its measurements, SAGE needs to be oriented facing nadir, or toward Earth. The location where SAGE will be installed does not provide a nadir-facing platform, so the instrument payload (IP) will be mounted to a Nadir Viewing Platform (NVP), an L-shaped bracket designed and built at LaRC. The NVP and IP will be attached to an ExPRESS Pallet Adapter (ExPA), the standard interface used on the ISS. A robotic arm will be used to attach the whole payload to the ISS.

SAGE III on ISS must also adapt to unique ISS physical and chemical environments and busy operations. To avoid contamination from the ISS and visiting vehicles, a special contamination-monitoring package was developed. If contamination near the instrument ever approaches unsafe levels, a clear contamination door on the instrument's sensor assembly will close to protect it, yet still allow measurements to be taken. There is also a disturbance-monitoring package to help identify and reduce noise in the instrument signal. Further, the orientation of the ISS, its attitude, cannot be controlled in the same way that can be done with a smaller, free-flying satellite. As a result, the SAGE III IP includes a Hexapod Pointing System (HPS). The HPS is a combination of a mechanical assembly and electronics unit that can adjust the instrument's pointing direction up to eight angular degrees, using six actuators to account for small directional changes in the ISS. The SAGE III on ISS Project team is working with a number of international partners to prepare the payload; these include NASA's Johnson Space Center, NASA's Marshall Space Flight Center, Ball Aerospace and Technology Corporation, SpaceX, Thales Alenia Space-Italia, and the European Space Agency.

Because no active SAGE instrument had been available since 2006, the international scientific community started requesting new (additional) data. The decision to fly SAGE III on the ISS came in 2010 with the fiscal year 2011 NASA budget; in 2011 scientists and engineers began preparing SAGE for the ISS.

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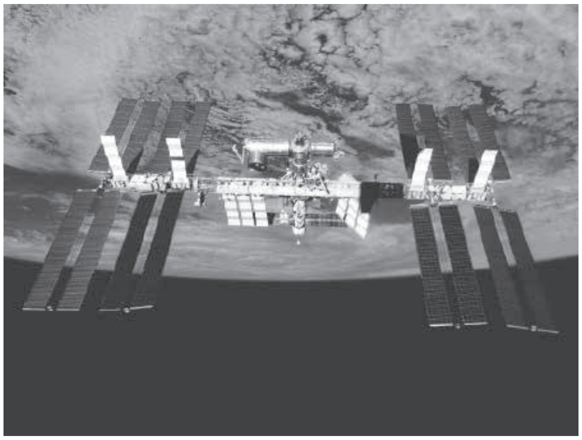
[1] To learn more about the plans for Earth observations from ISS, please see the Editor's Corner in this issue (page 2.)

Scientists and engineers at LaRC work to prepare the SAGE III sensor assembly for launch with the rest of the payload on a SpaceX Falcon 9 in 2015. **Image credit**: LaRC



The ISS provides a unique and beneficial platform for SAGE III. **Image credit**: NASA

Observations from SAGE III on ISS will be validated just as they have been during previous SAGE missions: Data from a number of similar instruments will be used to assess between-sensor biases and precision. Validation plans for SAGE III on ISS include working with ongoing ground-based operations, including the Network for the Detection of Atmospheric Composition Change (*www.ndsc.ncep.noaa.gov*), spaceborne sensors, and balloon-based ozone measurements, including those from the Southern Hemisphere Additional Ozonesondes (SHADOZ) network (*croc.gsfc.nasa.gov/shadoz*).

Conclusion

With SAGE III on ISS scientists expect to track the recovery of stratospheric ozone since ratification of the Montreal Protocol. By the 2020s—in most areas—expectations are that ozone will recover to about half of the amount lost since the pre-1980 levels. SAGE III will also be valuable in assessing the performance of the Ozone Mapping and Profilier Suite (OMPS) flying on the Suomi National Polar-orbiting Partnership (NPP). Data from SAGE III on ISS will help to reinstitute aerosol measurements crucial for more-accurate long-term climate and ozone models. SAGE III will also be valuable in assessing the performance of the Ozone Mapping and Profilier Suite (OMPS) flying on the Suomi National Polar-orbiting Partnership (NPP). Data from the Atmospheric Chemistry Experiment (ACE)—a concurrent satellite mission on the Canadian SCISAT-1—will be combined with data from SAGE III to produce a tropopause dataset. In addition, a new Science Utilization Team, led by researchers at Hampton University in Virginia, will assess SAGE III on ISS data products.

The remaining SAGE III instrument is being kept safe at LaRC for a future flight of opportunity. Once this last copy has been deployed, a new generation of instruments will be needed to continue the long-term record of stratospheric ozone and aerosol concentrations.

To learn more about SAGE, visit: *sage.nasa.gov.* ■

Data Release: Version 007 HIRDLS Atmospheric Products

The High Resolution Dynamic Limb Sounder (HIRDLS) team is pleased to announce the release of its *Version 007* Atmospheric Data Products, which include Level-2 products, Level-3 mapping-coefficient products, and Level-3 gridded products. This likely will be the final version of HIRDLS data.

These data are now publicly available from NASA's Goddard Earth Sciences Data and Information Services Center (GES DISC). The HIRDLS latest improved algorithms (V7.00.00 and V7.05.00) include newly added measurements of water (H_2O), nitrous oxide (N_2O), nitrogen dioxide (NO_2), and chlorine nitrate ($ClONO_2$).

All HIRDLS products, available from January 29, 2005 to March 17, 2008, have a vertical resolution of 1 km (~3280 ft) and are spaced approximately 100 km (~62 mi) apart along the orbit track. Additional information is available at

disc.sci.gsfc.nasa.gov/datareleases/hirdls_v007_data_release.