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8. Stratospheric Aerosol and Gas Experiment (SAGE III)

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Aerosols, ozone, and water vapor are among the most important global radiative forcings and feedbacks. Volcanic aerosols in the stratosphere can cool the climate significantly, especially after exceptional eruptions such as that of Mt. Pinatubo (Lamb, 1970; Toon and Pollack, 1980; Self and Rampino, 1988; Robock, 1991; Hansen *et al.*, 1992). Reductions in lower stratospheric ozone may have had a cooling effect during the last decade (Lacis *et al.*, 1990; Ramaswamy *et al.*, 1992; Hansen *et al.*, 1993). Tropospheric water vapor may increase in a warming climate, providing a positive feedback (Hansen *et al.*, 1984; Schlesinger and Mitchell, 1987; IPCC, 1990, 1992), but the magnitude of this feedback is sensitive to changes in water vapor in the upper troposphere which depend on poorly understood convective processes (Arking, 1993). In addition, it has been estimated that a doubling of stratospheric water vapor could lead to a 1°C global average warming of the surface (Wang *et al.*, 1976).

The proposed SAGE III instrument would be the principal source of data for global changes of stratospheric aerosols, stratospheric water vapor and ozone profiles, and a contributing source of data for upper tropospheric water vapor, aerosols and clouds (Table 8.1). The ability to obtain such data has been demonstrated by the predecessor instrument, SAGE II, but SAGE III will be substantially more capable, as discussed below. The capabilities for monitoring the profiles of atmospheric constituents have been verified in detail, including ground-based validations, for aerosols (Osborn *et al.*, 1989), ozone (Cunnold *et al.*, 1989a) and water vapor (Rind *et al.*, 1993). Indeed, because of its self-calibrating characteristics, SAGE II was an essential component of the international ozone trend assessments (Watson *et al.*, 1988), and SAGE II is now proving to be invaluable in tracking the aerosols from Mt. Pinatubo. Although SAGE profiles generally terminate at the height of the first tropospheric cloud layer, it has been found that the measurements extend down to 3 km altitude more than 40 percent of the time at most latitudes (Rind *et al.*, 1993). Thus, useful information can also be obtained on upper tropospheric aerosols, water vapor and ozone.

TABLE 8.1. **SAGE III measurement objectives, instrument characteristics and key advantages.**

Measurement Objectives

Principal source of data for global change of: stratospheric aerosols, stratospheric water vapor, and ozone profile.

Contributing source of data for upper tropospheric water vapor, aerosols, cloud tops, and temperature profiles.

Other parameters important to atmospheric chemistry and physics, e.g., NO_2, NO_3, OClO abundances and polar stratospheric clouds (PSCs).

Instrument Characteristics

Observes sun (and the moon, with SAGE III) during occultation by the Earth's limb.

Instantaneous field of view of 0.5 km, yielding high vertical resolution along the tangent path.

Grating spectrometer and linear CCD detector array yielding 1 nm (10^{-3} μm) spectral resolution from 0.29 to 1.02 to μm, with additional channel at 1.55 μm.

Self-calibrating to high precision, based on viewing sun (or moon) just seconds before or after occultation.

Key Advantages

High precision data for key climate forcings and feedbacks especially stratospheric and upper tropospheric aerosols, water vapor and ozone.

Extends important ongoing time series of these climate parameters.

SAGE III provides substantial improvements in spectral range, measured quantities and sensitivity compared to predecessor instruments.

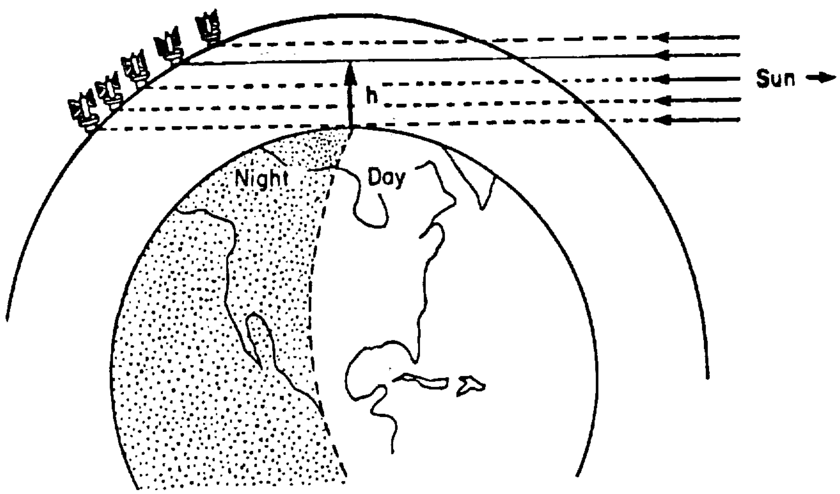

Fig. 8.1. Occultation geometry of spacecraft-earth-sun. The instrument views the sun during both sunrise and sunset as the sunlight passes through various depths of the earth's atmosphere, comparing the solar spectrum to that obtained by observing the sun above the atmosphere.

SAGE III and its predecessors are solar occultation instruments, that is, they measure the extinction of sunlight as the sun passes behind the earth's atmosphere as viewed from the spacecraft (Fig. 8.1). Because the sun is a strong source of energy, a small field-of-view can be used, typically 0.5 arc min, which corresponds to a height increment of only 0.5 km in the earth's atmosphere. The horizontal resolution across the earth's limb is about 200 km.

One advantage of occultation measurements is the simple relationship between the amount of adsorbing or scattering material and the magnitude of extinction of the transmitted radiation. But perhaps most important is the natural self-calibration that occurs before or after every measurement as the sun is viewed above the atmosphere; this greatly reduces the effect of potential changes of instrument transmission or detector sensitivity, allowing accurate measurement of even very small changes over long periods. However, even with the advantage of self calibration, it is important to document any instrument-to-instrument differences, and such capability is provided by the proposed two-satellite Climsat system.

SAGE III has a heritage of four instruments, listed in Table 8.2, none of which ever experience a failure in orbit. Indeed, SAM II and SAGE II continue to function today, although the Nimbus-7 spacecraft carrying SAM II is degrading. Each successive SAGE instrument has added new spectral channels while retaining the earlier channels. This allows the oldest data series to be continued, while initiating new monitoring of additional atmospheric constituents. Special care is required to minimize impacts of instrument-to-instrument change; for example, systematic differences appear to exist in the ozone profiles derived from SAGE I and SAGE II (Stolarski *et al.*,

TABLE 8.2. **SAGE III predecessor instruments.**

Instrument (Spacecraft)	Operation Period	Spectral bands	Mass
SAM (Apollo)	1975 (4 orbits)	1.0 μm	2 kg
SAM II (Nimbus-7)	Oct 1978 - present	1.0 μm	17 kg
SAGE I (AEM 2)	Feb 1979 - Nov 1981	0.385, 0.45, 0.6, 1.0 μm	30 kg
SAGE II (ERBS)	Oct 1984 - present	0.385, 0.448, 0.453, 0.525, 0.6, 0.94, 1.02 μm	30 kg

1991). The high spectral resolution of SAGE III, and the overlapping coverage of a two-satellite system, should minimize if not eliminate that problem.

The relationship between spectral occultation measurements and atmospheric extinction is illustrated in Fig. 8.2, which shows the sources of atmospheric extinction at 18 km altitude. The SAGE III predecessor instruments each used only a few specific channels within the indicated spectral range. However, SAGE III will take full advantage of the grating spectrometer which disperses the solar spectrum in all the SAGE instruments: SAGE III will use as its detector a CCD linear array covering the 290-1020 nm region with 1 nm resolution. This spectral resolution across absorption features of different gases will make retrievals of their abundance profiles significantly more accurate than for the predecessor instruments (Mount *et al.*, 1987). Extension of the wavelength coverage to 290 nm will allow O_3 measurements up to 85 km altitude. Data from several wavelengths at and near the oxygen 760 nm absorption band will yield a direct determination of temperature and density profiles, thus enabling the SAGE III retrievals to be independent of external data products. SAGE III will also include an isolated channel at 1550 nm; the increased wavelength coverage will provide valuable information on the aerosol size distribution, which is needed to accurately define the aerosol climate forcing (Lacis *et al.*, 1992).

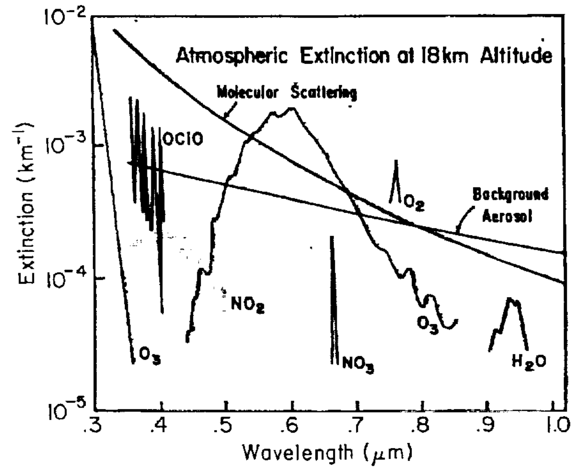

Fig. 8.2. Extinction contributions from different atmospheric constituents at 18 km altitude. On SAGE III a CCD linear array will provide 1 nm resolution from 0.29μm to 1.02μm, with an additional channel at 1.55μm.

The important improvements of SAGE III over its predecessors are summarized in Table 8.3. Observation of lunar occultations, as well as solar occultations, will increase the global sampling and include nighttime data. The use of 16-bit accuracy in A-D conversion will decrease the quantization error and increase the dynamic range of the data. Overall, the improved spectral resolution, increased

TABLE 8.3. **SAGE III design improvements over SAGE II, and expected science benefits.**

Addition	Improvement	Science Benefit
CCD	Increased wavelength discrimination (1-2 nm)	Differential absorption for H_2O, NO_2, O_3, OClO, & NO_3 Solar Fraunhofer spectra calibration Variable integration time Increased aerosol characterization Independence from external data
Lunar Occultation	Nighttime measurement	NO_3 and OClO key to O_3 chemistry Expanded geographic coverage
290 nm Channel	Short wavelength measurement	O_3 measurement through the mesosphere
1550 nm Channel	Long wavelength measurement	Better aerosol & cloud characterization Extended measurement into lower troposphere
16-Bit AD	Decreased quantization error Increased dynamic range	Improved accuracy & altitude measuring range

spectral coverage, and higher sensitivity of SAGE III will increase the accuracy of the aerosol, ozone and water vapor data, and extend the measurements deeper into the troposphere.

The single profile measurement accuracies of SAGE III are estimated in Table 8.4, on the basis of simulations using SAGE III design parameters as well as experience from SAM II, SAGE I and SAGE II validation programs. The validation included comparison of satellite profile retrievals with lidar and radiosonde measurements (Cunnold *et al.*, 1989a,b; Osborn *et al.*, 1989; Rind *et al.*, 1993).

The sparse density of occultation profiles is perhaps the greatest limitation of the data, the two solar occultations per orbit providing about 750 profiles per month. This sampling is increased about 50 percent by the lunar occultations of SAGE III. The internal variability of the existing data suggest that the SAGE sampling can provide accurate zonal mean seasonal mean stratospheric profiles. However, the quantitative numerical sampling studies discussed below should be extended to assess the potential of the SAGE measurements for tropospheric monitoring, particularly when complemented by measurements from EOSP and MINT.

TABLE 8.4. **SAGE III measurement capabilities for a single profile, based on simulations using SAGE III design parameters and experience gained in validating most of these species with SAM II, SAGE I and SAGE II "ground-truth" programs.**

Parameters Measured in Occultation	Spectral Range (μm) Profiles produced at these λ's	Alt. Range (km)	Vert. Resol. (km)	Single Profile Retrieval Estimated Accuracy (Random Component)	
				%	Vertical Range (km)
SOLAR					
Aerosols, Cloud tops, and PSC's	0.385, 0.440, 0.525, 0.760, 0.930, 1.020, 1.550	0-40	1	5	10-25
Ozone	0.290 and 0.600	6-85	1	5	10-50
H_2O	0.920-0.960	3-50	1	10	5-40
NO_2	0.430-0.450	10-50	1	10	15-40
O_2 and Temp.	0.740-0.780	6-70	1	2 2K	6-60 6-60
LUNAR					
Aerosols, Cloud tops, and PSC's	0.385, 0.440, 0.480, 0.525, 0.760, 0.930	0-40	1	5	10-25
Ozone	0.470-0.490	15-40	1	5	15-40
H_2O	0.920-0.960	3-50	1	15	6-25
NO_2	0.430-0.450	20-50	1	10	20-40
NO_3	0.640-0.680	20-55	1	10	35-50
OClO	0.380-0.420	15-25	3	25	At [OClO] peak during "disturbed" conditions
O_2 and Temp.	0.740-0.780	6-55	1	2 2K	10-40 10-40