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The ATLAS Series of Shuttle Missions

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Abstract. The ATLAS space shuttle missions were conducted in March 1992, April 1993, and November 1994. The ATLAS payload and companion instruments made measurements of solar irradiance and middle atmospheric temperatures and trace gas concentrations. The solar irradiance measurements included total and spectrally resolved solar irradiance. The atmospheric measurements included microwave, infrared, and ultraviolet limb sounding, nadir ultraviolet backscatter, and solar occultation techniques. This paper introduces a special section in this issue of *Geophysical Research Letters*.

Introduction

The Atmospheric Laboratory for Applications and Science (ATLAS) was a series of three Spacelab missions flown in 1992, 1993, and 1994 with three major purposes: (1) determination of highly accurate and precise information about the trace chemical composition of the Earth's middle and upper atmosphere and incident solar radiation for comparison with information from other space-based instruments measuring these quantities; (2) measurement of a range of atmospheric and solar parameters such that very detailed scientific studies on atmospheric composition could be carried out for the brief duration of a flight of the space shuttle (8–11 days); and (3) provision of space-flight opportunities for instruments with objectives compatible to those of the ATLAS instruments so that comparisons of their measurements with those of the ATLAS instruments could be done as well as complementary science between two or more instruments. Originally envisioned as a series of 10 missions over an 11-year solar cycle, the ATLAS series was truncated after three missions due to a combination of funding constraints and limited availability of the space shuttle with a reduced flight rate and increased demands on the shuttle for other activities.

A major focus of the ATLAS series has been on the accuracy and precision of the measurements made. The simultaneous measurements of an identical parameter by different instruments allows to assess absolute accuracy, noise level, and efficiency of method of retrieval. This strategy is not unique, being similar to that of the Upper Atmosphere Research Satellite (UARS) [*Reber*, 1993]. Unlike instruments flown on free-flying satellites, however, instruments flown on the space shuttle are brought back to Earth, so that for each measurement both pre- and post-flight calibrations can be carried out, along with any on-board calibration activities conducted over the course of the shuttle missions. Combining this calibration regimen with the short-duration flights that limit on-orbit instrument degradation should allow the ATLAS measurements to be among the best characterized space-based measurements of atmospheric chemistry and solar radiation.

Mission Descriptions

The three ATLAS flights took place on March 24–April 2, 1992 (ATLAS-1), April 8–17, 1993 (ATLAS-2), and November 3–14, 1994 (ATLAS-3). Summaries of the individual ATLAS missions have already appeared [*Torr*, 1993; *Miller et al.*, 1993; *Miller et al.*, 1995]. The present overview article summarizes the three ATLAS missions, including the differences among them, and serves as an introduction of the 33 papers presenting results from the instruments which flew aboard these missions.

The ATLAS core instrument package consisted of six instruments, which are briefly described in Table 1. Two are for atmospheric chemistry measurements (ATMOS and MAS), two are for measurements of spectrally resolved solar radiation (SOLSPEC and SUSIM), and two are for measurements of total solar irradiance (ACRIM and SOLCON). With the exception of MAS, all of these instruments flew on the space shuttle prior to the ATLAS series—ACRIM, SOLCON, and SOLSPEC aboard the Spacelab-1 mission in 1983, SUSIM aboard the Spacelab-2 mission in 1985 (as well as the earlier OSS-1 in 1982), and ATMOS aboard the Spacelab-3 mission in 1985. Flying along with the ATLAS payload on all three missions was the SSBUV instrument, which has now flown a total of eight times aboard the space shuttle. Other instruments have accompanied the ATLAS instruments as well, including several atmospheric science, space physics, and astronomy instruments which flew aboard ATLAS-1 as part of a reflight of much of the Spacelab-1 package and a student-run solar instrument from the University of Colorado (ESCAPE) which flew aboard ATLAS-2 and ATLAS-3. Co-manifested payloads deployed and retrieved from the space shuttle which accompanied the ATLAS missions were the SPARTAN-201 solar science package [*Fisher and Guhathakurta*, 1995] aboard ATLAS-2 and the German Shuttle Pallet Satellite (SPAS) platform which carried the CRISTA and MAHRSI atmospheric science instruments (see Table 1) aboard ATLAS-3 [*Offermann and Conway*, 1995].

A variety of "correlative measurement opportunities" were identified for the ATLAS instruments. Most notable among these is NASA's Upper Atmosphere Research Satellite (UARS), launched in September 1991. There is a great deal of complementarity between the UARS and ATLAS payloads, including each having two near-twin instruments (ACRIM and SUSIM), as well as instruments with very similar measurement objectives and experimental techniques (e.g., infrared absorption by occultation and microwave emission spectrometry). Significant attention has been paid to correlative measurement opportunities between the ATLAS and UARS payloads [*Harrison et al.*, 1992; 1993; 1995], and ATLAS data have

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Table 1. ATLAS Instruments

Instrument	Type	Institution
Active Cavity Radiometer Irradiance Monitor (ACRIM)	Total solar irradiance	Jet Propulsion Laboratory
Solar Constant (SOLCON)	Total solar irradiance	Institut Royal Meteorologique Belgium
Solar Spectrum (SOLSPEC)	Solar spectrum, IR through UV	CNRS France
Solar Ultraviolet Spectral Irradiance Monitor (SUSIM)	Solar UV output	Naval Research Laboratory
Atmospheric Trace Molecule Spectroscopy (ATMOS)	Middle atmosphere chemistry (solar absorption)	Jet Propulsion Laboratory
Millimeter-Wave Atmospheric Sounder (MAS)	Middle atmosphere chemistry (mm-wave emissions)	Max Planck Institute of Aeronomy (Germany)
Shuttle Solar Backscatter Ultraviolet (SSBUV)	Stratospheric ozone (UV backscatter)	NASA/Goddard Space Flight Center
Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere (CRISTA)*	Middle atmosphere chemistry (IR emissions)	University of Wuppertal (Germany)
Middle Atmosphere High Resolution Spectrometric Investigation (MAHRSI)*	Middle atmosphere OH, NO (UV solar fluorescence)	Naval Research Laboratory
Experiment of the Sun for Complementing the ATLAS Payload and for Education (ESCAPE)**	Solar far-UV output	University of Colorado

*CRISTA and MAHRSI flew with ATLAS-3 only.
**ESCAPE, a student experiment, flew with ATLAS-2 and ATLAS-3.

been used extensively in UARS validation [*Grose and Gille*, 1995; *Woods et al.*, 1996; *Gille et al.*, 1996]. SSBUV plays a critical role in the validation of the ozone and solar spectral irradiance measurements of the Solar Backscatter Ultraviolet/2 (SBUV/2) instruments aboard NOAA's polar-orbiting operational meteorological satellites [*Hilsenrath et al.*, 1995]. Other correlative measurement opportunities included solar flux measurements on the European Retrieval Carrier (EURECA) and the Earth Radiaion Budget Satellite (ERBS), and ozone measurements from the Total Ozone Mapping Spectrometer (TOMS) instruments on Nimbus-7 and Meteor satellites.

The two total solar irradiance instruments in the ATLAS payload, SOLCON and ACRIM, are both pyrheliometers, measuring the amount of energy absorbed in a cavity exposed to sunlight. The total solar irradiance ("solar constant") was measured to within 0.1% accuracy and precision [*Crommelynck et al.*, this issue]. In the context of a larger program with many measurements on several platforms over a long period of time, as well as instruments on long-duration, free-flying platforms, such as the UARS ACRIM instrument, this accuracy on periodic short missions can help establish our knowledge of possible variations in the total solar energy that drives Earth's climate system.

The two spectrally resolved solar irradiance instruments, SOLSPEC and SUSIM, covered different wavelength ranges, with SOLSPEC covering from the ultraviolet (UV) to near infrared wavelengths, while SUSIM examined only UV wavelengths but down to a short-wavelength cutoff of 110 nm. SSBUV, whose primary purpose is to measure the vertical profile of stratospheric ozone, also made measurements of solar UV radiation [*Cebula et al.*, this issue]. The ESCAPE instrument was designed to make measurements in the far UV, extending the ATLAS measurement range to wavelengths below the SUSIM short-wavelength cutoff.

A large number of atmospheric trace constituents and temperatures were measured using several methods (see Table 2). The MAS instrument [*Hartmann et al.*, this issue] measured altitude profiles of the emissions of atmospheric radiation in the millimeter wave range, specifically at frequencies corresponding to water vapor, ozone, chlorine monoxide, and molecular oxygen (used for temperature and pressure). ATMOS measured the absorption of infrared solar radiation by the Earth's atmosphere and from those data the concentrations of a very large number of trace species can be inferred as a function of altitude [*Gunson et al.*, this issue]. SSBUV measured the scattering of solar UV radiation from the Earth's atmosphere, and used this information to obtain both total column ozone and ozone vertical profile distributions, as well as nitric oxide amounts in the mesosphere and lower thermosphere. CRISTA measured emissions of infrared radiation in three viewing directions, obtaining detailed three-dimensional datasets of various trace gases. MAHRSI made limb scanning measurements of the UV solar resonance fluorescence of OH and NO to obtain their vertical density profiles in the middle atmosphere (*Conway et al.*, 1996).

All three ATLAS missions were carried out with an orbital inclination of 57 degrees, allowing the viewing of most of the Earth's surface. The orbit altitudes of ATLAS-1 and ATLAS-2 were both 296 km, and the altitude of ATLAS-3 was slightly higher (302 km). Because of the emphasis on highly accurate and precise measurements, significant attention was placed on consideration of contamination issues. In addition to the cleanliness requirements on the individual instruments and Spacelab pallet, a special wipe-down of the shuttle payload bay was used prior to the ATLAS-2 and ATLAS-3 missions. The solar instruments did not operate until the platform had been in orbit for some 24 hours to allow for outgassing of any contaminants.

Due to different launch times and seasons, the viewing regions and times of the ATLAS instruments differed from one mission to the next. This was particularly true for ATMOS, as it uses the occultation technique, and the position of the occultations is very sensitive to launch time. For ATLAS-1, the

Table 2. Atmospheric Constituents Measured by ATLAS-3 Approximate Altitude Range (km)

Gas	ATMOS	MAS	SSBUV	MAHRSI	CRISTA
O_3	10 - 100	20 - 90	20 - 55		15 - 95
NO	10 - 140		50 - 100	45 - 145	100 - 180
NO_2	15 - 50				15 - 40
N_2O	10 - 60				15 - 45
N_2O_5	20 - 40				20- 40
H_2O	10 - 90	20 - 90			15 - 80
HNO_3	15 - 40				15 - 40
CH_4	10 - 70				15 - 70
CCl_3F	10 - 25				15 - 20
CCl_2F_2	10 - 30				15 - 30
$ClONO_2$	10 - 35				20 - 40
ClO		30 - 45			
HCl	10 - 65				*
HF	10 - 60				40 - 65
OH				40 - 90	
CO	10 - 60				*
CO_2	10 - 120				15 - 150
$O(^3P)$					80 - 180

*Altitude range as yet undetermined.

In addition to the above, there are some 20 other constituents available in the spectra measured by ATMOS, and temperature and pressure were measured by ATMOS, MAS, and CRISTA.

occultations spanned a range of tropical and mid-latitude regions in both hemispheres, while for ATLAS-2, sunrise occultations were at high northern latitudes with sunset occultations at mid-high southern latitudes, and for ATLAS-3, sunrise occultations were at high southern latitudes with sunsets varying from the tropics to mid-latitudes in the northern hemisphere [*Gunson et al.*, this issue]. The ATLAS-2 and ATLAS-3 missions took place during the northern and southern hemisphere spring seasons, respectively, during which the corresponding polar vortices persisted (displaced somewhat from the pole), allowing for observations both inside and outside. More details on the meteorological conditions of the ATLAS-3 mission are summarized in a paper by *Manney et al.* (this issue).

Since instrument pointing was provided by the space shuttle, atmospheric and solar observations were carried out sequentially. For most of the mission, the shuttle was in a cargo-bay-down attitude for atmospheric observations, inter-

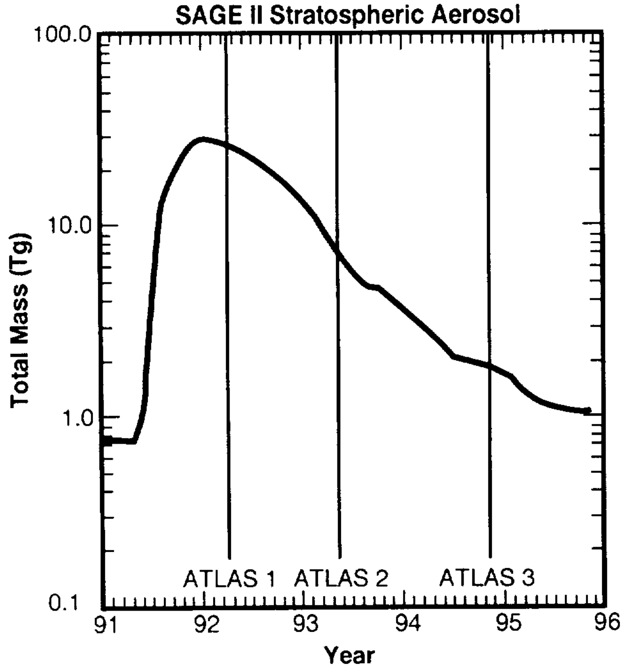

Figure 1. Plot showing estimated total mass of stratospheric aerosol as inferred from measurements made by the SAGE II instrument. Vertical bars are used to represent the dates of the ATLAS flights. Figure supplied by Larry Thomason of NASA's Langley Research Center.

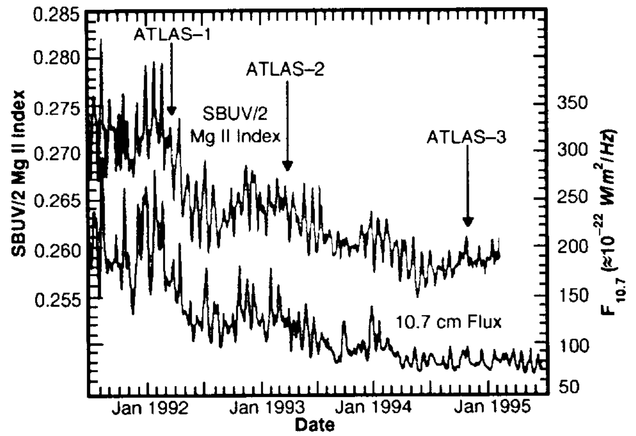

Figure 2. Plot showing globally averaged (65 degrees north to south) total ozone in Dobson Units (DU) for the period 1992 through 1994 as determined by the TOMS instrument. Arrows indicate the times of the ATLAS flights. The shaded area represents the climatology for the period 1979–1990, with the white line showing the mean of that period. The dashed line shows data from the Nimbus-7 TOMS instrument, which failed in May 1993, while the solid line shows data from the Meteor-3 TOMS, which failed in December 1994. Gaps in the latter curve reflect time periods where the orbit of the Meteor-3 satellite was inappropriate for quantitative determination of global total ozone. Figure supplied by Jim Gleason of NASA's Goddard Space Flight Center.

rupted approximately every 2 days for roughly 12 hours of solar observations. During solar observations, the orbiter changed orientations every orbit between the cargo bay pointing towards the Sun (day side) to pointing toward deep space for cooling (night side). Scientific observations were suspended during the deployment and retrieval of the SPARTAN 201 (ATLAS-2) and CRISTA/SPAS (ATLAS-3) carriers. There were also several short periods of time during the latter mission when scientific observations by the ATLAS instruments were halted so that the shuttle attitude was changed to one dedicated to communications with the SPAS.

All instruments performed well during the ATLAS missions, with the exception of the MAS instrument, which failed after 1 day of operations during ATLAS-3. However, MAS was still able to obtain near-global measurements of H_2O, O_3, ClO, and temperature during that period [*Hartmann et al.*, this issue].

The 2.5-year time interval between the first and last ATLAS missions saw several interesting and important changes in the atmosphere and solar forcing: (1) There was a significant decrease in the stratospheric aerosol burden (see Fig. 1) over this time period, since the ATLAS-1 mission occurred only 9 months after the Mt. Pinatubo eruption (June 1991) and only a few months after the peak in total stratospheric aerosol abundance as inferred from the Stratospheric Aerosol and Gas Experiment (SAGE). Given that there is an approximate 1-year lifetime for stratospheric aerosols, one sees that the stratospheric aerosol loading decayed by nearly a factor of 100 from the ATLAS-1 to ATLAS-3 mission. This decay allowed for significantly improved penetration of ATMOS occultations into the lower stratosphere and troposphere in ATLAS-3 as opposed to ATLAS-1 when most occultations could not observe the lower stratosphere (but interesting studies could be carried out on the aerosol optical properties [*Rinsland et al.*, 1994]; (2) There was a marked decline in global total ozone in the 1992–1993 time period believed to be related to the Mt. Pinatubo eruption. This decline was just beginning at the time of the ATLAS-1 flight, was near its maximum at the time of the ATLAS-2 flight, and was essentially recovered by the ATLAS-3 flight. The SSBUV instrument clearly showed the decrease in ozone from spring 1992 to spring 1993 [*Hilsenrath et al.*, this issue] which has also been seen from other instruments; and (3) There was a marked decrease in solar activity from the ATLAS-1 to ATLAS-3 mission (see Fig. 2), as measured from a variety of solar indices, including the F10.7 flux and the Mg II Index determined from the SBUV/2 instrument. The ATLAS-1 and ATLAS-2 flights were during the declining phase of solar cycle 22, while ATLAS-3 was very close to solar minimum. It is also worth noting that the halogen burden in the stratosphere continued to increase over this time period [*Gunson et al.*, this issue].

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