

INITIAL COMPARISON OF SAGE III DATA WITH GOMOS AND SCIAMACHY

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1. ABSTRACT/RESUME

In this paper, we will give a summary of the history and heritage of SAGE missions as well as a brief description of its latest member, SAGE III. Results of comparison between the measurements of SAGE III and SAGE II indicate a good agreement between the two. Early results from GOMOS Ozone comparison with SAGE III shows an agreement to 10 %. NO₂ looked noisy, but agree to 10% when it is averaged. A very early SCIAMACHY NO₂ profiles from limb scattering and solar occultation are compared to SAGE III and results are encouraging.

2. INTRODUCTION

SAGE III is the fifth generation of the successful remote sensing instrument utilizing the solar occultation technique [1] to measure the vertical profiles of aerosol, ozone and other constituents in the atmosphere. The series of instruments started with Stratospheric Aerosol Monitor (SAM) in 1975, SAM II, Stratospheric aerosol and gas Experiment I (SAGE I) in 1978, and SAGE II in 1984. The SAM instrument was onboard the Apollo spacecraft during the Apollo Soyuz Test Project in 1975 to perform the first successful solar occultation measurement of stratospheric aerosol [2]. SAM II was launched in 1978 onboard the NIMUS 7 spacecraft and operated for 14 years until the spacecraft finally failed [3]. Both SAM and SAM II were single spectral channel instruments measuring aerosol extinction near the 1000 nm wavelength region. Multiple spectral measurements began with the SAGE I instrument which was launched in 1979 on the Application Explorer II spacecraft. SAGE I was built with four spectral channels located at 1000 nm, 600 nm, 450 nm, and 385 nm to measure aerosol, ozone, and nitrogen dioxide signatures [1,4]. SAGE I mission terminated prematurely in 1981 due to spacecraft failure. SAGE II is an advanced version of SAGE I with seven spectral channels located at 1000 nm, 940 nm, 600 nm, 525 nm, 453 nm, 448 nm, and 385 nm which provided better aerosol, ozone, nitrogen dioxide measurements with additional water vapor measurements [5]. SAGE II was launched in 1984 on the Earth Radiation Budget Satellite and is currently still in operation after providing continuous data for the last seventeen years.

The measurements from the three instruments, SAM II, SAGE I, and SAGE II, have provided a long record of stratospheric aerosol and ozone data over the last 20 years. Solar occultation technique is well known to be mathematically a well-posed, well-behaved inversion problem. The measurement technique is self-calibrating with high vertical resolution and provides high signal-to-noise measurements. Therefore the SAGE-type instrument is well-suited for long term monitoring of atmospheric species which are important in assessing climatic and/or environmental changes. SAGE III builds on and improves on the previous experiments by including additional wavelengths to accomplish the following: increased aerosol characterization, especially at the larger particle size range with measurements of aerosol extinction extended out to 1550 nm; improved gaseous species retrievals of O₃, H₂O, NO₂, temperature and pressure profiles by using multi-spectral absorption measurements; extended vertical range of measurements with higher signal-to-noise measurements; independence from any external data set by measuring atmospheric density with the O₂ measurements at 760 nm; and, providing internal wavelength calibration capability by measurements of solar Fraunhofer lines. The number of wavelength channels has been increased by utilizing a linear array detector in the spectrometer optics, covering the wavelengths from 290 to 1020 nm with 1 to 2 nm spectral resolution. A photodiode with center wavelength at 1550 nm has been added for sensitivities to larger aerosol particles. Seven of these channels will be used for the aerosol and cloud characterization which will also aid in removing their effects from the gaseous retrievals. The linear array will allow for many absorption features of NO₂, O₂, H₂O, NO₃, and OCIO to be resolved making these retrievals highly accurate. Extending the wavelength coverage to 290 nm will allow SAGE III to measure O₃ to altitude of 85 km. In addition to the exoatmospheric solar radiance calibration measurement when SAGE III scans the unattenuated Sun, certain solar Fraunhofer lines will provide a wavelength calibration that would make SAGE III totally self-calibrating.

The SAGE III instrument on-board the Russian spacecraft Meteor 3M was launched from the Russian launch site Baikonur Cosmodrome in Kazakhstan on December 10, 2001. A Ukraine built Zenit 2 rocket put the spacecraft into a sun-synchronous orbit with inclination of 99.64° and the ascending node crossing time of 9:00AM, with an orbital height of 1018 KM. After the initial check out and outgasing period, the instrument was turned on to acquire the first solar data on February 27, 2002. By early March of 2002, the SAGE III instrument was acquiring all the available solar measurements.

Both GOMOS and SCIAMACHY are instruments on the ENVISAT satellite that was launched by ESA on March 1st, 2002 [6,7,8]. GOMOS performs stellar occultation at wavelengths from the near UV through the visible region and produces profile of ozone, NO₂, and other gaseous species as output products. SCIAMACHY is similar to the GOME instrument with extended wavelength coverage from the near UV to about 2.5 micron region and with significantly extended operational capability. SCIAMACHY performs nadir backscattering, solar occultation, lunar occultation, and limb scattering measurements to produce information on ozone, NO₂, aerosol, and other gaseous species. Both instrument have been in operation since launch.

3. SAGE III INSTRUMENT OPERATION

The SAGE III instrument is built with three different subsystems. The first subsystem is the scan head which consisted of the scan mirror mounted on an azimuth drive that can rotate over 360° for pointing in azimuth direction. The scan mirror scans in elevation so that it can point to the Earth's limb when the instrument is in orbit. The second subsystem is the imaging optics with the telescope and the azimuth target acquisition detectors. The telescope is a f/4 Dall-kirkham with an one-half by five arc-minute slit in the focal plane that serves as the science aperture and as the entrance slit to the grating spectrometer. The entire telescope assembly including scan mirror can rotate together in azimuth to eliminate the problem of image rotation during azimuth rotation. The target sensor assembly is mounted on the back of the telescope secondary and on the side of the telescope housing. The target sensor consists of a bi-level photodiode that can perform both solar and lunar acquisition with a change in dynamic range of six orders of magnitude. The last subsystem of the SAGE III sensor is the spectrometer detector package. The spectrometer consists of a holographic grating in a Rowland configuration operating in both zeroth and first orders. The first order dispersion is monitored with an 809 x 11 elements CCD, back-side thinned to enhance the UV response. The CCD is partitioned into eight segments with independent clock drives so that integration time for each segment can be varied separately. This particular design can provide maximum signal-to-noise detection of the solar spectrum at all wavelength regions with this CCD. The CCD detects incoming solar radiation from 290 nm to 1040 nm with a spectral resolution between 1.2 to 2.5 nm. The zeroth order reflection from the grating is used with a photodiode together with a spectral bandpass filter centering at 1550 nm.

The operation of the SAGE III instrument in orbit is similar to the operation of the previous SAGE instruments. Before a solar occultation event, the telescope and scan head is first slewed to the azimuth position where the sun will appear. As soon as the solar signature has been registered by the target sensor, the scan mirror begins to scan in elevation to acquire the solar image on to the instrument's field of view. The 0.5 arc-minute science aperture in the vertical direction provides for approximately half kilometer vertical resolution in the atmosphere. Measurements are obtained by repeatedly scanning up and down over the solar disk at the Earth's limb over height region from the ground to about 300 km high. There are three modes of operation during a solar occultation event. The first mode is the mirror calibration mode performed over a height region from 300 km to 150 km. These measurements are high above the Earth's atmosphere and are not sensitive to atmospheric absorption or scattering. The data from these measurements can be used to calibrate the change in reflectivity of the scan mirror at different incident angles for all the SAGE III spectral channels. The second mode of operation is the wavelength calibration mode where the solar spectrum will be monitored between 150 km and 120 km by all 800 elements of the CCD. The complete spectral information on the solar spectrum can be used to calibrate the wavelength registration of the CCD elements by monitoring the location of the different known solar Fraunhofer's lines on the CCD. The third mode of operation is the measurement mode. It occurs between about 120 km to the ground where atmospheric data will be taken. Lunar occultation measurements will also be performed by the SAGE III instrument when the phase of the moon is half or larger. Lunar measurement will be performed by removing the attenuator plate in the scan head and by increasing the integration time for each of the measurements to provide for the change in dynamic range going from solar to lunar measurements. The operation of the instrument for obtaining lunar data will be similar to solar measurement using only the measurement mode of operation.

During solar occultation event, SAGE III will be measuring atmospheric species in twelve spectral regions with each spectral region primarily targeted for each specific species. The level 2 data products from the SAGE III solar measurements will consist of ozone profiles from cloud-top to 85 km, aerosol extinction profiles in seven wavelengths from cloud-top to about 40 km, pressure and temperature profiles from cloud-top to 85 km, H₂O profiles from cloud-top to 50 km, and NO₂ profiles from 10 km to 50 km. For lunar measurements, the level 2 data products will consist of ozone profiles from 10 km to 50 km, NO₂ profiles from 15 to 45 km, NO₃ profiles from 20 to 55 km, and OCIO profiles under perturbed atmospheric condition from 15 to 25 km.

The SAGE III instrument has been operational since launch. Instrument performance has been nominal. Solar occultation events have been routinely acquired. Lunar event acquisition has been a challenge especially for acquiring moon rise events due to the low intensity target. Currently most of the lunar events for lunar phase of 40% full moon are being acquired. The instrument is also being tested for acquiring limb scattering data with some good initial success.

An anomalous noise pattern in the measured data has been observed in the SAGE III telemetry and has been investigated by the SAGE III team. The noise pattern manifested itself as a correlated noise across the neighboring CCD pixels, and is slowly varying with time. At this point in time, the cause of this anomaly has been traced to an etaloning effect from the solar attenuator plate. The attenuator plate is a 6-mm thick quartz plate with metallic coating on one side to provide a spectrally uniform attenuation of 99% from 300 nm to 1550 nm. The quartz plate turns out to be completely parallel, thus producing interference fringe over the CCD. A quick estimate will show that there exists from ten to thirty fringes over a single pixel of one nm wavelength bandwidth over the wavelength range of UV to the near IR. Thermal model calculation for the instrument during a solar event indicates that the attenuator plate can be heated up by 10 to 15 degree C, therefore producing the slowly time varying change in CCD response.

4. SAGE III DATA PROCESSING AND DISTRIBUTION

The SAGE III retrieval algorithm is the procedure that converts the instrument's response to solar or lunar flux at 70 to 80 wavelengths between 290 and 1550 nm into vertical profiles of the molecular density of gaseous species, aerosol extinction at 8 wavelengths, temperature, and pressure. This procedure consists of two main parts: the transmission algorithm and the inversion algorithm. Details of the transmission algorithm and the inversion algorithm for the different species can be found in the respective Algorithm Theoretical Basic Documents [9] and will not be repeated here. However, modification to the algorithm has been made to account for the correlated noise in the SAGE III measurements as mentioned before. The method used for the correction of the etaloning effect produced by the attenuator plate is to use Empirical Orthogonal Function to describe the pattern of the correlated noise in the spectral domain. Currently released SAGE III data are processed using this algorithmic approach.

The SAGE III data processing is currently being implemented at the SAGE III Science Computing Facility (SCF) in NASA Langley Research Center. The data products that will be generated consist of level 1B data and level 2 data products. Level 1b data will be primarily the solar slant path transmission data at the 85 wavelength bands that were used for the inversion into the different atmospheric species. The level 2 data products will consist of profiles of aerosol extinction at nine wavelengths, ozone, water vapor, nitrogen dioxide, nitrogen trioxide, chlorine dioxide concentrations, and temperature. The expected accuracy for most of the gaseous species is about 5 % for ozone and 10 to 15 % for water vapor and nitrogen dioxide at the peak of the concentration with reduced accuracy for lower concentration regions. Aerosol extinction will similarly be about 5% accuracy for the near IR wavelength regions with increased uncertainty to the shorter wavelength. Expected temperature measurement accuracy is about 2 degree K. The processed data will be delivered to the Langley Distributed Active Archive Center (DAAC) for public distribution. These data will be archived at the Langley DAAC after the validation activities have been completed. Release of the early SAGE III is expected to occur in December of 2002.

5. COMPARISON OF SAGE III TO SAGE II DATA

The following fig. 1 and 2 show the comparison of the early results from the SAGE III instrument as compared to near coincident SAGE II measurements for both ozone and aerosol. Fig. 1 (a) shows the mean of 7 ozone concentration profiles from SAGE III on 9, May, 2002 as opened circles. The locations of the SAGE III measurements occurred between latitudes of 50.2° N to 50.5° N and 77° E to 164° E. Comparing to the SAGE III mean profile is the solid line showing the mean of 5 SAGE II measurements over the same time period with measurement location from latitudes from 52.1° N to 52.8° N and 66° E to 162° E. The percentage difference between SAGE III to SAGE II is showed in fig. 1

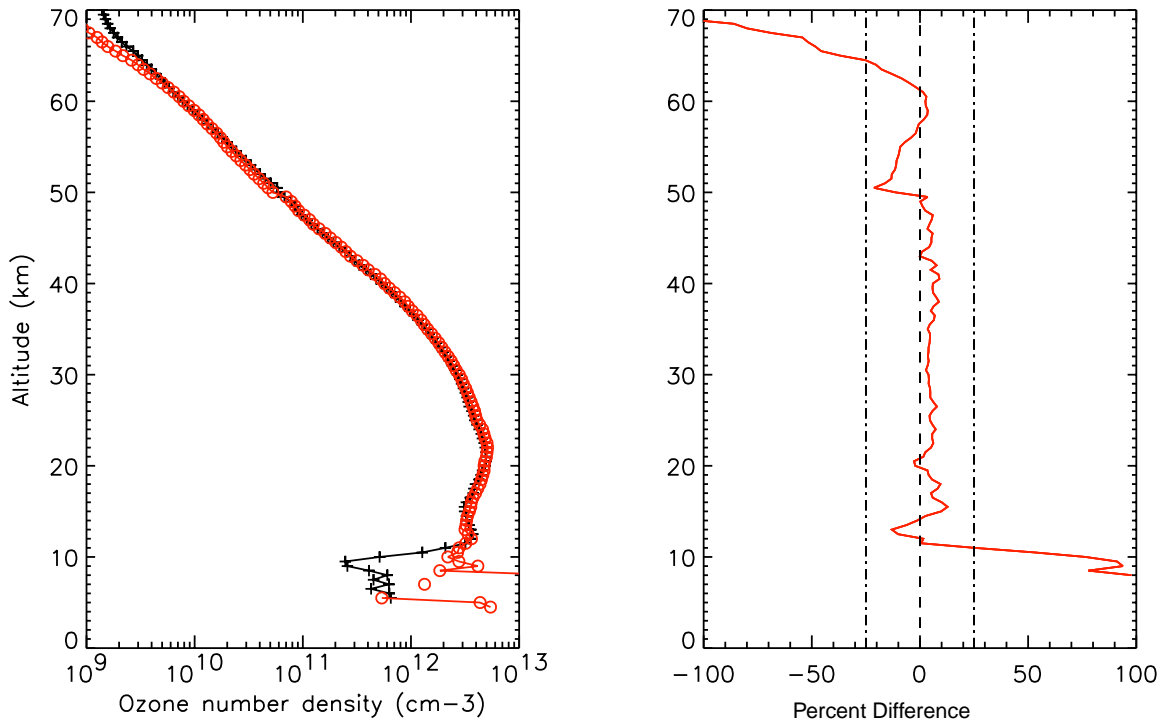


Fig 1. (a) Ozone SAGE III vs. SAGE II and (b) Relative Difference

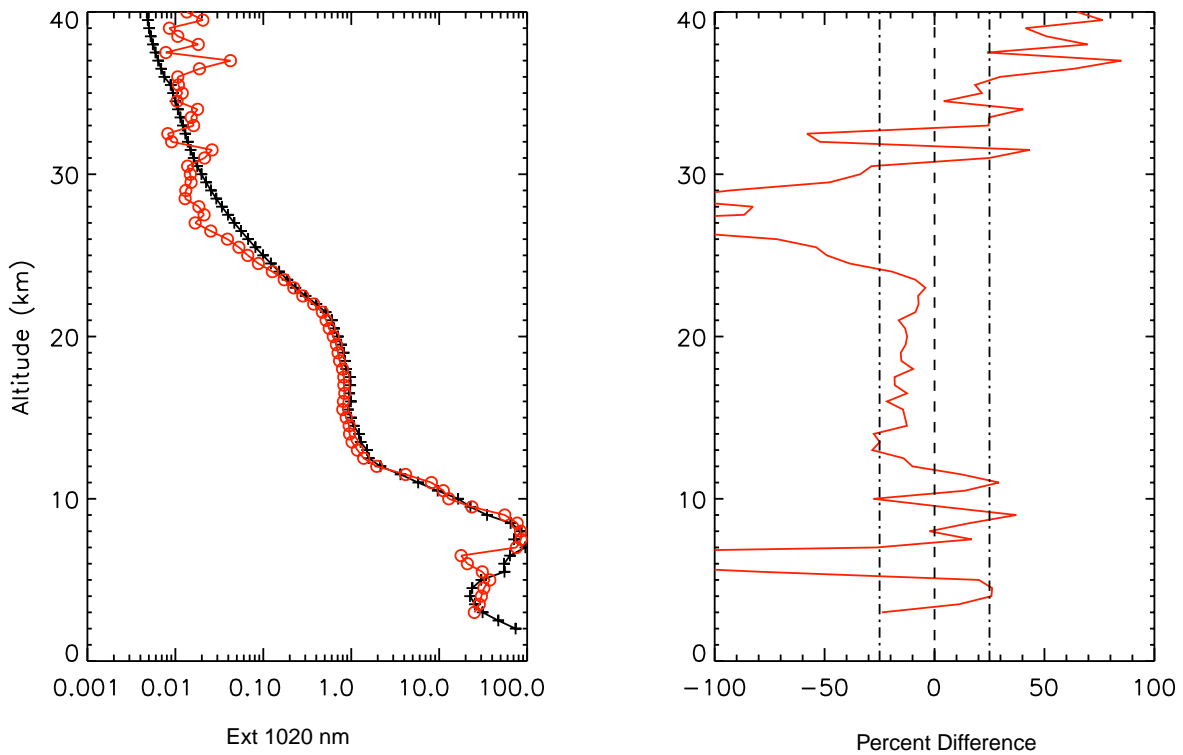


Fig 2. (a) Extinction Coefficient $\times 10^4$ SAGE III vs. SAGE II and (b) Relative Difference.

(b). The difference between SAGE III and SAGE II ozone measurements are well below 5 % over the altitude range between 20 and 50 KM. Fig. 2 (a) and (b) show the same comparison between SAGE III mean aerosol extinction profiles at 1000 nm to those measured from SAGE II. Again, the difference in the comparison is about 20 % between 25 Km to 15 KM in altitudes. Since SAGE III data have not been screened for cloud interference, the large difference below 15 KM is due primarily from the cloud signature in the SAGE III data.

6. SAGE III COMPARISON WITH GOMOS

Fig. 3 shows the comparison of the ozone profiles measured by the SAGE III instrument as compared to near coincident GOMOS measurements. The comparison was performed for the mean of 302 ozone concentration profiles from SAGE III from May to July, 2002 as opened diamonds. The coincidence criteria is $\Delta\text{Lat} = 5^\circ$, $\Delta\text{Lon} = 15^\circ$, and $\Delta\text{time} = 3\text{h}$. Fig. (3b) is the relative difference. The fig. show good agreement in the stratosphere region 16-50 km, about 10%. In the mesosphere, there seems to be a significant bias between SAGE III and GOMOS ozone measurements.

We have also performed comparison of GOMOS NO₂ profiles with coincident SAGE III NO₂ measurements. In general, the GOMOS NO₂ profiles are very noisy compared to the SAGE III profiles. However, when a large number of profiles are averaged and the means for GOMOS and SAGE III are compared, the agreement is about 10% in the altitude range of 23 –35 km.

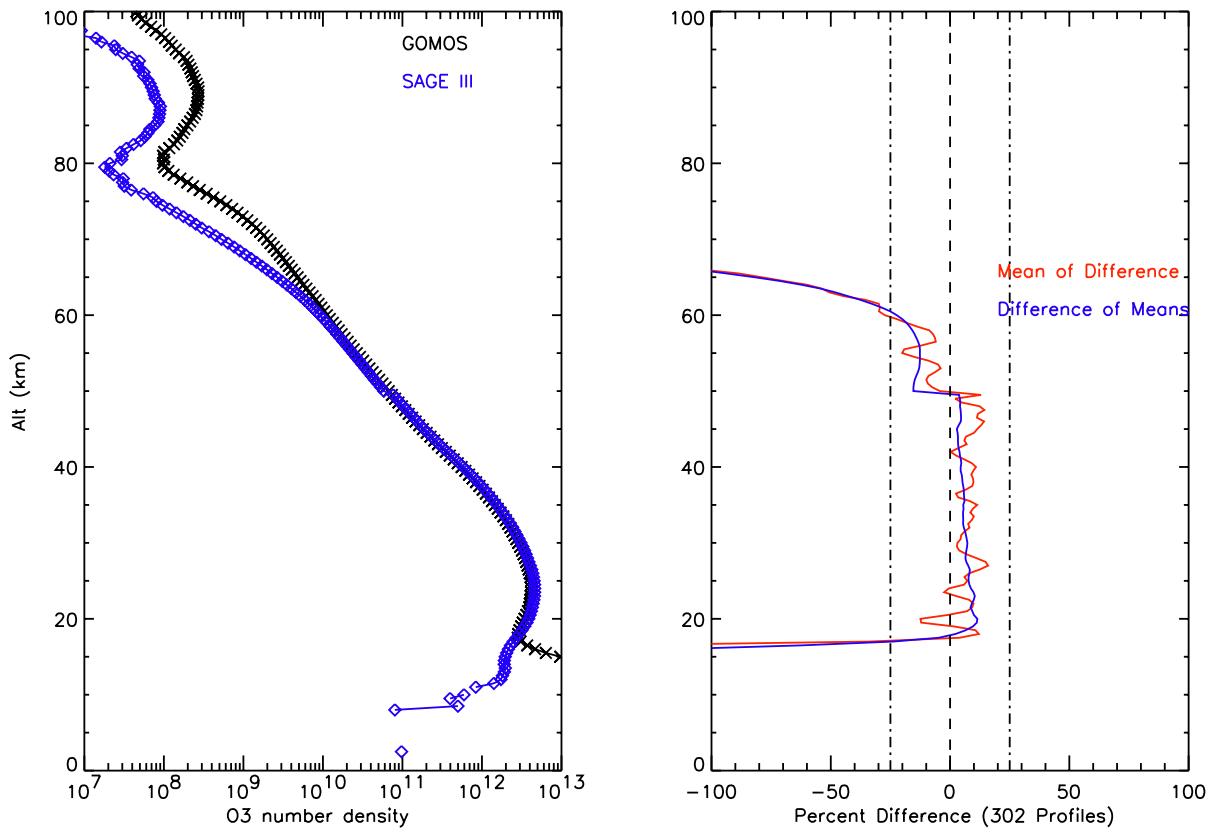


Fig. 3. (a) Ozone SAGE III vs GOMOS (b) Relative Difference.

7. SAGE III COMPARISON WITH SCIAMACHY

As of today, the operational data products from SCIAMACHY are still not available. However, preliminary results from both the occultation measurements and limb scattering measurements have been made available for comparison with

coincident SAGE III measurements. We have compared SCIAMACHY limb scattering NO₂ retrieval by SAO with coincident SAGE III NO₂ measurement, ~ 386km. The result from the comparison shows agreement to less than 10 % within the altitude range of 23 – 33 km. Similarly the comparison of SCIAMACHY solar occultation NO₂ retrieval by Bremen group to the coincident SAGE III measurements, ~ 468km, shows agreement of 20 – 25 % in the altitude range of 18 – 34 km. These results, because of the preliminary nature, will not be included in this paper but will be presented during the ENVISAT validation meeting for general discussion.

8. SUMMARY

In this paper, a brief description of the SAGE III mission has been given. The SAGE III data have been compared with SAGE II measurements and shows good agreement. Comparison of SAGE III data with GOMOS data has also been made and the results are very encouraging. There is only selected data from SCIAMACHY, and the comparison shows good agreement.

9. REFERENCES

1. M. P. McCormick, P. Hamill, T. J. Pepin, W. P. Chu, T. J. Swissler, and L. R. McMaster, Satellite Studies of the Stratospheric Aerosol, *Bull. Amer. Meteor. Soc.*, 60, 1038, 1979.
2. T. J. Pepin, M. P. McCormick, W. P. Chu, F. Simon, T. J. Swissler, R. R. Adams, K. H. Crumbly, and W. H. Fuller, Stratospheric Aerosol Measurements, in *Apollo-Soyuz Test Project. Summary Science Report*, NASA SP 412, 127, 1977.
3. W. P. Chu, M. T. Osborn, and L. R. McMaster, SAM II Data User's Guide, *NASA Reference Publication 1200*, July, 1988.
4. L. R. McMaster, W. P. Chu, and M. W. Rowland, SAGE I Data User's Guide, *NASA Reference Guide 1275*, August 1992.
5. L. E. Mauldin, et al., Stratospheric Aerosol and Gas experiment II instrument: a Functional description, *Opt. Eng.*, 24, 2, 307-312, 1985.
6. J. L. Bertaux, G. Mégie, T. Widemann, E. Chassefière, R. Pellinen, E. Kyrola, S. Korpela and P. Simon, Monitoring of ozone trend by stellar occultations: the GOMOS instrument, *Advances in Space Research*, Vol. 11, Issue 3, Pages 237-242, 1991.
7. Bovensmann, H., J. P. Burrows, M. Buchwitz, J. Frerick, S. Noël, V. V. Rozanov, K. V. Chance, A. P. H. Goede, SCIAMACHY: Mission Objectives and Measurement Modes. *Journal of the Atmospheric Sciences*, Vol. 56, No. 2, pp. 127–150, 1999.
8. S. Noël, H. Bovensmann, M. W. Wuttke, J. P. Burrows, M. Gottwald, E. Krieg, A. P. H. Goede and C. Muller Nadir, limb, and occultation measurements with SCIAMACHY, *Advances in Space Research*, Vol. 29, Issue 11, 1819-1824, 2002.
9. SAGE III Algorithm Theoretical Basis Documents: Transmission Level 1B Products, Solar and Lunar Algorithm, Cloud Data Products, LaRC, March 2002, can be accessed from <http://eosps0.gsfc.nasa.gov/atbd/sagetables.html>