Science Commissioning of the Atmospheric Chemistry Experiment (ACE)

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ABSTRACT

The Atmospheric Chemistry Experiment (ACE) was launched in August 2003 on board the Canadian scientific satellite SciSat-1. The ACE payload consists of two instruments: ACE-FTS, a high resolution (0.02 cm^{-1}) Fourier transform infrared spectrometer and MAESTRO (Measurement of Aerosol Extinction in the Stratosphere and Troposphere Retrieved by Occultation), a dual UV-visible-NIR spectrograph. Primarily, the two instruments use a solar occultation technique to make measurements of trace gases, temperature, pressure and atmospheric extinction. It will also be possible to make near-nadir observations with the ACE instruments.

The on-orbit commissioning of the instruments and spacecraft were undertaken in the months following launch. At the end of this period, a series of science-oriented commissioning activities were undertaken. These activities had two aims: the first was to verify and extend the measurement results obtained during the pre-launch Science Calibration Test campaign and the second was to confirm appropriate parameters and establish procedures for operational measurements (occultation and near-nadir observations and exo-atmospheric calibration measurements). One of the most important activities was to determine the relative location of each instrument field of view and optimize the pointing of the sun-tracker to provide the best viewing for both instruments.

Keywords: ACE, SciSat-1, instrument calibration and commissioning, atmospheric remote sensing

1. INTRODUCTION

The Atmospheric Chemistry Experiment (ACE) is a Canadian scientific satellite mission to investigate atmospheric chemistry and dynamics with a particular focus on examining ozone distribution in the stratosphere and upper troposphere[1]. On August 12, 2003, the SciSat-1 satellite, which carries the ACE payload, was launched into a 650 km, 74 degree inclined circular orbit. The operational phase of the mission officially began at the end of February 2004 with the completion of the on-orbit commissioning. This phase included functional testing of the spacecraft bus and instruments and science-oriented activities in preparation for the operational phase of the mission. Since the completion of the on-orbit commissioning, the satellite instruments have been making routine observations of the Earth's atmosphere. Initial retrieval results from SciSat-1 are discussed in a separate paper in these proceedings[2].

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There are two scientific instruments which comprise the ACE payload. The primary instrument, the ACE-FTS, is a high resolution (0.02 cm^{-1}, 25 cm OPD) Fourier transform infrared spectrometer (FTS) which measures from 750 – 4100 cm^{-1} using two detectors (MCT and InSb). It also contains two filtered imaging cameras, NIR and VIS, which operate at 1.02 and 0.525 microns, respectively. The secondary instrument, MAESTRO (Measurements of Aerosol Extinction in the Stratosphere and Troposphere Retrieved by Occultation), makes measurements between 260 and 1030 nm with a resolution of 1-2 nm using two slit grating spectrographs (UV and VIS). Fine pointing of the instruments is achieved using a suntracker which is sub-system of the ACE-FTS. The ACE instruments observe the atmosphere primarily by solar occultation. These sunrise and sunset measurements are used to determine atmospheric profiles of trace gases, temperature, pressure and atmospheric extinction. Several secondary measurement modes for near-nadir atmospheric observations and exo-atmospheric solar mapping and calibration sunscans have also been developed for the ACE instruments.

The on-orbit commissioning phase is an important part in the early lifetime of a satellite. The instrument functional testing and spacecraft bus commissioning activities verify that all of the components and sub-systems are fully functional. For the ACE mission, a "science" commissioning phase was also undertaken by the Science Team in order to better prepare for operations. During this phase, tests were made to confirm appropriate parameters and establish command sequences for operational measurements and also to verify and extend the results of calibration and performance characterization measurements made prior to launch.

A step-by-step approach was taken for the on-orbit commissioning of the SciSat-1 instruments and spacecraft. The instrument functional testing and spacecraft bus commissioning were completed in the four months following launch. The instrument functional testing and commissioning of ACE-FTS and MAESTRO were led by ABB and University of Toronto, respectively, and Bristol Aerospace led the spacecraft level commissioning. All of these activities were coordinated through the SciSat-1 Satellite Operations team at the Canadian Space Agency. Towards the end of the commissioning period, the science commissioning activities were carried out. This phase was led by the Science Operations Centre at the University of Waterloo. This paper outlines activities undertaken as part of the science commissioning phase and describes the results obtained.

2. PRELIMINARY MEASUREMENTS

Several preliminary tests had to be completed at the beginning of the science commissioning program before further measurements could be undertaken. The first test was to verify that both ACE-FTS and MAESTRO could be commanded to take measurements simultaneously. For the earlier instrument functional testing and commissioning activities, the ACE-FTS and MAESTRO were operated independently. However, for almost all operational measurements, both of the ACE instruments are commanded to take measurements at the same time using a combined timeline of events. The first measurements with both instruments measuring simultaneously were executed successfully in December, 2003. The remaining preliminary tests exercised a range of instrument settings for the FTS and imagers that were then used to choose the optimal operating parameters.

Preliminary settings for the FTS and imagers had been determined as part of the ABB on-orbit instrument functional testing. These parameters were optimized as part of the science commissioning program. For the FTS instrument, this involved verifying that the gain settings for the InSb and MCT channels were appropriate for occultation and exo-atmospheric observations. Measurements were made at all gain settings and resolution settings to exercise these modes of operation. For the imagers, three parameters (imager exposure time, ADC gain and number of frames to co-add for each measurement) had to be optimised. Measurements were taken at a series of exposure times to verify the linearity of the imager performance. During the ACE Calibration Test Campaign in February-March 2003[3], it was found that the imagers exhibit non-linear performance when operating at higher than 50% of the full ADC range (at the lowest gain setting). Similar results were found in the commissioning tests. Based on the on-orbit results, appropriate exposure times were chosen for the VIS and NIR imagers. The gain settings were chosen to maximize usage of the full ADC range and the frames settings were chosen to fill the measurement time.

Measurement parameters for the MAESTRO instrument vary significantly with the orbital beta angle (as the length of the sunrise or sunset changes). These parameter settings are stored on-board the instrument in tables

and the appropriate table is specified at the beginning of each measurement. As part of the science commissioning phase, a set of tables covering the full range of beta angles was developed and uploaded to the instrument.

3. INSTRUMENT POINTING AND SUNTRACKER OFFSETS

The next set of tests were done to verify the location of the FTS and MAESTRO fields of view (FOVs) and to optimize the sun-pointing of the instruments. Prior to launch, the FOVs of the FTS and MAESTRO were mechanically co-aligned by adjusting the viewing direction of the two MAESTRO spectrometers so that they overlapped as closely as possible with the FTS FOV. The pointing location of instrument FOVs on the Sun's disk was then to be optimised on-orbit by changing the position of the suntracker.

These on-orbit tests provided an opportunity to complete the characterization of the suntracker pointing and to exercise different suntracker operation modes. The two modes of operation that will be discussed in some detail here are the closed-loop mode which uses feedback from a quad cell detector to control the mirror pointing and the sunscan mode which can rapidly scan the instrument FOVs across the Sun's disk. The closed-loop mode is designed to keep the instruments pointed at the radiometric centre of the Sun during a measurement. This pointing position can be changed by applying relative offsets in elevation and azimuth to the suntracker mechanism. During the acceptance testing program for the ACE-FTS performed by ABB, it was found that the FTS FOV was offset from the radiometric centre of the Sun by ~2.9 mrad. So a fairly large adjustment was required to point the instrument FOVs to the Sun centre in closed-loop mode.

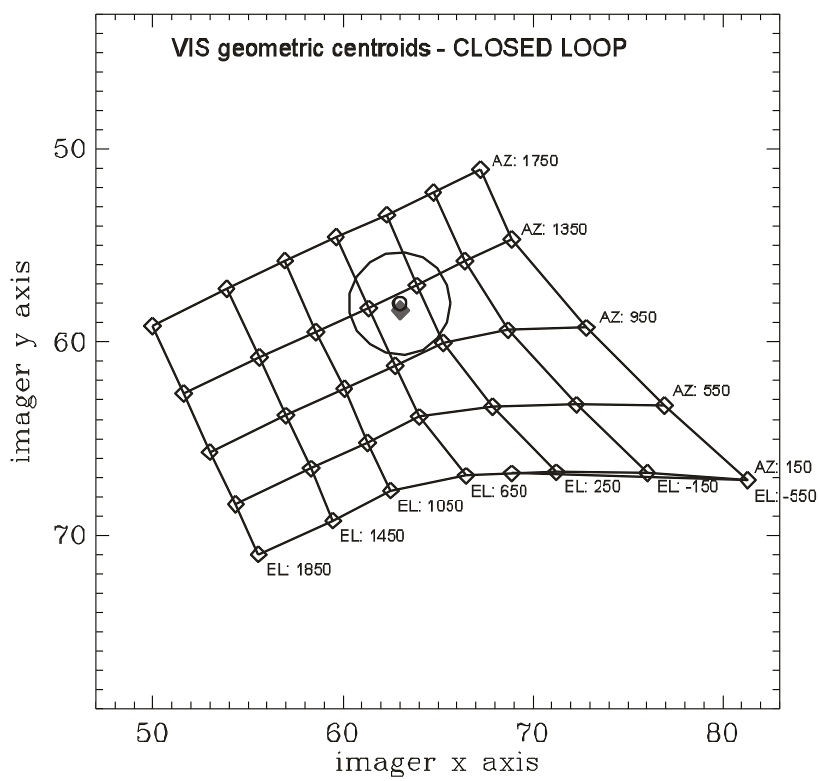

Figure 1: Results of suntracker stepsize test. The diamonds show the location of the Sun centre for each of the relative closed-loop offset positions. The small circle is the centre of the FTS FOV as determined during the Calibration Test Campaign and the large circle is the extent of the 1.25 mrad diameter of the FTS FOV. The solid grey diamond is the location of the Sun centre with the relative closed-loop offsets determined in this test.

To make this adjustment, the step size of the suntracker relative closed-loop offsets had to be characterized. This was not completed during the pre-launch Calibration Test Campaign because there were problems finding radiation sources of suitable uniformity and stability to accurately test the suntracker in closed-loop mode.

Because of these difficulties, closed-loop mode pointing was not used extensively during the ground-based calibration and testing. Since the Sun provides a uniform radiation source, the characterization was deferred until after-launch. Preliminary on-orbit data were obtained by ABB during the ACE-FTS instrument functional testing. They investigated the range of relative closed-loop offsets which could be used reliably without inducing unstable performance in the suntracker. However, they applied these offsets to only the elevation or azimuth individually and not to both at the same time.

The science commissioning tests investigated the relative closed-loop pointing offsets in both axes in order to understand the interdependencies and to determine the azimuth and elevation step-sizes for the offsets. The results from this test for the VIS imager are shown in Figure 1. The average step sizes for both elevation and azimuth are 0.0023 mrad and 0.0024 mrad for the VIS and NIR imagers, respectively. However, it can be seen that the step sizes are not uniform over the range of pointing positions. A more reliable way of determining the appropriate relative closed-loop offsets is to plot the results and use graphical analysis. The relative closed-loop pointing offsets were determined in this manner using the FTS and MAESTRO FOV positions determined in the Calibration Test Campaign. The Sun centroid position with the determined offsets is shown in Figure 1 as a solid grey diamond. This location appears slightly offset from the centre of the FTS FOV because there was a small difference in the best location as determined from the VIS and NIR imagers.

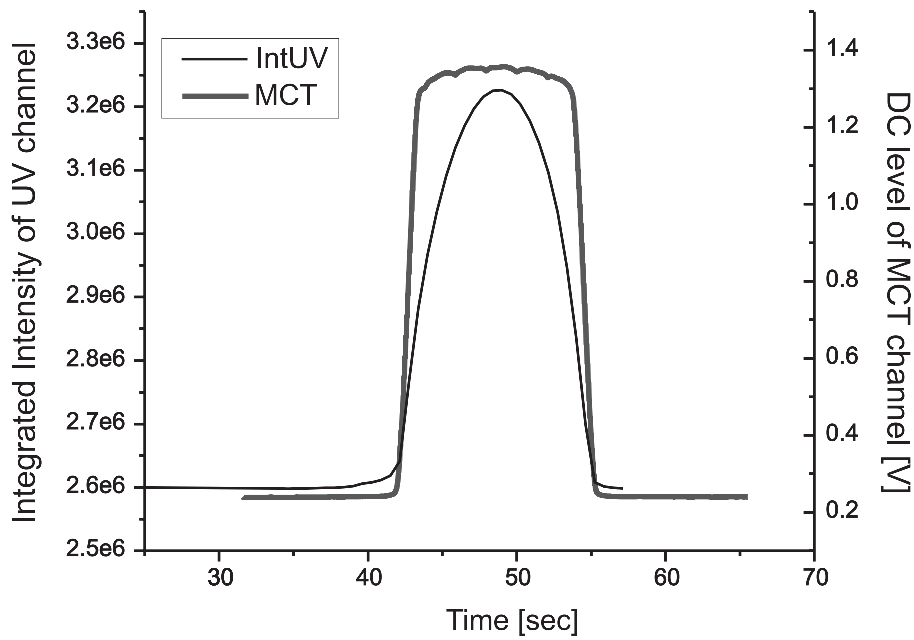

Figure 2: Results of sunscan in elevation February 21, 2004. The FTS FOV position was monitored using the DC level of the MCT detector. The position of the MAESTRO UV spectrometer slit was determined using the integrated intensity from the UV channel. This was also repeated for VIS spectrometer.

Once the relative closed-loop offsets required to point the instruments at the Sun centre had been determined, additional tests were done to verify the location of the FOVs. The sunscan mode was used to move the image of the Sun across the instrument FOVs in either elevation or azimuth starting from the Sun centre while data was recorded by FTS, MAESTRO and the imagers. Elevation scans were also made at two intervals along the MAESTRO slit (offset by ±0.5 degrees in azimuth from the Sun centre). The results for an elevation scan are shown in Figure 2. The response of the FTS was monitored using the DC level from the MCT detector and that of MAESTRO was obtained by integrating the signal from each of the spectrometer channels. The effects of solar limb darkening can be seen in both traces. From the results, the positions of the FTS FOV and the MAESTRO slits were determined on each imager array and the locations are shown in Figure 3. It appears that the current elevation offset is reasonable for both instruments. However the elevation sunscans offset in azimuth and the azimuth sunscans have verified that the MAESTRO UV spectrometer slit does not quite span the entire

Sun. Analyses and discussions are on-going to determine what further adjustments should be made to the relative offsets and weigh the benefits and impacts for each of the ACE instruments.

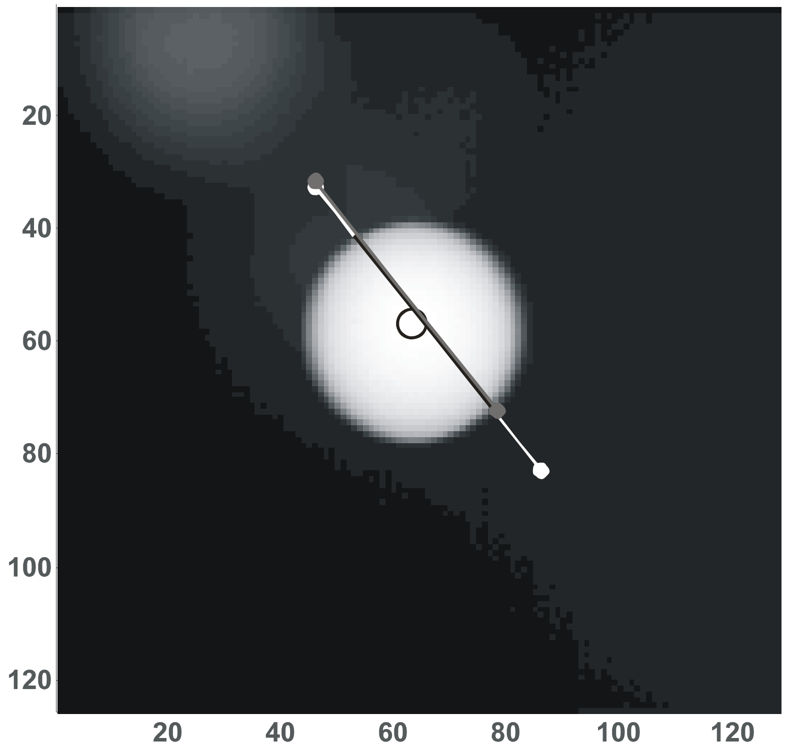

Figure 3: Image from VIS imager showing location of FTS FOV (black circle) and MAESTRO UV spectrometer slit (grey trace) and VIS spectrometer slit (white/black trace) with relative closed-loop pointing offsets implemented.

4. OCCULTATION COMMAND SEQUENCES

Throughout the science commissioning phase, occultation measurements were taken as frequently as possible. Initially, only sunset occultations were recorded because spacecraft pointing, when coming out of eclipse, was insufficient for the suntracker to reliably find the Sun at sunrise. An on-orbit calibration of the magnetometers used for attitude determination was done by the SciSat-1 Satellite Operations team and Bristol Aerospace. The implementation of this calibration data significantly improved spacecraft pointing at sunrise and now both sunrise and sunset occultations are measured routinely (since May 2004).

The occultation command sequences were refined throughout the science commissioning phase to improve performance. For each occultation, three "sets" of measurements are required for both the FTS and MAESTRO. For each instrument, a set of exo-atmospheric data is averaged and used to calculated transmission spectra for each in the series of atmospheric measurements (typical altitude range 15 – 100 km tangent height). A set of self-emission calibration spectra, taken with the suntracker mirror pointed away from the Sun towards deep space, is needed for the FTS to remove contributions from instrument self-emission. This is required to achieve 1% transmission accuracy for the FTS results. MAESTRO uses the period during eclipse, immediately preceding or following the occultation, to make calibration measurements to characterize the instrument dark current.

In the initial command sequences, the deep space measurement was taken between the exo-atmospheric and the atmospheric observations. It was found that there was too large a temperature difference in the FTS field stop

temperature between the measurements (one of the main sources of instrument self emission). Therefore the deep space measurement was moved so that the atmospheric and exo-atmospheric measurements were contiguous and the deep space measurement either proceeded or followed. Also the atmospheric part of the measurement was extended to include to altitude region from the ground to 150 km to ensure that the entire occultation sequence was measured.

5. SECONDARY SCIENCE MODES

The primary operation mode for the SciScat-1 instruments is solar occultation. However, each of the ACE instruments has a near-nadir secondary science measurement mode which will be used as often as the observing schedule permits. The FTS can make near-nadir measurements during eclipse using the Earth as the source of radiance and during the sunlit part of the orbit MAESTRO can make measurements using backscattered solar radiation. The primary objective of the secondary science mode tests was to optimise the command sequences and instrument parameters required for each measurement. These measurements were taken in April and May, 2004.

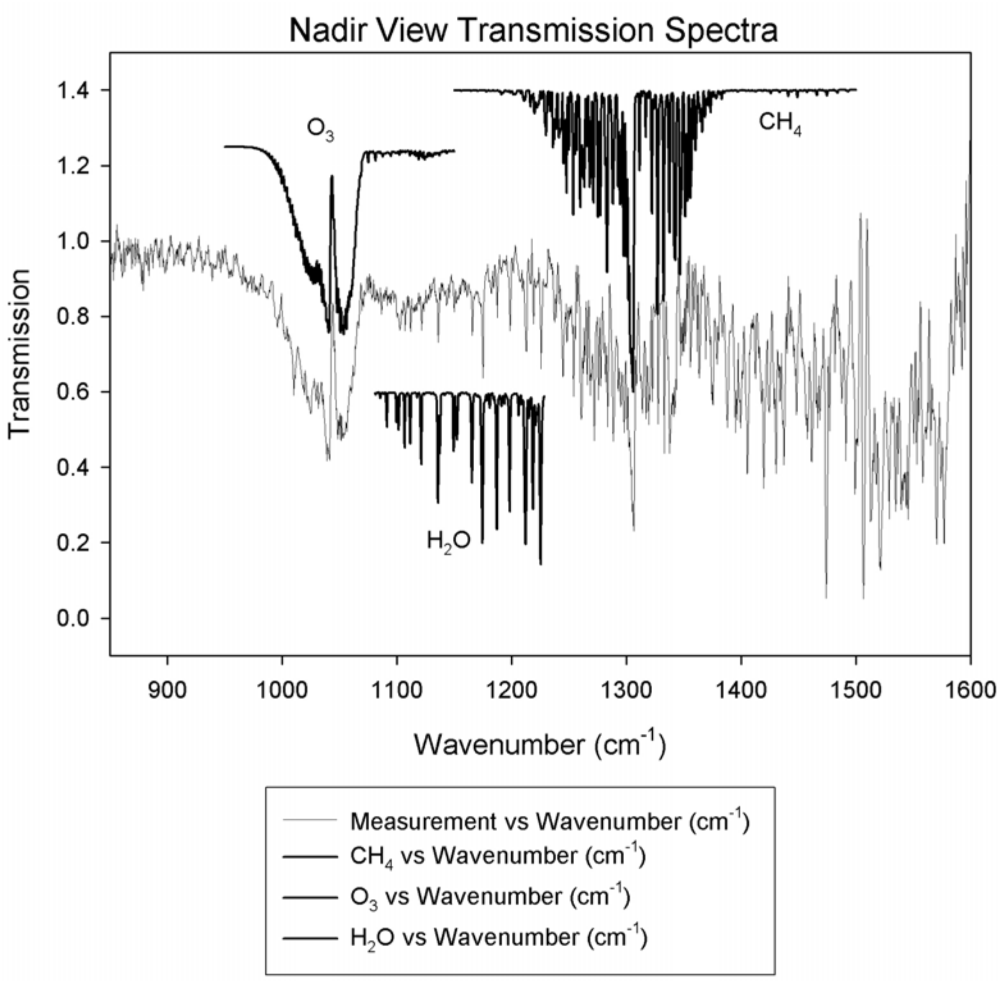

Figure 4: Downward viewing nadir spectra taken with FTS over South America on May 6, 2004. Several hundred spectra were taken in a low resolution rapid scan mode and then co-added to obtain this spectrum. The internal blackbody spectrum has been compensated for to obtain this transmission spectrum. Model spectra for ozone, methane and water vapour are shown for comparison. Column amounts of these gases can be obtained from the nadir spectra.

For the FTS nadir measurements, a command sequence was developed during the Calibration Test Campaign and was adapted for on-orbit operations. These calibration experiments yielded some promising results which reported at this meeting last year[4]. In a typical nadir measurement, the FTS rapidly measures sets of low resolution (0.4 cm^{-1}) scans (100 scans in ~18 s). In addition to the measurements during eclipse, deep space and exo-atmospheric calibration scans, at the same resolution, are made on the sunlit side of the orbit either preceding or following the eclipse event.

The results of a preliminary nadir measurement over South America are shown in Figure 4. All of the observations for a single nadir measurement period (~10 sets of 100 low resolution scans) were coadded. The "transmission" spectrum was obtained by ratioing the co-added nadir spectra with the deep space calibration results. For comparison, calculated spectra for ozone, methane and water vapour were obtained from a radiative transfer model (LBL RTM) and these are also given in Figure 4. These compare reasonably well with the "transmission" spectrum and show that this technique will be a feasible secondary science mode for the FTS.

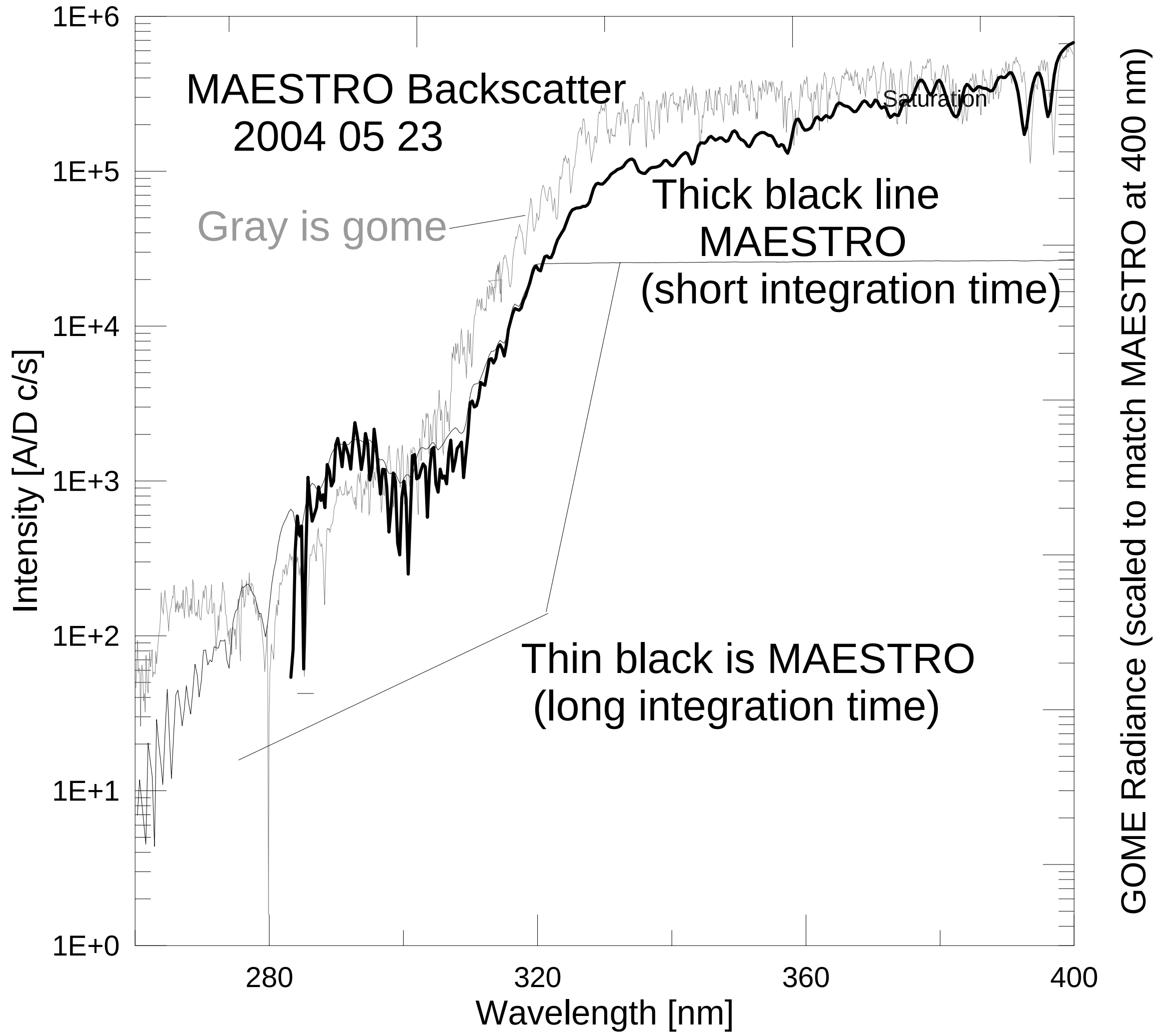

Figure 5: Solar backscatter measurements from MAESTRO UV spectrometer. The results from two different integration times are displayed. The long integration time saturated the detector above 320 nm.

Preliminary backscatter measurements have been made with the MAESTRO instrument to determine the appropriate instrument settings and command procedures. For these measurements, the suntracker mirror has

to be pointed away from the Sun toward deep space so that the radiation entering the spectrometers from the near-nadir looking backscatter ports can be measured. Dark current calibration measurements are made during the preceding or following eclipse period. Results from the preliminary backscatter measurements are shown in Figure 5. A range of integration times was used for the backscatter measurements to allow the integration time to be better tuned to suit the on-orbit conditions. The results for a longer and a shorter time are shown in the figure along with results from the downward looking GOME satellite instrument. The GOME results were chosen as a reasonable match to the MAESTRO measurements. The comparison of both solar and atmospheric features between the two instruments is reasonable. With the integration time fine tuning completed, the backscatter measurements by the MAESTRO instrument will provide valuable secondary science opportunities.

6. CONCLUDING REMARKS

A series of science-oriented commissioning activities were undertaken in January and February 2004 to prepare for the operational phase of the SciSat-1 mission. The command sequences to control measurements by the ACE-FTS and MAESTRO instruments have been fine tuned to provide operational processes for sunrise, sunset, nadir and backscatter observations. The instrument parameters required for both occultation, near-nadir and exo-atmospheric calibration measurements have been determined. The relative closed-loop offsets required to adjust the pointing of the suntracker have been characterized and the offsets necessary to point the FTS and MAESTRO FOVs at the Sun centre have been determined. The suntracker sunscan mode has been used to determine the location of the instrument FOVs on-orbit. The results from the tests of the secondary science modes (nadir for FTS and backscatter for MAESTRO) show promise for producing interesting science results during the ACE mission.

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