EOS-Aura Ozone Monitoring Instrument in-flight performance and calibration

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ABSTRACT

In-flight performance and calibration results of the Ozone Monitoring Instrument OMI, successfully launched on 15 July 2004 on the EOS-AURA satellite, are presented and discussed. The radiometric calibration in comparison to the high-resolution solar irradiance spectrum from the literature convolved with the measured spectral slit function is presented. A correction algorithm for spectral shifts originating from inhomogeneous ground scenes (e.g. clouds) is discussed. Radiometric features originating from the on-board reflection diffusers are discussed, as well as the accuracy of the calibration of the instrument's viewing properties. It is shown that the in-flight performance of both CCD detectors shows evidence of particle hits by trapped high-energetic protons, which results in increased dark currents and increase in the Random Telegraph Signal (RTS) behaviour.

Keywords: calibration, remote sensing, charge coupled devices, ultraviolet spectroscopy.

1. INTRODUCTION

The Ozone Monitoring Instrument (OMI) was launched on 15 July 2004 on NASA’s EOS AURA satellite. The primary objective of the OMI instrument is to obtain daily global measurements of ozone and nitrogen dioxide in both the troposphere and stratosphere. The science issues addressed by the OMI mission include the recovery of the ozone layer, the depletion of ozone at the poles, tropospheric pollution and climate change.1

OMI combines a high spatial resolution and daily global coverage. In this way tropospheric trace gases can be observed with high spatial resolution and cloud-free ground pixels are more easily obtained as compared to instruments with scanning mirrors. OMI delivers absolutely calibrated spectral radiances and irradiances in the spectral range from 264-504 nm. These are used to retrieve the primary data products: ozone total column, ozone vertical profile, UV-B flux, nitrogen dioxide total column, aerosol optical thickness, cloud effective cover, cloud top pressure and the secondary data products: total column SO2, BrO, HCHO and OClO. The atmospheric constituent concentrations are retrieved from nadir observations of backscattered light from the sun on the earth’s atmosphere in the ultraviolet-visible wavelength range (264-504 nm) using both Differential Optical Absorption Spectroscopy (DOAS) algorithms and algorithms that have been used before in the TOMS instrument series. The ozone profile is obtained from strong wavelength dependence of the absorption cross-section between 270 and 330 nm.

OMI follows in the footsteps of predecessor instruments like the Global Ozone Monitoring Instrument (GOME) on ERS-2, the Scanning Imaging Absorption Spectrometer for Atmospheric CartographHY (SCIAMACHY) on ENVISAT, TOMS and Solar Backscatter UltraViolet (SBUV), but OMI features a number of important improvements over these earlier generation instruments. The combination of a unique telescope design and the use of two-dimensional frame transfer CCD detectors provides a 115 degrees large field-of-view perpendicular to the flight direction. This yields a 2600 km wide ground swath that is wide enough to achieve daily global coverage of the earth’s atmosphere at the equator at a resolution of 13x24 km² (flight direction x swath direction) in nadir. By employing a two-dimensional CCD the spectrum of every ground pixel is recorded simultaneously. In one CCD dimension the spectrum is recorded, while the viewing direction is recorded in the other dimension. The use of a polarisation scrambler ensures that the instrument is insensitive to the polarisation of the incident light, which improves the accuracy of the radiometric calibration. A new type of quartz volume reflection diffuser designed for OMI considerably reduces spatial and spectral features in the measured solar spectra.
The entrance aperture, which is only about 9 mm² in area in order to suppress spatial stray light, does not limit the entrance slit (40 mm long, 300 µm wide). The telescope is f/15 in the flight direction and f/11 in the swath direction. A layout of the OMI optical bench depicting the telescope and the UV optical channel is presented in figure 1 (visible optical bench is 264 K and the temperature of the CCD detectors is stabilised to within 10 mK at a temperature of 265 K). Solar irradiance enters the instrument through the solar port, which is equipped with a 10% transmission mesh, to illuminate one of three reflection diffusers (C04, C06, C06'). The solar port is closed by a shutter when not in use to protect the on-board diffusers. A folding mirror (C03) couples the diffuser signal into the main optical path just before the polarisation scrambler. An on-board white light source (WLS) can be coupled in through a transmission diffuser C05 and the same folding mirror C03. For on-ground calibration purposes this optical path was also used by mounting external stimuli on a calibration port close to the WLS. The light reflected from one of the on-board diffusers illuminates the full length of the spectrograph slit and thereby all viewing directions (CCD rows) within the field-of-view. The entrance slit the main beam is split into two channels by dichroic mirror 009: the UV (264-383 nm) and the Visible (349-504 nm). The visible part of the spectrometer is shown in figure 2. The UV channel is separated into two sub-channels, UV1 (264-311 nm) and UV2 (307-383 nm), in order to suppress stray light at ultraviolet wavelengths and in order to compensate for the significantly lower light fluxes from the earth below 300 nm as a result of ozone absorption. Mirror 104 is segmented and has a spatially graded efficiency coating that reduces reflectance of higher wavelengths at the lower part of the mirror to reduce stray light at the low wavelengths (below 310 nm). The UV1 channel is scaled down by a factor two in both dimensions, meaning that both the spectral and spatial sampling distances are 2 times larger as compared to the UV2 sub-channel. This has been done to improve the signal-to-noise in the UV1.

The integration time of 2 seconds, consisting of co-added 0.4 s individual exposures, defines the spatial sampling in the flight direction to 13 km. The CCD detector has a frame transfer layout to allow simultaneous exposure and readout of the previous exposure, avoiding data loss during readout. In the nominal operational mode (global mode) eight CCD rows are electronically added (binned) during the readout. This decreases the contribution of the readout noise and the
internal data rate, and increases the signal to noise. This sets the ground pixel size in the swath direction to 24 km. A number of OMI instrument properties are summarised in the table 1. For in-flight calibration the OMI instrument is equipped with a number of possibilities. A set of three reflective diffusers (C04, C06, C06’”) for absolute radiometric calibration by daily measurement of the sun. Two of the three diffusers are ground aluminium diffusers, one used on a weekly basis, the other once per month to monitor the degradation of the first diffuser. The remaining diffuser is a quartz volume diffuser that is used on a daily basis. This diffuser is ground on both sides and aluminium coated on the backside. The term volume diffuser refers to the fact that the first ground surface is used as a transmission diffuser, while the second aluminium coated surface acts as a reflectance diffuser. Finally, the first surface acts once more as a transmission diffuser for the reflected beam. The thickness of the diffuser is about 6 mm. These multiple diffusive surfaces reduce the impact of surface structures. The volume diffuser was implemented, because ground aluminium diffusers exhibit wavelength dependent interference structures that affect the accuracy of the radiometric calibration and that have a detrimental impact on the DOAS retrieval of data products. As a result of its smooth surface and the multiple diffusive surfaces the spectral and spatial structures introduced by the volume diffuser are at least an order of magnitude smaller. The diffusers are well protected from contamination and solar irradiance by the solar aperture block C02 while not in use.

The white light source (WLS) C07 is used to monitor the pixel-to-pixel response non-uniformity calibration, the degradation of the detector (bad/dead pixels) and the instrument radiometric calibration, albeit with limited accuracy (about 0.5%), because the lamp, its thermal environment and the power supply have not been designed to be radiometrically stable beyond this accuracy. For the WLS the transmission diffuser C05 is used to fill the entrance slit homogeneously. Figure 3 shows the radiometric stability of the OMI instrument as measured with the WLS from launch to launch plus 500 days. No significant optical degradation can be observed in the wavelength range 270-500 nm. Two green LEDs per (sub)channel are mounted in the proximity of the CCD detector to trace bad/dead pixels. Both the WLS and LEDs can be used in flight to monitor the detector plus electronics non-linearity.

At the eclipse side of the orbit the dark signal is measured accurately by performing both long exposure time dark measurements (exposure times 22, 78 and 136 seconds) and dark signal measurements with instrument settings identical to radiance measurements at the dayside of the orbit. The latter measurements are performed with the folding mirror C03 in the position that lets the earth light pass. In addition, once per week the same measurements are performed with the folding mirror C03 in blocking position in order to study spurious light contributions in the eclipse. The spectral calibration is performed using the solar Fraunhofer lines in solar and earth spectra. More details on the optical and electronic design of the OMI instrument and on operational and 0-1 data processing aspects can be found elsewhere.2-4

Fig. 1. Layout of the optical bench of the OMI instrument: telescope + ultraviolet spectral channel. The light beam passing through dichroic mirror 009 is reflected by mirror 201 to the visible channel (figure 2).
Fig. 2. Optical layout of the OMI visible (VIS) channel.

Fig. 3. Radiometric stability of the OMI instrument in the UV1, UV2 and VIS channels as measured with the WLS from launch to launch plus 500 days.

Table 1: OMI instrument properties.

<table>
<thead>
<tr>
<th>Property</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral range</td>
<td>UV1: 264-311 nm</td>
</tr>
<tr>
<td></td>
<td>UV2: 307-383 nm</td>
</tr>
<tr>
<td></td>
<td>VIS: 349 – 504 nm</td>
</tr>
<tr>
<td>Spectral sampling</td>
<td>UV1: 0.33 nm / px</td>
</tr>
<tr>
<td></td>
<td>UV2: 0.14 nm / px</td>
</tr>
<tr>
<td></td>
<td>VIS: 0.21 nm / px</td>
</tr>
<tr>
<td>Spectral resolution (FWHM)</td>
<td>UV1: 1.9 px = 0.63 nm</td>
</tr>
</tbody>
</table>
3. **RADIOMETRIC CALIBRATION**

During the on-ground calibration of the OMI instrument the spectral slit functions as a function of wavelength and viewing direction have been calibrated accurately using a method and experimental measurement setup especially designed for OMI. Using these accurately calibrated spectral slit functions it is possible to convolve a literature high-resolution solar spectrum to OMI spectral resolution and compare the result with the irradiance as measured by OMI in flight over the quartz volume diffuser. The result of this analysis is shown in figure 4.

Any deviations from unity may be caused by:
- Errors in the OMI radiometric irradiance calibration.
- Errors in the OMI wavelength calibration.
- Errors in the determined OMI spectral slit functions.
- Errors in the high-resolution solar reference spectrum.

These four possibilities were carefully investigated and changes were made to all of the above parameters to improve the result of the comparison. Figure 4 shows that the calibration of the OMI irradiance is well understood within the expected accuracies. In the same analysis an accurate high-resolution solar reference spectrum with good radiometric calibration was obtained. This work will be continued in the future to further improve the calibration accuracies.
4. SPECTRAL CALIBRATION

The in-flight wavelength calibration for OMI is performed by use of the Fraunhofer lines in the sun and earth spectra. The results of the in-flight wavelength calibration on earth spectra along complete orbits show wavelength shifts of up to 0.5 pixel when the signal intensity changes, i.e. when the ground scene changes in the flight direction, e.g. in case of clouds. This holds particularly for the UV2 and VIS channels, but not for the UV1 channel, because for wavelengths below 305 nm the ground is not seen and scene-to-scene variability is much less. The effect can be explained in terms of partial or non-uniform filling of the spectrometer’s entrance slit in the flight direction, which is also the spectral dispersion direction. It turns out that it is possible to correct accurately for this effect, that is the main error source in the spectral calibration, by using the so-called small-pixel column data in the UV2 and VIS channel. Small pixel data, one column in the UV2 channel and one in the VIS channel, are available at a higher read-out frequency than the regular images. The correction for the observed wavelength shift makes use of the correlation that exists between the observed wavelength shifts and the gradients in the small-pixel column data. Figure 5 shows an example of this correlation in the VIS channel for an arbitrary orbit. By applying the wavelength correction for changing scenes in the 0-1 data processing the accuracy of the in-flight wavelength calibration of earth shine spectra is improved to about 0.02 px in UV1 and 0.01 px in UV2 and VIS, which is the goal accuracy for the in-flight wavelength calibration. More details about the correction to the spectral calibration for inhomogeneous ground scenes can be found in elsewhere.\textsuperscript{7}

Fig. 5. Correlation for earth shine spectra between wavelength shifts close to cloud transitions and gradients in small pixel column readouts for the VIS channel. This effect is attributed to partial slit illumination in the flight direction for inhomogeneous ground scenes and is corrected in the 0-1 data processor using correlations as shown. In the figure the correlation coefficient is 0.96, the slope is 0.92.
5. DIFFUSER SPECTRAL FEATURES

The on-board reflection diffusers that are used for the solar irradiance measurements exhibit spectral features. These spectral features are caused by interference from regular structures on the ground surface of the diffuser. Via their presence in the solar irradiance spectrum these features show up in the sun-normalised earth radiance spectrum. When the diffuser spectral features resemble the absorption features of atmospheric trace gases they affect the DOAS-based retrieval of these trace gases as the retrievals fit the absorption structures in the earth’s reflectance spectrum. DOAS retrievals are very sensitive to spectral artefacts such as diffuser features. In order not to interfere with the DOAS retrievals the diffuser features should be smaller than 0.01%. As mentioned in the instrument description, OMI has three on-board reflection diffusers for solar irradiance measurements, two ground aluminium diffusers and one quartz volume diffuser. The aluminium diffusers exhibit features with peak-peak amplitudes of several percent, which is well above the required level. The quartz volume diffuser (QVD) exhibits spectral features that are considerably smaller. For this reason the QVD is used for the daily solar irradiance measurements to provide the solar reference spectrum, that is used to calculate the earth reflectance spectrum. The QVD is a new-developed diffuser that consists of a quartz plate with two ground surfaces and the lower surface is covered with a reflective aluminium coating. Therefore light that hits the diffuser is scattered by the upper surface, travels through the quartz to be scattered and reflected by the lower surface and finally is scattered again by the upper surface and leaves the diffuser. As a result the light is scattered by three surfaces when reflecting from the diffuser, which effectively renders it a volume diffuser, and this considerably reduces the spectral features.

The diffuser spectral features are not directly visible in the solar irradiance spectrum, because these are much smaller than other spectral features like the solar Fraunhofer lines, but they can be visualised by taking the ratio of two solar irradiance measurements taken at different illumination angles. This stems from the fact that the features are caused by interference effects: their position and magnitude change with varying illumination (azimuth and elevation) angle. During a solar irradiance measurement 77 images are recorded while the elevation angle changes from –4° to +4°. By averaging the images with elevation angles between [–3°, +3°] the diffuser features are smeared and cancel to a certain extent, yielding an averaged irradiance image with smaller diffuser features. Furthermore, averaging improves the signal-to-noise of the spectrum.

As can be seen in figures 6 and 7, the spectral features of the quartz volume diffuser are about a factor 10 smaller than the spectral features generated by the aluminium diffuser. The plots were produced using in-flight measurements. Note the different vertical-axis scales for both figures.
6. GEO-LOCATION

The viewing properties of the OMI instrument were measured extensively during the on-ground calibration campaign, using a parallel with light beam entering the instrument through the nadir port. The optical stimulus produces a highly collimated beam with a $0.03^\circ$ divergence, which corresponds to 0.1 unbinned pixel. The instrument was rotated using a turn-tilt cradle to select the viewing swath angle, and by examining the signal for multiple pixel rows the pixel viewing direction was measured. Additionally the pixel field of view was measured by rotating the instrument and monitoring the response of a single CCD pixel.

Due to the fact that the turn-tilt cradle was not suitable to be used in vacuum conditions all viewing measurements were performed in ambient conditions. A number of measurements were taken to quantify the changes in viewing properties from ambient to flight representative vacuum conditions at 264 K. These results were included in the viewing properties calibration parameters. The viewing properties were validated by comparing geolocated level 1 data to known geographical features with high contrast, like coastal structures. For this purpose false colour RGB images were created from the visible channel data. An example is shown in figure 8. For the purpose of geolocation validation the instrument was operated for several days in the unbinned mode, which increases the cross track resolution at nadir approximately.
five times in comparison with the nominal binned mode. The results of these comparisons show that the geolocation in flight for various viewing angles is accurate to about 0.1 pixel, which corresponds roughly to 2 km.

7. DETECTOR DARK SIGNALS

It is well known from the literature that protons from the space environment can cause damage to the CCD detectors.\textsuperscript{8-11} In this section the CCD detector performance during the first two years in orbit is investigated. Once per day the CCD detectors are read out in unbinned mode on the eclipse side of the orbit with the folding mirror blocking the optical light path. These measurements are particularly well suited to determine dark currents of the individual (unbinned) pixels. Figure 9 shows a representative example from 24 October 2004 (black upper curve). The average dark signal is about 1700 BU, but hot pixels with higher signals can be clearly identified. A similar picture at the beginning of the mission or pre-flight shows no such hot pixels (red lower curve in figure 9). The peaks of the individual pixels originate from an increase in dark signal or dark current after the pixel was hit by a damaging particle, most likely a proton. For OMI we found that the increase in dark current can be up to a factor 10 for unbinned pixels. It must be noted that the peaks as shown in figure 9 can not be attributed to single events, such as the ones observed when the instrument passes through the South Atlantic Anomaly (SAA). In such cases increased activity is observed on the CCD images, but the increased signals disappear once the spacecraft leaves the SAA. An example of such increased temporary activity SAA behaviour is shown in figure 10. In contrast, the peaks as shown in figure 9 represent a permanent increase in dark current resulting from permanent damage to the CCD pixel in the form of lattice displacements. It must also be noted that figure 9 represents a measurement with an exposure time of 136 seconds and a gain factor of 40. For the usual exposure times of 0.5-2.0 seconds and gain factors of 1-10 used for earth and sun measurements the increase in dark signal is much less. Figure 11 shows the number of hot pixels as a function of time after launch for the image areas of the UV and VIS CCD detectors. It can be seen that the number of hot pixels increases about linearly with time and that the line extrapolates more or less through zero at launch, as expected.

Another way to visualise the changes in the CCD detector dark signal is to investigate the CCD histograms of the dark measurements. Figure 12 shows such histograms for two measurements with exposure times of 36 seconds and gain factor 40 obtained on 20 August 2004 and 5 February 2005. It can be observed that the tail of the distribution towards higher signals increases with time. This behaviour is known from and consistent with on-ground radiation testing with protons.

![Figure 9](image_url)

Fig. 9. Signal for row 300 of the UV channel on 24 October 2004 in the CCD image area (black curve). The red curve shows the same CCD row as measured prior to launch. The red curve of the pre-launch data has been given a negative offset of 700 binary units (BU) for clarity. The plot clearly shows the pixels with enhanced dark signals.
Fig. 10. Dark signal measurement with exposure time 136 seconds and gain factor 40 in South Atlantic Anomaly (SAA). The increased number of random hits and trails of particles can be observed.

Fig. 11. Number of hot pixels as a function of time after launch for the UV (blue) and VIS (red) CCD detectors.

Fig. 12. Left: Histogram of a dark signal measurement on 20 August 2004. Right: Histogram of a dark signal measurement on 5 February 2005. More pixels have moved from the main peak towards the high-end tail as compared to the figure from 20 August 2004.
Further investigation on the locations on the earth where hot pixels are mostly created reveals that most hot pixels with permanently increased dark current are created in the SAA and in the radiation belts of the earth. This suggests that trapped protons with high energies (>10 MeV) that are able to penetrate the 29 mm thick aluminium shield around the OMI CCD detectors are the main cause for the observed radiation damage. More studies on the origin, rate as a function of time and impact of the OMI CCD radiation damage are ongoing. In these studies other instruments with similar CCD detectors are also investigated (GOMOS on ENVISAT and OSIRIS on ODIN).

Proton radiation damage on CCD detectors is known from literature to cause a phenomenon known as Random Telegraph Signal or RTS.\textsuperscript{10,11} RTS in dark signal measurements manifests itself as a type of behaviour where the output of a pixel is unstable and jumps between multiple more or less stable energy levels. This is a statistical process and the time constants of such jumps can vary per pixel. The exact times when an energy transition will occur can not be predicted. It is known from the literature that the time constants between jumps become longer when the CCD temperature is lowered. This behaviour has been confirmed on proton irradiated CCD samples before launch for the OMI instrument. For OMI we found that nearly all pixels that have been hit by one or more protons show RTS behaviour. However, the magnitude of the RTS behaviour can vary strongly from pixel to pixel. From inspection of the pixels with increased dark current it is estimated that about 95 percent of these pixels can still be used for useful scientific measurements, because the dark current and/or noise and/or RTS behaviour shows large variations in time.

Pixels that are hit by protons thus show an increase in dark current by a factor of up to 10 and less or more serious RTS behaviour. However, such hot pixels can still be used for useful scientific measurements if earth shine spectra are corrected for dark signal with measurements that are obtained close in time to the light measurement, i.e. when the dark signal correction is sufficiently dynamic to correct for the permanent increase in dark current in a CCD pixel after a proton hit. The accuracy of such a dynamic dark signal correction scheme is influenced by the magnitude of the Random Telegraph Signal (RTS) behaviour of the pixels. In order to properly appreciate the impact of the CCD pixel proton radiation damage manifested by the increased dark current and RTS behaviour one must realise that the results shown so far have been obtained with measurements with exposure times of 136 seconds and gain factor 40. Typical earth-shine and sun measurements are performed with exposure times of 0.5-1.0 seconds and gain factors of 4 or 10, i.e. the impact of the proton damage on actual earth or sun measurements is typically three orders of magnitude smaller as discussed above. Furthermore, the earth and sun measurements are performed with electronic binning factor 4 or 8, whereas the long dark measurements shown above have been performed with binning factor 1. So even when the proton radiation damage on the CCD detectors is a compromising factor for the quality of the earth and sun measurements and the exact impact of the damage must be continuously monitored, the impact on the OMI science data is not as severe as might have been suggested by the results shown in this section, which present extreme cases obtained with extreme measurement settings that are not at all representative for the regular OMI science measurements. The pixel-dependent varying dark currents of the CCD detectors can be properly dealt with using a dynamic dark signal correction scheme that is able to use the appropriate dark signal measurements close in time to the earth and sun measurements.

8. CONCLUSIONS

A number of in-flight performance and calibration results of the Ozone Monitoring Instrument OMI, launched on 15 July 2004 on the EOS-AURA satellite, have been presented and discussed. The radiometric calibration in comparison to the high-resolution solar irradiance spectrum from the literature convolved with the measured spectral slit function was discussed. The correction algorithm to correct for spectral shifts originating from inhomogeneous ground scenes (e.g. clouds) was presented and it was shown that the accuracy of the in-flight spectral calibration is 0.02 pixel for the UV1 channel and 0.01 pixel for the UV2 and VIS channels. Radiometric features originating from the on-board reflection diffusers were presented and discussed and it was shown that the solar spectra measured over the on-board quartz volume diffuser have spectral features that are at least an order of magnitude smaller in amplitude than for the on-board aluminium diffusers. The accuracy of the calibration of the viewing properties was shown to be about 2 km. The in-flight performance of both CCD detectors shows evidence of particle hits by trapped high-energetic protons, which results in increased dark currents and increase in the Random Telegraph Signal (RTS) behaviour. The resulting detector performance changes can be sufficiently corrected for by using a dynamical dark signal correction scheme.
REFERENCES


