From OMI and SCIAMACHY to TROPOMI: recent improvements in sun backscatter atmospheric composition measurements

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Introduction

This paper describes similarities and developments in recent UV-SWIR trace gas spectrographs. The spectrographs considered are SCIAMACHY on ENVISAT (conceptually similar to its smaller offspring GOME on ERS-2), OMI on EOS-AURA and TROPOMI on TRAQ. SCIAMACHY is currently already 5 years in orbit and OMI is in orbit since 2004. TROPOMI is part of the TRAQ proposal to ESA for the next Earth Explorer Core Mission. TRAQ is currently one of the 6 candidates for this mission.

Starting with SCIAMACHY or GOME, instruments were brought in orbit measuring continuous spectra from UV to NIR (GOME) or SWIR (SCIAMACHY) with sufficient spectral resolution to retrieve the trace gases absorbing in these wavelengths. This is different from e.g. the older US TOMS instrument where a small number of separated wavelengths were measured which were carefully selected to have the UV absorbers.

SCIAMACHY is by far the most elaborate instrument in the sense that it has the longest wavelength range (240 to 2400 nm) and that it allows both nadir and limb viewing. In nominal operation it switches between nadir and limb to observe the same air masses from the two directions. This allows to perform the trace gas cartography from the name of SCIAMACHY (Scanning Imaging Absorption SpectroMeter for Atmospheric CartographY). This 'cartography' however is limited to the tropopause and higher as limb viewing is only possible for these altitudes, because of absorption and scattering in the long light path.

In the nadir viewing geometry it is in general possible to view down to the Earth surface and there is even a significant sensitivity to the boundary layer. This allows to use the technique also for air quality research, next to climate and ozone layer.

SCIAMACHY and GOME are however not optimised for air quality in view of their rather coarse ground pixels (GOME has nominally 320 x 40 km^2 and SCIAMACHY 120 x 30 km^2) and the global repeat cycle of 3 or 6 days. OMI is a big step forward in this sense with its ground pixels of nominally 13 x 24 km^2 and its coverage of the complete globe in 1 day. The smaller ground pixel has the obvious advantage of more detailed observation of sources and sinks of pollutants but it also significantly increases the fraction of cloudfree pixels (see Fig. 1, copied from ref. 1).

Other than SCIAMACHY and GOME, which have linear detector arrays and use a scanner for across-track imaging, OMI is a staring pushbroom instrument without scanner. It uses two dimensional detectors where one dimension is used for the spectrum and the other for the across-track imaging.

TROPOMI intends to have the best of the heritages of SCIAMACHY and OMI. It has OMI's wavelength range (270 to 500 nm) combined with SCIAMACHY channels (O_2A band and SWIR up to 2.4 μm). It continues OMI's daily global coverage but with even further reduced ground pixels of 10 x 10 km^2. TROPOMI will continue using OMI's staring concept with two-dimensional detectors, which is essentially required to obtain the quoted performances.
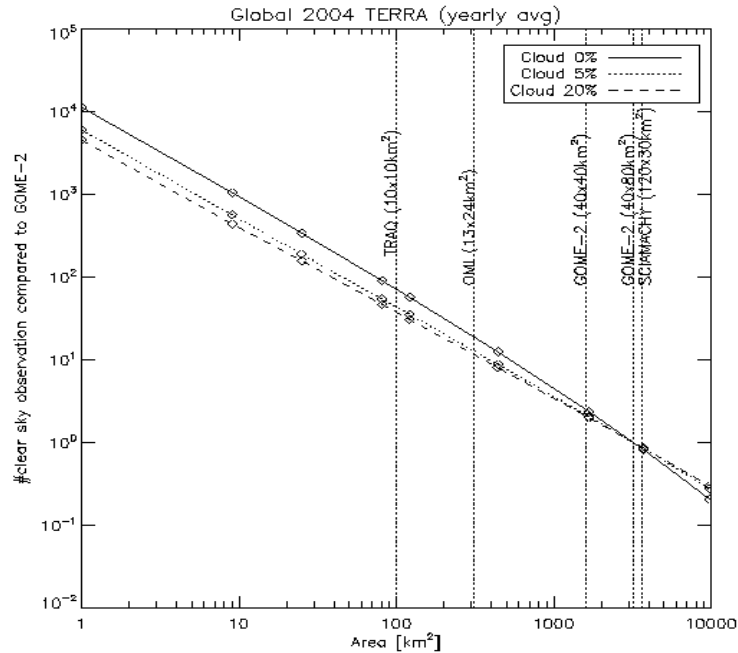
Fig. 1 Relative number of global cloud free pixels as a function of the ground pixel area, for various missions / instruments; there are three curves for different fractions of 'cloud free' [1]

### Similarities between SCIAMACHY, OMI and TROPOMI

SCIAMACHY, OMI and TROPOMI obviously use the same type of spectroscopy. This results in very similar requirements for e.g. signal-to-noise, spectral resolution. Signal-to-noises are typically in the order of 1000 - 2000 and spectral resolutions 0.2 to 0.5 nm. These are needed to retrieve with sufficient accuracy the minor trace gases, i.e. trace gases with absorptions in the order of a percent or lower. An improvement aimed for with TROPOMI is to have the signal-to-noises also in the case of very dark scenes (albedo 2 %). This makes the signal-to-noise requirements of 1000 - 2000 much more demanding for TROPOMI.

As explained in the introduction, the spectral bands are different between the instruments. However, this is not an essential difference but a means to select the wanted trace gas products or obtain supporting information (e.g. TROPOMI has the O_2A band to have improved cloud and aerosol information as compared to OMI).

An overview of the spectral ranges is given Fig. 2.

The other important similarities are in applying in-orbit sun diffuser measurements for calibration. This is in fact the obvious means for radiometric calibration since the older US ozone instruments TOMS and SBUV. The main development is that for the more recent instruments it became clear that diffuser plates introduce speckle-type features in the sun spectrum. These are very significant for the conventional aluminum diffusers and are reduced in the more modern instruments by a combination of diffuser design (QVD or quasi volume diffusers are used), optics design and using the motion of the satellite relative to the sun to average the features out.

The same sun measurements are used for spectral calibration. That is, SCIAMACHY does have a spectral line source on board, but it turns out that using the Frauenhofer structures in the sun's spectrum allows a more accurate spectral calibration. Therefore OMI does not have such a lamp and also TROPOMI will not have a line lamp.
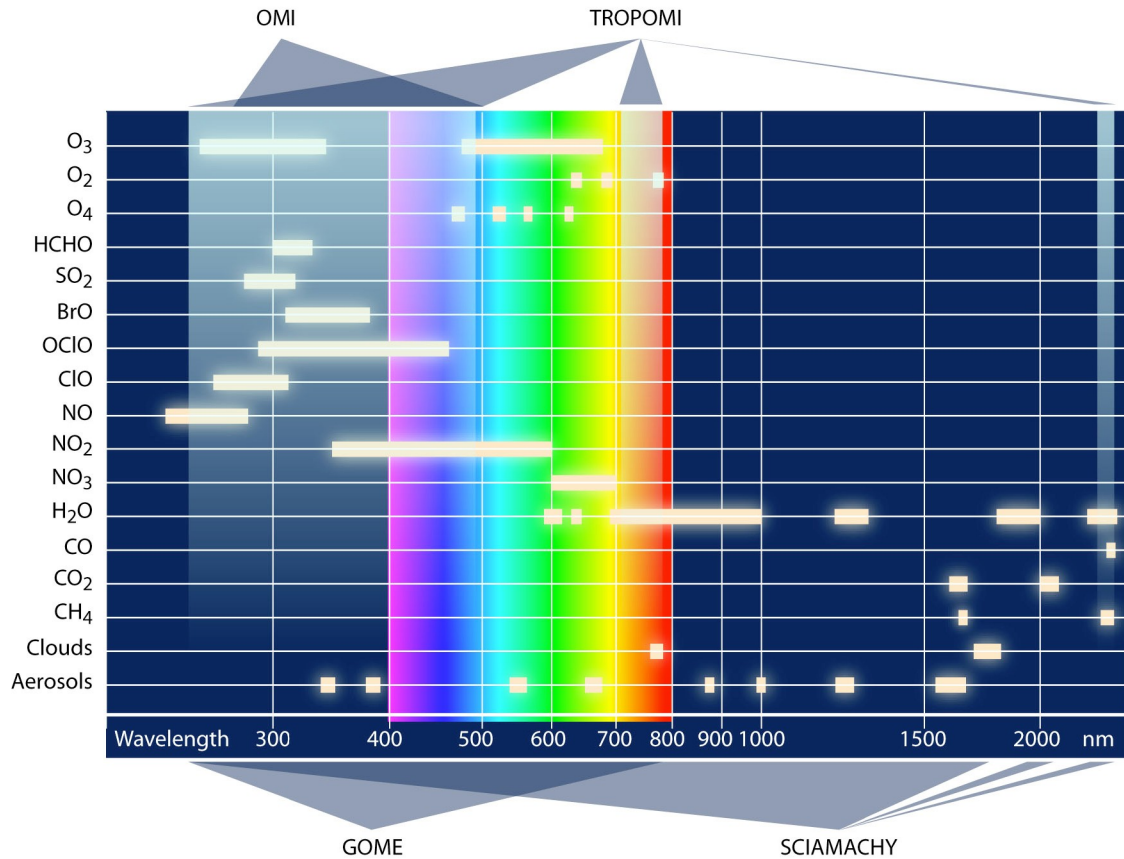
Fig. 2 Overview of spectral ranges and trace gas products from SCIAMACHY, GOME, OMI and TROPOMI.

Instrument hardware concepts

A very obvious difference between SCIAMACHY and OMI / TROPOMI, is the fact that the first is a scanning instrument (whiskbroom) whereas the latter are staring instruments using the second dimension of the detector to image the across flight swath.

For SCIAMACHY, using a whiskbroom concept was a obvious choice using the following arguments.

- SCIAMACHY allows both nadir and limb viewing and this is virtually impossible with a staring design, even if the design can switch between separate limb and nadir ports.
- For the SCIAMACHY SWIR, new InGaAs linear detector arrays were developed; it would have been one step too far to require two-dimensional SWIR detectors in that time (around 1988)
- SCIAMACHY is an exploring instrument without very stringent requirements on ground pixel size and revisit time

The OMI conceptual design was both a few years later (starting in 1994), the OMI was limited from the start to the UV-Visible wavelengths and we díd have requirements on ground pixel size and revisit time.

For OMI, the trade-off between whiskbroom and push broom was therefore different. It starts with the signal-to-noise argument because the pushbroom measures all ground pixels in the swath in

parallel whereas the whiskbroom has to distribute the satellite travel time over all pixels in the swath. In short, the available exposure times are as follows.

$$\text{Pushbroom: } t_{exp} = t_{flight}$$

$$\text{Whiskbroom: } t_{exp} = t_{flight} / N$$

Where
t_{exp}	exposure time per ground pixel
t_{flight}	satellite travel time for one ground pixel
N	number of ground pixels in the swath

The equations show that the pushbroom has a large advantage in case of a larger amount of ground pixels in the swath. For SCIAMACHY (and GOME) there are three ground pixels in the swath (of 320 km in a swath of 960 km). For OMI there are 60 ground pixels of 24 km in the swath of 2700 km and TROPOMI will have 140 ground pixels in the saem swath of 2700 km.

However, there is also a considerable difference in the design of the telescope and this results in significantly larger aperture for the whiskbroom as compared to the pushbroom, for SCIAMACHY this is 1.5 cm^2 whereas OMI has 0.045 cm^2. This clearly means that the whiskbroom has better signla-to-noises if the amount of ground pixels in the swath is not too large.

The situation is summarised in Fig 3 where the square root of the product of the aperture and exposure time is plotted as a function of the number of ground pixels in the swath. This value is proportional to the shot noise limited signal-to-noise for both instrument concepts and very representative for the signal-to-noise including all effects. The conclusion is that for a larger number of ground pixels in the swath, the pushbroom has better signal-to-noises. This is equivalent to the combination of small ground pixels and short revisit time because of the wide swath required for short revisit times.
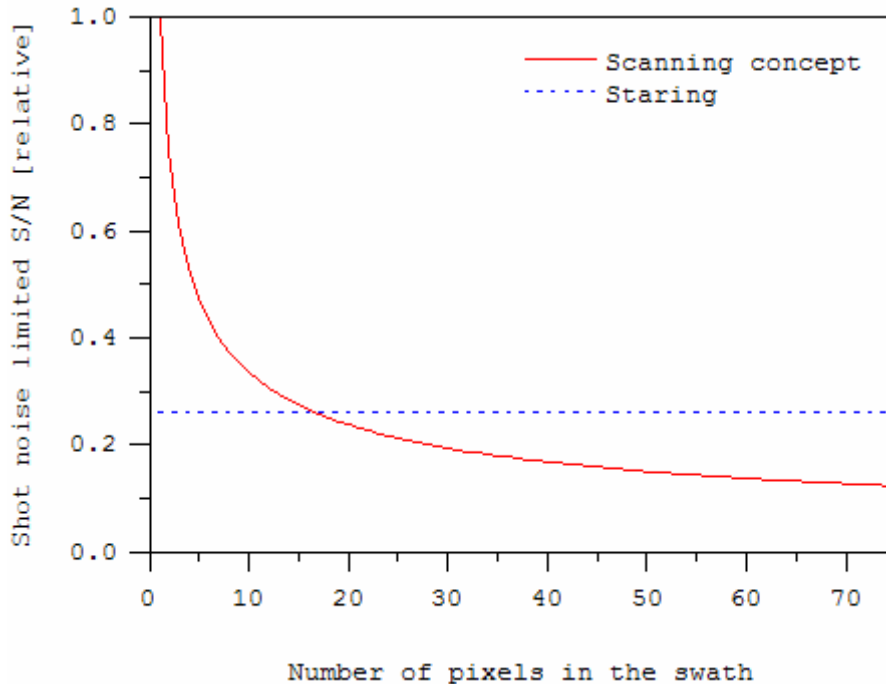
Fig. 3 Relative signal-to-noise as a function of the number of ground pixels in the swath, for both the whiskbroom (scanning concept) and the pushbroom (staring concept). It shows that for the combination of small ground pixel and wide swath / global coverage, the pushbroom has better signal-to-noises.

Another important difference between SCIAMACHY and OMI/TROPOMI is the fact that SCIAMACHY has its PMD's (Polarisation Measurement Devices) whereas OMI/TROPOMI have their polarization scrambler to make the instrument insensitive to polarization.

The SCIAMACHY PMD's allow a reduced spectral resolution measurement of polarization, next to the main spectral channels. The PMD's are in principle useful because they allow e.g. an improved aerosol product because of the polarization information. Also, because of the reduced spectral resolution, the spatial resolution of the PMD's is better as compared to the main spectrometer channels and this is useful for e.g. an improved cloud product.

On the other hand, the polarization sensitivity of SCIAMACHY requires the radiometric correction in SCIAMACHY's Level 0-1b processor to include the data and that turned out to be a significant complexity driver. This is also because the scanner mirror impacts SCIAMACHY's polarization sensitivity and results in complex correction algorithms.

On the other hand, OMI, with its smaller telescope aperture, allows to have a small polarization scrambler close to this aperture which virtually removes all instrument polarization sensitivity. The design of this scrambler is critical because it introduces tiny spectral and spatial features but once the scrambler is there, there is an important advantage for the on-ground calibration and the radiometric correction in the 0-1b processor.

Having polarization scrambler is continued for TROPOMI.

Conclusion

We have seen gradual development from SCIAMACHY/GOME towards OMI and TROPOMI where in principle the spectroscopy is continued and where conceptual change in the instrument designs allow for smaller ground pixels and shorter revisit times.
This is important as it makes the satellite data more useful for both climate research and air quality monitoring because there is better visibility of sinks and sources of trace gases and also, due to reduced number of partly clouded pixels, the amount of useful data is greatly improved. TROPOMI is the next step in this succesful series of instruments.

REFERENCES

[1]   Krijger, van Weele, Aben and Frey, "Technical note : the effect of sensor resolution on the number of cloud-free observations from space", Atmospheric Chemistry and Physics, 7, 2881-2891 (2007)