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COMPARISON OF ABSORBING AEROSOL INDEX PRODUCTS FROM GOME-2 AND SCIAMACHY

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Abstract

In this paper we present validation results obtained from a direct comparison between the Absorbing Aerosol Index (AAI) measured by GOME-2 (on MetOp-A) and SCIAMACHY (on Envisat) at roughly the same time and place. Because of the slightly different orbital periods, such an intercomparison is not possible for all days of the year. However, for many days on which intercomparison is possible, the orbit tracks overlap completely, ensuring that the scattering geometries (that is, the viewing and solar angles) are nearly identical, which increases the of accuracy and the credibility of the intercomparison. The agreement between the two AAI products is found to be quite good, with systematic differences of less than 0.1 index points over the entire overlapping time range (2007–2012).

DESCRIPTION OF GOME-2

The spectrometer GOME-2 (the 2nd Global Ozone Monitoring Experiment) (Callies et al., 2000) was launched on 19 October 2006 onboard the MetOp-A satellite. The MetOp-A satellite was brought in a polar sun-synchronous orbit at an altitude of about 800 km, with a local crossing time of the equator of 9:30 a.m. for the descending node. MetOp-A was launched as the first satellite in a series of three Meteorological Operational (MetOp) satellites. The second satellite platform, MetOp-B, was launched successfully in September 2012, and placed in the same orbit as MetOp-A but with a head start of 50 minutes (half an orbit) on MetOp-A. The third MetOp satellite, MetOp-C, is scheduled to be launched in 2017. All three MetOp satellites host or will host identical versions of the GOME-2 instrument.

GOME-2, like its predecessor GOME (in this paper also called GOME-1 for clarity) on the ERS-2 satellite (Burrows et al., 1999), measures the sunlight reflected by Earth in the wavelength range between about 240 and 790 nm, with a spectral resolution (FWHM) ranging from 0.2 nm in the UV to 0.4 nm in the NIR. The instrument scans the Earth from east to west in 4.5 s and back in 1.5 s by rotating an internal scanner mirror. The orbit swath sensed this way is 1920 km wide. The typical measurement footprint in the forward scan is 80 km × 40 km (across track × along track). Global coverage is achieved in 1.5 days. Since 15 July 2013 the orbit swath has been reduced to 960 km, leading to a measurement footprint of 40 km × 40 km and global coverage in three consecutive days.

DESCRIPTION OF SCIAMACHY

The SCIAMACHY (Scanning Imaging Absorption Spectrometer for Atmospheric Chartography) instrument (Bovensmann et al., 1999) was launched on 1 March 2002 onboard the Envisat satellite into a near-polar, sun-synchronous orbit, with an orbital period of about 100 minutes, comparable to the MetOp-A orbit. The local crossing time of the equator is 10:00 a.m. for the descending node, so SCIAMACHY observes a certain ground scene 30 minutes after GOME-2 does. A major difference with respect to GOME-2 is that SCIAMACHY has the ability to perform not only nadir measurements, but also limb measurements. These two measurement modes are being alternated along the orbit. The resulting data are stored in blocks, called ``states''. A typical nadir state has a duration of 65 seconds and covers a geographical area of roughly 960 km × 490 km (across track × along track).

The wavelength range covered by SCIAMACHY is 240–2380 nm, with spectral resolution 0.2–1.5 nm. The scanning sequence is similar to that of GOME-2: a forward scan in 4.0 s and a fast reverse scan in 1.0 s. The swath is 960 km wide, half of that of GOME-2. Another major difference with GOME-2 is that the nadir spectrum is divided into 56 wavelength regions, called ``clusters'', that are all read out with their own integration time (IT). This allows a higher spatial resolution for the most important spectral regions, at the expense of other wavelength regions where the spectrum is of less scientific interest, or would otherwise yield a weak signal. Typical ITs are 0.25 s (pixel size 60 km × 30 km) and 0.5 s (pixel size 120 km × 30 km). Owing to the alternation of nadir and limb modes and the smaller swath, global coverage (in nadir mode) is achieved in 6 days, four times longer than the 1.5 days that are needed by the GOME-2 instrument. Contact with the Envisat satellite was lost on 8 April 2012.

INTERCOMPARISON APPROACH

Figure 1 explains the approach that was followed in a graphical way. For a given day, in this case 17 October 2007, we gather all SCIAMACHY and GOME-2 AAI orbits that are available to us. For each SCIAMACHY orbit, we determine the equator passing point (EPP). Using this information, we look for a GOME-2 orbit that has a more or less identical EPP. If this orbit exists, then we have a match. Note that, because of the different equator passing times (GOME-2: 09:30 LT ; SCIAMACHY: 10:00 LT), there is a 30-minutes time difference. Related to this, there is also a slight difference in the solar zenith angle (SZA) which goes up to 7 degrees near the equator and which may influence the results.

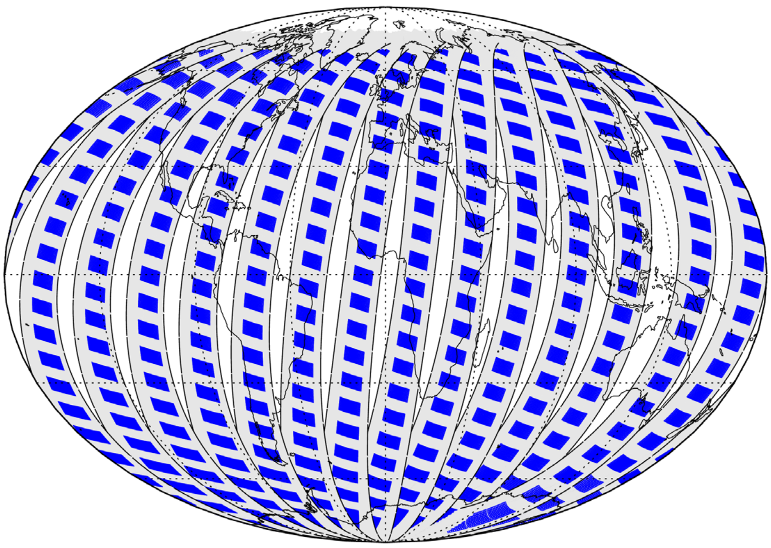

Figure 1: **Graphical explanation of the approach that was followed to compare the GOME-2 AAI's with the SCIAMACHY AAI's. The black curves indicate the GOME-2 swaths borders. The blue boxes indicate the individual SCIAMACHY footprints. The measurement footprints depicted in this figure are all taken from 17 October 2007.**

After that, we concentrate on all SCIAMACHY forward scan pixels between 70°N and 70°S that have a SZA below 80 degrees. For all the pixels in this subset, we start looking for the GOME-2 forward scan pixels that belong to it, record their residues, and take the mean if more than one are found. The result will from here on be called the ``collocated GOME-2 AAI''. We then analyse the results in scatter plots as shown in Figure 2. Here we plotted the collocated GOME-2 AAI versus the normal SCIAMACHY AAI for all collocated data of 13 July 2008. The version of the SCIAMACHY AAI data that were used is version 5.1, released on 7 June 2012. This is the most recent version available and this version has been validated extensively. The agreement we find is rather good, although there is quite some scatter around the expected one-to-one relationship. This scatter can be explained in a number of ways.

First of all, we have a 30-minutes time difference between SCIAMACHY and GOME-2, which could lead to a change in the observed scene in the case of clouds. By filtering out cloudy scenes we could indeed reduce the scatter a bit, of course at the expense of the number of available collocated data points. Secondly, there is a small difference in the solar zenith and solar azimuth angles of the collocated SCIAMACHY and GOME-2 observations. Thirdly, and most importantly, the SCIAMACHY and GOME-2 footprints do not overlap completely, so there will always be a small spatial collocation

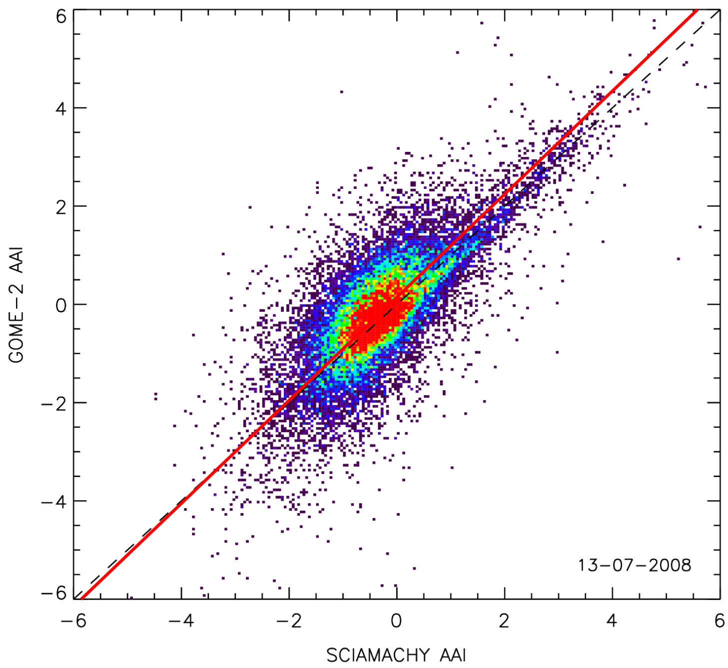

Figure 2: **The ``collocated GOME-2 AAI'' versus the SCIAMACHY AAI, for 13 July 2008. The agreement is reasonable, considering the fact that we took no effort to improve handling the spatial mismatch between the SCIAMACHY and GOME-2 footprints. The red line is a linear fit to the data, with slope close to one and intercept close to zero.**

mismatch between the SCIAMACHY and GOME-2 footprints. We took no action to improve on this, because the goal is to analyse the entire collection of data as a whole, not to improve the intercomparison of the individual ground pixels that are comprised in the comparison.

In Figure 2 we also present a red line, which represents a linear fit to the data points. Weighted fitting was not applied. Residues with values lower than −10 or higher than +10 were not trusted and were not allowed to take part in the fitting process. For the specific day shown in Figure 2, 13 July 2008, the slope was found to be 1.04 ± 0.06 and the intercept was 0.15 ± 0.05, pointing to a good agreement between the GOME-2 and SCIAMACHY AAI. Note that the SCIAMACHY AAI was found to be well calibrated w.r.t. the AAI from GOME-2's predecessor GOME-1 (Tilstra et al., 2007, 2011, 2013).

FIRST RESULTS – TIME SERIES A

The analysis described in the previous section was performed on the GOME-2/MetOp-A reprocessed AAI data set. This data set covers most of the period 2007–2015, has been processed using OPERA version 1.33 and is based on level-1 data versions 5.3 and 6.0. While processing the data set, we recorded the number of orbits for which we could successfully link the SCIAMACHY swath to GOME-2 swath. Whenever a SCIAMACHY monitoring orbit was encountered (narrow swath, nadir static, et cetera), the orbit was skipped altogether. When a GOME-2 narrow swath/nadir static orbit was encountered, this orbit was not skipped right away, but it was recorded that a narrow swath/nadir static orbit was used that day. We removed days with more than two of such orbits from the analyses.

Because of the slightly different orbital periods of SCIAMACHY and GOME-2, in general the orbit tracks of the two instruments do not overlap. Every nine days, however, the situation occurs that they do overlap, for a relatively short period of ~2 days (depending on how strict we are). For each day for which we could find SCIAMACHY and GOME-2 orbits with overlapping orbit tracks, we recorded the number of these orbits. Slope and intercept of the linear fit to the collocated AAI's, performed in the way described before, were also recorded. Figure 3 presents a time series of the calculated slopes of the linear fit as a function of time. The red circles are results which are not reliable, either because there were not enough orbit track overlaps found (say, less than 10), or because there were two or more narrow swath/nadir static orbits involved. The blue circles are the remaining, reliable results.

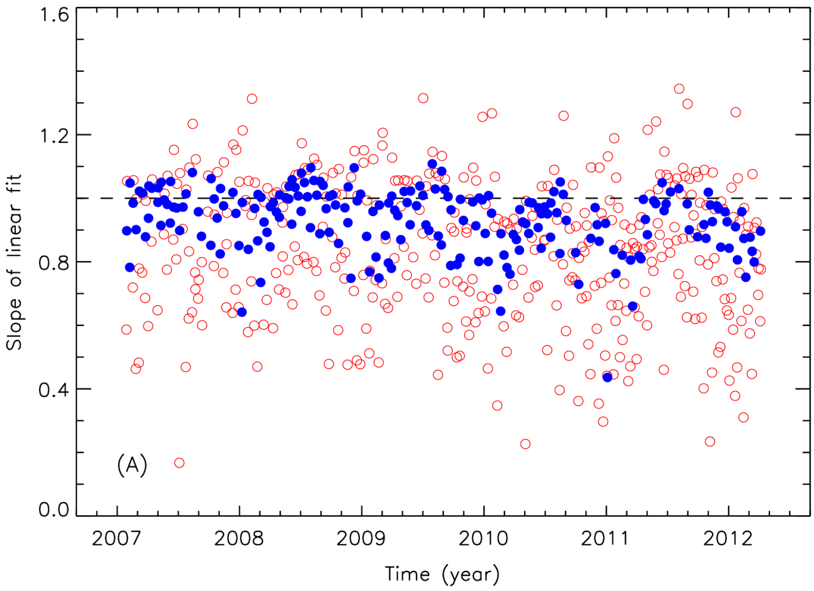

Figure 3: **Slope of the linear fits to the (GOME-2 versus SCIAMACHY) data points as a function of time. The red circles represent unreliable data points: not enough orbits with perfect orbit track overlap between SCIAMACHY and GOME-2, and/or too many GOME-2 narrow swath orbits included. The blue circles are believed to correspond to reliable data points, although some scatter is obviously also present in the blue data points.**

As can be seen, the red circles are scattered, but the blue circles are much more consistent in their behaviour. There appears to be a fair correlation between the SCIAMACHY and GOME-2 residues, with slopes in general close to one. On the other hand, there seems to be a periodic or seasonal variation hidden behind the scatter in the slopes. In Figure 4 we plotted the intercepts of the linear fits. The offset found is small and partially hidden by the noise in the data points. There does not appears to be a trend present in the time series. Such a trend, if it would exist, could be related to changes in the radiometric calibration of GOME-2 due to instrument degradation (Tilstra et al., 2010). The absence of such a trend in Figure 4 therefore adds to the credibility of the correction for instrument degradation that was developed for the GOME-2 instrument (Tilstra et al., 2012b). Note that a one index point offset can already be explained by a 2% error in the reflectance (Tilstra et al., 2012a).

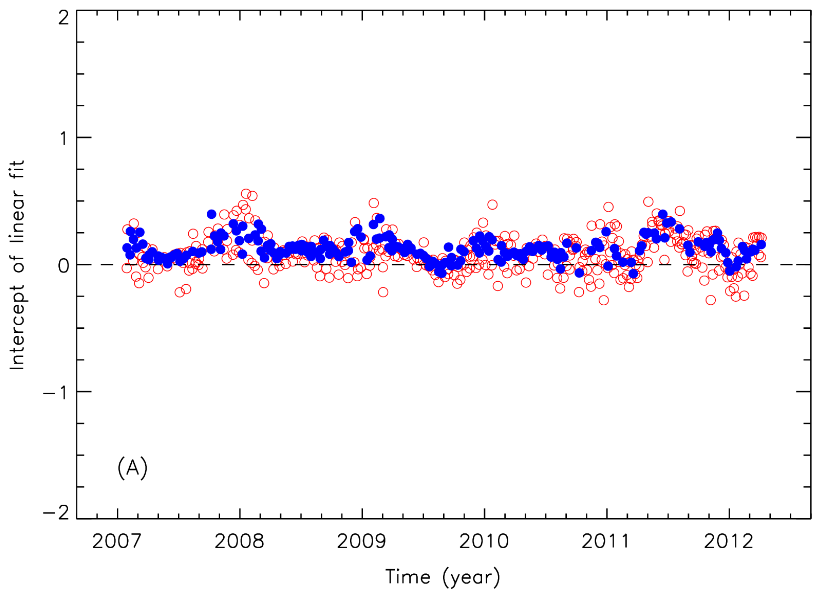

Figure 4: **Intercept of the linear fit as a function of time. The colour coding and its meaning are the same as in Figure 3. The result shows that there is no clear offset found over the studied time period.**

Looking at the time dependence present in Figures 3 and 4, we can conclude that – at least within the accuracy of the intercomparison – no clear systematic time dependence was found. This is expected for the slopes, because radiometric calibration errors only slightly affect the slopes, while they are known to strongly affect the intercepts. The intercepts also show no clear time dependence. This indicates that the GOME-2 AAI has been stable over the years covered by the analysis (2007–2012).

IMPROVING THE COMPARISON – TIME SERIES B

The statistical errors on slope and intercept, determined in the fitting procedure illustrated in Figure 2, are both on the order of 0.05. This is much less than the large variability that is actually seen in both Figures 3 and 4. The much larger errors are caused by systematic errors caused mainly by the unavoidable longitudinal misalignment between the SCIAMACHY and GOME-2 orbits. Figure 1 can be used to explain this more clearly. For the day in question, 17 October 2007, the first SCIAMACHY and GOME-2 orbits have near perfect overlap, but at the end of the day, the overlap is already quite poor. For the previous day, i.e., 16 October 2007, the situation is exactly the other way around. The best thing to do in this particular case would be to take the last ~7 orbits of 16 October 2007, and the first ~7 orbits of 17 October 2007, and to glue these together to form an artificial ``new day''. The resulting collection of orbits of this ``new day'' would have a much better average longitudinal alignment than the collection of orbits of the two original, individual days.

We therefore abandon the idea of letting each day start at 00:00:00 UTC and instead determine a careful selection of subsequent orbits for which the longitudinal misalignment, in the absolute sense, is below a certain threshold. The threshold used was 1.6 degrees in longitude which in normal situations yields between 14 and 17 contiguous orbits that fulfil this criterion. The artificial days created this way cover a time period of roughly 24 hours, i.e., the selected orbits are spread out over the entire longitude range of the globe. In Figure 5 we shows a plot of the relative longitudinal alignment for a selection of associated SCIAMACHY and GOME-2 orbits taken from 26 and 27 February 2007. All the orbits that are selected to participate in the artificial new day have an absolute relative longitudinal alignment difference less than 1.6 degrees.

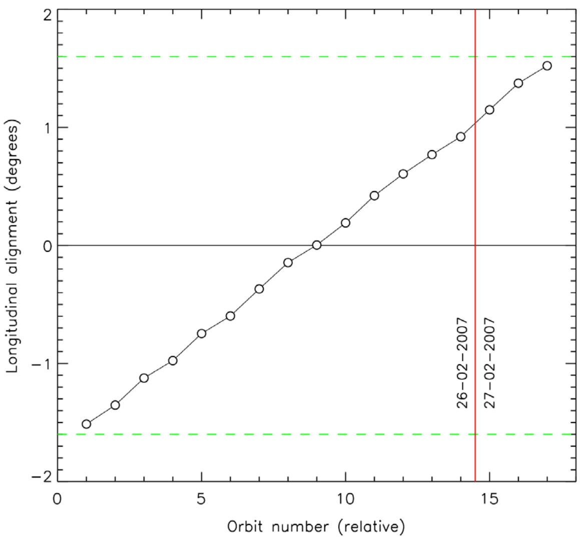

Figure 5: **Longitudinal alignment for a selection of overlapping SCIAMACHY and GOME-2 orbits from 26 and 27 February 2007. All orbits by definition have a longitudinal misalignment less than 1.6 degrees.**

In Figure 6 we present again a time series of the slope of the linear fit to the data points in the scatter plots, but now for the artificial ``new days''. As before, the red circles indicate days for which not enough orbits were available. Narrow swath and nadir static orbits were not considered. Compare with Figure 3. Clearly, the variability in the slopes has been reduced enormously. It now amounts to roughly 0.01–0.03, which relates well to the statistical errors reported by the fitting processes. This confirms that we have removed an important error source from the intercomparison approach.

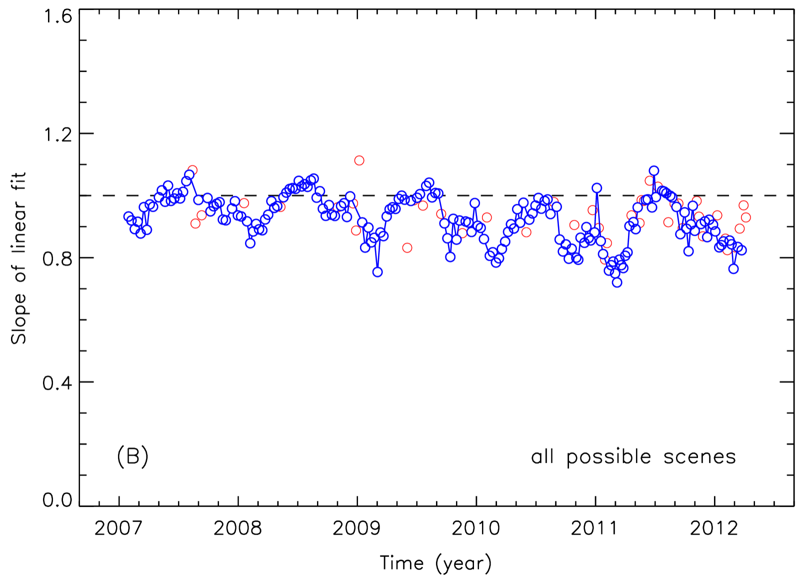

Figure 6: **Slope of the linear fits to the (GOME-2 versus SCIAMACHY) data points as a function of time, for the new approach in which artificial days are created (approach B, see text). The red circles are less reliable: not enough orbits and/or too many GOME-2 narrow swath orbits.**

The improved accuracy, and the resulting reduced variability, now reveal that there is a seasonal variation found in the SCIAMACHY versus GOME-2 intercomparison, at least for the slope of the linear fit. The existence of a seasonal variation in the slope is not understood, but may be related to the different overpass times, or to the seasonal variation in the scattering geometries, or to the mismatch between the orbits at higher latitudes due to the differences in orbit inclination. We do not expect it to be caused by calibration issues, because the effects of calibration issues would show up more prominently in the time series of the intercepts. Note that the seasonal variation in the slopes is modest. In Figure 7 we present the time series of the intercept of the linear fit to the data points in the scatter plots. The variability has been reduced considerably compared to the variability in Figure 3.

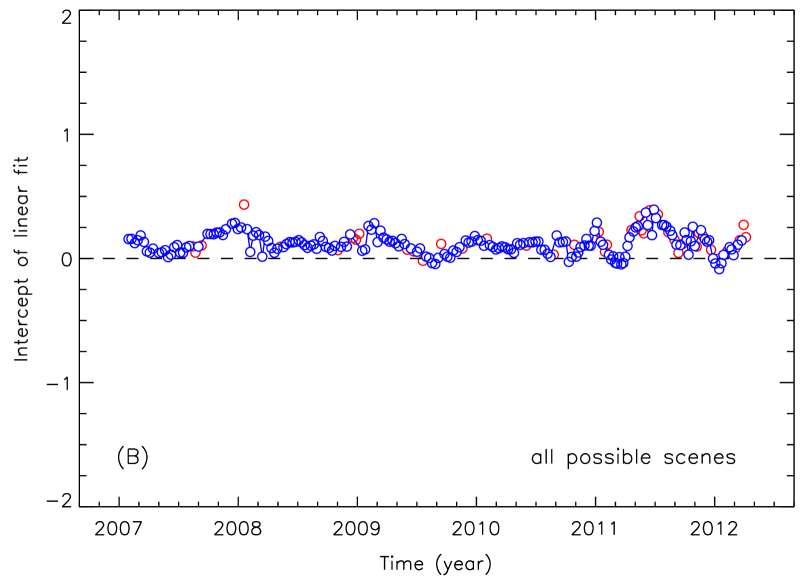

Figure 7: **Intercept of the linear fit, for the new approach B in which artificial days are created. The colour coding and meaning is the same as in Figure 6. We conclude that there is only a very small offset of the GOME-2 AAI w.r.t. the SCIAMACHY AAI, on the order of 0.1–0.2 index points.**

Figure 8 presents the standard deviation σ of the GOME-2 versus SCIAMACHY data points in relation to the achieved linear fit. That is, if the GOME-2 AAI's are represented by the array *y*, and the SCIAMACHY AAI's are represented by the array *x*, and the best linear fit to the data can be represented by $y = m \cdot x + n$, where m is the slope and n is the intercept of the linear fit, then the standard deviation is defined as $\sigma(y - m \cdot x - n)$. The standard deviation is on the order of 0.5 index points. Note that this means that the (bias-corrected) GOME-2 AAI is therefore shown to be validated against the SCIAMACHY AAI within an accuracy of ~0.5 index points. Also note that, although we went through a great deal of trouble to achieve an as accurate as possible intercomparison, there is still an inaccuracy to be attributed to the intercomparison procedure itself. That is, the ``real'' (intrinsic) uncertainty in the GOME-2 AAI will be less than the standard deviation of ~0.5 index points reported here, because of inaccuracies introduced by the intercomparison approach itself.

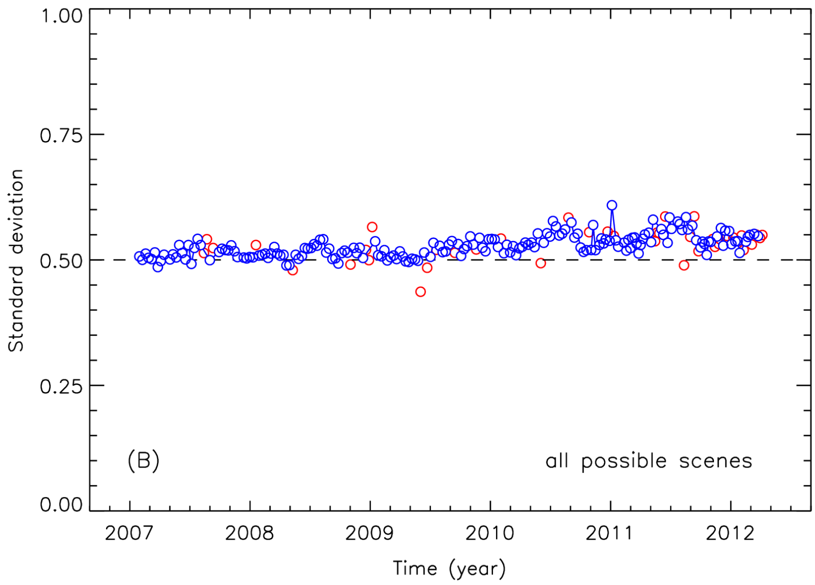

Figure 8: **Standard deviation of the difference between linear fit and the data, for the new approach B in which artificial days are created. The standard deviation is roughly 0.5 index points, showing a slight increase with time. As before, the results for the red circles are believed to be unreliable.**

SUMMARY

The results seem to indicate that there is a good correlation between the GOME-2 AAI and the SCIAMACHY AAI that was considered to be a reliable reference. The correlation is good in the sense that (i) there is a clear linear relationship between the GOME-2 AAI and the SCIAMACHY AAI, and (ii) the slope of the linear fit to the GOME-2 versus SCIAMACHY data points is close to one. On the other hand, a mild seasonal variation was found in the time series of the slope. This may be caused by the different overpass times of the two instruments, or by the seasonal variation in the scattering geometries, or by the mismatch between the orbits at higher latitudes due to the differences in orbit inclination. The offset between the GOME-2 AAI and the SCIAMACHY AAI is very small, indicating that there are no radiometric calibration problems involved.

The bias-corrected uncertainty in the GOME-2 AAI was found to be ~0.5 index point. As explained, this is only an upper limit, because this value is also determined by the quality of the SCIAMACHY AAI and the quality of our intercomparison approach. In any case, the (bias-corrected) value of roughly 0.5 index points relates well to the target uncertainty of 0.5 index points mentioned in the O3M SAF Product Requirements Document (PRD) (O3M SAF Project Team, 2014). Using the validation technique described in this chapter, it is not possible to reach a higher accuracy for the intercomparison results, and therefore it is impossible to assess whether or not the GOME-2 AAI could reach the PRD breakthrough level of 0.2 index points. This level might perhaps be reached, but this cannot be checked with the current intercomparison technique.

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