Report of the Short Term Scientific Mission: "Correction of the Brewer measurements for the dead time effect" (COST-STSM-ES1207-21218)

Ilias Fountoulakis[1]

[1]Laboratory of Atmospheric Physics, Aristotle University of Thessaloniki, PO Box 149, 541 24 Thessaloniki, Greece, iliasnf@auth.gr

04 November 2014

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1. Purpose of the STSM

During the last 30 years, there has been a great progress on the level of understanding of how the characteristics of the Brewer spectrophotometers are affecting their operation and consequently their final products (Garane et al. 2006; Karppinen et al. 2014; Lakkala et al. 2008). Though, there are still several technical issues that are not well understood, or not adequately documented.

Dead time is a measure of how long a photon counting circuit is "dead" (or cannot count a second photon) after a first photon has been detected (Cede, 2007). The dead time is characteristic for each instrument. A nominal value for the dead time is provided by the manufacturer and consequently the dead time is calculated by using a specific methodology (Savastiouk 2005). For most instruments the nominal dead time ranges between 20 and 50 ns. Although there are some studies regarding the methodology for the calculation of the dead time and the uncertainties of the final products related with it (Kiedron 2007; Cede 2007; Savastiouk 2005), there is still not clear if the used methodology for the calculation of the dead time provides the optimum results. Additionally, the uncertainties related with the dead time correction, especially those considering the calculation of ozone from direct sun measurements, are not adequately studied and documented.

Within the activities of the WG1 of the COST1207, an extended study regarding the dead time has been conducted at LAP (Laboratory of Atmospheric Physics, Thessaloniki, Greece) and at Izaña (Izaña observatory, Tenerife, Spain) independently. The first main objective of the STSM-ES1207-21218 (September 28 – October 8, 2014) is the exchange and the combination of knowledge, related with the dead time and its effects on measurements. The second main objective is the usage of the high quality facilities at the observatory of Izaña in order to perform experiments for the better understanding of the dead time. Additionally, the background, high altitude atmospheric conditions at the observatory of Izaña are ideal for performing field measurements for the same purpose.

2. Description of the work that carried out during the STSM

During the STSM, both theoretical and experimental work was carried out. Specifically, a revision of the works of Kiedron (2007) and Cede (2007) was performed and the different approaches which were referred in the specific studies were tested in order to decide which one is the more suitable for the calculation of the dead time. Additionally, we investigated the conditions under which, the assumptions made in the algorithm of Brewer in order to calculate the dead time, are valid.

For the calculation of the dead time for each Brewer, the measurements of the irradiance of an internal 12V tungsten-halogen lamp (standard lamp) are used. Using the standard lamp to determine the dead time leads to high uncertainties, especially when the signal of the lamp is low. Additionally, the operation of the lamp is not independent from the operation of the rest electronic circuits of the instrument. Thus, it is not always easy to detect if the observed changes are real changes of the dead time or not (Rodriguez et al. 2014). In order to avoid the uncertainties which are induced by the usage of the internal lamp, an effort to use the sun as a light source was performed. At both, LAP and Izaña, new routines were created in order to derive dead time from direct sun measurements. During the STSM, the potential problems of these routines were investigated. Additionally the clear sky and the stable atmospheric conditions (Figure 1) allowed us to perform direct sun measurements in order to determine the optimum instrument settings for the calculation of the dead time from direct sun measurements.

Figure 1. Clear sky over the Izaña Observatory (mount Teide, Tenerife, Spain)

It is recommended from the Brewers manufacturer, that if the calculated dead time does not differ from the nominal value by more than 2 ns, then the nominal value should be used. According to the findings of Rodriguez et al. (2014), for several instruments the calculated dead time difference from the nominal value is more than 2ns and it may even be of the order of 10 ns. Two main questions arise from these findings. The first is what might be the effect of these discrepancies on the measurements and the second is, if these discrepancies are real. The potential effects of differences up to 10ns on the UV and the total ozone column measurements were investigated. Subsequently, several cases of large deviations between the nominal and the calculated dead time were studied. In order to decide whether the observed deviations are real or not, we performed a test using the neutral density filters of the instrument. For older cases we couldn't use the test; thus we performed comparisons with satellite data.

In order to experimentally determine the most proper dead time value to use (the value for which we have the optimum dead time correction), we performed measurements of the neutral density filters attenuation (Sellitto et al. 2006). For this purpose we modified and evaluated the existing at.rtn (Redondas et al. 2011). The test was performed by using three light sources: the sun, an external 1000 Watt DXW lamp and the internal 12V standard lamp. We measured the attenuation of the neutral density filters for the operational wavelength range of each instrument with a step equal to 5 nm and for different intensities of the light sources. In order to have different sun light intensities, we performed direct sun measurements at several solar zenith angles. At Izaña, we also placed the 1000 Watt lamp (DXW with S.N. 1005) at different distances (ranging from 30 cm to 105cm) from the quartz window and then performed measurements. The positioning of the lamp at different distances was achieved by using a metallic arm, on which the lamp was mounted. The arm could move vertically on a metal rod (figure 2a), with length equal to about 1m. The instrument was positioned properly (figure 2b) in order to have the optimum measurements, while the intensity and the voltage of the lamp were continuously monitored in order to ensure the emitted light intensity is stable during the measurements. After the measurements, the intensity is corrected by using several different dead time values. Since the transparency of the neutral density filters is independent from the intensity, the optimum dead time value to use for each wavelength and each filter is determined as the one for which the calculated attenuation is independent from the intensity of the incident light (Fountoulakis and Bais, 2014). The calculated attenuation for the specific dead time value should also be the one that should be used. In LAP, moving the 1000 Watt lamp vertically would be very difficult. Thus, to perform these kind of measurements we placed the lamp to a standard distance about 30 cm from the quartz window, and then we achieved different light intensities by changing the lamp current.

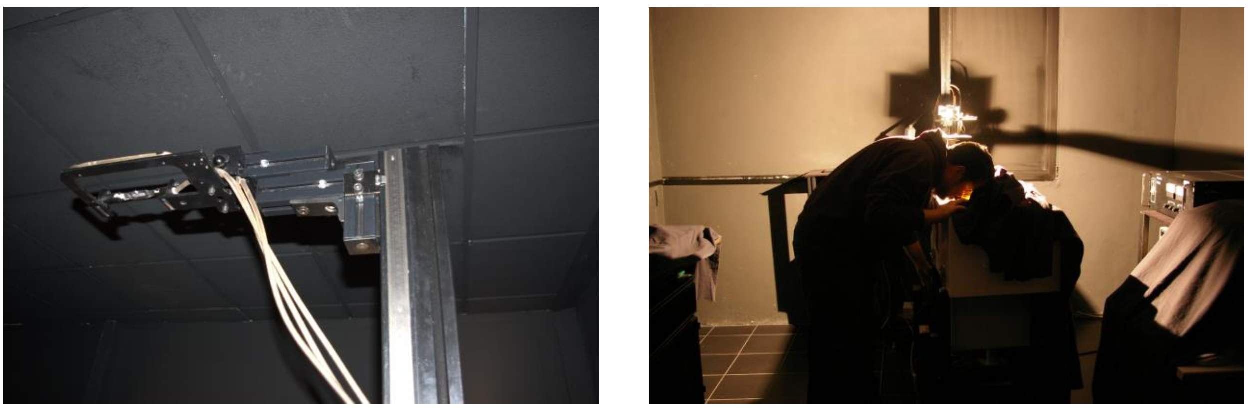

Figure 2. a) Mechanism used to change the lamp vertical distance from the quartz window, b) sighting of the Brewer with S.N. 185

3. Description of the main results

3.1. Dead time - Theoretical approach

3.1.1. Theoretical basis for the dead time calculation

In order to describe the theory on which the calculation of the dead time for Brewer is based on, in the following we quote from the personal notes of A. Cede (Cede 2007).

Dead time is a measure of how long a photon counting circuit is “dead” (or cannot count a second photon) after a first photon has been detected. When we assume a dead time τ and a count rate of pps photons per second reaching the photomultiplier (PMT), then the average number of photons hitting the PMT within a time τ is given by:

(1) $\mu = pps \cdot \tau$

A Poisson-distribution is assumed for the probability P(k) of k incoming photons within a time τ:

(2) $P(k) = \frac{1}{k!} \cdot e^{-\mu} \cdot \mu^{k}$

The sum of probabilities from 0 to infinity should be equal to unity, thus:

(3) $\sum_{k=0}^{\infty} P(k) = 1$

The probability for *exactly one* incoming photon within a time τ is given by:

(4) $P(k = 1) = \frac{1}{1!} \cdot e^{-\mu} \cdot \mu^{1} = e^{-\mu}$

The probability for *one or more* incoming photons within a time τ is given by:

(5) $P(k \geq 1) = 1 - P(k = 0) = 1 - e^{-\mu}$

The ratio of the number of photons that are detected against the number of photons that reach the photomultiplier, is then given by the relationship:

(6) $R = \frac{P(k=1)}{P(k\geq 1)} = \frac{\mu \cdot e^{-\mu}}{1-e^{-\mu}}$

Since μ is a small number, we could expand the exponential function in the denominator of (6) to obtain a simpler expression and approximation for R:

(7) $R = \frac{\mu \cdot e^{-\mu}}{1-[1-\mu+\frac{\mu^{2}0}{2} - \ldots]} \approx e^{-\mu} = R_A$

In the Brewer algorithm, the dead time is calculated by making the assumption that the ratio between the detected and the true count rate is given by R_A. Though, as can be perceived by figure 3, for the range of the dead times that we assume for Brewers, R and R_A may differ importantly, especially for count rates that are greater than one million counts per second

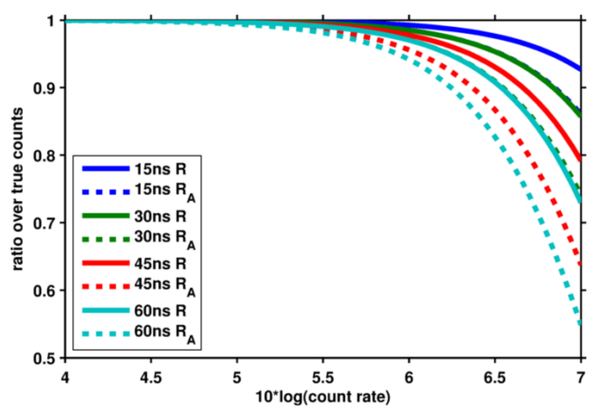

Figure 3. Relationship between the detected and the true count rate for the non-simplified (R) and for the simplified (R_A) case for four different values of dead time (15ns, 30ns, 45ns, and 60ns).

3.1.2. Different approaches for the calculation of the dead time

In the present paragraph we compare the different methodologies for the calculation of the dead time, given that the probability P(k) of k incoming photons within the dead time τ is described by a Poisson distribution. In order to describe different methodologies we were mainly based on the works of Kiedron (2007) and Cede (2007) where more information can be found.

Given the Poisson nature of photon statistics, there are two main formulas that can be used in order to calculate the dead time. The used formula depends on the nature of the counting system. If we assume that dead time is triggered only from the photons that are recorded from the PMT then the non-extended (non-paralyzable) dead time formula should be used. The Brewer algorithm for the calculation of the dead time has been created by assuming that both, the photons that are recorder and the photons that are not recorded by the PMT, trigger a new dead time period and the extended (paralyzable) dead time formula is used. The non-extended dead time formula is described by the relationship:

(8) $$cps = \frac{pps}{1+dt \cdot pps}$$

Where cps is the count rate (detected photons/second), pps is the rate of photons reaching the PMT (incident photons/second) and τ is the dead time. The extended dead time formula, as it is used in the Brewer algorithm, is described by the relationship:

(9) $$cps = pps \cdot e^{-\tau \cdot pps}$$

If the ratio R was used for the calculation of the dead time instead of the ratio R_A, then the following equation should be used:

(10) $$cps = pps \cdot \frac{pps \cdot dt \cdot e^{-\tau \cdot pps}}{1-e^{-\tau \cdot pps}}$$

In order to calculate the dead time for a Brewer, the micrometers are moved to the ozone measurement (zero) position. Then ten cycles of measurements are performed using the internal standard lamp as a light source. Within each cycle of measurements, the irradiance of the lamp is measured on the positions 3 (slit 2) and 5 (slit 4) of the slit mask motor and then on the position 7 (slits 2 and 4 simultaneously). Then the dead time is calculated by using the following methodology:

In the Brewer-software (**extended** dead time), the equation (9) is solved for the positions 3 and 5 (i=3 and i=5) by setting pps=cps as an initial guess and iterating 9 times (j=1 to 9) over the rearranged expression:

(11) $$pps_i^{j+1} = cps_i \cdot e^{pps_i^j \cdot \tau^j}$$

Each time, the equation (9) is solved for the position 7 in order to find τ:

(12) $$\tau^j = \frac{1}{pps_7^j} \cdot \ln\left(\frac{pps_7^j}{cps_7}\right)$$

Where:

(13) $$pps_7^j = pps_3^j + pps_5^j$$

Finally we assume that $\tau = \tau^9$.

If we use the **non-extended** dead time formula, then the equation (10) is replaced by the equation (14):

(14) $$pps_i^{j+1} = cps_i \cdot (1 + \tau \cdot pps_i^j)$$

If we use the **extended** dead time formula, **without making the simplification** of equation (7), the calculation of the dead time is performed by making 9 iterations for the more complex system of equations (15) and (16):

(15) $$pps_i = cps_i \cdot \frac{pps_i \cdot \tau \cdot e^{-pps_i \cdot \tau}}{1 - e^{-pps_i \cdot \tau}}$$

(16) $$\tau^j = \frac{1}{pps_7^j} \cdot \ln\left(\frac{\tau^{j-1} \cdot (pps_7^j)^2}{cps_7 \cdot (1 - e^{-\tau^{j-1} \cdot pps_7^j})}\right)$$

Where i = 3 and 5.

In Table 1, the results of the three different approaches for the calculation of the dead time are presented for the three Brewers that are operating at the Izaña observatory and the two Brewers that are operating at LAP. The results were derived for typical count rates (when using the standard lamp as a light source) on the positions 3, 5 and 7 of the slit mask motor, when no filter is used on filter wheel #2 (FW#2).

Table 1. Dead time values, as they were calculated using different formulas. The nominal dead time is also presented for each instrument.

Instrument Serial Number	Nominal (ns)	Measured - simplified extended (ns)	Measured - simplified non extended (ns)	Measured – not simplified extended (ns)
005	34	32	32	58.5
086	42	38	38	75
157	32	27	27	50
183	23	22	22	41
185	29	29	29	54

When the dead time is calculated with the non-extended formula it is generally less than 0.5ns lower (difference is less than 1%) compared to the value that is calculated with the extended formula. Thus, the use of the extended or the non-extended approximation makes no important difference. If we use the equation (6) instead of the simplified equation (7), the calculated dead time is near two times higher compared to the nominal dead time. However, the experimental study which is presented in the following paragraphs indicates that the dead time which should be used is the one calculated by using the equation (7).

3.1.3. Dependence of the calculated dead time from the count rates and the spectral characteristics of the light source

In the present paragraph we tried to theoretically estimate the boundaries of the incident intensity and of the ratio between the photons reaching the slits 2 and 4, between which the assumptions performed in the Brewer algorithm do not induce artificial biases to the calculation of the dead time. In this paragraph and during the above analysis we assume that for the range of the light intensities that reach the PMT, the dead time is independent from the true count rate.

In order to study the relationship between the calculated dead time and the count rate, we assumed count rates ranging from 10^2 to10^7 counts/sec for the position 7 and that the true count rates on positions 3 and 5 are equal. Then we assumed that the relationship between the true and the measured count rates is given by the corresponding value of R_A. Finally, we used the results to calculate the dead time by using the Brewer algorithm. The calculations were performed for four different "true" dead time values.

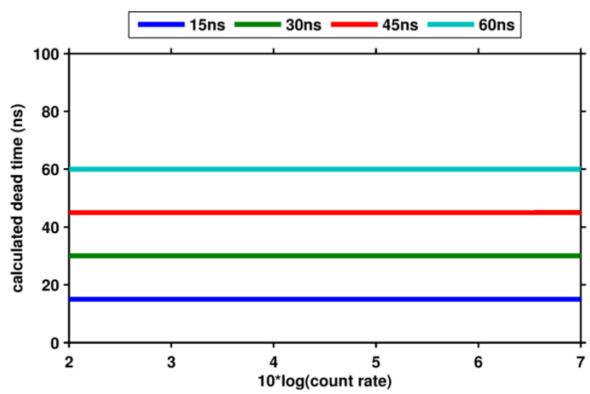

Figure 4. Dead time as it is calculated with the Brewer algorithm for different count rates and different "true" values of the dead time.

As it is clearly presented in Figure 4, the used algorithm seems to give results that are exactly the same with the "true" dead time for the entire range of the intensities that were studied.

In order to study the relationship between the ratios of the count rates on positions 3 and 5 and the calculated dead time, we repeated the process which is described above for different ratios. Ratios ranging from 0.01 to 0.49 between the true count rates for positions 3 (N3) and 7 (N) were assumed. The results shown in Figure 5 are for a count rate equal to 10^6 counts/sec on position 7.

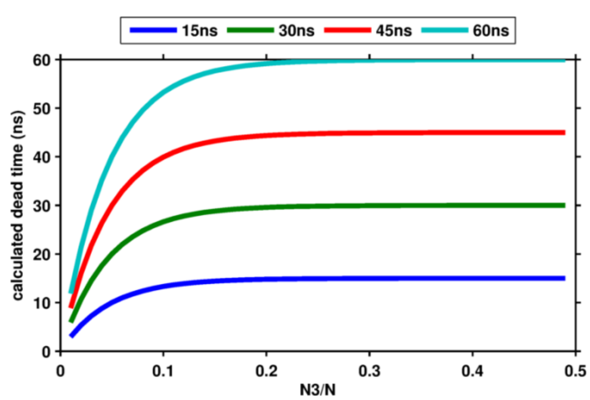

Figure 5. Dead time as it is calculated with the Brewer algorithm for different count rate ratios and different values of dead time as they result from Poison statistics.

As it can be perceived from Figure 5, the calculated dead time becomes lower than the “real” if the ratio between the incident photons on the positions 3 and 7 (or 5 and 7) is lower than about 0.2 - 0.25.

3.2. Effect on UV and TOC measurements

In the present paragraph the effects of the dead time on the UV and the TOC (total ozone column) measurements is studied. For brevity, each Brewer with serial number xxx is going to be referred as Bxxx in the following paragraphs.

3.2.1. Effect on UV measurements

The effect on the calculated UV irradiance is mainly dependent from the intensity of the incident light. In figure 6, the % change of the calculated irradiance as a function of the intensity of the incident light is presented. Differences of the used dead time which are equal to ±2ns and ±10ns are studied. The reference dead time is equal to (a) 15ns, (b) 30ns, (c) 45ns, and (d) 60ns.

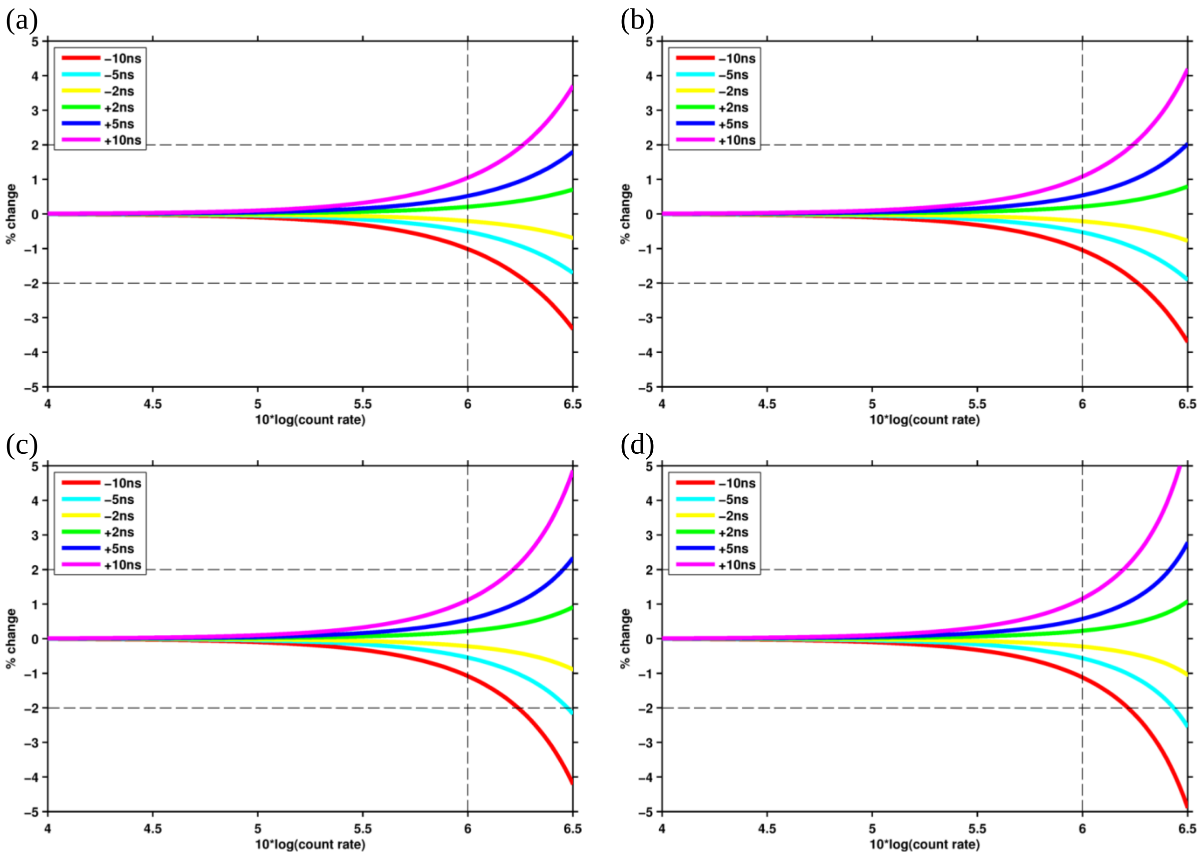

Figure 6. The effect of differences of the used dead time on the calculated irradiance for reference dead time equal to (a) 15ns, (b) 30ns, (c) 45ns, and (d) 60ns as a function of the incident photons/sec.

As long as the intensity of the light remains below 10^6 photons/sec, even a change of ±10ns in dead time lead to a corresponding change on the calculated irradiance, of the order of 1%. For higher intensities the effect of dead time becomes more important and is slightly increased for higher reference dead time values. For intensities near 3.2 million photons/sec, an overestimation/underestimation of the dead time equal to 2ns leads to a corresponding overestimation/underestimation of the incident intensity near 1%. A 10ns difference may lead to differences of the calculated irradiance ranging from about 3% to about 5%, depending on the reference dead time.

For low response instruments such as B086, even during a very clear day near the summer solstice, a 10ns difference of the used dead time leads to differences of the calculated noon global irradiance that (even for higher wavelengths) are lower than 2%. The effect of the same difference on the calculated 350nm irradiance for an instrument with higher response, such as B185 may reach 4% near the local noon as can be perceived from Figure 7(b). For wavelengths in the UV-B range, the effect of dead time is negligible since the intensities are much smaller. For the case of Figure 7, if no dead time correction would be applied, the underestimation of the global irradiance near the local noon would be about 9%. The change of the calculated daily integral due to a 10ns change of the dead time is of the order of 2.5%.

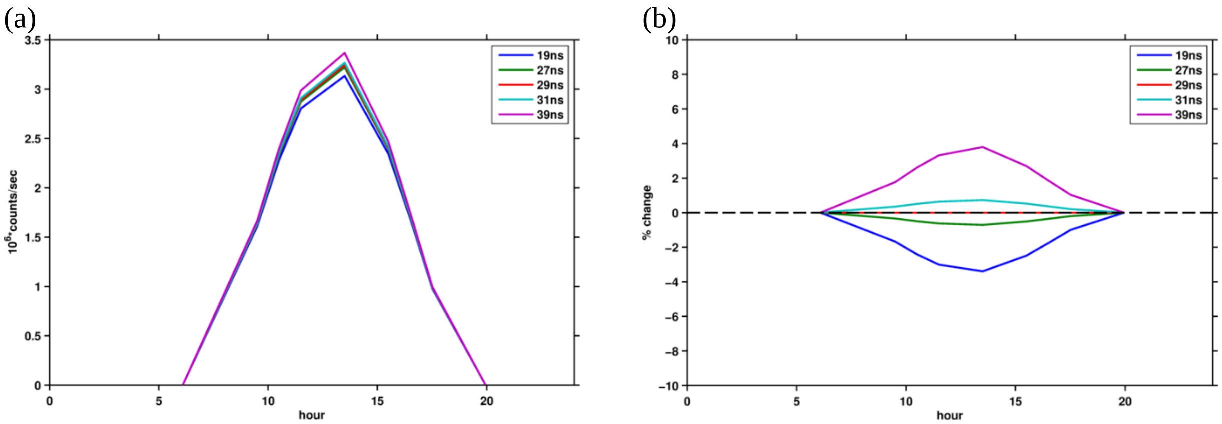

Figure 7. (a) Calculated count rates for the 350nm global irradiance during 26 June of 2013 for different dead time values and (b) % change of the calculated count rate with respect to count rate for the nominal dead time (which is equal to 29ns).

The direct solar irradiance can be also used for the calculation of the Aerosol Optical Depth (AOD). Thus, the overestimations/ underestimations on the calculation of the direct solar irradiance are transferred on the calculation of AOD. For air masses near unity, a 5% underestimation/ overestimation of the direct solar irradiance lead to an overestimation/underestimation of the AOD near 0.05. An overestimation/ underestimation on the direct solar irradiance or on the used extraterrestrial constant near 1% leads to a corresponding underestimation/overestimation or overestimation/ underestimation near 0.01 respectively on the calculation of AOD for air masses near unity. The error on the calculation of AOD is then reduced proportional to the air mass.

3.2.2. Effect on the calculation of TOC

The effect of the dead time correction on the calculation of TOC depends on the differences between the count rates on slits 2 – 5. These differences are determined by both the effects of the atmosphere on the solar spectrum and the spectral response of the instrument. The spectral response may differ importantly between different instruments. The presence of the $NiSO_4$ filter in the single monochromator (MKII and MKIV) Brewers changes the shape of the spectral response. This leads to greater discrepancies between the counts on different slits and to greater effects when non proper dead time values are used compared to the double monochromator Brewers. The effect of the dead time change is presented for the single monochromator B005 and for the double monochromator B185. The results for the MKIII Brewers B157 and B183 were similar with these for B185. B157 is operating with old electronics and the Brewers with serial numbers 183 and 185 are operating with the new electronics. However, the effect of the dead time changes on the calculation of TOC was found to be almost the same for all the three of them. In the following paragraphs the effect of the dead time changes on both the calculation of the extraterrestrial constant (ETC) and the calculation of TOC using direct sun measurements are studied.

3.2.2.1. Effect on the calculation of ETC from Langley plots

Errors in the value of the used dead time may induce errors on the calculation of the extraterrestrial constant (ETC) that is used for the calculation of TOC. In order to study the effect of the dead time changes on the calculation of the ETC, several Langley plots were created for the double monochromator Brewers with serial numbers 157, 183, and 185 and for the single monochromator B005. For the double monochromator Brewers, the difference of the ETC for a change of dead time equal to 2ns, is ranging between 3 and 4 units, while for a 10ns change the corresponding difference was generally found to be less than 15 units. The effect of the dead time changes is more important for the calculation of ETC from the single monochromator Brewer. A 2ns change of dead time may lead to 8 units change on ETC, while a 10ns change of dead time may lead to 40 units change on the calculated ETC. In the following, the effect of the dead time changes on the calculation of the ETC and the transferred error in the calculation of the TOC is studied for two typical cases for the single monochromator B005 and for the double monochromator B185.

In Figure 8, two Langley plots for the determination of the ETC are presented for (a) B005 and (b) B185. In both cases the AOD was very low and stable and the TOC variations were within ±3 DU during the time period of the measurements. The MS9 ratios are calculated for 2ns and 10ns differences from the nominal dead time and the corresponding ETC is calculated for each occasion. The results are presented in table 2.

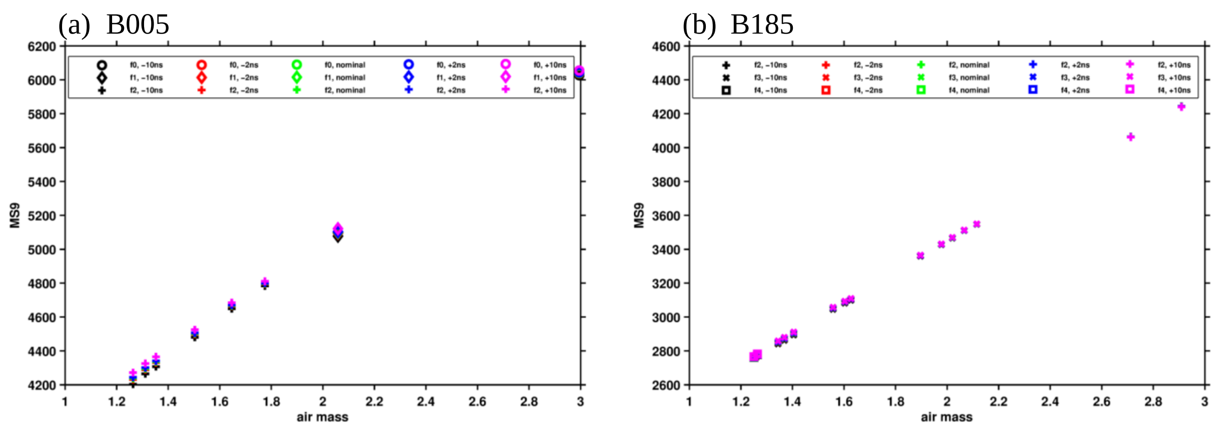

Figure 8. Langley plots for dead time changes ±2ns and ±10ns. Different markers indicate the use of different neutral density filters. Plots are for (a) B005 and (b) B185. The used data were collected during the morning of 2 July 2013 and during the evening of 4 October 2014 respectively.

Table 2. Change of the calculated ETC as a result of dead time changes.

ID \ Δ(τ) (ns)	-10	-2	+2	+10
005	-39	-8	+8	+40
185	-14	-3	+3	+15

In figure 9, the % changes of the calculated TOC as consequence of the corresponding changes in the ETC calculation are presented. The calculations are based on the results of table 2. The error that is transferred on the calculation of TOC is a smooth function of the ozone slant column. For B185, the change of the calculated TOC due to a 2ns change in the used dead time is generally less than 0.5%. A 10ns change of the used dead time leads to TOC changes of the order of 1% when the ozone slant columns are lower than 500 DU. The results for B185 can be generalized for all the double monochromator Brewers. For the single monochromator Brewers, the induced error is highly dependent from the spectral response of each instrument. For B005, the change of the calculated TOC for a 2ns change in dead time is of the order of 1% for low slant columns. The corresponding change which is induced from a 10ns change in the used dead time ranges from about 1% to about 4.5%.

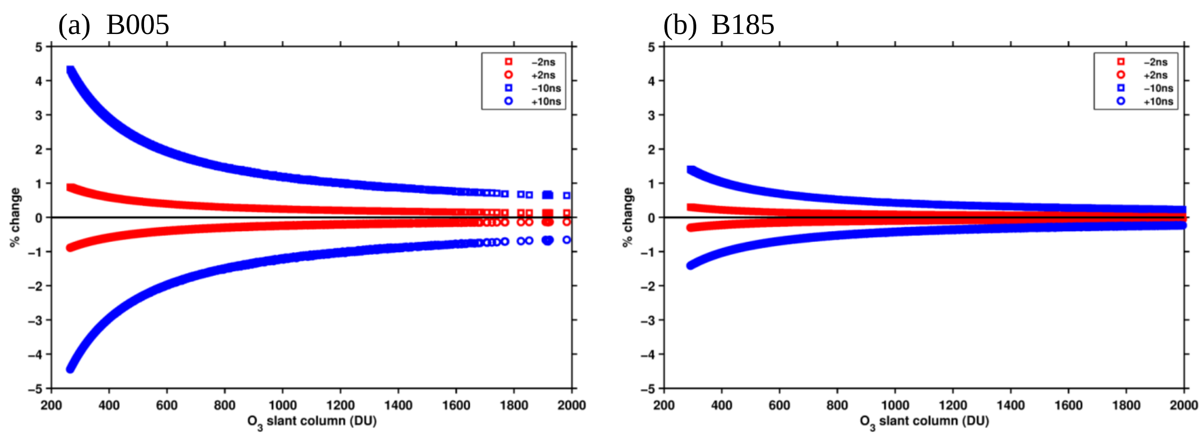

Figure 9. Change (%) of the calculated TOC as a consequence of the ETC change due to ±2ns and ±10ns differences in the value of the used dead time. Results are presented for (a) B005 and (b) B185.

3.2.2.2. Effect on the calculation of TOC from direct sun measurements

In the present paragraph, the effect of the dead time changes on the calculation of the TOC from direct sun measurements is studied. The presented results are for B005 and for B185. For each instrument the whole dataset of 2013 has been used for the analysis. The effects of different dead time changes on the calculated TOC are presented in Figure 10.

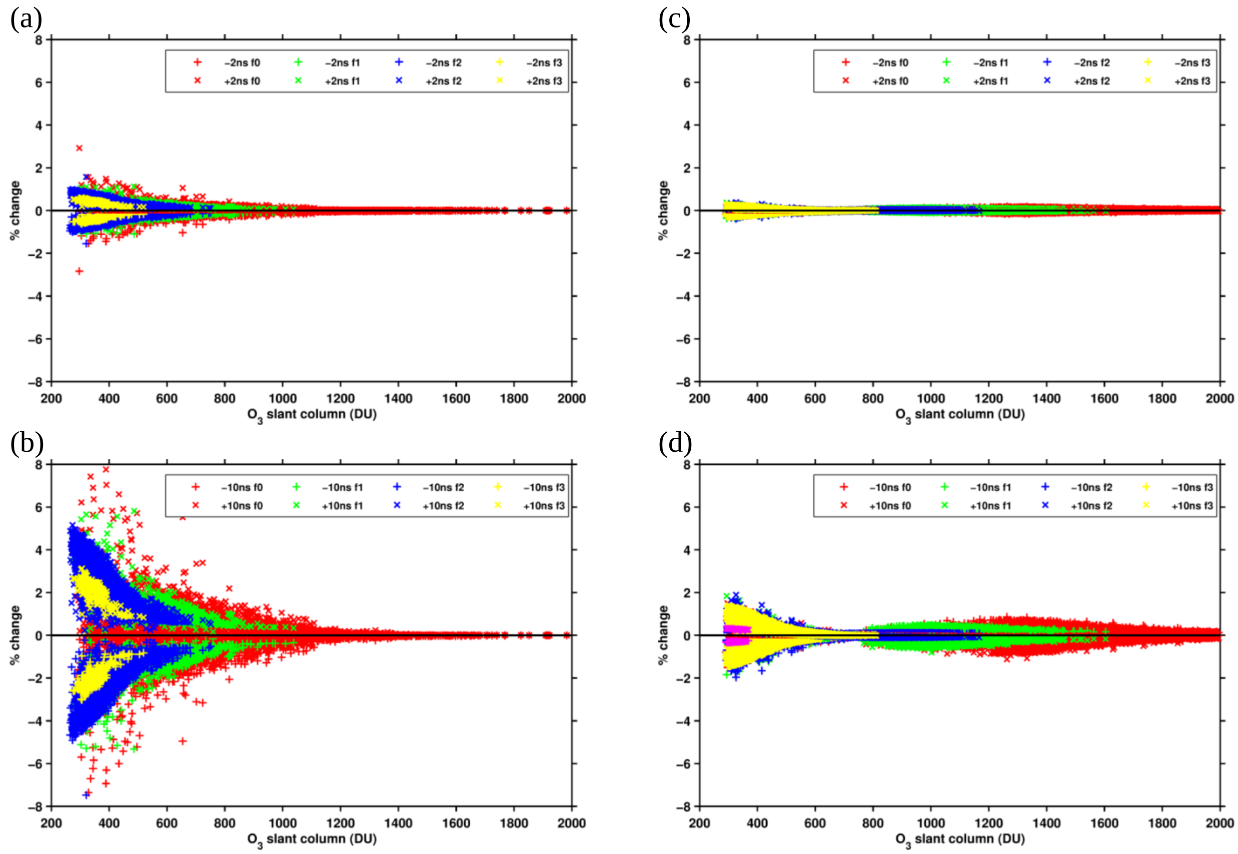

Figure 10. Change (%) of the calculated TOC (from direct sun measurements) due to ±2ns and ±10ns changes of the dead time. Different colors indicate the use of different neutral density filters. The presented results are (a) for B005 and a dead time change equal to 2ns, (b) for B005 and a dead time change equal to 10ns, (c) for B185 and a dead time change equal to 2ns, and (d) for B185 and a dead time change equal to 10ns.

For all the cases that are presented in figure 10, the changes become greater near the limit where the FW#2 moves from a lower to a higher attenuation position (or the opposite). This indicates that the effect on the calculated TOC becomes stronger for higher intensities of the direct irradiance. When the dead time differences are ±2ns, the effect on TOC from B185 is small and the observed differences are generally lower than 0.5%. For the TOC from B005, a 2ns change of the used dead time induces changes that exceed 1% for low O_3 slant paths. The results are impressive for the effect of a 10ns dead time change on the TOC calculation from B005, where changes that may reach 8% are observed.

3.2.2.3. Combined effect

In the present paragraph, there is an effort to estimate the change of the calculated TOC if both the ETC and the TOC are derived by using different dead time values. For this purpose, the results from paragraphs 3.2.2.1 and 3.2.2.2 were combined and are presented in Figure 11.

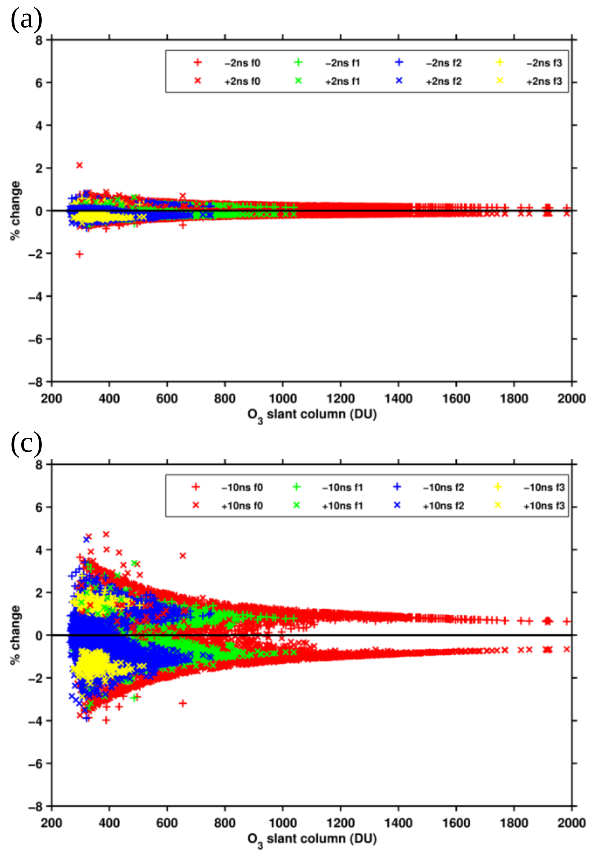

Figure 10. Change (%) of the calculated TOC (from direct sun measurements) due to ±2ns and ±10ns changes of the dead time. The dead time changes were applied for both the calculation of the ETC and the TOC. Different colors indicate the use of different neutral density filters. The presented results are (a) for B005 and a dead time change equal to 2ns, (b) for B005 and a dead time change equal to 10ns, (c) for B185 and a dead time change equal to 2ns, and (d) for B185 and a dead time change equal to 10ns.

For low O_3 slant columns, the effect of the dead time changes on the calculation of TOC is suppressed when the ETC which has been calculated for the same change is used. For high slant columns, the effect of dead time changes on the calculation of ETC is dominant. As can be perceived by Figure 10, the TOC which is calculated by a double monochromator Brewer that uses a dead time which is 10ns higher/lower than the reference can be underestimated/overestimated by about 1%. The corresponding underestimation/overestimation for a single monochromator Brewer may be of the order of 4 – 5%.

3.3. Dead time from the sun

As described in paragraph 2, at both, LAP and Izaña observatory, new routines were created in order to use the sun as a light source and then to calculate the dead time. The methodology which is used for the determination of the dead time from the direct sun measurements is similar with the methodology used for the determination of the dead time when the internal standard lamp is used as a light source (Savastiouk 2005). The main difference is that before each set of measurements, the intensity of the solar irradiance is tested and a proper neutral density filter is used in order to avoid the PMT overexposure. Then 5 sets of measurements are performed, from which the mean dead time and the relative standard deviation are calculated.

The main problem when we try to use the sun as a light source is that it may be partially or fully covered by clouds, leading to rapidly changing or very low irradiance respectively. In these cases, the uncertainty of the calculated dead time is extremely high. Thus, for the present analysis we rejected all the measurements for which the standard deviation is higher than 5ns and the count rate on position 7 of the slit mask motor is lower than 100000 counts/sec. In figures 11 (a) – (e), the results of the new routine are presented for the five Brewers (two at LAP and three at Izaña). Several differences between the results from different instruments can be noted, for both the results from the standard lamp and from the sun.

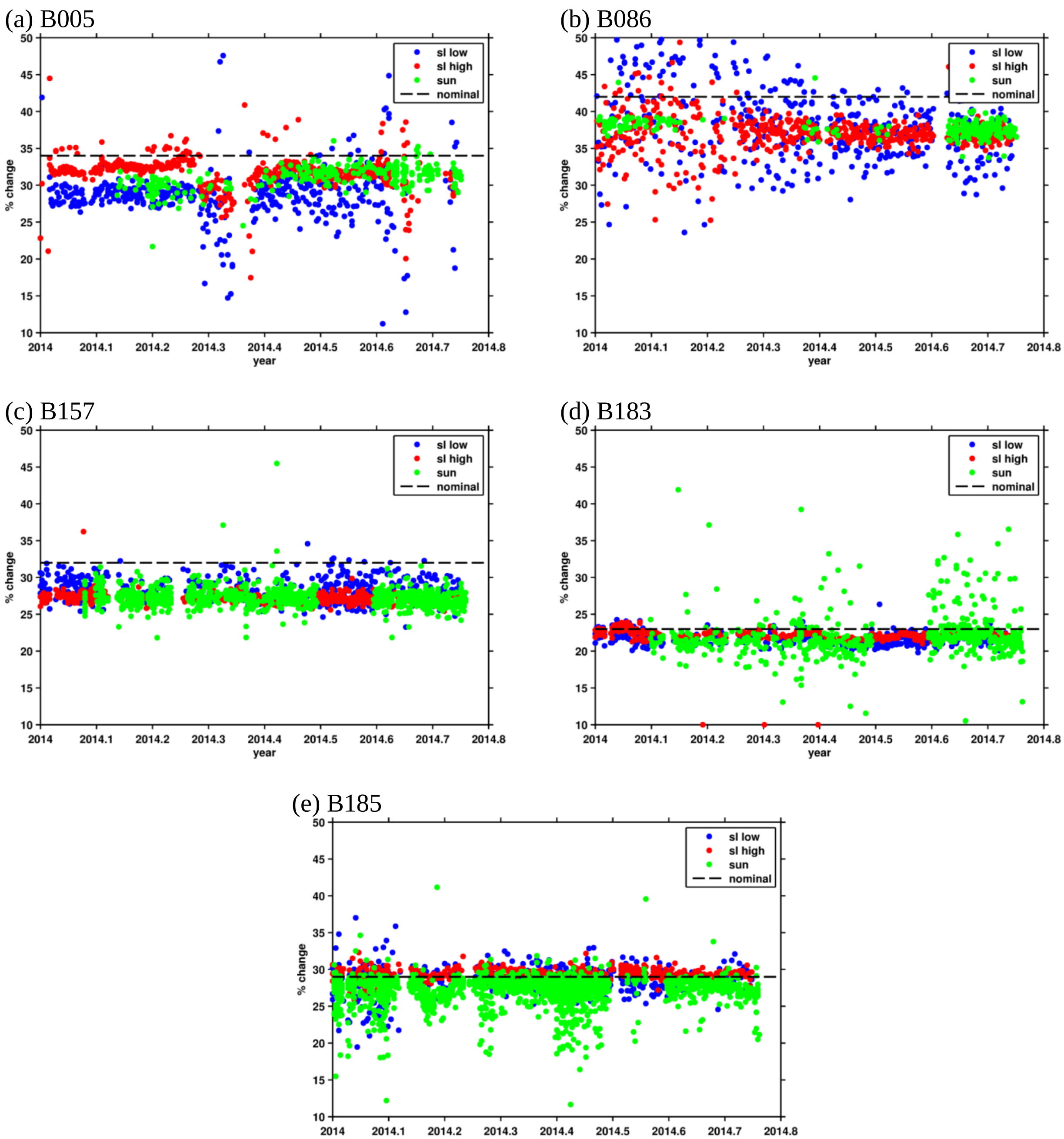

Figure 11. Calculated dead time from the standard lamp and from the sun for five different Brewers.

For B005, differences between the high and the low intensity dead time from the standard lamp are observed. The dead time which is calculated from the sun is different within the year. Initially it is in better agreement with the low intensity dead time from the standard lamp and gradually it raises and it agrees better with the high dead time. As it is analytically explained in paragraph 3.5, this is probably because the dead time of the specific instrument is dependent from the intensity of the incident irradiance.

During the entire period of measurements which were performed with the Brewers operating at LAP (serial numbers 005 and 086), for each one of the five sets, 10 cycles of measurements were performed. Until June, the same number of cycles was performed by the three Brewers that are operating at Izaña. Afterwards, the number of cycles was increased to 40. In the following there is an effort to analyze the observed results.

For B086 the dead time which is calculated from the standard lamp is much noisier than the dead time which is calculated from the sun until 2014.3. This is because of the very low intensity of the standard lamp. Near 2014.3 the standard lamp was replaced from a new one with higher intensity and the noise was reduced. Additional reduction of the noise can be observed after 2014.4. This is because the number of cycles was increased from 10 to 20. During the entire period of calculations, the dead time from the sun is very stable and less noisy than the dead time from the standard lamp. Until 2014.6 the direct sun measurements for the determination of the dead time were performed only once per day near the local noon in order to have relatively stable solar irradiance with high intensities. Thus, for the specific period, although the noise is very low, the number of available measurements is small. After 2014.6 (beginning of August), the measurements were performed several times per day for several solar zenith angles. Thus, the amount of available data is increased and the level of noise is decreased.

For B157, the agreement between the dead time from the standard lamp and the dead time from the sun is very good. The noisier results from the sun compared to those from the lamp (high intensity dead time) are due to the lower sun intensities during several of the measurements. For B183 and B185, the dead time from the sun is lower and noisier compared to the dead time from the standard lamp. As can be perceived from Figure 12, the main reason is the low ratio of the count rates between the positions 3 and 7 (N3/N) of the slit mask motor. Although the increase of cycles from 10 to 40 reduce the uncertainty after 2014.5, the calculated values for B183 and B185 remain lower than those calculated from the standard lamp, because of the big difference between the counts on slits 2 and 4.

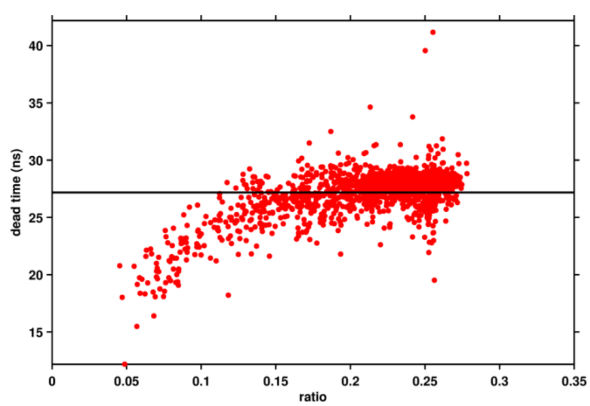

Figure 12. Dead time from the sun for B185 as a function of the ratio of count rates at positions 3 and 7 of the slit mask motor.

3.4. Experimental determination of the optimum settings for the calculation of the dead time from the sun

In order to determine the optimum settings for the calculation of the dead time from direct sun measurements, continuous measurements were performed during two consecutive very clear days (04/10/2014 and 05/10/2014). Each time, the measurements were performed for five different positions of the micrometer. Specifically, the wavelengths of the irradiance on slit 1 were 303nm, 314nm, 328.5nm, 342nm, and 351.5nm. By this way, measurements for different intensities, wavelengths, and N3/N ratios were performed for nearby solar zenith angles (SZA's) and very similar atmospheric conditions. The B185, which is a very stable instrument, was used to perform the measurements. During the first day, the measurements on position 1 (303nm) where performed with 40 cycles and on positions 2 – 5 (314 – 351.5nm) with 10 cycles. During the second day, the number of cycles was 10 and 5 respectively.

In Figure 13(a), the daily course of the calculated dead time and the corresponding standard deviation for the five micrometer positions are presented for the first day of measurements. In Figure 13(b) the corresponding values of the N3/N ratio are presented. The results for ratios that are ranging between 0.4 and 0.6 are very close to 29ns which is the nominal value (and the value which is calculated from the standard lamp). The 29ns is also the value for which we have the optimum dead time correction as it is shown in paragraph 3.5.

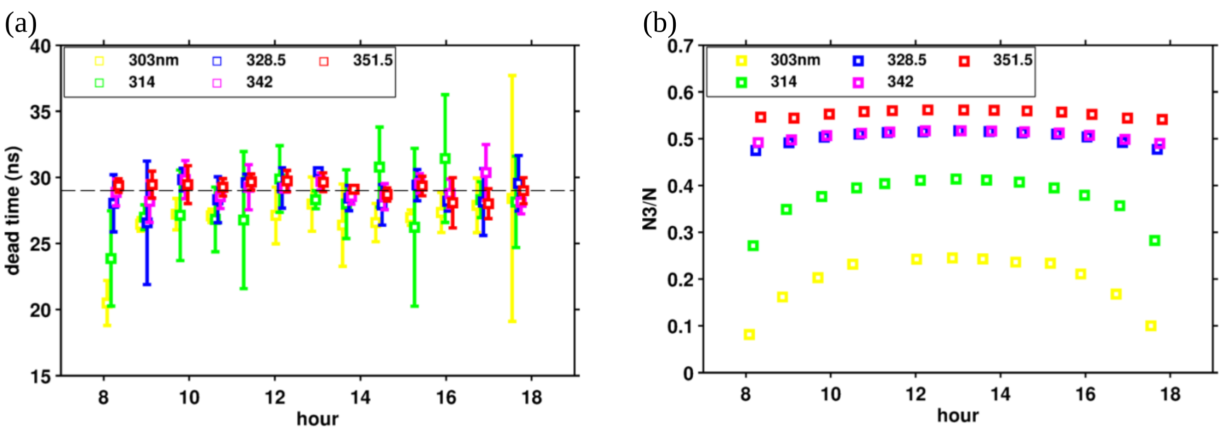

Figure 13. (a) Daily course of the calculated dead time and the corresponding standard deviation for the five micrometer positions and (b) daily course of the N3/N ratio.

As was expected by the theoretical calculations (paragraph 3.1), the N3/N ratio is the most important factor for the determination of the dead time from the sun. These conclusions are more obvious in Figure 14, where the mean dead time for each position, as it was calculated from the whole dataset for both days of measurements, is plotted against the mean N3/N ratio.

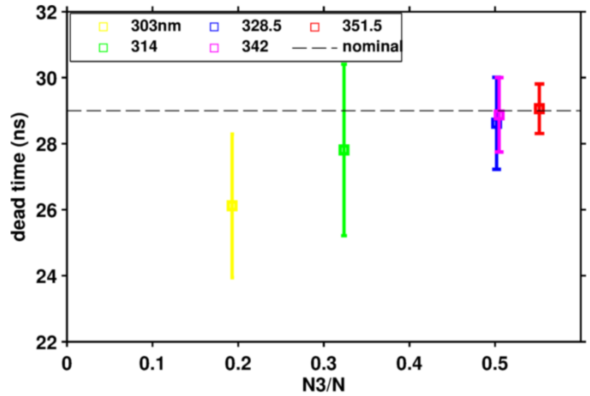

Figure 14. Dependence of the mean dead time for each position of the micrometer, from the mean N3/N ratio

In figure 15, the ratio between the standard deviation and the corresponding mean dead time is plotted against the count rate on the position 7 of the slit mask motor. According to the results, the calculated standard deviation becomes lower for higher intensities. For count rates which are lower than 1.000.000 counts/sec, the standard deviation may exceed the 10% of the calculated dead time value.

One more way to limit the uncertainty is to increase the number of cycles. By the comparison of the measurements between the two days, we concluded that if we increase the number of cycles from 10 to 40, the uncertainty is decreased by a factor of two. Though, if we perform measurements with the ratio N3/N near 0.5 and the number of counts/sec above 1.000.000 then 10 cycles are enough to limit the standard deviation below 3%.

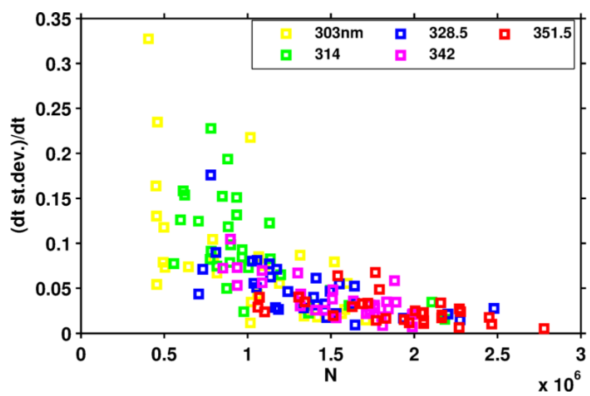

Figure 15. Dependence of the ratio between the standard deviation and the dead time from the intensity for each position of the micrometer.

As it can be perceived from figures 13 and 14 there is no detectable dependence of the calculated dead time from wavelength. The dead time was also found to be independent from the count rate if the ratio N3/N ranges from 0.4 to 0.6. We should also refer that there were efforts to find if there is any dependence from temperature, by using measurements of the dead time for different temperatures and no detectable dependence was found.

3.5. Examples for the determination of the dead time that provides the optimum correction

As already mentioned, there are several cases when the dead time which is calculated by Brewer may differ from the nominal by more than 2ns. In most of these cases, after fixing possible problems of the instrument electronics and resetting the high voltage, the calculated dead time is getting closer to its nominal value. Though, the decision for the dead time value that must be used for the correction of the measurements is not always easy, since we cannot be sure if the calculated dead time is real or if the main reason for what we see is a problem of the lamp or the electronics. There are more problems that can make difficult the decision, such as very noisy results or dependence of the results from the intensity of the incident light.

The attenuation of the neutral density filters is known to be independent of the intensity; thus measurements of the attenuation with different intensities can be used as a criterion for the dead time value that should be used. The process to achieve that has already been described in paragraph 2. After the measurements have been performed, by using different dead time values (with a step equal to 0.1ns), the attenuation for each wavelength and each filter is calculated. The dead time value that provides the optimum correction is considered to be the one for which the calculated relative attenuation between different positions of the FW#2 is independent from the intensity. In the following the results of the specific test are shown for three different instruments. For older cases, where measurements of the attenuation of the neutral density filters did not exist, the determination of the dead time value that provides the optimum correction can be achieved by making comparisons with near-simultaneous TOC measurements from satellites or from co-located ground based instruments.

Brewer#185

B185 is an instrument for which the nominal dead time was originally set to 33ns, while the calculated dead time was near 29ns. After 8 July of 2014 the nominal value was also set to 29ns. Both the nominal and the calculated dead time for the low and the high intensity of the lamp are presented in Figure 16.

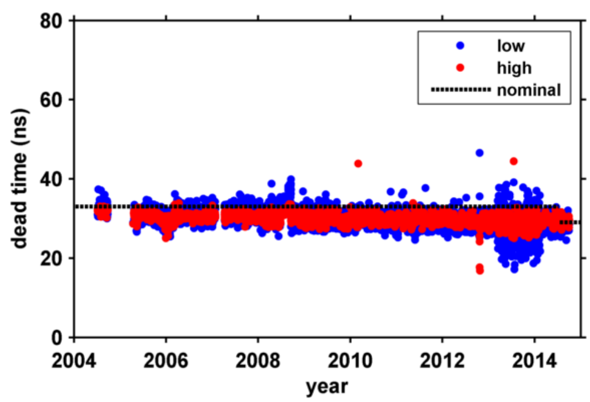

Figure 16. The nominal and the calculated dead time for B185

In order to validate the dead time correction we performed measurements of the attenuation of the neutral density filters using a wide range of intensities. As it is shown in Figure 17, there is a specific dead time value for which the calculated attenuation is independent from the intensity. The specific procedure can also be a criterion for the optimum value of the attenuation of the neutral density filters.

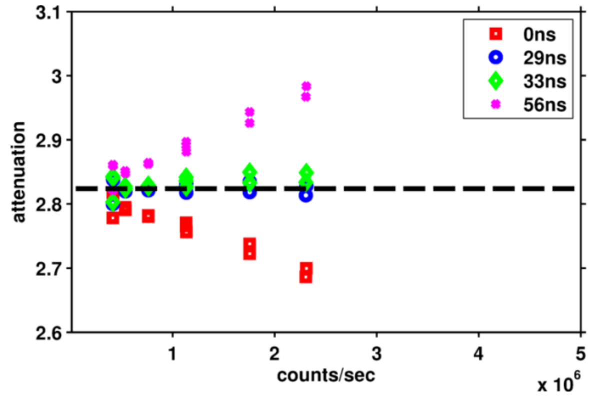

Figure 17. Calculated relative attenuation between the positions 1 and 0 of the FW#2 for 360nm and for different dead time values.

The procedure shown in Figure 17 is repeated for all the wavelengths and all the positions of FW#2. The values of the irradiance for which the noise to signal ratio is very high are not used. Additionally, the outliers are inspected visually and it is decided if they should be removed or not. The mean dead time and the corresponding standard deviation are then calculated from the remaining values as it is demonstrated in figure 18.

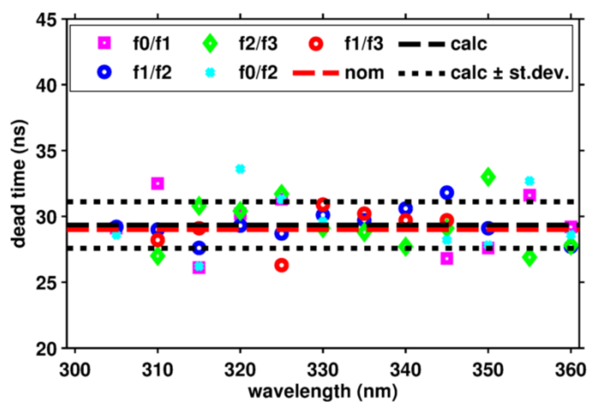

Figure 18. Calculated dead time for the B185, by using the neutral density filters.

For B185, the dead time value for which we estimated that the optimum correction of the irradiance is achieved, is very close to the nominal (and the calculated from the sun and from the standard lamp). The standard deviation is near 2ns.

<u>Brewer 005</u>

For B005 different kinds of problems are shown. In Figure 19, a sudden change of the calculated dead time occurred when the preamplifier board of the instrument was changed. Before the change, the calculated dead time was about 10ns lower compared to its nominal value.

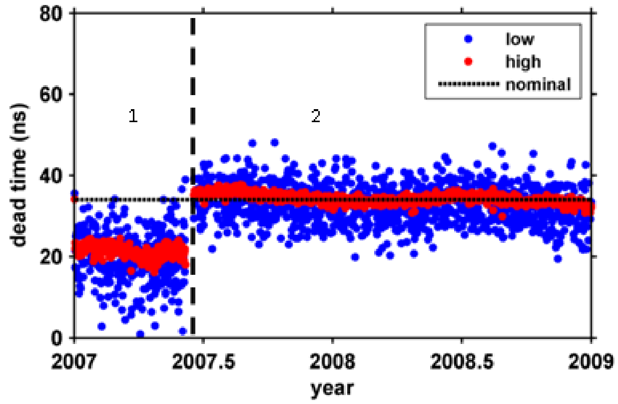

Figure 19. The nominal and the calculated dead time for Brewer 005 (period 2007 – 2009)

In order to decide the value of the dead time that should be used prior to 2007.5, the TOC was derived by using different dead time values and then it was compared with satellite data. The change of the preamplifier board was performed near the mid of June. Thus we used data from the mid of May until the mid of July. Specifically, the overpasses of OMI satellite above the location where the Brewer is set are performed near the local noon, which means that during May, June, and July the overpasses are performed for air masses which can be lower than 1.15. Thus, the TOC from one month before until one month after the "break" as it is calculated from Brewer for air masses lower than 1.15 is compared with the TOC from OMI. The comparison is performed for different dead time corrections. The ratio between the TOC from Brewer and the TOC from OMI was normalized and then its dependence from the measured intensity on slit 5 was found. The results are shown in Figure 20.

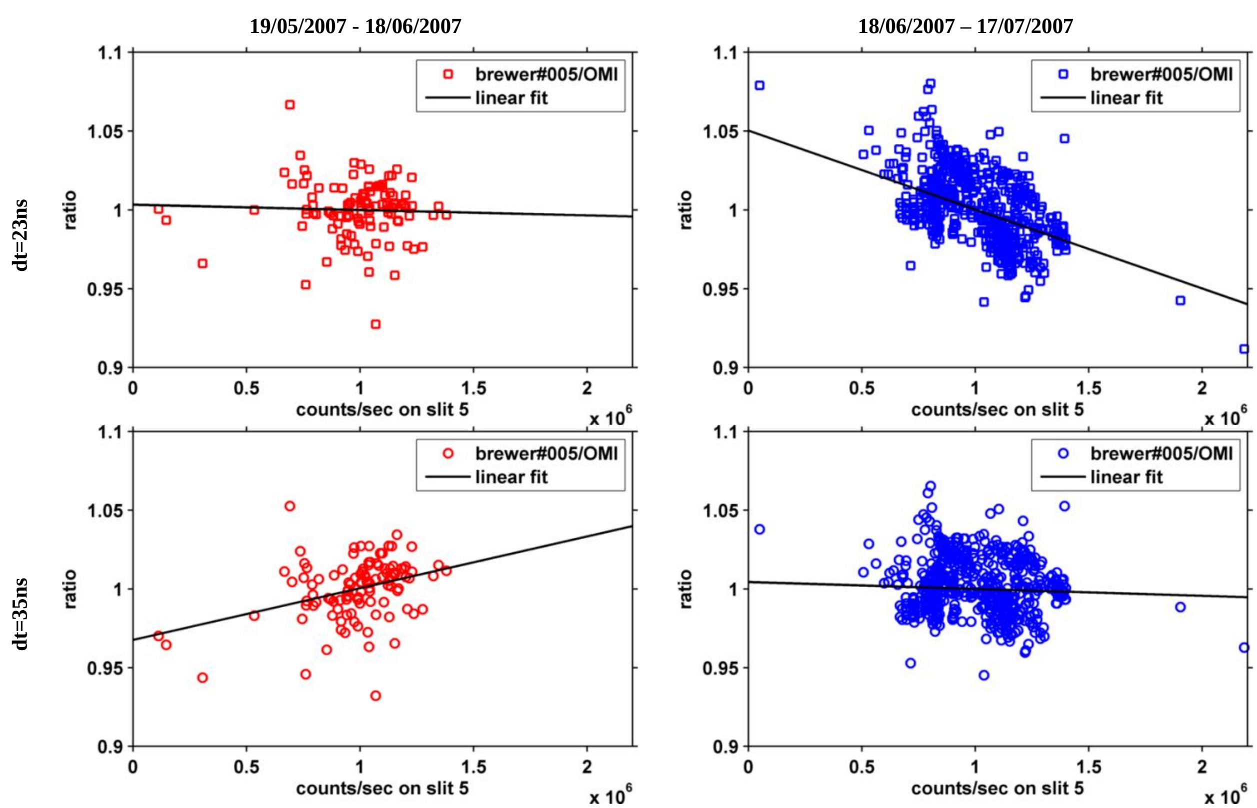

Figure 20. Comparison between the TOC from B005 for different dead time values and from OMI

Before the “break”, the use of a dead time value near the nominal leads to the calculation of intensity dependent TOC values. The dependence from the intensity is not observed if we use the mean calculated dead time value. After the “break”, the ratio is independent from the intensity when the new calculated dead time values are used.

For the period prior to 2007.5, it was relatively easy to decide if the mean calculated dead time is the one that should be used. Though, there are many occasions where the decision for the dead time value that should be used is more complex. In figure 21, the calculated dead time for the period 2012 – 2015 and for the same instrument is presented. The presented period has been divided in three sub-periods, in each of which, a different problem can be observed.

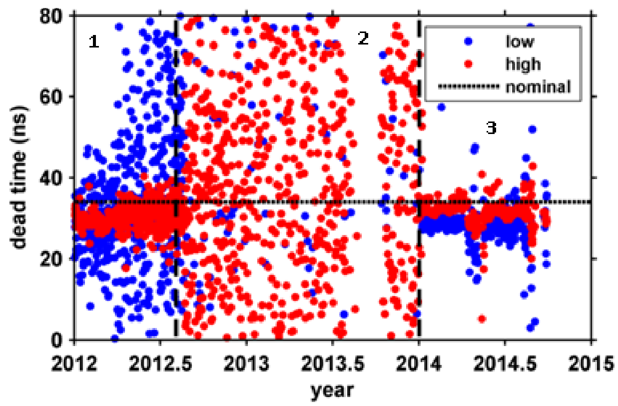

Figure 21. The nominal and the calculated dead time for B005 (period 2012 – 2015)

During period 1, the calculated dead time is lower than the nominal and noisy. The noise is due to the low intensity of the used standard lamp. The dead time value that should be used can be decided by a similar process as the one presented in figure 20. During the period 2, the standard lamp that was used during the period 1 was replaced by a new one. The noise during period 2 is even higher than in period 1 and the reason is that the filament of the new lamp was almost entirely out of the field of view of the instrument, for the specific type of measurements; thus the signal was even lower than in period 1. During period 3, the problem of the low signal is solved; though the calculated dead time for the high and for the low intensity is different. The specific result indicates that the dead time is dependent from the intensity. It is possible that a reset of the high voltage of the PMT is needed.

The dependence of the calculated dead time from the intensity is also obvious in the results from the direct sun measurements as can be seen in Figure 22. It should be noted that the ratio N3/N is close to 0.5 for the entire period and does not affect the calculated dead time.

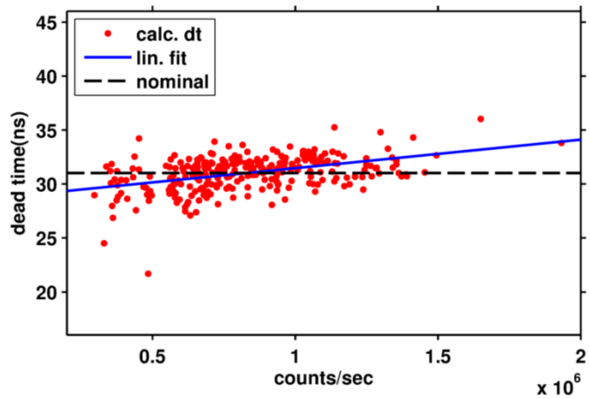

Figure 22. The dead time that is calculated from direct sun measurements during the period 3, as a function of the intensity on position 7 of the slit mask motor.

If we try to decide the dead time value that provides the optimum correction by using the neutral density filters test that was described in paragraph 2, the spread of the calculated values round the mean is very high (standard deviation is greater than 5ns). The reason is that the calculated dead time is dependent on the used intensity range. It should be noted that for the test, only direct sun measurements were used and the stray light correction was performed by subtracting the intensity at 290nm from the rest of the measurements.

<u>Brewer#086</u>

Finally, the period 2010 – 2015 for B086 is studied. Here, the specific period has been divided in 5 sub-periods. The calculated dead time from the standard lamp is presented in Figure 23.

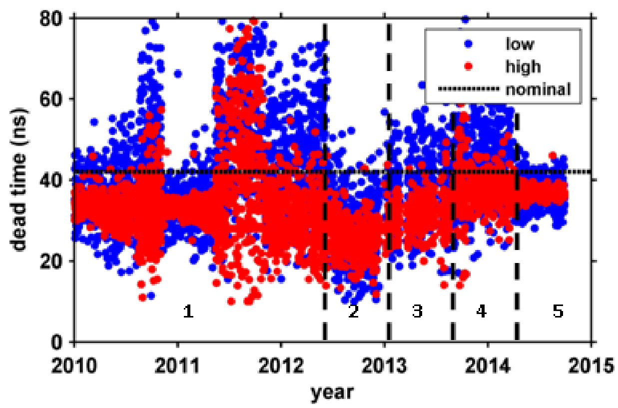

Figure 23. The nominal and the calculated dead time for B086 (period 2012 – 2015)

During period 1, the mean calculated dead time is lower than the nominal and ranges between 32ns and 35ns. The very high noise is due to the low signal of the standard lamp. In 2011, the neutral density filter test was performed and the results are shown in Figure 24. According to these results, the value that should be used is 34ns.

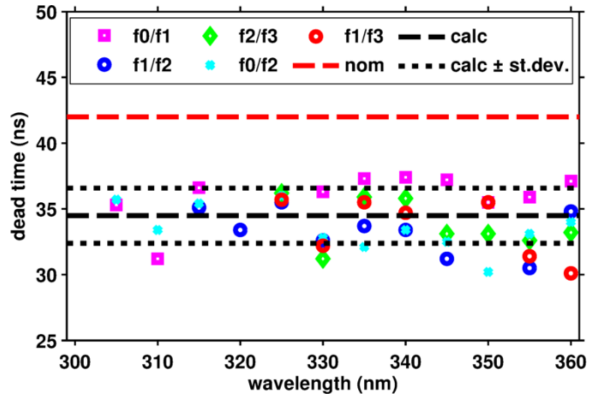

Figure 24. Calculated dead time for the B086, by using the neutral density filters (2011).

During the period 2, the mean calculated dead time drop to about 25ns. Since no measurements of the neutral density filters attenuation exist for that period, an effort to determine the dead time from comparison of the TOC derived from B086 with the TOC from OMI. Although a value near 25ns gives better agreement, the results are very uncertain. This is mainly because the effect of dead time on the calculation of TOC from double monochromator Brewers is weaker than the corresponding effect on single monochromator Brewers.

After the maintenance of the spectrometer and an effort to improve the focusing of the instrument, the mean calculated dead time escalated to about 34ns and remained to this level during the period 3. In the beginning of period 4, the High Voltage of the PMT was reset to a new value and the mean calculated dead time increased to near 38ns. To reduce the noise, the standard lamp was changed in the beginning of period 5, while after a few days the cycles of the slit mask were increased from 10 to 20. Both the results of the neutral density filters test and the dead time from the sun for the period 5 are in very good agreement with the calculated dead time.

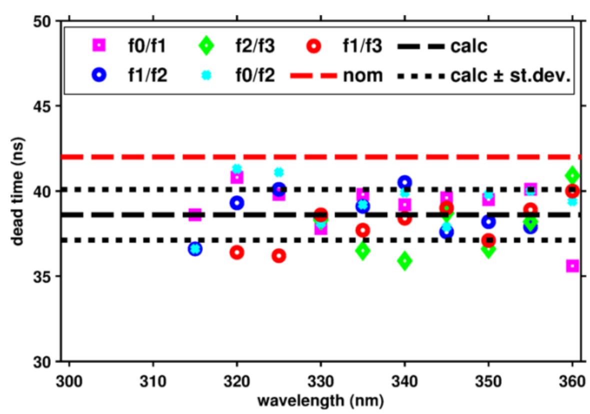

Figure 25. Calculated dead time for the B086, by using the neutral density filters (2014).

4. Main conclusions

In the present paragraph, the main results and the main conclusions that came up from the STSM are summarized. An important conclusion of the present study is that the key factor for the accurate determination of the dead time is the ratio of the count rates between the different positions of the slit mask motor. If the ratio between the count rates on the positions 3 and 7 is not within 0.3 and 0.7, then the dead time is underestimated. Increase of the signal and of the number of cycles leads to reduced noise on the final results. The two main theories for the calculation of the dead time (extended and non-extended) were tested and the final results did not differ by more than 0.5ns.

As long as the count rate remains below 1 million counts/sec, even an error of 10ns on the used dead time does not induce errors greater than 1.5% on the calculated irradiance. For higher intensities the errors are more important. The maximum count rate during global or direct sun UV scans does not exceed 3 – 3.5 million counts/sec. Even in this case, the error in the calculated intensity due to a 2ns error in the used dead time is of the order of 1%. Though there are instruments for which the used dead time differs from the calculated by more than 10ns. For these cases, the error in the calculated irradiance may be of the order of 5%.

For the calculation of TOC, the uncertainties which are related with the dead time are highly dependent from the type of the instrument. For the double monochromator Brewers, the error in the calculated TOC does not exceed 2%, even when the error in the used dead time is 10ns. The corresponding error in the calculated TOC for single monochromator Brewers may be of the order of 5 – 8%. The difference between the single and the double monochromator Brewers is mainly due to the different shape of the spectral response for instruments of different type.

Finally, within the context of the STSM, a new method was developed and optimized in order to determine the dead time value that provides the optimum correction of the measurements.

5. Future collaboration with the host institution

The collaboration with the host institution continues within activities of the WG1 of the cost action such as the temperature dependence and the cosine response of the instruments.

6. Foreseen publications to result from the STSM

The results of the STSM will be presented in the forthcoming COST1207 meeting in Delft. Additionally a paper based on the results of the STSM will be sent to a peer reviewed journal.

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