

Correction of SOHO CELIAS/SEM EUV Measurements Saturated by Extreme Solar Flare Events

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Abstract. The solar irradiance in the Extreme Ultraviolet (EUV) spectral bands has been observed with a 15 s cadence by the SOHO Solar EUV Monitor (SEM) since 1995. During remarkably intense solar flares the SEM EUV measurements are saturated in the central (zero) order channel (0.1 – 50.0 nm) by the flare soft X-ray and EUV flux. The first order EUV channel (26 – 34 nm) is not saturated by the flare flux because of its limited bandwidth, but it is sensitive to the arrival of Solar Energetic Particles (SEP). While both channels detect nearly equal SEP fluxes, their contributions to the count rate is sensibly negligible in the zero order channel but must be accounted for and removed from the first channel count rate. SEP contribution to the measured SEM signals usually follows the EUV peak for the gradual solar flare events. Correcting the extreme solar flare SEM EUV measurements may reveal currently unclear relations between the flare magnitude, dynamics observed in different EUV spectral bands, and the measured Earth atmosphere response. A simple and effective correction technique based on analysis of SEM count-rate profiles, GOES X-ray, and GOES proton data has been developed and used for correcting EUV measurements for the five extreme solar flare events of July 14, 2000, October 28, November 2, November 4, 2003, and January 20, 2005. Although none of the 2000 and 2003 flare *peaks* were contaminated by the presence of SEPs, the January 20, 2005 SEPs were unusually prompt and contaminated the peak. The estimated accuracy of the correction is about $\pm 7.5\%$ for large X-class events.

Key words: Sun: EUV radiation – Sun: flares – Sun: particle emission – Sun: solar-terrestrial relations

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1. Introduction

Solar Extreme Ultraviolet (EUV) variability has been observed by the SOHO Solar EUV Monitor (SEM) (Judge et al. 1998) since Dec 1995. SEM observations of extreme solar flare events with high temporal resolution (15 s) may reveal still unknown relations between the peak amplitude, the dynamics of a solar flare in the EUV bands, and the resultant ionospheric effects (Meier et al. 2002; Tsurutani et al. 2005). Tsurutani et al. (2005) compared some “Halloween” events (Oct–Nov, 2003) and the Bastille Day (BD, Jul 14, 2000) event using SEM first order (Ch 1) 26 – 34 nm count rates, the GOES x-ray flux, the Libreville, Gabon Total Electron Content (TEC) data, and the GUVI (TIMED) dayglow data. The comparison showed that the Oct 28, 2003 event was the most

intense flare of the four analyzed events in the SEM first order EUV wavelengths with the flare peak amplitude about two times larger than the Bastille Day event. The TEC increase was even larger, up to 25 TECU (Oct 28, 2003) compared to about 5 – 7 TECU for Nov 4, Oct 29 and the BD events.

Uncorrected SEM Ch 1 measurements of extreme solar flare events are strongly contaminated after the SEP flux arrives. The time of contamination depends on the SEP arrival time and may continue for several hours. A model of the SEM response to a quasi-isotropic SEP fluence allowed us to determine both the range of proton incident energies and the function of SEM sensitivity to the SEP flux which was found to have a maximum at about 12 MeV (Didkovsky et al. 2006). The SEP count rate contribution to the Ch 1 signal may be substantially larger than the EUV peak of an extreme solar flare. This SEP contamination does not affect the measured EUV peak amplitude of the solar flare when the SEP flux at

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1 AU comes after the EUV peak, but it creates a problem in the temporal analysis of the flare if the particles arrive within 10 – 15 min after the beginning of the flare, as happened in the Jan 20, 2005 event (Bieber et al. 2005).

The SEM zero order channel (Ch 0) detects both solar EUV and soft X-ray irradiation in contrast with the 26 – 34 nm Ch 1 spectral band, and a comparison of the two could thereby show flare related spectral variability. Unfortunately, the SEM Ch 0 measurements of large X-class solar flares are saturated by the soft X-ray and EUV fluxes during impulsive phases of these flares and must be corrected.

Thus, correction of saturated Ch 0 and contaminated Ch 1 SEM profiles is a critical task for analysis of EUV variability created by the intense X-class solar flares which have a profound impact on the Earth’s atmosphere. Our first attempt to evaluate the amplitude of the BD solar flare in the 19.5 nm bandpass was based on restored saturated SOHO/EIT EUV images (Didkovsky et al. 2005). The flare peak amplitude was modeled by extracting and integrating CCD pixel signals from the area surrounding the flare assuming an efficient pixel ‘bleeding’ (blooming) process. If the efficiency of the electron-hole charge transfer from the overfilled flare area to neighboring pixels is high, integrating the electrons trapped in the blooming areas of the EIT CCD can be used to rebuild the flare EUV amplitude, and provide a lower limit to the solar flux.

Here we propose an advanced technique to correct saturated and contaminated SEM measurements using Ch 0 and Ch 1 15 s count rates together with GOES X-ray and GOES proton flux data. For the work described in this paper, we used the term Ch 1 to reference a combined, mean for the + and - first-order, measurements of the SEM. Our model of SEM sensitivity to energetic particles (Didkovsky et al. 2006) showed a peak sensitivity at about 12 MeV. It allows us to use GOES proton data in the energy range of 8 – 16 MeV as a reference channel to represent the particle related increase in the SEM Ch 1.

2. Data Observations and Technique

The present technique for correcting SEM saturated measurements was applied to data from five extreme solar flare events: Jul 14, 2000, Oct 28, Nov 2, and Nov 4, 2003, and Jan 20, 2005. In this paper we will demonstrate a step by step procedure for correcting the BD SEM measurements.

Figure 1 shows SEM high cadence count-rate data for the BD solar flare event. The top panel represents the combined, mean for the ‘+’ and ‘-’ first order, measurements (thick line) after subtracting the pedestal of 272.4 cnt/s related to the full-disk solar background flux. The thin line shows the GOES proton flux profile in the energy range of 8 – 16 MeV with the particle starting time of about 10.9 UT. The bottom panel shows the original (raw) Ch 0 SEM count rate data saturated by the solar flare flux in the spectral band of 0.1 – 50.0 nm.

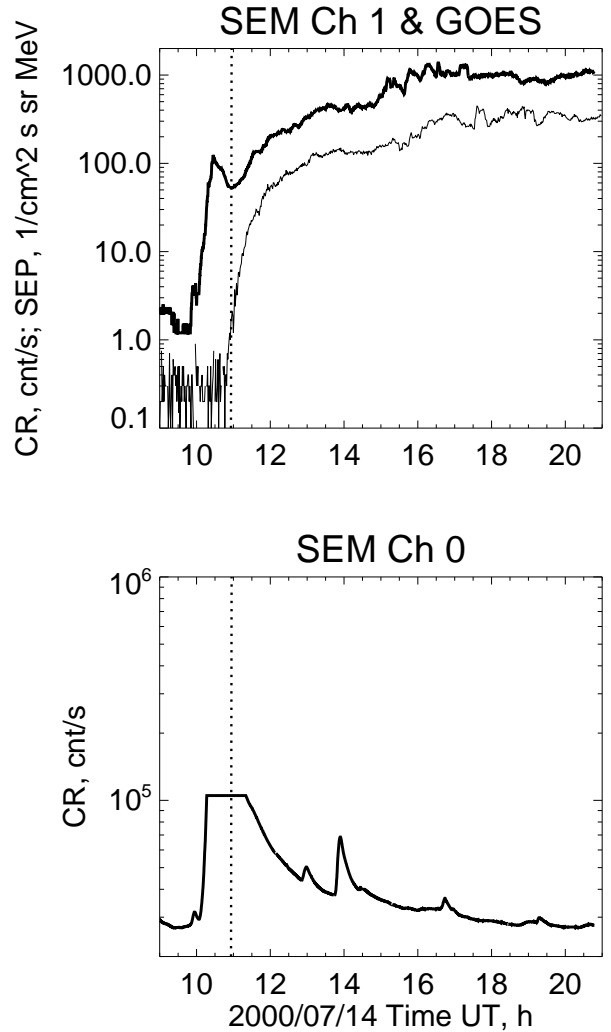


Fig. 1. SEM count-rate (CR) measurements (thick lines) and GOES 8 – 16 MeV particle flux (thin line) for the BD solar flare event. The SEM Ch 1 (top panel) is contaminated by the rise SEP flux after the time indicated by the vertical dotted line. The SEM Ch 0 (bottom panel) is saturated by the soft x-ray and EUV flux. The unsaturated decay portion of the SEM Ch 0 profile is only weakly affected by the increased SEP flux.

2.1. Assumptions and Simplifications of the Method

A 100% accurate correction of the saturated SEM Ch 0 is not possible, even for a known EUV response function of the SEM, due to the unknown spectral energy distribution of the solar flare in the observed spectral region. The unknown particle energy-flux distribution at the SOHO location presents a similar problem for the correction of the solar flare associated SEP-contamination of the Ch 1 signal. Thus, we have to make some simplifications and apply some assumptions resulting in corrected profiles that are of a lower level of accuracy than the typical data, (absence of extreme solar flares) which is both unsaturated and uncontaminated.

The simplification, which affects the amplitude of the saturated Ch 0 electromagnetic flux measurements is the replacement of the real (unknown) shape of the flare peak in the spectral band of 0.1 – 50 nm with a modeled peak based

on two converging power-law curves. Usually, this leads to a sharper (larger amplitude) modeled peak than the smoother real peak, introducing a peak amplitude error of a few percent. Each of the two converging power-law curves is modeled using a large number of count rate points (20 – 60 or more) on the lower amplitude channel profiles, either in the initial portion of the flare rise time profile or in the post-saturated decay profile. In addition to modeling the power-law curves with a large number of count rate points in the low amplitude parts of the flare profiles, we note that the amplitude of the peak restored with two power law curves depends on the temporal position of the converging point. Comparing the peak position in other spectral bands, we have found that with a few minutes uncertainty, the temporal position of the Ch 0 peak may be considered between positions of the GOES XL and the SEM Ch 1 peaks.

Another simplification, which does not affect the flare calculated peak amplitude and has a minor impact on the ionospheric effects, is the modeling of a flare decay profile. The Ch 1 uncorrected flare decay profile is usually contaminated by the SEP signal but, typically, well after the peak of the EUV flux. In contrast, the Ch 0 count rate signal for the decay profile of a solar flare has a substantially larger component related to the EUV and soft X-ray irradiation than to the SEP flux. With a spectral similarity simplification, the measured Ch 0 EUV and soft X-ray decay profile may be transferred with an appropriate scaling to the corrected Ch 1 profile.

2.2. Step by Step Procedure of Correction

A first step in the correction procedure includes two preparatory operations: a “clean up” of the Ch 0 decay profile by subtracting the SEP related count rate signal, and determination of the temporal position of the flare peak point. The Ch 0 decay profile consists of a sum of unknown X-ray, EUV and SEP related portions. With an assumption of a quasi isotropic SEP flux and similar Ch 0 and Ch1 instrumental response to the protons (Didkovsky et al. 2006), the SEP related portion of the Ch 0 signal may be considered as known from either the GOES (8 – 16 MeV) channel or from the Ch 1 count rate data. For extreme solar flare events with intense SEP flux, Ch 1 count rate measurements for the decay portion of the EUV solar flare profile are strongly contaminated by the SEP flux, with a SEP to EUV ratio of about 100 to 1. This means that Ch 1 data for the decay phase of the flare may be considered as a SEP signal with an error of about 1 %. Then, the EUV Ch 0 count rate signal for the decay phase, $EY0_D$, may be modeled as

$$EY0_D(k) = Y0_D(k) - Y0_{SEP}(k) \quad (1)$$

where $Y0_{SEP}$ is the SEP signal determined from the contaminated Ch 1 measurements as

$$Y0_{SEP}(k) = Y1_D(k) \quad (2)$$

where k is the index which corresponds to the time when the SEPs started to arrive and $Y1_D$ is the Ch 1 measurement. After this procedure a portion of the Ch 0 unsaturated decay profile consists of (with accuracy of about 99 %) the X-ray

and EUV signal and thus may be used to model the whole decay profile with a power law curve in the next step.

An evaluation of the time when the peak of the flare in the Ch 0 spectral band occurs is based on a comparison of temporal position of unsaturated Ch 1 and GOES XL (0.1 – 0.8 nm) flare peaks. The GOES channel XL has the same short wavelength limit as the SEM Ch 0 (0.1 – 50 nm) and represents the input from the soft X-ray radiation. The SEM Ch 1 (26 – 34 nm) adds the spectral irradiation component in the middle of the Ch 0 spectral band. A comparison of the temporal position of the unsaturated Ch 0 peak for a number of X-1 class solar flares (not in this paper) showed that maximal Ch 0 fluxes occur quite close (no more than a few minutes difference) to the time when the GOES XL channel had measured the corresponding flare peaks. For the BD solar flare we compared (Figure 2) both GOES-8 XL and XS (0.05 – 0.3 nm) flare profiles (thin lines) and the position of the flare peak for the Ch 1 signal (dotted line). We have assumed

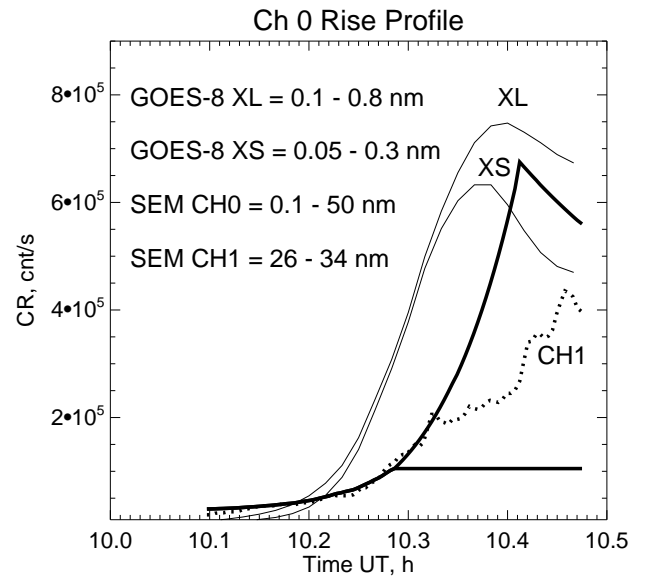


Fig. 2. A comparison of the temporal position of the solar flare peak in both GOES-8 X-ray channels (XL and XS) and the SEM Ch 1 (dotted line) for the BD 2000 solar flare. The location of the peak for the Ch 0 (thick line) is assumed to be between the Ch 1 and XL peaks. Ch 1 profile (dotted line) was scaled up to fit the initial rise phase of the Ch 0 profile.

that the temporal position of the Ch 0 peak should be between the GOES-8 XL peak and the Ch 1 peak. The exact temporal position of the flare peak in the SEM Ch 0 is unknown. With the above assumption the uncertainty of the time of the Ch 0 peak is about ± 1.8 min, which leads to a peak amplitude uncertainty of about $\pm 5.5\%$.

The second step in the correction is modeling of the whole decay portion of the saturated Ch 0 profile. The power law curve should fit the corrected EUV portion of the Ch 0 profile and be extended to the time of the evaluated peak of the flare. To model this profile we fit the “cleaned up” EUV

signal in the first step, $EY_{0D}(j)$, to a j -portion of the power law curve $Y_D(i)$, minimizing the distance between them:

$$\sum_j (Y_D(j) - EY_{0D}(j))^2 = \min \quad (3)$$

where $Y_D(i)$ is

$$Y_D(i) = \frac{a}{(i-b)^k} + P_0 \quad (4)$$

and a , b , and k are constant coefficients, i is the index, which begins with the time of the flare peak, j is the index, $j < i$, related to the unsaturated decay portion of the Ch 0 profile, and P_0 is the Ch 0 pedestal. The important point here is to fit the modeled curve to the measured curve after ‘removing’ the signals associated with both particles and EUV fluctuations. This means that the entire modeled curve (3) for the decay profile should ‘ignore’ both EUV and SEP fluctuations.

Figure 3 shows the modeled (dotted line) fit of the decay signal profile. The identification of the Ch 0 EUV fluctuations is done using the GOES XL reference signal shown in Figure 3 with the thin line. The entire modeled curve (4) is used

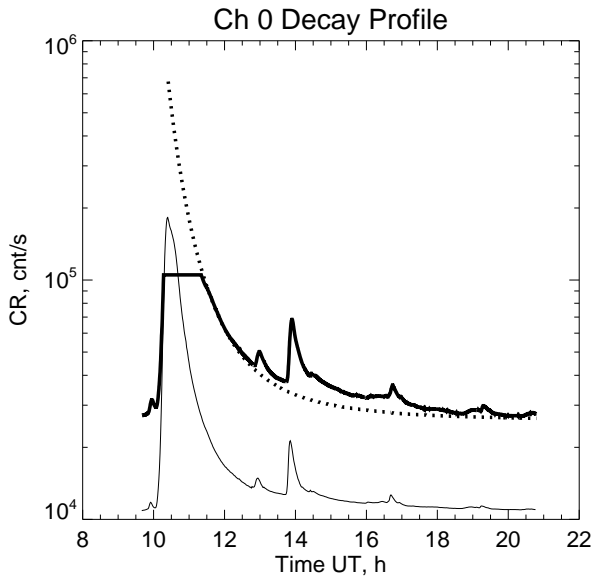


Fig. 3. A modeled curve (dotted line) to fit the decay signal profile of the BD 2000 extreme solar flare. Some signal fluctuations between about 13 and 20 UT are due to the EUV flux fluctuations visible in the GOES reference XL (soft X-ray) profile (thin line).

to determine the amplitude of the peak and the shape of the decay profile.

The third step in modeling is to fit the rise Ch 0 profile using the initial (unsaturated) portion of the Ch 0 profile and the amplitude of the peak determined in the second step. Figure 2 (above) shows the fitting curve of the rise profile. The Ch 1 measurements Y_{1R} are scaled up ($Y_{1R} * n_1$) to fit the initial rise time portion of the Ch 0 profile (before the saturation), shown by the dotted line in Fig 2. We have analyzed a number of X-class solar flares (not the issue of this work) to see how well the scaled Ch 1 could fit Ch 0 and found that they usually fit each other within 5 – 7%. This fitting ratio is

used in the next step to scale back the Ch 0 decay profile to the Ch 1 decay profile for complete correction of the channel.

The final step is to scale back the Ch 0 corrected decay profile to the Ch 1:

$$Y_{1B}(j) = Y_{0B}(j)/n_1 \quad (5)$$

The scaled back Ch 0 profile should match the entire decay profile of the Ch 1 at the point where Ch 1 is contaminated by the SEPs. The corrected profiles of both channels are shown in Figure 4.

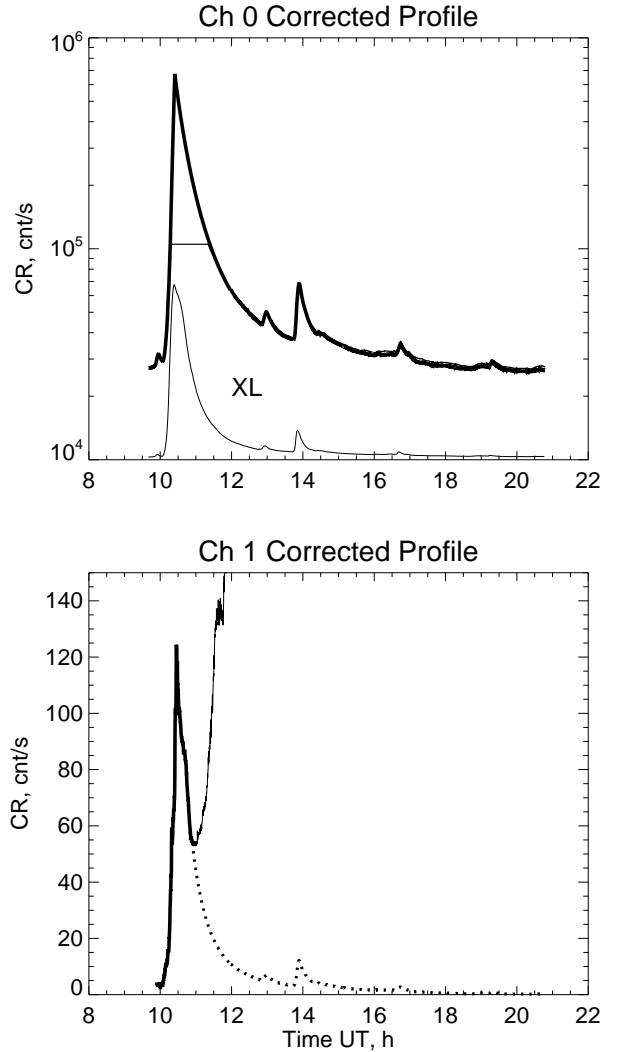


Fig. 4. Restored profiles of the Ch 0 (top) and the Ch 1 (bottom) count rates. The thin line on the top portion of Fig 4 shows the GOES XL profile as a reference for the EUV related fluctuations on the corrected decay parts of the flare.

3. Results

The results of correction of the SEM data for the analyzed events are shown in Table 1. Note that none of the 2000 – 2003 flare peaks were contaminated by the SEP fluxes and that the EUV Ch 1 peak amplitudes were determined directly from the SEM measurements. The errors of about $\pm 2.0\%$ for

Table 1. Summary of corrected amplitudes for the analyzed extreme solar flares

Date	Ch 1, cnt/s	Ch 0, 1E6 cnt/s	Time interval between Ch 1 and XL peaks, min
Jul 14, 2000	124.4 ± 2.4	0.68 ± 0.075	3.6
Oct 28, 2003	218.6 ± 4.4	1.55 ± 0.30	4.8
Nov 02, 2003	44.7 ± 0.9	0.68 ± 0.18	12
Nov 04, 2003	105.0 ± 2.1	1.42 ± 0.07	3.6
Jan 20, 2005	202.8 ± 12.6	1.40 ± 0.20	3.0

Ch 1 (and less for Ch 0) are related to the method of subtracting the full disk solar background. The Jan 20, 2005 EUV flare peak was contaminated by SEPs and the error of about $\pm 7.0\%$ is related to both the solar disk background, and to some uncertainty in the SEM Ch 1 response to the SEP flux. The peak amplitude mean error related to the uncertainty of the Ch 0 peak position is about $\pm 7.5\%$ for the analyzed extreme solar flare events.

4. Concluding Comments

We have developed a method for correcting SEM saturated Ch 0 and contaminated Ch 1 count rate measurements for five extreme solar flare events. The correction algorithm is based on SEM EUV data (both channels), GOES XL, and GOES proton flux measurements.

Comparing the temporal position of a usually unsaturated SEM Ch 1 flare peak with an unsaturated GOES XL peak gives us the temporal range for modeling the Ch 0 flare peak. The length of this temporal range (see Table 1, last column) is proportional to the uncertainty of the Ch 0 peak position. Calculating the Ch 0 peak amplitude at the limits of this interval allowed us to estimate the mean uncertainty of the Ch 0 corrected amplitude to be about $\pm 7.5\%$.

SEM modeled sensitivity to SEPs allowed us to use the GOES proton flux measurements in the energy range of 8 – 16 MeV as a temporal reference. These measurements show the approximate start time of Ch 1 contamination by the SEPs. This information was used to correct the Ch 1 flare profile by subtracting the SEP count rate from the Ch 1 data. After correcting the Ch 1 profile, it is possible to determine the net SEP flux in the energy range of the modeled SEM sensitivity.

In the correction process a flare specific Ch 0 to Ch 1 count rate normalization ratio, n_1 , was determined to fit the Ch 1 count rate data profile prior to Ch 0 saturation. Following Ch 0 saturation we assume that the Ch 1 count rate decay is proportional to the Ch 0 count rate, and with the same n_1 scaling factor.

Restored SEM EUV Ch 0 flare peak amplitudes for large (X-class) solar flare events allow us to extend the previous (Tsurutani et al. 2005) study of the effects of the Ch 1 and Ch 0 EUV flare dynamics and the resulting effects on the ionosphere and the Earth's atmosphere generally. The proposed algorithm allows one to model the entire Ch 1 flare profile

from beginning to end to obtain the total 26–34 nm flux. This could be useful for detailed ionospheric modeling work in the future.

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