The IMPACT Solar Wind Electron Analyzer (SWEA): Reconstruction of the SWEA Transmission Function by Numerical Simulation and Data Analysis

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Received: 15 January 2010 / Accepted: 13 May 2011 / Published online: 9 June 2011
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Abstract The IMPACT SWEA instruments on board the twin STEREO spacecraft detect the solar wind electrons with energies between 1 and 2000 eV. The instruments provide 3-dimensional velocity distributions, pitch angle distributions and solar wind properties at two vantage points in the ecliptic at 1 AU. A few days after launch suppression of the low energy solar wind electrons was detected, which makes data analysis challenging and causes a significant loss of information below 50 eV. This paper describes the methods used to both understand the nature of the problem and to recover the most information about the low energy solar wind electrons from the measured datasets. These include numerical simulations, in-flight calibration results, and data reconstruction methods that allow the calculation of solar wind parameter proxies with minor limitations.

Keywords Solar wind · Space instrumentation

1 Introduction

The twin Solar Terrestrial Relations Observatory (STEREO) mission (Kaiser et al. 2008) consists of two spacecraft (Ahead and Behind) positioned at two vantage points in the ecliptic and carry nearly identical instrumentation. As part of the In situ Measurements of Particles and CME Transients (IMPACT) experiment (Luhmann et al. 2008), the Solar Wind Electron Analyzer (SWEA) instruments (Sauvaud et al. 2008) provide in situ electron measurements at both STEREO spacecraft. The SWEA instruments are hemispheric top-hat electrostatic analyzers (Carlson and McFaden 1998) with deflector plates mounted at the

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aperture and with microchannel plate (MCP) detectors. SWEA is mounted at the end of the IMPACT boom (Ullrich et al. 2008) on the anti-sunward side of the STEREO spacecraft in order to avoid direct sunlight entering into the particle detector. The almost complete angular scan ($360^\circ \times 120^\circ$) and the energy sweep from 1–2000 eV aims to provide three-dimensional solar wind electron velocity distributions, pitch angle distributions of suprathermal electrons and to define the bulk properties with 30-s time resolution.

This paper describes the SWEA data reduction based on laboratory and in-flight calibrations supported with numerical simulations. In particular, it focuses on problems with the detection of electrons below 50 eV, apparent when the STEREO spacecraft are in heliocentric orbit, which in turn limit the availability of thermal core electron parameters. The primary SWEA measurements at the higher energies which are used for detecting the electron halo and strahl (heat flux) (Rosenbauer et al. 1997) populations are not affected, and are available as described in the earlier report by Sauvaud et al. (2008).

2 SWEA Instrument Details

Principal features of the SWEA instrument design relative to the low energy electron measurement issue are shown in Fig. 1. The sensor assembly has a negative potential V_0 relative to the spacecraft body. The sensor is inside a housing that is electrically connected to the spacecraft body. The incident electrons enter through the external grid, which is at spacecraft body potential, and then pass through the internal grid, decelerating through the potential V_0 . Before they hit a detector (red rectangle) the electrons have to pass the deflection system and the electrostatic analyzer that select the elevation angle and the energy of the detected electrons, respectively. The deflection system consists of two toroidal electrodes made from ULTEM insulator metalized on the external side. The entrance of the electrostatic analyzer is formed by the “top cap” electrode coated with NUFLON (conductive black PTFE with a carbon filler). We will call this electrode as “cap” in the paper text. It is important to note that both internal and external grids are attached to the posts by small screws with insulating washers seen from the deflector part (see Fig. 1, right panel). There are 8 grid posts, and insulator washers are located on 4 of 8 posts only.

Fig. 1 *Left*: the schematic of the SWEA sensor. *Black lines* correspond to the metal parts of the sensor. See text for details. *Right*: the design of the post carrying the grids. Insulator washers are shown in *red*

3 SWEA In-flight Measurements

At the beginning of the STEREO mission (launch on 25 October 2006) the SWEA instruments performed the first measurements on 29 October 2006. After the deployment of the boom on 1 November 2006 (STA 16:30 and STB 19:45) both SWEA instruments performed complete 3D solar wind electron measurements. The electron energy spectra obtained before and soon after boom deployment can be well fitted with a Maxwellian solar wind electron core plus halo population, using the anticipated instrument response. This can be obtained from a simulation based on laboratory calibration results and additionally with help of our knowledge about the secondary electron spectrum. The fitting procedure assumes that both the solar wind electron core and halo populations arriving at the instrument have Maxwellian distribution. The left panel of Fig. 2 shows a “proper” initial spectrum. Note that the electron spectra lack any signature of a photo-electron peak flux at lowest energies, a feature commonly seen with solar wind electron instruments mounted close to the spacecraft body.

The electron energy spectra below 50 eV measured by SWEA on STEREO were first observed to be distorted on 3 November 2006. The distortion is most evident in Fig. 2 as a minimum in the counts versus energy spectrum occurring around 10–20 eV.

Both SWEA instruments degraded in the same manner. The energy spectra degradation is gradual with time, appearing as a dip (giving the appearance of two bands in the energy time (ET) spectrogram in Fig. 3) that is formed by 4 November 2006. In the remainder of this paper, we will argue that the peak in counts seen above approximately 10 eV are

Fig. 2 “Good” electron spectrum measured on 1 November 2006 (*left panel*) and “distorted” spectrum measured two weeks later (*right panel*). *Light blue dashed curve* shows the expected real spectrum of the solar wind electrons. *Vertical line* shows the position of the spectral minimum of the “distorted” spectrum

Fig. 3 Energy-time electron spectrogram taken on 14 November 2006. SWEA was exposed to solar light at 1340 UT and the thruster was ON between 1400 UT and 1432 UT

associated with incoming solar wind electrons. We believe that the SWEA transmission for incoming particles decreases to zero between 100 eV and 10 eV, resulting in a peak in counts around 50 eV. The response to primary incoming solar wind electrons will be discussed in Sects. 4, 5, and 6. In addition we suggest that the peak seen below 10 eV is due to secondary electrons released from surfaces interior to SWEA as it is discussed in Sect. 7.

Since 4 November 2006 a two-peak distribution has been a constant feature of SWEA observation except for a few special cases. One case of temporary recovering of the “normal” behavior is shown in Fig. 3. On 14 November 2006 the thrusters of the spacecraft were fired between 1400 UT and 1432 UT on STA and between 1600 and 1623 UT on STB. It was rotated 35 degrees to the sun line for this maneuver. Before this maneuver the measured SWEA energy spectra were distorted. After the maneuver and particularly after the thruster firing the SWEA spectra almost returned to the expected undistorted shape for a few hours (see the one-band spectrogram in Fig. 3 after 1445 UT). Later the measurements gradually returned to a stable compromised state with the distorted low energy spectra. After the third Earth flyby (29–30 November 2006), both SWEA instruments gave improved (i.e. almost nominal) spectra for a short time, but then reverted in a similar fashion. The investigation of the compromised low energy electron measurements is the main subject of this report.

4 The Transmission Function of the Instrument

The general shape of the SWEA spectrum has not changed or changed negligibly since the 4 of November 2006 except for spacecraft operations and Earth flybys. At least the position of the low energy spectrum cutoff is almost constant. This SWEA property can be described in terms of a “transmission function” $T(E)$, where E is the electron energy. Let us define $J_E(E)$ to be the true solar wind differential energy flux in $\text{s}^{-1} \text{cm}^{-2} \text{sr}^{-1} \text{eV}^{-1} \text{eV}$, $G(V0, E)$ the geometrical factor of the sensor in $\text{cm}^2 \text{sr eV/eV}$ that depends on $V0$, $C_{Ideal}(E)$ the expected count spectrum of an ideal (as it was at the very beginning of the mission) SWEA sensor for some incident electron distribution and for zero spacecraft potential, and $C_{Meas}(E)$ the measured counts. Note that the geometrical factor G depends on $V0$ and energy E (see Sect. 5). Then

$$C_{Ideal}(E) = J_E(E) \cdot G(V0, E) \quad (1)$$

$$C_{Meas}(E) = C_{Ideal}(E) \cdot T(E) + C_{second}(E) \quad (2)$$

Here $C_{second}(E)$ is the count rate due to secondary electrons produced inside the SWEA sensor, and generating counts in SWEA energy channels below 30 eV. This effect will be discussed in detail in Sect. 7. We first address the measurements above 15 eV, for which we believe the secondary count rate contribution is generally negligible. We will show that the measured count rates above 15 eV are reasonably well accounted for by considering only the primary incoming solar wind electrons and applying a transmission function $T(E)$ derived from the data.

The data analysis shows that the same $T(E)$ can be applied for the entire data set. Figure 4 presents the analysis of two electron spectra measured with about 21 months time lag. The data are summarized in Table 1. The electron number density was taken from SWAVES data. Other significant parameters of the electron distribution shown in the table are obtained

Fig. 4 Data analysis of two SWEA spectra from Table 1. *Right panel*: the transmission function $T_{OBS}(E)$ applicable for both cases and for entire 2007–2010 period. *Left panel*: case (1). The blue curve is the measured spectrum $C_{Meas}(E)$. Green one is the $C_{Ideal}(E)$ obtained by fitting procedure (see the text). The red spectrum $C_{Obs}(E)$ is a convolution of the $C_{Ideal}(E)$ and $T_{OBS}(E)$. The *central plot* is the same as the *left one* but for case (2)

Table 1 Parameters of two analyzed spectra. In both cases the number density is obtained from the SWAVES instrument on STEREO. Other parameters are calculated by best fit of the measured spectra (see the text for details)

#	Date	$N_{total}, \text{cm}^{-3}$ from SWAVES	T_{Core}, eV	N_{Halo}/N_{Total}	T_{Halo}, eV
1	13 March 2007, 0110 UT	8.0	9.9	0.035	48.0
2	26 October 2008, 1643 UT	6.4	7.6	0.011	50.0

from fitting the observed spectra according to the following scheme:

This procedure performs a fit of $C_{Obs}(E)$ (red curves in Fig. 4) to $C_{Meas}(E)$, where $C_{Obs}(E)$ is calculated as a convolution of the assumed $C_{Ideal}(E)$ spectrum and the transmission function. An assumption of the $C_{Ideal}(E)$ is calculated in each step of the fitting loop from the assumed parameters as a sum of two Maxwellian (core and halo) distributions. The $C_{Obs}(E)$ fit was performed for energies greater than the characteristic energy of the valley between the secondary electrons spectrum and the “true” electron peak. We assumed that secondary electrons can not contaminate significantly the fit in this energy range. The reconstructed original spectra (green curves) in Fig. 4 look reasonable. Any $C_{Meas}(E)$ measured in the period 2007–2010 can be explained by the convolution of a realistic $C_{Ideal}(E)$ and the constant in time $T(E)$. Let us now define $T_{OBS}(E)$ to be the transmission function derived from the data. Function $T_{OBS}(E)$ was demonstrated to be independent of the azimuthal angle of the incident electrons (it is the same for any anode), but varies with elevation angle (see Sects. 2 and 6 for details).

In this section we have demonstrated empirically that SWEA is characterized by a transmission function with a low energy cutoff. In the next 2 sections we will explore the possible physical explanations for this behavior.

5 Spacecraft Potential and Wake Space Charge Versus Internal Problems

At the outset of our investigation the main question was: is the problem due to something blocking the low energy electrons outside or inside the instrument? If the problem is outside of the instrument, it should be either the satellite potential or a space charge in the spacecraft wake. Both these factors are not quite realistic because of a very high potential that would be needed to affect SWEA electrons, however this possibility should still be considered. We rejected the influence of a positive spacecraft potential, which could make a cutoff in the spectrum but would increase the count rate in the rest of the spectrum, contrary to the measurements (see Fig. 4).

A negative spacecraft potential would lead to $T(E) = T_{SCP}(E)$ shown in red in Fig. 5. Note that the argument E of $T_{SCP}(E)$ is the electron energy inside the analyzer. The spacecraft potential rejects low energy incident electrons, and transposes the remaining part of the electron distribution toward the low energies. The count rate of such transposed electrons decreases because the sensor geometrical factor is a linear function of the particle energy, but it is still not zero. Thus $T_{SCP}(E)$ is not zero for low energies, what is very different from $T_{OBS}(E)$ (blue) derived from observations. As a result, we can also rule out this hypothesis.

A space charge in the spacecraft wake is more complex to treat and so we had to consider this case in detail. Such a space charge is equivalent to a hypothetical case when the external housing of the sensor is completely disconnected from the instrument and has a negative potential V_{ext} . Note that the sensor itself still has a potential $V_{sc} + V_0$. Let us look to the potential hill profile in Fig. 6 (solid black curve).

Such an external potential hill can produce an energy cutoff in the observed spectrum. For this case, the transmission function would be similar in shape to $T_{OBS}(E)$ that was derived from the data. However, if we set V_0 equal to the value of the potential hill, the situation transforms to the spacecraft negative charge case, when the potential profile looks like a step (red dashed curve in Fig. 6), so $T(E) = T_{SCP}(E)$. In order to test whether the space charge was contributing to $T(E)$, we examined the data obtained during in flight V_0 sweeping test. We assume that the incident electron distribution is the same for all V_0 values applying

Fig. 5 Observed $T_{OBS}(E)$ (blue) and a theoretical $T_{SCP}(E)$ calculated for the -20 V spacecraft potential (red). Note that non-zero $T_{SCP}(E)$ at the energies less than 10 eV is created by the count of the incident electrons with energy above 20 eV and decelerated inside the instrument

Fig. 6 A negative potential hill (U_{ext}) in the case of a strong space charge or a floating external grid (black). Dashed red line shows the potential profile in the case of $V_0 = -20$ V

Fig. 7 Measured and simulated spectra for V_0 test performed on 12 Dec 2008. Left: $C_{Ideal}(E)$ (green solid), and $C_{SCP}(E)$ (green dashed) for hypothetical case when spacecraft potential equal to -25 V or (that is equivalent) $V_0 = -25$ V. Middle panel: $V_0 = 0$. Blue: observed spectrum $C_{Meas}(E)$, green: simulated incident spectrum $C_{Ideal}(E)$, and red: $C_{Obs}(E) = T_{OBS}(E) \cdot C_{Ideal}(E)$. Right: the same but for $V_0 = -25$ V, here the green $C_{SCP}(E) = C_{Ideal}(E) \cdot T_{SCP}(E)$ (equal to the green dashed curve in the left panel), and red is the convolution of the green spectrum with $T_{OBS}(E)$

during this test. The middle panel of Fig. 7 shows the observed spectrum $C_{Meas}(E)$ (blue curve in Fig. 5) for $V_0 = 0$, that is a convolution of the “ideal” spectrum (green) with our $T_{OBS}(E)$. Now let us apply $V_0 = -25$ V that should convert a hypothetical potential hill to a potential step described above. Thus

$$C_{SCP}(E) = C_{Ideal}(E) \cdot T_{SCP}(E)$$

Such $C_{SCP}(E)$ is shown by the green dashed curve in the left panel of Fig. 7. Note again that $C_{Ideal}(E)$ is the same for all V_0 values. But the observed spectrum shown in blue in the right panel is quite different from the expected one (green). The measured spectrum can be fitted by:

$$C_{Meas}(E) = C_{SCP}(E) \cdot T_{OBS}(E) = C_{Ideal}(E) \cdot T_{SCP}(E) \cdot T_{OBS}(E)$$

Thus we see that our transmission function $T_{OBS}(E)$ acts on the electron spectrum already modified by spacecraft potential. Hence we can conclude that the $T_{OBS}(E)$ is determined by something *inside* the sensor. It is worth noting here that the high count rate of the secondary electrons is additional evidence that an initial strong flux of electrons below 10 eV reaches the interior of the sensor without any significant modification (see Sect. 7 for details).

The conclusion is that none of the external factors, spacecraft potential or space charge in the satellite wake, can cause the observed effect.

6 Where is the “Bottle Neck” of the Instrument?

From the previous section we understand that the problem causing the observed spectrum cutoff is hidden inside the sensor. We considered several possibilities briefly presented below:

MCP Saturation

A high count rate of the electrons of the energy below 20 eV can saturate the MCP of the sensor. The simulations of the dynamic saturation (when the MCP continues to be saturated some time after the high incident electron flux drops off) shows a consistent measured spectrum. However, this result demands too many unrealistic assumptions: (1) too high front-end electronics threshold, and (2) too low number of MCP channels charged by one event. Moreover the effective transmission function should depend on V_0 since the MCP count rate is reducing dramatically when the $V_0 = -25$ V, and we see from Sect. 5 that the transmission function is always constant. So we have to reject this hypothesis.

Grids Insulators Charge

There is 0.1 mm Kapton foil between the grid posts and the internal grid of the sensor. Yet, as mentioned in Sect. 2, there are insulator washers on the inner side of the even grid posts. These insulators can retain a surface charge created by solar wind electron flux or they can retain a volume charge generated by high energy particles. We have tested both possibilities by numerical ray tracing and found that neither Kapton foil charge nor washers charged up to 1000 V can produce the proper transmission function. In the first case the electric field is never strong enough, and in the second case the sensor count rate should greatly vary from anode to anode since the washers are on the even posts only, but this is not observed.

Deflector Plates Charge

As mentioned in Sect. 2, the deflector plates are made from insulator, and the back surface of this deflector is not metalized. Numerical simulations show that volume charging of the deflector corresponding to the surface potential -3200 V can create a -25 V potential hill at the entrance of the top hat analyzer. The corresponding transmission function looks reasonable but not quite similar to $T_{OBS}(E)$ obtained from the experiment. The main problem of this hypothesis is: to reach such high volume charge the instrument has to be in the radiation belts almost permanently. If not, the volume charge is recombined within a week. The corresponding simulation was made using the “SPENVIS 4.6.00” ESA code. Additionally, such a potential hill should block the low energy secondary electrons that are seen in the measured spectra (see Sect. 7 for details). Thus we also rejected this hypothesis.

Tophat Surface Charge

All of the proposed explanations described above do not account for the observed transmission function at low electron energies. There is still one remaining possibility: a low (about -4 V) negative charge of the NUFLOON coating of the analyzer’s cap. Figure 8 shows that such a small potential can significantly change the trajectories of 30 eV electrons and even suppress them.

To provide more substantial evidence for this explanation we estimate the shape of $T(E)$ for this case. The theoretical calculation of a $T(E)$ function was carried out as follows: We

Fig. 8 Electron trajectories (*black*) in the case of the negative potential on the analyzer's top hat (*blue*). Test electrons of 30 eV starts from the analyzer. The majority can not leave the sensor. It means that very few of 30 eV electron from the solar wind can reach the analyzer. The analyzer central energy is 30 eV (that correspond to the 4.8 V on the inner hemisphere), and deflector plates are OFF

Fig. 9 The *solid curves* show $T_{OBS}(E)$ for the maximal deflection (*blue line*) and zero deflection (*red line*). The "histogram-like" profiles show the simulated transmission for -4 V cap voltage. See text for details

used full 3D numerical model of the analyzer that exactly reproduced the real instrument. The ray tracing was made for analyzer and deflector voltages equivalent to the flight voltage table. The individual runs were performed for 11 energy steps in the $[1-151]$ eV energy range, and for two characteristic deflections: the maximal deflection, and zero deflection. Actually, the simulation of the extreme deflection was a sum (as it is in flight) of 4 individual deflection levels filling the angular sector between 45° and 65° . The test electrons were launched by Monte-Carlo method from a random position on the vertical plane located outside of the sensor ($X = 80$ mm in Fig. 8). The elevation angle and the azimuthal angle of the test electrons were random in the $[-80^\circ - +80^\circ]$ and $[-11.5^\circ - +11.5^\circ]$ corresponding ranges. The particle energy was uniformly random in the $[0.5-1.5] \times E_i$ range. Here E_i is the analyzer central energy. Two runs were performed for each setup of the analyzer: one with a zero voltage of the cap ($U_{TH} = 0$) and another one with $U_{TH} = -4$ V. The total number of test particles for each run was 5×10^6 . The result of each run is the total number of particles reaching the MCP detector: $C_0(E_i)$ and $C_{-4}(E_i)$. Here index "0" or "-4" indicates the U_{TH} . Thus

$$T(E_i) = C_{-4}(E_i)/C_0(E_i)$$

The comparison of the resulting transmission function and $T_{OBS}(E)$ is shown in Fig. 9. The simulated transmissions agree with the transmissions derived from the data. Note again that this hypothesis is the only one that can reproduce the actual transmission. Section 7 gives additional support for the present approach.

NUFLON was already successfully used in space instruments (for instance it was used for the CODIF mass spectrometer onboard of the CLUSTER satellites). The charging problems of NUFLON have not to our knowledge been previously reported. The reason why we see an effect potentially related to NUFLON charging is in the conditions of the SWEA

accommodation on STEREO. At the end of the anti-sunward pointed IMPACT boom, the SWEA analyzer cap is always in the spacecraft shadow and always at very low temperature. The conductivity of NUFLON is provided by chains of the minuscule grains of carbon. Such chains may be fragmented at low temperature, leading to creation of small isolated domains on the NUFLON surface. These domains could be charged up to 100 eV by continuous electron fluxes from the solar wind. Since the relative surface of the isolated domains is small, the effective potential of the entire surface can be much smaller, like the -4 V derived from the observed $T_{OBS}(E)$. This hypothesis is consistent with observations (see Sect. 3). When due to a spacecraft maneuver the analyzer cap is exposed to the sunlight, the photoelectrons, created by UV photons striking the cap, neutralize the surface charge immediately and we observe the initial complete spectrum. The cold positive ions of high density produced by the spacecraft thruster produce the same effect. Note that the simulated transmission varies with the elevation angle in accordance with the variation of the real $T_{OBS}(E)$. The same effect was observed after the third Earth flyby when a significant flow of thermalized ions reduced the cap surface potential.

7 Secondary Electrons Produce the Observed Low Energy Peak

As mentioned in Sect. 4 (see formula 2) the SWEA counts below 10 eV are counts of the secondary electrons produced inside the analyzer. We can prove this with an enhanced ray tracing simulation. To do this we have to add a special feature to our original ray-tracing code as follows: When a test electron strikes any conductive surface of a simulated device, a procedure of secondary electron generation is invoked. The procedure uses the probabilistic model of a secondary electron emission described by Furman and Pivi (2002). The initial electron can be: (1) absorbed with emission of one, several or zero true secondary electron; (2) rediffused with emission of one, several or zero true secondary electrons; (3) backscattered. The probability of each process depends on the energy of the incident electron. The probabilistic energy spectrum of true secondary, rediffused and backscattered electrons depends on the energy of the incident electron. Thus the procedure of the secondary electron emission is a chain of random processes and outcomes: (a) a choice between an absorption, rediffusion or backscattering; (b) a choice of the energy of the rediffused or backscattered electron; (c) energy remaining for true secondary electrons; (d) number of secondary electrons born; (e) and the energy of each true secondary electrons. All electrons are emitted randomly and uniformly in the free hemisphere confined by the surface of the analyzer part that the test electron interacts with. All corresponding constants are taken from Furman and Pivi (2002) under the assumption of a copper interaction surface. We believe that this assumption generally works for any analyzer parts.

Each new born electron generates a new ray tracing vertex that can lead to the new electron absorption or to the generation of new ray tracing vertices. The electrons cascade until the total absorption of all secondary electrons by analyzer parts or by the detector occurs. In the last case the detector counts one event. Note that a single event is generated even if several secondary electrons reach the MCP.

For the complete simulation, each individual run for a specific central energy of the analyzer is performed in the energy range [1–2000 eV]. The initial electrons were launched randomly within this range with the probability density proportional to $1/E^2$ to keep the differential energy flux spectrum flat. Other simulation conditions were similar to those described in Sect. 6. Figure 10 shows the counts of secondary electrons only. Any initial electron reaching the detector without collision with analyzer electrodes was removed from

Fig. 10 2D distribution of secondary electrons that were generated inside the sensor and that reached the MCP as a function of the energy of initial electrons (*horizontal axis*) and the central energy of the electrostatic analyzer (*vertical axis*). Dashed line marks the location of the rediffused electrons. Left: $U_{TH} = 0$. Right: $U_{TH} = -4$ V

consideration. The plot is a 2D distribution of the detector counts as a function of the energy of the initial electrons and the central energy of the analyzer.

The count distribution generally consists of two clusters: (1) the rediffused and backscattered electrons generated by initial electrons with energy below ~ 100 eV (the elongated distribution near green dashed line); (2) the low energy true secondary electrons generated by initial electrons with energy greater than 50 eV. One can see that the rediffused electrons have a maximum count at the lowest energy, but the same distribution for a negative potential on the analyzer cap has a maximum at $E_{An} \sim 3\text{--}10$ eV. This means that the cap itself is the source of many secondary electrons that reach the detector. Let $S(E, E_{An})$ be the 2D secondary electron differential spectrum in $\text{s}^{-1} \text{eV}^{-1}$. Here E is the energy of the initial electrons and E_{An} the analyzer central energy. Let $J_F(E) = \text{const}$ be a flat differential energy flux spectrum of initial electrons in $\text{cm}^{-2} \text{sr}^{-1} \text{eV}^{-1} \text{s}^{-1} \text{eV}$ (test electrons are distributed uniformly in the angular space). Then:

$$\frac{S(E, E_{An})}{J_F(E)/E} = G_S(E, E_{An})$$

Here $G_S(E, E_{An})$ is similar to a differential geometrical factor in $\text{cm}^2 \text{sr}$, but for secondary electrons only. Now if a true incident differential energy flux spectrum is $J_E(E)$, the observed count rate of the secondary electrons is:

$$C_{second}(E_{An}) = \int J_E(E) \cdot G_S(E, E_{An})/E dE = \int C_{Ideal}(E)/G \cdot G_S(E, E_{An})/E dE$$

That is: for each E_{An} the count rate of the secondary electrons is a convolution of the input flux and $G_S(E, E_{An})$.

Now we can add the secondary electrons to our procedure to reconstruct the $C_{Meas}(E)$. Figure 11 shows such a reconstruction made for two characteristic examples (see Table 2 for details). We see that a good $C_{Meas}(E)$ taken on November of 2006 fits perfectly to bi-Maxwellian $C_{Ideal}(E)$ and $C(0)_{second}(E)$ calculated from $C_{Ideal}(E)$ for zero potential on

Fig. 11 In all panels: Blue histogram-like spectrum is $C_{Meas}(E)$; green curve is $C_{Ideal}(E)$; red dashed curve shows $C(0)_{second}(E)$ in the panels (a) and (b) and $C(-4)_{second}(E)$ in the panel (c). Red solid curve is a final best fit $C_{Obs}(E)$. The panel (a) shows the best fit of the “good” spectrum in the assumption of $U_{TH} = 0$ and $T(E)$. The panel (b) shows the best fit of a “damaged” spectrum with a standard $T_{OBS}(E)$ and secondary electrons calculated assuming $U_{TH} = 0$. The panel (c) shows the same but with secondary electrons calculated for $U_{TH} = -4$ V

Table 2 Parameters of two analyzed spectra. All parameters are calculated by best fit procedure described in the text

# and comment	Date	$N_{total}, \text{cm}^{-3}$	T_{Core}, eV	N_{Halo}/N_{Total}	T_{Halo}, eV
(1) Originally “Ideal” spectrum	2 Nov 2006	5.1	5.5	0.01	40.0
(2) Characteristic “damaged” spectrum	12 Jun 2007	5.1	6.9	0.01	55.0
(3) The same as (2), with corrected secondaries	12 Jun 2007	8.0	6.5	0.01	55.0

the analyzer cap. But the same approach does not work for a “damaged” spectrum measured on June of 2007: $C_{Ideal}(E) + C(0)_{second}(E)$ does not fit to the measured spectrum. But if we replace $C(0)_{second}(E)$ for $C(-4)_{second}(E)$ (“-4” denotes secondary electrons simulated for -4 V cap potential), we see a very reasonable fit (see panel c).

8 A Proxy of Solar Wind Electron Core Parameters

During the periods of uncompromised thermal solar wind electron detection (beginning of mission, after Earth flybys and spacecraft maneuvers) the core, halo and strahl electrons are well measured. As a result the velocity distribution moments can be calculated, and core and halo parameters are also available. Section 7 (Fig. 11(a)) shows that even for this period the resulting data can be improved if we take into account the secondary electrons generated inside the sensor. During compromised periods when the SWEA instrument transmission under 50 eV is too low, the majority of core electrons is lost, but halo, strahl, and the high energy wing of the core distribution (unless the temperature is too small) are measured. At this time the only possibility to calculate the solar wind electron core properties is the use of the secondary electron measurements, as described below.

The proxy of the core distribution is calculated by determining the best fit of the total energy spectrum under the assumption that the angular distribution of the core electrons is

Fig. 12 Blue: electron number density proxy for June 2007 calculated from “SWEA-behind”1 data. Black: ion number density from the PLASTIC instrument

uniform and by taking into account variation of $T(E)$ with the elevation angle (see Fig. 9). The fit is made according to the procedure described in Sect. 7. The fitting function is:

$$C_{Ideal}(E) \cdot T(E) + C(-4)_{second}(E)$$

Here $C_{Ideal}(E)$ is the sum of the core and halo Maxwellian distributions calculated from four free parameters: N_{total} , T_{Core} , N_{Halo}/N_{Core} , T_{Halo} . Note that $C(-4)_{second}(E)$ is recalculated at each step of the fit process from new $C_{Ideal}(E)$. An example of this proxy for core + halo solar wind electron density is shown in Fig. 12. There are limitations of the algorithm: (1) the number density below 4 cm^{-3} is not reconstructed due to contamination of $C_{second}(E)$ by photoelectrons. (2) $C_{second}(E)$ exhibits a very weak dependence on the temperature of the initial spectrum. As a result the temperature below 5 eV can not be determined.

9 Conclusions

In summary, the accommodation of the SWEA instrument on the end of the STEREO spacecraft IMPACT boom in the antisunward direction in the spacecraft (photon and bulk ion) shadow causes the analyzer cap to cool down to temperatures where the characteristics of the coating material NUFLON are modified. Its conduction capability decreases and results in charging of the cap by the dominating flux of the solar wind electrons. This must be about -4 V from simulations. The cap charging modifies the instrument transmission for low energy ($< \sim 50 \text{ eV}$) solar wind electrons. A special technique allows us to construct a proxy of the initial electron distribution using the low energy secondary electron peak. However, there are several limitations to this approach. The most significant of them is the inability to reconstruct the temperature below 5 eV. On the other hand, if the contamination of $C_{second}(E)$ by photoelectrons could be estimated, that could lead to a better proxy of the electron parameters for number densities below 4 cm^{-3} . Absolute measurements of the solar wind electron number density remain a challenge with the STEREO instrumentation set. SWEA has the problem described in the present paper, and SWAVES lacks an antenna of enough length. However, the estimation of the relative electron number density is well covered: SWEA as it is shown above, and SWAVES fortunately can use the antenna shot-noise.

The very important technical lesson learned from SWEA is that NUFLON coating should not be used for sensor parts always exposed to the high electron flux in the absence of any important flux of positive ions or solar UV photons. The NUFLON surface may be slightly charged, and a low temperature can significantly enhance this charge. In particular,

accommodations on a spacecraft with fixed orientation with respect to the Sun need to be carefully considered when using normally acceptable insulating materials in a SWEA-like instrument.

Acknowledgements We are grateful for the entire SWEA, IMPACT and STEREO team. The authors acknowledge Paul Kellogg, Benoit Lavraud, Milan Maksimovic and the SWAVES team for useful discussions.

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