ASPERA-3 ELS Measurements of Photoelectrons from Carbon Dioxide at Mars

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Abstract

The Mars Express Space Analyzer of Space Plasmas and Energetic Atoms (ASPERA-3) experiment determines the electron, ion, and neutral particle components of plasma using four instruments: Electron Spectrometer (ELS), Ion Mass Analyzer (IMA), Neutral Particle Imager (NPI), and Neutral Particle Detector (NPD). The ELS instrument determines the electron energy spectrum by collecting 128 logarithmically spaced samples of the electron spectrum between 1 eV and 20 keV every four seconds. Its 8% energy resolution is used to resolve the carbon dioxide photoelectron peaks (generated from He 30.4 nm photons) which are a dominant feature in the Martian Ionosphere. However at times, ELS oversamples the electron spectrum by conducting measurements with separation energies smaller than an 8% difference. This oversampling technique is used to improve the ELS measurement of the Mars photoelectron spectrum. During times of oversampling, ELS may be stepped in a linear fashion from 1 eV to 127 eV. In order to recover the photoelectron spectrum oversampling cases, detailed knowledge of the instrument response function must be used along with inversion methods. The procedure increases the energy resolution in the oversampled region of the energy spectrum, and thus, improves the measurement of the amplitudes of the carbon dioxide peaks.

Introduction

The European Space Agency (ESA) Mars Express spacecraft (launched June 2, 2003) reached Mars and was injected into orbit on December 25, 2003. One of the Mars Express experiments is the Analyzer of Space Plasmas and Energetic Atoms-3 (ASPERA-3) experiment [Barabash, et al., 2000, 2004] which has been measuring ions, electrons, and energetic neutral atoms (ENAs) at Mars. The Electron Spectrometer (ELS) is the instrument of the ASPERA-3 experiment which measures the electron plasma.

Prior to launch of the Mars Express spacecraft, it was known that the ionospheric spectrum contained photoelectron peaks from the atmospheric gasses, measured most recently by Mars Global Surveyor (MGS) Electron Reflectometer (ER) [Mitchell et al., 2001]. The major photoelectron peaks in the range of 21-24 eV and 27 eV result from CO2 ionization by a solar He 30.4 nm photon [Mantas and Hanson, 1979; Fox and Dalgarno, 1979]. The ELS was designed to measure these photoelectron peaks using its high-resolution modes to probe the high-altitude ionosphere and obtain a spectrum of the major photoelectron peaks. ELS is the first high-resolution ($\Delta E/E$ = 8%) electron spectrometer to observe the electron plasma in the region of a planet other than Earth.

Instrument

The ELS is a spherical top hat which samples electrons from a 4° high plane, divided into 16 sectors, each sector is 22.5° wide. ELS k-factor (average value is 7.23 ± 0.05 eV/volt) and resolution (average value is 0.083 ± 0.003 $\Delta E/E$) are slightly sector dependent and were determined by laboratory measurements at 10 keV. Energy deviations of the k-factor and resolution were folded into an energy-dependent relative microchannel plate (MCP) efficiency factor. This allowed determination of the energy independent physical geometric factor as 5.88×10^{-4} cm^2 sr.

ELS covers the energy range from 1 eV to 20 keV with two deflection power supplies. ELS deflection voltage ranges from 0 to 20.99 V for the low range and 0 to 2800.0 V for the high range (energy conversion is sector dependent, but approximately 150 eV and 20 keV for the max values). Each supply has a control resolution of 4096 linear voltage values within its full range. Of the 8192 possible deflection voltage values, 128 are selected to comprise the ELS energy sweep which occurs in 4 sec. The ELS energy sweep is a decay step sequence from its highest voltage to its lowest voltage. The last sweep step is used as a flyback step and ignored.

ELS was modeled and tested with the input spectrum taken from Mantas and Hanson [1979] at 145 km altitude as the parent electron population. Using the instrument model, instrument counts were processed to reconstruct the parent spectrum at the instrument resolution. This lead to the design of two operating mode classes, referred to as the normal or survey mode, and oversampling modes. During normal or survey mode, the energy steps are separated logarithmically and are adjacent to each other at the 50% point on the energy response curve. The reconstruction software substitutes the instrument energy response shown in Figure 1 (which is nearly Gaussian) with a box car response. The result is shown in Figure 2 where there are three points measuring the photoelectron peaks predicted by Mantas and Hanson. In the highlighted region, a blow-up in Figure 3 shows that the data values are determined from adjacent box car energy responses.

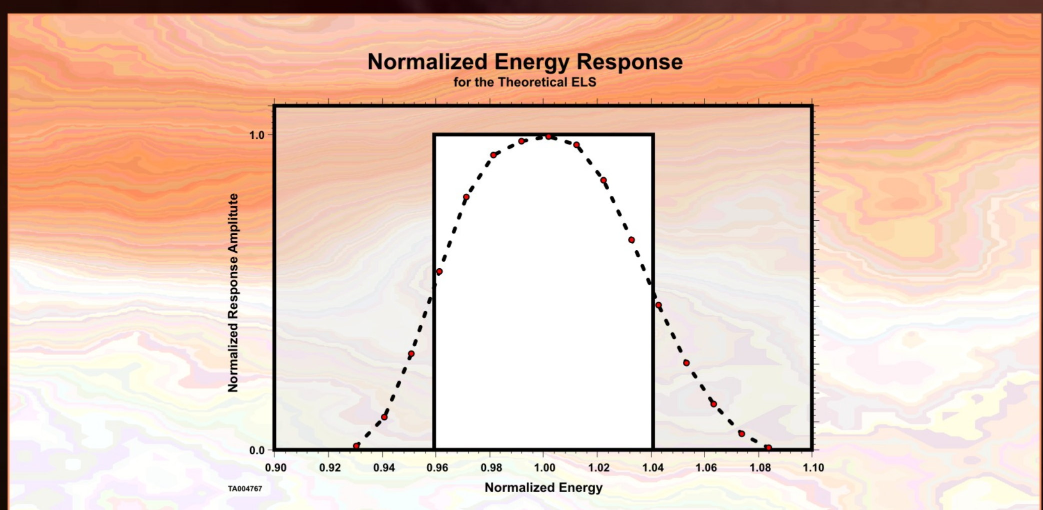

Figure 1. ELS Energy Response. The box car model used for count-to-flux reconstruction is indicated in bold and the dashed curve indicates the real instrument energy response determined from the instrument model (red dots show instrument ray trace data locations).

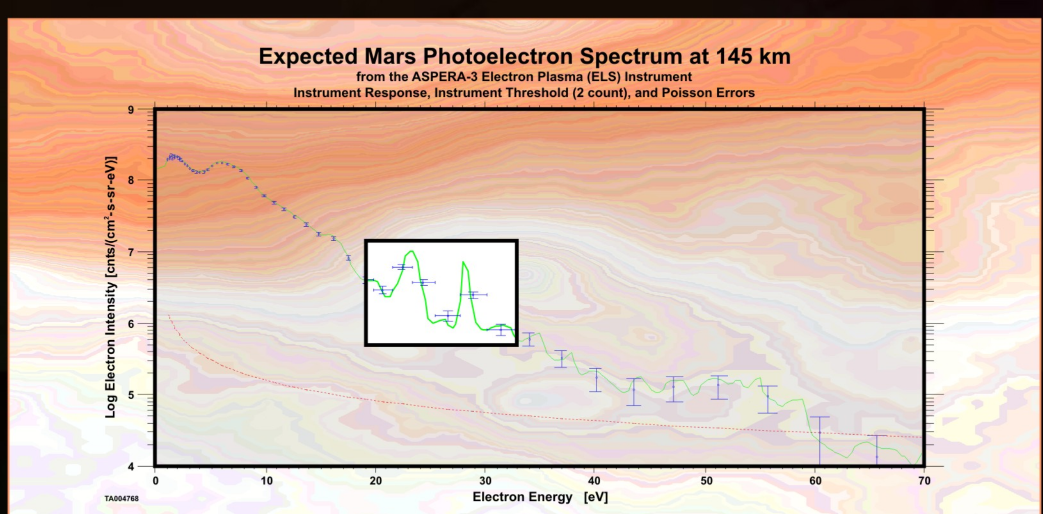

Figure 2. ELS Survey Mode Measurements. The parent spectrum (green) from Mantas and Hanson [1979] was used as the source electron distribution. Along with the ELS instrument model energy response (Figure 1 dashed curve), instrument counts were determined. Instrument characteristics (using Figure 1 bold curve) were used to reconstruct the spectrum as a series of points (blue) at the instrument's 8% energy resolution.

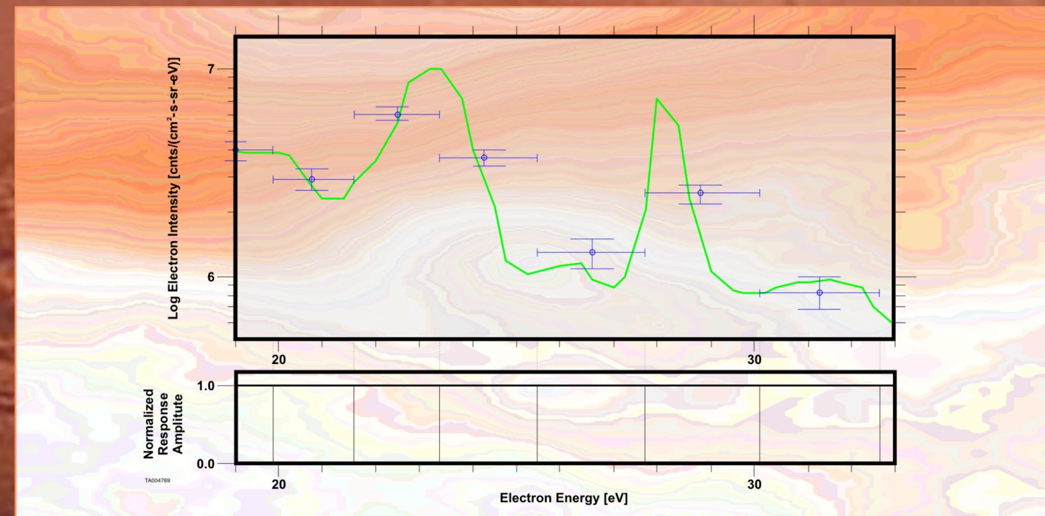

Figure 3. Determination of Survey Mode Flux. The parent spectrum (green) from Mantas and Hanson [1979] is shown with the measured flux values (blue) at the instrument's 8% resolution. The instrument response function for each datum is shown below the spectrum and is taken as box car shape.

Oversampling modes were designed to take advantage of the ELS ability to increase its sampling at selected energies. This produces a response which more closely resembles the parent electron distribution. By an overlap of four, the effective energy response has a 2% energy shift for each successive sample. Figure 4 shows this four times oversampling where the CO_2 peak structure becomes more recognizable than the survey mode sample shown in Figure 2. In the oversampling modes, the measured values still occur at the instrument resolution of 8%. A blow-up of the CO_2 peak region for this oversampling case is shown in Figure 5. The data points in Figure 5 show that the detected locations for each datum have a broader peak with lower amplitude that the input spectra. This is because the measured values are made at the instrument resolution of 8% and a box car energy response (shown at the bottom of Figure 5) is still used in the reconstruction of the energy response. These points fool the eye because they are overlapping.

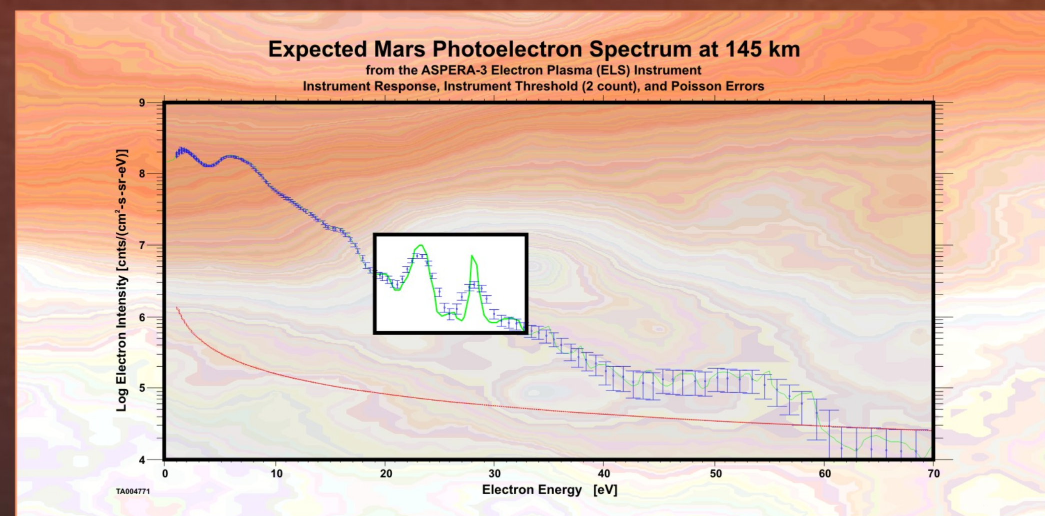

Figure 4. ELS Measurements during Oversampling Modes. The parent spectrum (green) from Mantas and Hanson [1979] was used as the source electron distribution. Along with the ELS instrument model energy response (Figure 1 dashed curve), instrument counts were determined. Instrument characteristics (using Figure 1 bold curve) were used to reconstruct the spectrum as a series of points (blue) at the instrument's 8% energy resolution. Instrument measurements overlap each other in energy space.

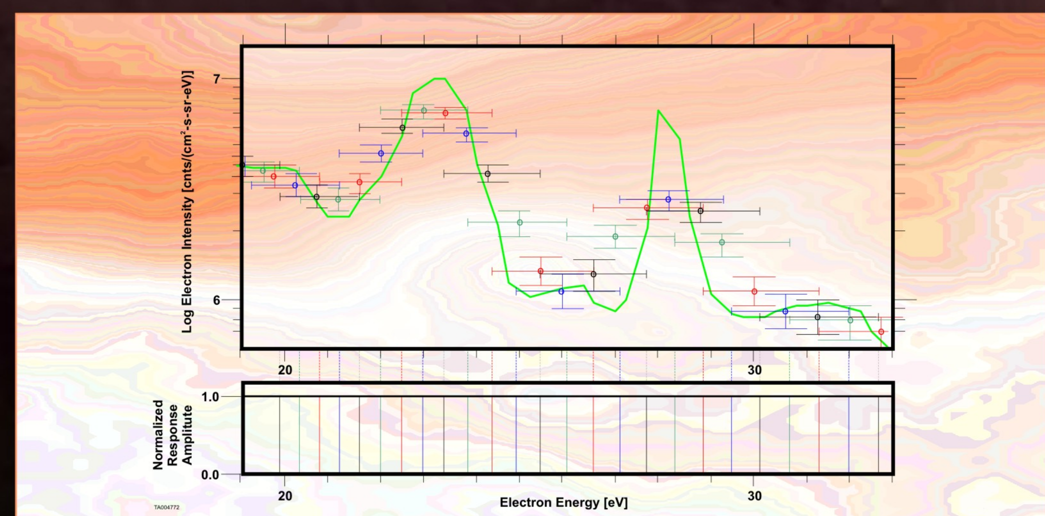

Figure 5. Measured Oversampling Flux. The parent spectrum (green) from Mantas and Hanson [1979] is shown with the measured flux values (blue) at the instrument's 8% resolution. The instrument response function for each datum is shown below the spectrum and is taken as box car shape. Note that each measurement overlaps with another measurement.

As a practical limitation, the ELS energy sweep in the ASPERA-3 instrument configuration is fixed to be 128 steps taken in 4 sec, which means that the entire ELS energy range can not be covered when performing oversampling. Different ELS oversampling modes are designed to increase the oversampling in certain regions of the spectrum, while at the same time, undersampling other regions in order to maintain the step count and timing requirement. In addition, the bit resolution and voltage stability of the ASPERA-3 data processing unit is coarser at lower voltages than at higher voltages, affecting oversampling resolution at the lower energies. Since the Mars Express spacecraft is mainly charged negatively when atmospheric CO_2 photoelectron signatures are observed, the actual oversampling achieved is less than four times within the CO_2 peak region.

ELS Oversampling

Sample overlapping provides extra information, which when combined with the instrument energy response function (dashed line in Figure 1), should act to reduce the energy resolution and produce flux values which are closer to the input parent electron distribution. This situation is illustrated in Figure 6 for the CO_2 photoelectron peak region. The photoelectron region is highlighted here because the primary CO_2 ionization peak occurs with an energy window which is less than the instrument energy response at 27 eV.

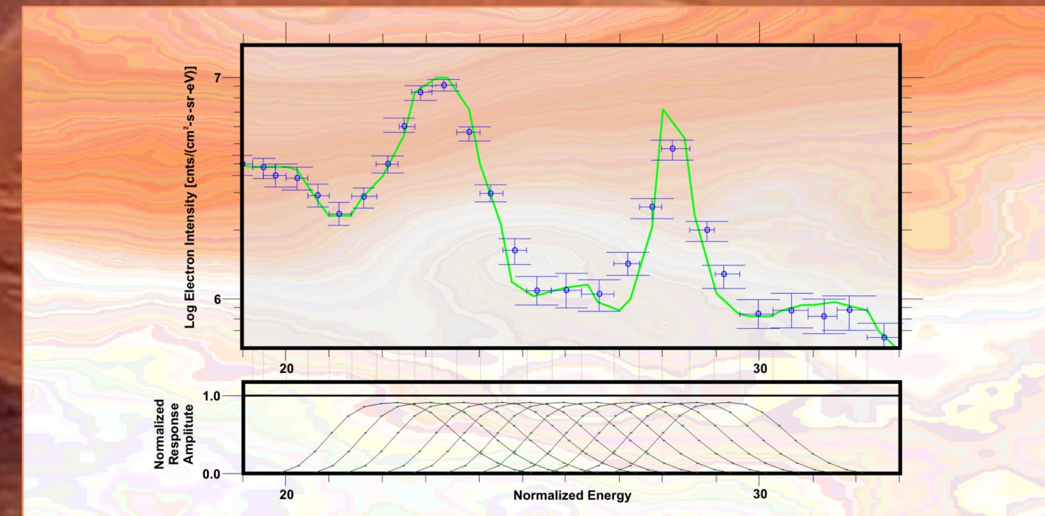

Figure 6, Projected Oversampled Resolution. The blow-up shown in Figure 5 is adjusted to show the expected oversampled energy resolution fluxes. These oversampled fluxes should provide values which are closer to the parent electron population than the oversampled measurement before the oversampled energy resolution is taken into account.

For the measured flux, let Fi (where i represents the energy step) represent the flux values measured by ELS at the 8% energy resolution. At each measurement, the instrument response function may be divided into sections that are dominated by the parent input spectrum at the oversampled resolution. If the oversampled flux that we wish to determine is Fj' and we figure the fraction, f, of the flux measured in step i by the oversampled flux j (written as fij), then we can express the measured flux as a sum of the oversampled flux as

$$F_i = \sum_{j=1}^{N} F_j' * f_{ij} \qquad i=1,2,\ldots,N-1,N$$

where N is the number of samples taken in the spectrum.

Since we are using fractions of the response function at each oversampled energy, we also know that

$$1 = \sum_{j=1}^{N} f_{ij} \qquad i=1,2,\ldots,N-1,N$$

So our flux expression can be written as a series of linear equations for each energy step and expressed in matrix form as

$$\begin{bmatrix} F1 \\ F2 \\ F3 \\ \cdot \\ \cdot \\ \cdot \\ FN \end{bmatrix} = \begin{bmatrix} f11 & f12 & f13 & \ldots f1N \\ f21 & f22 & f23 & \ldots f2N \\ f31 & f32 & f33 & \ldots F3N \\ \cdot & \cdot & \cdot & \cdot\ \cdot \\ \cdot & \cdot & \cdot & \cdot\ \cdot \\ \cdot & \cdot & \cdot & \cdot\ \cdot \\ fN1 & fN2 & fN3 & \ldots fNN \end{bmatrix} * \begin{bmatrix} F1' \\ F2' \\ F3' \\ \cdot \\ \cdot \\ \cdot \\ FN' \end{bmatrix}$$

Since all of the fij values are known and the Fi are just the measurements, the Fj' values (the higher resolution flux values) may be solved by the additive algebraic reconstruction technique (AART) used to enhance the resolution of image data [Early and Long, 2001]. AART is iterative where after 30 iterations, the criteria of halting each individual fine resolution solution at local minimum in the additive deviation is used.

$$F_j'\Big|_{k+1} = F_j'\Big|_k + D_j'\Big|_k$$

$$\text{and } D_j'\Big|_k = \frac{\sum_{i=1}^{N} (F_i - P_i) * f_{ij}}{\sum_{i=1}^{N} F_{ij}} \qquad j=1,2,\ldots,N-1,N$$

$$\text{and } P_i = \sum_{j=1}^{N} F_j'\Big|_k * f_{ij} \qquad i=1,2,\ldots,N-1,N$$

and for k > number of free iterations, if $(D_j'|_{k-1} < D_j'|_k)$ then $D_j'|_k = 0$

Oversampled Resolution Spectrum

The previous formulas are executed in order to retrieve the oversampled resolution. Results are shown in Figure 7. The retrieved data values now have finer energy resolution and are closer to the input electron distribution than the original oversampled measurements. In the region of the CO_2 photoelectron peaks, the points at the oversampled resolution show that the peaks are narrower in energy and larger in amplitude for both the direct ionization and extended ionization peaks of CO_2 than the measurements at the instrument resolution.

Now that the process of dealing with oversampled spectra have been developed and the results proven to generate spectra closer to the parent electron population, the next step will be to use the sector dependent instrument energy response functions with the measured ELS telemetry in order to generate spectra at the oversampled resolution for those cases when ELS is in a oversampling mode.

In summary, the process of using the oversampled spectra has been developed and applied to a return spectra which is more representative of the parent electron population (when compared with measurements in the normal sampling mode). The next step will be to use the sector dependent instrument energy response functions with the measured ELS telemetry to generate spectra at the oversampled resolution for those cases when ELS operates in the oversampling mode.

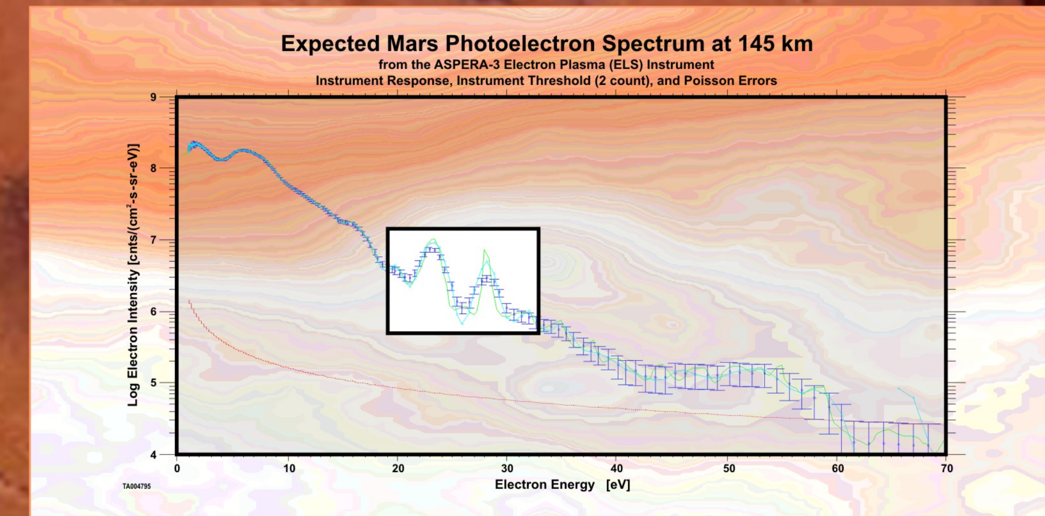

Figure 7. Oversampled Resolution Spectrum. Shown is the same spectrum as in Figure 4 with matrix inversion applied to recover the parent input spectrum to a finer degree than the instrument resolution.

Conclusion

The ELS instrument measures atmospheric photoelectrons at Mars. During these times, ELS may be in an oversampling mode where portions of the electron spectrum are measured with overlapping energy steps and under sampled at other locations within the same spectrum. When ELS is oversampling, it is possible to determine the parent electron spectrum with higher precision than that of the instrument.

Development of a matrix inversion procedure and a test of the ELS inversion during oversampling is conducted in order to recover the parent electron spectrum at a finer oversampled resolution. The ELS instrument model was used with a realistic ionosphere photoelectron spectrum to generate ELS telemetry. This telemetry is converted to a flux using the instrument characteristics in order to reproduce the electron spectrum. This reproduced electron spectrum is compared to the original spectrum. Matrix inversion software was developed which used the same instrument energy response function in order to adjust the measured values to account for instrument oversampling. The spectrum with the oversampled resolution is compared with the original input electron spectrum to show that the oversampling improves the effective energy resolution of the electron spectrum.

Aknowledgements

The ASPERA-3 experiment on the European Space Agency (ESA) Mars Express mission is a joint effort between 15 laboratories in 10 countries, all sponsored by their national agencies. We thank all these agencies as well as the various departments/institutes hosting these efforts. We wish to acknowledge support through the National Aeronautics and Space Administration (NASA) contract NASW-00003 in the United States, Particle Physics and Astronomy Research Council (PPARC) in the United Kingdom, and wish to thank those NASA officials who had the foresight to allow augmentation of the original ASPERA-3 proposal for ELS so that it would provide the additional capabilities which allowed the science described in this paper to be conducted. We also wish to acknowledge the Swedish National Space Board for their support of the main PI-institute and we are indebted to ESA for their courage in embarking on the Mars Express program, the first ESA mission to the red planet.

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