

Text of the presentation at:

International Evoked Response Audiometry Study Group (IERASG-2023)

Live demonstration of a portable, affordable and versatile AEP recording system mostly based on off-the-shelf electronics

A. de la Torre^{1,2}, J.T. Valderrama^{1,2,3}, I.M. Alvarez^{1,2}, J.C. Segura^{1,2}, J.L. Vargas^{4,5}, A.J. Palma^{6,2}, M.A. Carvajal^{6,2}, A. Pousibet^{6,2}

¹*Department of Signal Theory, Telematics and Communications, University of Granada, Spain.*

²*Research Centre for Information and Communication Technologies (CITIC-UGR), University of Granada, Spain.*

³*Department of Linguistics, Macquarie University, Sydney, Australia.*

⁴*Department of Surgery and its Specialties, University of Granada, Spain , Granada, Spain.*

⁵*ENT Service, Hospital Universitario Clinico San Cecilio, Servicio Andaluz de Salud, Granada, Spain.*

⁶*Department of Electronics and Computer Architecture, University of Granada, Spain.*

E-mail: atv@ugr.es (A. de la Torre)

Slide 1 (Title and authors):

Good morning, thank you very much. I will present an auditory evoked potential recording system, mostly based on commercially available consumer electronics.

Slide 2 (Objectives of our team):

In our team, our long term objectives regarding auditory evoked potentials are:

- The development new methods for acquiring evoked potentials, including tools for deconvolution and for multi-response deconvolution (as described in our previous presentations).
- The development of new experiments using more natural stimuli and exploring new strategies for conditioning the auditory system.
- The development of new applications of auditory evoked potentials, for a deeper understanding of the hearing processes, and also for improving the diagnosis of hearing pathologies.

- And to extend the target audience of this knowledge, including, in addition to audiologists, ENT specialists or engineers, also students (and not only university students, but also high school and primary school students), and in general, the society.

Slide 3 (AEP outside the lab, problem 1):

But recording evoked potentials out of the laboratory is not easy. There are two important problems to be solved. The first one is the noise: the amplitude of the evoked potentials is very low, and the recorded signal is severely affected by noise.

In order to minimize its effect: low noise instrumentation amplifiers are used in the recording systems; usually a large number of epochs are averaged in the response estimation; and procedures are adopted in order to minimize external electrical interference or internal interference mainly associated to myogenic activity.

A particularly important source of noise is the electromagnetic interference from the 50/60 Hz power line. This interference is significantly reduced if AEPs are recorded in a shielded booth, but recording AEPs out of the laboratory is usually challenging.

Slide 4 (AEP outside the lab, solution to problem 1):

Taking into account that the interference from the power line is a common-mode noise, in order to reduce this noise we estimate both, the differential signal containing the evoked response (and contaminated with common-mode noise) and the common-mode signal, using a two-channel recording system. Both signals are then processed in order to subtract the common-mode component from the differential signal, and therefore obtaining a clean differential signal (that is, a clean EEG).

This procedure provides some immunity to electromagnetic interference and alleviates the need of shielded booth.

Slide 5 (AEP outside the lab, problem 2):

The second problem is that AEP recording systems are usually expensive (particularly if we plan to use them for research, educational or dissemination purposes). Additionally, open AEP recording systems (providing flexible configuration of the stimulation and synchronization and providing the raw EEG) are necessary for interesting experiments, but more expensive and also difficult to be used.

Slide 6 (AEP outside the lab, solution to problem 2):

In order to solve this problem, we decided to develop our own AEP recording system, with minimum specific hardware and most of the components acquired in the context of professional audio consumer electronics.

Additionally, we also decided to develop (and share) our own open code and methods, including functions for efficient deconvolutions and scripts (for recording, analysis of recorded signals and estimation of responses), designed for specific experiments.

Slide 7 (Block diagram of the AEP recording system):

This slide shows the diagram of the AEP recording system. It includes an audio interface connected to a computer, earphones or headphones to provide stimulation, a custom-made interface for the electrodes, the recording electrodes and some audio cables.

The stimulation is configured with the computer and provided to the earphones/headphones through the audio output of the audio interface. Three electrodes provide the electrical signals differential-active (at the forehead) differential-

reference (at the mastoid) and ground (that can be set in the wrist, in the face, in the middle forehead, etc.) which are inserted into the custom-made interface, where the differential and the common-mode signals are provided to the audio interface. The audio interface amplifies, digitizes and records both signals. The signals are processed in the computer, to remove common-mode noise from the differential signal (and obtain a clean EEG) and to average or deconvolve the AEP responses.

Slide 8 (Reduction of the common-mode noise, manual procedure):

This slide illustrates the function of the custom-made electrode interface. The differential signal (forehead V1, mastoid V2) is amplified with a first differential amplifier. A common-mode signal is estimated by averaging the signal from V1 and V2 with two equal resistors, using as reference the ground electrode. This common-mode signal is also amplified with a second differential amplifier.

Both signals are combined by adding or subtracting the common-mode signal with an appropriate gain to the contaminated differential signal. With the optimal sign and gain in this combination, the amount of common-mode noise in the differential signal can be minimized. The reduction of the common-mode noise can be performed manually by listening to the combined signal and modifying the gain until the common-mode noise is minimized.

Slide 9 (Reduction of the common-mode noise, statistical procedure):

Alternatively, both pre-amplified signals can be acquired and digitized with the audio interface, and the reduction of the common-mode noise can be performed in a statistical framework: Since the differential EEG and the power-line interference are statistically independent, the gain for the optimal combination is that one minimizing the energy of the processed EEG.

Different methods (with simpler or more complex models describing the contamination of the differential EEG) can be formulated for simpler or more advanced noise reduction procedures.

Slide 10 (Specific hardware):

These pictures show the specific hardware of the AEP recording system, i.e. the interface for the electrodes. In the left, the first prototype (hand-made, built at home); in the right side, a more elegant second prototype (manufactured at an industrial engineering factory).

This interface contains only passive components (connectors and resistors), since the preamplifiers for the differential and common-mode output are external. [In addition to the electrode interface, these boxes also include connectors and passive circuits for impedance measurement, not described in this presentation].

Slide 11 (The complete AEP recording system):

This picture represents the complete AEP recording system: a laptop; the audio interface (a commercially available audio interface, manufactured by RME); the custom-made electrode interface with the external preamplifiers (commercially available microphone preamplifiers manufactured by Triton Audio); the stimulation headphones (we are using headphones instead of insert earphones in these experiments in order to clearly observe the stimulation artifact as reference); the cable with three crocodile connectors for the adhesive skin electrodes, and some standard audio cables.

Slide 12 (Detail - headphones and cable for electrodes):

This picture shows a detail with the headphones and the cable with 3 crocodile connectors for the skin electrodes.

Slide 13 (Detail - electrode interface and preamplifiers):

This picture shows a detail of the custom-made interface and the preamplifiers.

Slide 14 (Detail - preamplifiers):

And here a detail of the preamplifiers. The preamplifiers are a critical part of the AEP recording system. We are using commercially available ribbon/dynamic microphone preamplifiers (model FetHead manufactured by Triton Audio), providing an excellent response for our requirements [27 dB gain, ultra-low noise input, input impedance 22 kOhm, powered by 24-48 V phantom].

Slide 15 (Detail - audio interface):

And here the audio interface: a RME fireface UCX interface. It includes several analog and digital inputs and outputs, with accurate configuration of the gain, filtering and synchronization. We are using both microphone input channels, one for the differential signal and the other for the common-mode signal, from the preamplifiers.

Slide 16 (Audio interface configuration tool):

This screenshot shows the configuration tool for the RME audio interface.

[Hardware-inputs 1 and 2 are activated for acquiring the differential and common-mode signals provided by both preamplifiers. Stimulation signals for left and right ears are provided at software-playback channels 1 and 2. Stimulation can be provided either with hardware-output channels 1 and 2 (for insert earphones) or with stereo hardware-output channels 7/8 (connected to the headphones output). In the demonstration, the stimulation was provided with headphones. Software-playback channel 3 is used for synchronization. Synchronization signal is recorded internally with loopback in the hardware-output channel 3. Other configurations are possible for synchronization.]

Slide 17 (Figure of the matlab application for AEP recording):

This screenshot shows one of the figures provided by the matlab application for AEP recording.

[In particular, this figure compares the ABR/MLR responses estimated from the EEG, before (left) and after (right) removing the common-mode noise. Different plots represent the deconvolved responses corresponding to different stimulation levels. In the first milisecond, the stimulation artifact is observed. In the latency range between 1 and 10 ms ABR components are observed. In the latency range between 10 and 100 ms, some MLR components can be identified. Responses are very contaminated when they are estimated before removing the common-mode noise.]

Slide 18 (The recording system):

This picture shows a recording session, the subject with the adhesive electrodes, the cable with the crocodile connectors, the electrode interface (first prototype), preamplifiers, audio interface, stimulation headphones and the computer.

Slide 19 (ECG recording out of the lab):

The impact of the common-mode noise and the effect of the procedure for reducing it are difficult to be observed in AEP experiments. For this reason, we applied the procedure before in the context of electrocardiography. In the left side we can see three portions of the same electrocardiogram, in the top directly recorded with our system without common-mode

noise reduction, in the middle, after applying a basic procedure for common-mode noise reduction, and in the bottom after applying and advanced procedure.

The figures in the right represent the corresponding power spectral density plots for these ECGs. Before common-mode reduction, a large peak is observed at 50 Hz, together with some harmonics at 100, 150, 250, 350 Hz. With the basic procedure, these peaks are significantly attenuated. With the advanced procedure most of the harmonics are below the background noise.

Slide 20 (ECG recording, detail):

And in this plot we can see a detail of the electrocardiograms.

Slides 21 and 22 (ECGs severely affected by power line interference):

[These slides were not discussed in the presentation due to lack of time.]

This figure shows the electrocardiograms acquired in conditions in which the power line interference is significantly larger, as can be observed in both, the signals and the power spectral densities. In this case, the basic procedure for common-mode reduction is insufficient, but the advanced method provides an appropriate reduction of the power line interference.

The detailed representation of the electrocardiograms shows the limitations of the basic procedure and the effectiveness of the advanced procedure for common-mode reduction.

Slide 23 (AEP recording out of the lab):

In this slide, in the left figure we can see electroencephalogram portions recorded in an AEP experiment: from top to bottom, before common-mode noise reduction, with basic procedure for noise reduction and with the advanced procedure.

The power spectral density figures show how the harmonics associated to the power-line interference are significantly attenuated with the basic procedure, and even more attenuated with the advanced procedure.

Slides 24, 25, 26 (ABR responses):

In this slide (24), we can see the deconvolved ABR responses using the original EEG. Each plot correspond to the deconvolution from 2000 epochs provided at a specific stimulation level between 20 and 80 dB. The ABR waves are not very consistent in this plot.

When the procedure for common-mode noise reduction is applied, significantly more consistent ABR waves are observed. The estimated responses look similar with the basic and the advanced procedures.

The demonstration of the recording system

Configuration of the recording system

At the conference room, while the description of the recording system was being presented by Angel de la Torre, Joaquin Valderrama set the adhesive electrodes on his forehead and mastoid. The elements of the recording system were previously unpacked and deployed on a table before the session. After the speech describing the recording system, the recording session was carried out in the conference room, with Joaquin Valderrama as experimental subject.

The electrodes were connected to the interface, and a MatLab script was run in order to provide the stimulation (using the RME audio interface and the headphones), to acquire the signals (using the RME audio interface, the electrode



Figure 1: Pictures taken during the demonstration session at IERASG (2023-Sep-19).

interface and the preamplifiers), to process the recorded signals, and to present the deconvolved evoked potentials during the recording procedure.

The stimulation consisted in rarefaction clicks of 120 μ s presented at an average rate of 44.4 Hz (a random inter-stimulus interval uniformly distributed between 15 and 30 ms was configured). The stimulation level of the clicks was in the range between 40 and 80 dB, in steps of 10 dB (due to expected background acoustical noise, a lower stimulation level is not recommendable in a demonstration environment). The recording procedure was organized in segments of around 24 seconds, with 200 stimuli per level in each segment. After the recording of each segment, the recorded signals (differential and common-mode EEGs) were processed in order to reduce the common-mode component in the EEG signal. The EEG signal was filtered with two bandwidths: 250-3500 Hz for ABR responses; 25-3500 Hz for simultaneous presentation of ABR and MLR responses. The filtered EEGs were deconvolved in order to estimate the evoked potentials, using the multi-response deconvolution procedure previously described in the conference. The estimated evoked potentials corresponding to each segment were averaged and the total estimated responses were updated in the screen as a new segment was processed. Therefore, every 24 seconds, the evoked potentials were updated in the screen. At the end of the procedure (configured for recording during 6 minutes, with 15 segments and 3000 epochs per stimulation level), the script saves a binary file with all the relevant parameters and signals for a subsequent analysis.

The recording session

The figure 1 shows some pictures taken during the recording session. The first one shows the subject with the headphones and the adhesive electrodes (at forehead and right mastoid), the cable with crocodile connectors from the electrodes to the electrode interface. On the table, the electrode interface, with the preamplifiers, and the yellow and orange audio cables from the preamplifiers to the RME audio interface. In the second picture, the rest of the recording system can be seen on the table, including the previous components, the RME audio interface and the computer.

The pictures on the bottom show the responses presented on the screen after three minutes of recording (1400 epochs averaged per stimulation level). The figure corresponds to the simultaneous deconvolution of ABR-MLR responses, after the common-mode is reduced. For each stimulation level three plots are included: the average (in black) and the averages for two disjoint halves of the epochs (in red) in order to evaluate reproducibility of the estimated responses.

In this figure, the latency is represented in logarithmic scale, between 0.1 ms and 200 ms. A clear stimulation artifact is easily observed before 1 ms, with a very fast increasing of the amplitude with the stimulation level (since the artifact is linear with the stimulation level, an increase of 20 dB in the stimulation level causes an increase in a factor 10 in the artifact amplitude). In the latency interval between 1 and 10 ms, the ABR components can be observed, with a consistent wave V with latency around 6 ms at 80 dB, and around 8 ms at 40 dB. Some MLR components can be observed between 10 and 100 ms. Later components of MLR present a relatively low amplitude due to the presented stimuli (short clicks) and the bandwidth configuration (25-3500 Hz) for filtering the EEG.

Due to limitations in available time in the session, and since after 3 minutes the plots presented during the demonstration provided evidence of the viability of the recording procedure (and the advantages of applying the method for common-mode reduction), the recording procedure was aborted, and unfortunately the file with the signals (for subsequent analysis) was not saved.

However, the day before, during a coffee break, a recording procedure was completed (as rehearsal) in order to verify that there would be no technical problems during the demonstration and to evaluate the noise conditions in the conference room. The binary file with the signals was saved, and it can be analyzed.

Analysis of the recorded signals (rehearsal of recording procedure performed the day before)

The figures 2 and 3 describe the recording session of the day before to the demonstration. During this recording session, the conference room was occupied by speakers preparing the next session, and therefore the acoustical conditions were not optimal for AEP recording. In the top plots of figure 2 some EEG portions (10 seconds at the beginning of the first

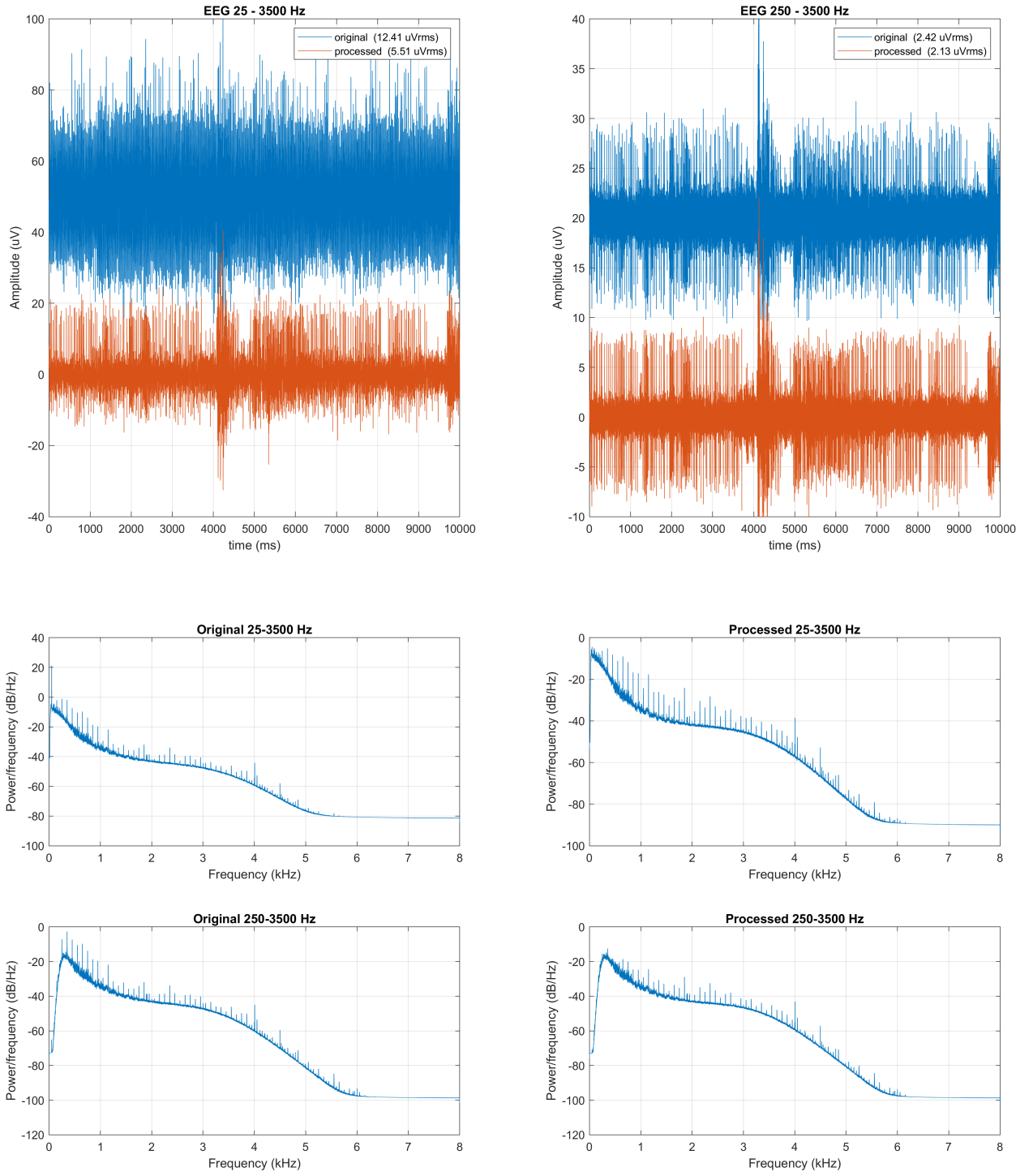


Figure 2: EEGs and PSDs of the signals recorded in the conference room the day before (2023-Sep-18).

segment) are represented. The EEGs are represented after filtering in the band 25-3500 Hz (left side) and 250-3500 Hz (right side). The EEGs in blue and red correspond, respectively, to the differential signals before and after applying the method for common-mode reduction. The standard deviation of each EEG (in $\mu\text{V rms}$), indicated in the legend, illustrates the effect of the procedure for common-mode reduction. The plots in the bottom represent the power spectral density of each EEG. The harmonics of the power line can be observed (at frequency multiple of 50 Hz). The applied procedure reduces the amplitude of most prominent harmonics.

The plots in figure 3 represent the evoked responses deconvolved from the EEGs for ABR (in the top) and ABR-MLR (in the bottom), before and after the application of the procedure for common-mode reduction (in the left and in the right, respectively).

In the ABR responses (top), the artifact can be observed in the first milisecond, and some consistent ABR components can be identified (waves III and V). In this case, the effect of the common-mode reduction is not very relevant. In the ABR-MLR plots (bottom), the latency is represented in logarithmic scale. The artifact is observed in the first decade (before 1 ms); the ABR components are in the second decade (between 1 and 10 ms) and the MLR components in the third one (between 10 ms and 100 ms). Some consistent waves can be identified, more easily when the common-mode noise is reduced (in the right). In this case, the impact of the common-mode reduction procedure is more evident.

Slide 35 (The team and the web):

The last slide shows the research team and the projects supporting this research. All these results, with examples, code etc. are or will be available in our web, <https://wpd.ugr.es/~sig.proc.audiology/>.

Additional information: plots, signals and code

With the initial objective of sharing the know-how with the research community and extend the target audience, we have prepared a folder including:

- The code (MatLab scripts and functions) used for recording, analysis, processing and AEP estimation.
- Several binary files containing the data obtained during recording sessions, which can be analyzed and processed with the provided code.
- Some plots with EEG signals, power spectra and estimated AEPs, obtained from the provided binary files (that can be generated with the provided code).

The directory (or folder) is provided as a zipped file “Demo_Nov_2023.zip”, available at our web site <https://wpd.ugr.es/~sig.proc.audiology/>, and is described below.

Content of the provided directory

After extracting the zip file, in the directory “./Demo_Nov_2023/” you will find the following files:

- “Basis_LinLog_RRC.m” and “Basis_reconstruction.m”: MatLab functions related to latency dependent filtering and down-sampling (used by the scripts and necessary for an effective multi-response deconvolution, particularly for long responses, like in the case of ABR-MLR plots).
- “f_CM_reduction_basic.m”: MatLab function for reduction of the common-mode component from the EEG (basic procedure). Used by the scripts and necessary to remove the common-mode noise.
- “RSLSD_SCLS_Nresponses.m”: MatLab function providing subspace-constrained LS deconvolution in a multi-response model. Used by the scripts and necessary to perform multi-response deconvolution.

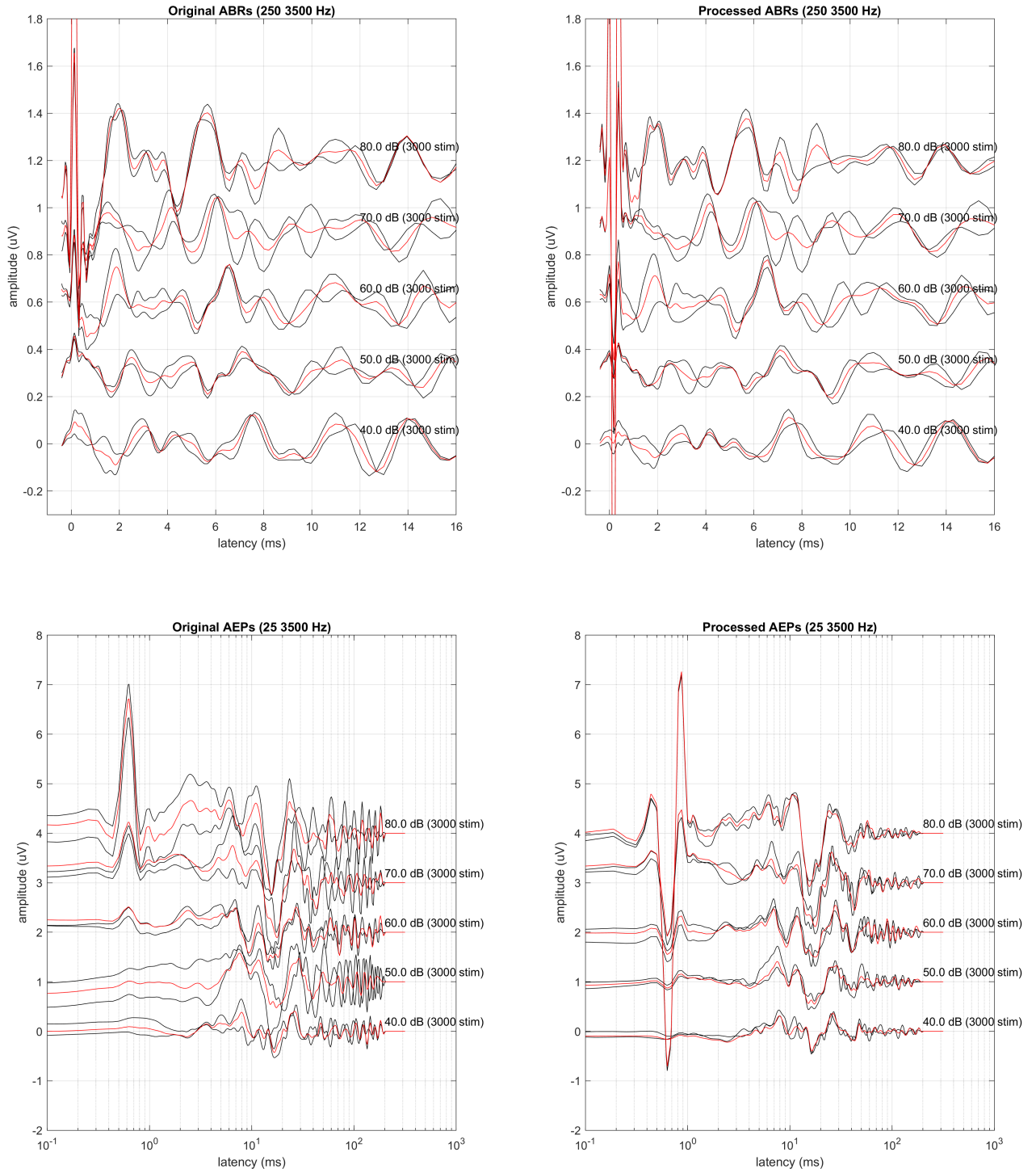


Figure 3: Deconvolved AEP responses for recordings in the conference room the day before (2023-Sep-18).

- “script_recordingCM_RME_demo.m”: MatLab script for AEP recording. This was the script used in the demo session. It configures the recording session and the stimulation; for each segment, the script prepares the playing/recording for the audio interface, provides the stimulation and synchronization signals and records the EEG (differential and common-mode signals) and the synchronization signal; then the script processes the signals in each segment and provides the cumulative AEP responses; finally, when all the segments are recorded and processed, the script saves the signals and parameters into an output file.
- “script_analysis_RME_segments.m”: MatLab script performing an off-line analysis of the recorded signals similar to that performed by the recording script.
- Folder “Bak”: Back-up folder with the previous MatLab functions and scripts. Useful to restore damaged files.
- “registro_01_Nov_2023_17_46_25_Nseg15.mat”: Binary file containing the signals of a 6 minutes session (15 segments) recorded on November 1st 2023 at Granada (Spain).
- “registro_18_Sep_2023_11_01_35_Nseg15.mat”: Binary file containing the signals of a 6 minutes session (15 segments) recorded on September 18th 2023 at Cologne (Germany), at the conference room of IERASG, the day before to the demonstration. These signals were recorded as rehearsal for the demonstration.
- “registro_25_May_2023_18_49_32_Nseg25.mat”: Binary file containing the signals of a 10 minutes session (25 segments) recorded on May 25th 2023 at Salamanca (Spain), outside the conference room during the Workshop on Advances in Audiology, the day before of the demonstration. These signals were recorded as rehearsal for the demonstration.
- “registro_26_May_2023_18_21_48_Nseg25.mat”: Binary file containing the signals of a 10 minutes session (25 segments) recorded on May 26th 2023 at Salamanca (Spain), outside the conference room during the Workshop on Advanced in Audiology. These signals were recorded during the demonstration.
- Folder “Figures”: Contains one folder for each of the four previous binary files, each one containing the figures generated by the script “script_analysis_RME_segments.m” with the corresponding binary file. The figures are similar to those in 2 and 3. The evoked responses are represented for each segment.

How to use the code and binary files

The binary files contain raw data including the recorded signals and some additional parameters. The content of the binary files is described in the header of the script “script_analysis_RME_segments.m”. For those familiar with MatLab or Octave programming languages: one can see details about how these files were created by reading the code of the script “script_recordingCM_RME_demo.m” (since these files were created with this script); one can see details about how to use these files by reading the code of the script “script_analysis_RME_segments.m”.

The script “script_recordingCM_RME_demo.m” requires some audio device with ASIO interface to be connected to the computer. It works with the RME audio interface used in the demo. It should work with other models of RME audio interfaces and also with audio interfaces manufactured by other companies (assumed that they are appropriately configured and calibrated).

The script “script_analysis_RME_segments.m” provides a step-by-step analysis and processing of the binary files and generates the figures with the EEGs, the PSDs and the segment-by-segment cumulative AEP responses. There are several details to be considered in order to use this script (particularly for non-experienced MatLab/Octave users):

- The script is configured in lines 45 and 48. Line 45 should be “SAVE_FIGURES = 1;” if you want to generate png files with the figures, or “SAVE_FIGURES = 0;” if you don’t. In line 48, you can select the binary file by writing a number between 1 and 4 (because there are 4 binary files “reg. . . .mat”).

- The AEP responses are plotted including the response deconvolved from all the epochs, and responses deconvolved from disjoint halves of epochs (for evaluating reproducibility of the responses). In this script, the halves are defined randomly. In order to obtain repetibility in the AEPs estimated from both halves the random number generator is initialized in line 46 with the command `“rng(12345);”`. If this command is removed (or commented) the halves (and the corresponding AEPs) changes from execution to execution.
- At the end of the script, lines 240 to 246, there is some code inside an `“if 0”` block, which is not executed. Writing `“if 1”` will allow execution of this code. This lines prepare 5 second of EEG and plays the EEG through the audio device, and therefore the user can hear the recorded EEG.

Some comments on the other recording sessions

Figures 4 and 5 show the plots for a recording session with Angel de la Torre as explored subject, recorded in Granada (Spain), on November 1st 2023. The noise affecting the EEG is significantly different to that in the previous recording (in figures 2 and 3). The reduction of noise, in figure 4 is effective in both, the band 25-3500 Hz and 250-3500 Hz. For this reason, the improvement is clearly observed in both, the ABR responses and the ABR-MLR responses (top and bottom plots in figure 5, respectively).

Figures 6 and 7 show the plots for a recording session with Joaquin Valderrama as explored subject, recorded in Salamanca (Spain), on May 25th 2023. This recording corresponds to the rehearsal before the demonstration presented at the Workshop on Advances in Audiology. In these EEGs, the harmonics of the power line are not so large as in the previous files. However, this signal was affected by interference from a radio station. The radio can be easily perceived from the EEG. This session includes 10 minutes of recording. The effect of common-mode reduction is not very important in the case of ABR, but the reduction of the common mode is very effective for improving the ABR-MLR responses.

Finally, figures 8 and 9 show the plots for a recording session with Joaquin Valderrama as explored subject, recorded in Salamanca (Spain), on May 26th 2023. This recording corresponds to the demonstration presented at the Workshop on Advances in Audiology. This recording session is reported in our web, <https://wpd.ugr.es/~sig.proc.audiology/2023/salamancaworkshop/>. This report includes a video of the demonstration. Again, this signal was affected by interference from a radio station. The radio can be easily perceived from the EEG. This session includes 10 minutes of recording. As in the previous case, the effect of common-mode reduction is not very important in the case of ABR, but the reduction of the common mode is very effective for improving the ABR-MLR responses.

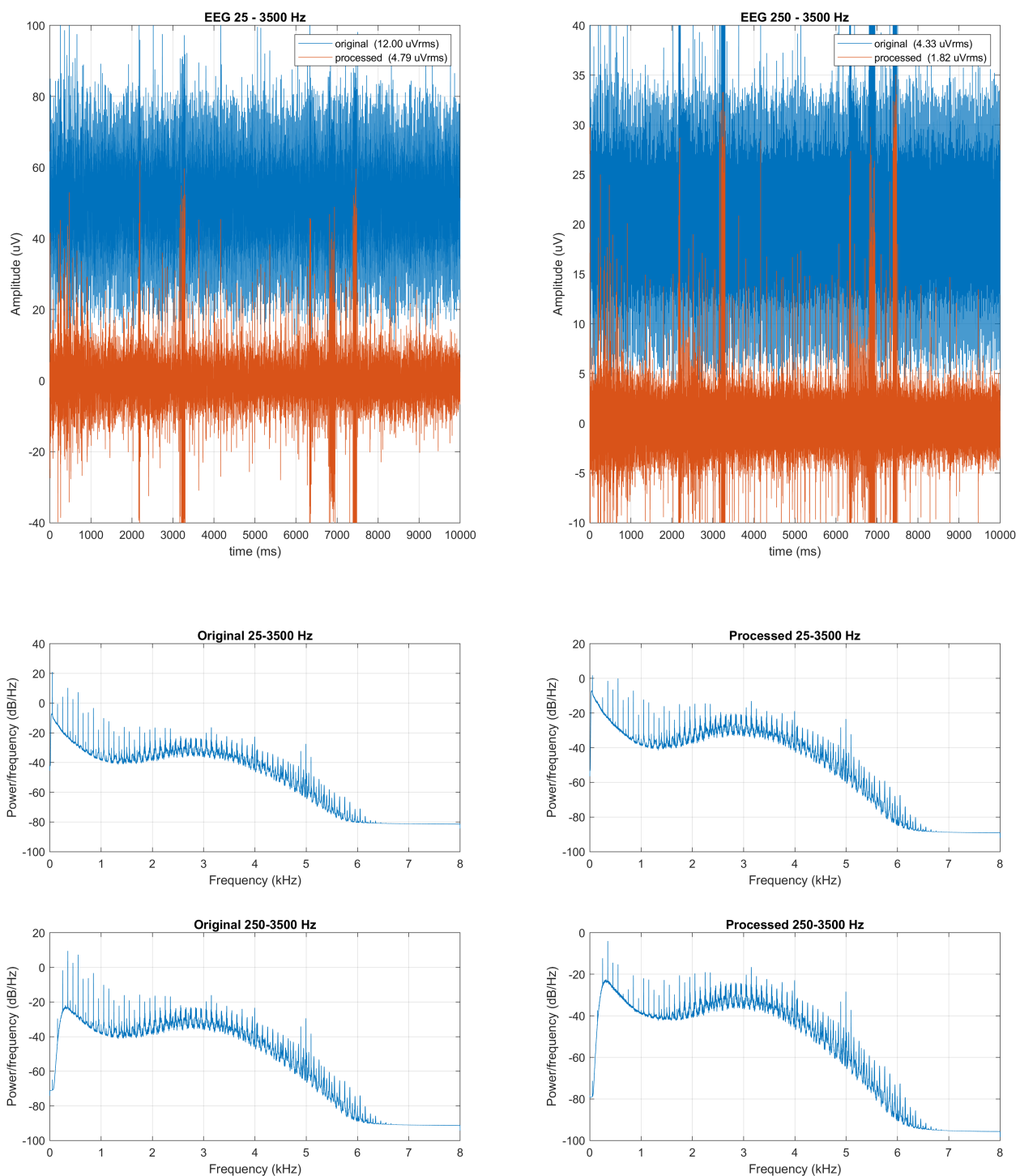


Figure 4: EEGs and PSDs of the signals recorded at Granada (2023-Nov-01).

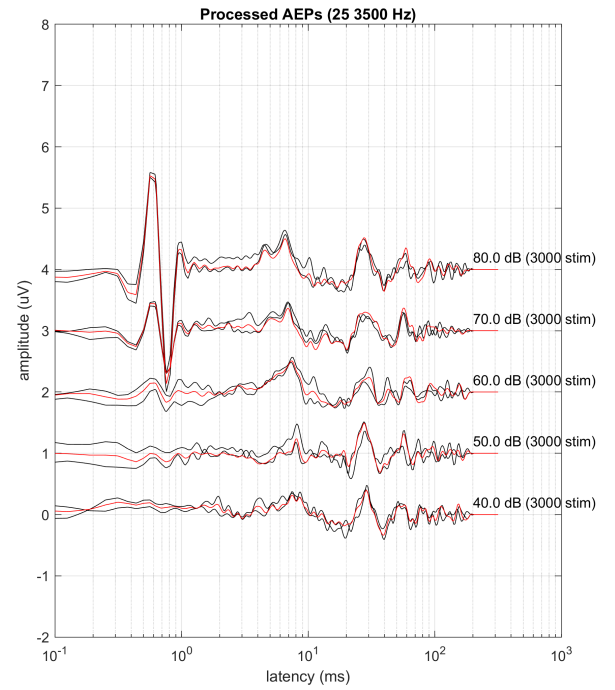
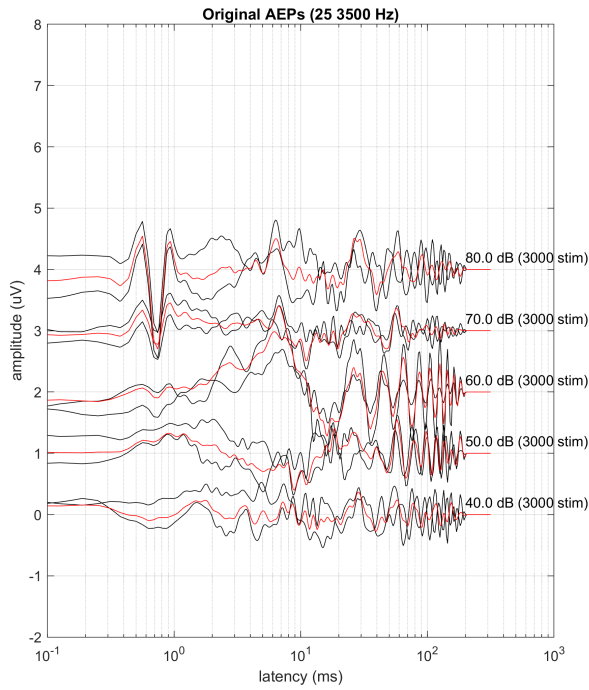
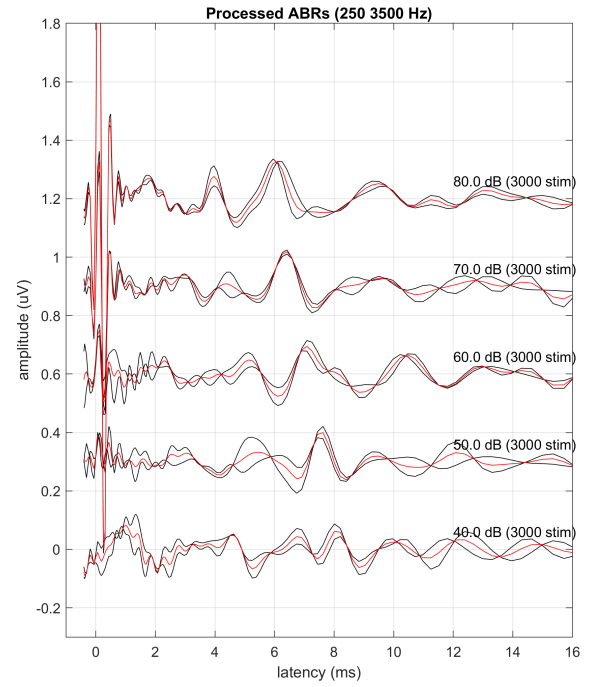
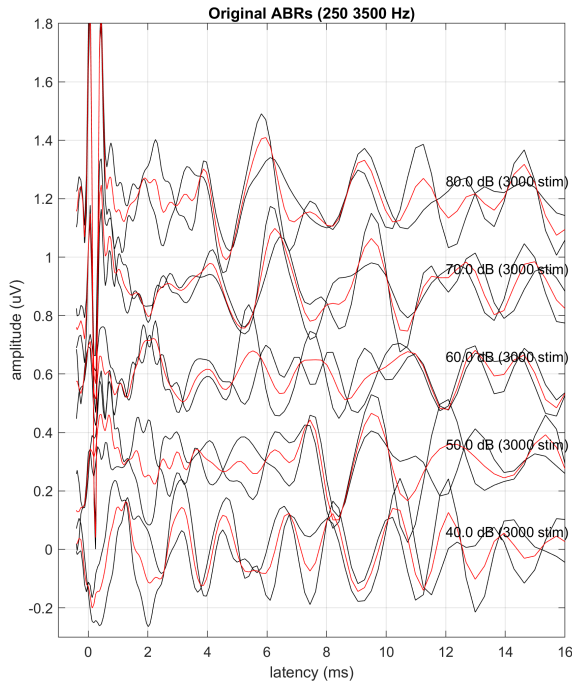


Figure 5: Deconvolved AEP responses for recordings at Granada (2023-Nov-01).

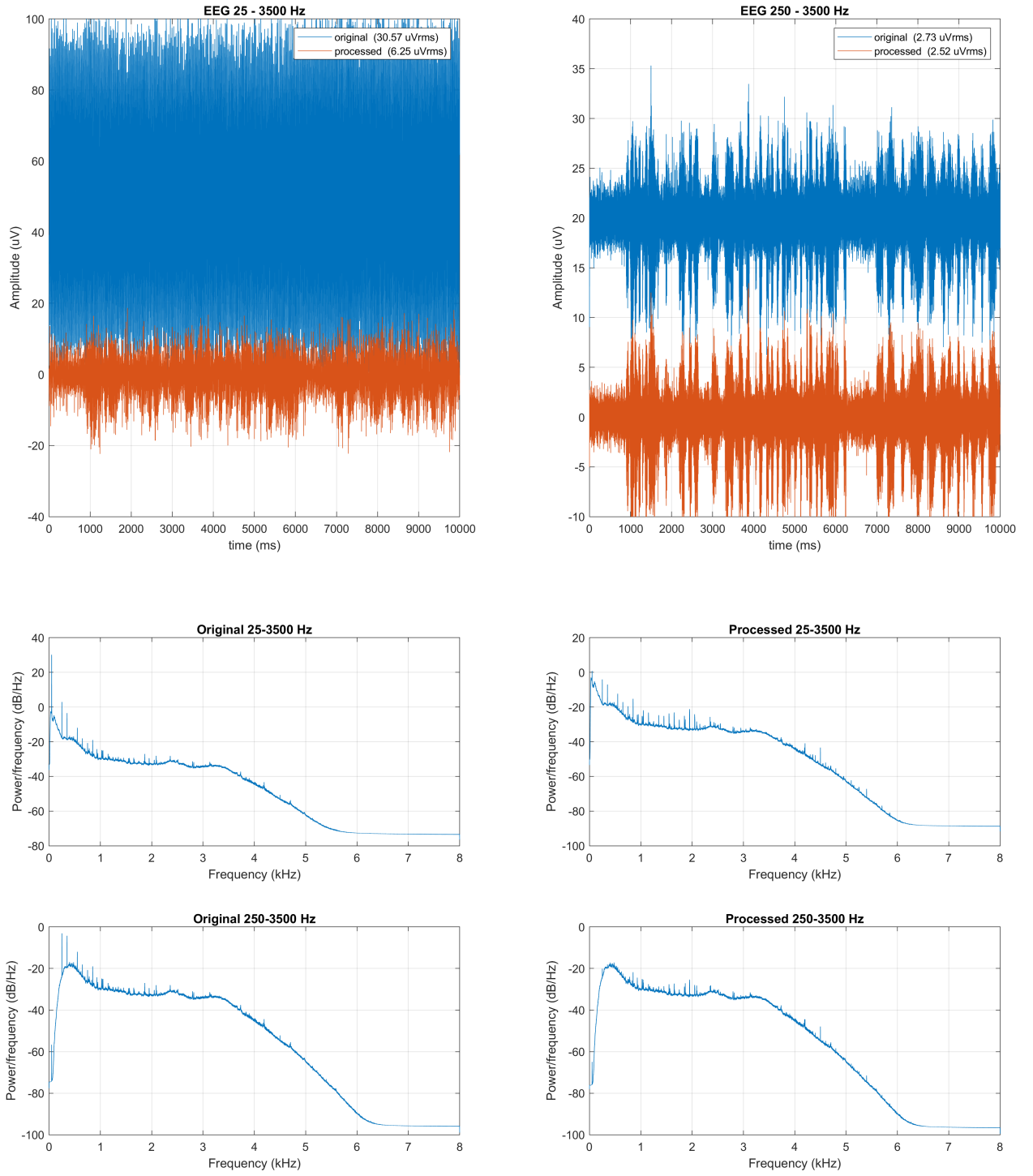


Figure 6: EEGs and PSDs of the signals recorded at Salamanca (2023-May-25).

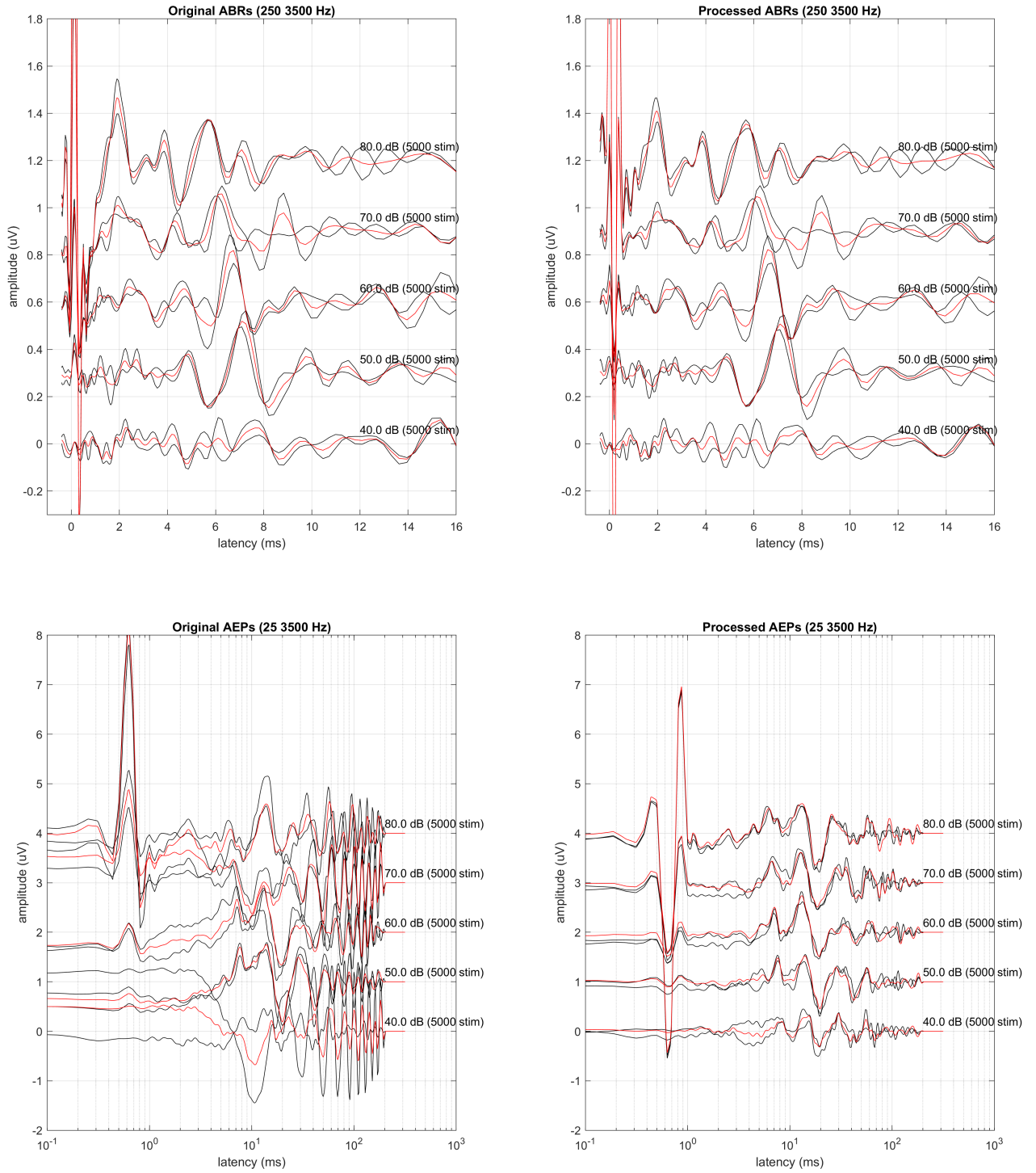


Figure 7: Deconvolved AEP responses for recordings at Salamanca (2023-May-25).

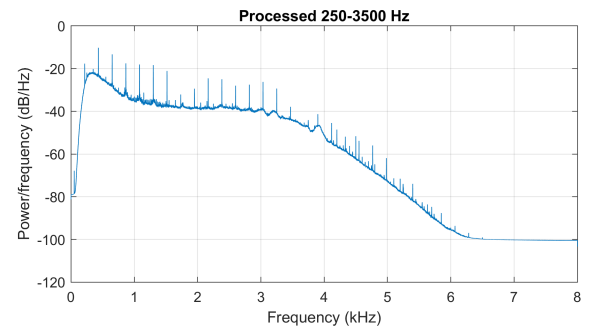
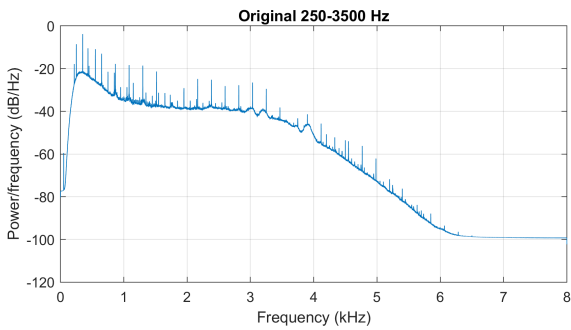
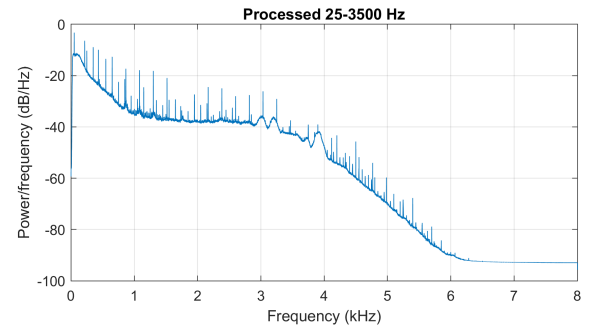
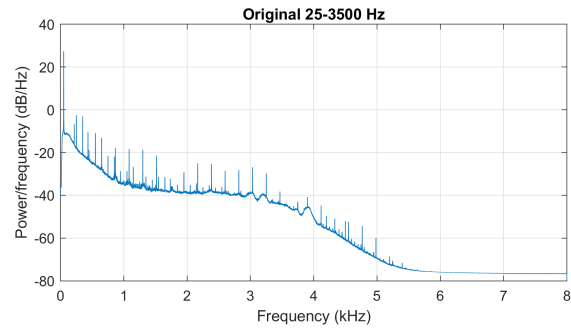
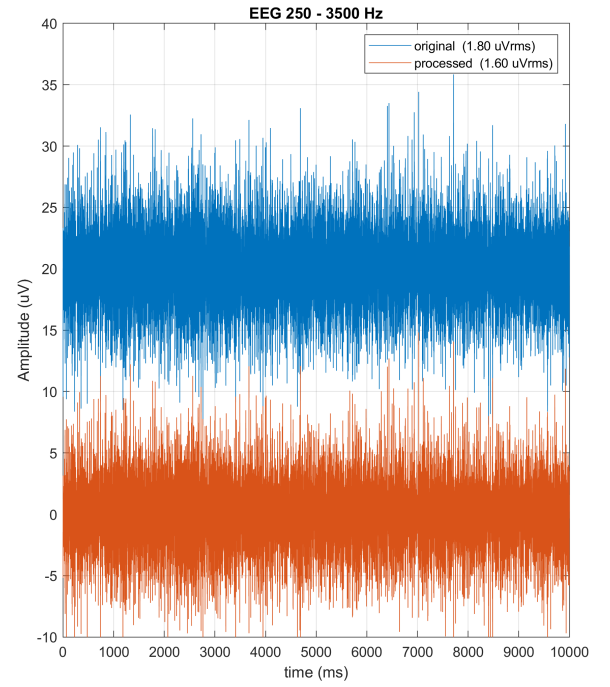
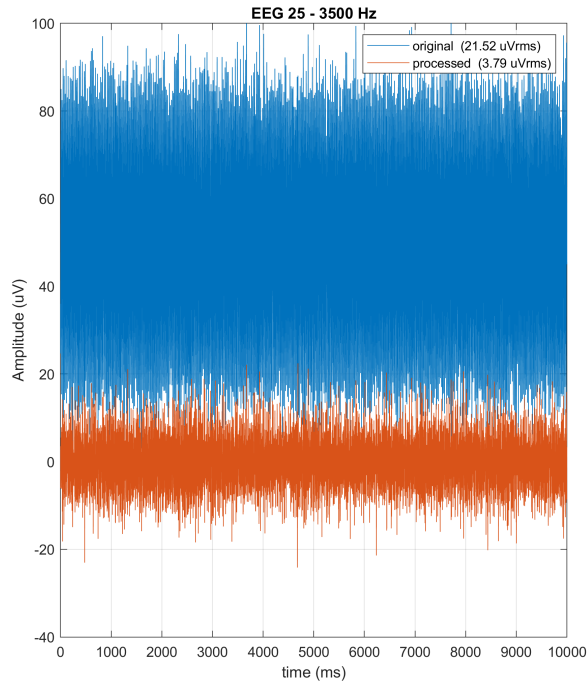


Figure 8: EEGs and PSDs of the signals recorded at Salamanca (2023-May-26).

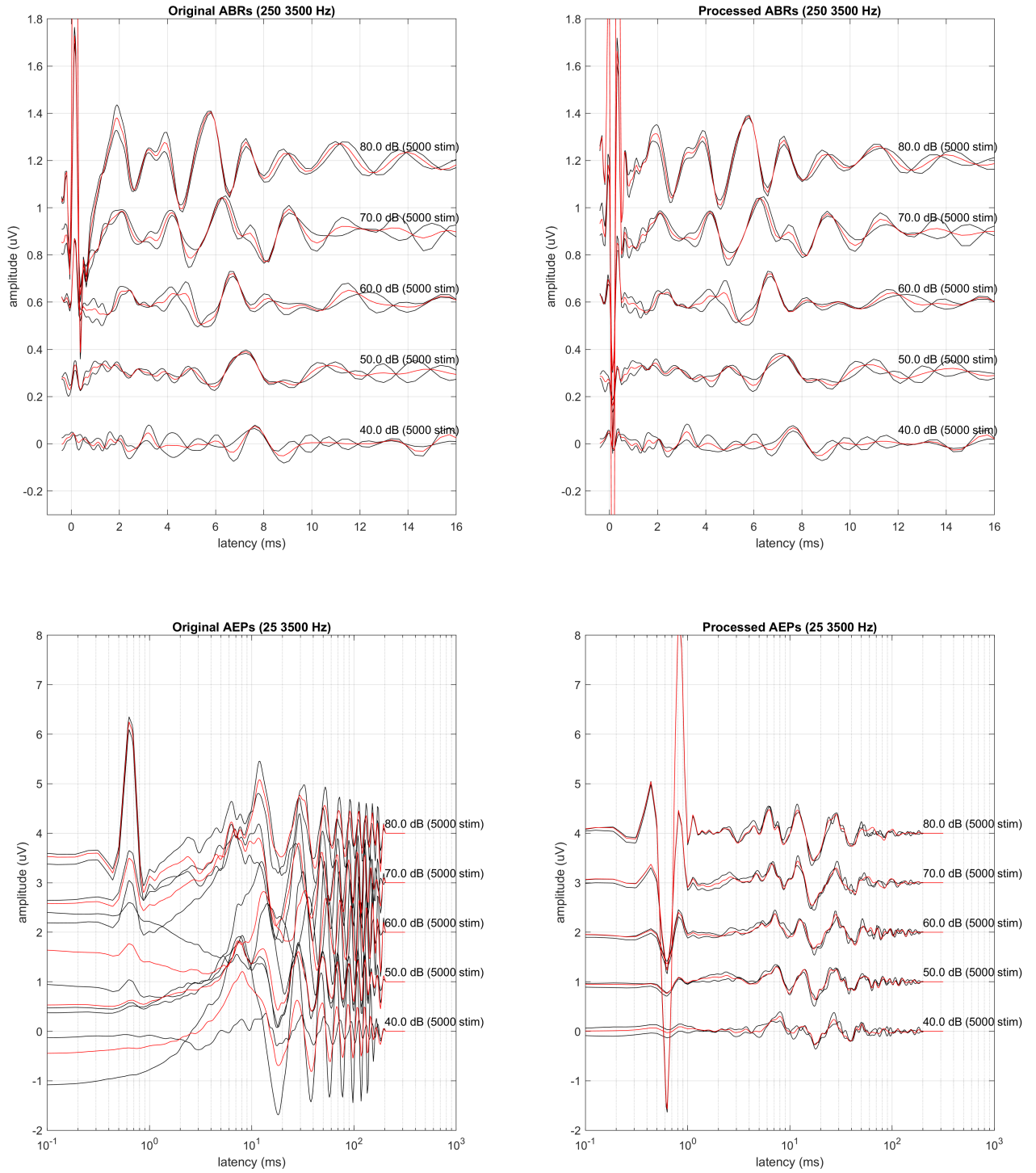


Figure 9: Deconvolved AEP responses for recordings at Salamanca (2023-May-26).