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Title: RFcap: A software analysis tool for multichannel cochlear implant signals

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Abstract: Being able to display and analyze the output of a speech processor which encodes the parameters of complex stimuli to be presented by a cochlear implant (CI) is useful for software and hardware development as well as for diagnostic purposes. This firstly requires appropriate hardware which is able to receive and decode the radio frequency (RF) coded signals, and then processing the decoded data using suitable software. The PCI-IF6 clinical hardware for the Nucleus CI system, together with the Nucleus Implant Communicator and Nucleus Matlab Toolbox research software libraries, provide the necessary functionality. RFcap is a standalone Matlab application that encapsulates the relevant functions to capture, display and analyze the RF coded signals intended for the Nucleus CI24M/R, CI24RE and CI500 multichannel cochlear implants.

1 Introduction

1 2 The ability to display and analyze the output of the speech processor which encodes the stimuli to
2 3 be delivered by a cochlear implant (CI) can be extremely helpful and even essential in many
3 4 instances, both in research as well as clinical settings. For example, when developing new speech
4 5 coding strategies, the output of the new algorithms need to be examined systematically and
5 6 thoroughly. This is not difficult with simple inputs, but it becomes cumbersome when complex
6 7 inputs such as real speech tokens are used. Displaying the complex signal output makes it possible
7 8 to examine this output for patterns that may otherwise not be easily observed when using simple
8 9 input signals. Another example, in a clinical environment, is to examine the output of a speech
9 10 processor for diagnosing hardware problems such as defective microphones or accessories.
10 11 With the present generation of commercial cochlear implant systems approved for clinical use,
11 12 stimulus parameters are transmitted via radio frequency (RF) coded signals transcutaneously to the
12 13 cochlear implant. By capturing and decoding these RF coded signals, it is possible to examine the
13 14 output of the entire signal processing chain.
14 15 Capturing these RF coded signals requires appropriate custom hardware as well as software.
15 16 Previously, this was possible for the Nucleus family of cochlear implants using sCILab (Lai et al.
16 17 2003), a 16-bit Borland Pascal application which communicated with standard clinical hardware, in
17 18 particular with the Nucleus DPI-IF4 (Dual Processor Interface and Nucleus IF4 interface card) and
18 19 PCI-IF5 (Processor Control Interface and Nucleus IF5 interface card) hardware combinations.
19 20 However, these clinical hardware combinations have since been superseded, and the subsequent
20 21 hardware combination of PCI with the Nucleus IF6 interface card is not compatible with sCILab.
21 22 Furthermore, the latest clinical hardware with a USB programming Pod does not have any decoding
22 23 or storage capability.
23 24 The PCI-IF6 combination, while no longer the latest clinical hardware for the Nucleus CI system,
24 25 represents the most recent and still available hardware configuration able to continuously decode
25 26 and store the RF signals. The software functionality to communicate with the hardware and thus

1 capture the decoded data is provided by the Nucleus Implant Communicator (NIC) and the Nucleus
2 Matlab Toolbox (NMT) research software libraries (Irwin 2006, Swanson and Mauch 2006) from
3 Cochlear. NIC comprises a C/C++ library which is called by NMT, the latter of which is intended
4 for the Matlab (by Mathworks) software environment.
5
6 RFcap is a standalone Matlab application designed and written by the first author which, similar to
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8 sCILab, utilizes this capture and decode functionality to provide a practical means for displaying
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10 the CI stimuli, together with a number of analysis and diagnostic functions. Although NIC and
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12 NMT are only available to collaborative research groups working with the Nucleus CI24M/R,
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14 CI24RE and CI500 cochlear implants, the general principle of signal capture analysis and
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16 diagnostics is applicable to other cochlear implant systems.
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1 System Description

1 2 Typically, a CI speech processor receives its input signals via its microphone, or from a direct
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4 3 connection to a separate signal source. The input signal is then processed according to a particular
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6 4 coding strategy, resulting in a sequence of stimuli which is then encoded into RF signals for
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8 5 transmission to the target CI. Instead of being sent to the implant of a CI user, the RF signals can
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11 6 be intercepted by specific hardware capable of receiving and decoding these signals. The decoded
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14 7 information can then be transferred to software for subsequent analysis as well as storage. Figure 1
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16 8 illustrates a typical configuration of such a capture and analysis system.

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18 9 << Figure 1 about here >>
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23 11 Suitable hardware for the Nucleus CI24M/R, CI24RE and CI500 cochlear implants consists of the
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26 12 PCI unit together with the IF6 interface card, both of which belong to standard clinical hardware
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28 13 (although no longer the latest) for the Nucleus cochlear implant system. The PCI contains the
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31 14 necessary circuitry for receiving and decoding the RF signals. The decoded information consists of
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33 15 a series of parameters describing each biphasic pulse in the stimulus sequence being sent to the
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36 16 target cochlear implant. Each set of parameters (i.e. active and reference electrode, phase width,
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38 17 interphase gap and duration till the next stimulus) defining a single stimulus pulse make up a
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40 18 “frame”. The decoded frames are continuously stored and refreshed in hardware data buffers whose
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43 19 contents can in turn be read using the appropriate software functions provided by the NIC and NMT
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45 20 libraries. RFcap is such a software application which uses these functions to transfer the stimulus
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48 21 data from the hardware buffers into the PC. Once transferred, RFcap can process the data for visual
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50 22 display as well as for analysis.

51 52 23 53 54 55 24 *Hardware Limitations*

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57 25 More recent speech processor models equipped with telemetry capability (e.g. the Nucleus Freedom
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60 26 or the Nucleus CP810 Sound Processors) may check the implant type to which it is transmitting,
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1 and automatically stop its RF transmission if the expected implant type is not found. The PCI,
2 which is equipped with a CI24M/R implant chip, would make it impossible to check the output of
3 Freedom or CP810 processors programmed for CI24RE or CI500 implants. This behaviour is
4 defined in the speech processor's firmware, and as such, can be circumvented either by using a
5 version of the firmware that does not behave this way, or by reloading the processor with a map for
6 a CI24M/R implant. This restriction does not apply to the SPrint, ESPrIt and ESPrIt3G speech
7 processors, which do not check for the implant type.

8 *Software Requirements*

9 Although RFcap is a Matlab application, it has also been compiled as a standalone application
10 which can be executed on a PC which does not have Matlab installed on it. RFcap was developed
11 using Matlab version r2007b and has also been successfully tested with version r2009b. Since
12 RFcap also permits the user to connect to the Nucleus Custom Sound clinical patient database, the
13 Database Toolbox from Matlab is also required for the database connection to function properly.
14 The functionality to communicate with the capture and decoding hardware is provided by the NIC
15 and NMT research software libraries from Cochlear, and the latest versions (presently v2.23 and
16 v4.31 respectively) are required. Use of the NIC and NMT libraries are subject to agreement with
17 Cochlear.

1 **RFcap Functions**

1 2 Once RFcap is running, the PCI continuously decodes all RF input signals and stores the
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4 3 corresponding data in the hardware buffers as frames. The data transfer from the hardware is
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6 4 controlled by RFcap, and is specified either in terms of the desired number of frames, or as a time
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8 5 interval. RFcap initiates the transfer, and this is stopped when either the specified number of frames
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11 6 has been transferred or the specified time interval has elapsed, whichever occurs first. The
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14 7 maximum number of frames that can be transferred in a single capture is 65535 frames. The
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16 8 corresponding time interval depends on the duration of each frame, which is in turn defined by the
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18 9 overall stimulation rate of the speech processor map used to generate the stimulus sequence (e.g. a
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21 10 500Hz ACE map with 10 maxima (overall rate of 5000Hz) has a frame period of 200us. RFcap
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23 11 terminates the data transfer if no decoded RF signal is available for a specified time interval
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26 12 (timeout).

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28 13 RFcap can also control the playback of an arbitrary sound token over the PC's sound system. Since
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31 14 the data transfer is controlled by RFcap, synchronized playback of sound tokens and capture of the
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33 15 resultant RF signals is also possible. By default, RFcap sets the time interval to the length of the
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35 16 sound token. The user can still adjust the number of frames to be captured as desired.

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40 18 The transferred data is displayed in the form of an electrodogram, which very closely resembles a
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43 19 spectrogram. Figure 2 illustrates such an electrodogram for the input utterance "asa" as captured
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45 20 from a Freedom SP using a 500Hz ACE map with 10 maxima. The elapsed time is shown on the x-
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48 21 axis, and the electrode number (in increasing order of its frequency mapping) on the y-axis. Each
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50 22 stimulus is shown as a vertical bar whose height is proportional to the corresponding stimulus
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52 23 intensity. The height of the vertical bar is also colour coded using a 10-step two-colour (the
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55 24 example in Figure 2 ranges from light blue to dark blue) graduated scale. The colours can be
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57 25 manually altered by the user to optimize the visual appearance of the electrodogram. Some of the
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60 26 time information in the stimulus sequence is simplified in the electrodogram display. For instance,

1 biphasic pulses with finite phase widths and interphase gaps are represented simply by vertical bars
1 2 with a fixed onscreen width of 1 pixel. Thus, timing information such as the phase width and
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3 3 interphase gap, although available in the decoded data, are not represented visually in the
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6 4 electrodiagram by the width of the vertical bar. The time interval between stimuli, however, is
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8 5 correctly displayed. A summary of the data's stimulus parameters is also provided below the
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11 6 electrodiagram. Powerup pulses are represented as stimuli presented on electrode 0.

13 7 << Figure 2 about here >>

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18 9 The height of each vertical bar is scaled as a percentage between the minimum and maximum
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20 10 Current Level values possible for each electrode, for instance, as defined by the Threshold and
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23 11 Comfortable levels (T and C levels) of a speech processor map. RFcap allows the user to connect
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25 12 to the clinical Custom Sound database to read these speech processor maps. When a map is loaded,
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28 13 RFcap will use the map's corresponding T and C levels to encode the height of the vertical bars. If
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30 14 a map is not loaded, RFcap simply assumes the T and C levels to be 0 and 255 respectively.
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33 15 It is up to the user to load the correct map into RFcap which corresponds to the one being used in
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35 16 the speech processor at the time the RF capture is being performed. Loading the wrong map into
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37 17 RFcap will result in erroneous decoding of the signal intensities, for instance, captured stimulus
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40 18 intensity values may lie outside the range given by the T and C levels in the loaded map. The
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42 19 loaded map also contains other parameters such as the phase width, interphase gap, the stimulation
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45 20 rate and the number of maxima, which can also be used to cross-check the captured and decoded RF
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47 21 stimulus data for mismatches or errors. RFcap provides such a basic check of the captured RF data
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50 22 and reports if there are mismatches in these parameters.
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52 23 By default, RFcap displays the entire captured signal, scaling the horizontal time axis accordingly.
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54 24 However, the user can also examine the electrodiagram in detail by zooming in and out on different
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57 25 portions of the electrodiagram.

1 Once the stimulus data are available in digital form, they can be saved to file. Saved data can be
1 2 read into RfCap for analysis in the same manner as data that have just been captured.

3 3 4 3 5 6 4 *Analyzing the stimulus data*

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8 5 The stimulus data can be analyzed in various ways as described below. The corresponding
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11 6 examples are all based on the captured stimulus data for the utterance “asa” as shown in Figure 2.

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15 8 The amount of activity on each of 22 electrodes over the entire signal is summarized in the form of
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18 9 electrode histograms, either by simply counting the number of stimuli presented on a particular
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20 10 electrode, or each stimulus on that electrode can be weighted according to its intensity before being
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23 11 added together. The weighted histogram gives a better impression of the relative signal intensity on
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25 12 each of the channels. The weights are linearly distributed between 0.0 and 1.0. If a map is loaded,
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28 13 weighting will be relative to the T and C levels of the corresponding electrode. A stimulus intensity
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30 14 at T level is given a weighting of 0.0, while a stimulus intensity at C level corresponds to a
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33 15 weighting of 1.0. If a map is not loaded, weighting will be relative to the full range of 0 to 255
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35 16 Current Levels. For instance, a stimulus intensity of 153 Current Level units would yield a weight
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37 17 of $153/255 = 0.6$. The upper and lower electrode histograms in Figure 3 respectively show that in
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39
40 18 general, the distribution of unweighted and weighted activity are similar. Closer examination
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42 19 shows that although more stimuli were presented on electrode 7 than electrode 5, the stimuli on
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45 20 electrode 7 were generally weaker, thus yielding a smaller weighted sum than that on electrode 5.

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47 21 << Figure 3 about here >>
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52 23 Additionally, the distribution of the stimulus intensities (in Current Level units) on a selected
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54 24 electrode (or channel) can be examined, as well as the instantaneous channel stimulation rate
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57 25 between two consecutive stimuli on that electrode. Figure 4 shows that the stimuli presented on
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59 26 electrode 20 were well distributed across the dynamic range between the T and C levels, and the
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1 instantaneous channel stimulation rate corresponded well to the expected 500Hz (502Hz was
1 2 computed due to discretization) from the map used to generate the stimulus sequence. Fluctuations
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3 3 around this value are due to the order in which the sets of maxima were selected. When a particular
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6 4 channel is not repeatedly selected, the time interval to the next occurrence becomes larger, resulting
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8 5 in a lower instantaneous rate.

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11 6 << Figure 4 about here >>

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15 8 The instantaneous (pulse-by-pulse) stimulation rate can be computed from the time interval between
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18 9 any two consecutive stimulus pulses (including powerup pulses) in the stimulus sequence.

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20 10 Generally, this should match the overall stimulation rate for the corresponding map, given by the
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23 1 product of the channel stimulation rate and the number of maxima, and is expected to be constant.
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25 12 If the input signal is too weak to yield the specified number of maxima, the signal is padded with
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28 3 powerup pulses.

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30 14 The ACE coding strategy selects the specified number of maxima from the input signal, and
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33 15 presents them in a basal-to-apical order at the channel stimulation rate. Thus, the channel
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35 16 stimulation rate can also be determined by examining the stimulus sequence for sets of maxima and
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38 17 computing the rate at which these maxima sets are presented. Powerup pulses are ignored when
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40 18 determining maxima sets. Weak input signals resulting in less than the nominal number of maxima
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42 19 specified in the corresponding speech processor map will result in shorter time intervals for that
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45 20 maxima set, and accordingly a higher “channel stimulation rate”. Irregularities in the instantaneous
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47 21 stimulation rate and the channel stimulation rate can be seen in the onset and offset portions of the
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50 22 utterance “asa” as shown in Figure 5.

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52 23 << Figure 5 about here >>

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57 25 The maxima sets found in a stimulus sequence can be summarized according to the number of
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60 26 maxima in each set as well as their corresponding duration, as shown in Figure 6.

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<< Figure 6 about here >>

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When there is no signal input, and hence no signal output to the implant, the speech processor nevertheless continues to send RF pulses to the implant in order to keep the implant powered up. These powerup pulses produce no stimulation, with a stimulation level of 0CL. However, these powerup pulses are detectable in the RF signal stream. The time interval (period) between two consecutive powerup pulses, as well as the distribution of these powerup periods for the utterance “asa” are shown in Figure 7. The various powerup periods found in the signal are primarily responsible for the fluctuations in the instantaneous stimulation rate and channel stimulation rate observed in Figure 5.

<< Figure 7 about here >>

RFcap allows the electrodiagrams from two different sets of stimulus data to be displayed superimposed over one another for comparison. The second stimulus data set is loaded from file as a “Reference Signal” and the two electrodiagrams are shown in different colours. The electrodiagrams in Figure 8 are for the sound token “asa” obtained with the MP3000 coding strategy (Noguiera et al. 2005) in the foreground (dark blue) and the ACE coding strategy in the background (light blue). It can be seen that MP3000 produces less activity, but still has a very similar spectral representation. The horizontal slider allows the user to shift the shorter of the two electrodiagrams left or right to align the patterns when two stimulus data sets are being displayed.

<< Figure 8 about here >>

When a Reference Signal is loaded, the Electrode Activity as well as Channel Activity analysis functions also display the results from the Reference Signal (superimposed in the background) in the same display. Figure 9 show the corresponding electrode activity for the electrodiagrams from

1 Figure 8, confirming that the MP3000 activity (pink or red) is less in number as well as intensity
2 than the ACE activity (light blue).

3 << Figure 9 about here >>
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8 RFcap also provides a diagnostic function to check the “frequency response” of a speech processor.
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10 Basically, this involves presenting a discrete frequency sweep consisting of 7 consecutive pure tone
11 bursts (125, 250, 500, 1000, 2000, 4000 and 6000Hz respectively) of equal lengths (e.g. 500ms) and
12 intensity, to a speech processor, and then capturing the corresponding output activity. The sound
13 playback level is assumed to be appropriately calibrated, and as pure tones are being used, the
14 playback should be in anechoic surroundings, for instance a soundproof test box. The captured
15 stimulus data are divided into seven corresponding equal time segments, and for each segment, the
16 modal electrode number (assuming that this is the central electrode if the activity is spread over
17 several electrodes) as well as the modal stimulus intensity for that electrode is computed and
18 summarized onscreen. Note that the “frequency response” here refers to the input-output function
19 for the entire signal path, including the microphone plus any additional filtering, as well as
20 threshold, clipping and discretization associated when mapping the input signal into Current Level
21 units. Measurements at different intensity levels (e.g. varying in 5dB steps) can also be combined
22 into a single diagnostic display as shown in Figure 10.
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42 << Figure 10 about here >>
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45 Ideally, when measuring the “frequency response”, an artificial map with all electrodes having the
46 same T and C levels should be loaded into the speech processor as well as RFcap.
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1 **RFcap as a development and research tool**

1 2 RFcap allows for easy comparisons of new speech coding strategies against existing ones. For
2 3 instance, the MP3000 coding strategy based on forward masking effects (Noguiera et al. 2005)
3 4 results in a reduction in the overall amount of stimulus activity, but should retain the overall
4 5 spectral representation. Figures 8 and 9 show how the MP3000 output compares to the standard
5 6 ACE coding strategy output. The electrodiagrams have the same spectral extent, but the MP3000
6 7 signal is clearly more sparse.

7 8
8 9 Although it is also possible to examine the decoded signals using "implant in a box" hardware
9 10 together with a multichannel digital oscilloscope, the analysis options and the maximum number of
10 11 channels are often limited. RFcap has the advantage that it is able to capture and display the
11 12 activity on all 22 stimulation channels using hardware that is already available in the CI clinic.
12 13 Custom analysis functions for the captured data can also be created as required, whereas the data
13 14 analysis functions available with a digital oscilloscope may not necessarily be suitable.

14 15
15 16 The predecessor sCILab software continues to be used and cited in various cochlear implant studies
16 17 (e.g. Henry and Turner 2003, Müller-Deile 2009, Sagi et al. 2009, Sagi et al. 2010, Zeng et al.
17 18 2008). Other examples are cited in Lai et al. (2003). With the old clinical hardware now already
18 19 superseded, the need for a similar software that works with more recent clinical hardware is quite
19 20 urgent, and RFcap is intended to fulfil this need. As the present trend continues towards even
20 21 smaller and simpler interface hardware (such as the Nucleus USB Programming Pod), the PCI-IF6
21 22 hardware is all the more valuable as it represents the last widely available clinical equipment with
22 23 full decoding and buffering capability, which RFcap is able to take advantage of.

1 **RFcap as a diagnostic tool**

1 2 RFcap can also be used in the clinical environment to diagnose problems with speech processors
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4 3 and their related accessories. Occasionally, CI patients have complaints of background noises in the
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6 4 speech processor, or that the sound has become muffled. With RFcap, it is possible to quickly test
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8 5 the output of the speech processor before sending the unit for repair. There is at present no such
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11 6 diagnostic tool available for testing in a CI clinic for the current generation of Nucleus speech
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14 7 processors.

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16 8 RFcap allows the following diagnostics to be performed:

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18 9 a) By capturing the RF activity without any signal input, spontaneous noise can be detected and
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21 10 documented. For instance, when the telecoil of a speech processor is enabled, it has been
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23 11 reported that this can produce spurious background noise which may irritate the CI user.
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26 12 b) Testing the output with a given input signal (particularly one calibrated at a known level) allows
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28 13 the tester to compare the resultant activity with expected electrodiagrams. The sound source
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31 14 level is typically calibrated, be it free-field or in a soundproof test box. It is unusual to use the
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33 15 direct accessory input as this bypasses the microphone input. However, direct input is useful for
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35 16 testing with signals such as pure tone sinusoids when an anechoic test box is not available.
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38 17 c) Using the Frequency Response function, the user can quickly check if the “frequency response”
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40 18 of the speech processor is according to specifications. The discrete nature of the mapping into
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43 19 Current Level units limits the output resolution somewhat, but this function will nevertheless be
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45 20 able to detect large deviations from the expected norm.
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48 21 Note that the PCI-IF6 hardware is not compatible with older Nucleus 22 implants. Diagnostics for
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50 22 Nucleus 22 implants will have to be made using either sCILab or a digital oscilloscope.
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53 23 It should also be kept in mind that it is not possible to check the output of Nucleus Freedom or
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55 24 Nucleus CP810 sound processors programmed for CI24RE or CI500 implants without
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57 25 reprogramming the processors with a map for the CI24M/R implant when testing in conjunction
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60 26 with the PCI-IF6 hardware.
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1 Summary

1 2 In summary, RFcap is a software analysis tool which is capable of capturing and storing the
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4 3 decoded output RF signals from Nucleus speech processors for the CI24M/R, CI24RE and CI500
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6 4 cochlear implants. Such an analysis tool can be applied to many situations ranging from basic
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9 5 research developments to clinical diagnostics.

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1 **References**

- 1 2 Henry, B. A. and Turner, C. W. (2003) 'The resolution of complex spectral patterns by cochlear
2 3 implant and normal-hearing listeners', J Acoust Soc Am, 113(5): 2861-73.
3 4
4 5 Irwin, C. (2006) 'NIC v2 Software Interface Specification E11318RD (Technical Report) ', Lane
6 7
7 8 Cove NSW, Australia, Cochlear Ltd.
8 9
9 10
10 11 Lai, W. K., Bögli, H. and Dillier, N. (2003) 'A software tool for analyzing multichannel cochlear
11 12
12 13 implant signals', Ear and Hearing Baltimore (MD), 24(5): 380-391.
13 14
14 15
15 16 Müller-Deile, J. (2009) 'Speech intelligibility tests in cochlear implant patients', HNO, 57(6): 580-
16 17
17 18 92.
18 19
19 20
20 21 Noguiera, W., Büchner, A., Lenarz, T. and Edler, B. (2005) 'A psychoacoustic "NofM"-type speech
21 22
22 23 coding strategy for cochlear implants', EURASIP Journal of Applied Signal Processing, 18: 3044-
23 24
24 25 3059.
25 26
26 27
27 28 Sagi, E., Kaiser, A. R., Meyer, T. A. and Svirsky, M. A. (2009) 'The effect of temporal gap
28 29
29 30 identification on speech perception by users of cochlear implants', Journal of Speech Language &
30 31
31 32 Hearing Research, 52(2): 385-95.
32 33
33 34
34 35 Sagi, E., Meyer, T. A., Kaiser, A. R., Teoh, S. W. and Svirsky, M. A. (2010) 'A mathematical
35 36
36 37 model of vowel identification by users of cochlear implants', J Acoust Soc Am, 127(2): 1069-83.
37 38
38 39
39 40 Swanson, B. A. and Mauch, H. (2006) Nucleus Matlab Toolbox 4.20 Software User Manual, Lane
40 41
41 42 Cove NSW, Australia, Cochlear Ltd.
42 43
43 44
44 45 Zeng, F. G., Rebscher, S., Harrison, W. V., Sun, X. and Feng, H. (2008) 'Cochlear Implants: System
45 46
46 47 Design, Integration and Evaluation', IEEE Rev Biomed Eng, 1: 115-142.
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1 **Figure captions**

1 2 Figure 1: A typical system configuration for capturing and analyzing RF signals. An acoustic
2 3 signal is processed by the speech processor (A) and coded as an RF signal, which, instead of being
3 4 sent to a patient's implant, is sent to the receiver coil of the PCI (B). The hardware continuously
4 5 decodes the incoming RF signal, storing the data in hardware buffers which are read by RFcap
5 6 software on a computer (C) connected to the PCI via a Nucleus IF6 card.
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8 9 Figure 2: The captured and decoded stimulus activity for the utterance "asa" is displayed onscreen
9 10 as an electrodogram. Note that the "centre of gravity" (CGrav) of the electrodogram is computed as
10 11 the modal electrode and its corresponding modal stimulation level. Figures 3 to 9 are also based on
11 12 this same signal.
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28 29 Figure 3: Electrode histograms show the distribution of activity across the array of 22 intracochlear
29 30 electrodes for the entire signal. The lower histogram is weighted by the stimulus intensity
30 31 computed as a percentage of the dynamic range between T and C levels for that electrode.
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61 62 Figure 4: The activity on a selected electrode (or channel) is summarized here, showing the
62 63 distribution of stimulus intensities in Current Level units, as well as the instantaneous stimulation
63 64 rate between every 2 consecutive stimuli on the same electrode. The x-axis of the upper graph is in
64 65 Current Level units, while the x-axis of the lower graph is the frame number of the first stimulus in
65 66 the pair used to compute the instantaneous channel stimulation rate.
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96 97 Figure 5: The overall instantaneous stimulation rate is computed from the time interval between
97 98 each consecutive stimulus (i.e. including powerup pulses) regardless of the corresponding electrode.
98 99 The stimulation rate per set of maxima assumes that the selected maxima within a set are presented
99 100 in a basal-to-apical order. This should correspond to the channel stimulation rate.
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1 2 Figure 6: The number of maxima found in each set, and the duration of each set are summarized
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3 3 here, as well as their respective distributions.
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8 5 Figure 7: The occurrences of powerup pulses and the distribution of their corresponding durations
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11 6 are summarized here.
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15 8 Figure 8: Two superimposed electrograms in different colours allow for visual comparisons. In
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18 9 this example, the activity in the foreground (dark blue) from the MP3000 coding strategy can be
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20 10 seen to be less than the activity in the background (light blue) from the ACE coding strategy, but
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23 11 still has a very similar spectral representation.
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28 13 Figure 9: The electrode histograms for the signals in Figure 9 confirm that MP3000 has less
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30 14 activity (number of stimuli), and this has generally less intensity (weighted number of stimuli) than
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33 15 the corresponding ACE activity.
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37 17 Figure 10: The “frequency response” assumes that the input signal consists of 7 equal time
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40 18 segments. The modal electrode number with the largest intensity within each segment, and the
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42 19 modal stimulation level (in Current Level units) within each segment are then summarized for each
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45 20 segment. Here, the results from 5 sweeps at different intensity levels are shown combined in the
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47 21 same display.
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Figure 1

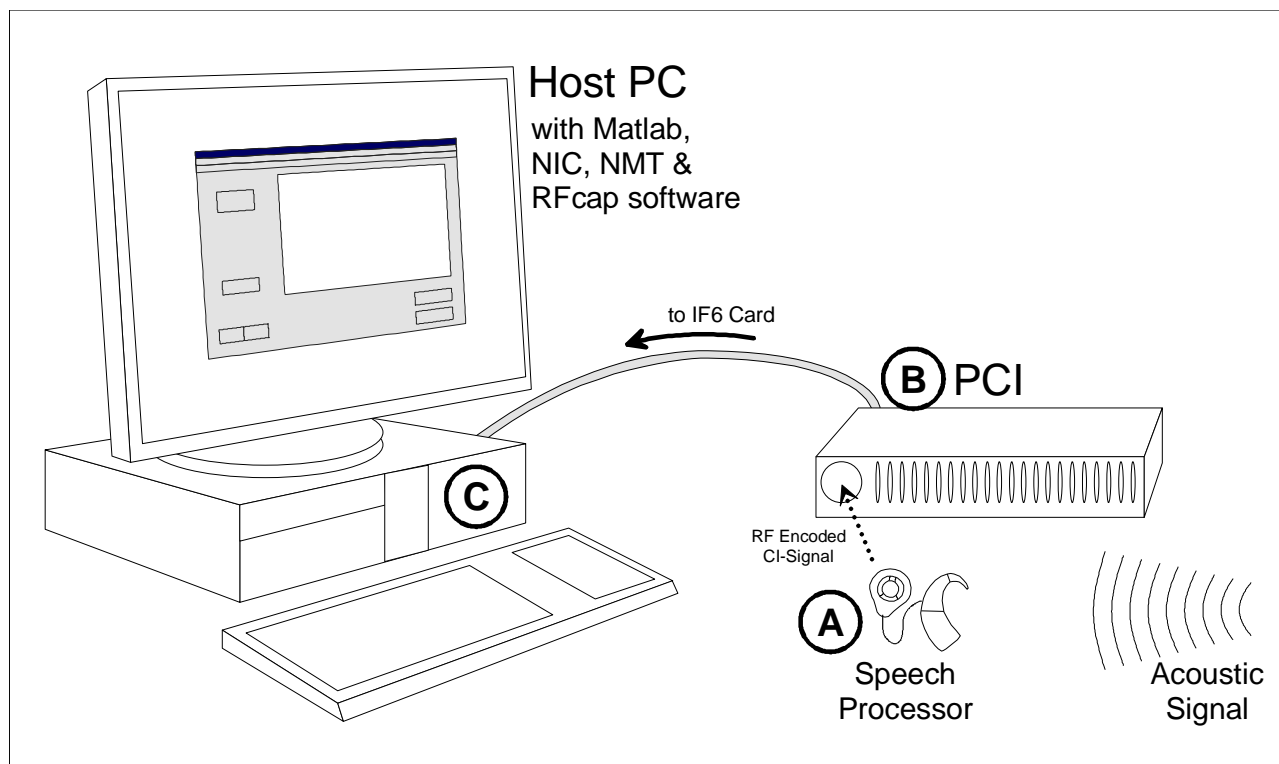


Figure 2

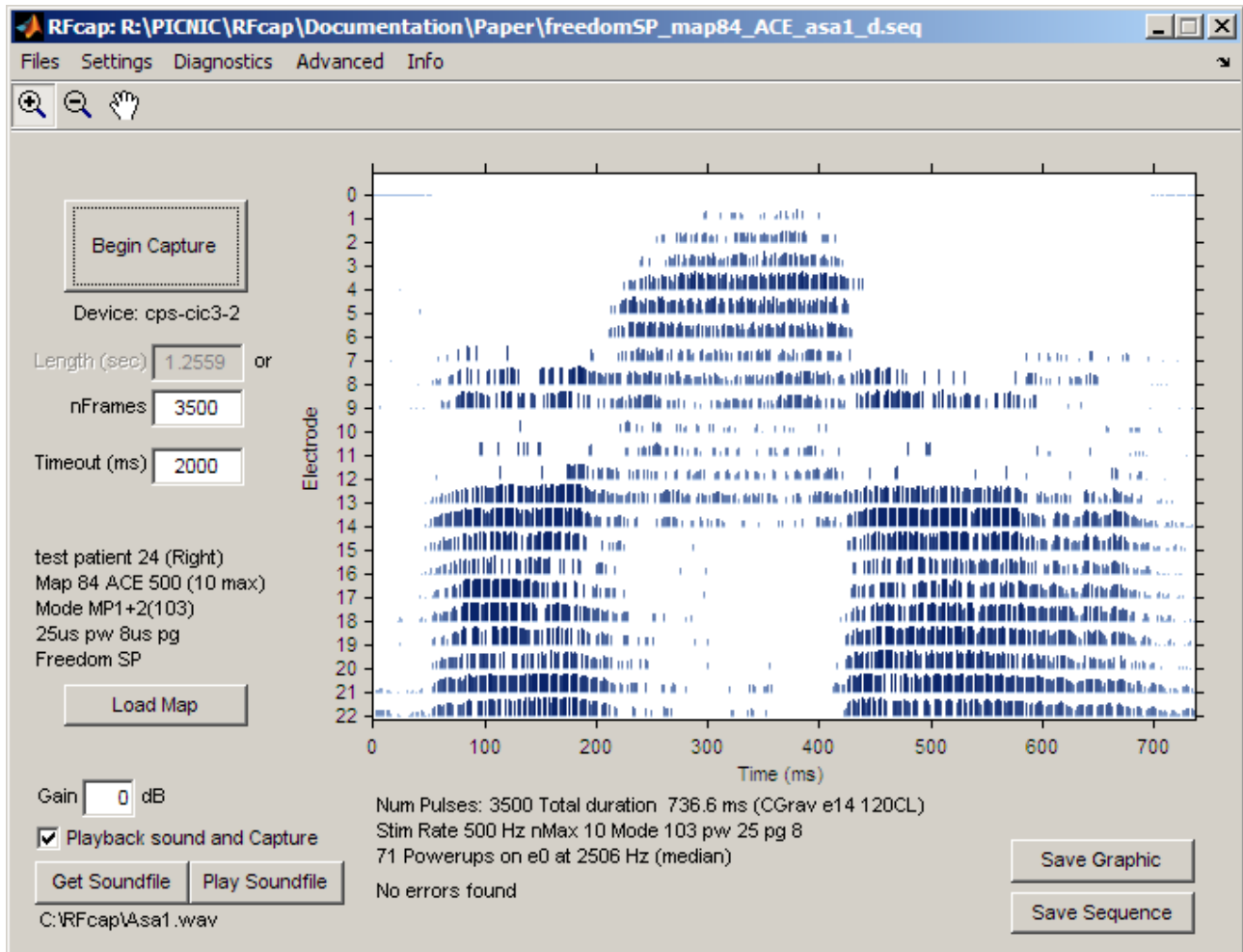


Figure 3

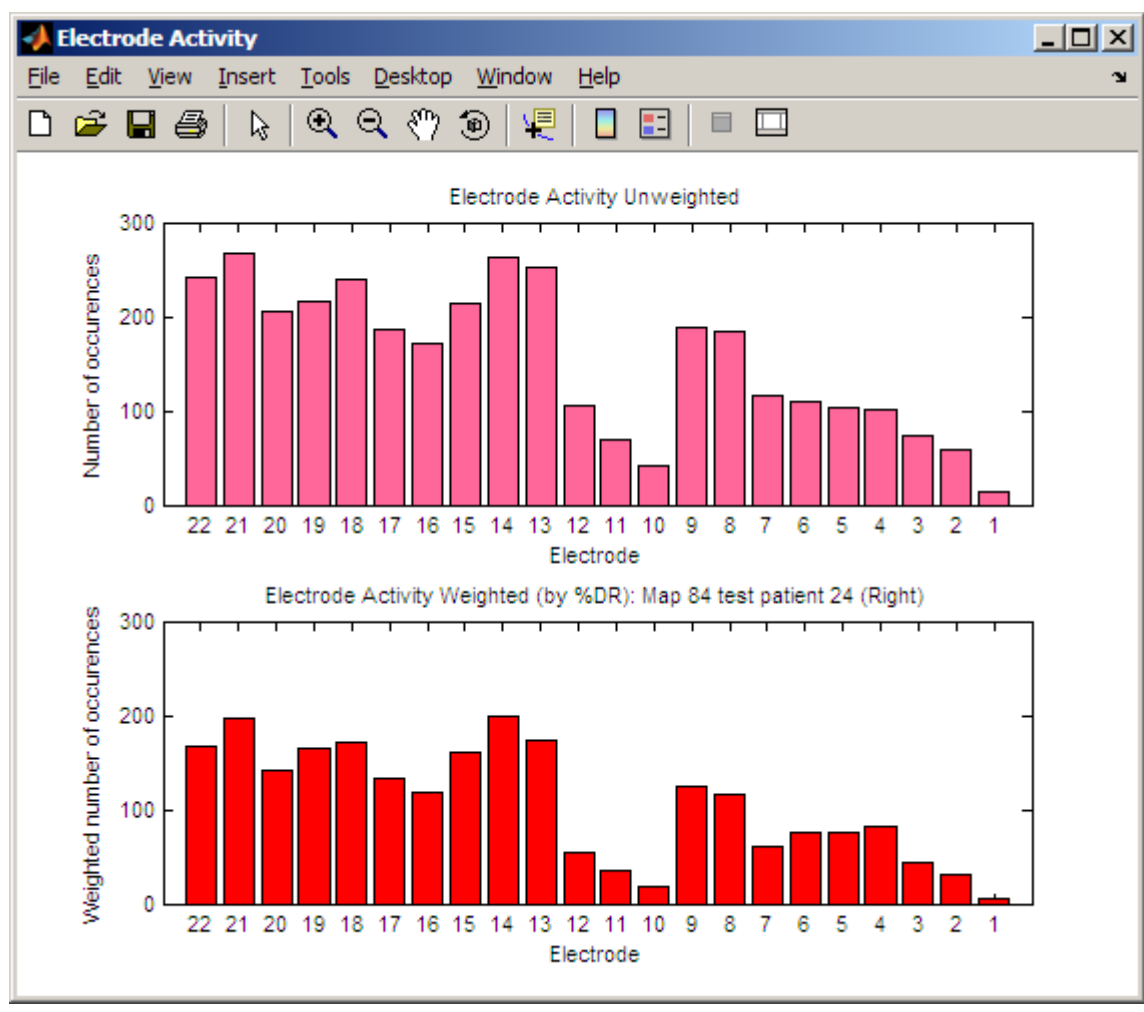


Figure 4

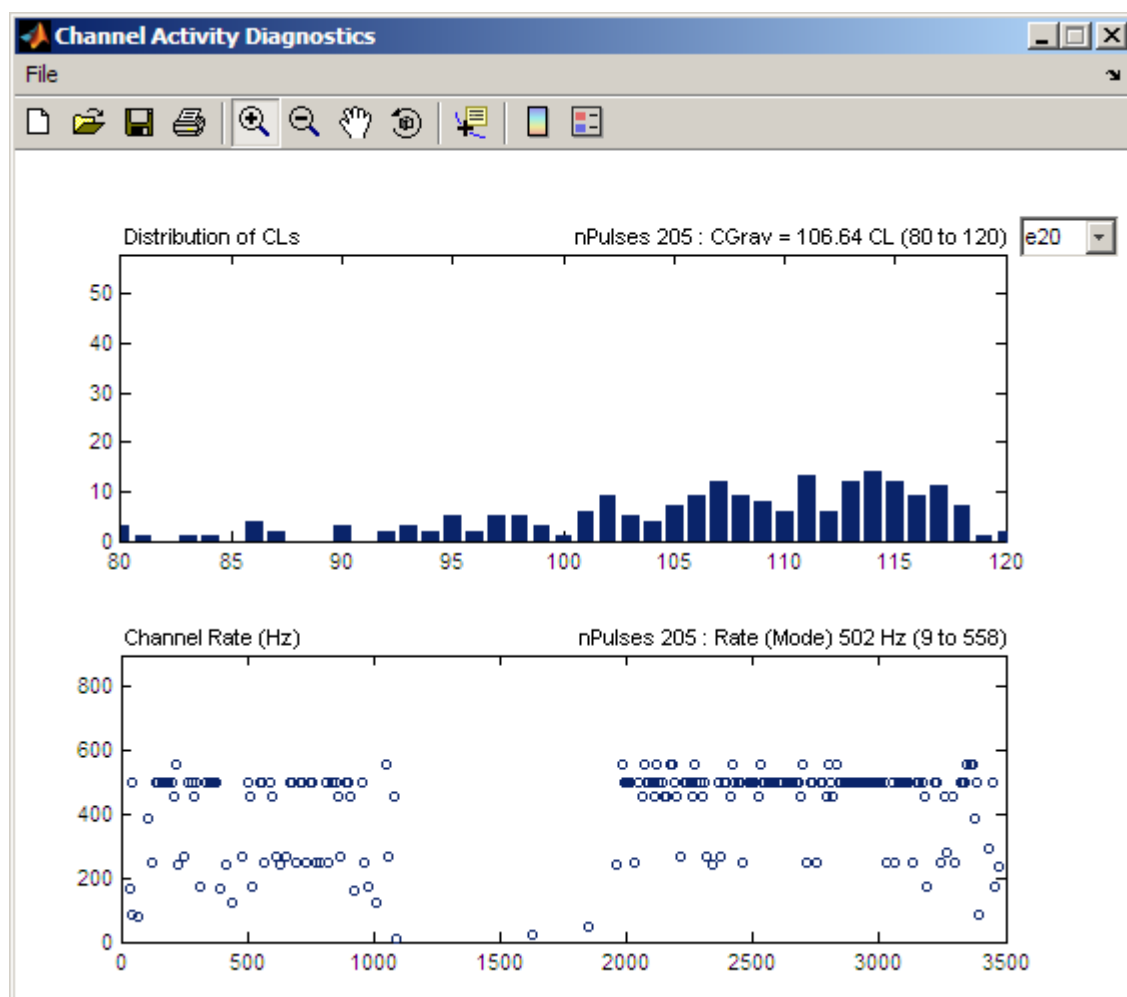


Figure 5

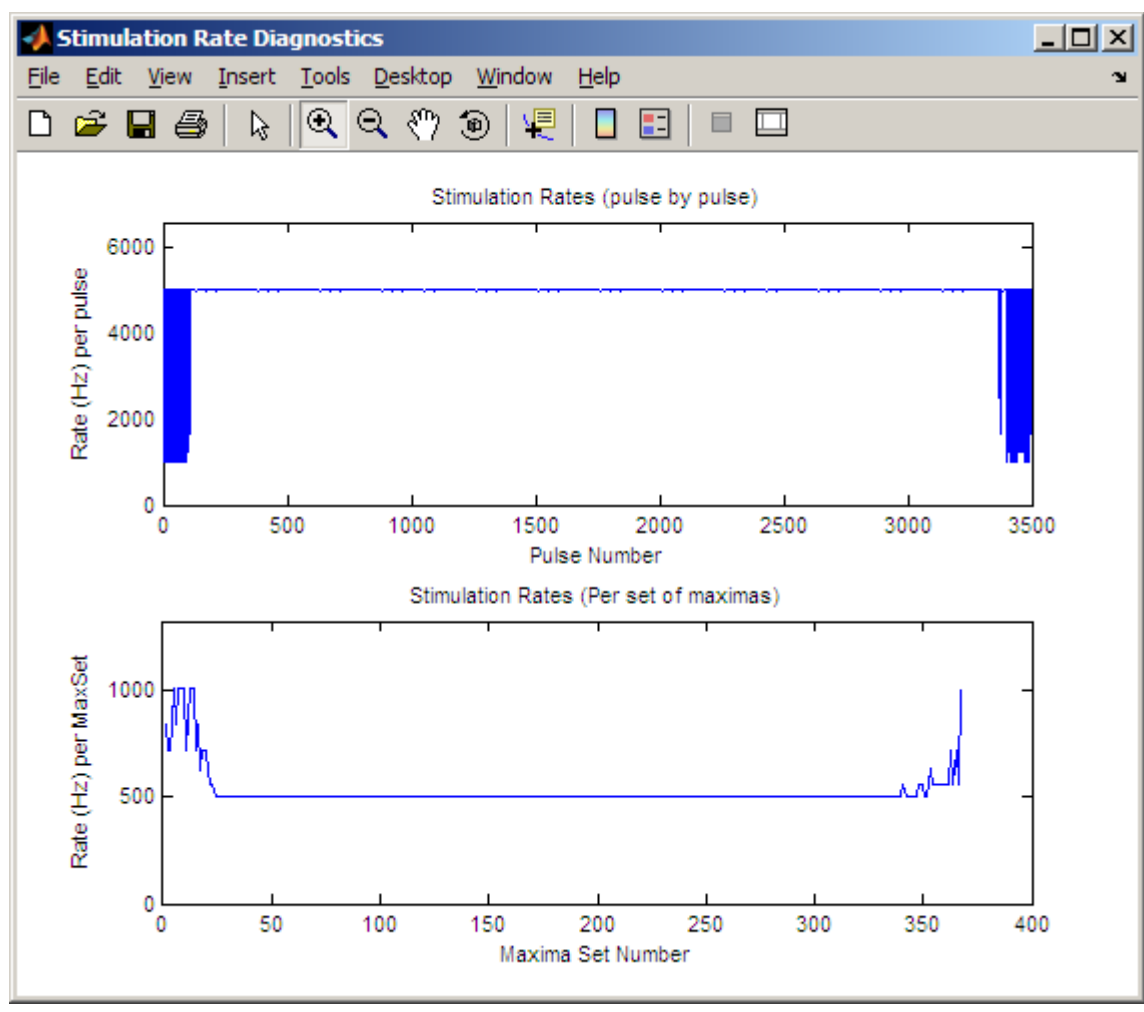


Figure 6

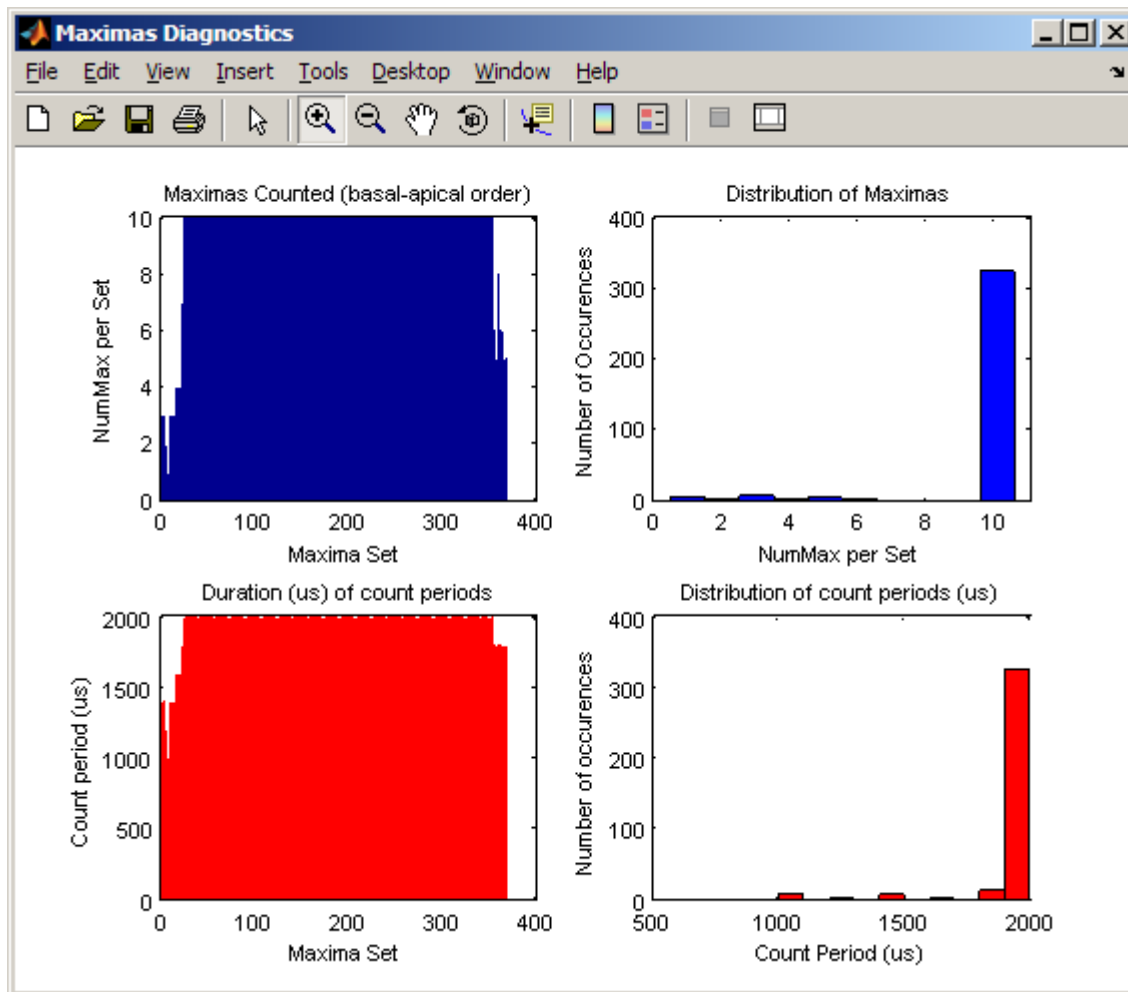


Figure 7

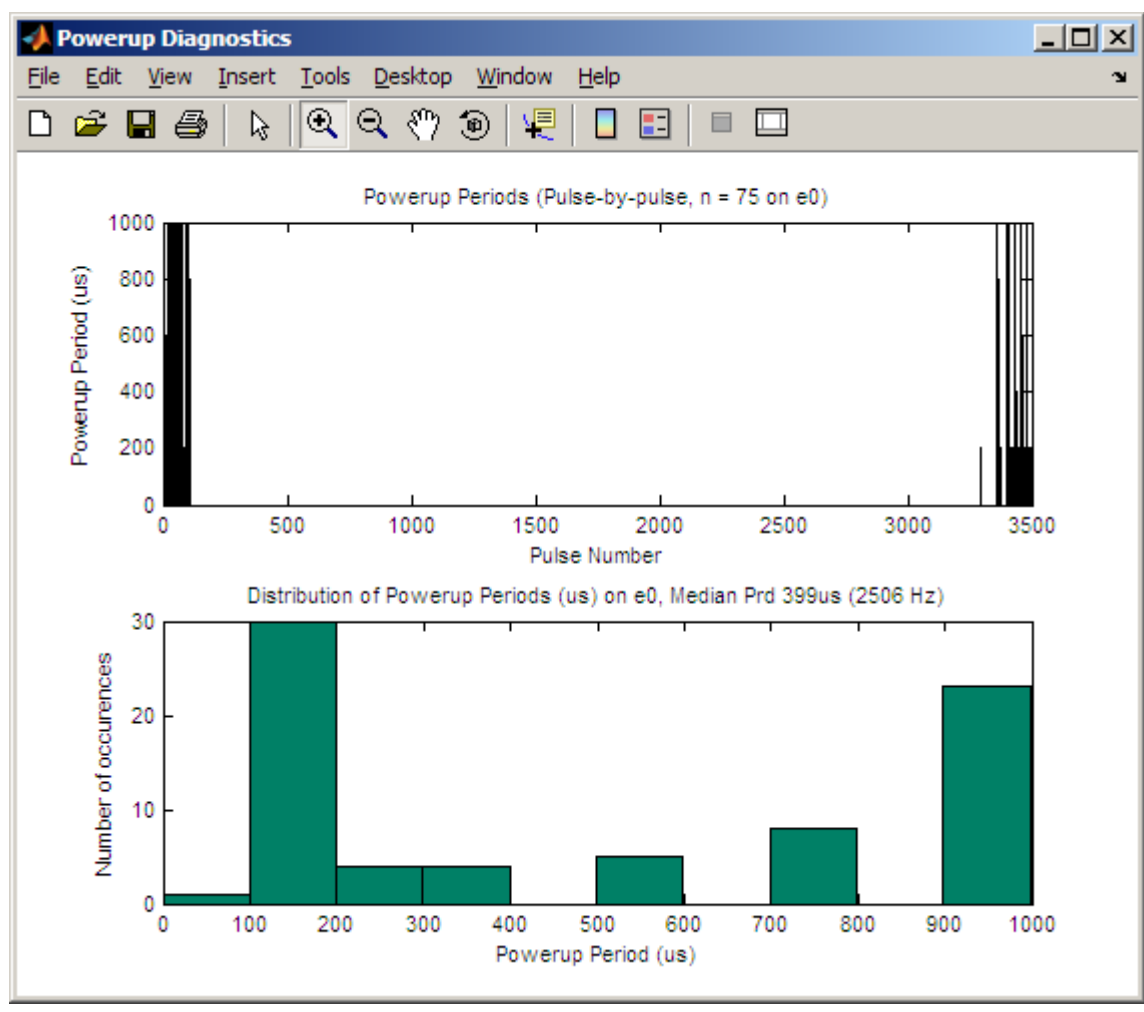


Figure 8

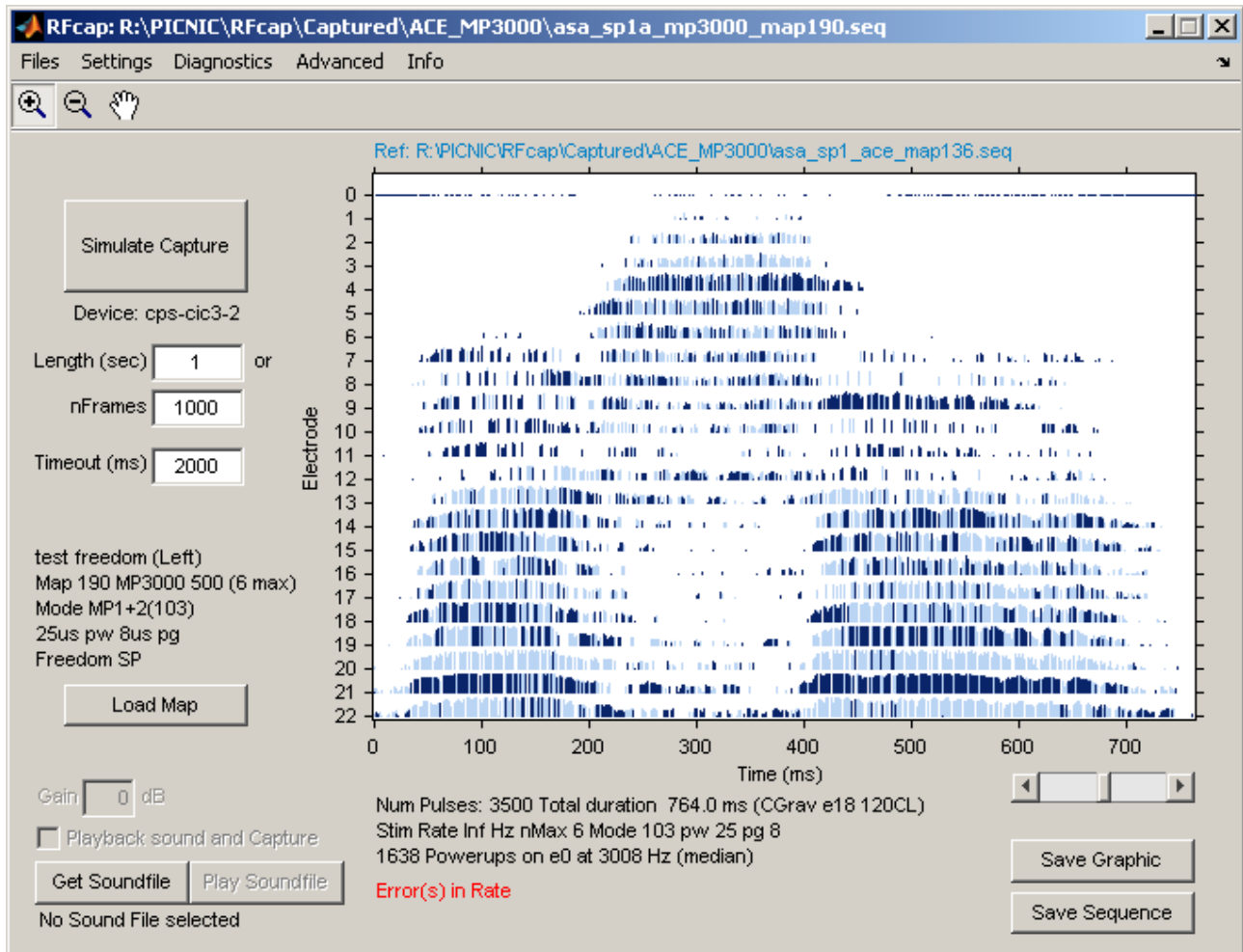


Figure 9

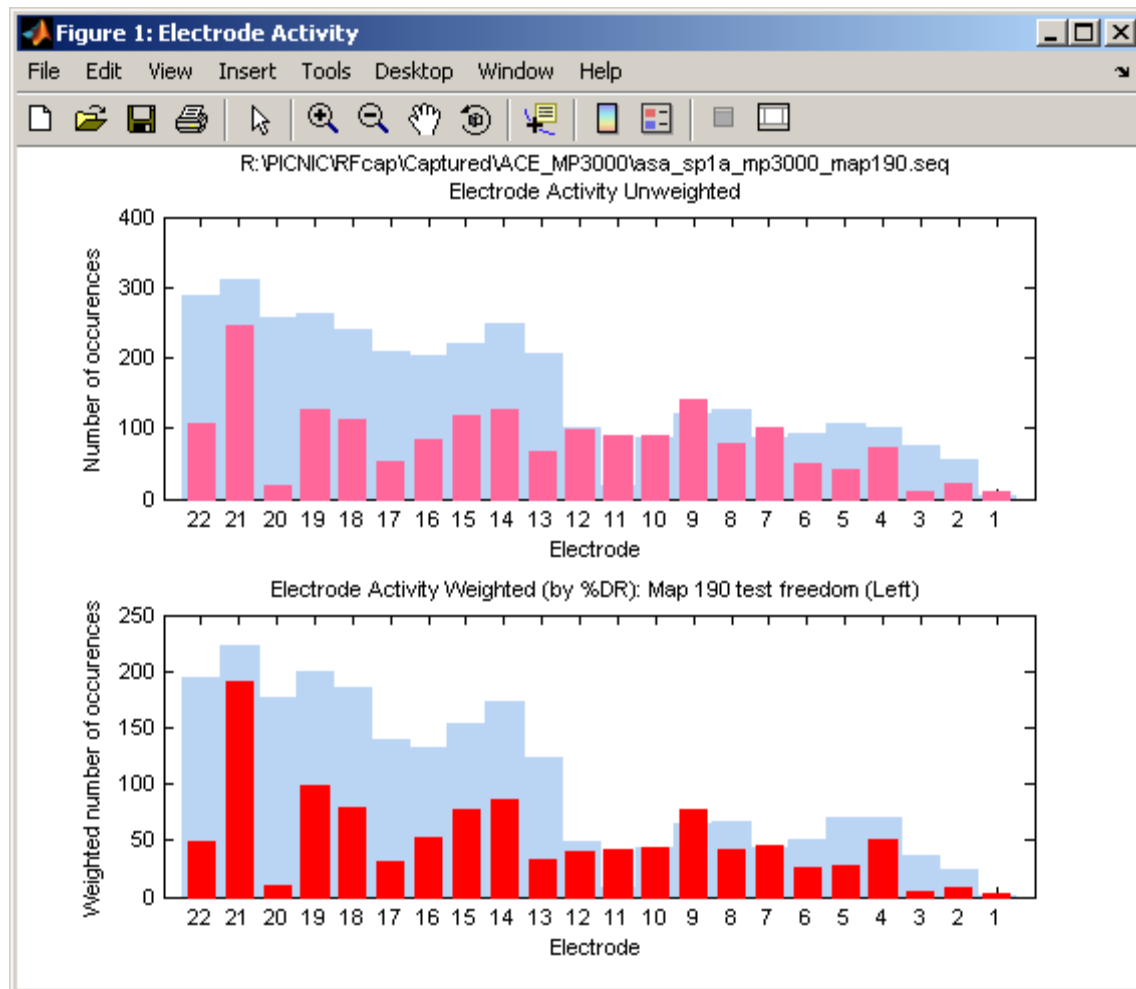


Figure 10

