Figure 4.9: Overall system drift with fan cooled mainboard/power supply.

Comparing both measurements allows further discrimination of the main factors influencing the overall system drift: The strongest factor influencing drift performance seems to be the temperature increase of the ADC unit caused by power supply heating.

The NIRS module itself shows a very low drift of max. $-10^{-6} V/s$ which is in the order of the TCR of the $1\,\Omega$ current regulator sensing resistors. So far, the changes in the total radiated power of the LEDs resulting from temperature changes seem to be negligible or comparable to the influence of current sensing resistor heating effects.

4.2 Physiological Verification of the System

4.2.1 Qualitative Physiological Signals: Pulse and local Blood Pressure

To verify that the instrument's output NIRS signal contains physiological information of significant strength, simple qualitative experiments were conducted:

Fig. 4.10 depicts the effect of overall blood pressure in the head on the signal, leading, amongst others, to an increase in cerebral blood volume (CBV). To influence the blood pressure in the head, the short experimental protocol was as follows: First, the subject inhaled, followed by piping down together with contracting the diaphragm (Start) for a period of 5 seconds. This period was then followed by 10 seconds of relaxation (Relax) and normal breathing until the start of the next trial.

A strong fall of the optical signal strength resulting from increased blood volume in the head can be observed instantly after each starting period. During relaxation periods, the signal immediately recovers with about the same speed to the baseline of the experiment's start as the blood volume in the head normalizes.

The visibility and strength of pulse artifacts in the overall optical signal is an indicator for the signal quality and has been widely documented in NIRS literature, as the pulse artifact's strength is in the order of functional brain activity influences. Thus, a clear pulse artifact is a first indicator for sufficient signal quality to measure brain activation. Fig. 4.11 shows an example of the clearly visible pulse artifacts in the signal during a cognitive relaxation period.
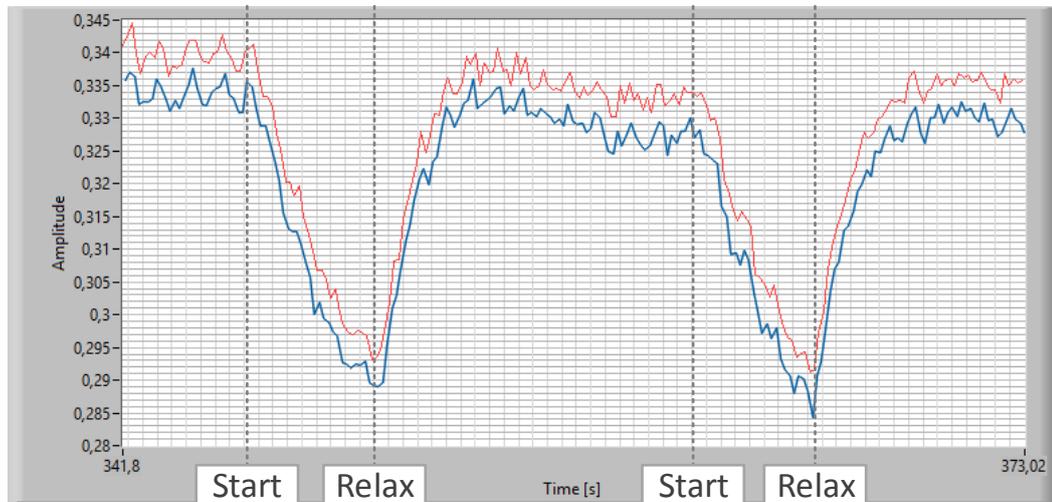
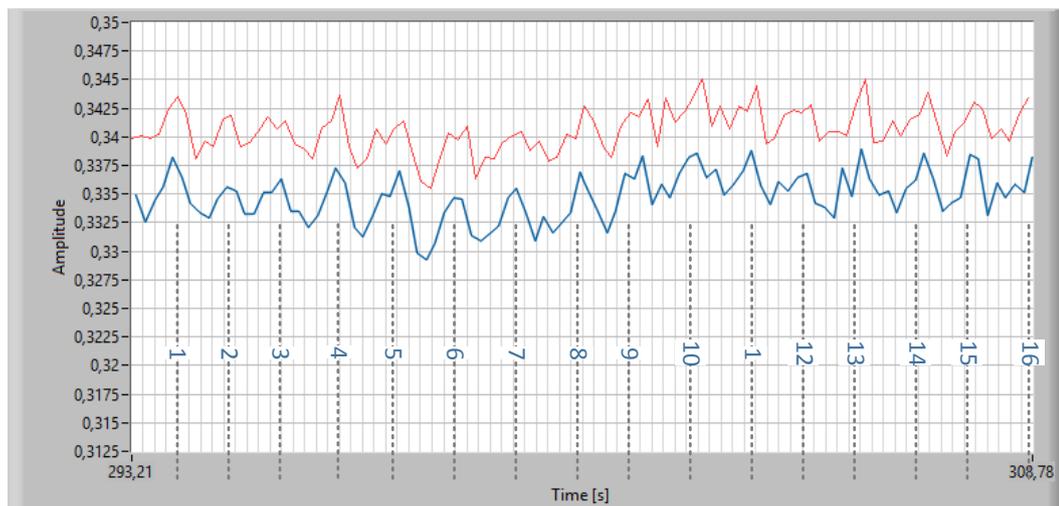**Figure 4.10:** Influence of blood pressure variations in the head (cerebral blood volume (CBV)), raw signal.

Figure 4.11: Pulse artifact in the raw signal.

The visible heart rate of approx. $\frac{16\,pulses}{15\,s} = 64\,pulses/min$ in the experiment was verified by a 60-second pulse measurement with a heart rate result of $65\,pulses/min$.

4.2.2 BCI Trials: Mental Arithmetics

For verification of the device's capability to measure functional brain activity, 32-trial BCI classification experiments were conducted both with the designed fNIRS instrument and an Oxymon Mk III reference fNIRS system from Artinis Medical systems. The Oxy-

mon Mk III uses laser diodes with $765\,nm$ and $856\,nm$ with fiber optical guided optodes and is a commercial tabletop system with two sensors and 4 emitters.

Both instrument's performances were evaluated on two subjects with mental arithmetics based experiments measuring brain activity at the prefrontal cortex:
The first experiment was conducted using a prototype version of the designed fNIRS instrument and single channel acquisition at $7\,Hz$ and was repeated with a single channel $10\,Hz$ acquisition using the Oxymon reference system.
The second experiment was conducted using the final fNIRS instrument with two channels sampled at $8\,Hz$ each and repeated with a two-channel $10\,Hz$ acquisition using the Oxymon system.

For all experiments, the following protocol was followed:
With an emitter-detector distance of $3.5\,cm$, the light emitting probes were placed approximately on the places of Fp1 & Fp2 of the international 10-20-system and the light detector placed approximately on AFz (see fig. 4.12). In the single channel experiment, only Fp1 versus AFz was measured.
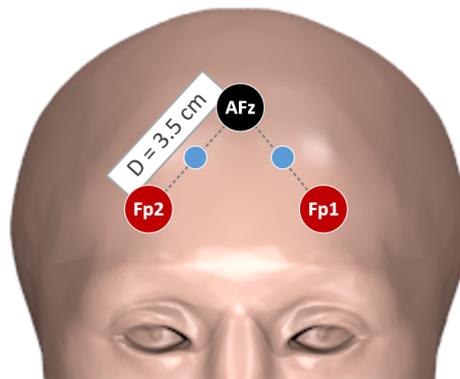

Figure 4.12: Optode placement for BCI experiments. Red: NIR light emitter placement, black: NIR detector placement, blue: approximate point of maximum sensitivity.

Using a Cognitive Systems Lab (CSL) BCI trial Matlab script, the fNIRS signal was recorded during 32 trials of 8 seconds each, with the subject alternately executing a mental arithmetic task (16 trials) and relaxing (16 trials). For the mental arithmetic tasks, the subject was given a random number between $100 - 9999$ at the beginning of each 8 second arithmetic trial and iteratively subtracted the number 17 until the end of the trial.

For evaluation of the data, a signal processing, a feature extraction and a classification step were performed.
In the signal processing step, biological artifacts, mainly the heartbeat (see section 2.2), were reduced using a digital filter. The signal was filtered by an elliptic IIR 0.7 Hz low-pass filter of the order 6 in both the forward and reverse directions.
For feature extraction, HbO and HbR were calculated from the raw data using the modified Beer-Lambert Law. Then, for each channel (and both HbO and HbR) of each trial, the slope of a least-squares-fitted line to the signal time series was calculated, resulting in a 4-dimensional feature vector per trial.

For classification, a Linear Discriminant Analyis (LDA) classifier using leave-one-out cross-validation was applied. To do so, one trial of the data of one subject was left out for evaluation in a round-robin manner, while the remaining data was used for training.

For the single-channel experiment, the classification results were a cross validation accuracy of 62.9% with a normalized standard deviation of $\sigma_N = \frac{0.492}{\sqrt{32}} = 0.087$ for the prototype fNIRS system and a cross validation accuracy of 69.23% with a normalized standard deviation of $\sigma_N = \frac{0.471}{\sqrt{32}} = 0.083$ for the Oxymon Mk III reference system.
For the two-channel experiment, the classification results were a cross validation accuracy of 75.0% with a normalized standard deviation of $\sigma_N = \frac{0.440}{\sqrt{32}} = 0.078$ for the final fNIRS system and a cross validation accuracy of 65.63% with a normalized standard deviation of $\sigma_N = \frac{0.483}{\sqrt{32}} = 0.085$ for the Oxymon Mk III reference system.
The presented accuracies are averaged over all folds.
Figure 4.13 shows the average signal responses (MBLL concentrations) of the trials for the two-channel experiment.
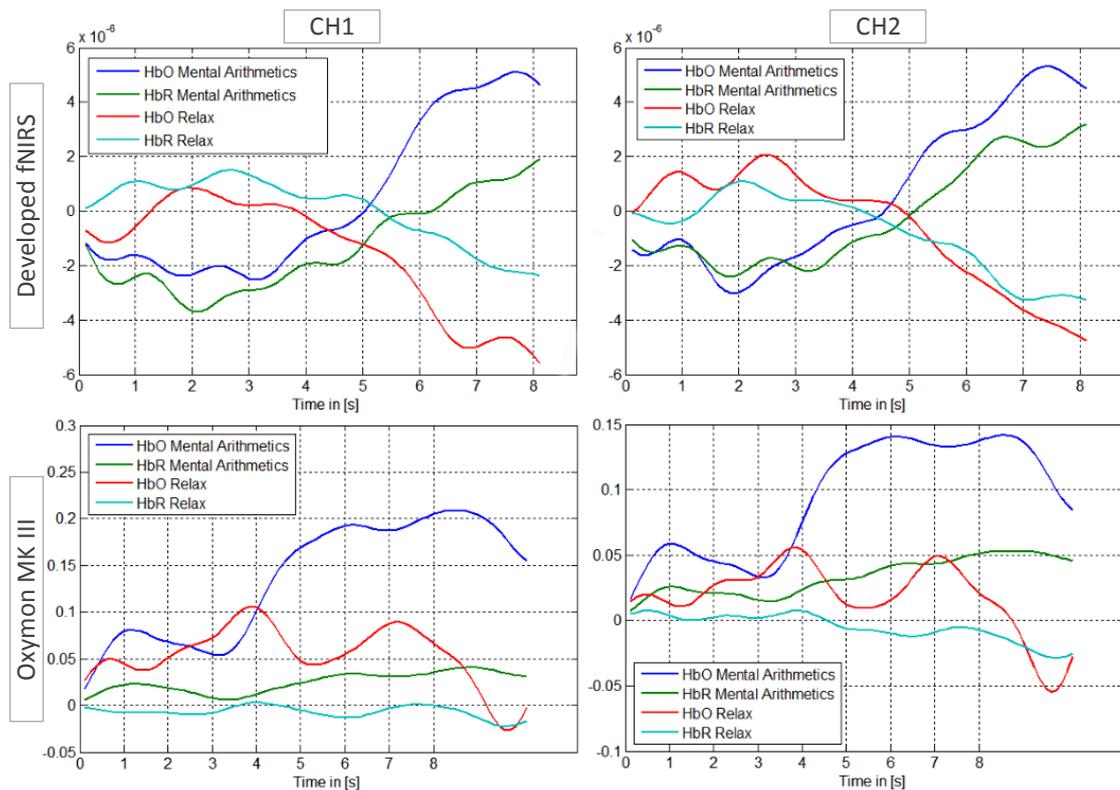

Figure 4.13: Average signal responses of the BCI trials for both channels and both instruments.

The experiments showed similar results for both systems regarding averaged signal trends and classification accuracy. While the commercial Oxymon system performed better in the single-channel experiment, the classification accuracy for the two-channel experiment using the developed fNIRS instrument was 10% higher than with the Oxymon instrument.