

Impedance Cardiography at Higher Frequencies

A Study on the Sources of the Signal

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Abstract

Impedance cardiography is a non-invasive method to measure both stroke volume and cardiac output of the left ventricle. As a medical technique it is both cheap and simple to use, requiring little training. While there exists a fair amount of literature and documented experimentation on the subject, it still remains a lesser used technique in spite of its many pro's. A major reason for this is the fact that there is still a large amount of uncertainty around the subject. Both regarding the source(s) of the measured signal, and the data that can be extracted from the different parts of the signal, their ratios and time intervals.

This experiment will attempt to further our understanding of the sources of these signals. By using new equipment that allows us to not only measure with higher than normal current frequencies, but also with a sufficiently high sampling frequency, the goal is to get a better look at what parts of the signal are dependent on the frequency of the current, and which parts are not. More directly, we are attempting to look at the change, or lack thereof, in the amplitude of the differentiated impedance as current frequency rises. This will allow us to begin to categorize which bodily events may have an effect on the impedance cardiography, and to what extent relative to others.

The experiment will be conducted using a fairly standard ICG setup, including a tetrapolar electrode system, a commercial ICG product and a newer ICG product more angled towards lab work. The experiment itself will be conducted on a small number of test persons, all young and with no reported cardiac issues.

Although a small sample size, every subject showed a reduced ICG amplitude at higher frequencies, however the signals did not completely disappear, rather dampen by around 50%. This implies that the sources of the ICG measurements are split between several bodily effects. Some dependent on the current frequency and some not.

Preface

In spite of all the obstacles and troubles during this experiment, it is finally a finished product.

A great thanks to my guidance advisors Ørjan Grøttem Martinsen and Jon Vedum. Thank you for all the help, resources, time and sound advice, not to mention the opportunity to work on such an exciting project.

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Chapter 1 – Background & Theory

1.1 Bioimpedance

What is bioimpedance?

Bioimpedance most commonly refers to the ability of tissue to impede electric current flow. Impedance is the ratio between voltage and current, its inverse is admittance. Impedance is a measurement of something's ability to impede current.

This is most commonly paired with a galvanic coupling between the tissue and electrodes, which simply means two separate materials connected by an electrolyte. By using these electrodes to let a controlled current travel through the body, and to pick up the differences in voltage between two positions one may calculate the impedance of the material between application and extraction of current.

Bioimpedance holds a lot of information about the respective tissue while also having the advantage of being non-invasive [9, 11].

Usage

The field of bioimpedance is perhaps not the most well-known, or well explored one. It does however, have a multitude of uses, both theoretical and practical. Below are just a few examples of the things that can be achieved with the use of bioimpedance.

Impedance cardiography, the main subject of this thesis. Often shorted to just 'ICG', bioimpedance is a method for measuring the impedance due to mechanical changes in the thoracic region, giving us information about the heart activity, such as stroke volume or expansion [9, 10, 13, 15]. There have been some studies that suggests that ICG is a viable method of determining the near-term risk of heart failure, provided the measurements are regular [19].

It is a quite simple and low-cost technique however, it does have a lot of uncertainties. Some of these uncertainties are tied to how the individual person is put together, inhomogeneous material, organs etc. Some uncertainties may exist in the physical shape of the person, and finally there is a lot of uncertainty in how the measurement is done, with regards to electrode placement, skin and hair.

Finger print sensor security. Bioimpedance an easy solution to the problem with finger print sensors: how do you know it is a real finger? Vine gummy can be used to replicate fingers, and pulse plethysmography, which uses optics to measure blood perfusion, is dependent on the finger having a certain amount of heat so that the microcirculation is not so weak that it is undetectable, which would be troublesome for example, in the winter.

Tenderness of meat. Fat naturally has an effect on the impedance, bioimpedance can be used to 'cartograph' the layers of a piece of meat, determining its composition and by extension, it's tenderness.

Time of death. We know that the bioimpedance in dead organisms changes with time as a result of rigor mortis, which could be used to quickly come up with a rough estimate of the time of death [5, pg.109].

1.2 Skin impedance

When dealing with bioimpedance measurements on living (human) subjects, in almost all cases the contact area between electrode and tissue will be the interface between electrolyte and skin. This is, of course, also the case in this experiment.

Stratum corneum dominates at lower frequencies, with gradually lower impedance values at higher frequencies. It is the outermost layers of the human skin composed of dry, compressed, dead cells. These layers form gap junctions and are shunted by the sweat ducts in the skin. Simply putting the skin in contact with an electrode does reduce the impedance because of the liquids in the living layers of skin beneath the stratum cornea penetrates and establishes a contact with the electrode. This does however take some time, which is why one usually use electrodes in conjunction with an electrolyte, something that significantly reduces the time with poor contact between the skin and electrode [1].

Skin impedance may also be lowered by skin stripping technique, in its simplest form it consists of applying and tearing off pieces of sticky-tape. This is of course done to easily, and quickly remove dead skin cells, and has been shown to be a valuable and easy solution for lowering skin impedance, either by itself or in conjunction with other techniques such as using electrolytes.

It should also be noted that the impedance of the stratum corneum is also dependent on moisture. Things like the relative humidity in the air around the skin and general area do change the skin impedance. This does, of course, also extend to wetting the skin. In this experiment the skin has been wetted with alcohol right before electrode onset.

1.3 Muscle impedance

Muscle consists of long fibres, running in one direction, the line of action. These fibres are a source of impedance. The direction of the current path with regards to the fibre orientation is a large source of difference in impedance. It has been shown that the difference between a current path running parallel to the muscle fibres, and a current path running perpendicular to the fibres might be as high as 8:1 [12]. As will be shown later in the experiment, there was discovered a big difference in impedance measurements between measuring primarily the impedance in areas with muscle underneath the electrodes (pectorals) and areas where we have primarily just skin and bone (sternum, upper and between pectorals).

1.4 Current paths

As we know, current takes paths inversely proportionally to their impedance. As such, there are certain properties of tissue that will alter the current path, especially when considering inhomogeneous tissue.

Non-native causes of changed current path. Mainly implants, depending on the material these implants may range from insulating to conductive. This, of course, is relative to the electrical properties of the tissue in the immediate area surrounding the foreign object. A conductive implant will present a lower resistance path for the current, thus altering the current path by leading the current towards and through itself. An insulating implant will of course do the opposite and obstruct, or impede, the current path. Which in turn will increase the measured impedance because the path of lower resistance will be one circumventing this object [5] (pg.112-113).

One natural cause of a change in current path is the blood cells. It is the most common cell in the body, and is shaped like a doughnut. The blood cells, like most other cells are covered by an outer lipid membrane. This membrane, being a dielectric, gives rise to a maxwell-wagner effect. Because of this we are left with a capacitive effect, with the admittance being dependent on the signal frequency. At low frequencies, the charge build up is low, and the current does not penetrate the membrane around the erythrocytes, but rather circumvents the cells entirely. This of course is a source of impedance, and it is the goal of this experiment to determine how big of an impact on the total impedance this circumvention has [5] (pg.86 & pg.93-95).

Relaxation and Dispersion

In short, when a system is affected by an excitation signal, such as when a material is polarized (polarization being when the charge distribution in a system is changed because of an electric field) by an external field, relaxation is the process in which this system over time returns to a new equilibrium. The concept of dispersion is the frequency component of this phenomenon, the change of permittivity as a function of frequency.

Maxwell-Wagner

Deals with the interface between two different dielectrics in parallel and the build-up of charge between them as frequency rises, showing how an inhomogeneous interface can be imagined as two dielectrics, and how they might be frequency dependant in conjunction even though none of them have a frequency response by themselves. Partially explains why current penetrates the erythrocytes only at higher frequencies. This would be what we categorize as a beta-dispersion. The characteristic frequency of this type of dispersion is in the 1 kHz – 100 MHz range. [5, pg.73]

Adsorbed Counterions

In wet systems, with large numbers of small particles, the effect of counterions on the surface dominate. In 1962, Schwartz proposed a that the large increase in permittivity of a suspended particle was a result of tightly packed counterions on the surface of the particle. The reason for this theory was that the classical Maxwell-Wagner theory could not wholly explain the large increase in permittivity. The relaxation and by extension the dispersion of these particles are what opens up for this low-frequency permittivity. This would be what we categorize as an alpha-dispersion. The characteristic frequency of this type of dispersion is in the mHz - kHz range. [5, pg.73]

Dipolar Mechanisms

Some material, the simplest example perhaps being water, is what we would call polar. In short, this means that the atoms building up the molecules of the material, have different charges. If we go back to the water molecule, the hydrogen atoms are negatively charged while the oxygen is positive. This slight separation of charge gives rise to a dipole moment, a vector pointing from the negative towards the positive charge.

Normally, these dipole moments are completely random. However, when exposed to an external electrical field, these dipoles will reorient themselves along the direction of the field. This reorientation of polar molecules is what we would categorize as gamma-dispersion. The characteristic frequency of this type of dispersion is in the 0.1-100 GHz range. [5, pg.73]

1.5 The electrode

In its essence, an electrode is a device that transforms charge carriers. In living tissue, the charge carriers are free ions, now to make this compatible with the standard modern-day electronics, we need to transform these carriers to free electron carriers (in short, current through a wire). And this is just what the electrode does. When the electrode comes in contact with an electrolyte with free ions as charge carriers a double layer is created. This double layer may function as a capacitor in parallel with a resistor. The electrons in the electrode metal exchanges charges with the arriving ions somewhere in the double layer.

The electrode itself is usually a metal plate with a connecting wire on the "top-side". Underneath one would usually find some sort of gel or liquid, that acts as an electrolyte, and sometimes also as an adhesive. The electrolyte is not always necessary, as it can be shown that electrode-ion transfer may occur even with dry electrodes, however much of this is because of a natural liquid build-up underneath the electrode which is a slightly time-consuming process with no apparent advantages for whole body measurements, and as such there is no reason not to bypass this process completely by introducing an electrolyte. This of course is different if one wishes to do measurements on the impedance of the skin. In such cases one might prefer to use dry electrodes or solid gels. For this specific experiment an Ag/AgCl electrode was used, one of the more common ones. It is simple, sufficiently nonpolarizable for this application, which means it does not compromise the tissue measurements with its own polarization impedance. It comes pre-packaged with an electrolyte.

There are of course different metals used in electrodes, which metal to use is dictated by circumstances. Such as biocompatibility (e.g. Nickel produces thin and flexible plates, but is a fairly common allergy), polarization, implants or surface.

1.6 Electrode skin interface

The skin is often very variable and poorly conductive when not wetted and as such will dominate the electrical properties, especially at lower frequencies as it has a substantial capacitive element. As mentioned earlier a metal electrode can be applied directly to dry skin, but this is not recommended. At first the skin impedance will be very high, before it starts to drop as fluids underneath the skin build up and seep through the pores, this however is a time-consuming process that is hard to control. And it is therefore we use what is called electrolytes.

An electrolyte is the substance one would place between two electrode plates or an electrode and the surface of what we want to measure, for example human skin. The electrolyte is an electrically conducting solution that, amongst other things, forms a high-conductance salt bridge from the metal to the tissue, enables the metal-tissue interface to be kept at a distance from the tissue, fills out spaces between electrode plate and tissue, moistens the poorly conducting skin with electrolytes.

One of the main uses for electrolyte is to penetrate and wet the outer layers of the skin. Electrolytes with high concentration actively penetrate the skin, with a noticeable effect after only a few minutes, however the penetration may continue for longer periods of time, even shown to last for days. The higher the concentration the better the penetration however it is also more irritating for the skin, therefore care must be taken to select the right electrolyte concentration for any given procedure.

The contact area between the electrode and the electrolyte is called the electrode area and the area between the tissue and electrolyte is known as the effective electrode area. Since the electrode plate is usually smoother than the skin surface it would be natural to say that in most cases the effective electrode area is greater than the electrode area. Both of these values are of great importance when it comes to electrodes. Having a large electrode area will often lead to a low electrode polarization impedance while a large effective electrode area may lead to low noise and averaging effects.

The placement of the electrode is, of course, also of importance. One example is neural activity, (short explanation of nerves). Neural activity can be picked up by electrodes, when measuring bioimpedance, this is not necessarily a cause for worry, however when talking about biopotential, especially in two-electrode systems, placing both electrodes on a site with the same neural activity, e.g. the palm of the hand, could impact the measurements greatly [5] (pg.220).

Another thing to consider is what kind of tissue is directly underneath the skin in the measuring area, and how thick is the skin? Muscle, fat, thick skin, bone etc. All have different impacts on the impedance measurements [6], which will become apparent later in this experiment.

1.7 Electrode systems

1.7a 2-point

For any given application, a minimum of at least two electrodes are necessary. This is in part so that they together create a circuit for the applied current to travel through, and because they measure potential difference in the case of potential measurements. In which case, we measure the DC potential between the two.

In this case, they are usually what we would call PU-electrodes, or pick-up electrodes. A two-electrode system can also be used to measure impedance, in which case we need to introduce an AC source to the system, the AC current being delivered via the electrodes. In which case, the electrodes also act as CC-electrodes, or current-carrying electrodes.

Measuring sites is always something to consider in bioelectric measurements, but it is especially important when dealing with two-electrode biopotential systems. If both electrodes are on skin with the same nervous control the difference in biopotential between the electrodes will naturally be small and little to no signal will be measured. Therefore, one would often want to place the electrodes on different skin sites, e.g. One electrode on passive skin site and one on an active skin site, for example one electrode on the forearm and one electrode on the neural active palm of the hand. However, when dealing with bioimpedance, and not biopotential, two electrodes on the same neuroactive site might suffice.

1.7b 4-point

In contrast to the 2-electrode system, where both electrodes act as CC (Current carrying) and PU (Pick up) for bioimpedance purposes the 4-electrode system usually consists of two CC and two PU electrodes. In this case, the current is applied with the CC electrodes, while the PU electrodes apply no current, and simply measure the difference in potential of the two sites. Normally one would situate the two CC electrodes outside of the two PU electrodes however If the system is reciprocal one can place the PU electrodes outside of the CC electrodes, reasons for doing this could be to reduce the effect of the CC proximal zones. Generally, this is also why one would use a 4-point setup, to reduce the effect of the proximal zones.

It is also worth mentioning that this application is a two-port network with four terminals, and what we actually measure is the transfer impedance between the two ports.

1.8 Penetration depth

For bipolar electrodes, the depth of the current is highly dependent of the distance between the centres of the two electrodes. While the current density decreases with increasing distance, the relative contribution to the deeper layers increase. However, the sensitivity is proportional to the current density, which means that a given volume further away from the electrodes has a smaller impact on the results than an equally large volume close to the electrodes. This of course is because, as mentioned earlier, the current density decreases as we move further away from the electrodes. The size of the electrode however has very little effect on the penetration depth compared to the difference caused by distance.

1.9 ECG and ICG

1.9a ECG

Electrocardiography (or ECG for short), is simply put, a way to measure the electrical activity of the heart. This is done using skin electrodes that pick up the electrical changes generated by the hearts cycle of polarization and depolarization. In the routine ECG examination today, one usually uses 10 electrodes, that together compose 12 leads. However, in its most basic form, the measurement only uses three electrodes, usually one on each arm and one on the left leg.

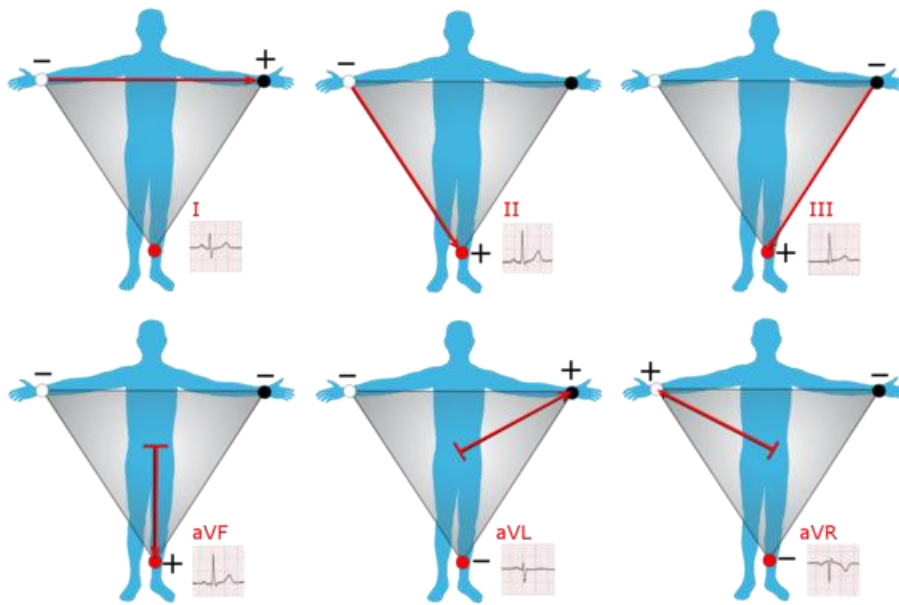


Fig.1.9a.1: Figure showing the six-limb leads that constitute the basic idea behind the standard ECG measurement. This is also what we would call the Einthoven triangle. [22]

This is partially the technique that will be used in this experiment, utilizing ECG equipment borrowed from SINTEF, however the skin electrodes will be situated on each side of the thorax, around the lower ribs, with the third indifferent electrode somewhere around the right side of the pelvis. In essence, this means our measurements are relatively close to the vector called 'I', top left in fig.1.9a.1

Einthoven triangle

The Einthoven triangle, named after its creator, is a way to view the ECG as a sum of vectors in a two-dimensional space intersecting the human body, with the triangle spanning from both shoulders to the pelvis, or both wrists (in this case with both arms stretched out at a 90-degree angle) to the left foot.

With the heart in the middle of this hypothetical triangle, the sum of the potentials should be zero if the electrodes are placed correctly, making its main purpose is to determine any misplacement of any of the three electrodes used in the classic ECG by looking at the vector sums. See fig.1.9a.1 for a visual representation.

A non-zero sum would indicate misplacement. Its main critique is of course that the human body itself is not two-dimensional, and that the hearts activity cannot be completely mapped in a two-dimensional plane, but should rather be viewed in a three-dimensional space. In this manner, the 10-electrode setup is a much closer and precise setup to measure total heart activity. This isn't to say that the 3-electrode setup does not have a multitude of uses however, but it does not necessarily give all the information.

1.9b ICG

Impedance cardiography (ICG), refers to the measurement of bioimpedance in the thoracic region, or more commonly, the differential of the measured impedance, or the rate of change of impedance. This gives us information about the mechanical changes in the thorax such as expansion and contraction of tissue, stroke volume and cardiac output [9, 10, 13, 15, 18]. In this experiment we will mostly be focused on the blood vessels, both their expansion and the orientation of the blood cells within. ICG measurements also pick up on the respiratory signals, the expansion and contraction of the lungs, and by extension, the thorax.

The reason for using the differential and not the absolute values of impedance is because the value itself is of little importance under the given circumstances, and the only thing we are interested in is the rate of change at different points in the cardiac cycle. Do note that we are talking about Impedance, and not resistance, so there is the possibility of an imaginary component and a phase, which is why we use the term absolute value. It is worth mentioning that the changes in impedance values in the thoracic region is very small.

Fig.5.7.1 showcases how the maxima and minima of the measured impedance is only about 0.6 Ohms apart, and this is of course without removing the big changes caused by respiration [14]. Furthermore, looking at any of the ICG plots in the results section, we can see that the ICG values are, at least with this given setup, in the 10^{-5} range. As one can see, the absolute impedance we measure is quite large when compared to the rate of change. Fig.1.9b.1 shows one single ICG-wave from one of the test persons.

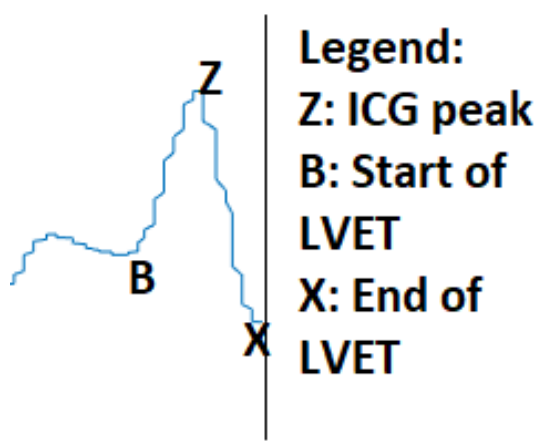


Fig.1.9b.1: Snippet of a longer ICG measurement. Pictured is one whole cardiac cycle, shown as the ICG values, with points of interest marked.

Fig.1.9b.1 also shows what we in this experiment will call the ICG peak (point Z), and the B-X interval, also known as LVET or left ventricular ejection time. The B-point is where the aortic valve opens up, to let blood shoot out of the left ventricle, and the X-point is where the aortic valve closes up, preventing the blood from flowing back into the ventricle.

We can view the thorax as a cylinder, roughly, with the goal of finding stroke volume and expanding this into finding the cardiac output. The rationale being that, if the thorax is a conducting cylinder (a very rough approximation) a change in volume will change the impedance. Of course, there are two ways for such a cylinder to change its volume, either by increasing its thickness or by increasing its length.

Obviously, the change of volume in the thorax happens by increasing its circumference.

Using the equation [5 pg.441]

$$v = G\rho L^2$$

Eq.1

one can find the volume of the thorax by measuring the conductance.

In 1950, Nyboer used a tetrapolar band electrode setup in his measurements of impedance cardiography[11]. And, using this same cylindrical regard of the thorax expressed the change in volume as [5 pg.441, 11]

$$\Delta v = \Delta z\rho\left(\frac{L}{z_0}\right)^2$$

Eq.2

As we can see from eq.1 and eq.2, an increase in volume is corresponding to an increase in conductance (G, eq.1) and a decrease in impedance (following that $G = 1/Z$).

Usually the recording current has a frequency of between 50-100 kHz. At least for commercial products this combines a high enough frequency to extract all relevant and wanted data, while at the same time having low requirements in regards to voltage supply e.g. small batteries making the devices both compact and light. The Bionomadix instrument used in this experiment runs a 50 kHz recording current with a 1 kHz sampling frequency normally. The sampling frequency however, has been lowered to 200 Hz to be in accordance with the ScioSpec instrument and its limitations.

The ICG signals have been found to span from about 1 Hz to about 30 Hz [2,3], with the FFT-analyses of the measured signal somewhat supporting this, showing that most of the energy in the signal lies at around 1Hz. The frequency which the ICG signals span have been shown to increase in accord with a higher heart-rate [2], however since all the test persons will be at rest this is not a great concern.

The FFT-analysis also highlights the need for a high-pass filter as there are relatively strong signals below the 1 Hz threshold, probably coinciding with respiration, that it is recommended to filter out if one wishes to view the ICG signal.

1.9c Safety

When dealing with electromedical equipment and live patients, safety is of course a priority. Normal procedures are either to ground the patient, or keep the patient floating with respect to ground. This can be achieved, for example, by galvanic separation which means there is no direct current path between the two parts of the circuit (the part in contact with the patient and the power line).

1.10 Synchronization unit

(Courtesy of Jon Vedum)

To better line the ECG-measurements up with the ICG-measurements it was decided that a small circuit that would help create a distinctive signal form in both measurements were to be used. The decision was originally made before the weakness in the ScioSpec equipment was found (see section 4.2), with the intention of getting a better look at what happened after each heartbeat. Later this was less critical, seeing as how the ICG-signals are sufficiently clear and spaced enough that little doubt can be had. However, it still serves a purpose in the fact that it ensures that the measurements are not subject to this 'stretching'-effect to any substantial degree.

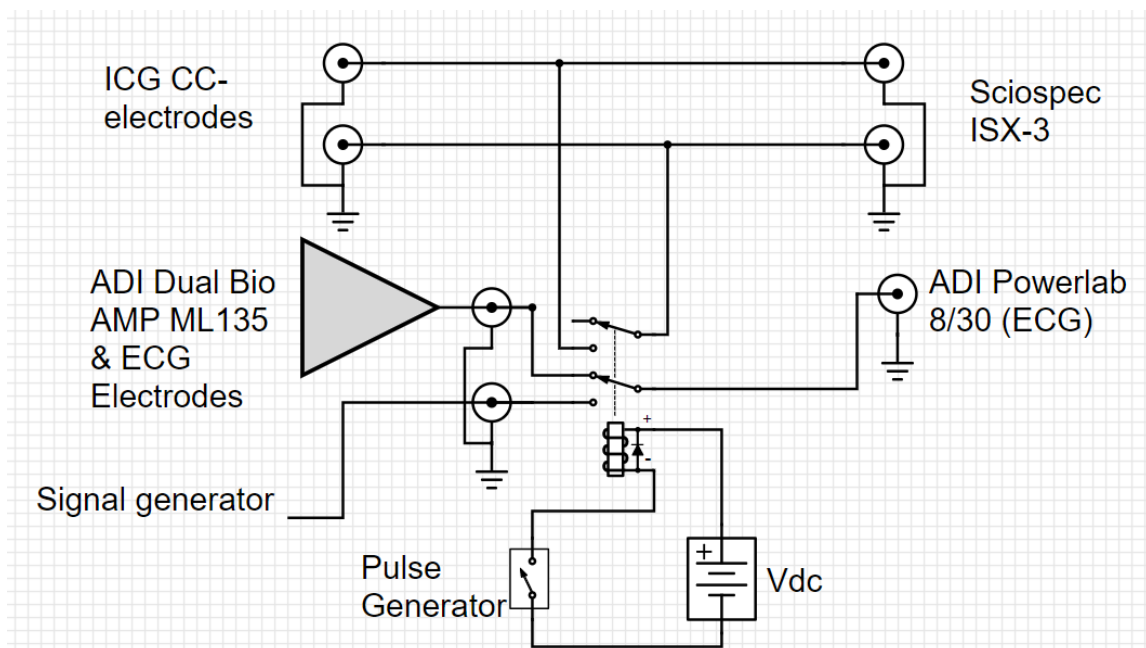


Fig.1.10.1: Block schematic giving an overview of the final setup used in the measurements.

The circuit itself is driven by two 9-volt batteries and consists of a switch and a relay. When the pulse generator activates, the switch signals the relay to short the current carrying electrodes of the ICG-equipment, while simultaneously sending a square pulse, generated by a waveform generator, into the ECG-equipment. The result is a clearly visible square pulse in the ECG plot, and a clearly visible drop in impedance in the ICG equipment as a result of shorting the CC-electrodes. Because of the square waveform, and its near instantaneous drop from maximum to minimum, there is a certain degree of oscillations in the ensuing ICG-plot, thus the raw impedance plot is needed to align the ECG- and ICG-plots when analysing the data.

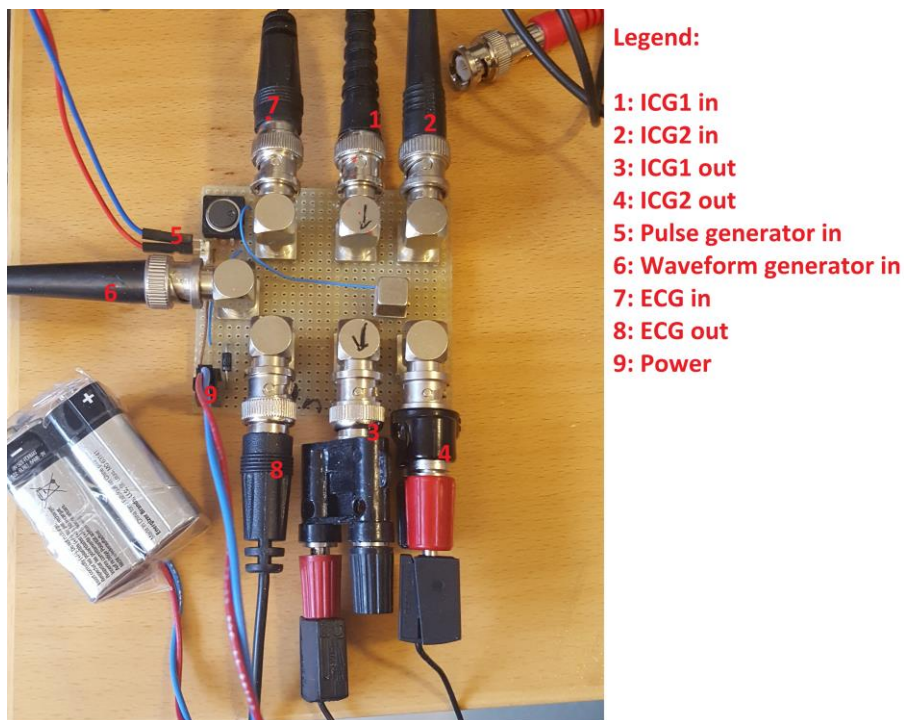


Fig.1.10.2: Picture showing the topside of the synchronisation circuit.

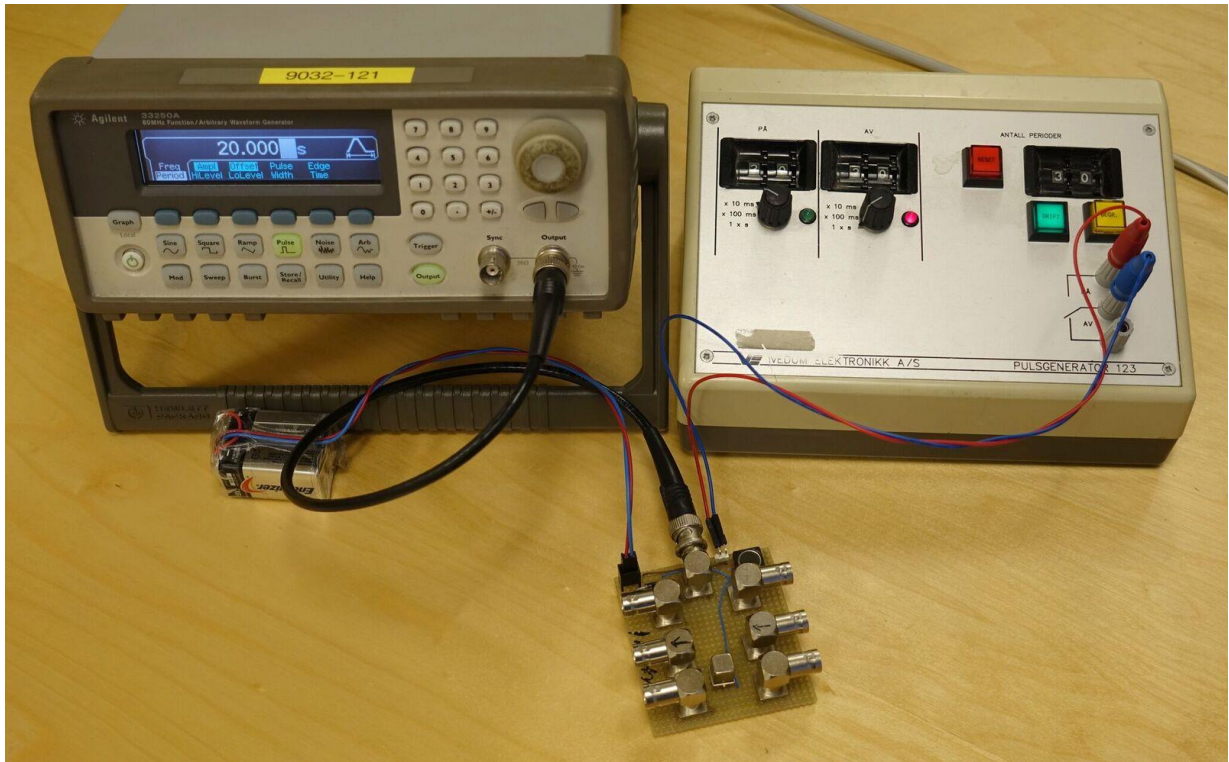


Fig.1.10.3: Relay circuit with pulse generator and waveform generator.

Chapter 2 - Introduction

The purpose of this experiment is to look at measured impedance in the thoracic region and see how the impedance varies with differing frequency values of the input voltage. Theory suggests that the blood cells have a quite large impedance, especially when compared to the liquid in which it is suspended, at lower frequencies. As such it might be the source of a difference in impedance because of varying current paths, measured in the thoracic region, between diastole and systole because of the orientation of the blood cells. At one point in the cardiac cycle the blood cells would all be practically lined up so that the current will find a free lane between the lined-up blood cells, and at another point in the cycle the blood cells will be scattered and the current will take the longer path around them. Theory also suggests that this membrane surrounding the blood cells will let higher frequency currents pass.

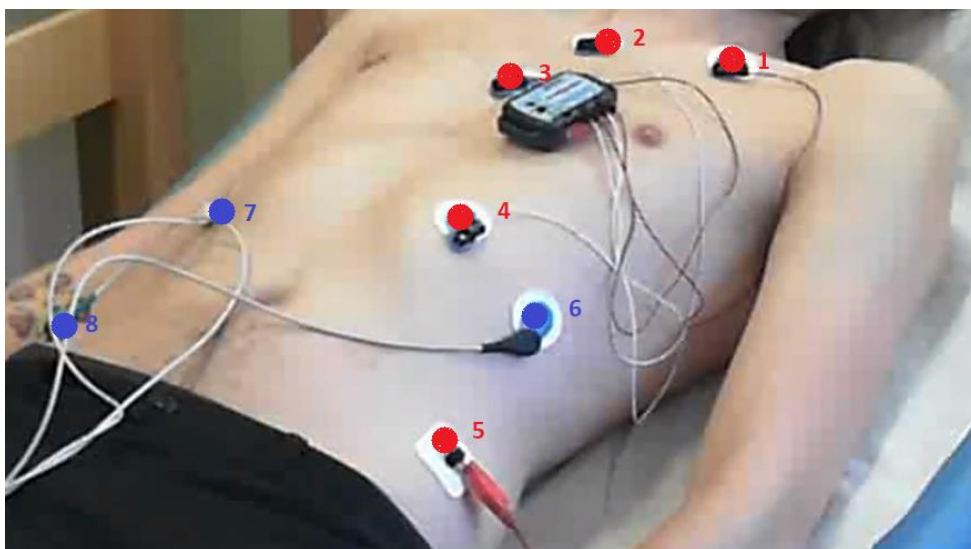
If this holds up, one should be able to see the difference in measured impedance between diastole and systole drop once the current frequency gets high enough, since the orientation of the blood cells is now of little concern, and as such there should be little to no difference in impedance between the different parts of the cardiac cycle.

The counter point to this theory is that the large change of impedance can be caused by a rapid volumetric change. As the heart pumps blood, the blood pressure rises and so naturally veins and tissue get expanded or compressed as an effect of this increased pressure. Compression and expansion of tissue is something that has an effect on the measured impedance and so it is natural to consider this as a cause for the signal as well (Belmont, 2013). If the signal does not disappear at higher frequencies then this would suggest that we might be dealing with a volumetric change as the cause for the ICG signal.

In this experiment we will primarily be using a frequency spectrum spanning from about 40 kHz up to 3 MHz. Were the peaks in the signal to disappear after derivation, this would indicate that the majority of this difference in impedance is caused by the blood cell membranes. However, a small change in measured difference (or potentially none) between the low and high frequencies would indicate that the source is not the blood cells but some other anatomical phenomenon, most likely the expansion of the aorta which would occur at the same time as the momentary alignment of the blood cells.

3 Methods

The current will be delivered by an electrode pair, with one electrode situated on the subjects left shoulder, either by the clavicle or scapula, depending on the individual subject. The second current carrying electrode will be situated near the lower rib on the left side of the body, the exact location for optimal signal strength might vary greatly from person to person. Generally placing it below and to the left of the pectoral muscle should suffice, however better signal strength might be obtained by placing it at the bottom of sternum to the right of the heart. Two passive electrodes will be placed between the two CC-electrodes, preferably high up on the sternum. One at the very top of the sternum, where sternum and clavicle meet, and one about 5-8 cm below have proven to be a good configuration.



Electrode Legend:

- 1: Upper CC-electrode
- 2: Upper PU-electrode
- 3: Lower PU-electrode
- 4: Lower CC-electrode
- 5: Ground ICG, optional

- 6: Right side ECG-electrode
- 7: Left side ECG-electrode
- 8: ECG zero-reference electrode

Fig.3.0.1: Picture showing the preferred electrode locations for this experiment.

The passive electrodes will pick up the signal and the instrument will calculate the impedance. A MATLAB-script will then be used to find the derivative of the signal with regards to time. The results will first be passed through a high-pass filter at about 1 Hz and a low pass filter at about 25 Hz. A differential filter with a frequency of 50 Hz will then be used to obtain the final ICG signal [3].

The electrodes used will be standard circular one-time use patch electrodes (Ag/AgCl) Ambu BlueSensor M, packed with an already applied adhesive that also acts as an electrolyte. A skin stripping technique could be used to lower the skin impedance, however in this experiment most of the measurements were done with the skin cleaned quickly with alcohol at the electrode sites.

The test will be performed on various test subjects, to enhance the certainty of the results. Test subjects will preferably be relaxed, so that the measurements can be performed on the basis of a resting heart rate. Test persons will be lying on an exam table and be asked to move as little as possible while the measurements are underway. Previous literature has shown that posture does impact the impedance measurements [16, 17]. Furthermore, own experiences have shown that both talking and moving have visible effects on the ICG measurements. The goal is, naturally, to remove all sources of difference between the measurements provided that we do not weaken the measurements in the process (see section 4.3 and 4.4 on electrode placements).

To ensure that we are actually observing ICG signals and not some other faster or slower (like respiration) periodic signal it is advised to simultaneously do an ECG measurement. In this case one would then have a graph showing the heart activity. This graph can then be lined up with the ICG measurements, and one would quickly be able to see if the periodic signals follow the individual's heart beat or not. In this experiment we did not have the ability to easily get the measurements into the same system to ensure they were synchronized. This was because of differing equipment and a non-flexible software which did not allow for additional signal input.

The solution was then to have an intermediary device between the test person and the devices gathering data, the ECG and the ScioSpec impedance measuring device, which would short out the electrodes. A square pulse with significantly larger amplitude than the expected signals was then applied to the input of the ECG while simultaneously the ICG CC-electrodes were shorted. With a highly visible square pulse in both signals they can now be lined up closely enough that there is minimal margin for error.

The intermediary device was provided by my guidance advisor Jon Vedum (see chapter on Synchronisation Unit). The pulse generator used in conjunction with this is a 'Vedum Elektronikk 123'. For the majority of this task it will be delivering pulses at an interval of 20 seconds, with the pulse itself lasting for 200 milliseconds. The waveform generator is an Agilent 33250 Waveform Generator, delivering square pulses with a frequency of 4Hz and an 800mV peak-to-peak value. The ECG itself consisted of an ECG pre-amp of the type 'ADI Dual Bio Amp' and of course the ECG device itself which was an 'ADI Powerlab 8/30'.

Every measurement was preceded with a 50 kHz measurement with a Bionomadix portable ICG device, to ensure that we had good ICG signals, because the Bionomadix device and its software allowed us to see the ICG signals in real time. The Bionomadix device was then replaced with a Sciospec ISX-3 device (see fig.1.10.1 for a diagram of the setup).

List of Equipment Used:

Data acquisition: AD Instrument PowerLab 8/30 with software LabChart 8

ECG pre-amp: AD Instrument Dual Bio Amp ML135

ICG wireless transmitter: Biopac Bionomadix BN-TX

ICG wireless receiver: Biopac NICO-R with IPS100C power/analog module

Electrodes: Ambu BlueSensor M

Pulse generator: Vedum Elektronikk Pulsgenerator type 123A

Sync signal generator: Agilent 33250A

Impedance measurement device: Sciospec ISX-3, Advanced mode

Relay board: Custom made

Chapter 4 - Experimentation

The first series of measurements paid little attention to things such as electrode placement etc. Seeing as the Sciospec equipment was new and relatively untested, a lot of time would be dedicated to familiarising myself with the equipment and writing a compatible script. Naturally there were problems with the options on the equipment itself and a significant amount of time was used to make everything run smoothly.

Tests were set up where the impedance would be measured with both Bionomadix equipment and Sciospec equipment. Care was taken to make the difference in method as small as possible, this involves doing the measurements right after each other, with the same electrodes. The impedance values measured by the Sciospec equipment would then be run through the script and compared to the values measured and differentiated by Bionomadix. Already some differences could be seen in the raw data gathered, which was mainly attributed to the fact that the Bionomadix equipment removed the DC-values of the signal and digitised the remaining signal.

4.1 Issues with filtering

Early stages of experimentation wrongly used a high-pass filter at about 5Hz. This was used as a basis for early tests combined with a low-pass filter at 20Hz. Results were very noisy and little information could be extracted. There did seem to be a periodic signal under all that noise, and a good amount of time was used trying to extract this signal. Further reading and experimentation showed that a high-pass filter with values around 0.5-1 Hz would work much better. An FFT-analysis of the signal showed a great deal of energy under 1 Hz, and a significant albeit much lower concentration around 1-1.5 Hz depending on the person.

Allowing the components below 1 Hz through results in the differentiated signal being completely dominated by a signal about 2-3 times slower than the heartbeat. The most likely explanation for this signal is respiration. This signal component is not something we are interested in when dealing with these kinds of measurements, and so a high-pass filter at 1 Hz is recommended to ensure this signal is filtered out. Articles based on earlier experiments and the manual for the Bionomadix equipment supports this notion [2, 3, 7].

Tests proved however that the differentiated values were vastly different, however the raw data were similar enough that suspicions of error in the script was raised. The script was altered to be compatible with the Bionomadix values, and using the same method as with the Sciospec equipment the Bionomadix raw data was differentiated. The result was, again, very different from the expected result. The most obvious conclusion to draw from this was that there had to be an error in the script. Up until this point the filter values were wrongly applied, a misunderstanding had the high pass filter valued at 5 Hz. However, a paper suggested the ICG values should run from either DC or 1 Hz up to about 15 or 30 Hz [2, 3]. The high pass filter was then lowered to meet this suggestion and the resulting signal differentiated from the Bionomadix raw data was now closer to what we were expecting. Applying the same methods to the ScioSpec equipment, however, did improve the signals somewhat, mainly removing a lot of the noise. However, the differentiated signal still did not look like an ICG signal, there were periodic peaks but these peaks were too far apart to be an ICG signal. Even though the ICG and ECG was not lined up one can still use the interval between the same parts of the ECG signal (commonly the interval between peak to peak) and equate this to the ICG signal, seeing as both are results of the same events.

4.2 Locating and Documenting the Error

Effort was then placed into trying to line the ECG measurements and the ScioSpec differentiated signals up more closely, to see if there was some pattern that could be found. One theory was that the respiratory signals were so dominating that the ICG signals were drowned out, as mentioned earlier the FFT-analysis showed great amounts of energy in the signals below 1 Hz. Subsequently, this is why the filters were of such high order and with such sharpness.

A small circuit (fig. 1.10.2) courtesy of Jon Vedum was used for this purpose. The circuit is an intermediary step between the electrodes and both the ECG and impedance measuring equipment. Its function is to short the impedance electrodes and deliver a pulse from a pulse generator to the ECG at the same time, creating easily distinguishable waveforms in both plots. Thus, one can quite easily line the two signals up. The reason for wanting to line these up so precisely is to see if there is any correlation between heart activity and the unfamiliar shape of the ICG signal. However, since the pulses also come at very regular and controlled intervals it was quickly discovered that the ScioSpec instrument could not keep up with the sampling frequency. We could quickly see, in real time, that both the length of the pulses and the interval between them was growing on the ScioSpec instrument. This proved that the previous samples had been distorted, the instrument passing the samples through to the software at a significantly slowed rate and producing duplicate samples with successive timestamps, leading to a 'stretching' effect.

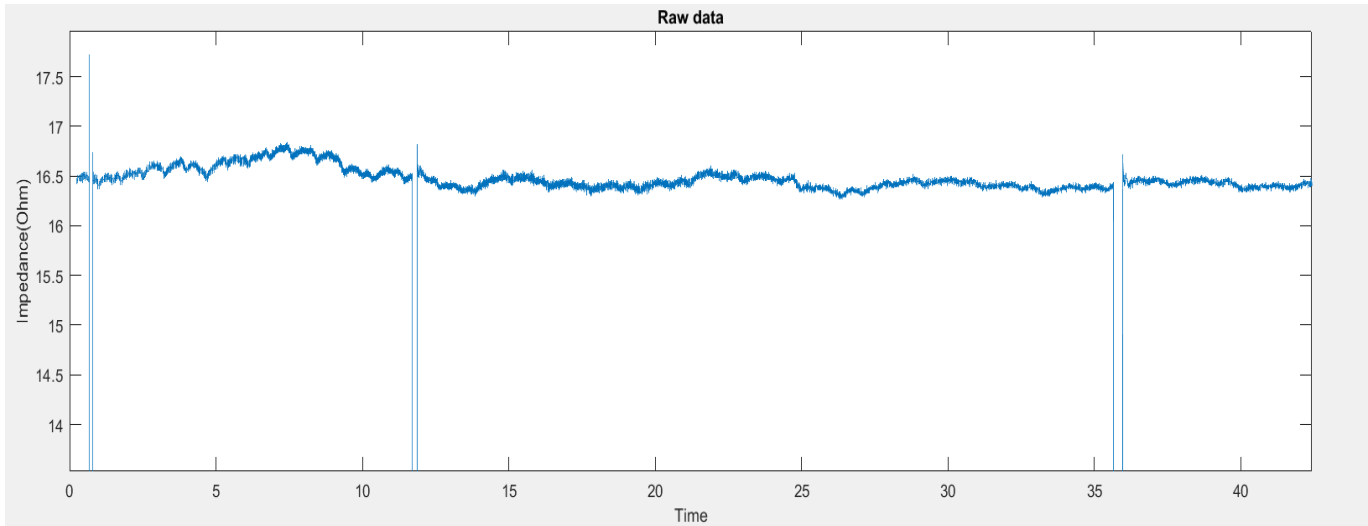


Fig.4.2.1: Raw data sampled over 45 seconds with a sampling rate of about 700Hz. The bars are square pulses injected into the signal. The pulses are the same length and controlled by an external device, injecting a pulse every 10 seconds. As can clearly be seen, both the gap between pulses and the length of pulses are displayed erroneously.

Tests then had to be conducted to try and gain some more knowledge about this stretching effect, and when it would start to be noticeable. A setup consisting of five resistors was made, which would crudely represent a human body with four electrodes. (note however that the human body has a capacitive element, so this representation is far from perfect.)

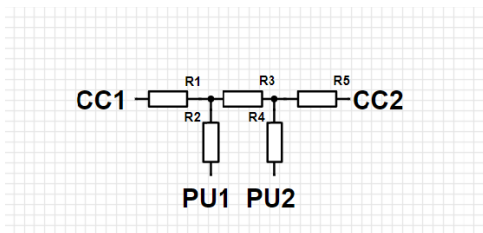


Fig.4.2.2: The setup for documenting the error. R1, R2, R4 and R5 are of equal resistance, and meant to represent electrode resistance. R3 is our simulated 'body'.

The sampling rate of the equipment was then progressively lowered, to see if a sufficiently low sampling rate would eliminate or at the very least postpone the stretching effects. As can be seen in fig.4.2.1 the stretching effect sets in quite early, being noticeable to the naked eye already at 12 seconds, which would greatly reduce the validity of any measurement made. The problem however is that if the sampling frequency becomes too low, one might miss the important parts of the cardiac cycle.

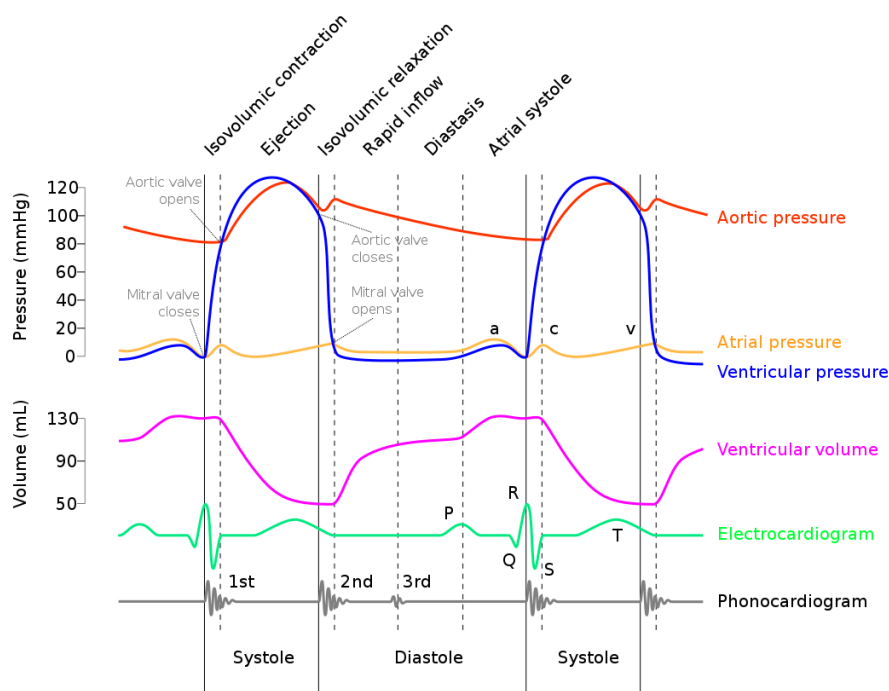


Fig.4.2.3 Wiggers diagram, showing the different events of the heart cycle. [21]

With the average heart-rate being 60-100 beats per minute, or in other words, the total interval between one R peak to the next one being an average of 0.6-1 seconds, it is quite obvious that there is a limit to how low one can go with regards to the sampling frequency before important parts of the heart activity is lost.

A middle ground was eventually found, by introducing a delay of 5 milli-seconds between each sample, effectively making the sampling frequency 200 Hz.

While this does indeed cause the results to be somewhat blocky, tests showed that we can expect close to 200 seconds of good measurements before they become visibly distorted even at the higher frequencies. As such, letting the instrument run for no longer than around 70 seconds at the maximum should ensure minimal to no error caused by this weakness.

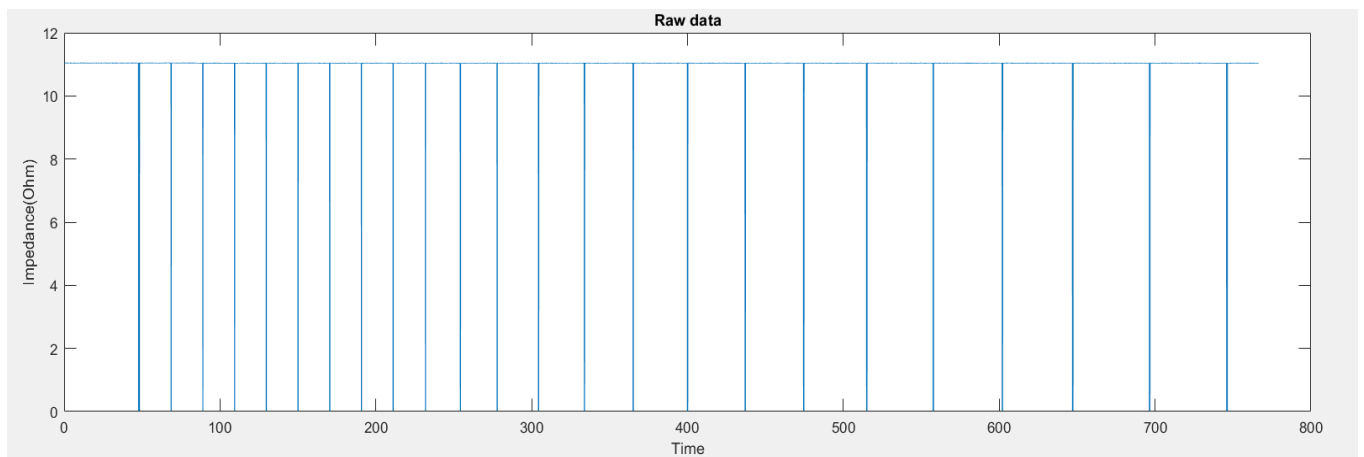


Fig.4.2.4: Raw impedance values plotted as a function of time, measured on a series of multiple resistors meant to simulate a purely resistive human. Current frequency 50 kHz, sampling frequency 200 Hz. The vertical bars are square pulses with constant gaps of 20 seconds, clearly highlighting the stretching effect and how it propagates as time goes on.

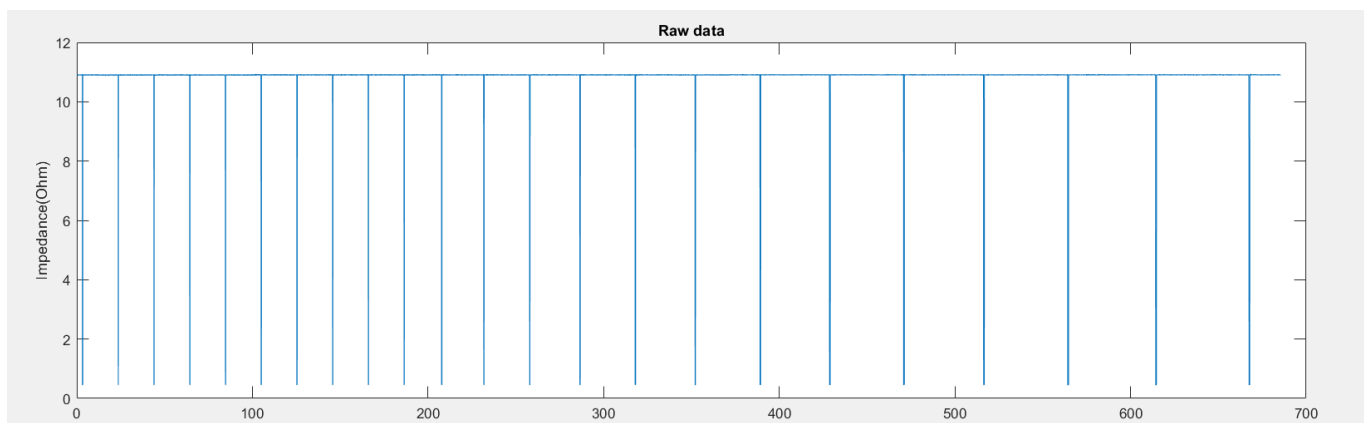


Fig.4.2.5: Raw impedance values plotted as a function of time, measured on a series of multiple resistors meant to simulate a purely resistive human. Current frequency 3 MHz, sampling frequency 200 Hz. The vertical bars are square pulses with constant gaps of 20 seconds, clearly highlighting the stretching effect and how it propagates as time goes on.

Do note that the plot in fig.4.2.4 runs for about 100 seconds longer than the 3 MHz plot in fig.4.2.5, one can still see that the stretching effect is even greater in the shorter 3 MHz plot, suggesting that this effect also is affected by the current frequency.

Due to the inherent uncertainty with regards to the aforementioned distortion of data, care must be taken to ensure that we are not utilizing compromised data. For this reason, it was decided to keep injecting these pulses into the measurements at regular intervals so that any eventual distortion could be quickly discovered and the unusable part of the measurement could be discarded. The pulses arrive at intervals of 20 seconds, with the pulse itself lasting for about 20 milliseconds. This essentially splits the measurement into blocks of 20 seconds.

This injected pulse, of course has to have a significantly higher amplitude and a steep incline, so that it is clearly visible when the data is plotted post-measurement. This steepness and relatively great amplitude has certain effects on the filtering processes. Before this pulse generation became a part of the measurements the filters were relatively steep, partially because the errors in the differentiated signal was wrongly attributed to the respiratory signals which have a much greater energy content according to the FFT-plot. With filters this sharp (5th order and up) the resulting oscillations take so long to dampen that the whole dataset between two pulses are affected by the pulses themselves. It is therefore not suggested to use any filters with an order higher than 2 while simultaneously injecting these square pulses with intervals at around 20 seconds.

4.3 Electrode placement

The early stages of measurements paid little attention to the PU-electrode placements. For most of the early measurements electrodes situated just above and below the heart was used. Since there also were problems with filtration and high amounts of noise, the impact of this was not immediately noticed. As filtration improved, the question as to why the signal was so low was brought up. Some quick tests showed that the placement of the electrodes on the thorax might be of great importance. (picture, sintef, sternum vs heart) It was found that placing the electrodes on the sternum, between the pectoral muscles greatly improved the derivate ICG signal.

The discovery of problems with separation of the ICG signal and other underlying signals led to further experimentation with electrode placement, mainly the second current-carrying electrode, the counter electrode. Earlier tests done by Jon Vedum at SINTEF showed the possibility of a much clearer ICG signal should the electrode be placed on the left side of the body, at or just below the lowermost rib. There is of course a great deal of uncertainty in this experiment, seeing as not only is the sample size very small, but bioelectric measurements in itself do have a lot of variations from person to person.

At a later measuring session further experimentation with electrode placement was done. The reason for this was the finding of surprisingly weak ICG signals from the test person. The shape of the ICG signal, as one can see, consists of one large peak corresponding to the c-wave of the ECG, and then one or two smaller peaks preceding this ICG peak. For this test person, the preceding peak was as high as the ICG signal.

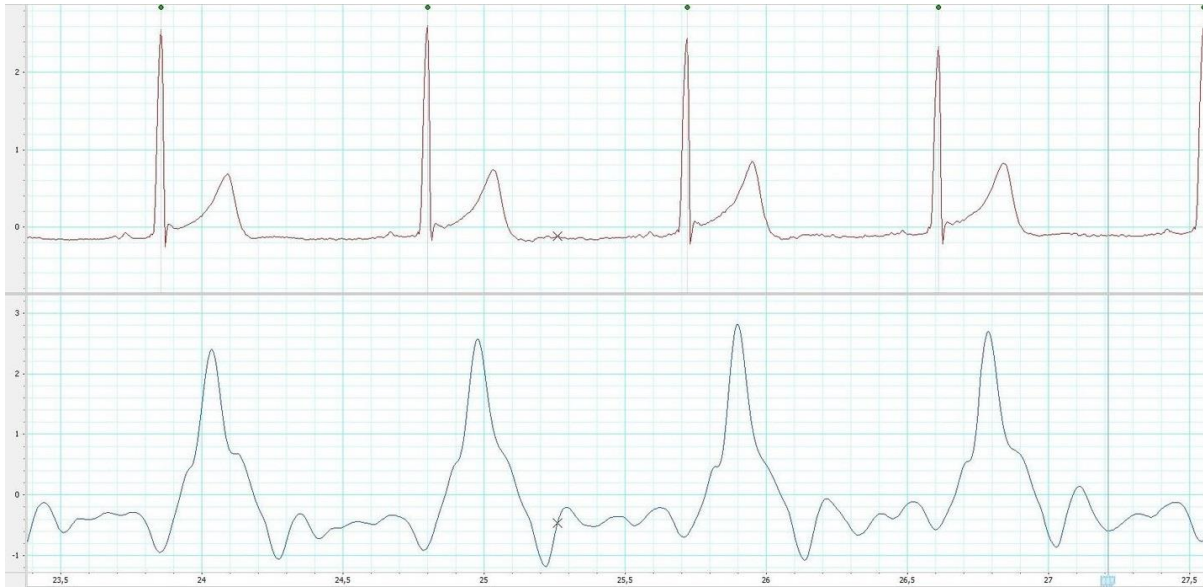


Fig.4.3.1: Example of a fairly standard ICG curve. Shown here are four heartbeats (top) and the four corresponding ICG peaks (bottom). The shape of these peaks and the shape of the signal in between these peaks are highly individual, however the general pattern of one large distinctive peak (relative to the circumstances) after each heartbeat is fairly standard.

Several different electrode configurations were tried, one notable being a parallel connection for the uppermost current carrying electrode, by adding another electrode to the right shoulder and connecting these. This proved to have little effect, however disconnecting the usual left electrode left us with an even lower ICG signal, and now the unknown, and for this experiment, unimportant preceding pulse was now larger than the ICG signal. The next step was to move the pick-up electrodes. The electrodes were moved from between the pectoral muscles to high up on the sternum, with the uppermost electrode being placed where the sternum and the clavicle meet, with the other electrode about 5-7 cm below. This proved to be a tremendous improvement, taking the test persons ICG signal from a barely discernible one to one well above average.

This discovery was then tested on other test persons, and found to consistently give great ICG results on every subsequent test person, thus changing the standard electrode placement for this experiment.

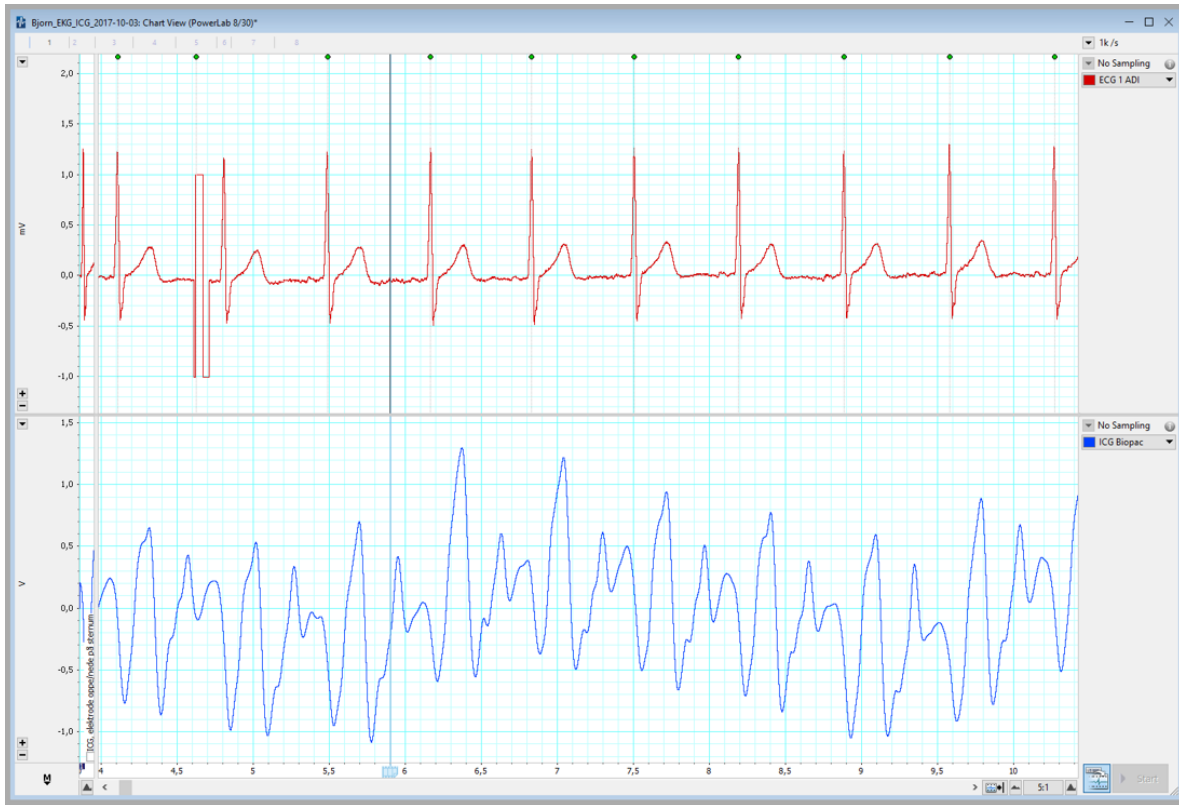


Fig.4.3.2: ICG reading of test person 3, with PU-electrodes between the pectoral muscles (see fig.4.3.3). Unusually weak ICG signal causing the two observed waves to be almost same amplitude.

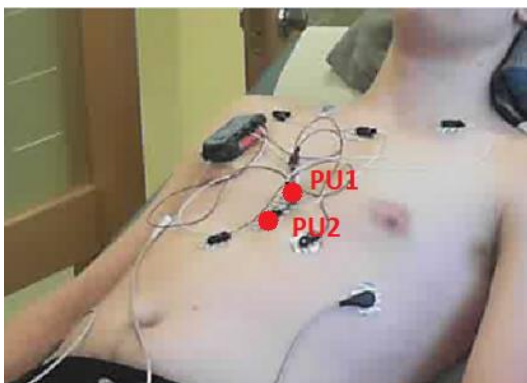


Fig.4.3.3: The previously standard setup. This setup had worked well for all previous persons, however in this case, as seen in fig.4.3.2, the signal was unusually low.



Fig.4.3.4: New electrode placement (fig.4.3.5), amplitude of ICG wave now greatly increased, making it much more distinguishable. Do note that the amplitudes of the peaks in-between the ICG did not drop, the picture is simply re-scaled.

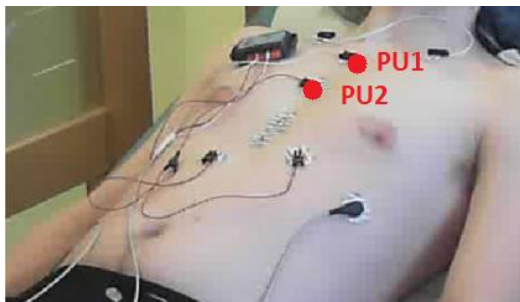


Fig.4.3.5: Showing the new electrode placement, with the PU-electrodes higher up on the breastbone. This configuration proved to work well for all subsequent measurements, and thus became our new standard.

4.4 Positioning of current carrying electrodes

For most subjects, the positioning of the lower current carrying electrode was quite generous in its effect on the measurements. Usually, placing the electrode in the general area of the lower ribs along the person's right side would suffice and a strong signal would be obtained given that we followed the previously mentioned 'guidelines' for the PU-electrodes.

In one of the subjects however we discovered an unusually weak signal. Given that the PU-electrodes seemed to be the most critical in regards to the effect on the ICG signal an attempt at an older electrode setup was made, where the electrodes were moved from the upper sternum and downwards, between the pectoral muscles. This proved to have little consequence and attention was turned towards the placement of the CC-electrodes.

Moving the lower current carrying electrode from being situated on the lower rib, almost under the left arm to right under the left pectoral proved to improve the signal greatly, bringing it from about 10% of the expected amplitude towards about 30%. Moving the upper current carrying electrode from the shoulder and closer to the intersection between the clavicle and sternum proved to have the opposite effect, dampening the ICG signal to where it was almost undetectable.

This unusual sensitivity to CC-electrode placement for this specific test subject proves to show how vastly different the ICG measurements and procedures are from person to person.

4.5 Electrode onset and hair

Having used wet gel electrodes, the wait time between electrode onset and when one could expect clear ICG signals was close to non-existent in most cases. The electrodes would be applied to the skin and measurements would follow immediately. The difference in amplitude as a function of time was, in these cases, undetectable. In one case however, the signal was measured to be about 30% of the expected value at electrode onset, and in the following 5 to 10-minute period. Since the Sciospec equipment does not show the differentiated ICG values in real time, and since the signal amplification is different between the two sets of equipment we were unable to see the development of the signal strength.

However, performing another measurement with the Bionomadix equipment after about 20 minutes of electrode contact showed that the signal had now gone from 30% of the expected amplitude to a more standard value. (See fig.5.4.5 and fig.5.4.6)

The only immediately apparent difference between this person and the other test persons, who all had a standard amplitude from the start of electrode onset, was a greater amount of hair in the sites where we would place the PU-electrodes.

This could imply that body hair plays a great role in the measurements at electrode onset, extending the time before a sufficiently strong signal can be measured. Or that the time for the wet gel to enable good signal strength is highly individual. The latter would seem less likely as both literature [1] and our own tests showed no significant individual differences from person to person. However, a sample size of one person is far too small to make any definitive conclusions. Although, it certainly is something to be wary of if one were to reproduce the experiments using test persons with significant amounts of hair at the electrode sites.

Chapter 5 - Results & Discussion

The following chapter will showcase the results of the measurements. All measurements have been done with the same equipment and setup, and have been treated with the same MATLAB-script. The results are aligned by hand, and in part due to the inherent delay in the filtering and differentiating process, the alignment is not perfect. This means that time differences between the ECG and ICG should not be used to draw any conclusions. The time differences may contain a fair amount of information, as suggested by Meijer et al. [5 pg. 443, 20] The focus of the experiment was to gain some insight into the changes in amplitude in the ICG plot at different frequencies, and as such little time and resources have been dedicated to ensuring the time intervals are accurate beyond what was described in section 4.

5.1 Test person 1:

Male, 25 years(SHL)

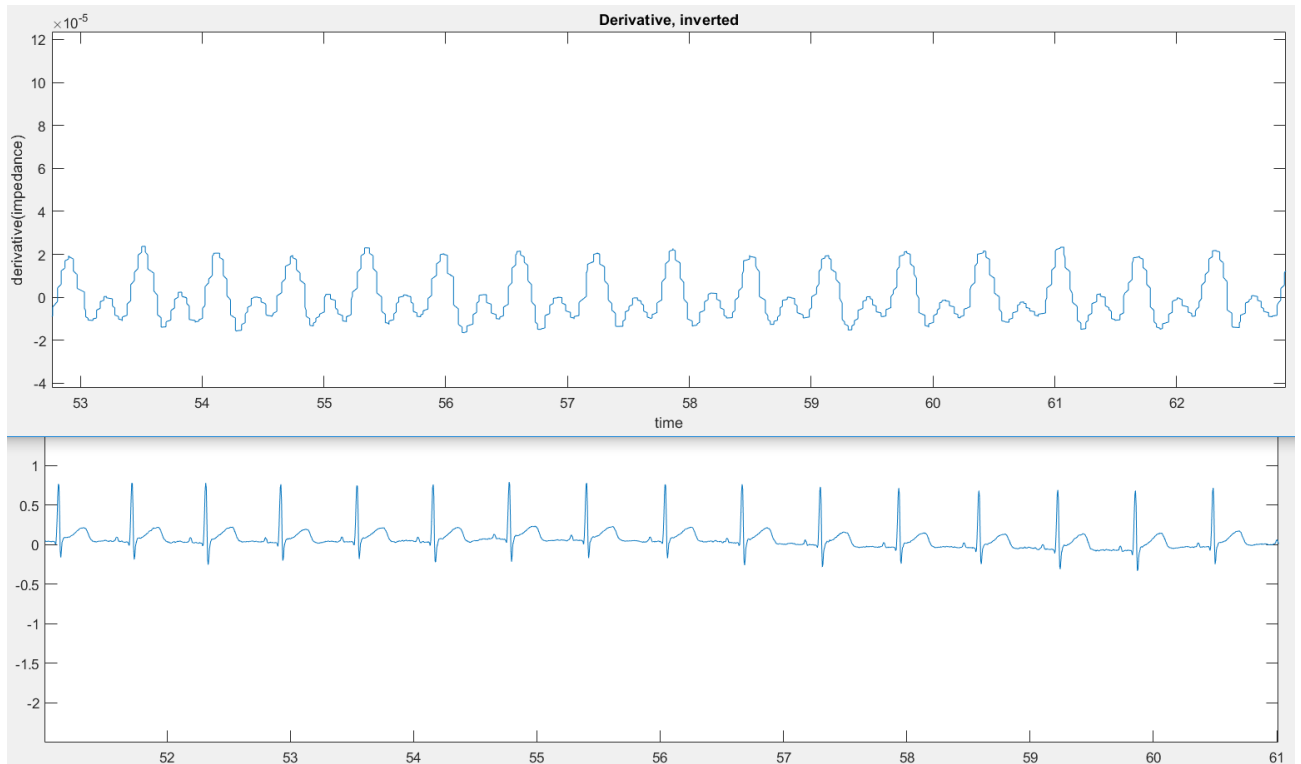


Fig.5.1.1: 50 khz measurement, peak $\sim 2 \times 10^{-5}$

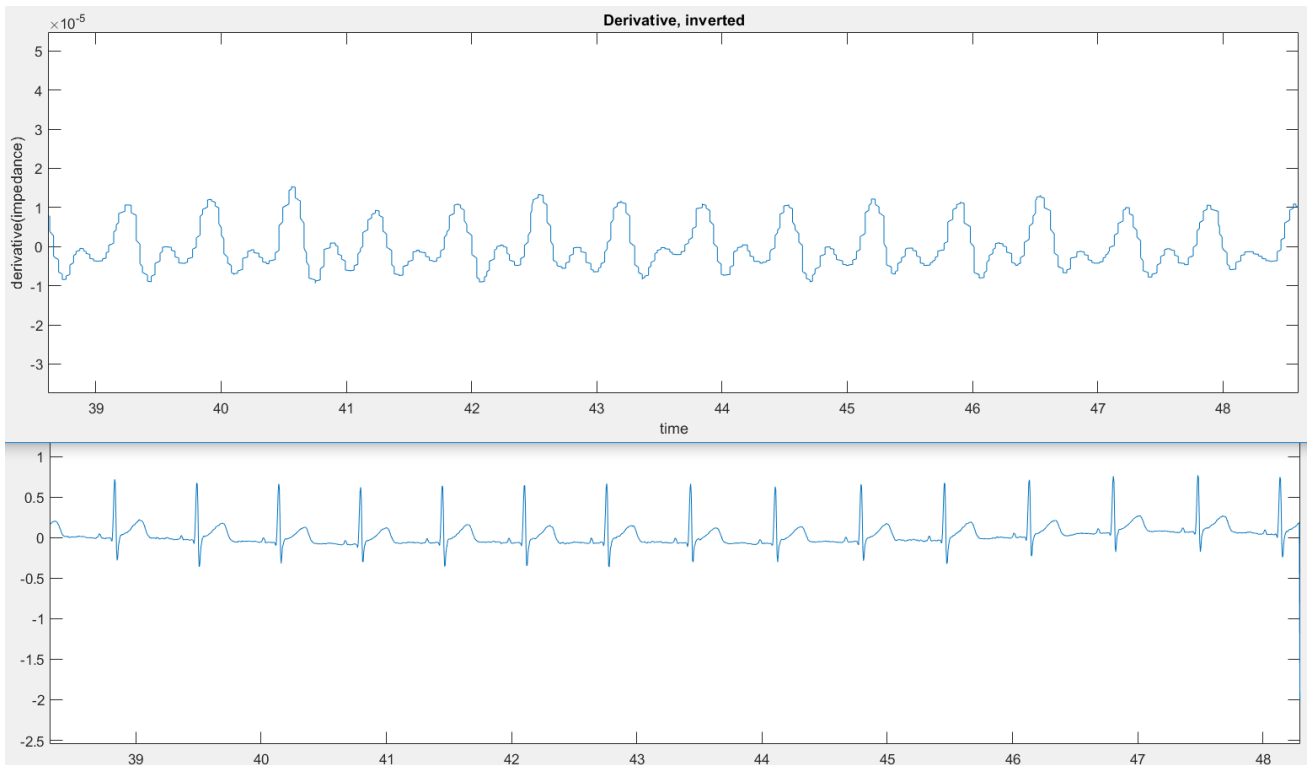


Fig.5.1.2: 1.6 MHz measurement, peak $\sim 1 \times 10^{-5}$

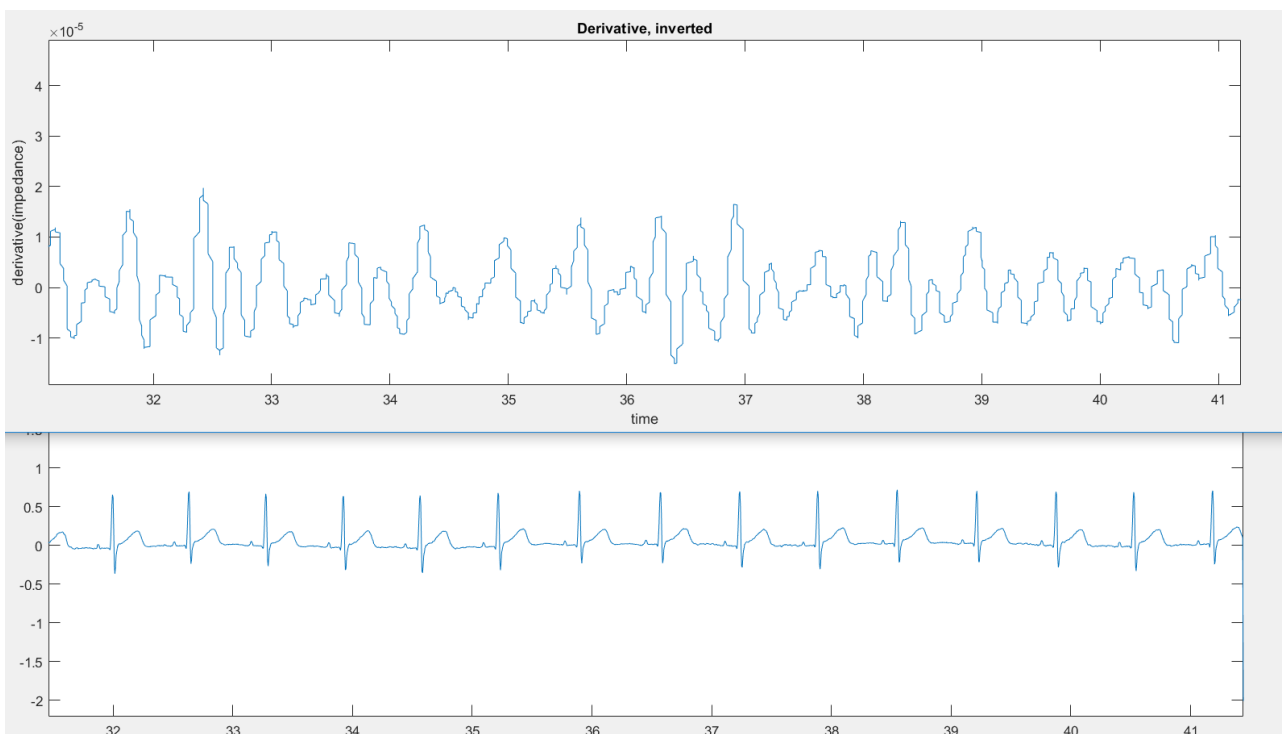


Fig.5.1.3: 3 MHz measurement, peak clearly below 2×10^{-5} , however significant amount of noise.

Test person 2:

5.2 Male, 25 years(ATS)

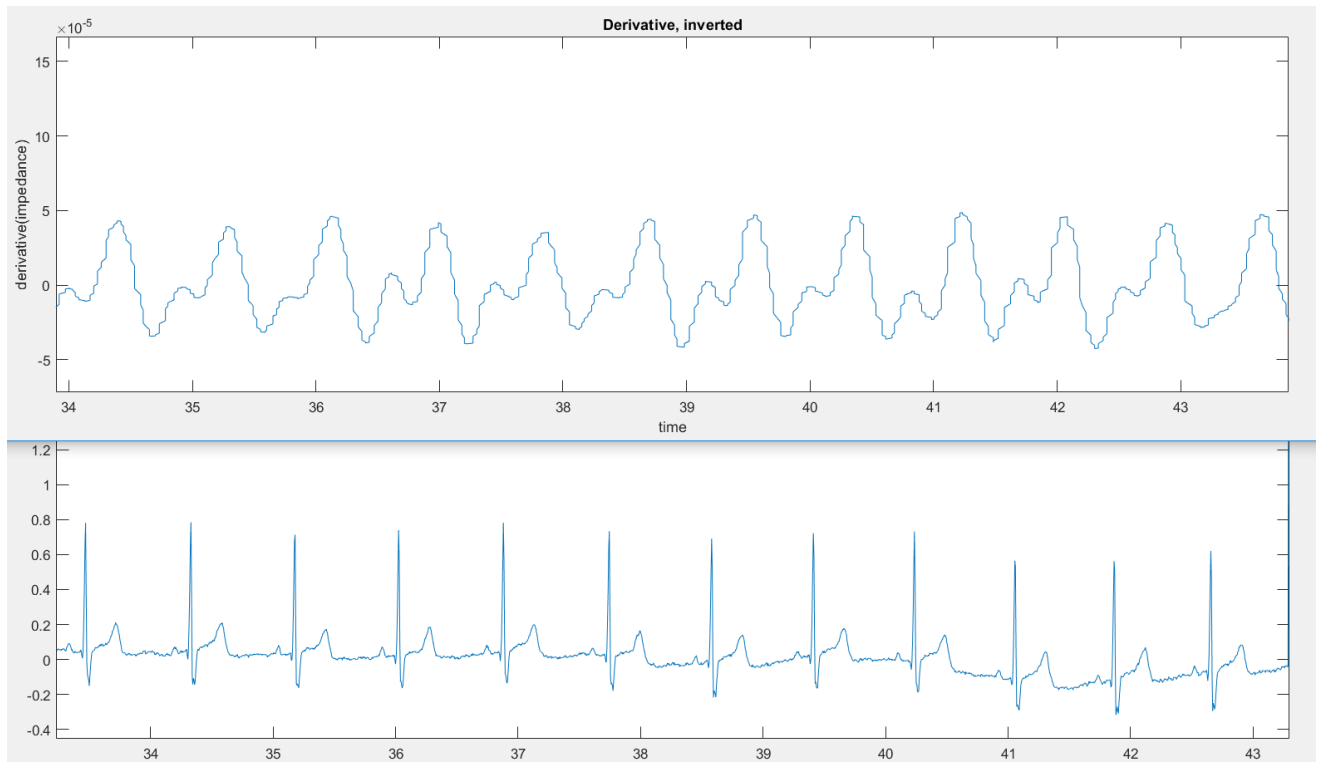


Fig.5.2.1: 20 kHz measurement, peaks $\sim 5 \times 10^{-5}$

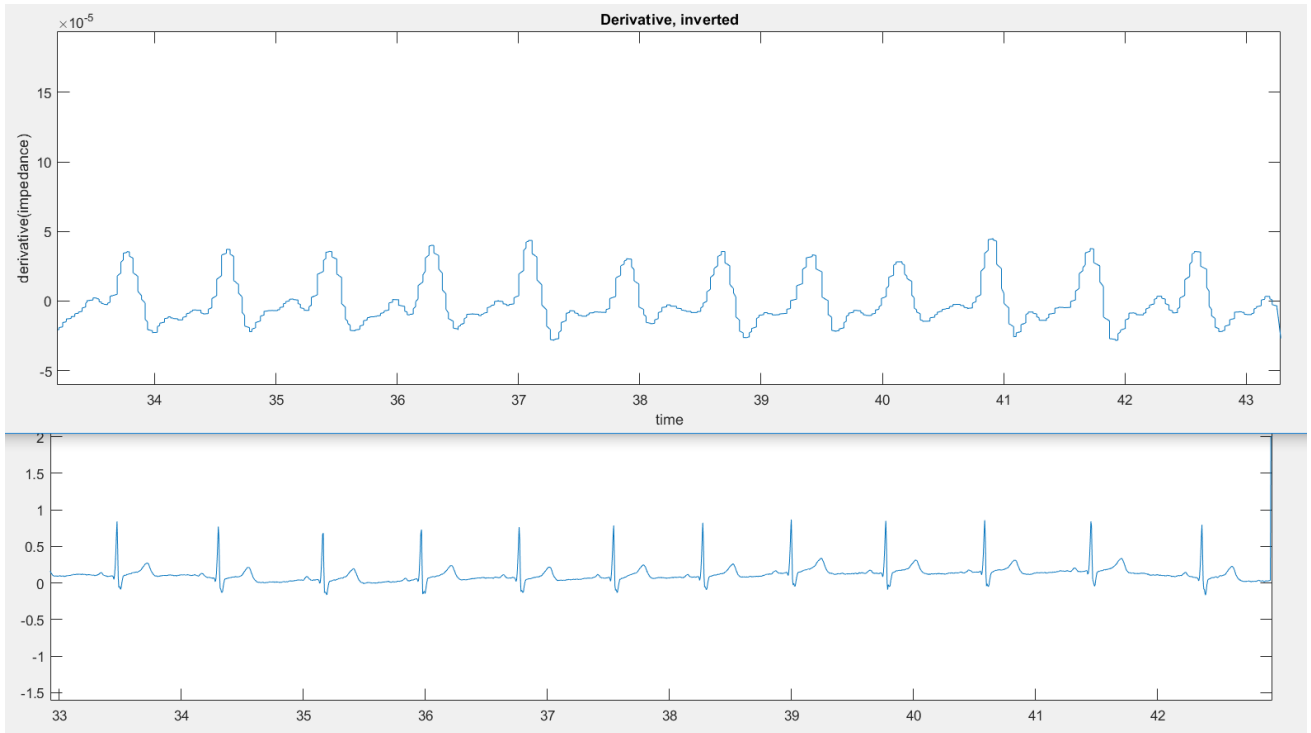


Fig.5.2.2: 50 kHz measurement, peak $\sim 5 \times 10^{-5}$

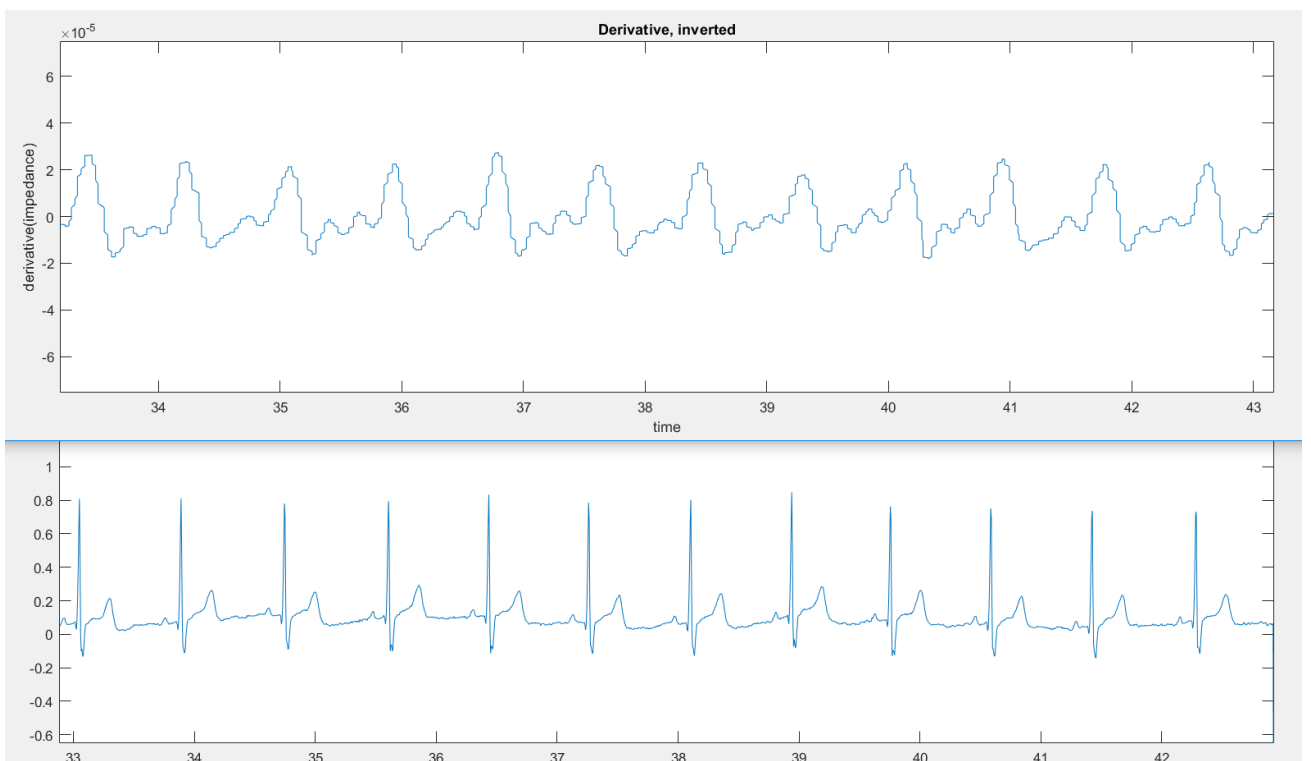


Fig.5.2.3: 500 kHz measurement, peak $\sim 2.5 \times 10^{-5}$

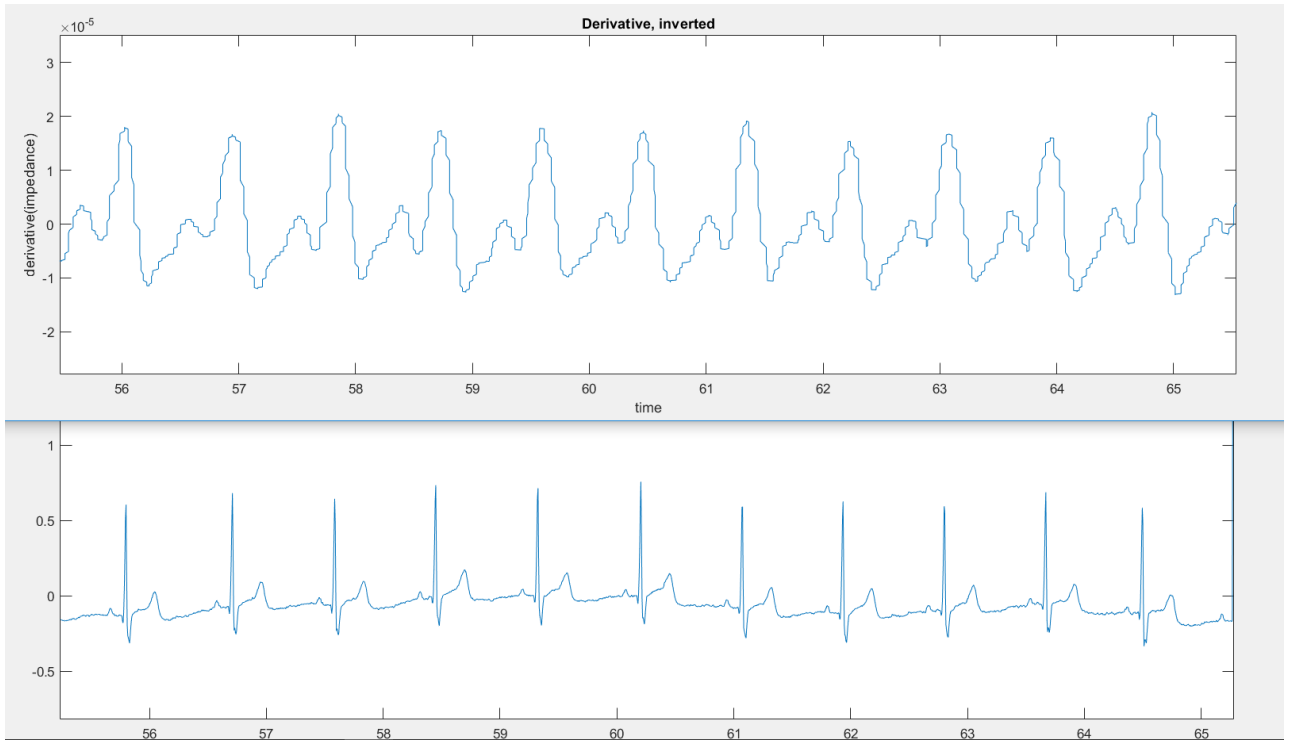


Fig.5.2.4: 1.6 MHz measurement, peak $\sim 2 \times 10^{-5}$

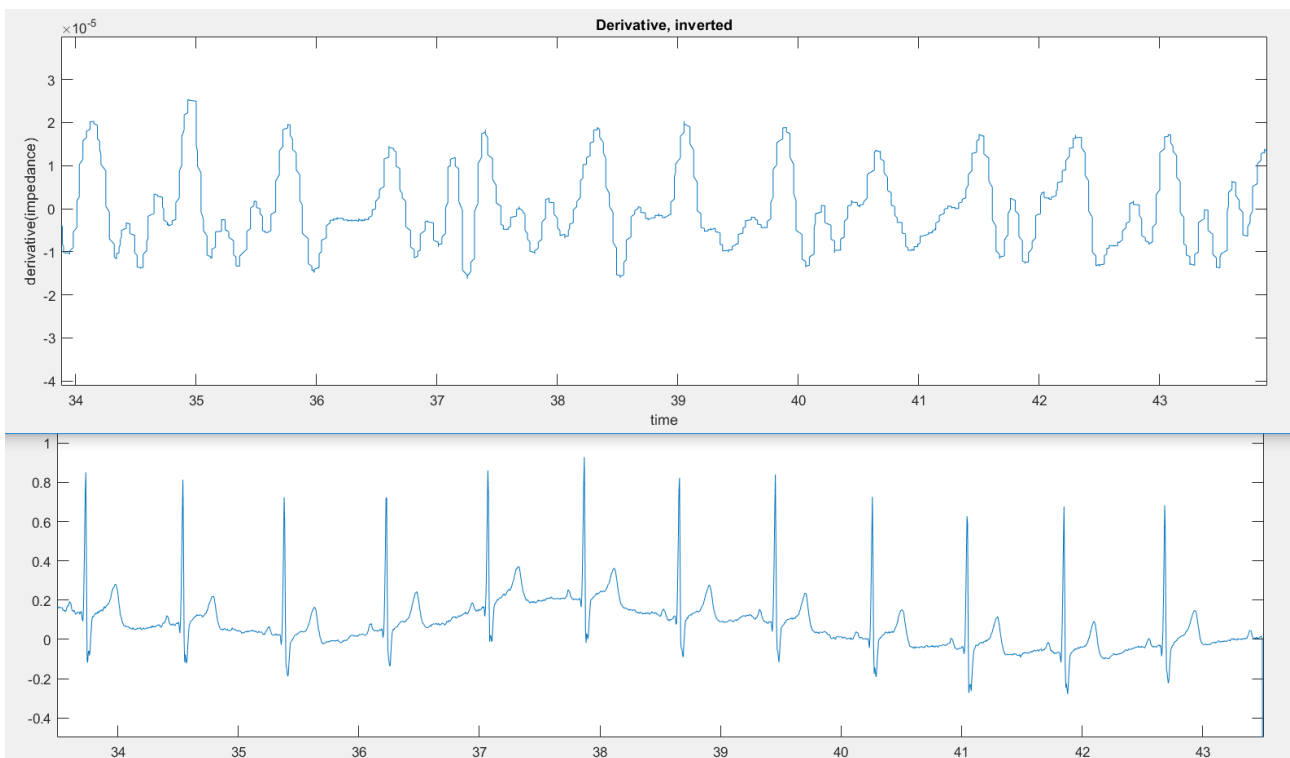


Fig.5.2.5: 3 MHz measurement, peak $\sim 2 \times 10^{-5}$

5.3 Test person 3:

Male, 25 years (BIB)

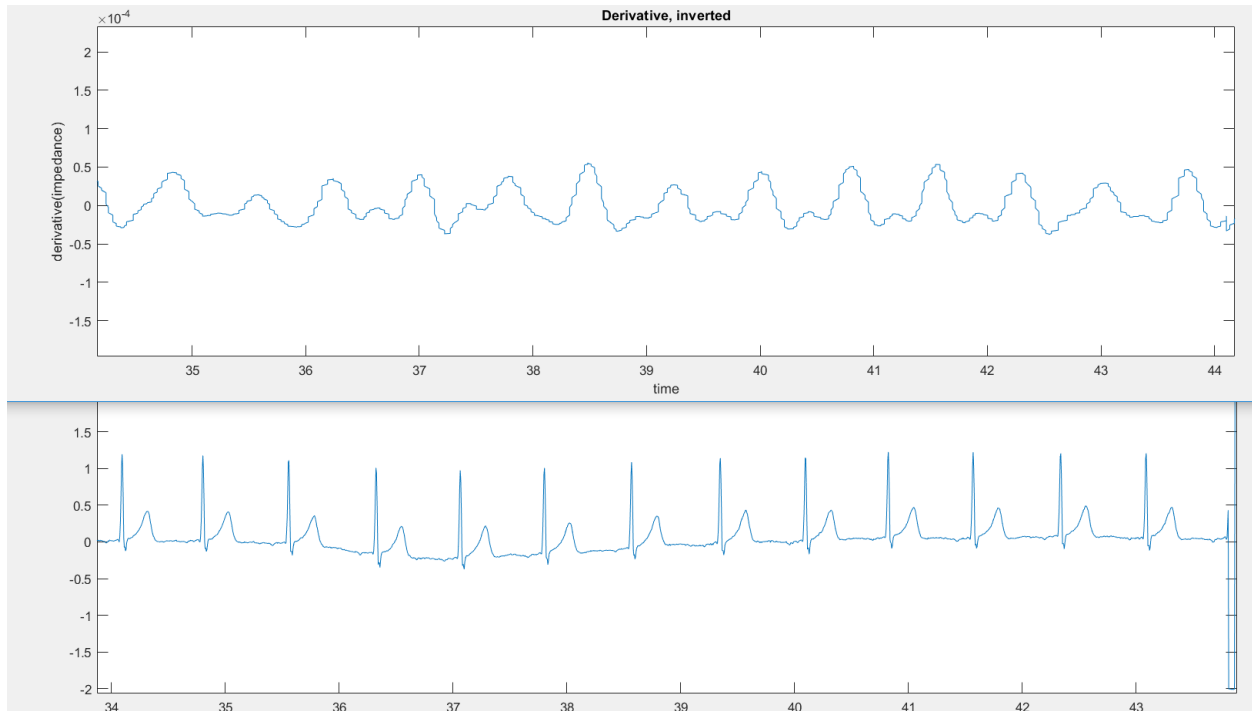


Fig.5.3.1: 20 kHz measurement, peak $\sim 5 \times 10^{-5}$

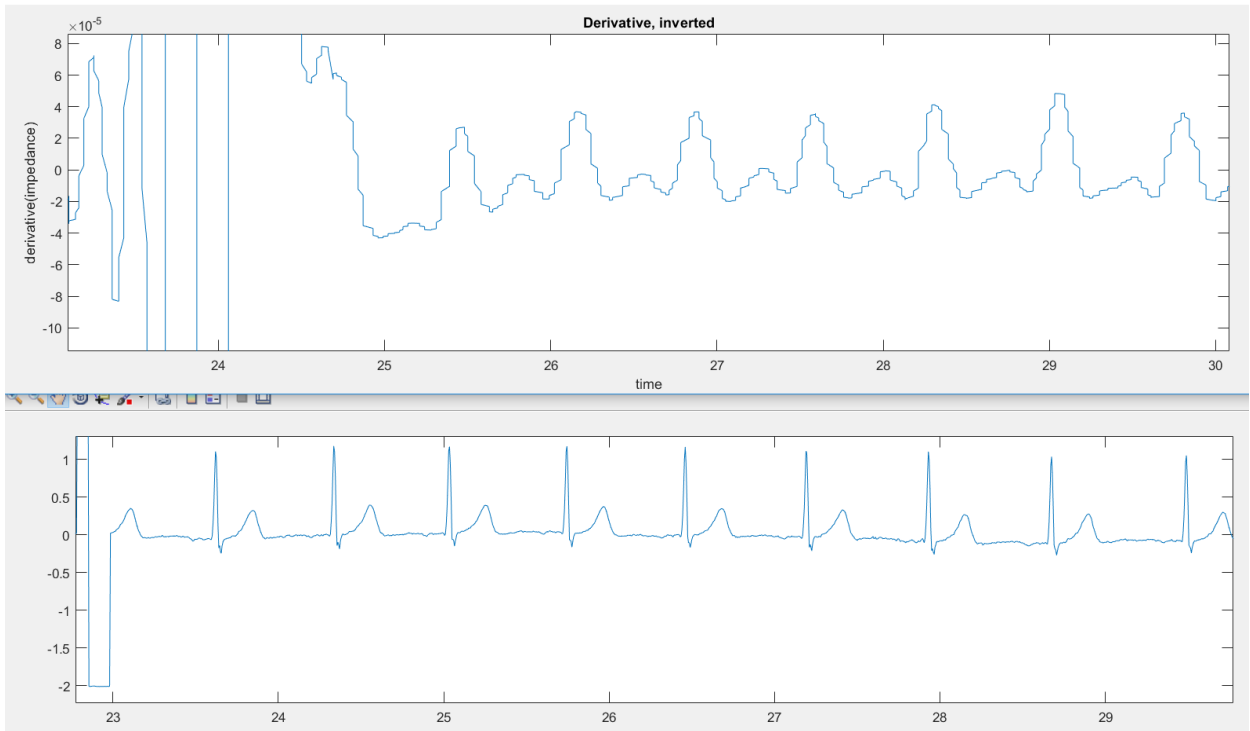


Fig.5.3.2: 50 kHz measurement, peak $\sim 4 \times 10^{-5}$ (right side oscillations from shorting the CC-electrodes)

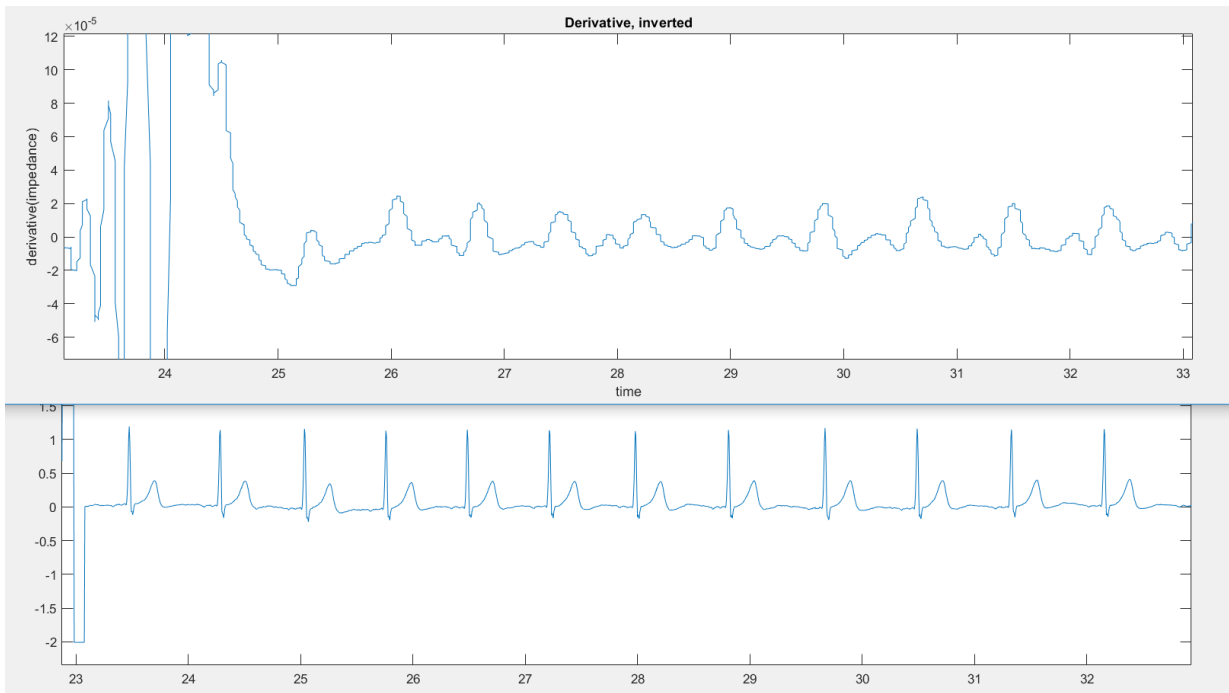


Fig.5.3.3: 500 kHz measurement, peak $\sim 2 \times 10^{-5}$

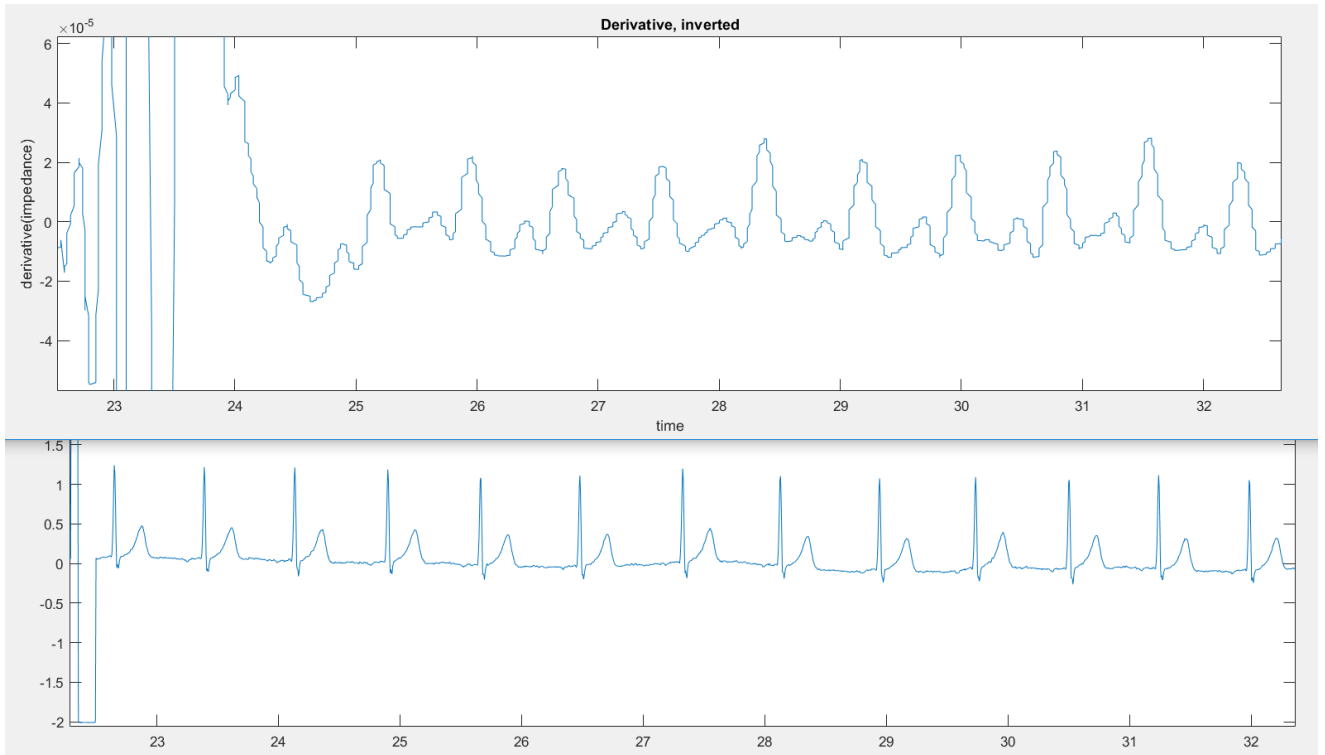


Fig.5.3.4: 1.6 MHz measurement, peak $\sim 2 \times 10^{-5}$

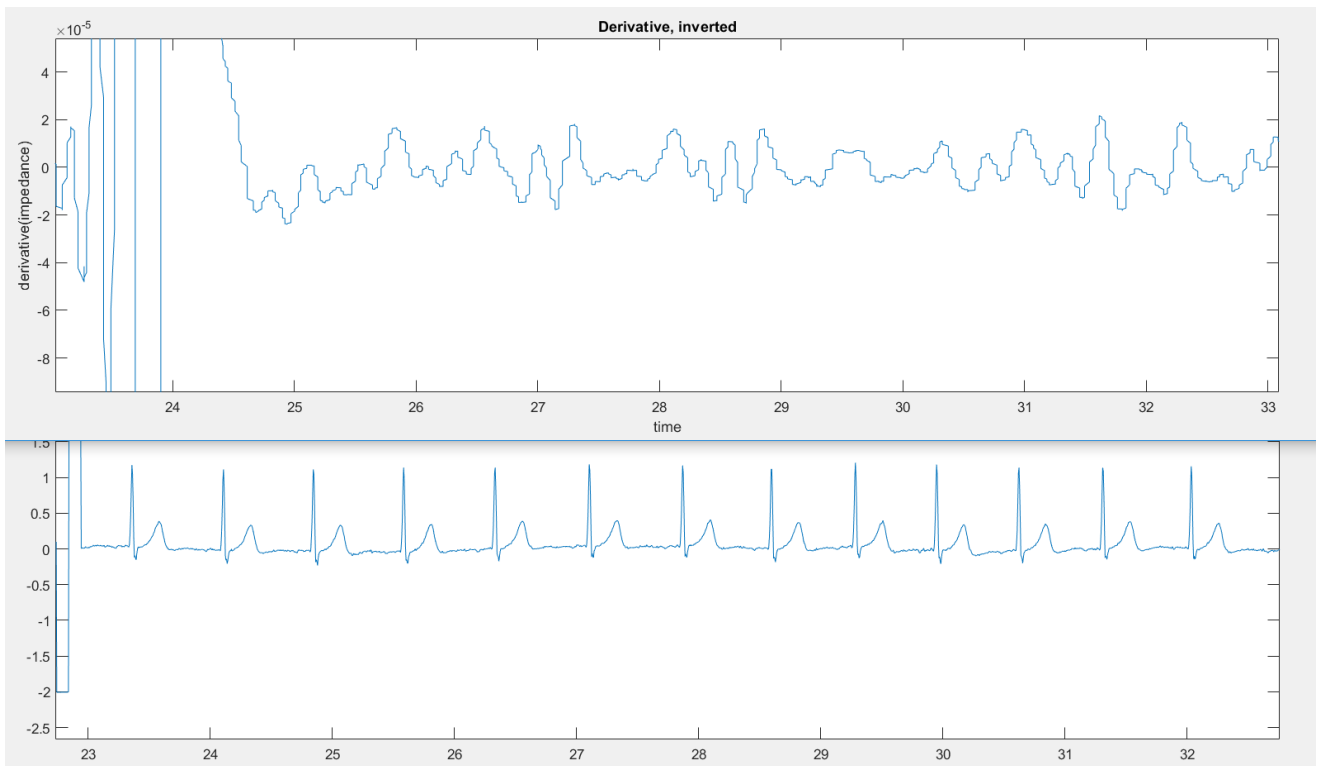


Fig.5.3.5: 3 MHz measurement, peak $\sim > 2 \times 10^{-5}$, great amounts of noise

5.4 Test person 4

Male, 26 years (KB)

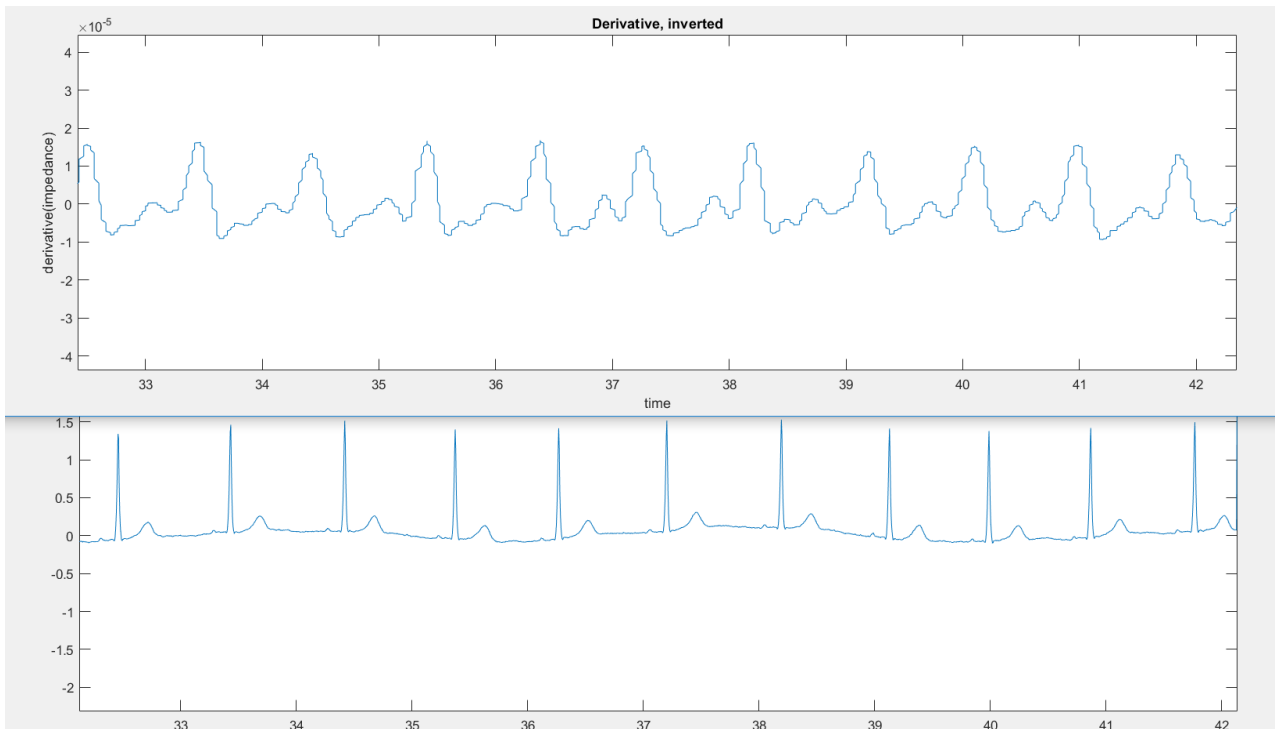


Fig.5.4.1: 50 kHz measurement, peak $\sim 2 \times 10^{-5}$

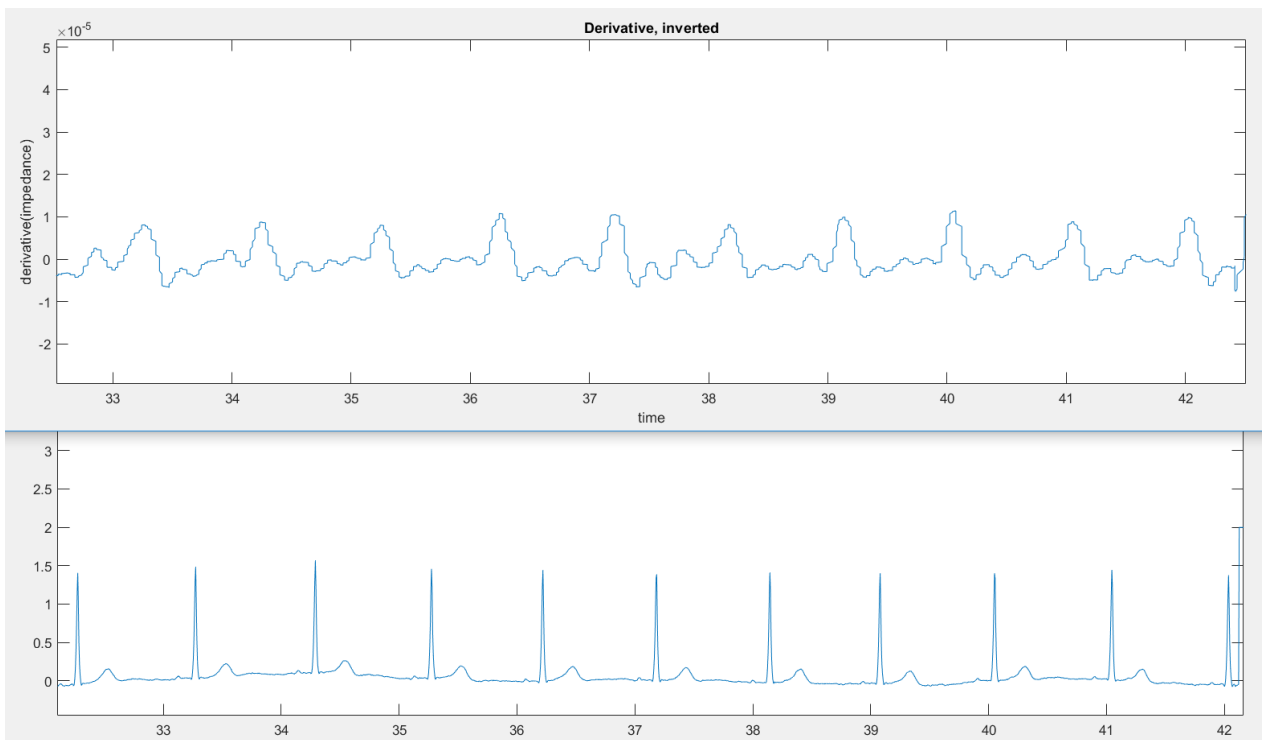


Fig.5.4.2: 500 kHz measurement, peak $\sim 1 \times 10^{-5}$

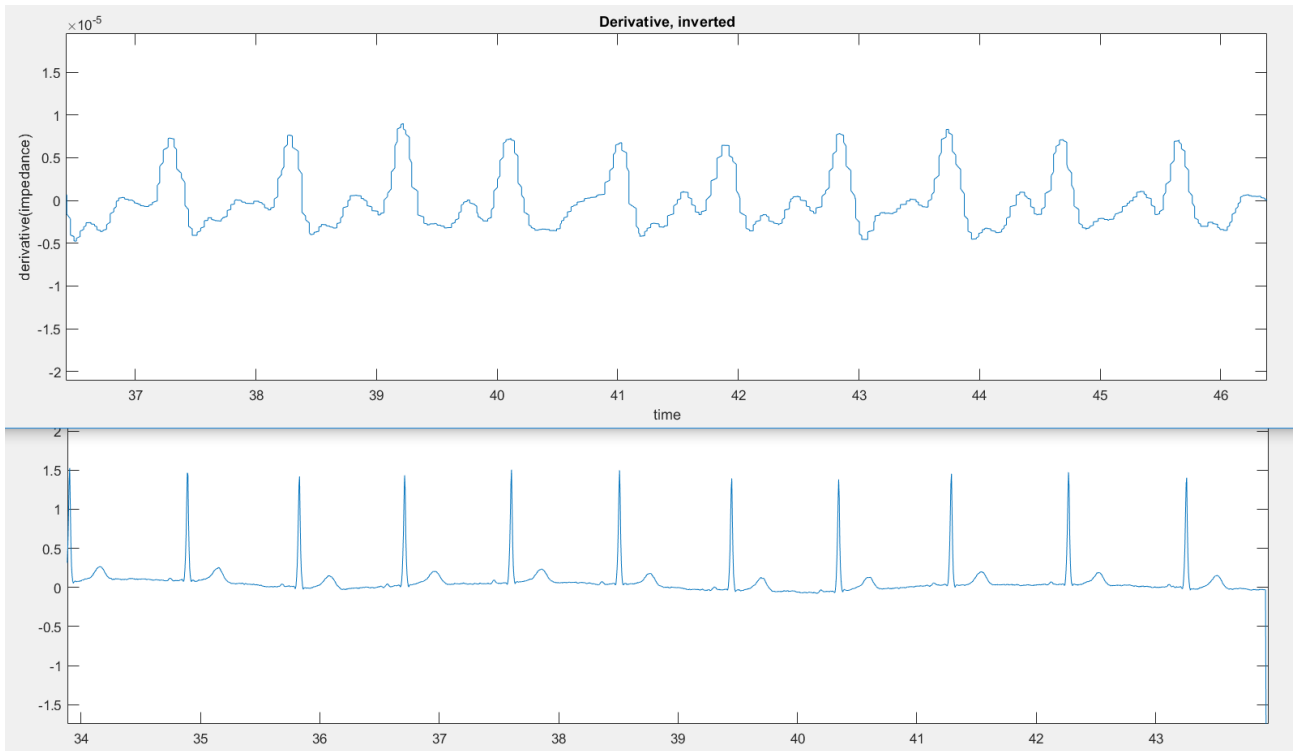


Fig.5.4.3: 1.6 MHz measurement, peak $\sim 1 \times 10^{-5}$

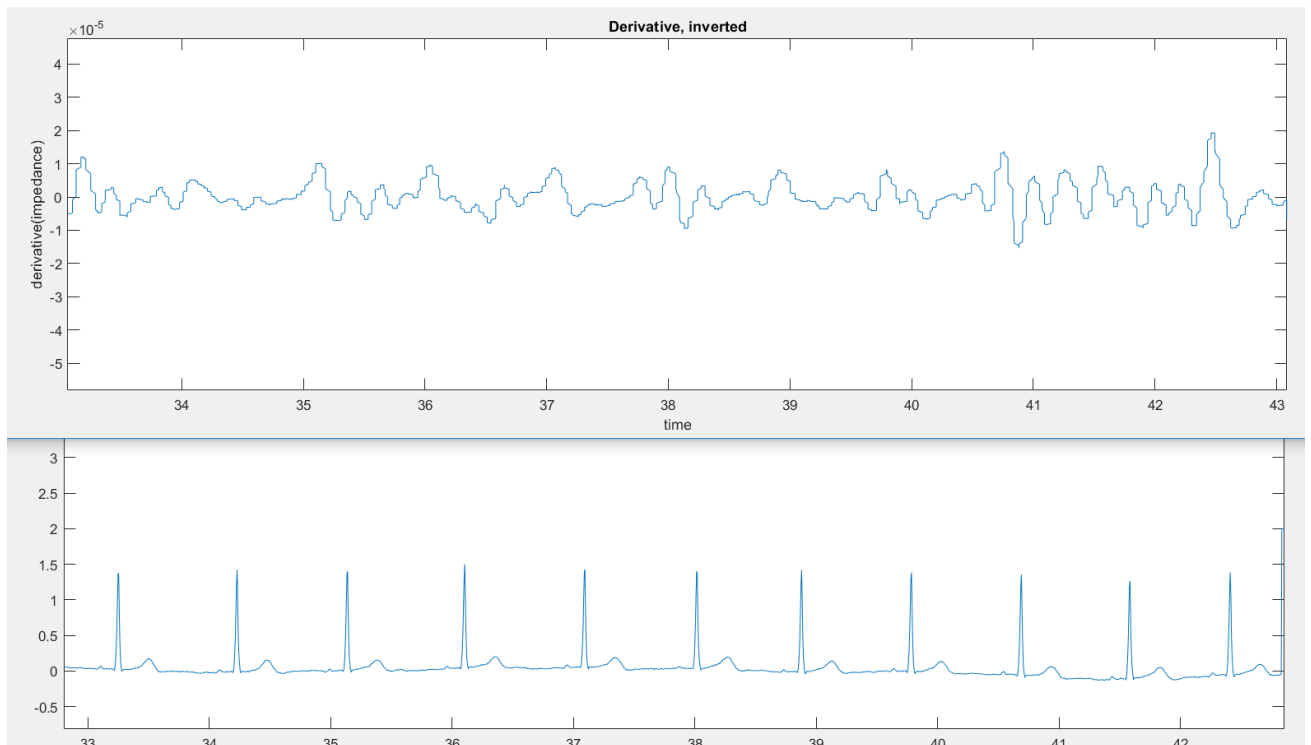


Fig.5.4.4: 3 MHz measurement, no peaks above 2×10^{-5} (see additional notes)

Additional notes on person 4:

Person showed an unusually weak signal at electrode onset, showing almost undetectable signal with lower CC-electrode on the right side of rib. Moving the electrode proved to enhance the signal somewhat, increasing its amplitude to about 30-40% of the 'normal' value observed in previous subjects during 50 kHz measurements with SINTEF equipment.

The only obviously observable difference between this person and the other test person is a greater amount of body hair under the electrode.

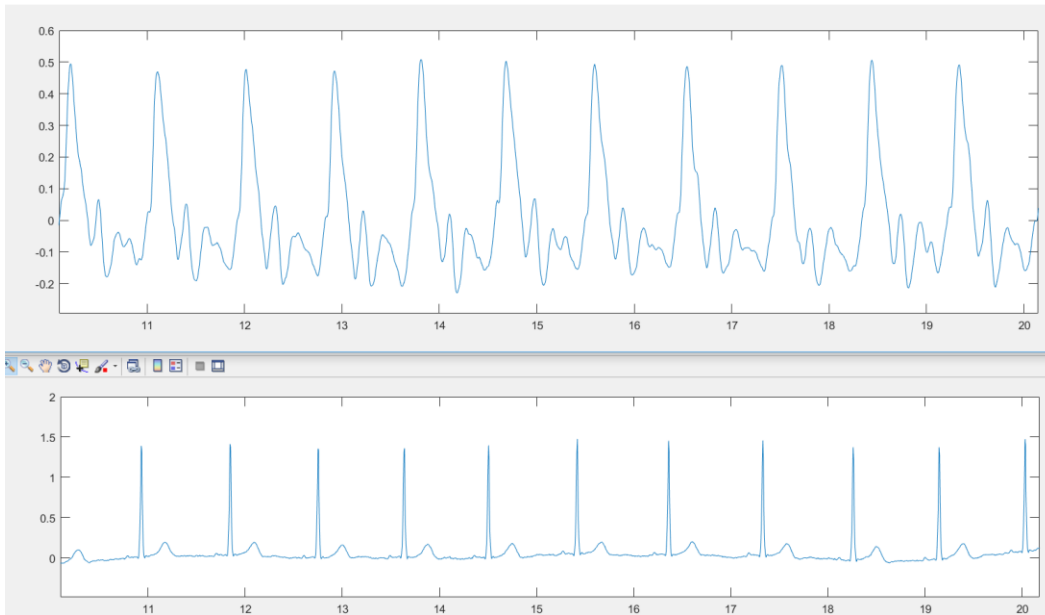


Fig.5.4.5: 50 kHz measurement, impedance data extracted directly from SINTEF (Bionomadix) equipment. At the moment of electrode onset. Standard peak value for these measurements usually in the region of 1.5-3 V

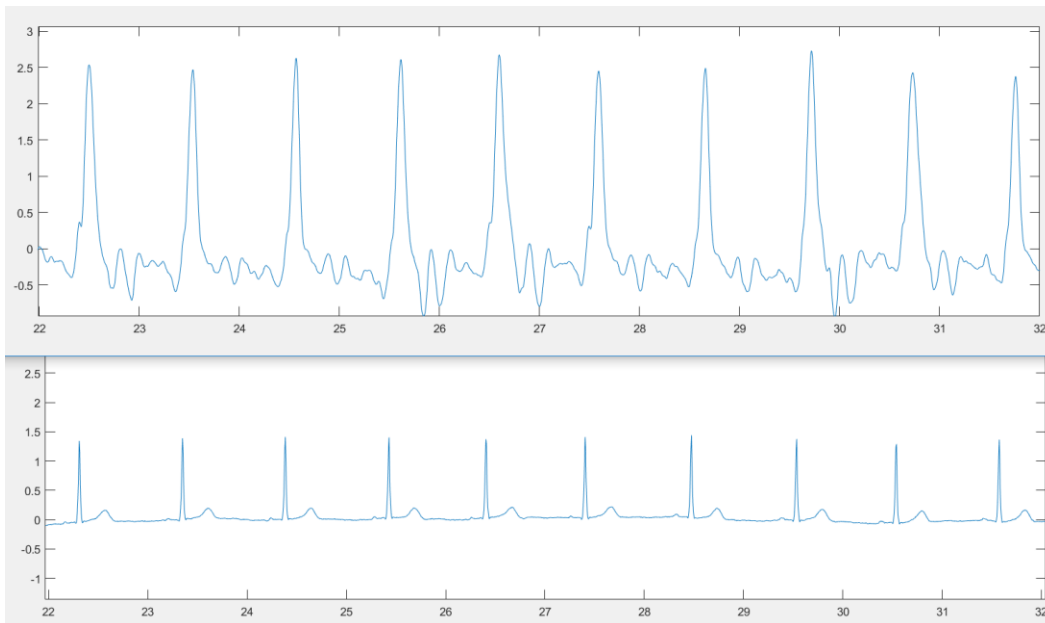


Fig.5.4.6: The same person, 50 kHz measurement, same setup but around 20 minutes later. Results extracted directly from SINTEF(Bionomadix) equipment. Peak value has now risen to expected values of 1.5-3 V

5.5 Test person 5

Male, 29 years (TA)

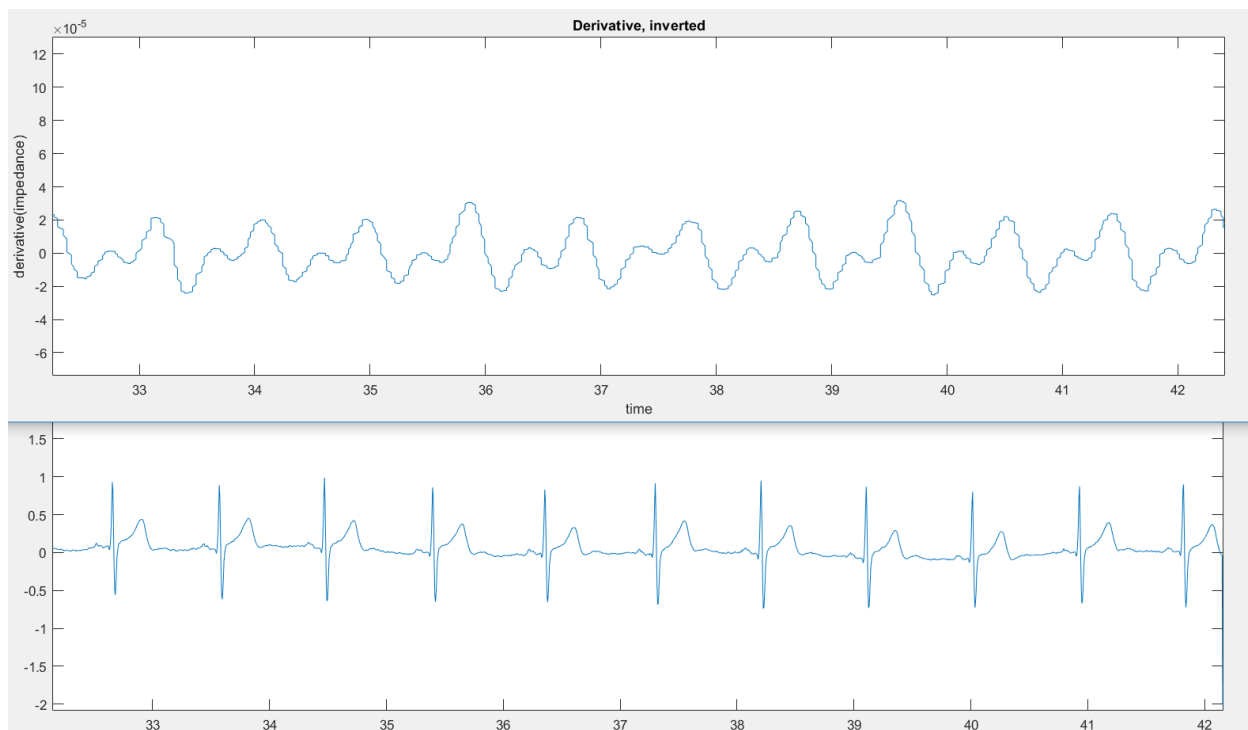


Fig.5.5.1: 20 kHz measurement, peak $\sim 3 \times 10^{-5}$

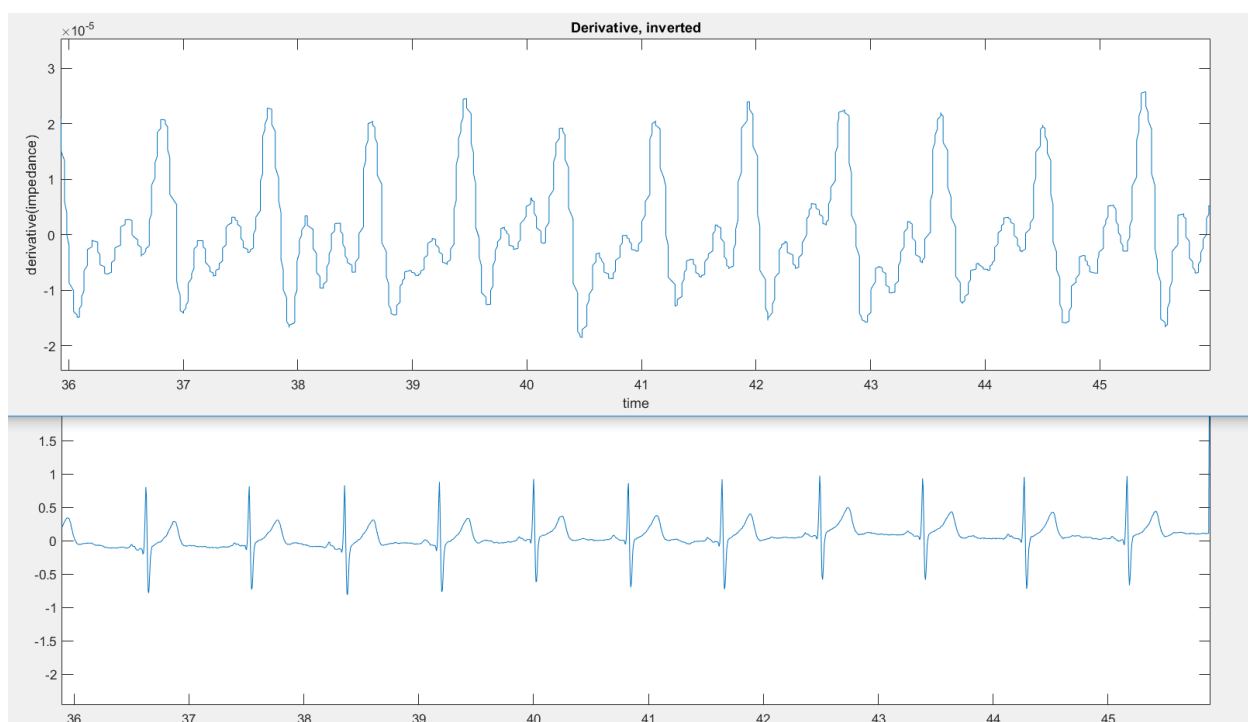


Fig.5.5.2: 50 kHz measurement, peak $\sim 2.5 \times 10^{-5}$

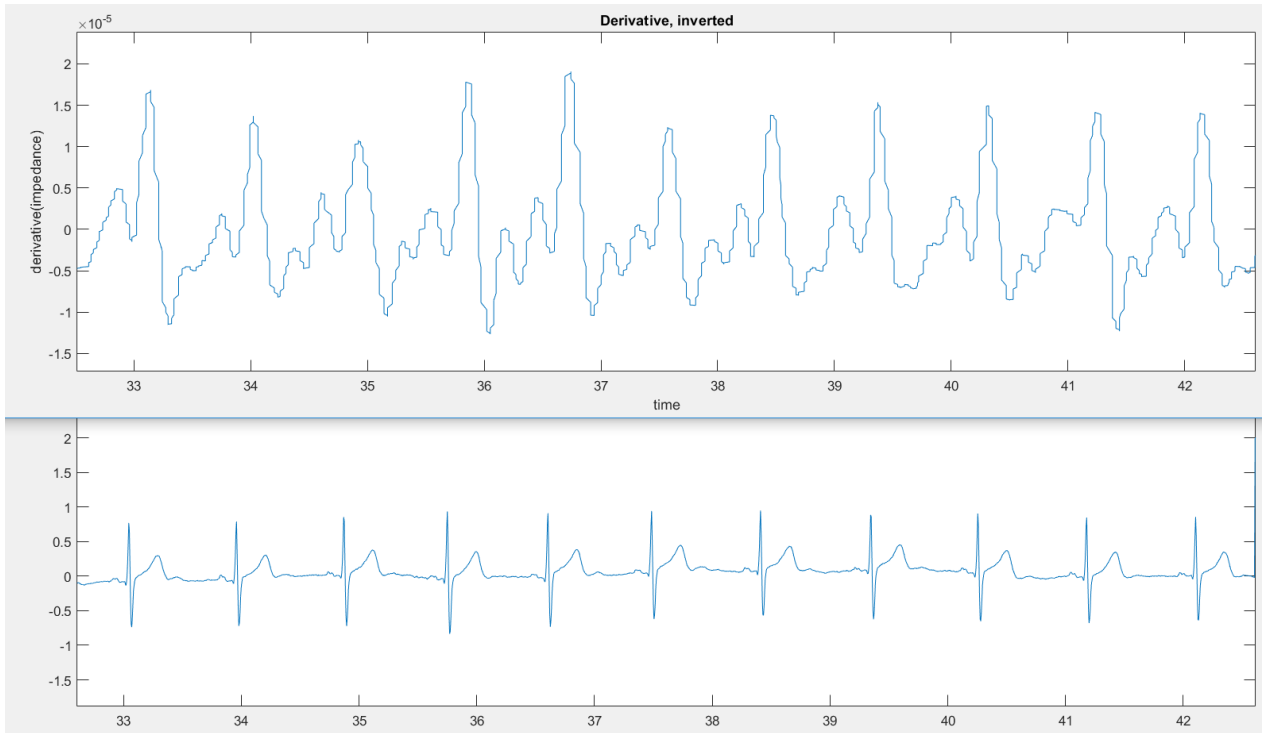


Fig.5.5.3: 500 kHz measurement, peak $\sim 2 \times 10^{-5}$

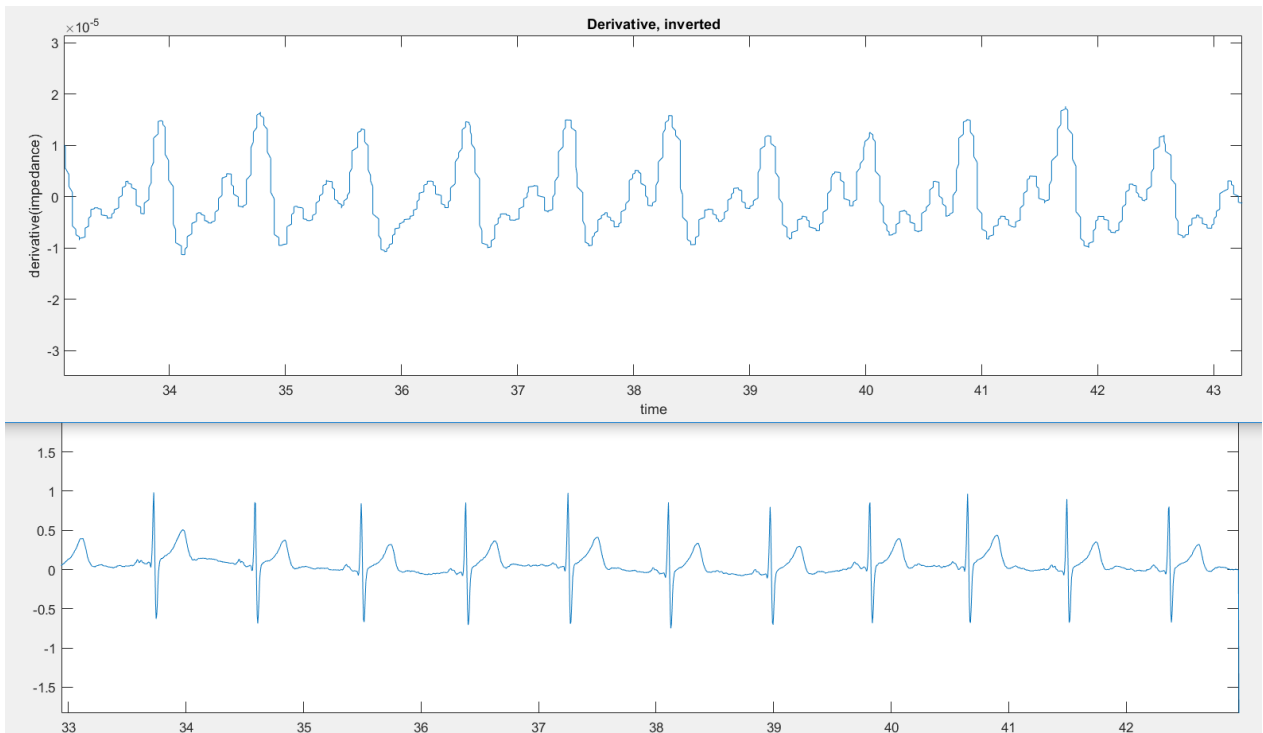


Fig.5.5.4: 1.6 MHz measurement, peak $\sim 2 \times 10^{-5}$

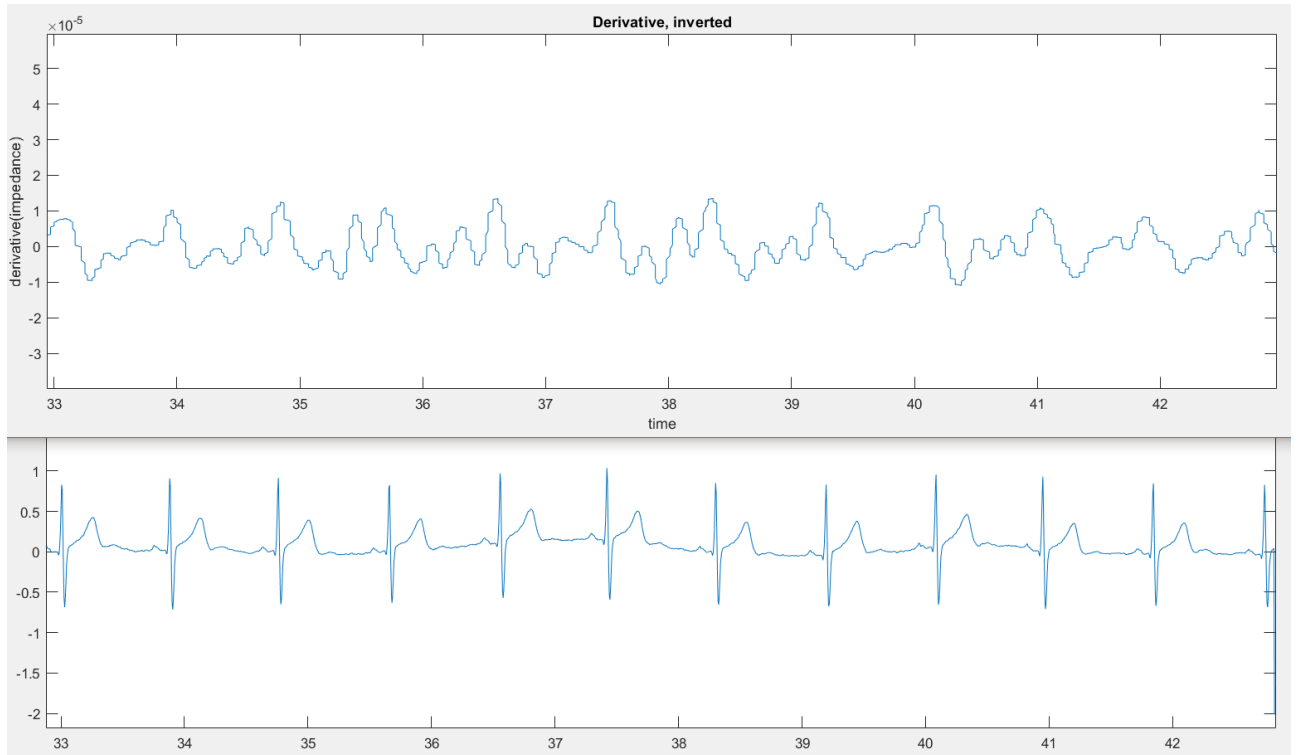


Fig.5.5.5: 3 MHz measurement, peak $> \sim 2 \times 10^{-5}$

5.6 Test person 6

Male, 18 years (JR)

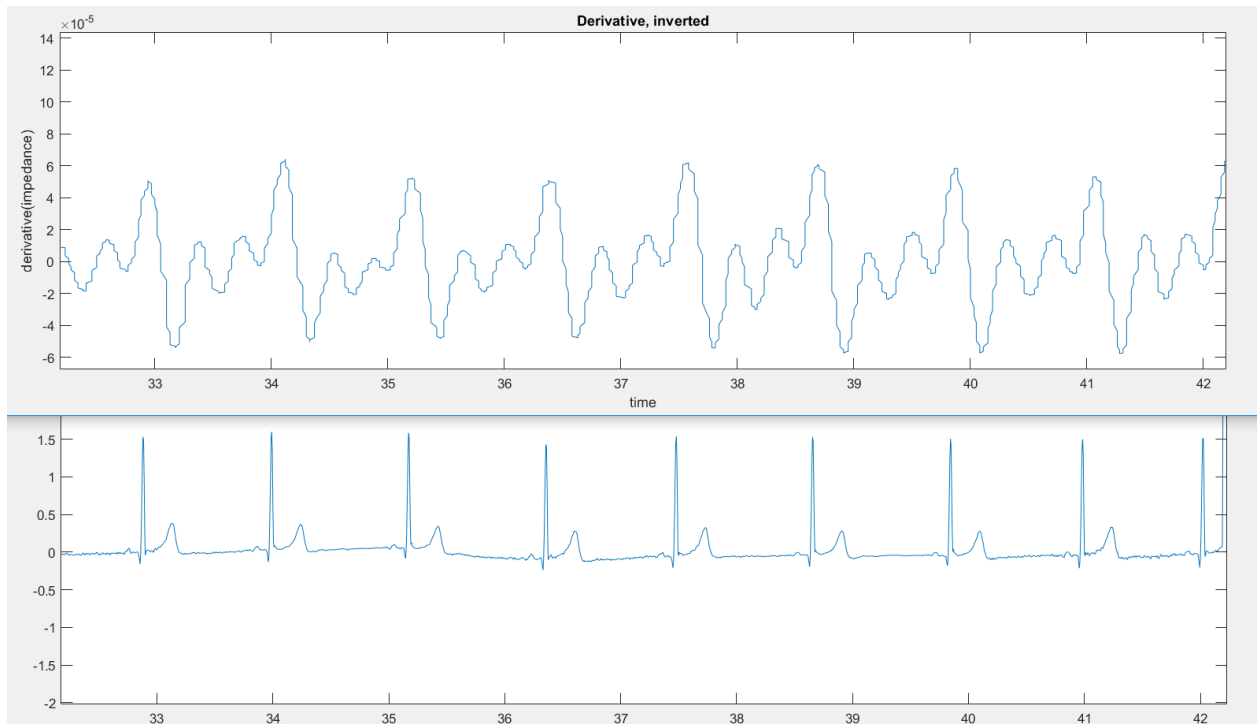


Fig.5.6.1: 50 kHz measurement, peak $\sim 6 \times 10^{-5}$

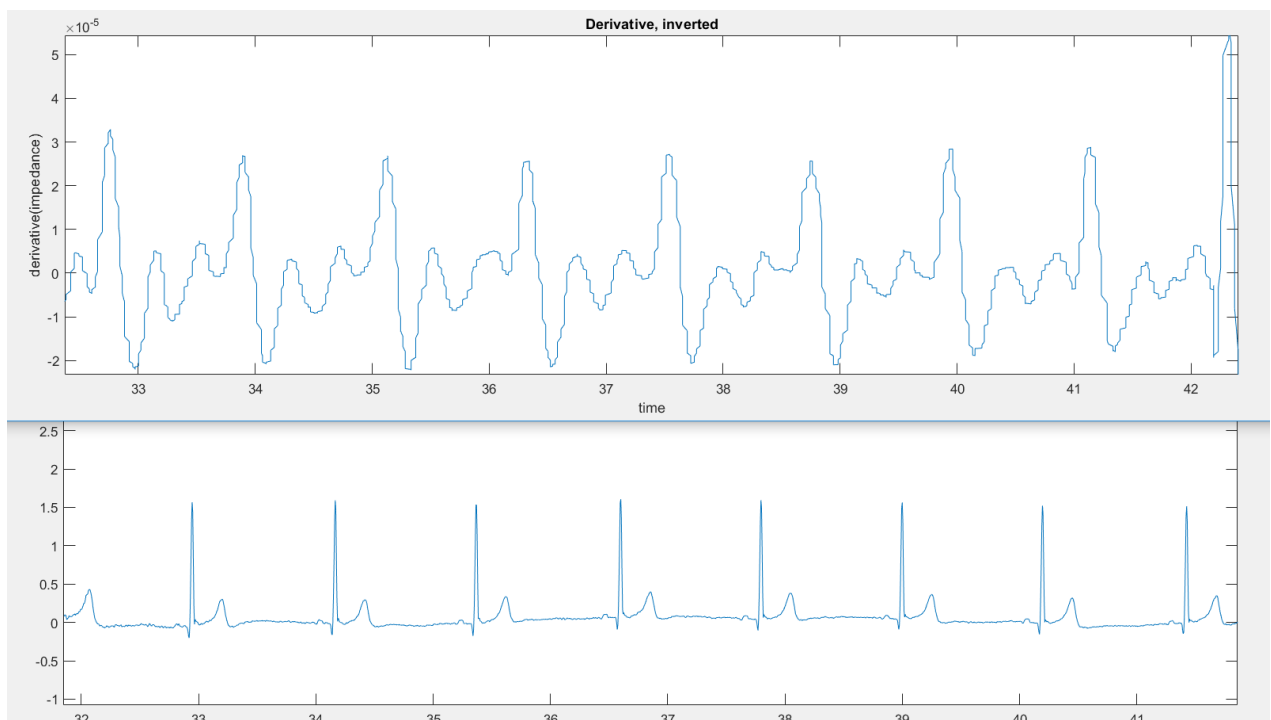


Fig.5.6.2: 1.6 MHz measurement, peak $\sim 3 \times 10^{-5}$

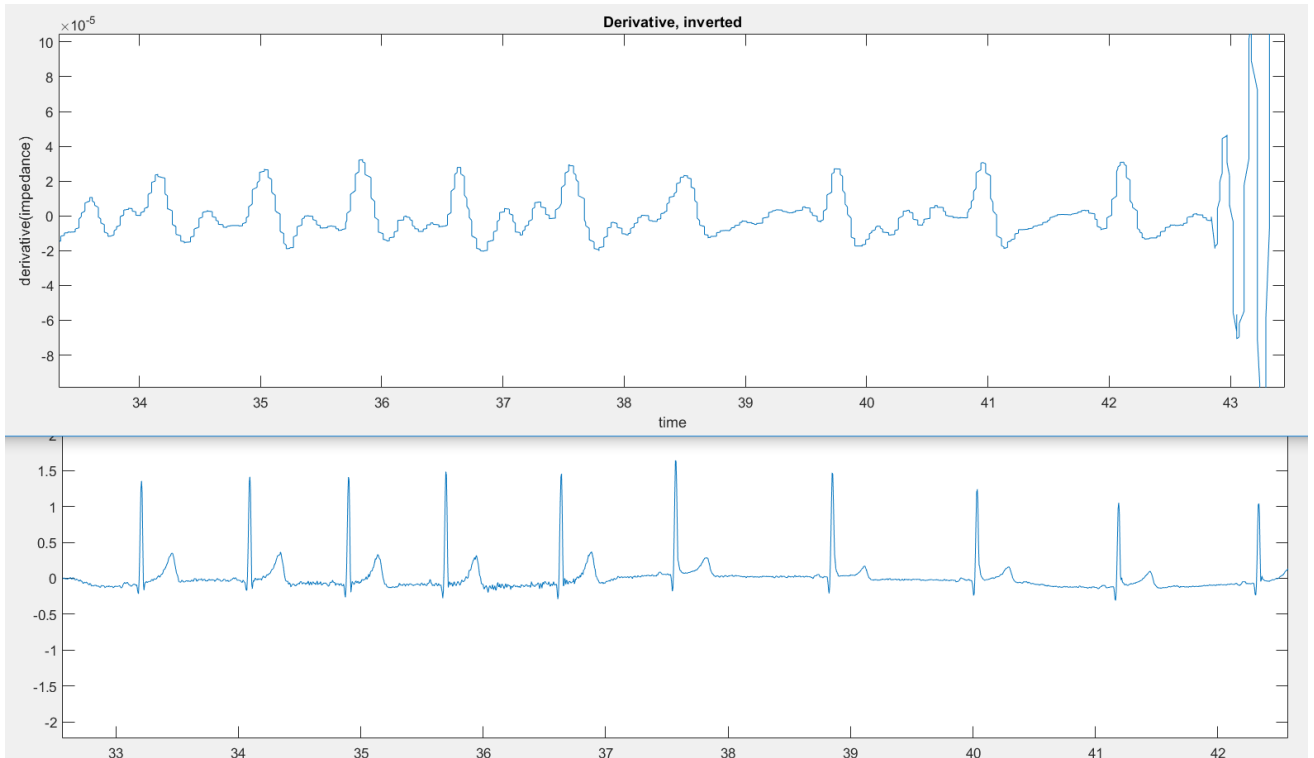


Fig.5.6.3: 3 MHz measurement, peak $\sim 3-4 \times 10^{-5}$

5.7 Discussion

Person	20K	50K	500K	1.6M	3M
1(SHL)	N/A	2×10^{-5}	N/A	1×10^{-5}	$> 2 \times 10^{-5}$
2(ATS)	5×10^{-5}	5×10^{-5}	2.5×10^{-5}	2×10^{-5}	2×10^{-5}
3(BIB)	5×10^{-5}	4×10^{-5}	2×10^{-5}	2×10^{-5}	2×10^{-5}
4(KB)	N/A	2×10^{-5}	1×10^{-5}	1×10^{-5}	1×10^{-5}
5(TA)	3×10^{-5}	2.5×10^{-5}	2×10^{-5}	2×10^{-5}	2×10^{-5}
6(JR)	N/A	6×10^{-5}	N/A	3×10^{-5}	$3-4 \times 10^{-5}$

Table 5.7.1: Table showing the (very rough) estimations of peak values at different frequencies for the different test-persons.

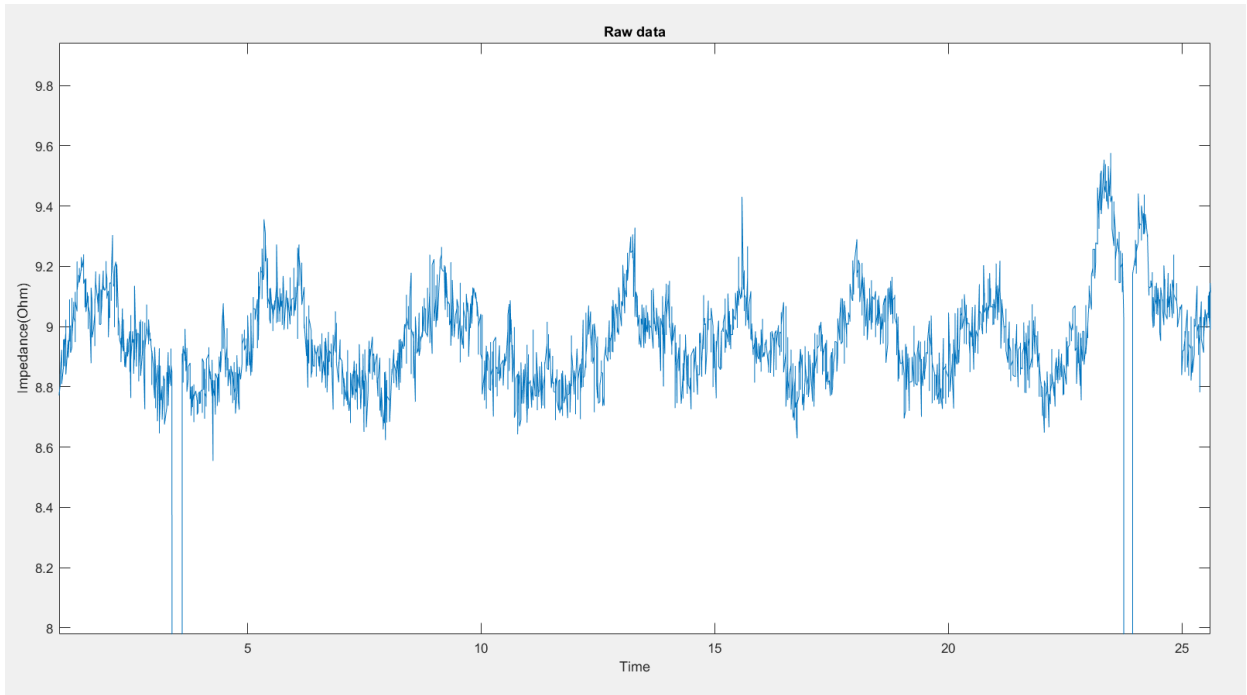


Fig.5.7.1: Raw impedance data, 20 kHz, person 3

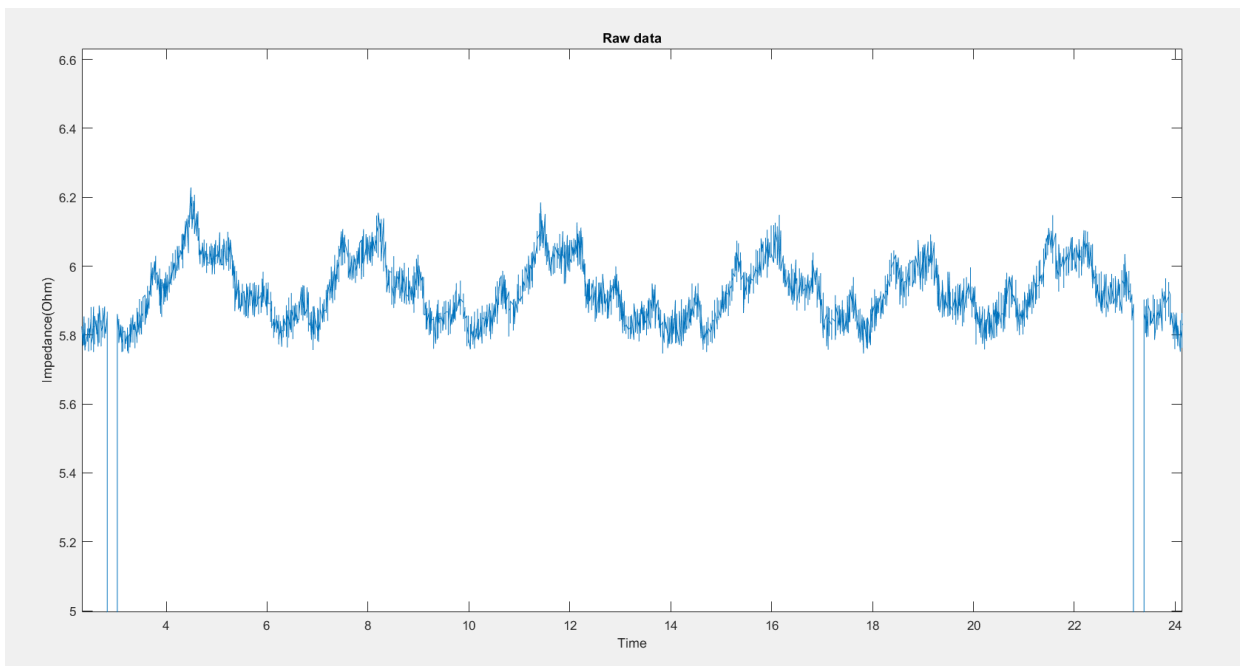


Fig.5.7.2: Raw impedance data, 500 kHz, person 3

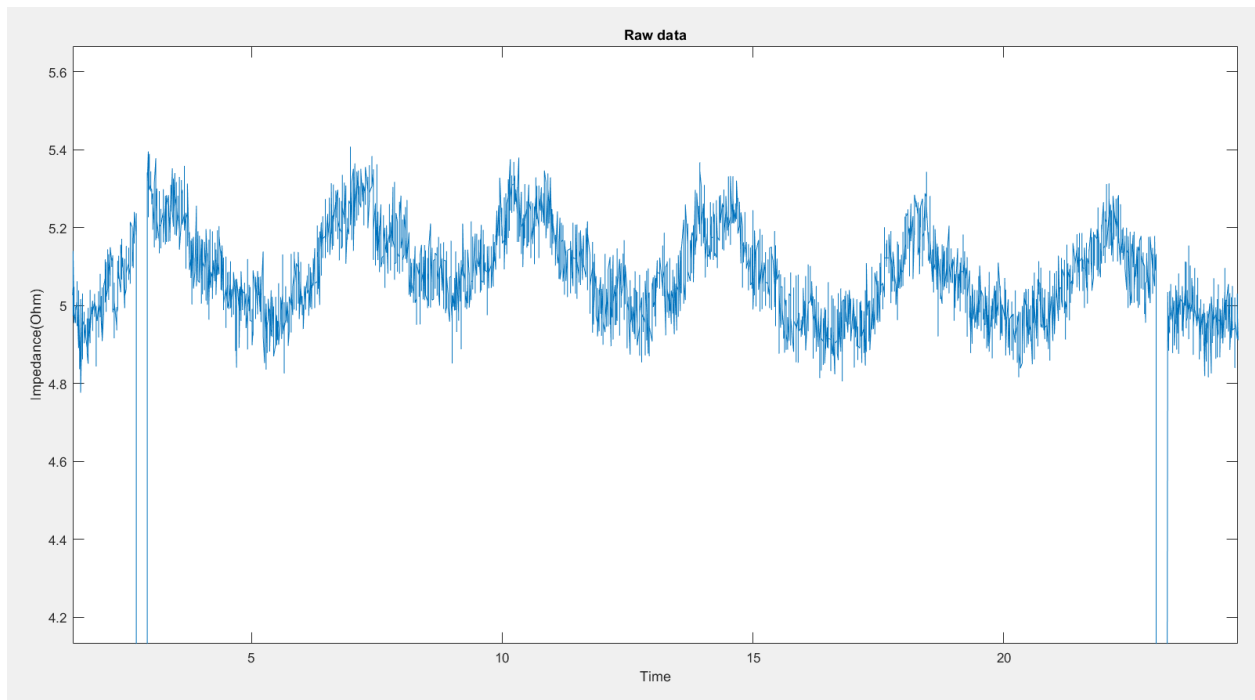


Fig.5.7.3: Raw impedance data, 3 MHz, person 3

From the three previous figures (fig.5.7.1, fig.5.7.2, fig.5.7.3) one can clearly see an increased level of noise when performing the 3 MHz measurements compared to the measurements at lower frequencies. This is reflected in the ICG graphs, where the ICG curves for the 3 MHz measurements become almost indistinguishable from the peaks caused by noise. For this specific assignment, the goal was to see if we could remove any parts of the ICG signal by increasing the current frequency. Seeing as this has been accomplished well before we reach 3 MHz, this noise does not impact the conclusion significantly.

Due to the large difference in individual ICG response from person to person and the great variation due to electrode placement it is very hard to compare results from different sessions and people. At least when considering minute differences. General trends, however can still be found by comparing the data. The main observable trend here is that somewhere between 50 kHz and 500 kHz there is a quite significant dampening of the ICG signal, in most cases cutting the amplitude by about half. Raising the frequency any further, as we can see in the 1.6 MHz plots does however not seem to have any effect, and unfortunately the 3 MHz data is perhaps too noisy to be considered trustworthy. What this does imply, is that we indeed have a roughly even split between frequency dependent and frequency independent sources of change in impedance. This does comply with the ideas of dispersion being frequency dependent and volumetric changes being frequency independent.

A paper by R. P. Patterson [6] suggests that the blood vessels and skeletal muscles in the upper thorax have a greater contribution to the ICG signal than previously thought. Our findings with the frequency independent sources and increased ICG signals in the upper thoracic region do seem to support this theory.

Chapter 6 - Future work:

The results clearly suggest that there is a divided cause of these ICG pulses, one that is dependent on low frequency and one that is not. In most of the measurements done during the experiment one can clearly see the amplitude of this ICG pulse dampen with a relatively consistent magnitude. As mentioned earlier, comparing ICG results from different persons is quite hard. As we have seen, both small differences in electrode placement, and the person itself are some of the larger causes of differences in ICG values. One can, however, compare the general trends. One way to improve this experiment would be to increase the precision with which we read these results. The script could, perhaps, be made to find an average peak value across a singular measurement. One could then compare these average peak values with the other measurements, with differing frequencies, on the same person to gain a more precise idea of how much the amplitude falls once we move upwards in frequency. As mentioned by Nagel et al. [14], it is recommended to remove the modulation to the ICG signal caused by respiration. Removing this modulation would be a natural next step in the process of more precisely measuring the differences between the ICG peaks.

This leads to another point, when it comes to improving this experiment. Due to unforeseen difficulties with the experiment, there simply was not enough time to go back and do more expansive measurements. The goal, of course, was to search for differences in ICG signal between high and low frequency measurements. Once this was done, it could be interesting to go back and attempt to pinpoint at which frequencies this difference happens, to try and answer questions such as:

Is this an abrupt change or a gradual one?

Is the frequency, or frequency range, where this happens fairly equal for all the test persons?

This of course leads to yet another point, and a weakness in this particular experiment; a wider spread of test persons, primarily in age and sex. As of now, all test persons have been within five years of age, with one exception being another 7 years younger than the rest, and every test person has been a male. It would be interesting to see if the magnitude of the ICG dampening as we increase frequency changes with age, and if the frequency range where this dampening starts to happen does as well.

Some test persons have shown to have a peculiar shape of their measured ICG pulse. Instead of one peak, we find a double peak. It would be interesting to see if this is a shape that is related to something purely individual or something that has to do with the setup. As we have seen, electrode placement has a large effect on the result, could this be another result of electrode placement? If so, can this be recreated on other test persons? Furthermore, it would be interesting to see what happens to this formation at higher frequencies. Does the ICG keep its double peaked shape, with both peaks experiencing the same amplitude dampening effect, or does one of the peaks disappear?

Chapter 7 - Conclusion

Using a standard tetrapolar setup, a series of ICG measurements have been done with new equipment (from ScioSpec) that can measure with reasonably high sampling frequency and at higher frequencies than normal. The current frequencies used span from 20 kHz to 3 MHz. By looking at the differences in magnitude of the ICG signal at different frequencies, we should be able to get a better understanding of what the sources of the ICG signal is.

There are clear ICG signals at both 1.6 Hz and 3 MHz, however a consistent decrease in amplitude in the magnitude of about 40-60% is observed when compared to the 50 kHz measurements. The most substantial part of this change in amplitude seems to primarily happen between 50 kHz and 500 kHz. This would imply that the source of the change of impedance is actually a sum of both a frequency dependent and a non-frequency dependent event. This could mean that both the volumetric expansion of the tissue in the thoracic region and the momentary alignment of blood cells both play a similarly large role.

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[22] Npatchett - Own work, License: <https://creativecommons.org/licenses/by-sa/4.0/legalcode>

Appendix A

The matlab script

```
function ICGdiff = ReadICGtxtData(filename)

%READ FILE
%-----
fid = fopen(filename, 'r') ;      % Open source file.
fgetl(fid) ;                      % Delete unwanted header lines.
fgetl(fid) ;
fgetl(fid) ;
buffer = fread(fid, Inf) ;        % Read rest of the file.
fclose(fid);
fid = fopen('values.txt', 'w') ;  % Create new file with wanted values.
fwrite(fid, buffer) ;             % Save to file.
fclose(fid) ;
data = csvread('values.txt');

%VARIABLES
%-----
X = data(:,1); %Time values.
Y = data(:,2); %Impedance values.

L = length(X) %Finding appropriate step size for differentiation
T = X(L)
```

h = T/L %no longer needed

Fs = 1/h %no longer needed

rate = 200%1/h

%CREATE FILTERS

%-----

```
lpFilt = designfilt('lowpassfir','PassbandFrequency',0.04, ...  
    'StopbandFrequency',0.06,'PassbandRipple',1, ...  
    'StopbandAttenuation',40,'DesignMethod','kaiserwin');
```

```
% lpFilt = designfilt('lowpassiir','FilterOrder',2,'PassbandFrequency',26, ...
```

```
%    'PassbandRipple',0.2,'SampleRate',rate);
```

```
fvtool(lpFilt);
```

```
hpFilt = designfilt('highpassiir','FilterOrder',2,'PassbandFrequency',1.1, ...
```

```
'PassbandRipple',0.1,'SampleRate',Fs);
```

```
fvtool(hpFilt);
```

```
d = designfilt('differentiatorfir','FilterOrder',3); %Creating diff. filter.
```

%RUN DATA THROUGH FILTERS

%-----

```
dataOut = filter(lpFilt,Y);
```

```
dataOut = filter(hpFilt,dataOut);
```

```
Yder = filter(d,dataOut)/rate; %Passing impedance values through filter.
```

```
Yder2 = filter(d,Y)/1;
```

```

%dydx = diff([eps; Y(:)].)/diff([eps; X(:)]);
%dydx = diff([eps; Y(:)].)/h; %Simple attempt at numerical differentiation
dydx = diff([eps; dataOut(:)].)/h;
FY = gradient(Y); %Another version of numerical differentiation

%FFT
%-----

    dy = detrend(Y); %removes trends in the FFT-plot, makes it easier to see in the case of
extremely large numbers of a singular frequency
    Yr = fft(dy,L);
    Pyy = Yr.*conj(Yr)/L;
    f = Fs/L*(0:(L/2));
    t1 = length(Pyy)
    t2 = length(f)
    plot(f,Pyy(1:(t2)))
    title('Power spectral density')
    xlabel('Frequency (Hz)')

%PLOTS
%-----

figure()
%subplot(2,3,1)
plot(X,Y);
title('Raw data')
xlabel('Time')
ylabel('Impedance(Ohm)')

%subplot(2,3,2)

```

```
figure()
plot(X,dydx);
title('Derivative, numerical')
xlabel('Time')
ylabel('Derivative(Impedance)')
```

```
%subplot(2,3,3)
figure()
plot(X,FY);
title('Derivative, Ramp function')
xlabel('Time')
ylabel('Derivative(Impedance)')
```

```
%subplot(2,3,4)
figure()
plot(X,Yder);
title('Derivative, diff-filtered')
xlabel('Time')
ylabel('Derivative(Impedance)')
```

```
%subplot(2,3,5)
yderIn = (-1)*Yder; %Multiplying the ICG values by -1 to flip, so we have peaks instead of
dips, purely for visualisation
figure()
plot(X,yderIn);
title('Derivative, inverted')
xlabel('time')
ylabel('derivative(impedance)')
```

```
end
```


The matlab script is quite simple, however due to its simplicity and singular purpose it is very little flexible. It is only meant to read and differentiate the text files that are the result of using the ScioSpec ISX-3 and its 'Advanced' mode. The resulting text file has three header lines before the values. The values are separated by a comma, (Time,Impedance), whole numbers and decimal points are divided by a dot.

0111_ats_1.6Mhz

12057x2

0.26,5.697133019575972

0.26,5.699507668368421

0.26,5.699329435438406

0.26,5.697719637821031

0.3,5.68965703586041

As shown here, the five first samples of a 1.6 MHz measurement done with the equipment.

The script removes the three first lines, and puts the rest of the data into two arrays, time and impedance, respectively. Following that the data is run through a high-pass, low-pass and then differential-filter. The data is then plotted. If one were to use this script some manual work is expected after plotting the data, as the ICG values are very small, especially compared to the injected pulses (as outlined in sections 1.10 and 3). Manual zooming is therefore required, as there was not enough time to implement 'Ease of use' functions. The script does include a short FFT-plot of the data, and several different methods of differentiation. These different methods were simply there to cross-check if the differential-filter was doing its job in the early phases of the experiment. If one were to use the script it is recommended to comment them (subplot 2,3,2 and subplot 2,3,3) out.

Appendix B: ScioSpec ISX-3 Manual



Manual

ISX-3v2 High Frequency Electrical Impedance Spectroscopy

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WARNING



Please pay attention to the warning.

DANGER



Danger to life due to electric current.

COMMENT



Please pay attention to the comment.

1. General

1.1. Which products are described in this document?

- single channel impedance analyzer ISX-3v2 High Frequency

1.2. Warranty

This instrument product is warranted against defects in material and workmanship for a period of one year. During the warranty period any parts or services that show defects with a cause that was present before the transfer of risk shall – at the option of Sciospec – be replaced, reworked or re-performed free of charge (rectification).

For warranty service or repair, this product must be returned to a service facility designated by Sciospec. The buyer shall pay all shipping charges, duties, and taxes for products returned to Sciospec from another country.

Sciospec warrants that its software and firmware designated by Sciospec for use with an instrument will execute its programming instruction when properly installed on that instrument. Sciospec does not warrant that the operation of the instrument, or software, or firmware will be uninterrupted or error free.

Further details on the warranty and transfer of risk are described in the general terms and conditions of Sciospec. No other warranty is expressed or implied. Sciospec specifically disclaims the implied warranties of merchantability and fitness for a particular purpose. Further and/or divergent regulations require contractual agreements in written form.

The foregoing warranty shall not apply to defects resulting from improper or inadequate maintenance by the buyer, operation or service through unauthorized personnel, the buyer-supplied software or interfacing, unauthorized modification or misuse, operation outside the environmental specifications for the product, or improper site preparation or maintenance.

1.3. Intended (normal/contractual) use

The impedance analyzers ISX-3v2 High Frequency are indoor use products intended for use in qualified technical environments and laboratories with all necessary safety measures for electric installations and cabling to the measurement object/"device under test" (DUT) in place. In order to fulfill the requirements towards electrical safety and electromagnetic compatibility the system is to be installed in a safe environment with electrical connections (especially power supply) according to general safety regulations. In addition to general safety regulations all safety measures and precautions noted in this document are to be followed.

For outdoor use separate precautions and safety measures are required. Specifically it might be required to mount the system into a protective housing according to the ambient/environmental conditions.

1.4. Non-intended use

Any form of use deviating from the intended use qualifies as non-intended use/misuse/maloperation. Other applications, modes of operations, modifications or types of installations can impair safety and functionality and are thus for safety reasons not permitted for the user or third parties.

1.5. Authorized personnel

In general different levels of qualification of operating and maintenance personnel have to be distinguished.

WARNING



Danger through insufficient qualification of operating/service personnel.

The instrument may only be operated, functionally tested and serviced by sufficiently qualified personnel. Work reserved for professional technical personnel may only be done by staff authorized through Sciospec.

Users

Users are all personnel older than 18 years that have been instructed in the operation of the instrument by Sciospec or an authorized representative. They have to have read and understood this manual completely.

User may be tasked with the following:

- General operation of the system through externally accessible interfaces
- Operation of external controls on the instrument
- functional tests through externally accessible interfaces
- to some extent elimination of malfunctions or initiation of measures to eliminate malfunctions through externally accessible interfaces

Professional technical personnel

Professional technical personnel are all persons who in accordance to their professional education, professional experience and contemporary professional occupation

- possess respective knowledge of electrical impedance analyzers
- have been trained, authorized and instructed by Sciospec for maintenance, installation and service tasks on/for the instrument

Further the professional technical personnel have to be qualified for those tasks through their professional education, experience and technical knowledge on electrical impedance analyzers.

In addition to the authorization of users professional technical personnel may be tasked with

- Elimination of malfunctions exceeding the measures permissible for a user
- installations
- maintenance and service work as instructed by Sciospec

Unauthorized personnel

WARNING



Through operation and service procedures executed by unauthorized personnel substantial danger up to danger to life may arise.

Defects and damage caused by measures performed by unauthorized personnel are not covered by warranty and Sciospec will not be made liable for these.

1.6. Danger and risks

Even with proper professional installation and proper condition of the instrument not all dangers can be covered. Following some of the remaining risks are described.

Electrical currents

DANGER



Danger to life through electrical currents

- operation and maintenance only to be done by trained personnel
- no access to the instrument for other than authorized personnel
- never bypass fuses or protective parts
- maintenance and installation only in volt-free state
- keep moisture and excessive heat away from the instrument

Risk for danger to personnel

Increased risk for danger to the user exists

- when minors, elderly or disabled persons are allowed to operate the instrument
- when proper instruction, training and monitoring of the user is not possible
- when no authorized personnel exist
- when the number of users to the instrument are very high
- when modifications to the instrument or its installation are done


Modifications, extensions/additions to the instrument are not permissible without prior authorization through Sciospec. Any unauthorized technical or procedural modification voids the permission for operation and the warranty.



1.7. Safety Information and precautions



When you notice any of the unusual conditions listed below, immediately terminate operation and disconnect the power cable. Contact Sciospec Scientific Instruments for repair of the instrument. If you continue to operate without repairing the instrument, there is a potential fire or shock hazard for the operator.

- Instrument operates abnormally.
- Instrument emits abnormal noise, smell, smoke or a spark-like light during the operation.
- Instrument generates high temperature or electrical shock during operation.
- Power cable, plug, or receptacle on instrument is damaged.
- Foreign substance or liquid has fallen into the instrument.

The following measures help assuring safe instrument operation and are to be followed in order to comply with intended use specifications.

COMMENT	
	Technical expertise is required. Risk of damage to the instrument exists through unintended use and wrong cabling/installation.

WARNING - Ground The Instrument		
		<p>DANGER to life through electrical currents!</p> <p>The instrument is grounded through the Protective Earth lead of the power cord. To avoid electric shock, it is essential to connect the earth terminal of power cord to the Protective Earth terminal before any inputs or outputs.</p>

WARNING – Installation and Cabling Tasks		
		<p>DANGER to life through electrical currents!</p> <p>Disconnect the power supply prior to conducting installation and cabling tasks. Dangerous voltage levels, capable of causing death, are present in this instrument. Use extreme caution when handling, testing, or adjusting this instrument.</p>

- To avoid electric shock, the instrument chassis and cabinet must be grounded with the supplied power cable's grounding prong.
- Do not operate the instrument in the presence of inflammable gasses or fumes. Operation of any electrical instrument in such an environment clearly constitutes a safety hazard.
- Keep Away from Live Circuits - Operators must not remove instrument covers. Component replacement and internal adjustments must be made by qualified maintenance personnel. Do not replace components with the power cable connected. Under certain conditions, dangerous voltage levels may exist even with the power cable removed. To avoid injuries, always disconnect the power and discharge circuits before touching them.
- Do not attempt internal service or adjustment unless another person, capable of rendering first aid and resuscitation, is present.
- To avoid the danger of introducing additional hazards, do not install substitute parts or perform unauthorized modifications to the instrument. Return the instrument to an Agilent Technologies Sales and Service Office for service and repair to ensure that safety features are maintained in operational condition.

WARNING - Electro static discharge warning



This product, like all electronic products, uses semiconductors that can be damaged by electrostatic discharge (ESD). Use care when handling the devices to prevent damage. Damage due to inappropriate handling is not covered by the warranty.



ESD damage is most likely to occur as the test fixtures are being connected or disconnected. Protect them from ESD damage by wearing a grounding strap that provides a high resistance path to ground. Alternatively, ground yourself to discharge any static charge built-up by touching the outer shell of any grounded instrument chassis before touching the test port connectors.

Do not exceed the operating input power, voltage, and current level and signal type appropriate for the instrument being used, refer to technical specifications sections in this manual (chapter 2).

1.8. Replacement parts and equipment

Obtain replacement parts only through Sciospec, authorized customer support services or authorized distributors.

WARNING



Danger of injury through use of wrong or faulty replacement parts!

The use of wrong, faulty or unauthorized/unintended replacement parts can lead to danger of injury to the operating/service personnel, malfunction or complete failure of the instrument.

COMMENT



Use of unauthorized replacement parts voids the instruments warranty.

2. Technical Specification

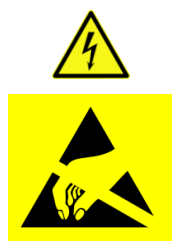
Measurement Parameters

impedance	absolute value of impedance, phase of impedance in degree, phase of impedance in radiant, resistance, reactance, absolute value of admittance, phase of admittance in degree, phase of admittance in radiant, conductance, susceptance
-----------	--

Measurement Terminal

configuration	four wire configuration, two wire configuration (counter <i>C</i> , reference <i>R</i> , work <i>W</i> , working sense <i>WS</i>)
connector type ISX-3v2 High Frequency	four BNC (female, standard polarity) connectors
Input voltage range <i>R</i> , <i>WS</i> ports	± 3.5 V
Absolute maximum Input voltage <i>R</i> , <i>WS</i> ports	± 10 V
Input Impedance <i>R</i> , <i>WS</i> ports	≈ 10 M Ω , 1 pF
Output voltage range <i>C</i> port	± 3.5 V
Absolute max. short circuit current (source/sink) <i>C</i> port	150 mA
Absolute max. continuous current (source/sink) <i>W</i> port	30 mA [Warning: <i>W</i> is a current measurement port actively biased to virtual ground (0 V) and thus no voltage should actively be applied to this terminal]

WARNING - Measurement terminals protection



Be aware that the measurement terminals (Counter, Reference, Working Sense and Work Electrode Terminals) are very sensitive to electro static discharge, over-current and over-voltage. Protection of the terminals of the instrument and strict adherence to the specified maximum ratings has to be ensured by the user. For further information on how to connect specific device under test to the instrument contact Sciospec or an authorized representative directly.

Frequency

range	150mHz to 40MHz
resolution	<150mHz
precision absolute	±100ppm (at 25°C)
temperature drift	±10ppm over operating temperature range
long time stability	±5ppm first year

Excitation Signal

Range	1mV to 1000mV peak-amplitude
Resolution	0.1 mV
Maximum continuous output current	50 mA

Output Impedance

output impedance	20Ω (nominal)
------------------	---------------

DC Bias (optional)

voltage range	-3 V to 3 V
voltage resolution	10 mV
current range	-20 mA to 20 mA
current resolution	25μA

Precision settings

precision range	0 to 1 high speed, lower accuracy 1 standard configuration $\Delta Z / Z < 0.1\%$ 1 to 10 high accuracy, low speed see Fig 4 and Fig 5
averaging	1 to 1024

Sweep Settings

available parameters	sweep	frequency, amplitude, DC bias voltage, DC bias current, kinetic, point delay
sweep type		linear, logarithmic, list
points		1 to 2046
sweep delay ¹		0s to 3min in 1 μ s steps
point delay ²		0s to 3min in 1 μ s steps

Synchronization Ports (SyncPort)

sync ports	two inputs, two outputs,
sync input type	point hold off, sweep hold off, immediate stop
sync output type	sweep complete, point complete
connectors	four SMA (female, standard polarity)
ESD protection	$\pm 12\text{kV}$ IEC 61000-4-2 contact ESD $\pm 15\text{kV}$ IEC 61000-4-2 air-gap ESD clamp voltage 10.5V (min) break-down voltage 7V (min)
absolute maximum input voltage	5.5V
absolute minimum input voltage	-0.3V
high level input voltage	$\geq 2\text{V}$
low level input voltage	$\leq 0.8\text{V}$
high level output voltage	$\geq 2.7\text{V}$ (open drain buffer with 1k Ω pull up resistor to 3V)
low level output voltage	$\leq 0.55\text{V}$
maximum output current	24mA
typical input capacitance	3pF

¹ Sweep-Delay...Timing delay between two consecutive measurements of complete impedance spectra

² Point-Delay...Timing delay between two consecutive measurements of single frequencies

IO Port (optional)

connector type	D-Sub-Mikro-D 20Pin (Type: 3M Electronic Solutions Division PN: 10120-3000PE)
signal level standard	LVC MOS 3V
absolute maximum input voltage	3.6V
Fehler! Textmarke nicht definiert.	
absolute minimum input voltage	-0.3V
high level input voltage	≥1.7V
low level input voltage	≤0.8V
high level output voltage	≥2.8V
low level output voltage	≤0.2V
maximum output current	12mA
ESD Protection of IOs	±12kV IEC 61000-4-2 contact ESD ±15kV IEC 61000-4-2 air-gap ESD clamp voltage 10.5V (min) break-down voltage 7V (min)
number of IOs	eight (freely distributable between input and output)
IO configuration	GPIO, UART, I ² C
UART configuration	115.2kBaud, 1 start bit, 8 data bits, 1 stop bit, even polarity, idle high
I ² C configuration	100kbit, 7bit address, standard mode, device behaves as master
number of temperature sensors	2
temperature sensor type	Negative temperature coefficient (NTC) Reference resistance: 10kOhm (default, configurable) Nominal temperature: 25°C (298.15 K) (default, configurable) Beta value: 4300K (default, configurable) Temperature range: -40°C...150°C Temperature resolution: 0.01 K
pin assignment	See Tab 1
connector layout	See Fig 1

PIN	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Mode																				
GPIO	GND	NTC1	GND	NTC2	GND	IO1	GND	IO2	GND	IO3	GND	IO4	GND	IO5	GND	IO6	GND	IO7	GND	IO8
I ² C	GND	NTC1	GND	NTC2	GND	SCK1	GND	SDA1	GND	SCK2	GND	SDA2	GND	d.n.c.	GND	d.n.c.	GND	d.n.c.	GND	d.n.c.
UART	GND	NTC1	GND	NTC2	GND	Rx	GND	Tx	GND	d.n.c.	GND	d.n.c.	GND	d.n.c.	GND	d.n.c.	GND	d.n.c.	GND	d.n.c.

Tab 1: IO Port pin assignment for different modes of operation

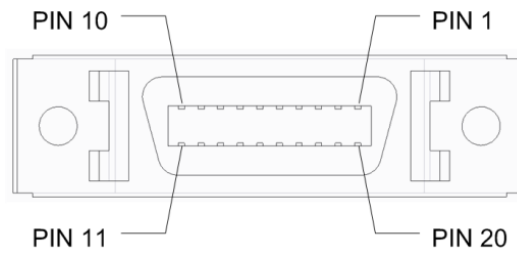


Fig 1: IO Port connector

Ethernet Interface

standard conformity	10/100 Base-T, RJ45
protocol	TCP/IP

USB Interface

standard conformity	USB 2.0 Type B
protocol	High Speed USB
ESD Protection	±12kV IEC 61000-4-2 contact ESD clamp voltage 13V (min) break-down voltage 5.5V (min)

General Specifications ISX-3v2 High Frequency

power requirements	100-240V AC (typ.), 50/60Hz, 60W (max)
Input fuse	Miniature Fuse, 5 x 20 mm, 1A, 250V, Fast Blow
Timing accuracy	1% accuracy over the full temperature range
dimensions	248.67mm x 97.1mm x 193.2mm (width x height x depth) see Fig 2 and Fig 3
weight	2.5kg (typical)
operating conditions	0°C to 40°C, <80% relative humidity non condensing, 0...3000m altitude
non-operating conditions	-25°C to 80°C, <80% relative humidity non condensing ³

³ The temperature gradient should not exceed 1K/min to reach operating conditions.

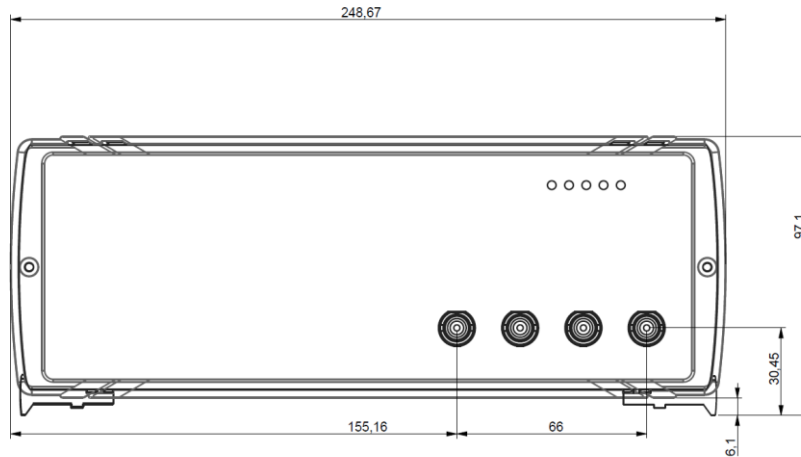


Fig 2: ISX-3v2 High Frequency front view

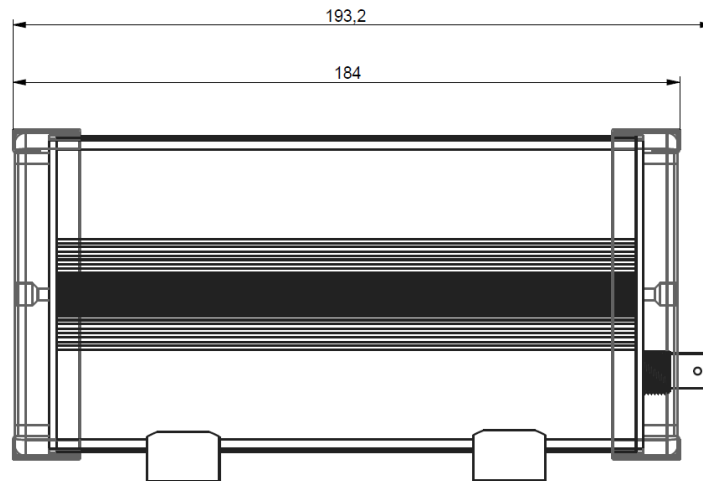


Fig 3: ISX-3v2 High Frequency side view

WARNING - Maximum ratings

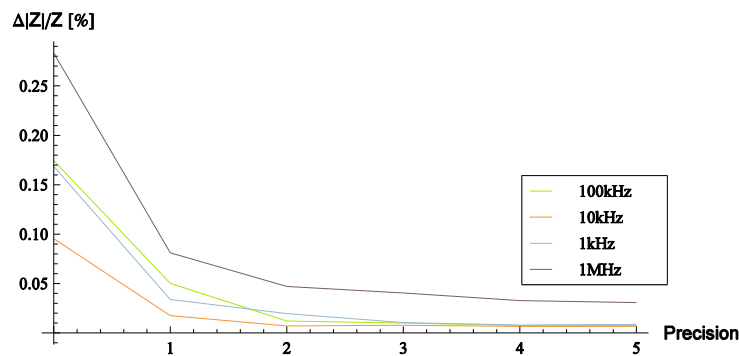


Stresses above the listed absolute maximum or maximum ratings may cause permanent damage to the device. This is a stress rating only; functional operation of the device at these or any other conditions above those indicated in the operational section of this specification is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

Specifications

All specifications above are stated for a operating of temperature of 0°C to 40°C. Warm-up time must be greater than or equal to 30 minutes after power on to comply with all specifications.

Relation between the precision setting and the measurement time and measurement accuracy



The diagram on the left shows the influence of the precision settings on the accuracy and time for the measurement of an impedance value at the specified frequency.

Low precision settings correspond to fast measurements with lower accuracy. High precision settings correspond to greater accuracy at longer measurement times.

Fig 4: Accuracy over Precision Parameter

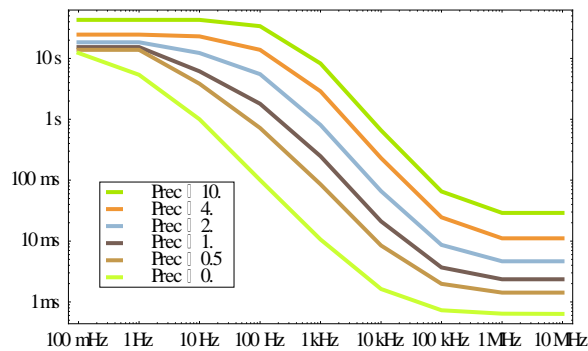
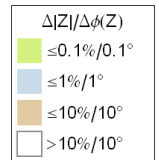
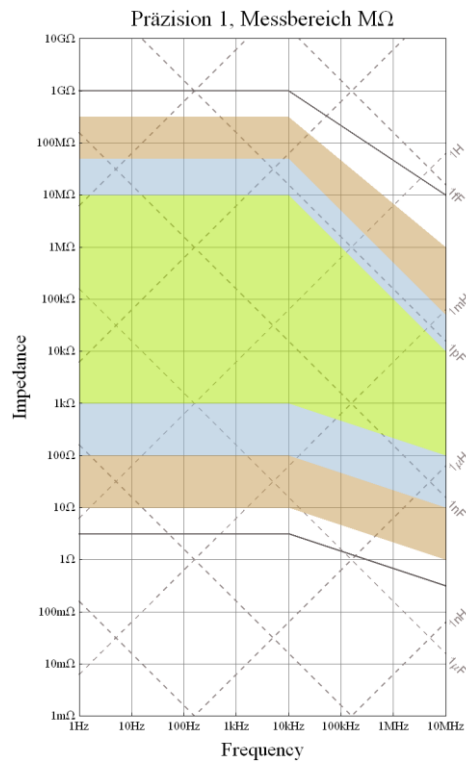
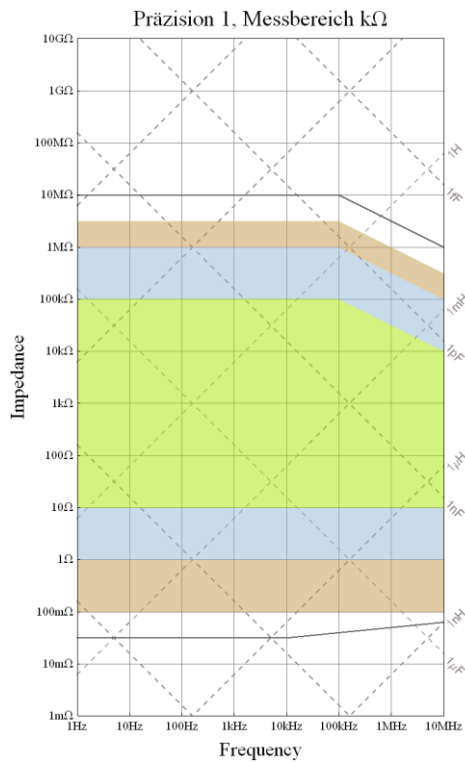
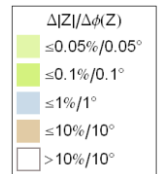
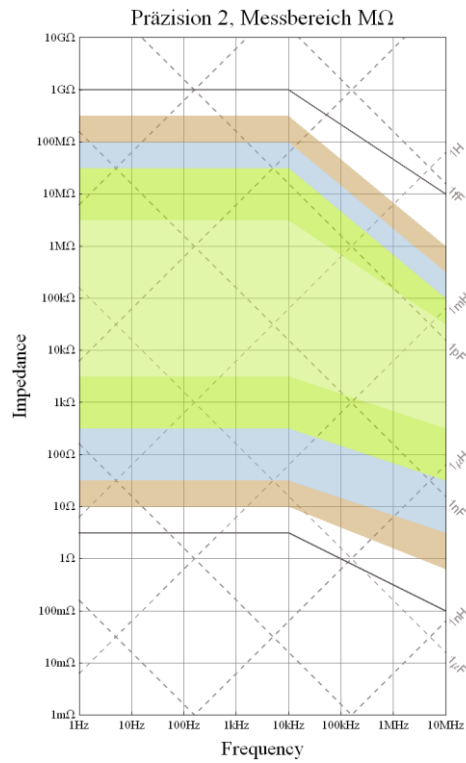
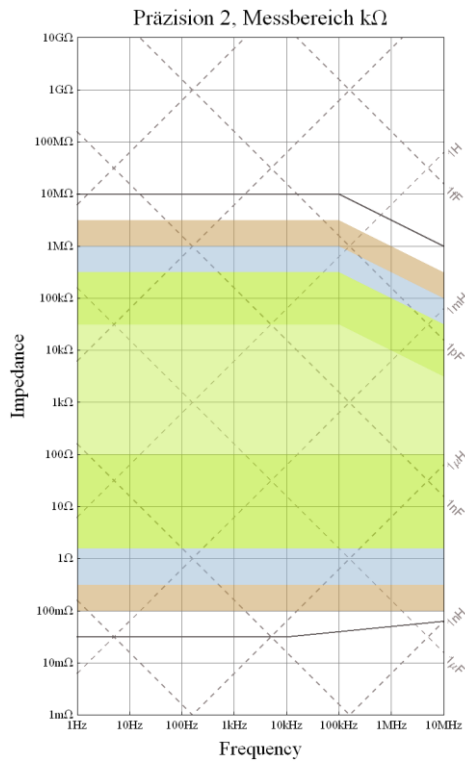


Fig 5: Measurement Time over Precision Parameter

Overview of the different range and precision settings



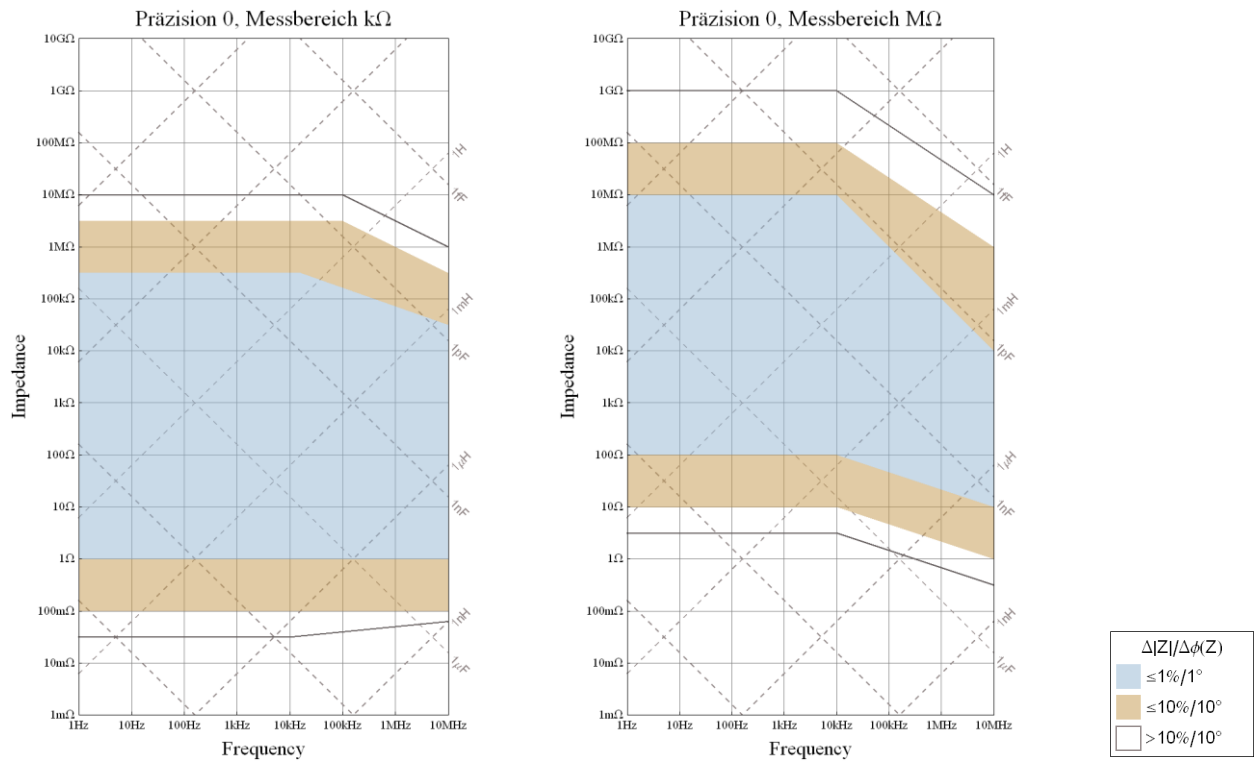


Fig 6: Precision-Range Plot

Note

The accuracy contour plot was determined under lab conditions and should be used for reference purposes. Please note that the true limits of an impedance measurement are influenced by all components in the system, like cables, cell, and the instrument.

3. Installation

■ **System requirements:**

- Java Runtime Environment 7 (jre7) 32bit⁴ or more recent
- Windows XP® or more recent

COMMENT



Attach all required extension modules to the ISX-3v2 High Frequency before you connect the power cable

■ **Installation**

- Extract ZIP archive “Sciospec_ISX3v2.zip” to a folder on your PC
- Run Install.bat

■ **Start the Software**

- Click on „Start.bat“

COMMENT



Run the Installation before connecting your ISX-3v2 High Frequency to the PC!

⁴ 32bit Java runtime environment is required even the operating system is running in 64bit mode.

4. Measurement Software description

4.1. Setting up a connection to the device

After the software has started, one can choose the type of connection USB or Ethernet.

By clicking on [USB] all by USB connected devices are shown in the connection window. Select the desired device and press [connect]. In case no device is listed, try to replug the USB cable and restart the software again.

To connect to an ISX-3v2 High Frequency device via Ethernet click the [Eth] button, enter the desired IP address and push [OK]. If the socket connection is successfully established the device ID will be shown in the devices list of the connection dialog. Afterwards the software can be used in the same way as using the USB connection.

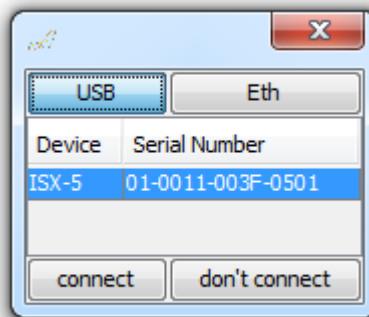


Fig 7: ISX-3v2 High Frequency software connection dialog

The option [not connect] gives you the opportunity to load and visualize the data without the need of a connected Sciospec ISX-3v2 High Frequency.

The main window opens by default in the “Simple Mode”, to switch to the “Advanced Configuration” see chapter 4.3.

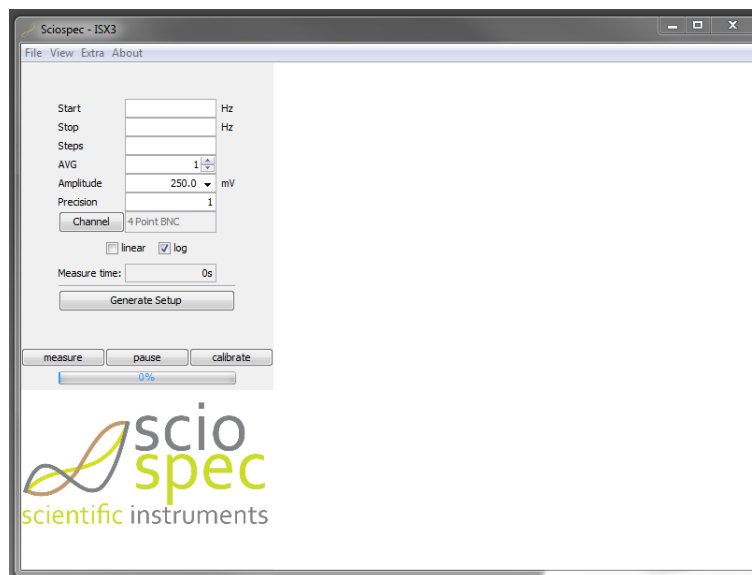


Fig 8: Main Window

4.2. Simple Mode

The main window opens by default the “Simple Mode” view, this mode is designed for an easy and fast setup of the instrument. The measured data will be visualized in a plotter. The data cannot be stored or analyzed; this is only available in the “Advanced Mode”.

Enter the following parameters to start the measurement

- Start frequency in Hz (for example 500k for 500kHz is possible)
- Stop frequency in Hz
- Number of frequency steps
- Number of averages taken
- Amplitude of the excitation signal in mV
- Setup of the desired [Precision] (≥ 0):
 - 1 → Standard configuration (max relative Deviation < 0.1%)
 - < 1 faster measurement but less precise
 - > 1 more precise but slower measurements
- Setting of the measurement channels
- Setting of the type of frequency distribution over the given interval

Once all parameters are set this has to be completed by selecting [generate setup]. The estimated measurement time per spectrum is displayed. By selecting [measure] the measurement starts. The measured spectra are displayed and continuously updated. By pressing [measure] again the acquisition of the data stops.

4.3. Advanced Mode

In advanced mode the user has far more options for configuring a measurement, displaying, editing and saving of measured impedance spectra.

This mode can be selected by choosing [advanced] under [View] in the upper software dialog.

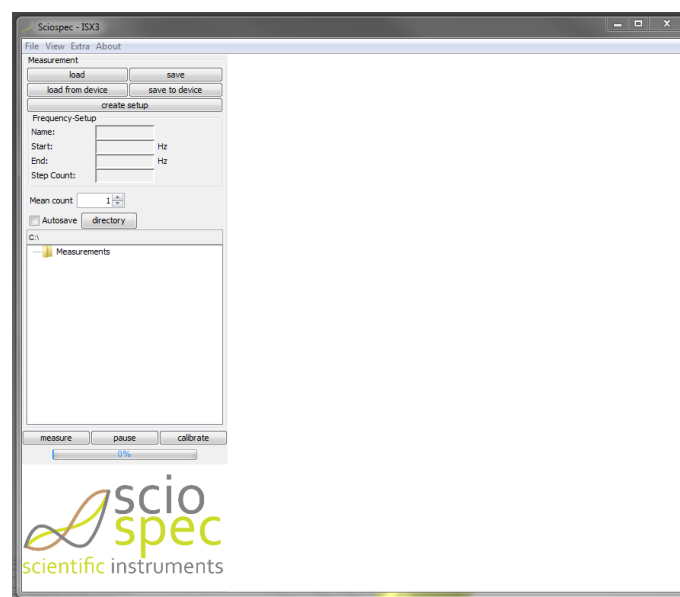


Fig 9: Advanced Mode

4.3.1. Configuring a measurement setup in the Advanced Mode

By choosing [\[create setup\]](#) a new configuration of the system can be created. The selection of the frequency list can be configured block wise, which enables a very freely distribution of the selected frequency points. First organize the complete setup by selection of the frequency range, measurement range, amplitude of the excitation signal and number of repeats.

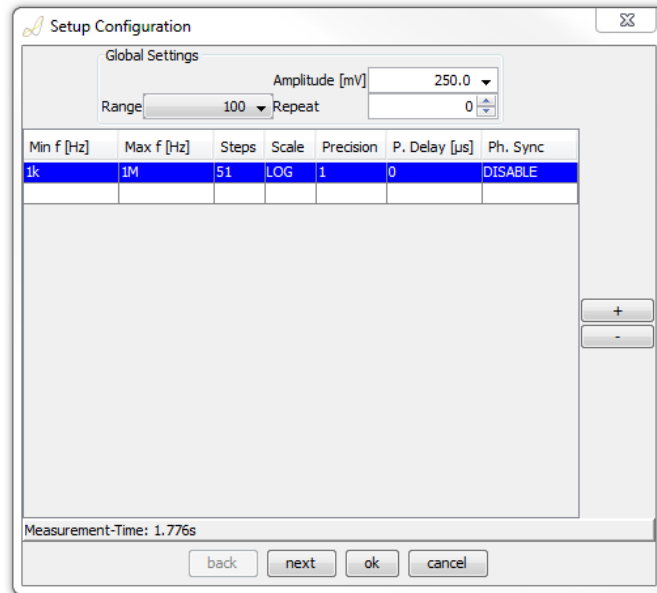


Fig 10: SetUp Configuration Dialog

- Amplitude:
 - Amplitude of the excitation signal in mV (peak amplitude = half of peak-peak value)
- Measurement Range:
 - 100OHM for impedance values up to 1k Ω
 - 10kOHM for impedance values up to 100k Ω
 - 1MOHM for impedance values greater than 100k Ω

The following settings have to be made for each frequency block. It is possible to combine as many frequency blocks as needed. The total number of frequency points is limited to 2048. Duplicated frequencies are eliminated automatically.

- Choosing the minimal [Min f], maximal [Max f] frequency and the number of points in between [Steps]
- Selection of the type of scale [Scale] (logarithmic or linear distribution)
- Setting of the precision value [Precision] (≥ 0):
 - 1 → Standard configuration (max relative Deviation < 0.1%)
 - < 1 faster measurement but less precise
 - > 1 more precise but slower measurements
- Setting the point delay in μs . (Time between two consecutive frequency measurements)
 - Minimum $0\mu\text{s}$
 - Maximum $180\text{E}6\ \mu\text{s}$ (= 3 min)
- Configuring the Phase Synchronization
 - Disabled: Standard
 - Enabled: Use for resonant sensors only

Switch to the channel selection panel by clicking on [next]

- Select the terminal configuration
 - 2 Point configuration: One only needs to connect the device under test to the Counter and Work Port. (Please disconnect Reference and Working Sense Ports)
 - 4 Point configuration: Connect the device under test to all four ports of the instrument
- Select the measurement channel (ExtensionPort Modules have a specific setup dialog)
 - BNC – Standard Configuration

Confirm the parameters by pressing [Ok]

4.3.2. Running a measurement in the „Advanced Mode“

- Choose [\[measure\]](#) to start the measurement
- Options of visualization of the data:
 - In a PlotterGrid with the currently measured data, by right click on the desired setup and choosing “add new PlotterGrid” from the drop down menu.
 - In a static plotter (with absolute value and phase) by double clicking on the measured dataset in the data tree
 - In a static plotter (with absolute value) by dragging a dataset into the display area
 - In a static plotter (with phase) by dragging a dataset into the display area while pressing the control key.
 - In a user defined PlotterGrid, see Chapter 4.7
- To stop the measurement press [\[measure\]](#) again
- Additionally a user defined averaging can be selected in the field [\[mean count\]](#).
- The measurement can be paused any time by clicking on [\[pause\]](#). To start again click on [\[pause\]](#) once more.
- It is possible to start multiple setups at once. Select them by holding the control key while clicking on each one. Once the measurement has been started each setup will run one after another. A selection of a repeat count of 0 in one of the setups will result in never reaching the next setup, therefore this is not possible. Select a number of 1 or higher for repeat.

4.3.3. “Autosave” feature

The [\[Autosave\]](#) Option allows to automatically saving the measured data to a previously selected folder.

- Select the path of the folder by clicking on [\[directory\]](#). (By default is the folder “Data” in the Sciospec ISX-3v2 folder selected)
- Once a measurement is started a subfolder with the name of the setup configuration will be created and all data will be saved there. The data will not be displayed in the data tree to reduce the amount of memory needed by the software.
- The saved data can be displayed by loading them into the software.
- It is also possible to display the current data by creating a PlotterGrid as described above.
- The major advantage of this feature is that the required program memory will not increase significantly over the runtime of the experiment and all measured data is stored to the hard drive. A fault condition will not compromise the already measured spectra. In case the “Autosave” feature is not active the measured data will only be held in the program memory.

COMMENT



It is highly recommended to use the “Autosave” feature when performing long experiments.

4.3.4. Performing a calibration routine for a setup

To compensate for parasitic impedance effects induced by the cabling it is possible to calibrate the system with an easy open-short-load compensation. The calibration procedure has to be done for each setup used, but can be stored with the setup to the device and reloaded for later use.

The calibration requires arranging three different cabling connections. For all following configurations Counter and Reference-Terminals have to be shorted and Working Sense and Work-

Terminals have to be shorted separately. Use the same cables as in the actual device und test measurement.

“short” both terminal groups (CR and WSW) have to be shorted

“open” both groups must not be connected

“load” connect a well known resistor or capacitor to both groups.

The calibration routine can be started in the software by selecting the setup configuration and click on calibrate. The software then prompts to set the open arrangement as described above (see Fig 11). Followed by short and load arrangement.

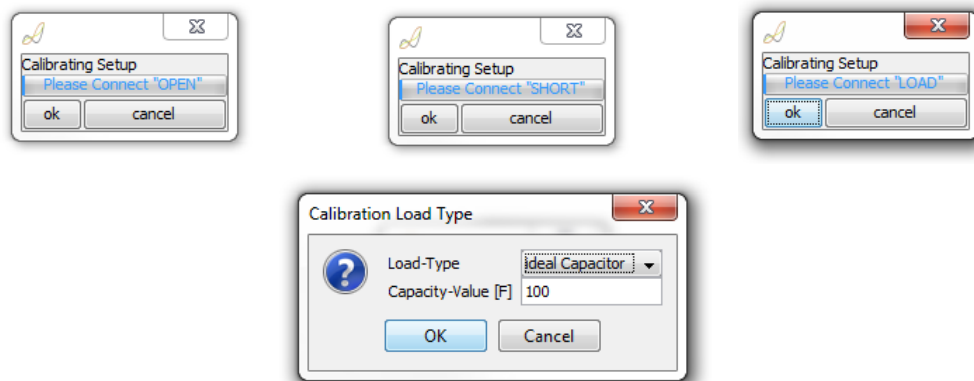


Fig 11: Calibration Dialog

Choose a load device in the impedance range of your device under test. It is possible to use an ideal resistor or a capacitor as a standard load device.

4.4. Kinetic-Mode

The Kinetic-Mode is an easy-to-use tool to track the impedance measured at a multiple frequencies points over a period of time. It can be configured for one or for multiple channels.

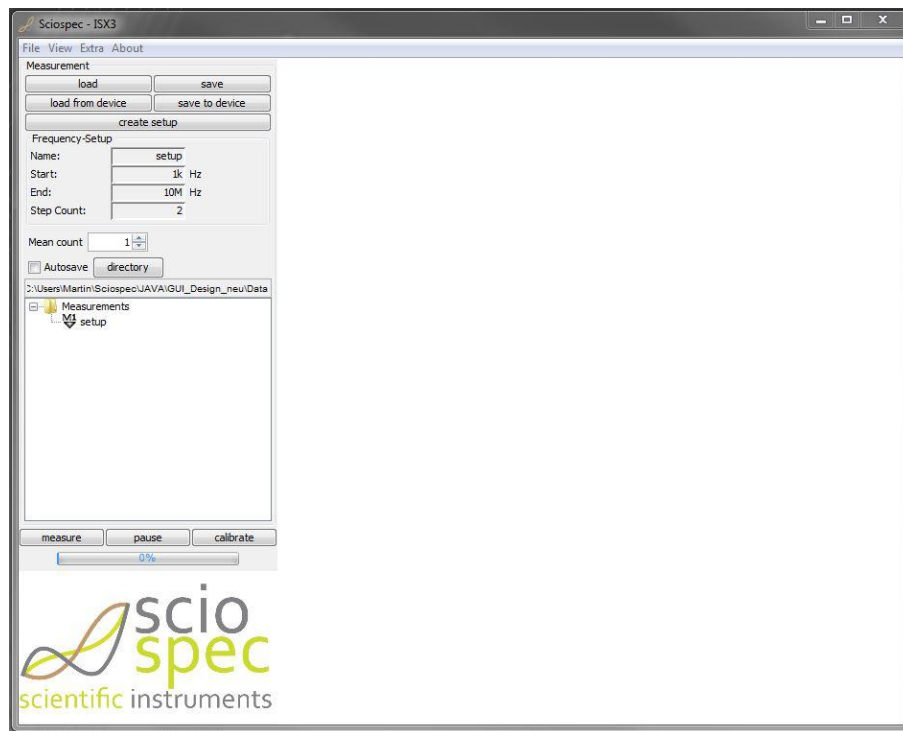


Fig 12: Kinetic Mode Main Window

The Kinetic Mode can be configured just like a normal measurement in advanced mode. Press “create setup” and configure a setup as described in chapter 4.3.1.

COMMENT



The total number of different frequencies in the setup is limited to 16 in the Kinetic Mode.

To start a measurement in the kinetic mode press measure.

4.5. Handling setups and spectra

Setup and spectrum datasets can be renamed by pressing F2.

4.5.1. Spectra

- Saving spectra
 - Select the datasets you want to save
 - Press [save]
 - The files will be stored in the selected directory including a number and with the file extension “spec” (see Chapter 4.5.2)

- Loading spectra
 - Press [\[load\]](#)
 - Select the datasets you want to load and confirm by pressing [\[Open\]](#)
 - You can also “Drag and Drop” the data files into the software
- The [\[Autosave\]](#) option allows for automatic saving of files to the hard drive (see chapter 4.3.2).
- By selecting [\[show Info\]](#) from the right click drop down menu from a dataset additional information can be stored with a dataset.

4.5.2. File description „.spec“











Basically the files can be interpreted as a plain text comma separated (csv) file with a header and a main part.

Row	Content
1	Number of header rows N (including this one)
2	Name of file
3 to N-3	Comment
N-2	Channel
N-1	Time of the measurement
N	Column labels
N+ to End	Data according to the column labels


4.5.3. Setups

- Saving setup configurations
 - Right click a setup or press on [\[save\]](#) after a setup is selected.
 - You can automatically save all data obtained with this setup by selecting “include sub data”
 - The file extension is „setUp“.
- Loading setup configurations
 - Press [\[load\]](#)
 - Select the file extension „setUp“ from the file filter drop down menu
 - Select the setup file you want to load and confirm by pressing [\[Open\]](#)
 - Or „Drag and Drop“ a setup file into the software

4.6. Plotter functions

Middle mouse button or 	Auto zoom
Mouse wheel or  / 	Zoom
Left mouse button or  and drag	Zoom of select rectangle
Right mouse button or 	Selection of axes types (linear, x-Log ,y-Log ,double log)
Right mouse button and drag	Moving the displayed area
	Copy of the current zoom setting
	Paste of zoom setting
	Saving the displayed data to a “.csv”
	Creating a new marker
	Taking a snapshot as a „png“ file
Holding [shift] while opening data	Only the absolute value will be displayed
Holding [ctrl] while opening data	Only the phase value will be displayed
Dragging a dataset into an active Plotter while holding [shift]	The absolute value will be added to the plotter
Dragging a dataset into an active Plotter while holding [ctrl]	The phase value will be added to the plotter
Double click on the plotter	Full screen mode (Escape to exit full screen)

Graphs menu

	Table of the data values
Double click on the data	Selection of color
Right click on the data	Disabling or enabling the visualization of the data
	Hiding the graphs menu

4.7. The PlotterGrid

The PlotterGrid gives more options for displaying of measured data.

4.7.1. Setting up a PlotterGrid

- Right click in the white empty area of the software
- Select [new PlotterGrid] or [default PlotterGrid]

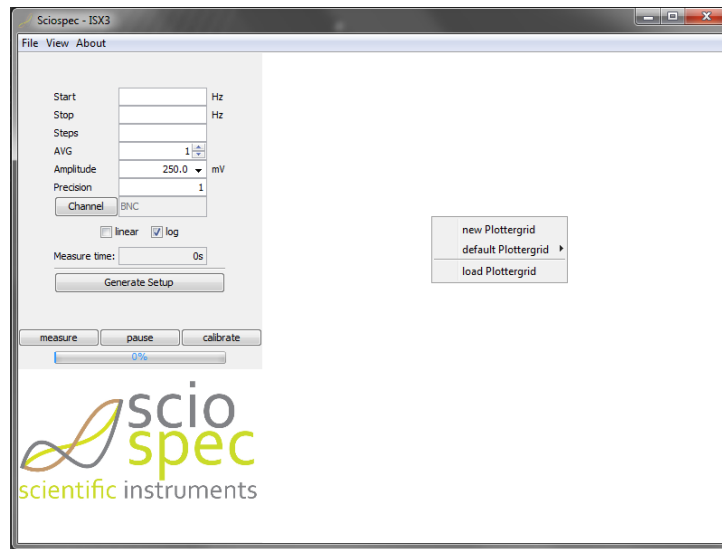


Fig 13: Setting up a PlotterGrid

- State the number and the arrangement of the desired Plotters (maximal 8 rows and 8 columns)
 - for example: row 1 → 2 columns, row 2 → 1 columns

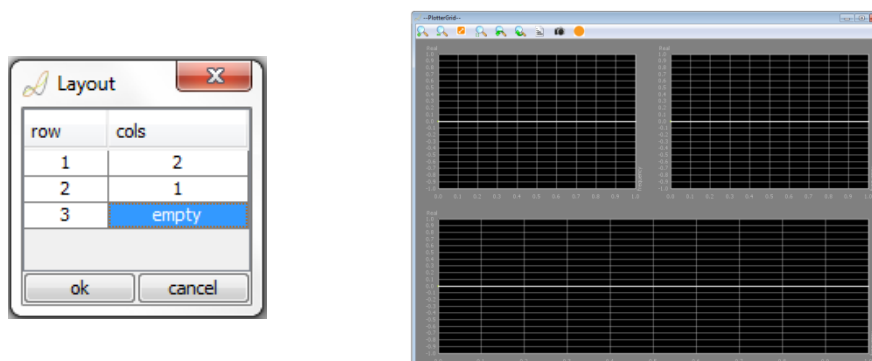


Fig 14: PlotterGrid layout

Every created part can now be filled with data. Configure each one by right clicking it and selecting [\[configure\]](#). The following dialog appears.

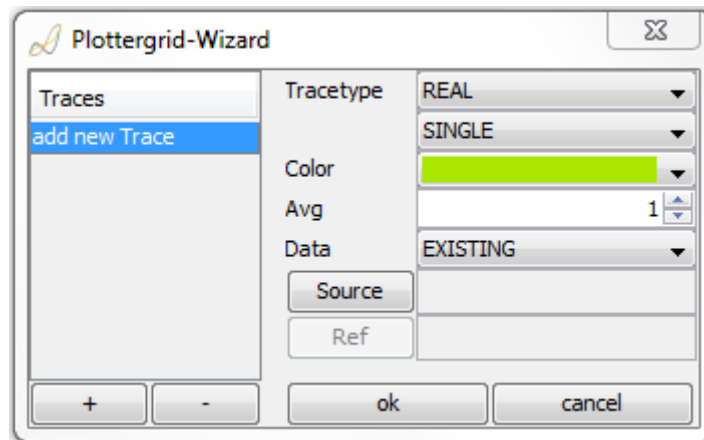


Fig 15: PlotterGrid Wizard

Trace type Type of the data to be visualized. Real part, imaginary part, absolute value or phase over frequency can be selected. Additionally a Nyquist plot (negative imaginary over real part) is possible.

„Single“, „Difference“ and „Relative Difference“ gives you the ability to track changes in the impedance. A reference spectrum has to be selected.

Color Color of the plotted points

Avg Number of Points used for a moving average.


Data Selection of existing or currently measured data to be displayed

Source Select the data to be visualized. For existing data select the datasets from the data tree. For currently measured data select the channel of interest.

Ref Select the reference spectrum for the “Difference” and “Relative Difference” modes.

4.8. Saving and loading of a PlotterGrid

It is possible to save a PlotterGrid to a file and load it again later.

- To save press the button  in the active PlotterGrid. State the save path of the file. The file extension is “.grid”
- To load a PlotterGrid right click into the empty display area a select [\[load PlotterGrid\]](#) from the drop down menu

5. „Sync In“ & „Sync Out“

For synchronization with other customer hardware the Sciospec ISX-3v2 High Frequency is equipped with two “Sync Out” and two “Sync In” ports located at the back of the instrument. Use standard SMA cables to connect your hardware. Each port is equipped with an open drain buffer to allow different logic voltage levels.



The outputs are equipped with a 1kOhm pull up resistor to 3V. If you require different voltage levels please contact Sciospec directly for support.

The “Sync Out I” port gives information about the current state of the measurement.

- Logic high → Measurement is running
- Logic low → Measurement is paused between two measurement sweeps. This time can be configured by setting the sync time ([File]→[set SyncTime]) in the range 0s to 200s in 1μs steps. Default is 0 seconds.
- The setting 0 seconds results in no change of the signal between two measurements
- If an average count higher than 1 is configured there will be a change in between one measured spectrum.

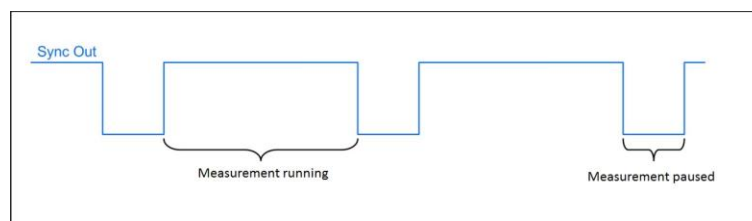


Fig 16: : Sync Out Signal

- The “Sync In” port allows to control the measurement process
 - By default the signal is logic high, which allows for a continuous measurement.
 - By connecting this port to ground (logic low) the next measurement will be paused until the signal is released again.
 - An already running sweep will not be interrupted by the “Sync In 1” signal.
 - Do not apply any voltage source directly to the synchronization ports.
- The ports “Sync In II” and “Sync Out II” are not used by default. Please contact Sciospec directly for further assistance when requiring different types of synchronization.

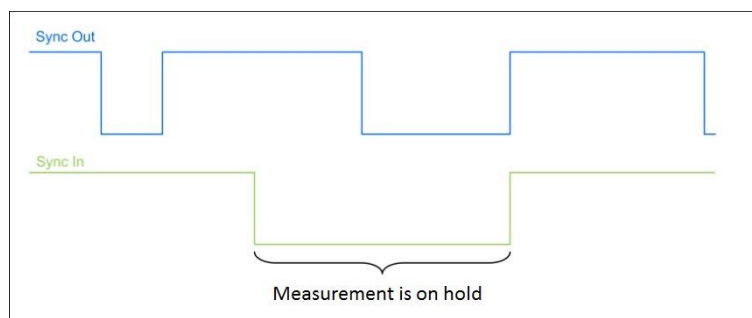


Fig 17: Sync In Signal

6. Sciospec Communication Interface

The Sciospec Communication Interface enables the user to access all functions of the device by using any of the available system interfaces (USB, Ethernet or other). The actual command structure is identical in all connection types. For use of the impedance measurement module within a ISX-5/MSX-8 platform system refer to the respective system manual for guidance on specific communication within those systems⁵.

6.1. Establishing the connection

6.1.1. USB Interface

The device identifies itself to the USB-host (e.g. PC) by a unique combination of VID (Vendor-ID) and PID (Product-ID):

VID	0x0403
PID	0x89D0

The communication-interface to the driver is provided by the FT2xx.dll. The complete specification of the functionality can be found in the “D2XX Programmers Guide”(<http://www.ftdichip.com>).

After the connection is established the mode of communication must be set to “245-FIFO-Mode” before data can be transferred to the device. This can be done with the “FT_SetBitMode”-function.

C-Code-example for establishing a connection

```
FT_STATUS ftStatus;

FT_DEVICE_LIST_INFO_NODE* devInfo;

DWORD numDevs; // create the device information list

ftStatus = FT_CreateDeviceInfoList(&numDevs); // allocate storage for list based on numDevs

devInfo = (FT_DEVICE_LIST_INFO_NODE*)malloc(sizeof(FT_DEVICE_LIST_INFO_NODE)*numDevs); // get the device information list

ftStatus = FT_GetDeviceInfoList(devInfo,&numDevs);

FT_HANDLE handle;

int i;

for (i = 0; i < numDevs; i++) {

    if((devInfo[i].ID & 0xFFFF) == 0x89D0){

        ftStatus = FT_Open(i, &handle);

    }

}
```

⁵ Commands and functionality are the same as described here, but additional framing and setup commands will be required due to the multi slot system structure within ISX-5/MSX-8.

```

ftStatus = FT_SetBitMode(handle, 0x00, 0x40);

break;

}

}

```

6.1.2. Ethernet Interface

The ISX-3v2 High Frequency uses a directional socket communication in which it implements the socket server and the connected PC the socket client. The ISX- 3v2 High Frequency supports DHCP to receive an IP address from a DHCP server. This is the default setting. The DHCP support can be deactivated using the Ethernet configuration dialog in the software (Extras→Ethernet) or by the “set Ethernet configuration” command. In this case a static IP address should be set using the same command.

6.2. Syntax

The general structure of each communication between the Sciospec ISX-3v2 High Frequency and a PC:

- The communication is done by frames
- Each communication frame is constructed as follows
 - 1 Byte command-Tag (Frame-Start)
 - 1 Byte number of data-bytes (0...255)
 - 0...255 data-bytes
 - 1 Byte Command-Tag (Frame-End)
- The command-tag identifies the command (see Command list)
- Frame-Start and -End must be identical

Example: "System-Ready-Message"

CMD-Tag	Number of Bytes	Data	CMD-Tag
0x18	0x01	0x84	0x18

6.3. Wake up & acknowledge messages

Special Messages from the Sciospec ISX-3v2 High Frequency to the user:

- At the start of the boot-process the device sends the “Wake-Up” message
- After the System is operational and ready to receive the “System-Ready” message is send
- Communication-frames with incorrect syntax will cause a “Frame-Not-Acknowledge” message
- If the transmission of a communication-frame is interrupted for more than 10 ms a “Timeout” message is send
- Every invalid command-tag will cause a “Not-Acknowledge” message
- Every valid command (valid command-tags: see 6.5) is acknowledged with an acknowledge command [ACK]

- For commands with a return value the returning frame comes before the acknowledge message
 - When commands are sent during the current measurements, measurement data can be transmitted between the command and the following returning frame and the acknowledge-message (commands are handled asynchronously)
 - Before sending a new command, the resulting acknowledge or not acknowledge is to be seen.
- Note: When starting the measuring process, first comes the ACK and then starts sending the data ("stream").

The ACK-Frame:



Possible values for [ACK] and their meaning	
0x01	Frame-Not-Acknowledge: Incorrect syntax
0x02	Timeout: Communication-timeout (less data than expected)
0x04	Wake-Up Message: System boot ready
0x81	Not-Acknowledge: Command has not been executed
0x82	Not-Acknowledge: Command could not be recognized
0x83	Command-Acknowledge: Command has been executed successfully
0x84	System-Ready Message: System is operational and ready to receive data

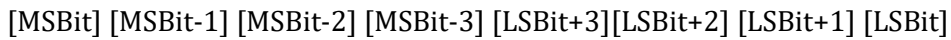
6.4. Data formats

All data sent to the device or sent from the device is either "Integer-Straight-Binary" or 32 Bit Float coded (according to IEEE 745). Either way the data is in Big-Endian format.

Big-Endian means that if a value consists of more than one byte the byte order is according to their value:

- Example 4 Byte Big-Endian Value: [MSByte] [MSByte-1] [LSByte-1] [LSByte]

The bit order also MSBit-first:



Float data format



The float value is calculated as follows:

$$float = (-1)^S * (1 + M * 2^{-23}) * 2^{E-127}$$

6.5. Command list

Command	Name
0x90	save Settings
0x97	set Options
0x98	get Options
0x99	set IO Port configuration
0x9A	get IO Port configuration
0x9B	set NTC parameters 1
0x9D	set NTC parameters 2
0x9C	get NTC parameters 1
0x9E	get NTC parameters 2
0xA1	software reset
0xB0	set channel settings
0xB1	get channel settings
0xB6	set setup configuration
0xB7	get setup configuration
0xB8	start/stop measurement
0xB9	set synchronization time
0xBA	get synchronization time
0xBD	set Ethernet configuration
0xBE	get Ethernet configuration
0xD1	get device information

6.6. Command description

6.6.1. General command description


Code	Command	Description
0x90	save Settings	<p>90 00 90</p> <p>Saves the following parameters permanently into the flash memory of the ISX-3v2 High Frequency:</p> <ul style="list-style-type: none">• NTC Parameters 1 and 2• Parameter stack synchronization time <p>This command can only be used if no measurement is currently running.</p> <p>Return ACK</p>
0x97	set Option	<p>97 DC OP DD 97</p> <p>Configuration of the Instrument.</p> <p>OP Option Byte:</p> <p>0x01 Activate time stamp of measured data</p> <p>DD Data, depending on the option byte</p> <p>OP = 0x01 → DC = 0x02</p> <p>0x01 Enable Time Stamp 0x00 Disable Time Stamp</p> <p><i>Depending on this setting the return frame of the measured data changes (see command 0xB8)</i></p> <p>Remarks: It is not possible to change this setting while a measurement is running. This setting cannot be saved persistently.</p> <p>Return ACK</p>


Code	Command	Description
0x98	get Options	<p>98 01 OP 98</p> <p>Returns the currently configured options of the instruments.</p> <p>OP Option Byte:</p> <p>0x01 Time Stamp</p> <p>Return 98 02 OP DD 98 ACK</p> <p>DD...Currently configured option depending on option byte</p>
0x99	set IO Port configuration	<p>99 02 OP DD 99</p> <p>Configuration of the IO Port.</p> <p>OP Option Byte:</p> <p>0x01 Port configuration: selected GPIOs can be configured as input or output 0x02 Port state: if a port is selected as an output, it can be set to high or low</p> <p>DD Data, depending on the option byte</p> <p>OP = 0x01 Port configuration is coded bitwise; 1=output, 0=input Ex: 0x15 (00010101) pins IO1,IO3 and IO5 are outputs</p> <p>OP = 0x02 Port state is coded bitwise: 1=high, 0=low Ex: 0x11 (00010001) Pins IO1 and IO5 are high, Pin IO3 is low</p> <p>Return ACK</p>
0x9A	get IO Port configuration	<p>9A 01 OP 9A</p> <p>Returns the current values of the IO Port</p> <p>OP Option Byte:</p> <p>0x01 Port configuration: current selection of the GPIOs 0x02 Port state: current state of the input and output pins</p> <p>Return 9A 02 OP DD 9A ACK</p> <p>DD...Current configuration depending on option byte</p>

Code	Command	Description
0x9B	set NTC Parameter 1	<p>9B 05 OP DD DD DD DD 9B see chapter 7.1</p> <p>OP Option Byte:</p> <p>0x01: beta parameter [K] 0x02: nominal resistance at T_N [Ω] 0x03: operating temperature T_N [K]</p> <p>DD Data: 32Bit Float value</p> <p>Return ACK</p>
0x9D	set NTC Parameter 2	<p>9D 05 OP DD DD DD DD 9D see chapter 7.1</p> <p>OP Option Byte:</p> <p>0x01: beta parameter [K] 0x02: nominal resistance at T_N [Ω] 0x03: operating temperature T_N [K]</p> <p>DD Data: 32Bit Float value</p> <p>Return ACK</p>
0x9C	get NTC Parameter 1	<p>Returns the currently configured NTC-parameters 1</p> <p>9C 01 OP 9C</p> <p>OP Option Byte:</p> <p>0x01: beta parameter [K] 0x02: nominal resistance at T_N [Ω] 0x03: operating temperature T_N [K] 0x04: current temperature [°C]</p> <p>Return 9C 05 OP DD DD DD DD 9C ACK</p> <p>DD...4 byte float value according to selected option byte.</p>

Code	Command	Description
0x9E	get NTC Parameter 2	<p>Returns the currently configured NTC-parameters 1</p> <p>9E 01 OP 9E</p> <p>OP Option Byte:</p> <p>0x01: beta parameter [K] 0x02: nominal resistance at T_N [Ω] 0x03: operating temperature T_N [K] 0x04: current temperature [°C]</p> <p>Return 9E 05 OP DD DD DD DD 9E ACK</p> <p>DD...4 byte float value according to selected option byte.</p>
0xA1	reset system	<p>A1 00 A1 complete restart of the system</p> <p>Return ACK Wake-Up Message System-Ready-Message</p>
0xB0	set FE settings	<p>Frontend configuration</p> <p>B0 03 PP CH RA B0</p> <p>PP: Measurement mode 0x01: 2 point configuration 0x02: 4 point configuration</p> <p>CH: Measurement channel 0x01: BNC Port</p> <p>RA: Range Settings 0x01: 100Ohm 0x02: 10kOhm</p> <p>Return ACK</p>

Code	Command	Description
0xB1	get FE settings	<p>B1 00 B1</p> <p>Returns the currently selected frontend configuration</p> <p>Return:</p> <p>B1 03 PP CH RA B1</p> <p>ACK</p> <p>PP: Measurement mode 0x01: 1 point configuration 0x02: 4 point configuration</p> <p>CH: Measurement channel 0x01: BNC Port</p> <p>RA: Range Settings 0x01: 100Ohm 0x02: 10kOhm</p>
0xB6	set setup	<p>B6 DC OP DD B6</p> <p>DC data count (depending on the selected option byte)</p> <p>OP Option Byte</p> <p>DD Data (depends on the selected option byte)</p> <p>For further details see chapter 6.6.2.</p> <p>Return</p> <p>ACK</p>
0xB7	get setup	<p>B7 DC OP DD DD B7</p> <p>Reads the currently configured setup configuration.</p> <p>DC data count (depending on the selected option byte)</p> <p>OP Option Byte</p> <p>For further details see chapter 6.6.2.</p> <p>Return</p> <p>ACK</p>

Code	Command	Description
0xB8	start measure	<p>Starts the measurement. B8 DC OP DD B8</p> <p>DC data count (depending on option byte)</p> <p>OP Option Byte 0x00 Stop -> DC = 0x01 (1) 0x01 Start -> DC = 0x03 (3)</p> <p>DD option specific data 0x00 Stop -> no data to be send 0x01 Start -> number of spectra to be measured (2 byte Integer value) The setting 0 starts a continuous measurement. Send the command (B8 01 00 B8) to stop the continuous run.</p> <p> <i>Info: If the measurement has been started with a repeat greater than 0 no stop command is required. The data will be transmitted as soon as each frequency point has been measured. The system therefore does not wait for the spectrum to be completed before it will send the data.</i></p> <p>Return</p> <p>If time stamp is disabled (see command 0x97 and 0x98) B8 0A ID ID RE RE RE RE IM IM IM IM B8 ACK</p> <p>Else B8 0E ID ID TT TT TT TT RE RE RE RE IM IM IM IM B8 ACK</p> <p>ID→ id number of the frequency point (2 byte integer) TT→ time stamp of the frequency point in ms (4 byte integer) RE→ real part of impedance (4 byte float) IM→ imaginary part of impedance (4 byte float)</p>

Code	Command	Description
0xB9	set sync time	<p>Set the synchronization time in μs. (Time between the measurement of two spectra)</p> <p>B9 04 DD DD DD DD B9 DD...Synchronization time in μs (4 byte integer value)</p> <p>Default: 0s \rightarrow 0μs Min: 0s \rightarrow 0μs Max: 180s \rightarrow 180E6μs (0x0ABA9500) = 180s</p> <p> <i>Info: This is also the time the SyncOut signal is in its low state between two measurements.</i></p> <p><i>Use save settings command (0x90) to save this parameter persistent.</i></p> <p>Return ACK</p>
0xBA	get sync time	<p>Reads the currently configured synchronization time.</p> <p>BA 00 BA</p> <p>Return BA 04 DD DD DD DD BA ACK</p> <p>DD...Synchronization time in μs (4 byte integer value)</p>
0xBD	set Ethernet configuration	<p>BD DC OP DD ... DD BD</p> <p>DC – Data Count</p> <p>OP – Option Byte</p> <p>0x01 set IP address 0x03 set DHCP status (requires system reboot, when changed)</p> <p>DD – Command Data (length and content depends on OP)</p> <p>OP 1 IP address; 4 byte IPv4 value OP 3 DHCP status; 1 byte (0x00 = disabled; 0x01 = enabled)</p> <p>These settings need to be stored with “Save Settings” command.</p> <p>Return ACK</p>

Code	Command	Description
0xBE	get Ethernet configuration	<p>BE 01 OP BE</p> <p>OP Option Byte</p> <p>0x01 get IP Address 0x02 get MAC Address 0x03 get DHCP status</p> <p>Return BE DC OP DD BE ACK</p> <p>OP Option Byte</p> <p>0x01: DC=0x05; DD...IP address 0x02: DC=0x07; DD...MAC address 0x03: DC=0x02; DD=0x00 Disabled, DD=0x01 Enabled DHCP</p>
0xD1	get device info	<p>D1 00 D1</p> <p>Reads the device specific data.</p> <p>Return D1 DC XX XX ... XX D1 ACK</p> <p>DC...number of bytes of the serial number (depends on the device configuration) XX...Serial number of the device (including firmware revisions)</p>

6.6.2. Set setup 0xB6 command description

B6 DC OP DD B6

DC data count (depending on the selected option byte)

OP Option Byte

DD Data (depends on the selected option byte)

Detailed description of the data to be send with a set setup frame (0xB6) for each option byte

Initialization and configuration of setups

Option 0x01: Init

This option resets the currently configured setup and an empty setup is initialized.

DC = 1 (No further data is needed)

Example: B6 01 01 B6

Option 0x02: Add single frequency point

This command is used to add a single frequency point to the currently configured setup.

DC = 13 (frequency, precision, amplitude)

frequency			precision			amplitude		
MSB	...	LSB	MSB	...	LSB	MSB	...	LSB

In this case the point delay (= 0 ms) and phase sync is not used.

DC = 21 (frequency, precision, amplitude, point delay, use phase sync)

frequency			precision			amplitude			point delay			use phase sync		
MSB	...	LSB	MSB	...	LSB	MSB	...	LSB	MSB	...	LSB	MSB	...	LSB

Frequency: frequency in Hz (4Byte float)

Precision: precision value (4Byte float)

Amplitude: amplitude in V (peek value, 4Byte float)

Point delay: delay between this frequency and the next frequency in μ s (4Byte unsigned integer)

Use phase sync: phase synchronous switch between this and the next frequency

→ Use: 0x00000001

Don't use: 0x00000000

Example: B6 0D 02 46 FA 00 00 3F 80 00 00 3E 80 00 00 B6

Frequency = 32 kHz

precision = 1.0

amplitude = 0.25 V

Option 0x03: Add frequency list

This command is used to add multiple frequencies to the currently configured setup.

DC = 22 + extended options (start-frequency, stop-frequency, count, scale, precision, amplitude)

start-frequency			stop-frequency			count			scale	precision			amplitude		
MSB	...	LSB	MSB	...	LSB	MSB	...	LSB	MSB	MSB	...	LSB	MSB	...	LSB

In this case the point delay (= 0 ms) and phase sync is not used.

start-frequency			stop-frequency			count			scale	precision			amplitude			EOP	point delay			EOP	use phase sync		
MSB	...	LSB	MSB	...	LSB	MSB	...	LSB	MSB	MSB	...	LSB	MSB	...	LSB	1	MSB	...	LSB	2	MSB	...	LSB
															optional			optional					

Start-Frequency: start-frequency of the frequency block in Hz (4Byte float)

Stop-Frequency: stop-frequency of the frequency block in Hz (4Byte float)

Count: number of frequency steps used (4Byte float, rounded to the next smaller integer)

Scale: linear or logarithmic scale (1Byte integer)

→ linear: 0

→ logarithmic: 1

Precision: precision value (4Byte float)

Amplitude: amplitude in V (peek value, 4Byte float)

Point delay: delay between this frequency and the next frequency in μ s (4Byte unsigned integer)

Use phase sync: phase synchronous switch between this and the next frequency

→Use: 0x00000001

→don't use: 0x00000000

Example: B6 20 03 44 7A 00 00 4B 18 96 80 41 20 00 00 01 3F 80 00 00 3D CC CC
CD 01 00 00 03 E8 02 00 00 00 00 B6

start frequency = 1 kHz

stop frequency = 1 MHz

count = 10

scale = logarithmic

precision = 1.0

amplitude = 0.25 V

point delay = 1000 μ s

phase sync = disable

Calibration Commands

A detailed example of the required communication necessary to calibrate a setup can be found in 6.6.4.

Option 0x10 – Start Calibration

This command starts the calibration of the setup.

DC = 1

Example: B6 01 10 B6

Option 0x11 – Calibration Acknowledge

The calibration acknowledge (CACK) is used to answer a “Calibration-Interaction-Request”

DC = 1

Example: B6 01 11 B6

Option 0x12 – Calibration Not-Acknowledge

The calibration acknowledge (CNACK) is used to answer a “Calibration-Interaction-Request”

Example: B6 01 12 B6

Option 0x13 – Calibration-interaction-request Open

This is a message from the ISX-3v2 High Frequency to request an open configuration on the measurement channel. This request must be answered with a CACK to continue the calibration or with a CNACK to abort the calibration.

Option 0x14– Calibration-interaction-request Short

This is a message from the ISX-3v2 High Frequency to request a short configuration on the measurement channel. This request must be answered with a CACK to continue the calibration or with a CNACK to abort the calibration.

Option 0x15 – Calibration-interaction-request Load

This is a message from the ISX-3v2 High Frequency to request a load configuration on the measurement channel. This request must be answered with a CACK to continue the calibration or with a CNACK to abort the calibration.

Before the answer to this request is send the load value and type must be have been send to the device (Option 0x16).

Option 0x16

The connected load value must have been send in the data part (DD) of the command, too:

	Load Type	Value
0x01	resistance	4 Byte float in Ohm
0x02	capacitor	4 Byte float in Farad

Example: B6 06 16 01 44 7A 00 00 B6
resistance = 1000 Ohm

Saving to Slot

Option 0x20

It is possible to load all information required for a measurement from the internal storage of the impedance analyzer. The system holds up to 255 setup configurations including any calibration data. For addressing, the configurations are numerated from slot 1 to slot 255.

DC = 2

Example: B6 02 20 05 B6
load configuration from slot 5

DC Bias

Option 0x30 DC-Bias

This command activates or deactivates the dc-bias on the configured channel. When the dc-bias is activated dc-bias is regulated towards the selected value. This process can be aborted by sending the “DC-Bias-Not-Acknowledge”.

If the dc-bias is reached a “DC-bias-Acknowledge” is send from the ISX-3v2 High Frequency.

If the dc-bias could not reached “DC-Bias-Not-Acknowledge” is send from the ISX-3v2 High Frequency.

DC = 2

DD = 0x01 (activate) || 0x00 (deactivate)

Example: B6 02 30 01 B6

Option 0x32 DC-Bias-Not-Acknowledge

This command is to abort the dc-bias regulation.

Example: B6 01 32 B6

Option 0x33 DC-Bias-Set Value

This command sets the value for the dc-bias.

Example: B6 05 33 3F 80 00 00 B6

Sets the bias value to 1 V

6.6.3. Get setup 0xB7 command description

B7 DC OP DD B7

DC data count (depending on the selected option byte)

OP Option Byte

DD Data (depends on the selected option byte)

Initialization and configuration of setups

Option 0x01: Get total number of frequencies

This command reads the total number of frequencies configured in the setup.

DC = 1

Example: B7 01 01 B7

Return: B7 03 01 DD DD B7

DD .. 2 Byte unsigned integer, number of rows configured

Option 0x02: Get information of frequency point

This command gets information of a configured point of the setup.

DC = 3

DD = row number (2 Byte unsigned integer)

Example: B7 03 02 00 0A B7

Returns information about frequency point 10

Return: B7 13 02 [4 Byte float frequency] [4 Byte float precision] [4 Byte float signal amplitude] B7

Option 0x04: Get frequency list

This command gets a list of frequencies configured in this setup.

DC = 1

Example: B7 01 04 B7

Return: B7 [DC] 04 [4 Byte float frequency₁] [...] [4 Byte float frequency_N] B7

Since one data frame is limited to a total of 255 bytes of data the returning command will be split into multiple separate frames. For example if the setup contains 64 frequency points the first 63 will be transmitted in a

*frame containing 253 bytes (=63*4+1) and in a separate frame containing 5 bytes (=1*4+1) bytes of data.*

Option 0x13 – Calibration-interaction-request Open

This is a message send by the ISX-3v2 High Frequency to request an open configuration on the measurement channel. This request must be answered with a CACK to continue the calibration or with a CNACK to abort the calibration.

Option 0x14– Calibration-interaction-request Short

This is a message send by the ISX-3v2 High Frequency to request a short configuration on the measurement channel. This request must be answered with a CACK to continue the calibration or with a CNACK to abort the calibration.

Option 0x15 – Calibration-interaction-request Load

This is a message send by the ISX-3v2 High Frequency to request a load configuration on the measurement channel. This request must be answered with a CACK to continue the calibration or with a CNACK to abort the calibration.

Before the answer to this request is send the load value and type must have been send to the device (Option 0x16).

Option 0x20: save setup to slot

This command saves the setup-configuration.

DC = 2

DD = 1 Byte slot number [1 ... 255]

Example: B7 02 20 01 B7

[save the current setup to slot 1](#)

Option 0x33: Get frequency list

This command reads the currently configured dc-bias from the device.

DC = 1

Example: B7 01 33 B7

Return: B7 05 33 [4 Byte float dc-bias in V] B7

6.6.4. Example of impedance calibration procedure

This example demonstrates the communication required to calibrate an already configured setup.

Direction of communication:

PC to ISX-3v2 High Frequency		ISX-3v2 High Frequency to PC								
#	Command	Communication								
1	Initiating the calibration routine	B6	01	10	B6					
2	Acknowledge	18	01	83	18					
3	Request to leave the terminals open	B7	01	13	B7					
4	Calibration acknowledge	B6	01	11	B6					
5	Acknowledge	18	01	83	18					
Calibration measurement on open terminal is performed										
6	Request to short all terminals	B7	01	14	B7					
7	Calibration acknowledge	B6	01	11	B6					
8	Acknowledge	18	01	83	18					
Calibration measurement of shorted terminals is performed										
9	Request to connect a known load impedance to the device	B7	01	15	B7					
10	Set known value of the load impedance (e.g. 1000hms)	B6	06	16	01	42	C8	00	00	B6
11	Acknowledge	18	01	83	18					
12	Calibration acknowledge	B6	01	11	B6					
13	Acknowledge	18	01	83	18					
Calibration measurement of load device is performed										
14	Calibration done	B7	01	10	B7					

6.6.5. Example of dc bias calibration procedure

This example demonstrates the communication required to calibrate an already configured setup. It is essential the frontend settings (channel, measurement mode and range) are correctly initialized before starting the dc bias calibration routine

Direction of communication:

PC to ISX-3v2 High Frequency		ISX-3v2 High Frequency to PC							
#	Command	Communication							
1	Setting the dc bias voltage	B6	05	33	3F	00	00	00	B6
2	Acknowledge	18	01	83	18				
3	Init the dc bias calibration	B6	01	30	B6				
4	Acknowledge	18	01	83	18				
Calibration measurement is performed									
5	Calibrate DC Bias acknowledge	B7	01	31	B7				
7	Getting the dc bias voltage	B7	01	33	B7				
8	DC Bias	B7	01	33	3E	FF	FE	B0	B7
9	Acknowledge	18	01	83	18				

6.7. Code Example (ANSI C)

```
/*
=====
Name       : ISX3ComDemo.c
Author     : Sciospec
Version    : Revision 1
Copyright  : Sciospec 2014
Description: ISX3 Communication Demo in C, Ansi-style
=====
*/

#include <stdio.h>
#include <stdlib.h>

#include "windows.h"    //'windows.h' is needed for ftd2xx.h
#include <ftd2xx.h>

#define ISX3_PID      0x89D0

byte connectToIsx3(FT_HANDLE* handle);
byte readAck(FT_HANDLE handle);
void writeToDevice(FT_HANDLE handle, byte* data, DWORD dataCount);

int main(void) {

    FT_HANDLE handle;
    if(!connectToIsx3(&handle))
        return -1;
    printf("Connection established\n");

    byte *cmd, *readBuffer;

    /* ***** *
     *   Reading DeviceID   *
     * ***** */
    int numberOfBytes = 3;
    cmd = (byte*)malloc(sizeof(byte)*numberOfBytes);
        cmd[0] = 0xD1;    cmd[1] = 0x00; cmd[2] = 0xD1;
        writeToDevice(handle, cmd, numberOfBytes);
    free(cmd);

    DWORD availableBytes = 0, bytesToWrite, currentStatus, bytesRead;

    while(availableBytes != 15)
        FT_GetStatus(handle, &availableBytes, &bytesToWrite, &currentStatus);

    readBuffer = (byte*)malloc(sizeof(byte)*availableBytes);
    FT_Read(handle, readBuffer, availableBytes, &bytesRead);

    printf("DeviceID: ");
    int i;
    for(i=0; i<availableBytes;i++){
        printf("%.2X ", readBuffer[i]);
    }
    printf("\n\n");
    free(readBuffer);
}
```

```

/* ***** *
 * Initialize setup *
 * ***** */
printf("Initialize setup.\n");
numberOfBytes = 4;
cmd = (byte*)malloc(sizeof(byte)*numberOfBytes);
    cmd[0] = 0xB6;    cmd[1] = 0x01; cmd[2] = 0x01; cmd[3] = 0xB6;
    writeDataToDevice(handle, cmd, numberOfBytes);
free(cmd);
readAck(handle);
printf("\n");

/* ***** *
 * Initialize Freq.Block *
 * ***** */
printf("Set setup-config: frequency-block (500Hz .. 5MHz, log-scale, prec=1,
                                             amplitude=1V)\n");

float startFrequency    = 500; //Hz
float stopFrequency     = 5e6; //MHz
float frequencyCount    = 80;
float precision         = 1;
float amplitude         = 1; //V
byte scale              = 1; //log
numberOfBytes = 0x16 + 3;
cmd = (byte*)malloc(sizeof(byte)*numberOfBytes);
    cmd[0] = 0xB6; cmd[1] = numberOfBytes-3; cmd[numberOfBytes-1] = 0xB6;
    cmd[2] = 0x03;          // add multi frequency block

    unsigned long tmp = *(unsigned long*)&startFrequency;
    byte counter = 3;
    cmd[counter++] = (tmp>>24) &0xFF;
    cmd[counter++] = (tmp>>16) &0xFF;
    cmd[counter++] = (tmp>>8) &0xFF;
    cmd[counter++] = (tmp) &0xFF;

    tmp = *(unsigned long*)&stopFrequency;
    cmd[counter++] = (tmp>>24) &0xFF;
    cmd[counter++] = (tmp>>16) &0xFF;
    cmd[counter++] = (tmp>>8) &0xFF;
    cmd[counter++] = (tmp) &0xFF;

    tmp = *(unsigned long*)&frequencyCount;
    cmd[counter++] = (tmp>>24) &0xFF;
    cmd[counter++] = (tmp>>16) &0xFF;
    cmd[counter++] = (tmp>>8) &0xFF;
    cmd[counter++] = (tmp) &0xFF;

    cmd[counter++] = scale;

    tmp = *(unsigned long*)&precision;
    cmd[counter++] = (tmp>>24) &0xFF;
    cmd[counter++] = (tmp>>16) &0xFF;
    cmd[counter++] = (tmp>>8) &0xFF;
    cmd[counter++] = (tmp) &0xFF;

    tmp = *(unsigned long*)&amplitude;
    cmd[counter++] = (tmp>>24) &0xFF;
    cmd[counter++] = (tmp>>16) &0xFF;
    cmd[counter++] = (tmp>>8) &0xFF;
    cmd[counter++] = (tmp) &0xFF;

    writeDataToDevice(handle, cmd, numberOfBytes);
free(cmd);

readAck(handle);
printf("\n");

```

```

/* ***** *
 *      Set FrontEnd Settings      *
 * ***** */
printf("Set Frontend configuration: 4Pt-config, BNC, 100Ohm-Range\n");
numberOfBytes = 6;
cmd = (byte*)malloc(sizeof(byte)*numberOfBytes);
cmd[0] = 0xB0;      cmd[1] = 0x03;      cmd[numberOfBytes-1] = 0xB0;
cmd[2] = 0x04;      //MeasureMode = 4PointMode
cmd[3] = 0x02;      //Channel = BNC
cmd[4] = 0x01;      //RangeSetting = 100Ohm
writeDataToDevice(handle, cmd, numberOfBytes);
free(cmd);
readAck(handle);
printf("\n");

/* ***** *
 *      Start Measurement          *
 * ***** */
byte numberOfSpecs = 5;
printf("Start Measurement: Burstmode, Burstlength=%d\n", numberOfSpecs);
numberOfBytes = 6;
cmd = (byte*)malloc(sizeof(byte)*numberOfBytes);
cmd[0] = 0xB8;      cmd[1] = 0x03; cmd[numberOfBytes-1] = 0xB8;
cmd[2] = 0x01;
cmd[3] = (numberOfSpecs>>8)&0xFF;
cmd[4] = (numberOfSpecs)&0xFF;
writeDataToDevice(handle, cmd, numberOfBytes);
free(cmd);
readAck(handle);
printf("\n");

/* ***** *
 *      Receive Specs              *
 * ***** */
readBuffer = malloc(13); //3Byte Framing, 2Byte idNumber, 4Byte RE, 4Byte Im
byte j;
UINT16 id;
UINT32 tmp32;
float re, im;
for(j=0; j<numberOfSpecs; j++){
    printf("Spec#%i:\n", j+1);
    printf("id\tre\tim\n");
    for(i=0; i<frequencyCount;i++){
        while(availableBytes != 13)
            FT_GetStatus(handle, &availableBytes, &bytesToWrite,
                &currentStatus);

        FT_Read(handle, readBuffer, availableBytes, &bytesRead);

        id = (readBuffer[2]<<8) + readBuffer[3];
        tmp32 = (readBuffer[4]<<24) + (readBuffer[5]<<16) +
            (readBuffer[6]<<8) + (readBuffer[7]);
        re = *(float*)&tmp32;
        tmp32 = (readBuffer[8]<<24) + (readBuffer[9]<<16) +
            (readBuffer[10]<<8) + (readBuffer[11]);
        im = *(float*)&tmp32;

        printf("%i\t%f\t%f\n", id, re, im);
    }
    printf("\n");
}

FT_Close(handle);

return 1;
}

```



```

/* ***** *
 * Finds available devices and connect to first available ISX3 *
 * @param handle - the pointer to USB-Conection-Hanlde *
 * @return True if connection was successfull else false *
 * ***** */
byte connectToIsx3(FT_HANDLE* handle){

    FT_STATUS ftStatus;
    FT_DEVICE_LIST_INFO_NODE* devInfo;
    DWORD numDevs; // create the device information list
    ftStatus = FT_CreateDeviceInfoList(&numDevs); // allocate storage for list
                                                    based on numDevs

    devInfo =
        (FT_DEVICE_LIST_INFO_NODE*)malloc(sizeof(FT_DEVICE_LIST_INFO_NODE)*numDevs);
                                                    // get the device information list
    ftStatus = FT_GetDeviceInfoList(devInfo, &numDevs);
    if(ftStatus != FT_OK){
        printf("Error while reading device-count");
        return FALSE;
    }

    printf("Number of devices found: %d\n\n", (int)numDevs);
    int i;
    for (i = 0; i < numDevs; i++) {
        printf("#%i\t%.4X\t%.4X\n", i, ((int)devInfo[i].ID>>16)&0xFFFF,
                                                    ((int)devInfo[i].ID)&0xFFFF);
    }

    for (i = 0; i < numDevs; i++) {
        if((devInfo[i].ID & 0xFFFF) == ISX3_PID){
            ftStatus = FT_Open(i, handle);
            if(ftStatus != FT_OK){
                printf("Error while connecting to device");
                return FALSE;
            }

            ftStatus = FT_SetBitMode(*handle, 0x00, 0x40);
            break;
        }
    }
    if(i == numDevs){
        printf("No ISX3 found");
        return FALSE;
    }

    return TRUE;
}

/* ***** *
 * Tries to Write Data to the device *
 * ***** */
void writeDataToDevice(FT_HANDLE handle, byte* cmd, DWORD dataCount){

    DWORD bytesWritten;
    byte i;
    for(i=0; i<dataCount;i++){
        printf("%.2X ", cmd[i]);
    }
    printf("\n");
    FT_Write(handle, cmd, dataCount, &bytesWritten);
}

```

```

/* ***** *
 * Tries to Read ACK Frame *
 * @return true if ACK is received, else false *
 * ***** */
byte readAck(FT_HANDLE handle){

    DWORD availableBytes = 0;
    DWORD bytesToWrite = 0;
    DWORD currentStatus = 0;
    DWORD bytesRead = 0;

    byte* readBuffer;

    while(availableBytes != 4)
        FT_GetStatus(handle, &availableBytes, &bytesToWrite, &currentStatus);
    readBuffer = (byte*)malloc(sizeof(byte)*availableBytes);
    FT_Read(handle, readBuffer, availableBytes, &bytesRead);

    printf("ACK-Frame: ");
    UINT8 i;
    for(i=0; i<availableBytes;i++){
        printf("%.2X ", readBuffer[i]);
    }
    printf("\n");

    if(readBuffer[2] == 0x83){
        free(readBuffer);
        return TRUE; //ACK
    }else{
        free(readBuffer);
        return FALSE; //NOT ACK
    }
}

```

7. Appendix

7.1. Temperature Sensors - negative temperature coefficient (NTC) thermistor

The temperature measurement works by connecting a NTC thermistor to the specified port. The instruments needs to know the following characteristics of the connected thermistors to calculate the temperature correctly

name	symbol	description	unit	typical value
Beta parameter	β	material constant, refer to the datasheet of the thermistor	K	3800K
Reference temperature	T_N	operating temperature	K	298,15K (25°C)
resistance at T_N	R_N	Nominal resistance at the operating temperature	Ω	10k Ω

The conversion formula for the temperature ϑ is:

$$\vartheta = \frac{\beta * T_N}{\beta + \ln\left(\frac{R}{R_N}\right) * T_N} - 273,15$$

7.2. Measurement delay options and phase synchronization

There are different options to define delays during a measurement. Basically there are two possibilities. Either way the measurement pauses after a full sweep is completed (sweep delay, synchronization time) or after a specific frequency point has been measured (point delay). In the case of a none zero point delay, the next frequency excitation will be used and before the actual measurement starts the defined time will elapse. Both parameters can be set in the software or by a corresponding command via USB or Ethernet (see chapter 6.6.1 command 0xB9 and command 0xB6).

The optional phase synchronization feature ensures that change of frequency in the excitation signal, which is exerted on the device under test, with no change in phase and without any glitches. This is for example needed for precise measurements of the impedance of resonant devices under test. The disadvantage of this option is that a longer time for the measurement is needed (see chapter 6.6.1 command 0xB6).

8. Changes

Revision 1.0

- Initial Release of this document