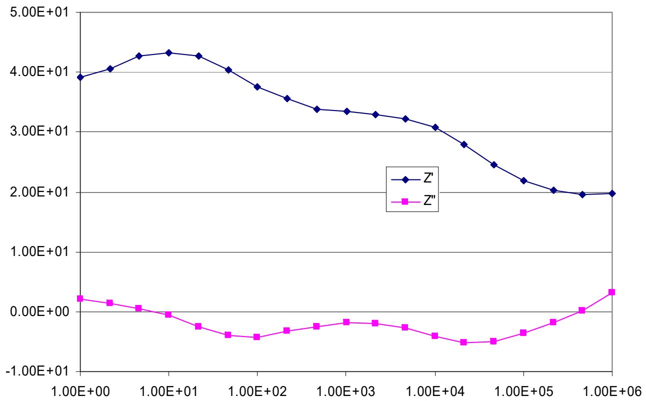
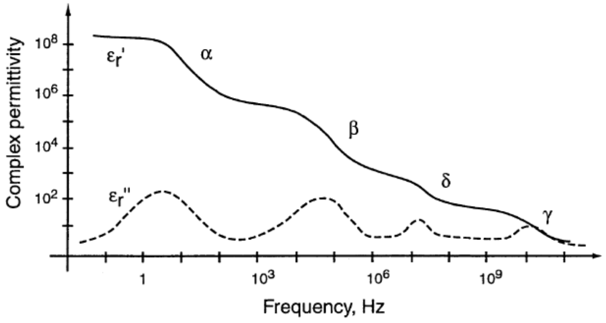
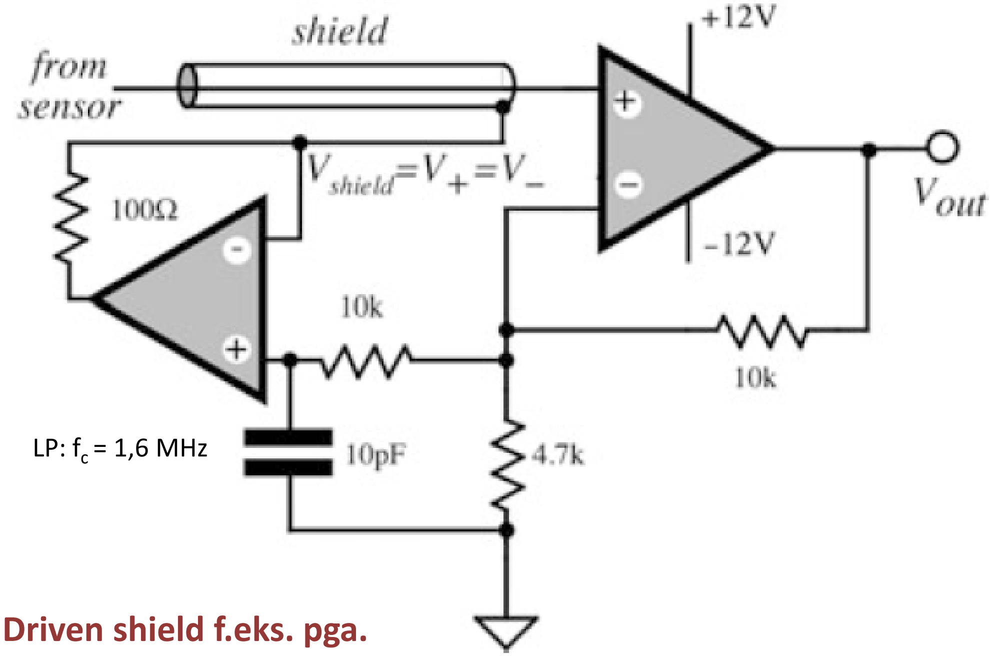
Instrumentering og bioimpedans



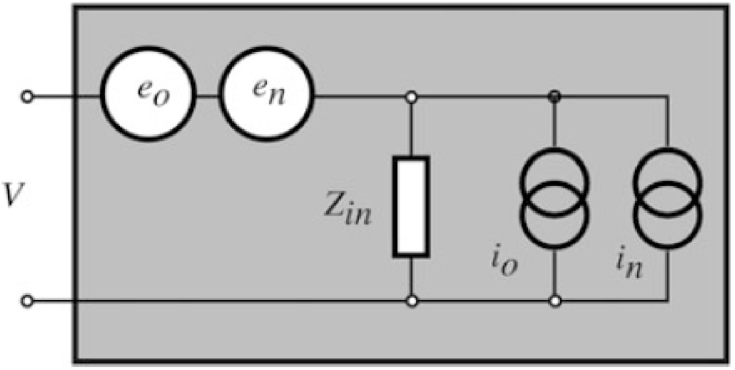




LP: f_c = 1,6 MHz

Driven shield f.eks. pga. høyohmig inngang

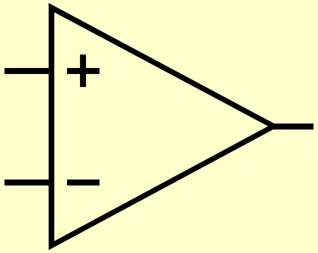
- **Offset voltage**
- **Bias current (kan gi stor spenning over utgangsimpedansen til en sensor)**
- **Noise**



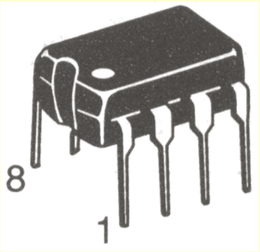
Input Stage of Interface Circuit

Operasjonsforsterker - OPAMP

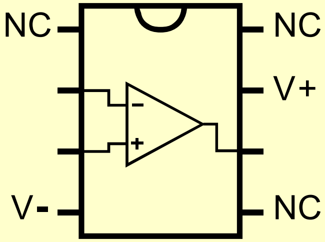
$$v_o = K(v_+ - v_-)$$



a)

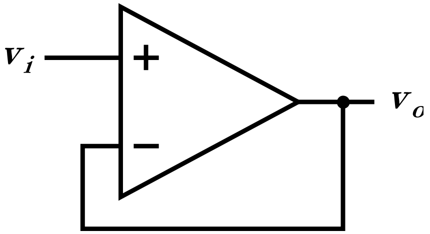


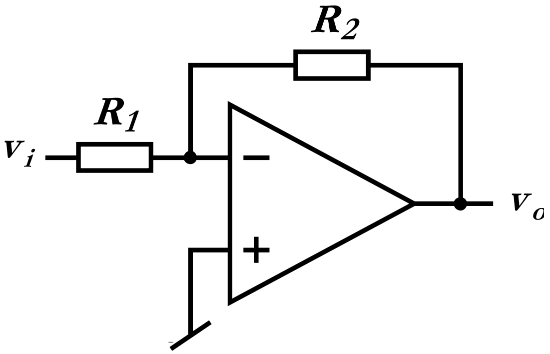
b)

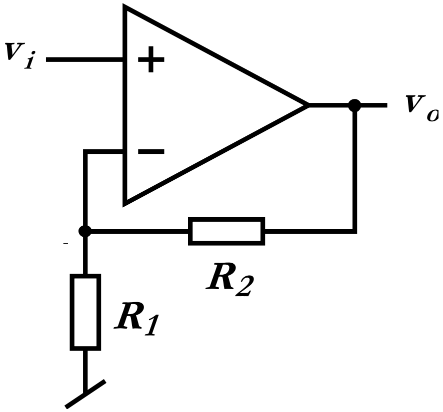


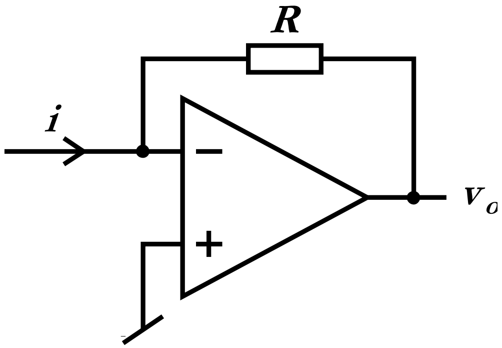
c)

"Golden rules"





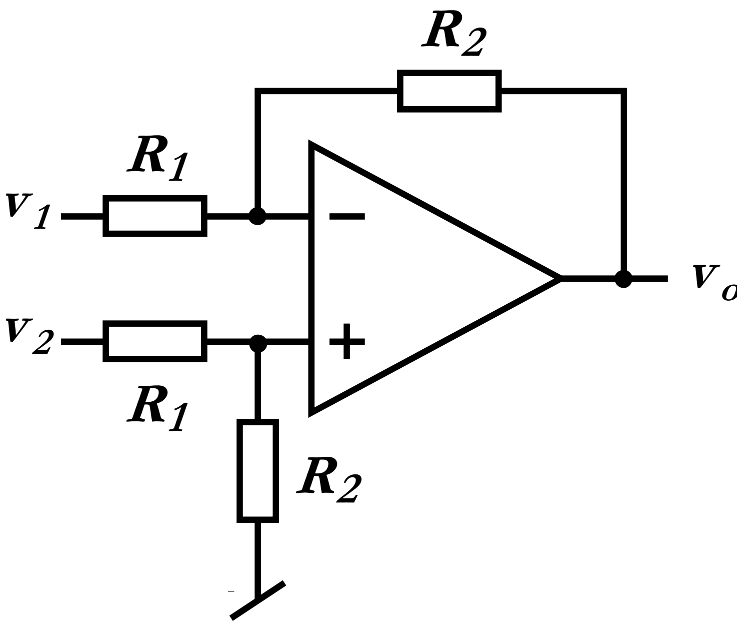




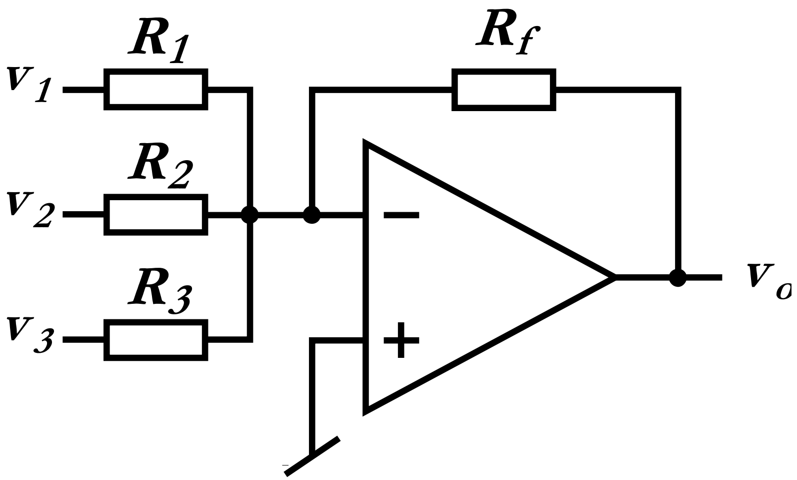
Les selv ...

Flere forsterkere

Differensialforsterker



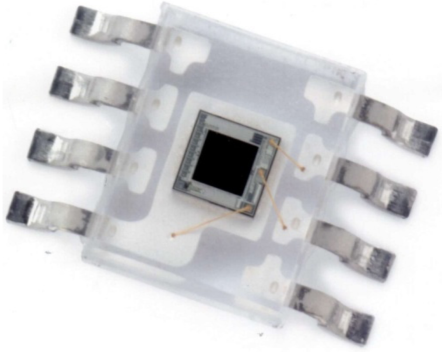
Summasjonsforsterker



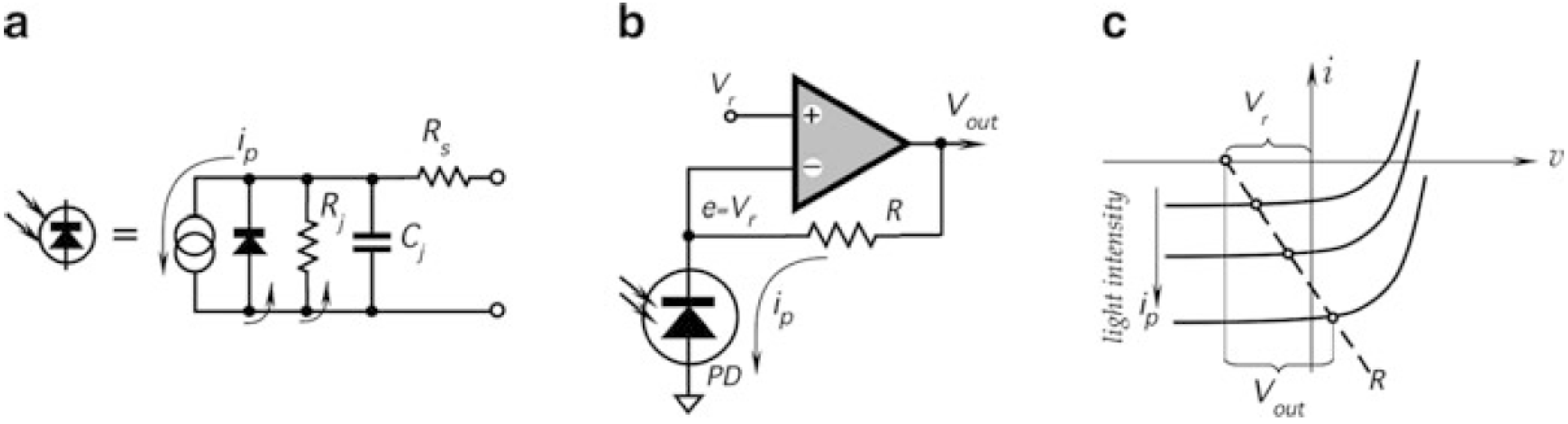
Les selv ...

Lys-til-spenningsomformer

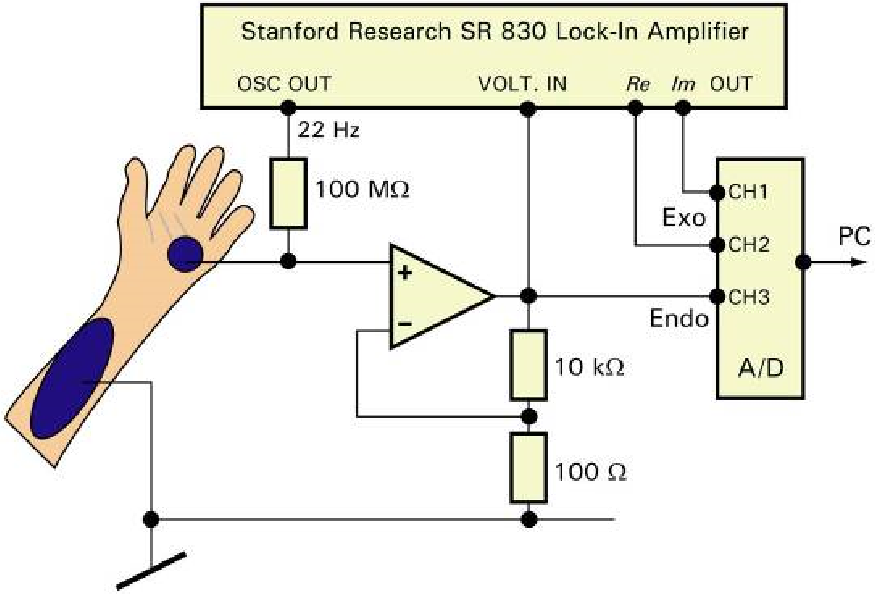
Fotosensor + transimpedansforsterker



- Fotosensor
    - Fotodiode
    - Fototransistor
    - Fotoresistor
- Albert Einstein – fotoelektrisk effekt – Nobelpris 1921



Konstant-strømkilder



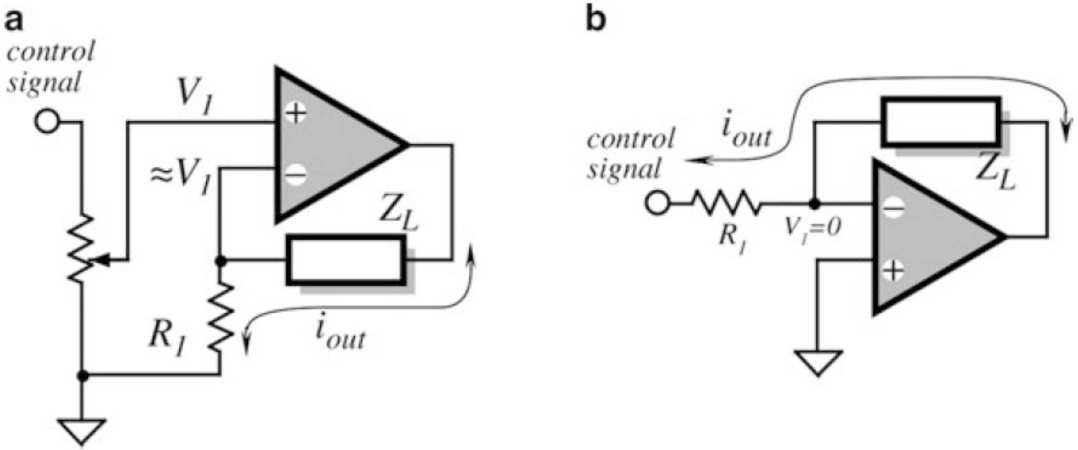


Fig. 5.17 Bipolar current generators with floating loads noninverting circuit (**a**); circuit with a virtual ground (**b**)

Les selv ...

Howland current pump

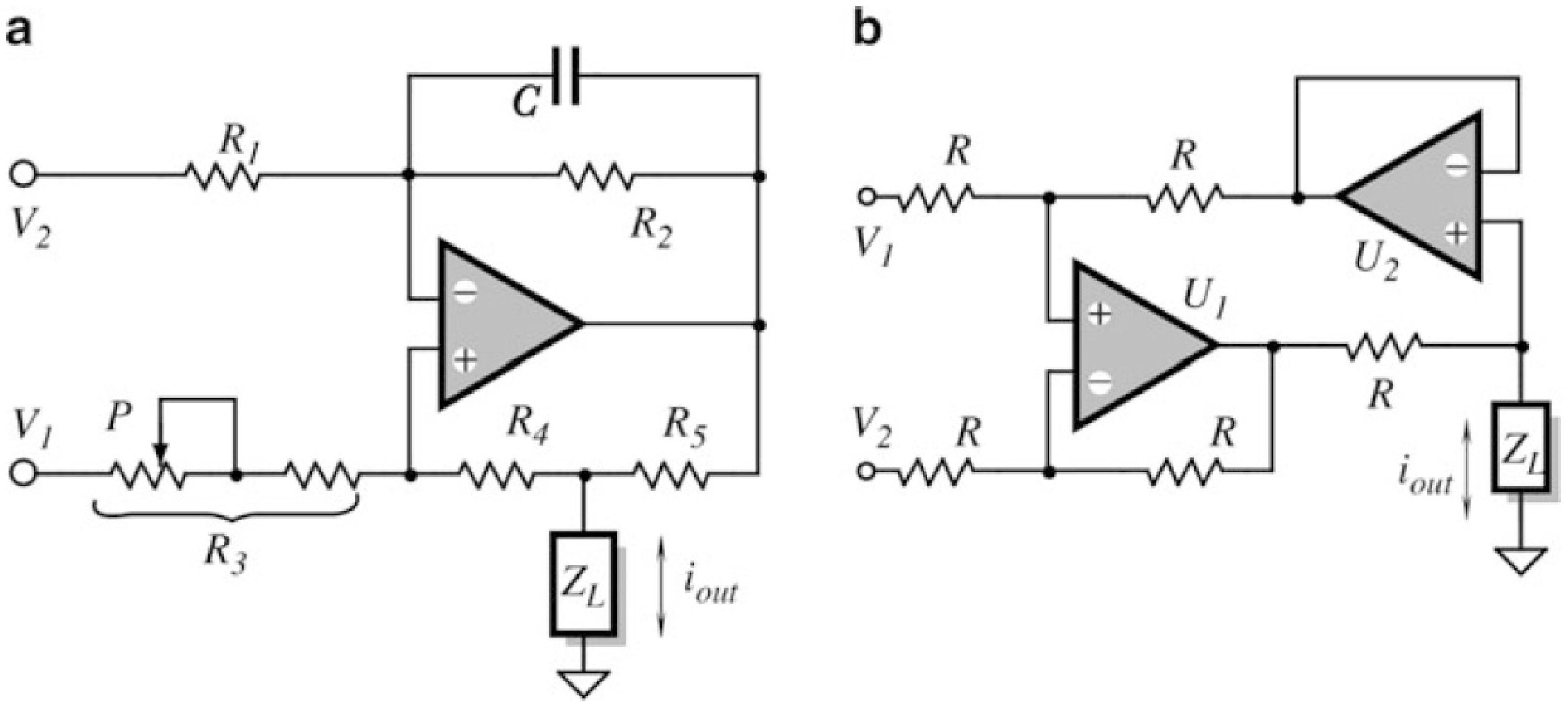
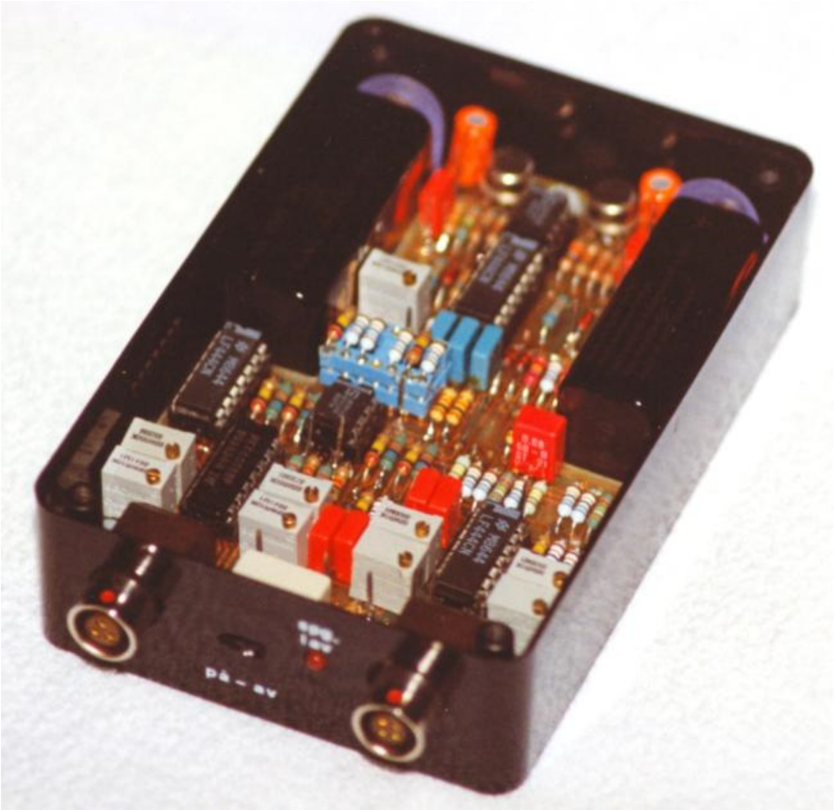


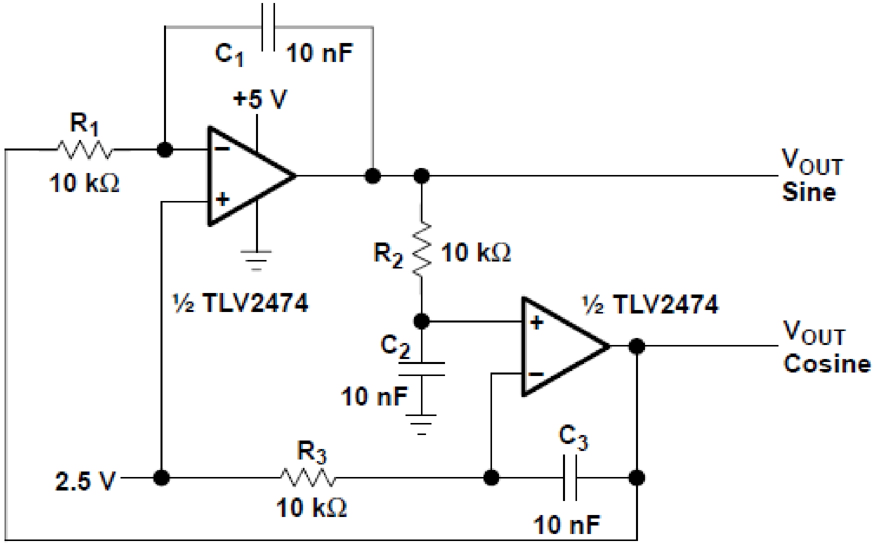
Fig. 5.18 Current generators with ground referenced loads Howland current pump (**a**); current pump with two OPAMs (**b**)

$$i_{out} = \frac{R_2}{R_1}\frac{(V_1 - V_2)}{R_5} \qquad R_3 = R_1 \frac{R_4 + R_5}{R_2}$$

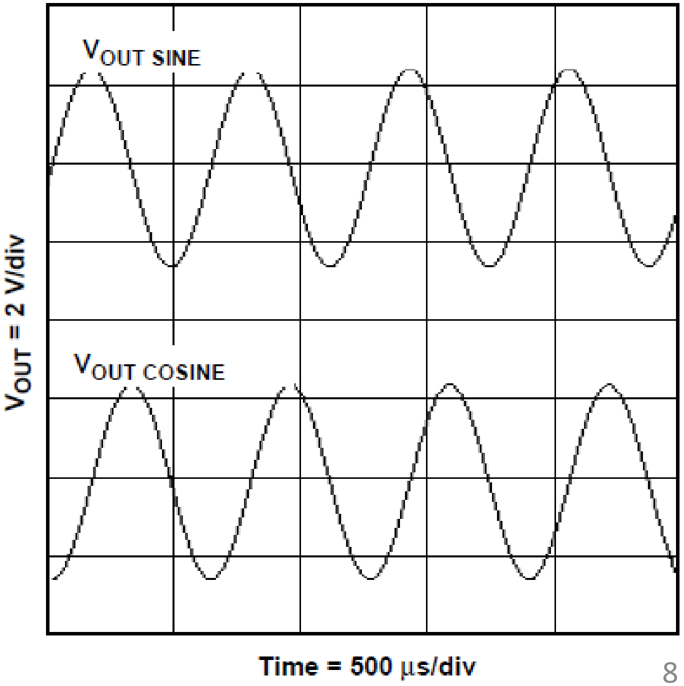
Kvadratur-oscillator

- Hvert steg fasedreier 90 grader
- Gir positiv feedback

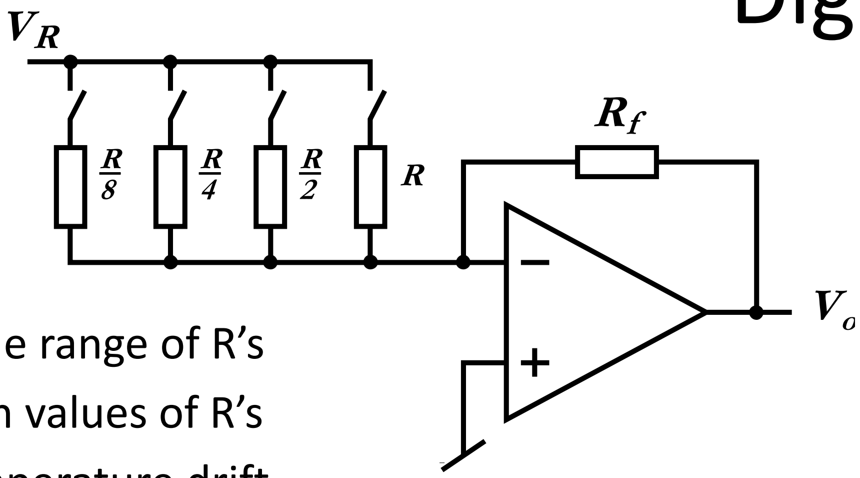




Quadrature Oscillator

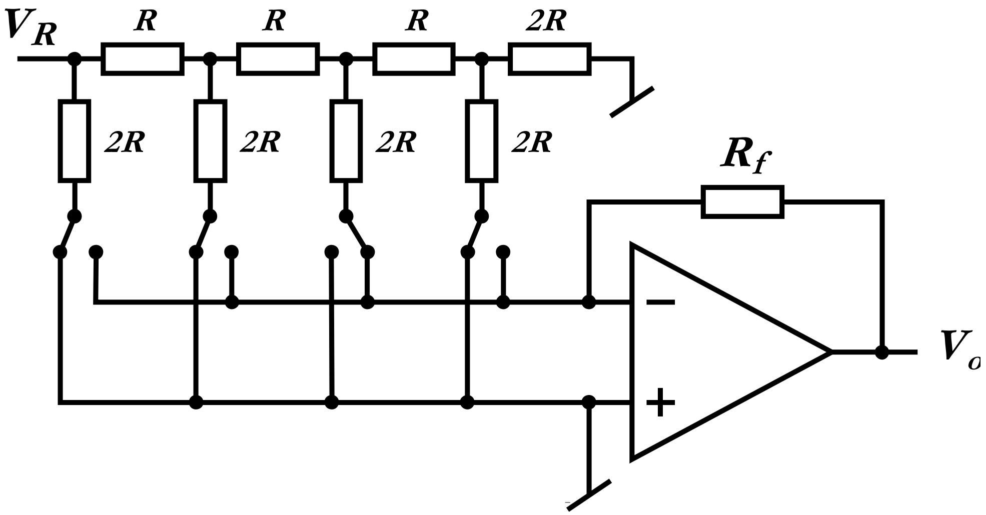


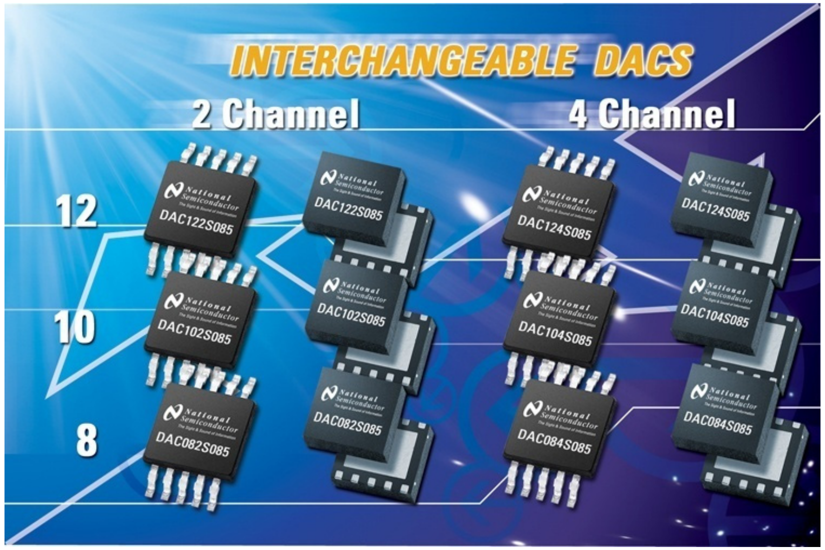
Digital til analog omformer



- Wide range of R’s
- High values of R’s
- Temperature drift

Also: One-bit DAC

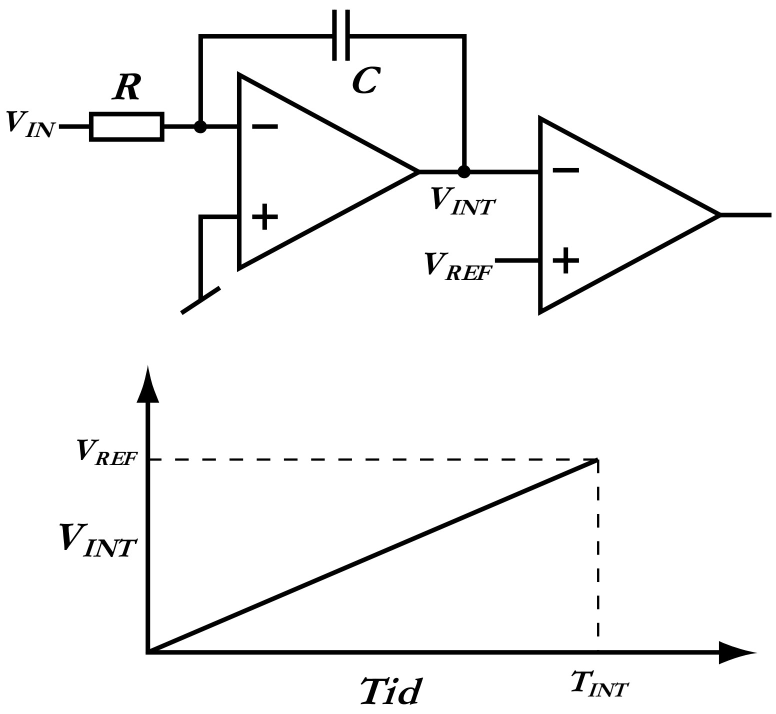




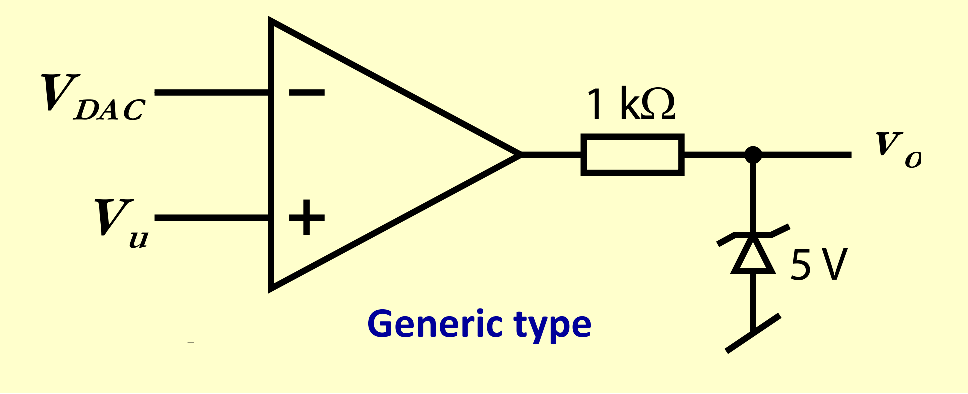
Analog to digital converter

Les selv …

$$T_{INT} \propto V_{IN}$$

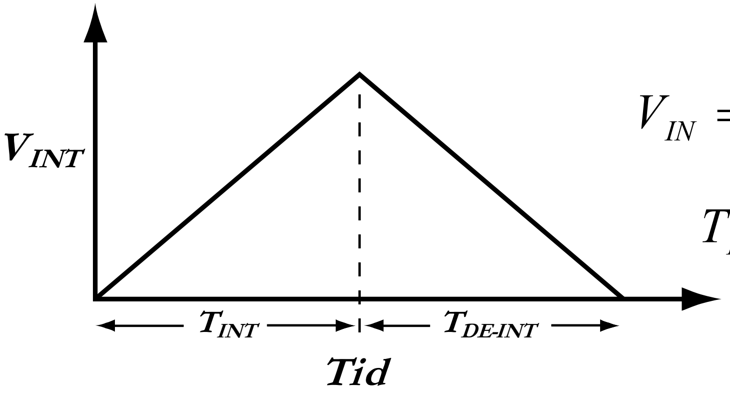


Single slope



Generic type

Successive approximation



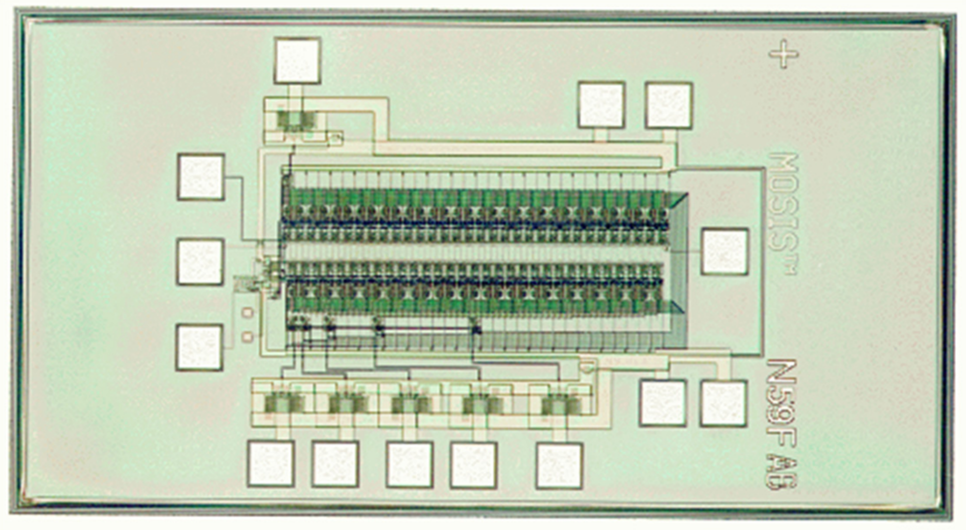
Dual slope

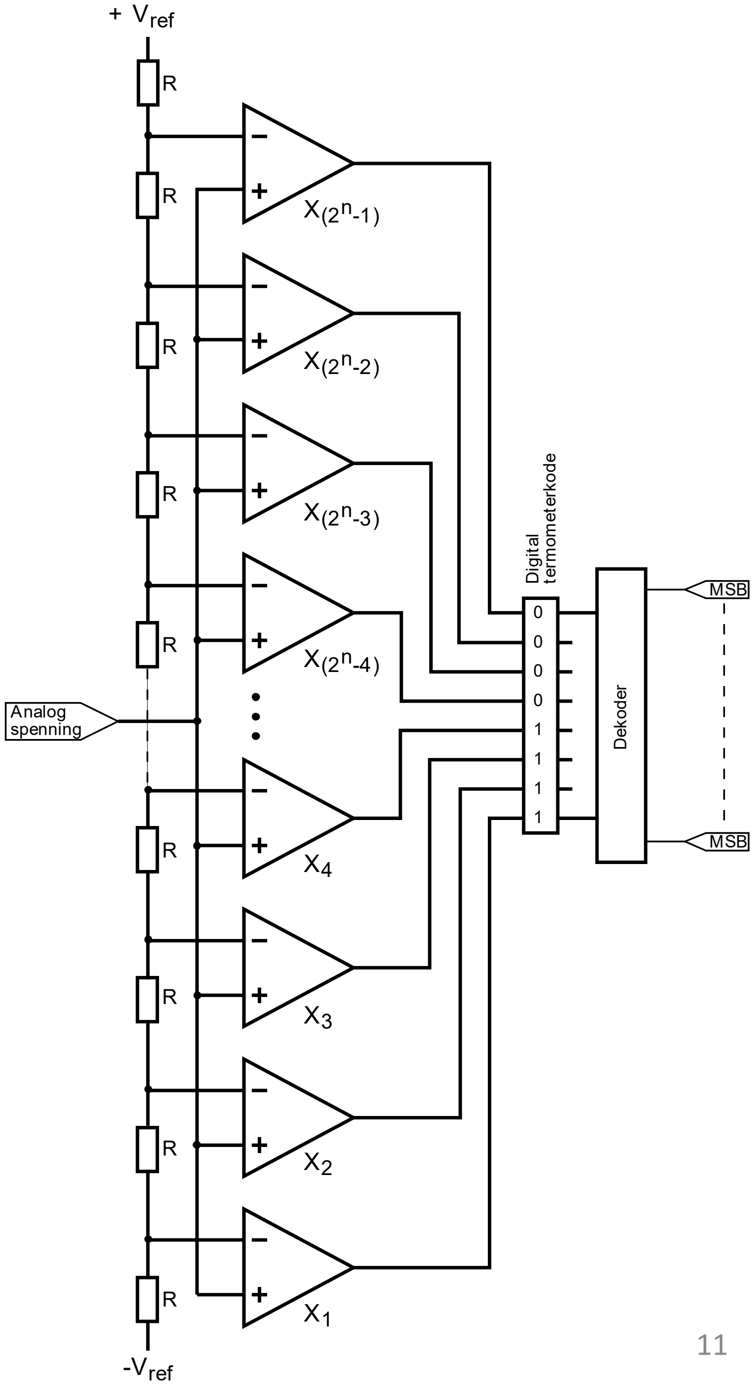
$$V_{IN} = V_{REF}\frac{T_{DE-INT}}{T_{INT}}$$

$$T_{INT} = \text{constant}$$

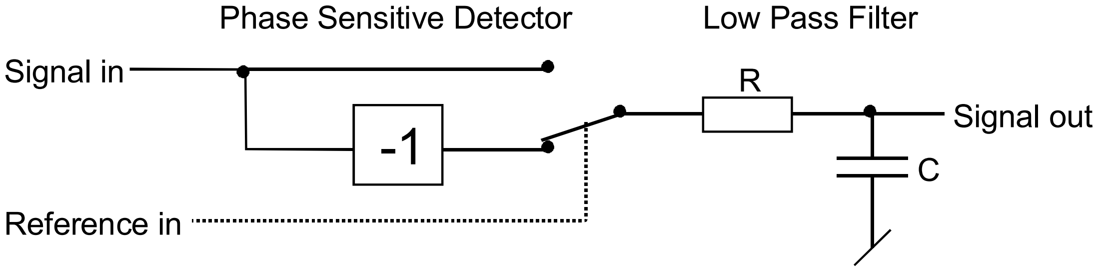
Flash ADC

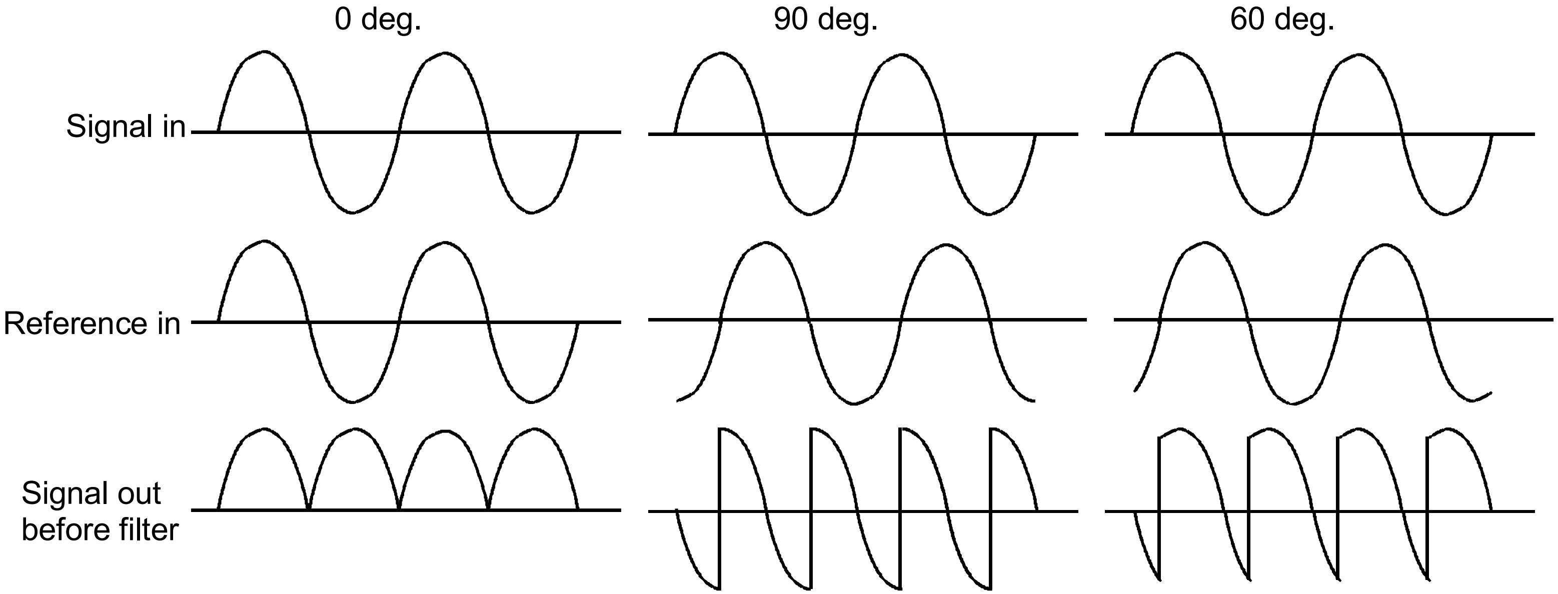
- Similar to succ. approx.
- All tests simultaneously
- n-bit → 2^n-1 comparators
- Fast but much hardware



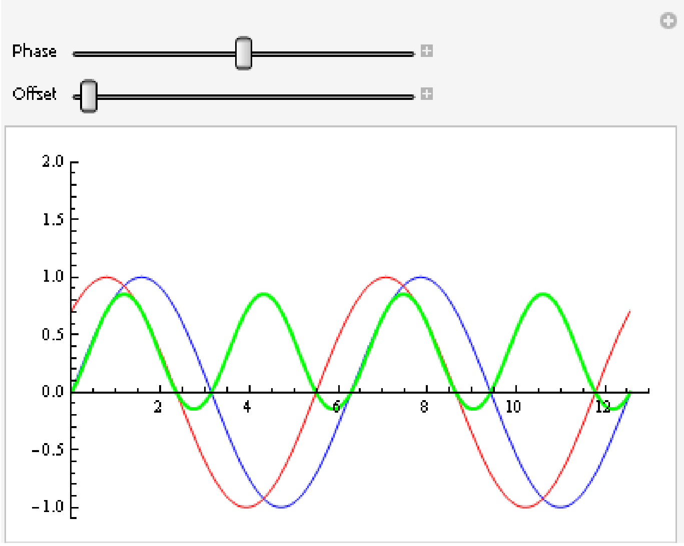


Synchronous rectifier, square wave





Digital syncronous rectifier (lock-in amplifier)



If the reference signal is: $v_r = \sin(\omega_r t)$

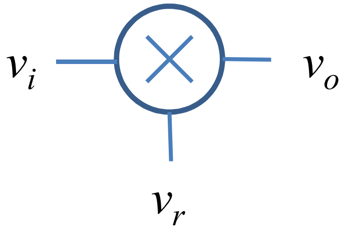
and the input signal is: $v_i = v_1 \cdot \sin(\omega_i t + \varphi)$

the output signal will be:

$$
\begin{aligned}
v_o &= v_1 \cdot \sin(\omega_i t + \varphi) \cdot \sin(\omega_r t) \\
&= \frac{v_1}{2} \cdot \left[\cos\left((\omega_i - \omega_r)t - \varphi\right) - \cos\left((\omega_i + \omega_r)t + \varphi\right)\right]
\end{aligned}
$$

A low pass filter will follow this multiplier module, and the right hand cosine expression may therefore be ignored. In fact the only dc signal that will appear at the low pass filter output, will be the one corresponding to $\omega_i = \omega_r$, which gives:

$$v_o = \frac{v_1}{2} \cdot \cos\varphi$$



Digital syncronous rectifier (lock-in amplifier)

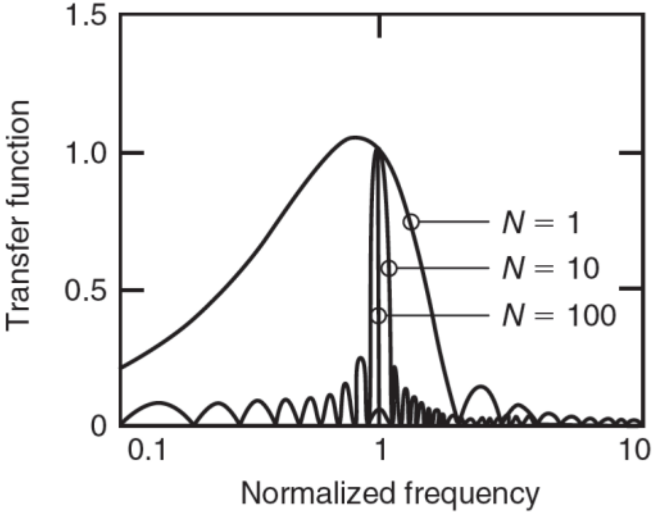
Total suppression of noise in this system is of course only possible if the integration time is infinite, i.e. the multiplication is carried out over an infinite number of signal cycles. Gabrielli (1984) shows that the suppression of random (white) noise is given by an equivalent filter function with a bandwidth Δf given by

$$\Delta f = \frac{f_r}{N}$$

where f_r is the analysed frequency and N the number of cycles. Hence, in a 10 Hz measurement, the bandwidth is 0.1 Hz when integrating over 100 cycles, but only 2 Hz when integrating over only five cycles of the signal. The corresponding transfer function is given by

$$\left|\mathbf{H}(\omega)\right| = \frac{2}{\pi N}\left[\frac{\sin(N\pi\omega/\omega_0)}{1-(\omega/\omega_0)^2}\right]$$

where ω/ω_0 is the normalised angular frequency. The transfer function is also shown in the figure as a function of number of integration cycles.



Relative målinger

- Måler i forhold til en referanse som påvirkes på samme måte av støy, aldring, temperatur, ustabil spenningsforsyning, etc.
- Det gjøres en divisjon mellom de to signalene
- Egner seg derfor kun for multiplikative feil
- For additive feil egner differensialmålinger best

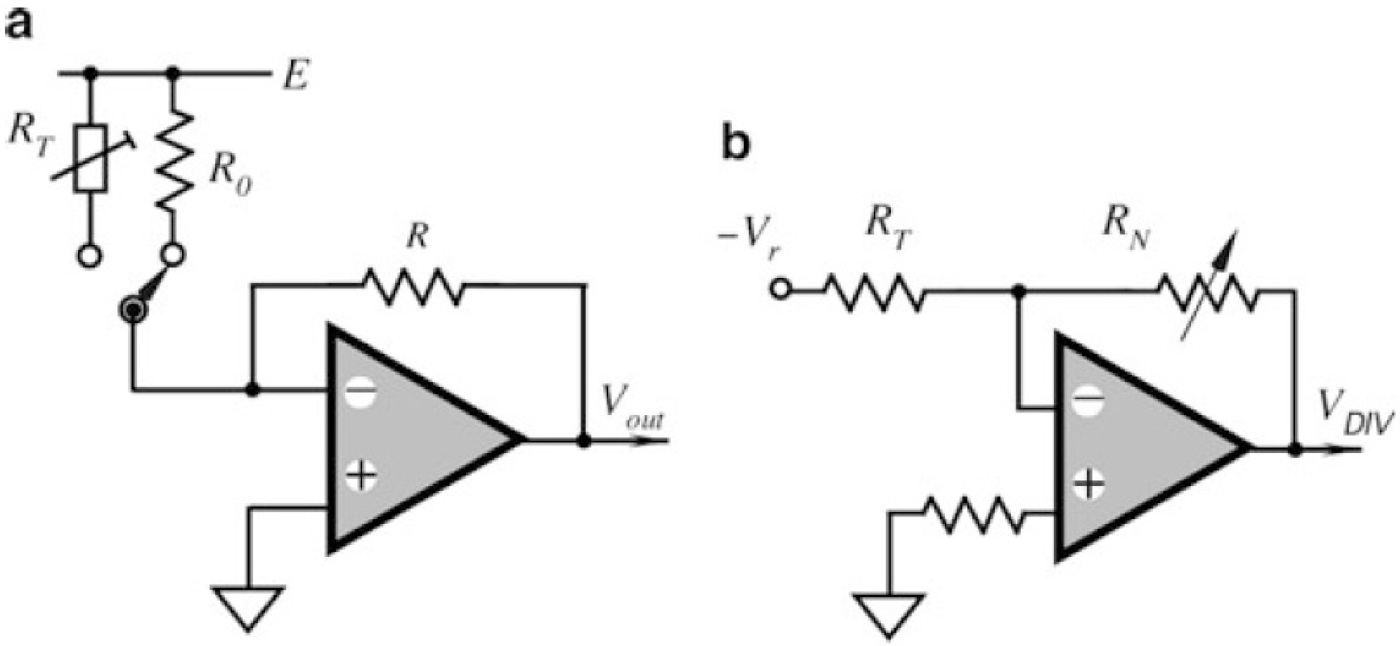


Fig. 5.35 Ratiometric temperature detector (**a**) and analog divider of resistive values (**b**)

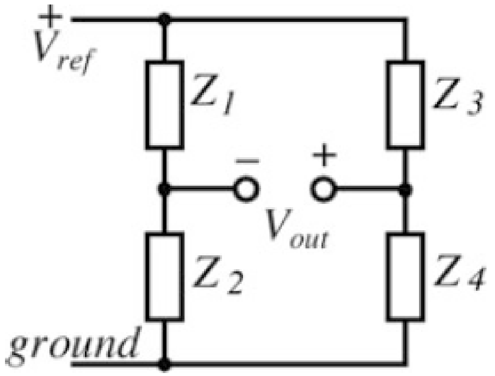
Les selv ...

Wheatstone bridge

- Hvis Z_1 er sensor, kan det vises at:

$$\frac{dV_{out}}{V_{ref}} = \frac{dZ_1}{4Z_1}$$

- Balanced bridge
- Disbalanced bridge
- Autobalancing bridge



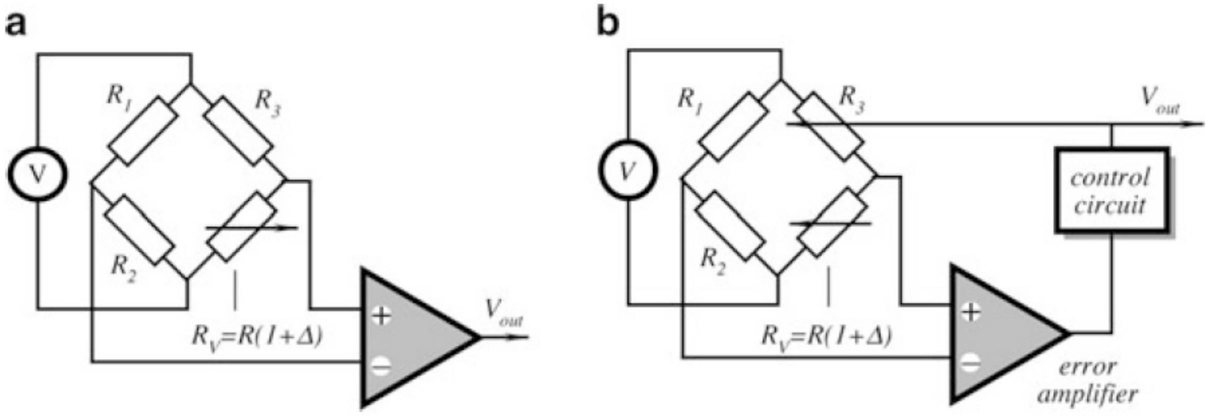


Fig. 5.38 Two methods of using a bridge circuit: Disbalanced bridge (**a**) and Null-balanced bridge with a feedback control (**b**)

Strømsløyfe

- Slipper spenningsfall ved lange overføringer (f.eks. skip)
- Resistiv sensor med lange tilkoblinger: firepunktsmåling

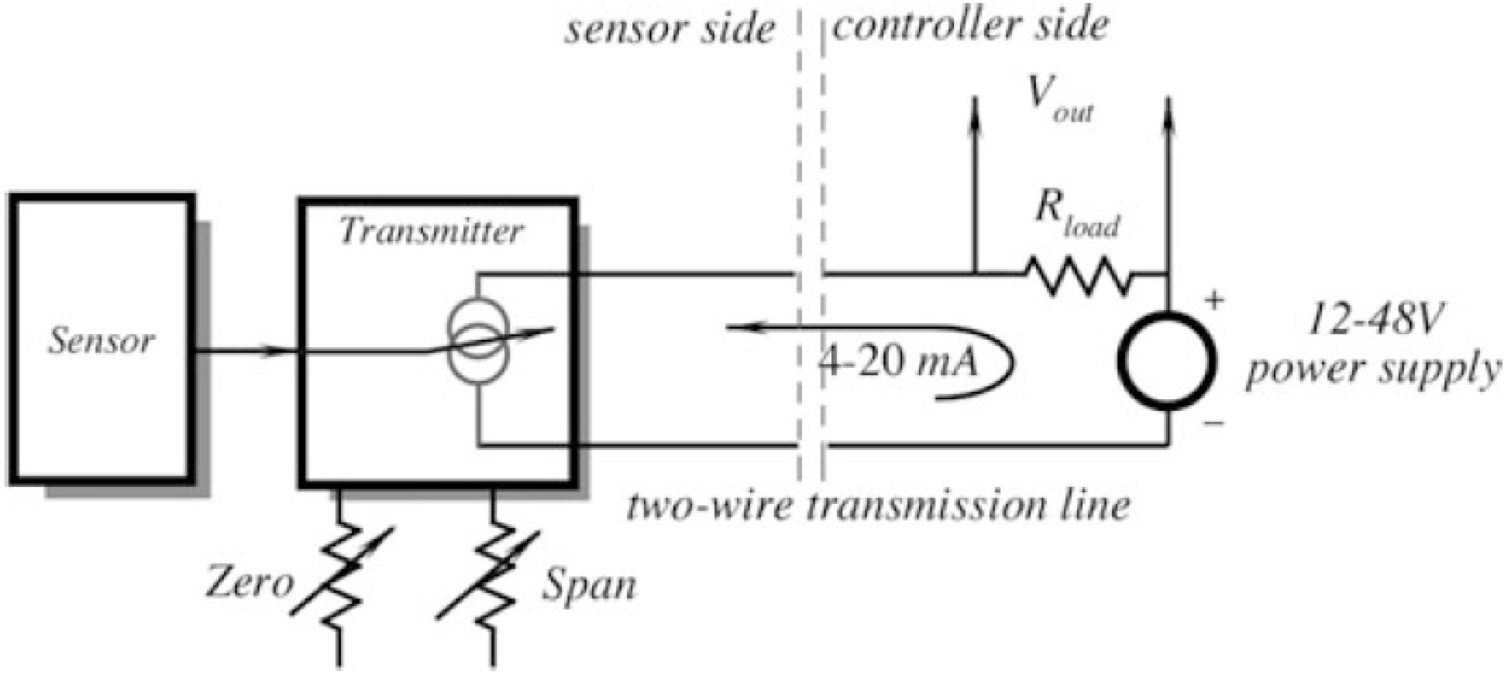


Fig. 5.41 Two-wire 20 mA analog data transmission

Intern (endogen) støy

- LSB i en digital representasjon
- Input offset spenning og bias-strøm
- Johnson noise (white noise)
  - Skyldes termiske bevegelser av elektronene
  - Støyspenningens mean-square-value: $\bar{e}_n^2 = 4kTR\Delta f \ [\mathrm{V}^2/\mathrm{Hz}]$

Frekvensområdet som målingene gjøres i

- Shot noise (white noise)
  - Pga. DC strøm i halvledere
  - Verre dess mer bias-strøm (bedre i FET og CMOS)
- 1/f (flikker) noise (pink noise)
  - < 100 Hz

Ekstern (eksogen) støy

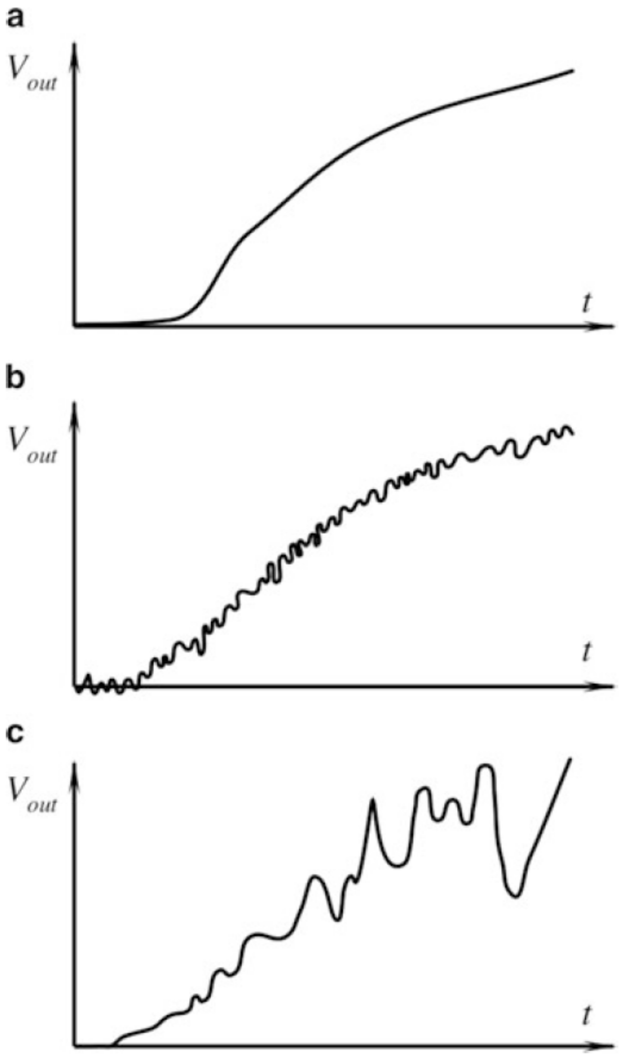
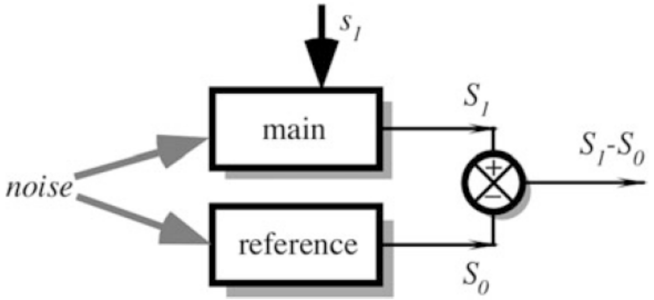


Fig. 5.45 Types of noise noise-free signal (**a**); additive noise (**b**); multiplicative noise (**c**)

- Transienter i lysnettet, 50 Hz, radiosendere, elektromagneter
- Additiv støy: Differensialmålinger



CMRR ~~CMMR~~ $= 0.5\,\dfrac{S_1 + S_0}{S_1 - S_0}$

CMRR viser hvor mange ganger sterkere inngangssignalet vil være representert på utgangen enn et common mode støysignal med samme amplitude

Les selv ...

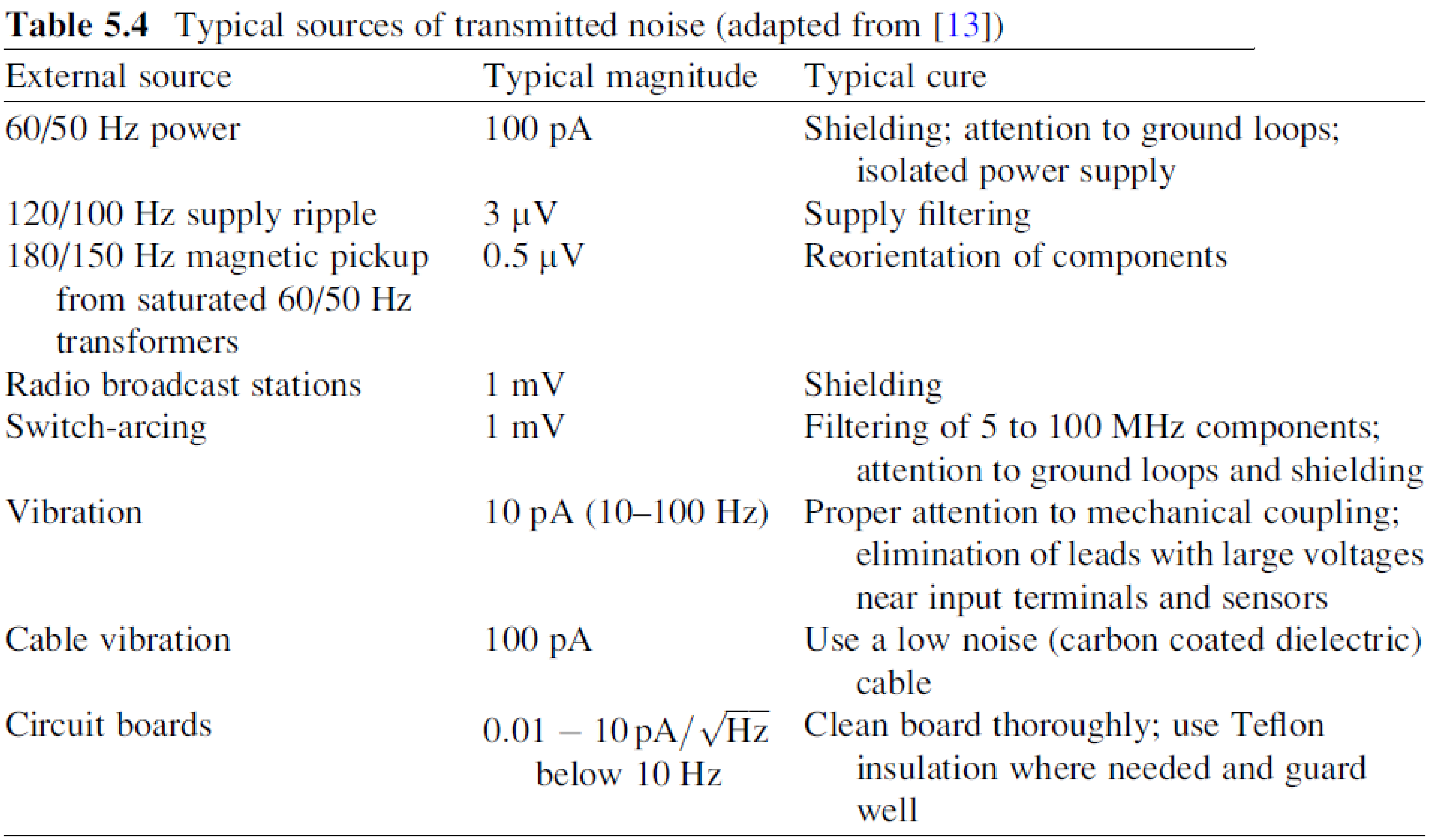


Table 5.4 Typical sources of transmitted noise (adapted from [13])

External source	Typical magnitude	Typical cure
60/50 Hz power	100 pA	Shielding; attention to ground loops; isolated power supply
120/100 Hz supply ripple	3 μV	Supply filtering
180/150 Hz magnetic pickup from saturated 60/50 Hz transformers	0.5 μV	Reorientation of components
Radio broadcast stations	1 mV	Shielding
Switch-arcing	1 mV	Filtering of 5 to 100 MHz components; attention to ground loops and shielding
Vibration	10 pA (10–100 Hz)	Proper attention to mechanical coupling; elimination of leads with large voltages near input terminals and sensors
Cable vibration	100 pA	Use a low noise (carbon coated dielectric) cable
Circuit boards	$0.01 - 10\,\mathrm{pA}/\sqrt{\mathrm{Hz}}$ below 10 Hz	Clean board thoroughly; use Teflon insulation where needed and guard well

Skjerming

- Skjermet kabel «jordes» på signalsida
- Oppdelte skjermer seriekobles
- Skjermen må bare jordes ett sted
- Hvis sensoren er innkapslet så jordes skjermet kabel til boksen
- Skjermen må alltid ligge på 0 volt (unntatt ved driven shield)
- Bruk korte ledninger til jord for å minimere induktans

- Vanskeligere å skjerme for magnetfelt, spesielt LF felt
- Må bruke metall med høy permeabilitet (mymetall)

Faraday's Law of Induction

$$\mathcal{E} = -\frac{d\,\Phi_B}{d\,t} \ (for\ one\ loop)$$

$$\mathcal{E} = -N\frac{d\,\Phi_B}{d\,t} \ (for\ multiple\ loops)$$

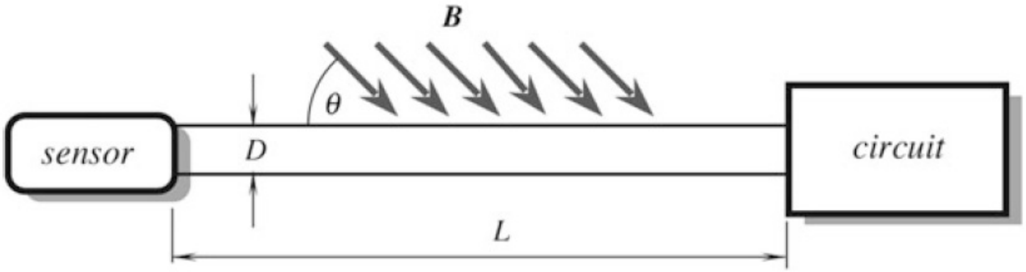
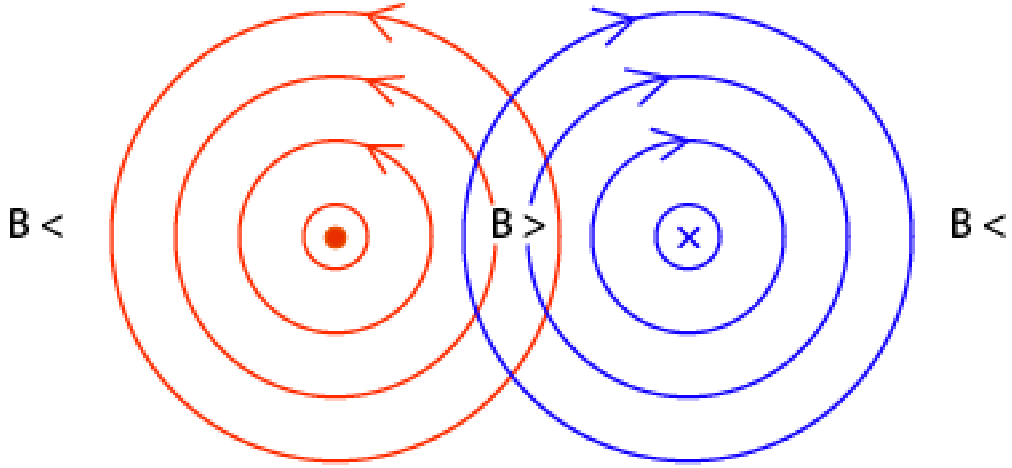


Fig. 5.52 Receiver's loop is formed by long conductors

Reduser lengden på ledningene, avstanden eller bruk twisted pair → mindre fluks

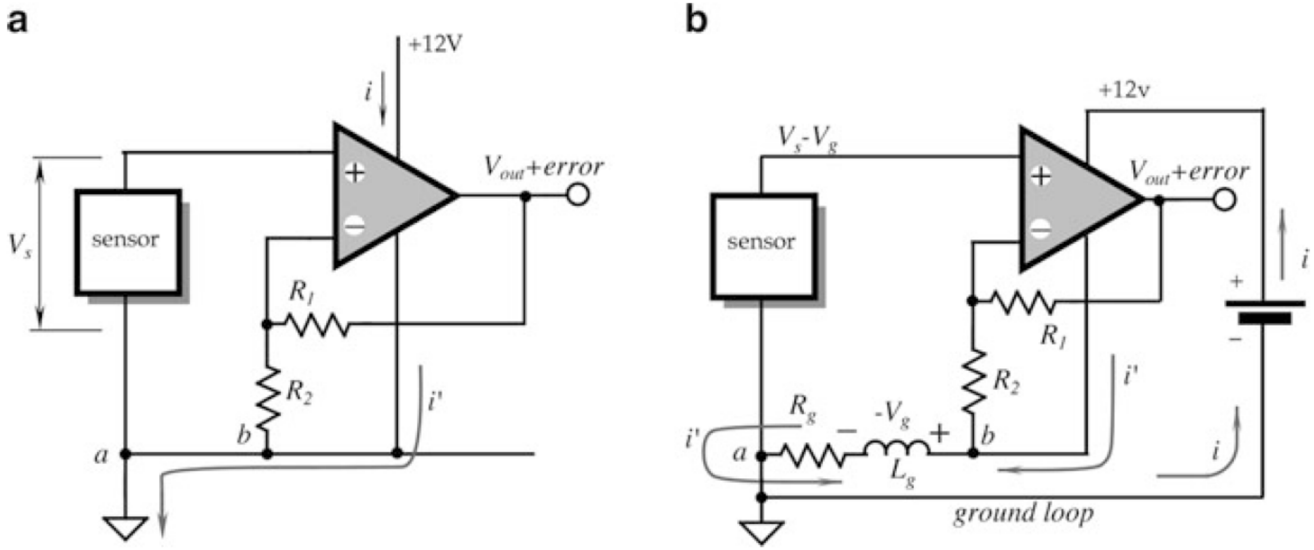
Jordplan

$$B = \frac{\mu_0 i}{2\pi r}$$



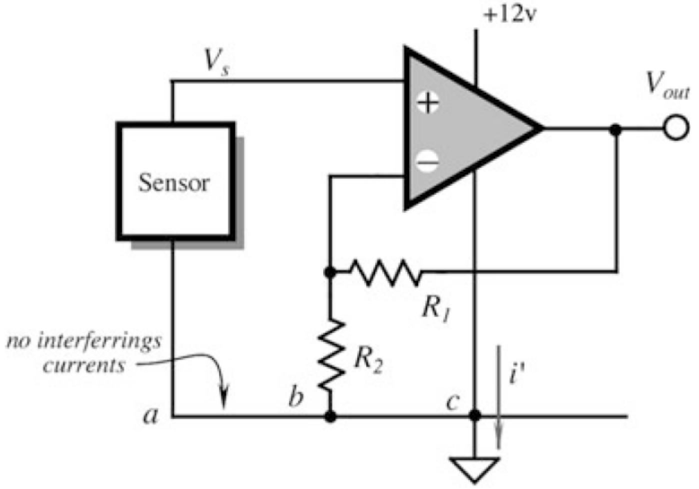
- Hovedsakelig for å redusere induktans (ved å redusere magnetfeltet)
- Gir en returvei for strømmen rett under lederen (ved riktig design av jordplanet)
- Gir lavere resistans pga mindre skin-effekt
- Kobler strøkapasitanser til jord
- Spesielt viktig under digitale eller HF signaler
- Bruk separat analog og digital jord som kun forbindes ett sted (ved tilkobling til strømforsyning)

Jordsløyfer



👎

Never use same conductor for a reference signal and power supply



👍

Direct current - DC

- From direct current (DC) theory we know that resistors in series:

$$R = R_1 + R_2 + \cdots + R_n$$

- If resistors are in parallel:

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n}$$

- The inverse value of resistance is then called conductance, which gives:

$$G = G_1 + G_2 + \cdots + G_n$$

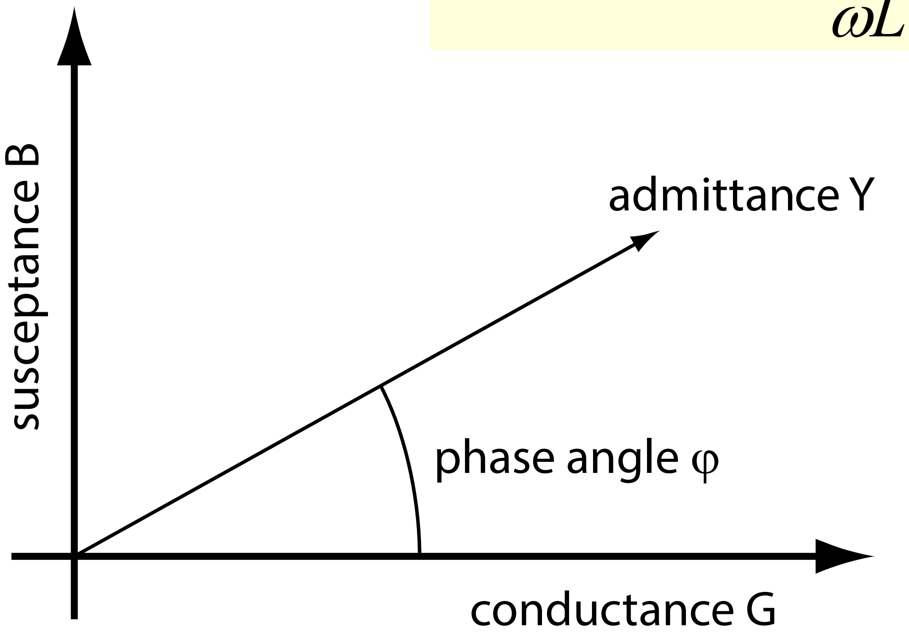
- Equations often become simpler using conductance for circuits which predominantly are in parallel and resistance for series-circuits. But only a practical matter !

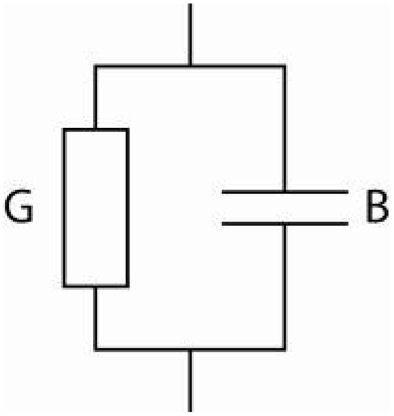
Alternating current - AC

- **R** = 1/**G** ⇒ **Z** = 1/**Y**
- Immittance is common for impedance or admittance

$$\mathbf{Y} = G + jB$$

$$\text{Inductor}: \; B = \frac{-1}{\omega L} \qquad \text{Capacitor}: \; B = \omega C$$

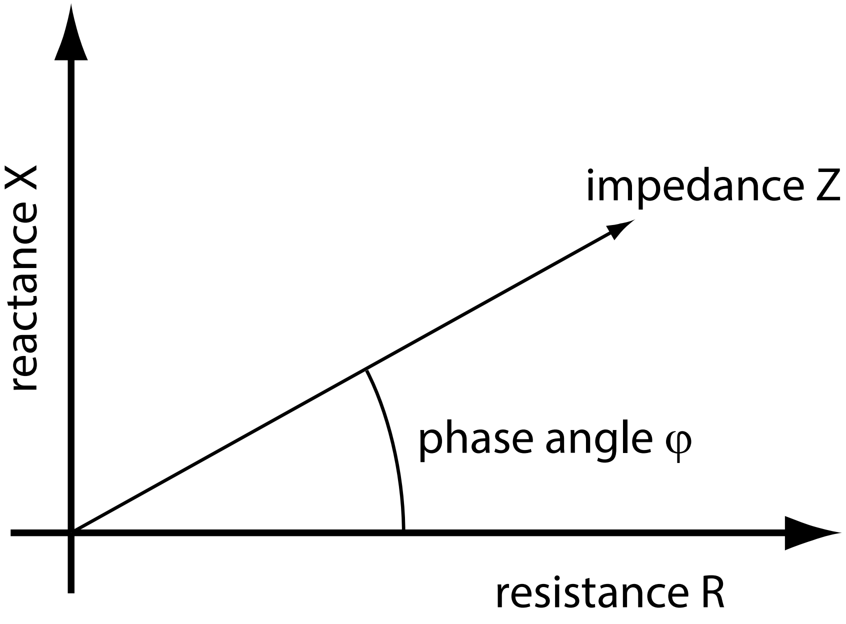


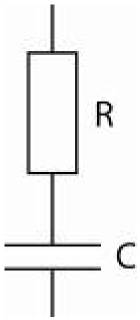


Impedance

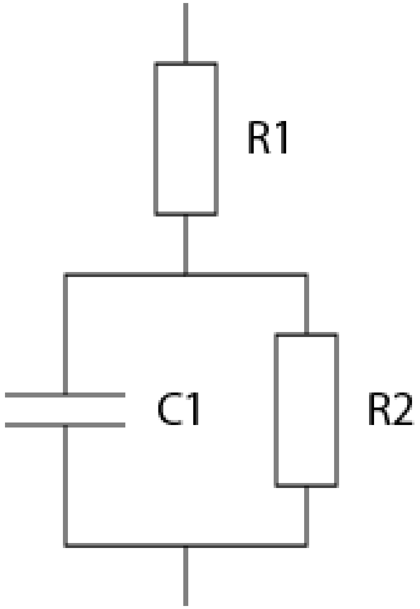
$$\mathbf{Z} = \frac{1}{\mathbf{Y}} = \frac{1}{G + jB} \quad \rightarrow \quad \mathbf{Z} = \frac{1}{G + jB} \cdot \frac{G - jB}{G - jB} = \frac{G - jB}{G^2 + B^2}$$

$$\mathbf{Z} = R + jX \quad \rightarrow \quad R = \frac{G}{G^2 + B^2} \quad \text{og} \quad X = \frac{-B}{G^2 + B^2}$$





Example using three components



$$\mathbf{Z} = R1 + \frac{1}{\dfrac{1}{R2} + \dfrac{j}{X1}} \quad \text{where} \quad X1 = \frac{-1}{\omega C1}$$

$$\mathbf{Z} = R1 + \frac{R2}{\left(R2\omega C1\right)^2 + 1} - j\frac{R2^2\,\omega C1}{\left(R2\omega C1\right)^2 + 1}$$

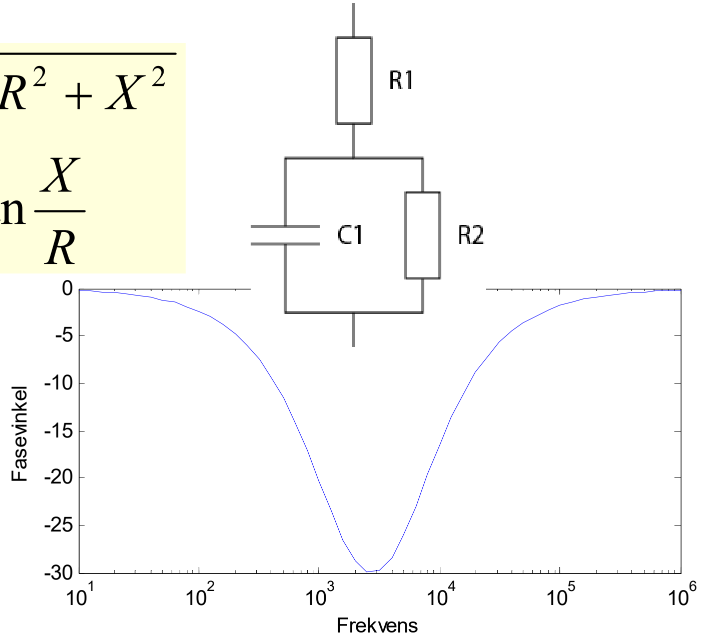
$$\mathbf{Y} = \frac{1}{\mathbf{Z} - R1} = \frac{1}{\dfrac{R2}{(R2\omega C1)^2 + 1} - j\dfrac{R2^2\,\omega C1}{(R2\omega C1)^2 + 1}} = \frac{(R2\omega C1)^2 + 1}{R2 - jR2^2\,\omega C1}$$

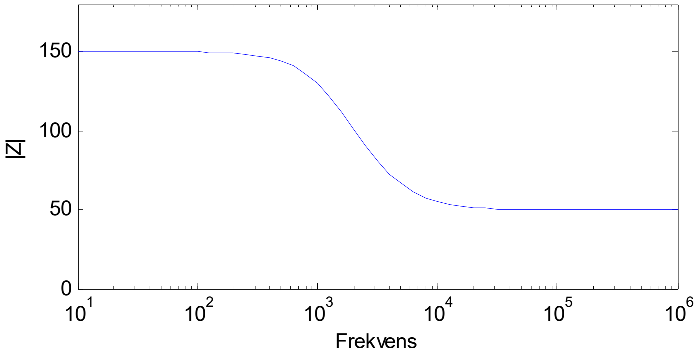
$$\mathbf{Y} = \frac{1}{R2} + j\omega C1$$

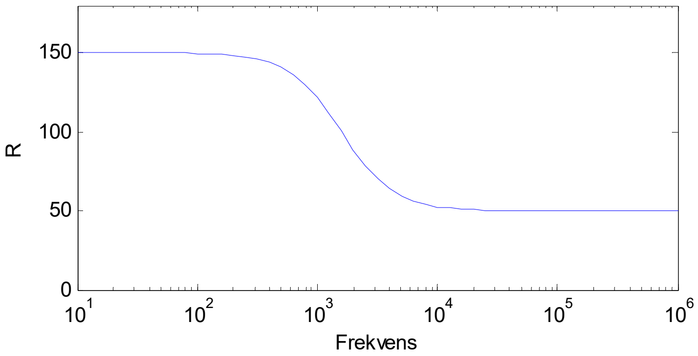
R1 = 50 Ω
R2 = 100 Ω
C1 = 1 μF

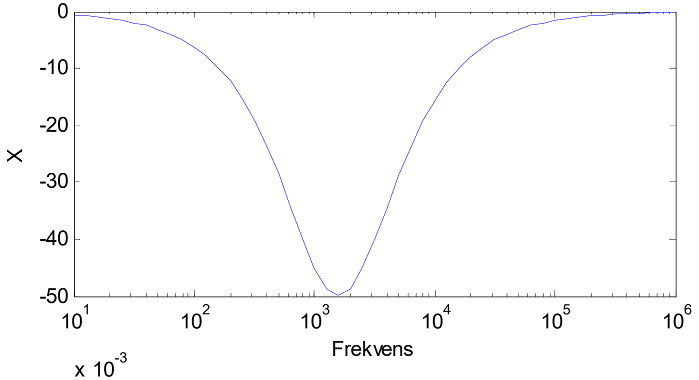
$$|\mathbf{Z}| = \sqrt{R^2 + X^2}$$

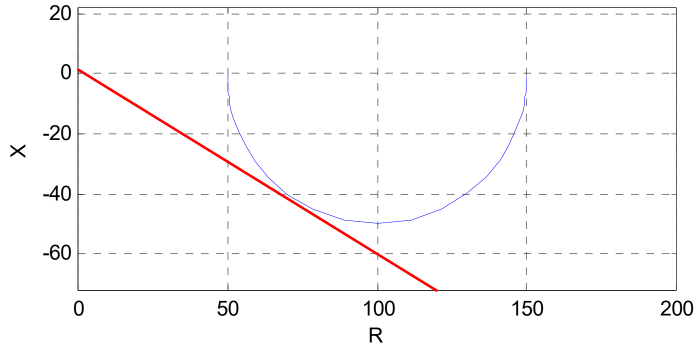
$$\varphi = \operatorname{atan}\frac{X}{R}$$

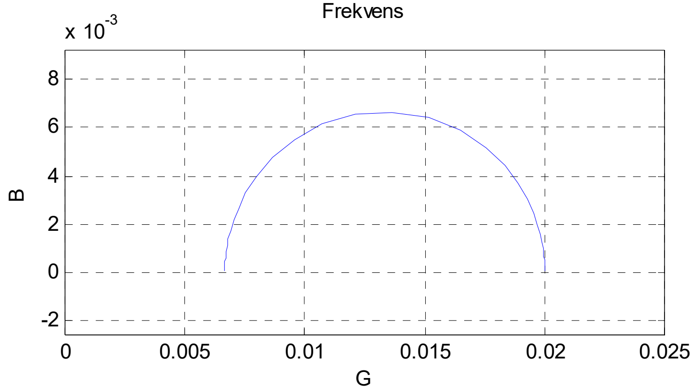












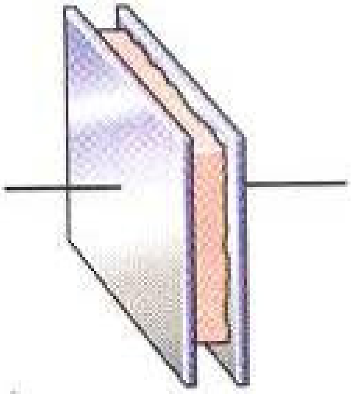
Material properties

Simple parallel plate:

$$\text{Resistivity}: \quad \rho = \mathrm{R}\frac{\mathrm{A}}{\mathrm{d}}$$

$$\text{Conductivity}: \quad \sigma = G\frac{d}{A}$$

$$\text{Permittivity}: \quad \varepsilon = \varepsilon_0 \varepsilon_r = C\frac{d}{A}$$



Complex values

$$\boldsymbol{\sigma} = \sigma' + j\,\sigma''$$

$$\boldsymbol{\rho} = \rho' + j\,\rho''$$

$$\boldsymbol{\varepsilon} = \varepsilon' + j\,\varepsilon''$$

In tissue

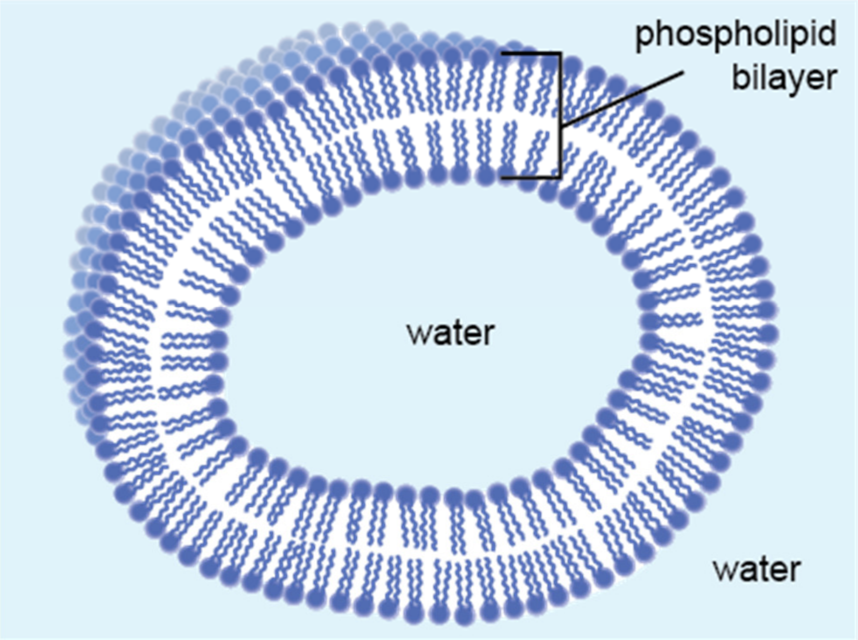
Conductance: Na^+, K^+, Ca^{++}, Cl^-

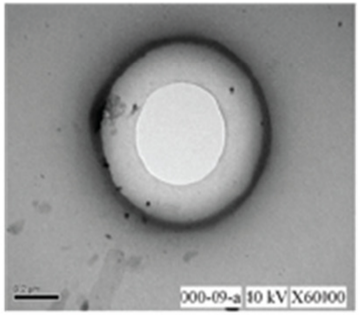
$$\text{Susceptance: } B = \omega C = 2\pi f \varepsilon_0 \varepsilon_r \frac{A}{d}$$

$\approx 1 \mu F / cm^2$

A few nanometers

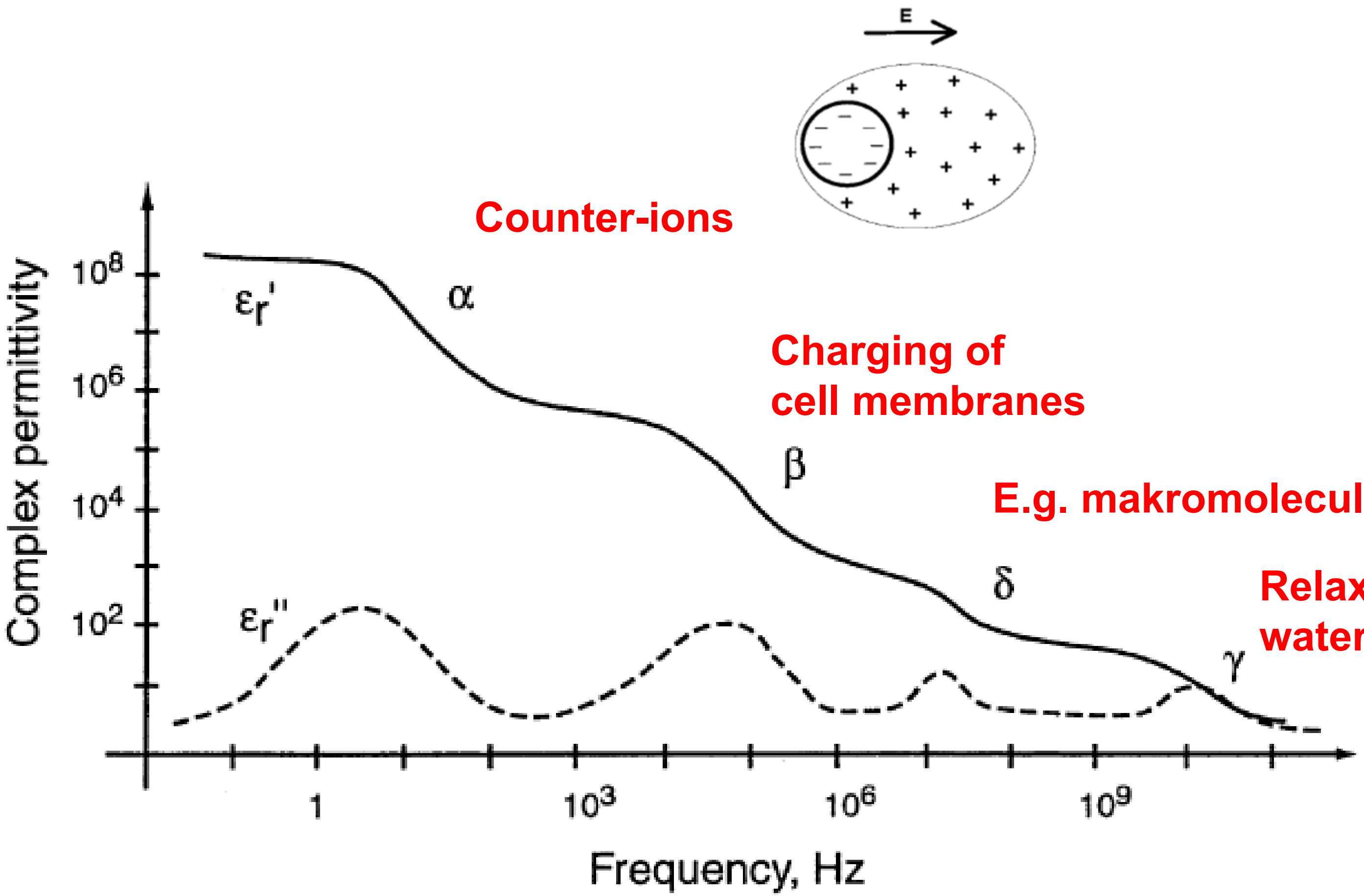
- **Electrode =** transfer between ionic and electronic current
- Susceptance – polarization due to:
  - Ions moving along cell surface (low frequency)
  - Membrane as dielectric (higher frequencies)
  - Water dipole orientation (GHz)





TEM image of a liposome at 60,000x magnification

Dispersions



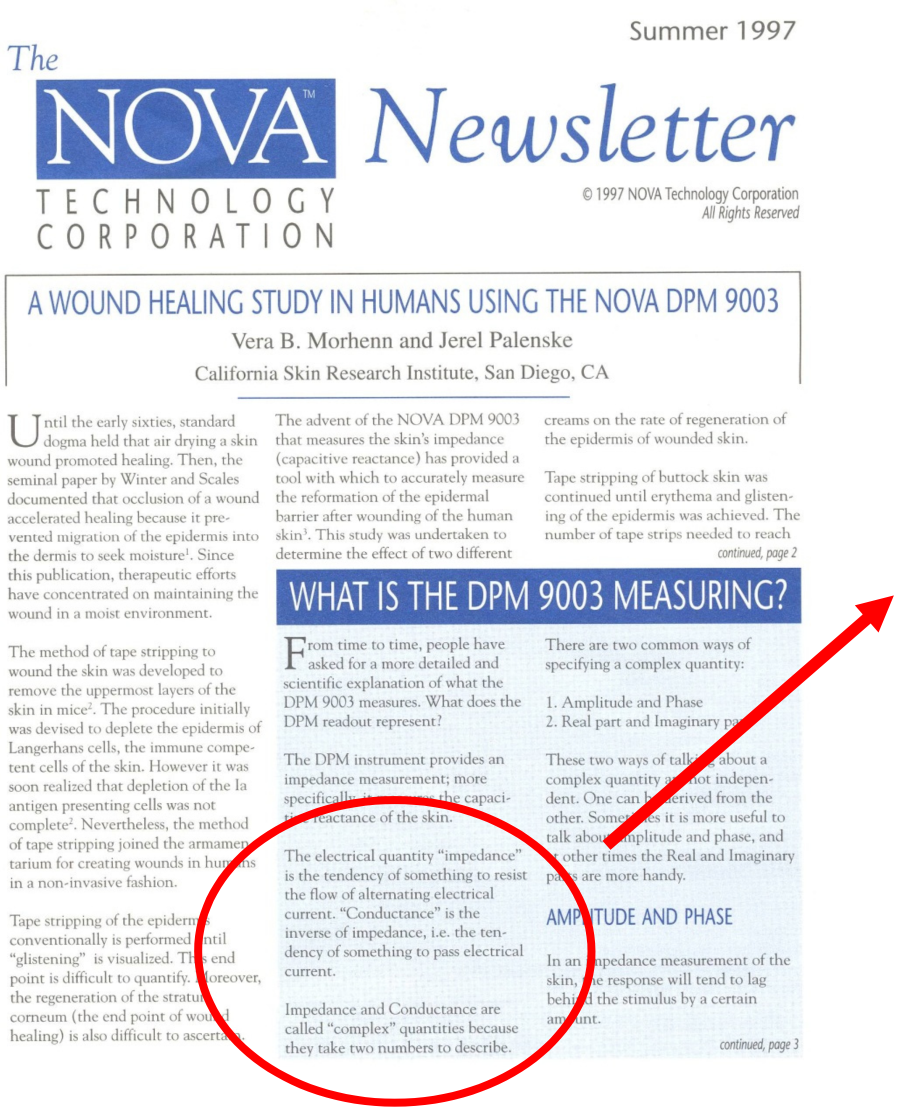
Counter-ions

**Charging of
cell membranes**

E.g. makromolecules

**Relaxation of
water molecules**

Important to speak the same language …



Summer 1997

The NOVA™ Newsletter

NOVA TECHNOLOGY CORPORATION

© 1997 NOVA Technology Corporation
All Rights Reserved

A WOUND HEALING STUDY IN HUMANS USING THE NOVA DPM 9003

Vera B. Morhenn and Jerel Palenske
California Skin Research Institute, San Diego, CA

Until the early sixties, standard dogma held that air drying a skin wound promoted healing. Then, the seminal paper by Winter and Scales documented that occlusion of a wound accelerated healing because it prevented migration of the epidermis into the dermis to seek moisture[1]. Since this publication, therapeutic efforts have concentrated on maintaining the wound in a moist environment.

The method of tape stripping to wound the skin was developed to remove the uppermost layers of the skin in mice[2]. The procedure initially was devised to deplete the epidermis of Langerhans cells, the immune competent cells of the skin. However it was soon realized that depletion of the Ia antigen presenting cells was not complete[2]. Nevertheless, the method of tape stripping joined the armamentarium for creating wounds in humans in a non-invasive fashion.

Tape stripping of the epidermis conventionally is performed until "glistening" is visualized. This end point is difficult to quantify. Moreover, the regeneration of the stratum corneum (the end point of wound healing) is also difficult to ascertain.

The advent of the NOVA DPM 9003 that measures the skin's impedance (capacitive reactance) has provided a tool with which to accurately measure the reformation of the epidermal barrier after wounding of the human skin[3]. This study was undertaken to determine the effect of two different creams on the rate of regeneration of the epidermis of wounded skin.

Tape stripping of buttock skin was continued until erythema and glistening of the epidermis was achieved. The number of tape strips needed to reach

continued, page 2

WHAT IS THE DPM 9003 MEASURING?

From time to time, people have asked for a more detailed and scientific explanation of what the DPM 9003 measures. What does the DPM readout represent?

The DPM instrument provides an impedance measurement; more specifically, it measures the capacitive reactance of the skin.

The electrical quantity "impedance" is the tendency of something to resist the flow of alternating electrical current. "Conductance" is the inverse of impedance, i.e. the tendency of something to pass electrical current.

Impedance and Conductance are called "complex" quantities because they take two numbers to describe.

There are two common ways of specifying a complex quantity:

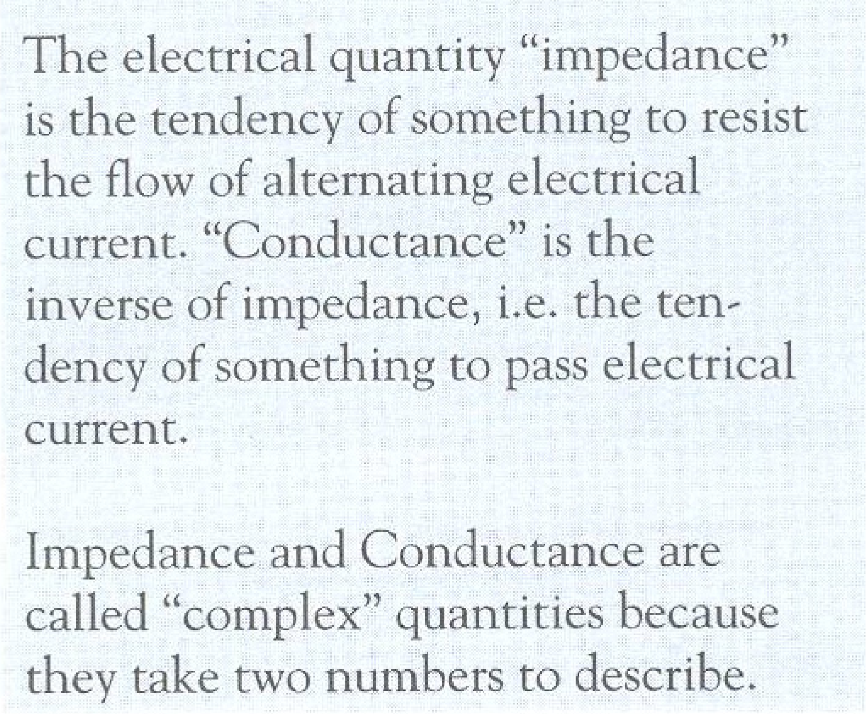
1. Amplitude and Phase
2. Real part and Imaginary part

These two ways of talking about a complex quantity are not independent. One can be derived from the other. Sometimes it is more useful to talk about amplitude and phase, and at other times the Real and Imaginary parts are more handy.

AMPLITUDE AND PHASE

In an impedance measurement of the skin, the response will tend to lag behind the stimulus by a certain amount.

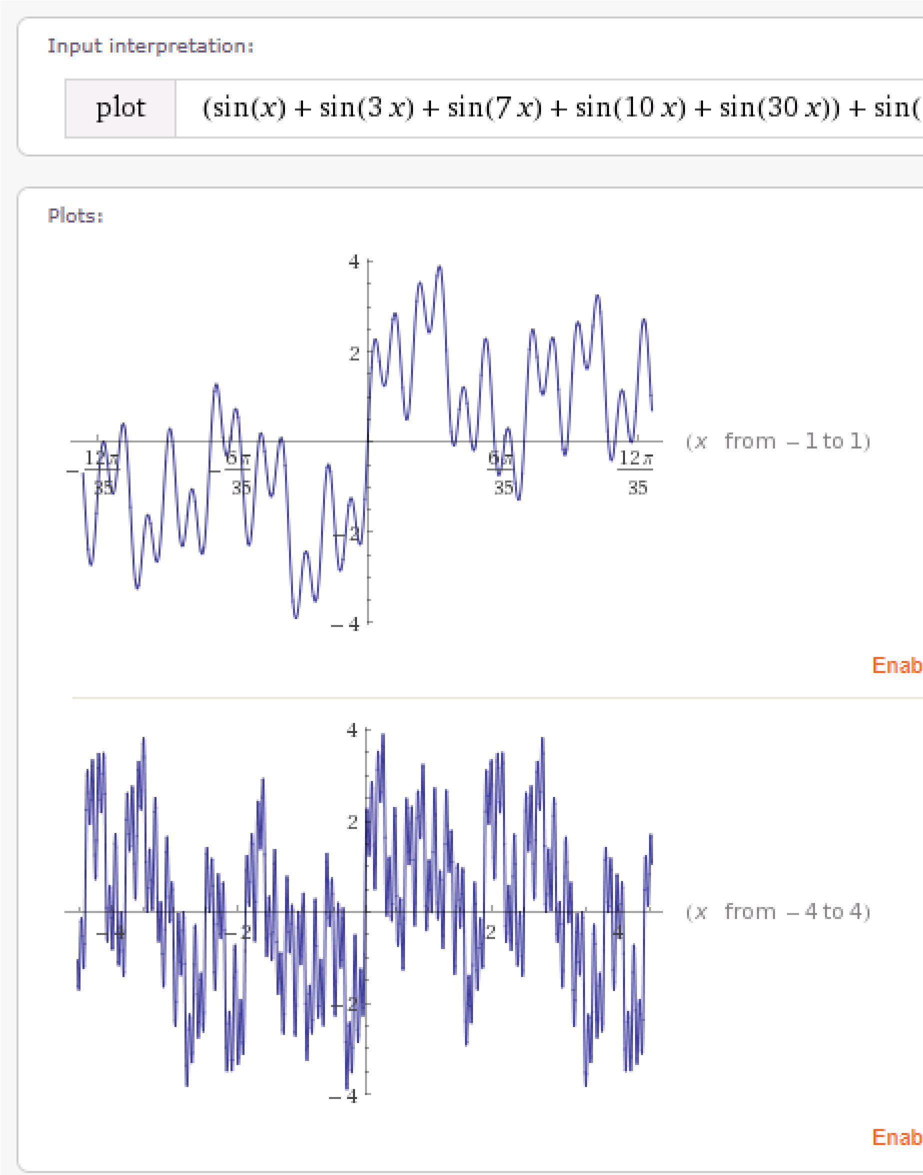
continued, page 3



The electrical quantity "impedance" is the tendency of something to resist the flow of alternating electrical current. "Conductance" is the inverse of impedance, i.e. the tendency of something to pass electrical current.

Impedance and Conductance are called "complex" quantities because they take two numbers to describe.

Multi-sine, chirp, etc.



Input interpretation:

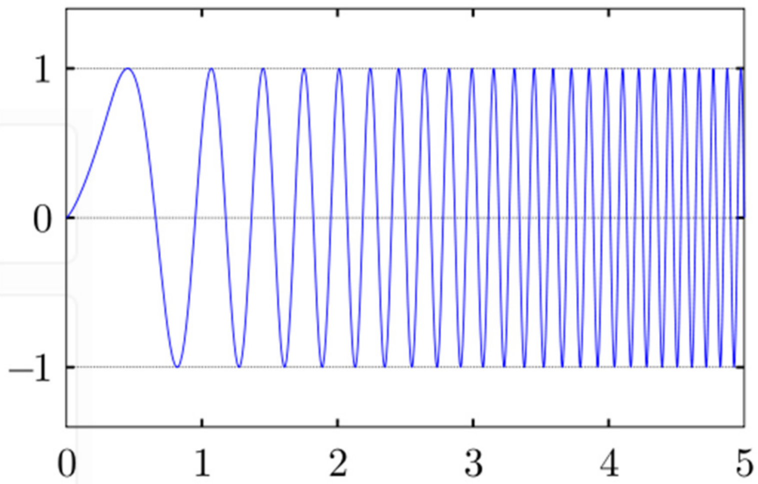
plot	$(\sin(x) + \sin(3x) + \sin(7x) + \sin(10x) + \sin(30x)) + \sin(70x)$

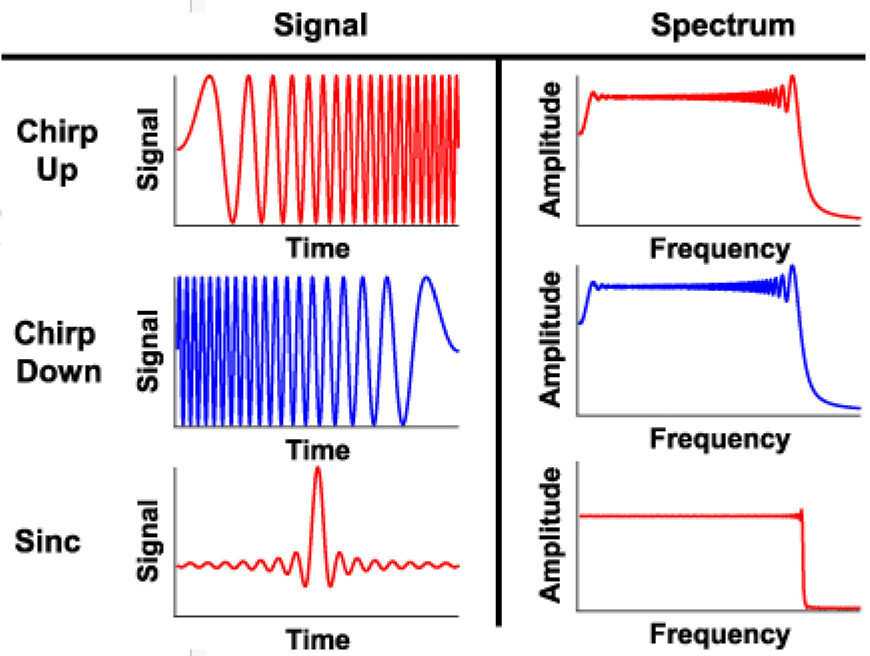
Plots:

(x from −1 to 1)

(x from −4 to 4)

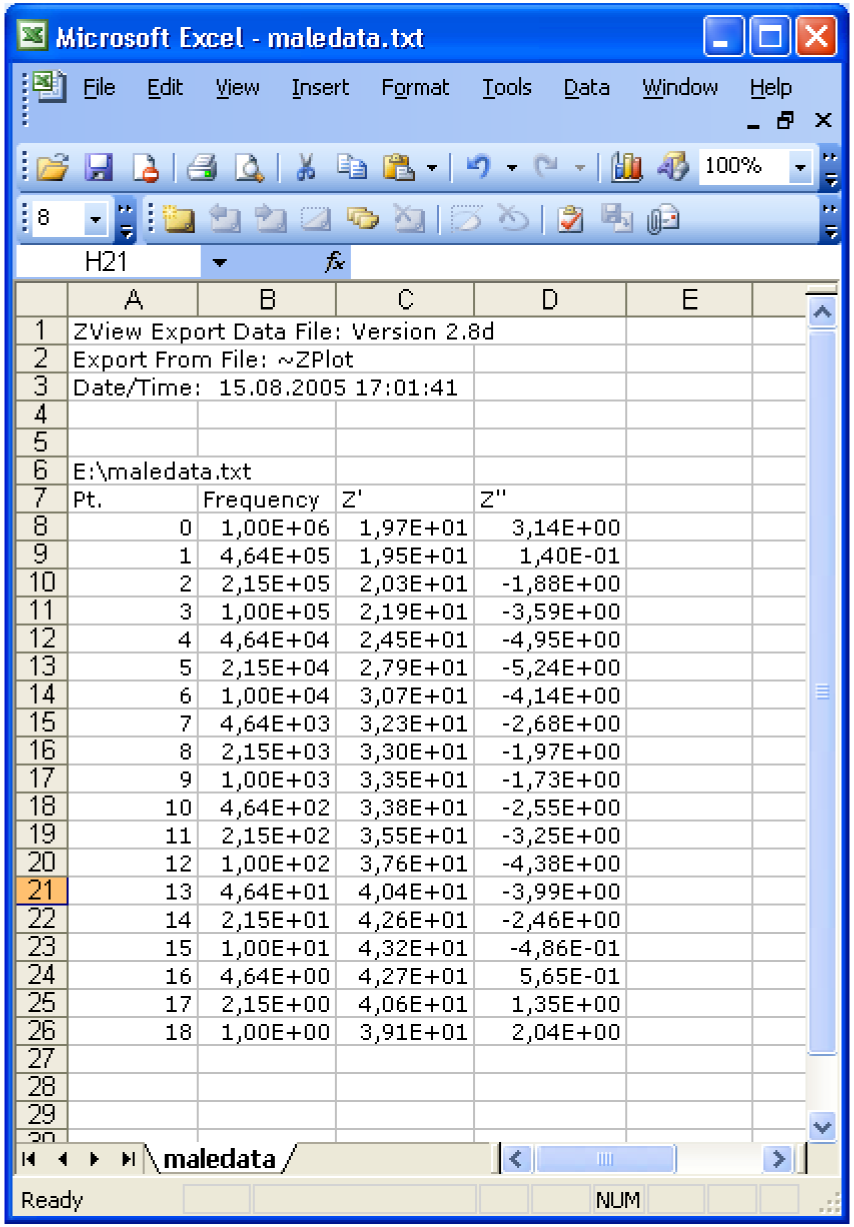
Enable interactivity





The raw data

- Measured with Solartron 1260 + 1294
- Four electrodes on lower leg
- Exported as text file

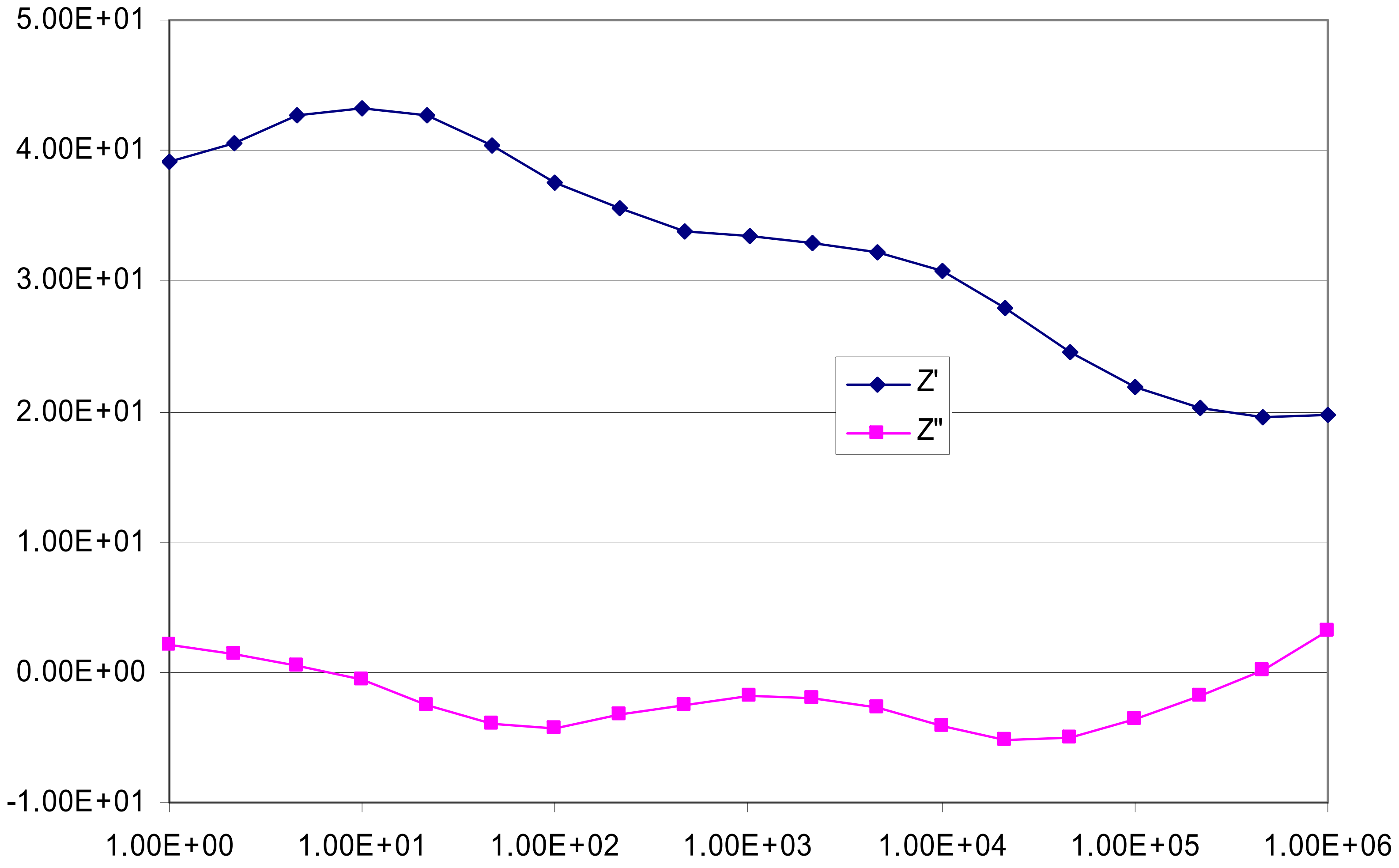


ZView Export Data File: Version 2.8d
Export From File: ~ZPlot
Date/Time: 15.08.2005 17:01:41

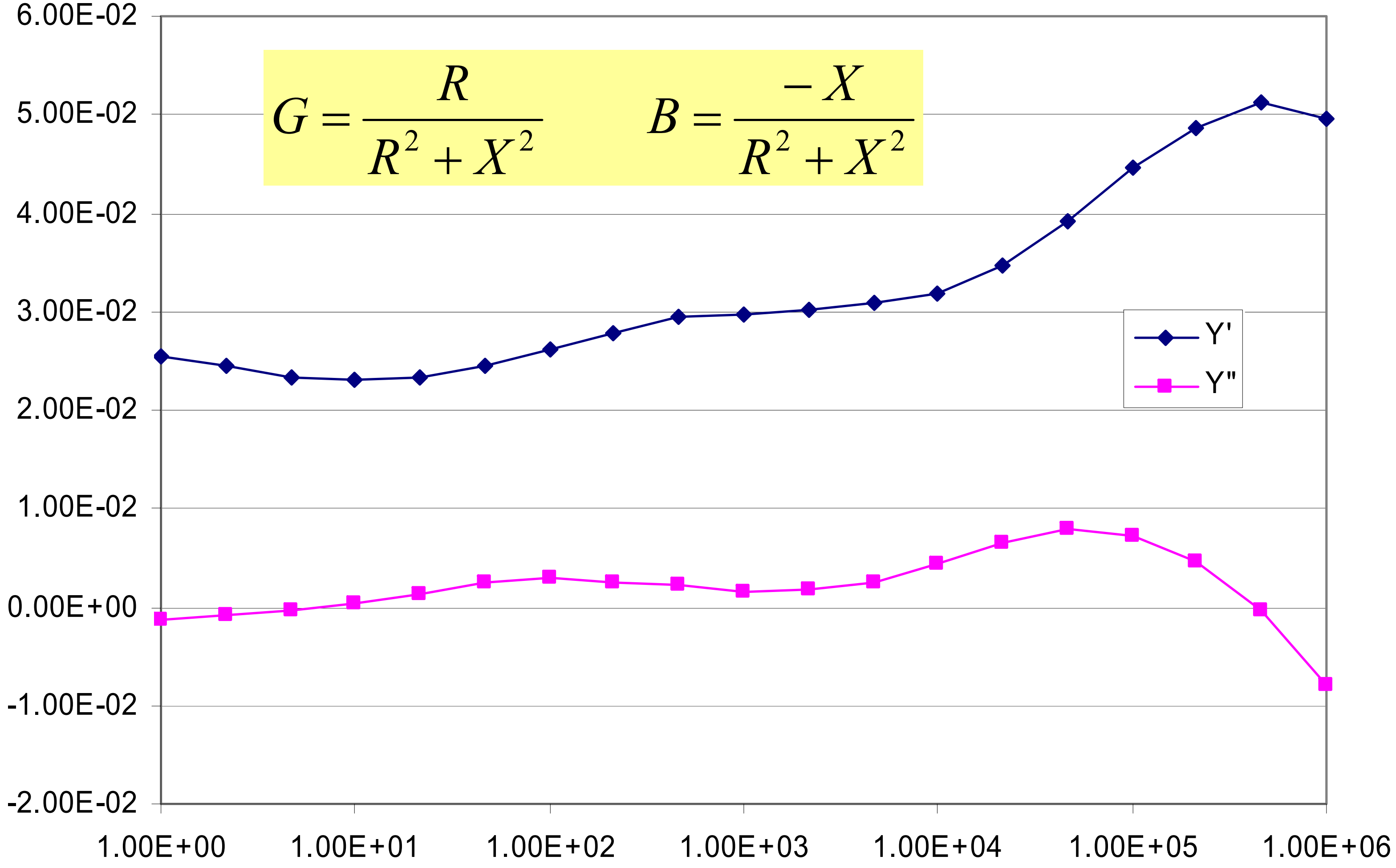
E:\maledata.txt

Pt.	Frequency	Z'	Z''
0	1,00E+06	1,97E+01	3,14E+00
1	4,64E+05	1,95E+01	1,40E-01
2	2,15E+05	2,03E+01	-1,88E+00
3	1,00E+05	2,19E+01	-3,59E+00
4	4,64E+04	2,45E+01	-4,95E+00
5	2,15E+04	2,79E+01	-5,24E+00
6	1,00E+04	3,07E+01	-4,14E+00
7	4,64E+03	3,23E+01	-2,68E+00
8	2,15E+03	3,30E+01	-1,97E+00
9	1,00E+03	3,35E+01	-1,73E+00
10	4,64E+02	3,38E+01	-2,55E+00
11	2,15E+02	3,55E+01	-3,25E+00
12	1,00E+02	3,76E+01	-4,38E+00
13	4,64E+01	4,04E+01	-3,99E+00
14	2,15E+01	4,26E+01	-2,46E+00
15	1,00E+01	4,32E+01	-4,86E-01
16	4,64E+00	4,27E+01	5,65E-01
17	2,15E+00	4,06E+01	1,35E+00
18	1,00E+00	3,91E+01	2,04E+00

Bode plot of impedance

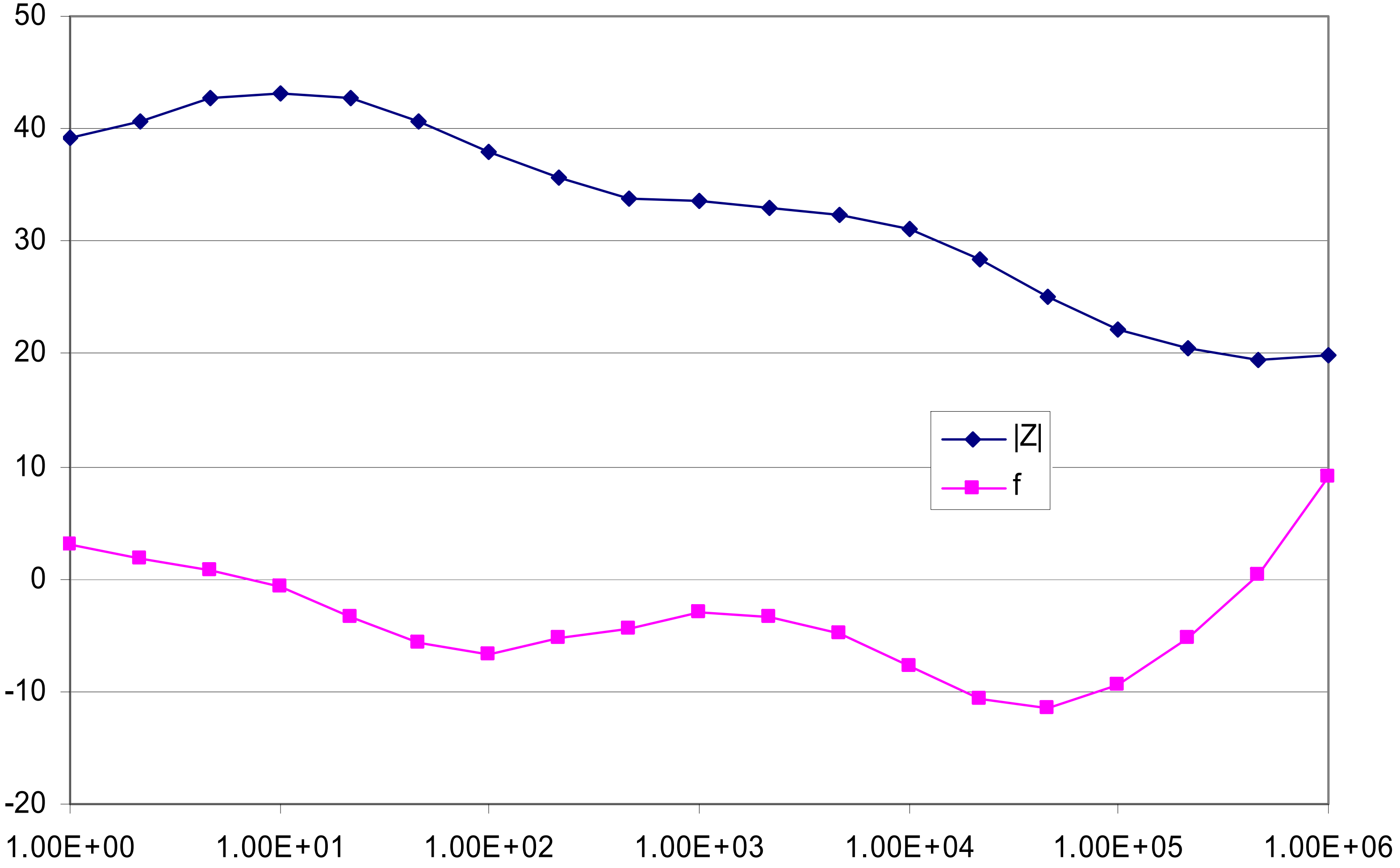


Bode plot of admittance

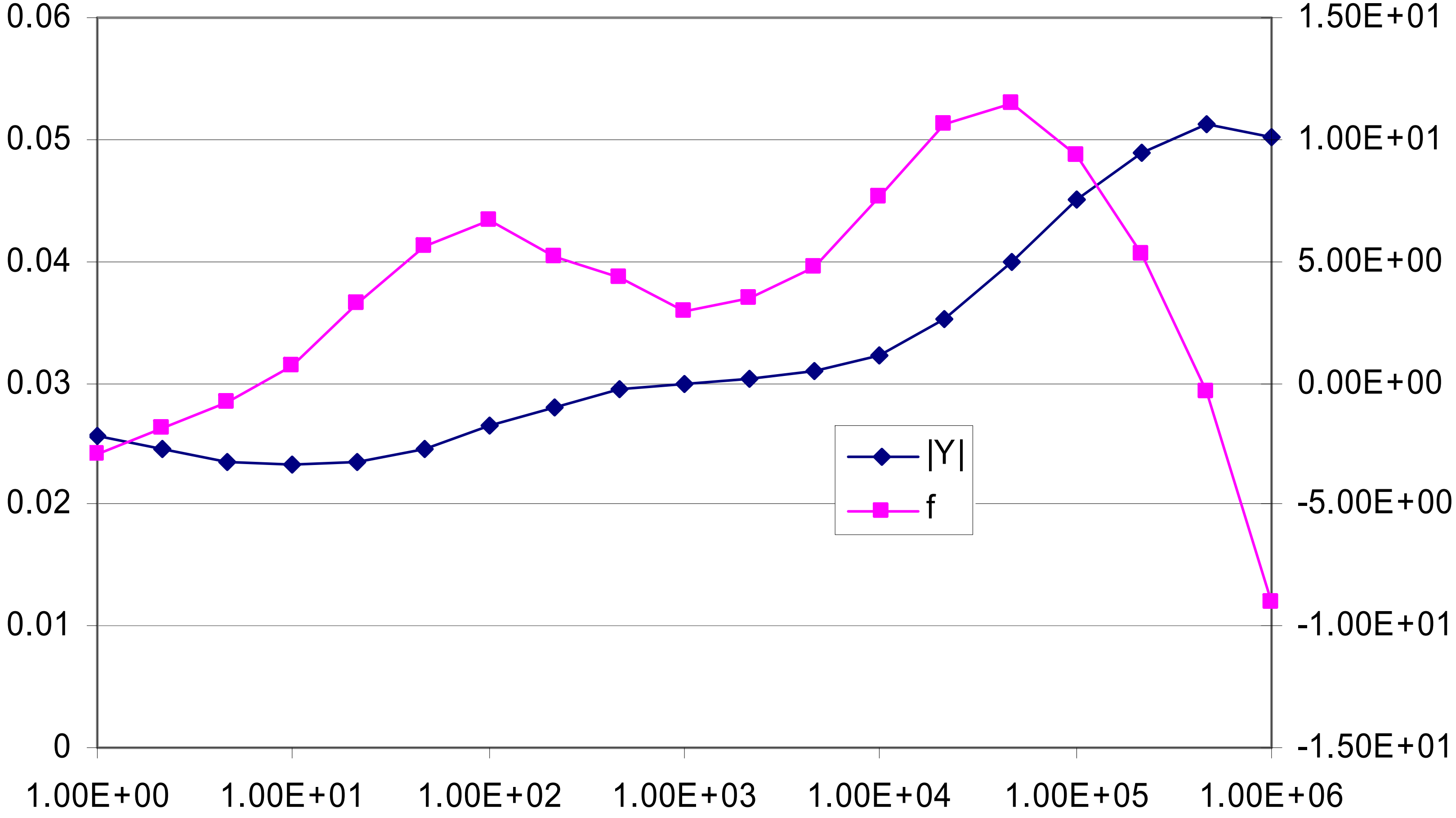


$$G = \frac{R}{R^2 + X^2} \qquad B = \frac{-X}{R^2 + X^2}$$

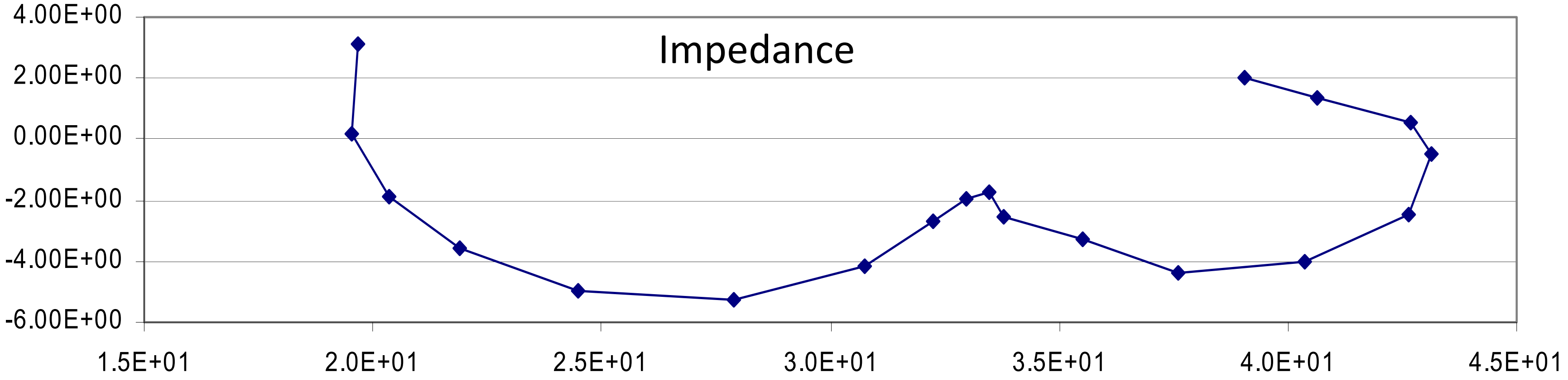
Bode plot of |**Z**| and ϕ

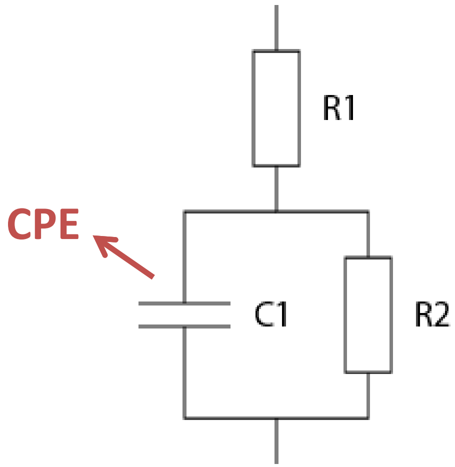


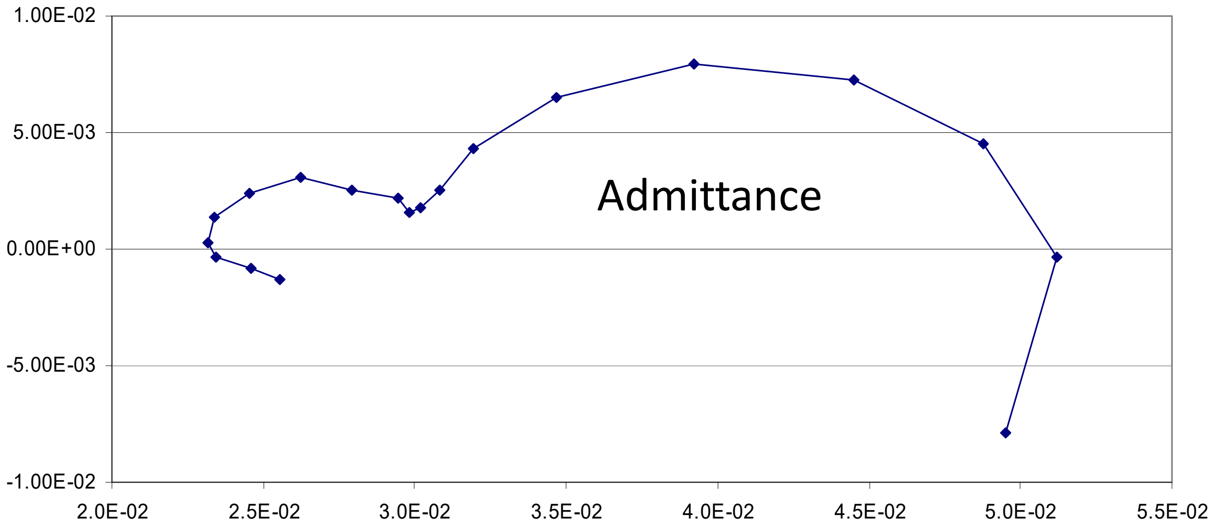
Bode plot of |**Y**| and ϕ



Wessel, Nyquist, Argand, Cole, …

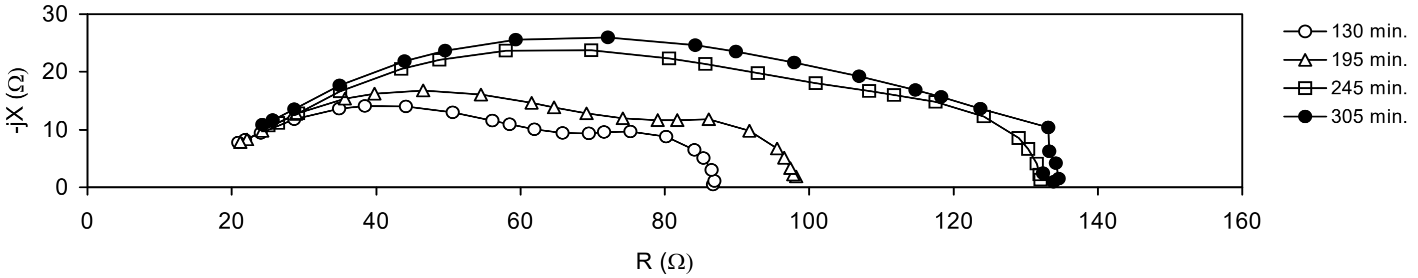


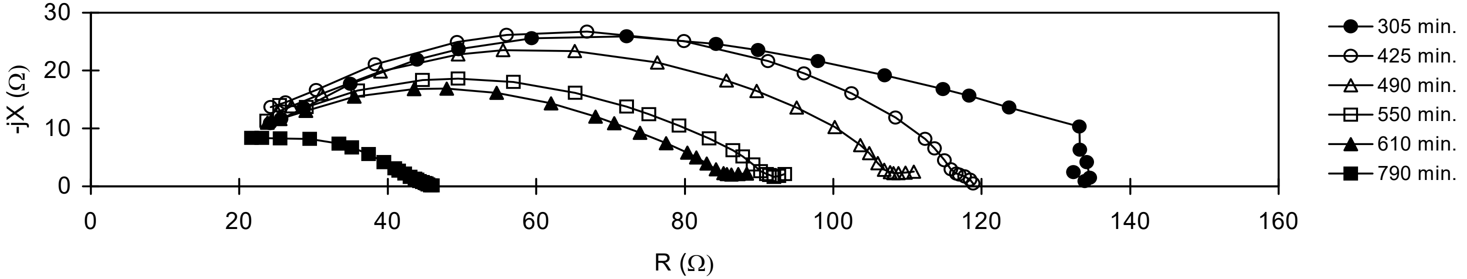




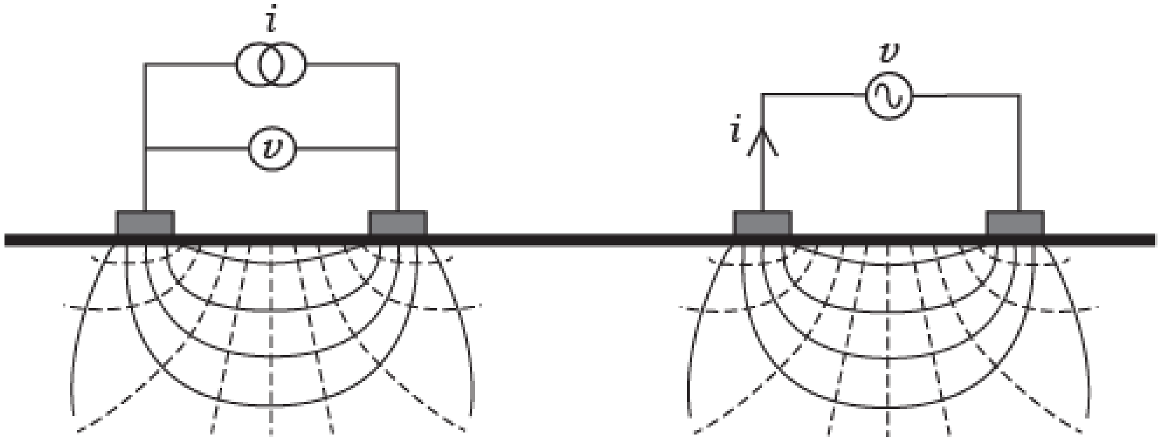
Fish and meat

- Measured on haddock muscle with surface electrodes





Two-electrode system



Impedance $Z = \frac{v}{i}$

Resistance $R = \frac{\mathrm{Re}(v)}{i} = \frac{v}{i}\cos\varphi$

Reactance $X = \frac{\mathrm{Im}(v)}{i} = \frac{v}{i}\sin\varphi$

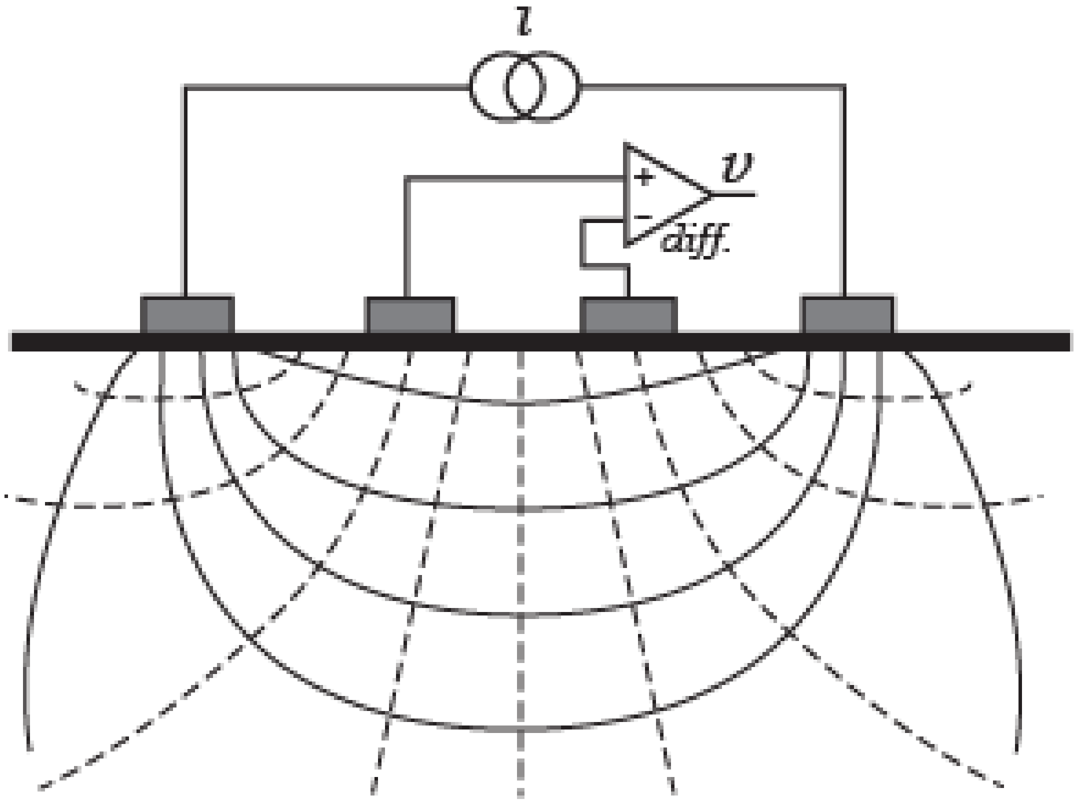
Admittance $Y = \frac{i}{v} \quad \left(= \frac{1}{Z}\right)$

Conductance $G = \frac{\mathrm{Re}(i)}{v} = \frac{i}{v}\cos\varphi$

Susceptance $B = \frac{\mathrm{Im}(i)}{v} = \frac{i}{v}\sin\varphi$

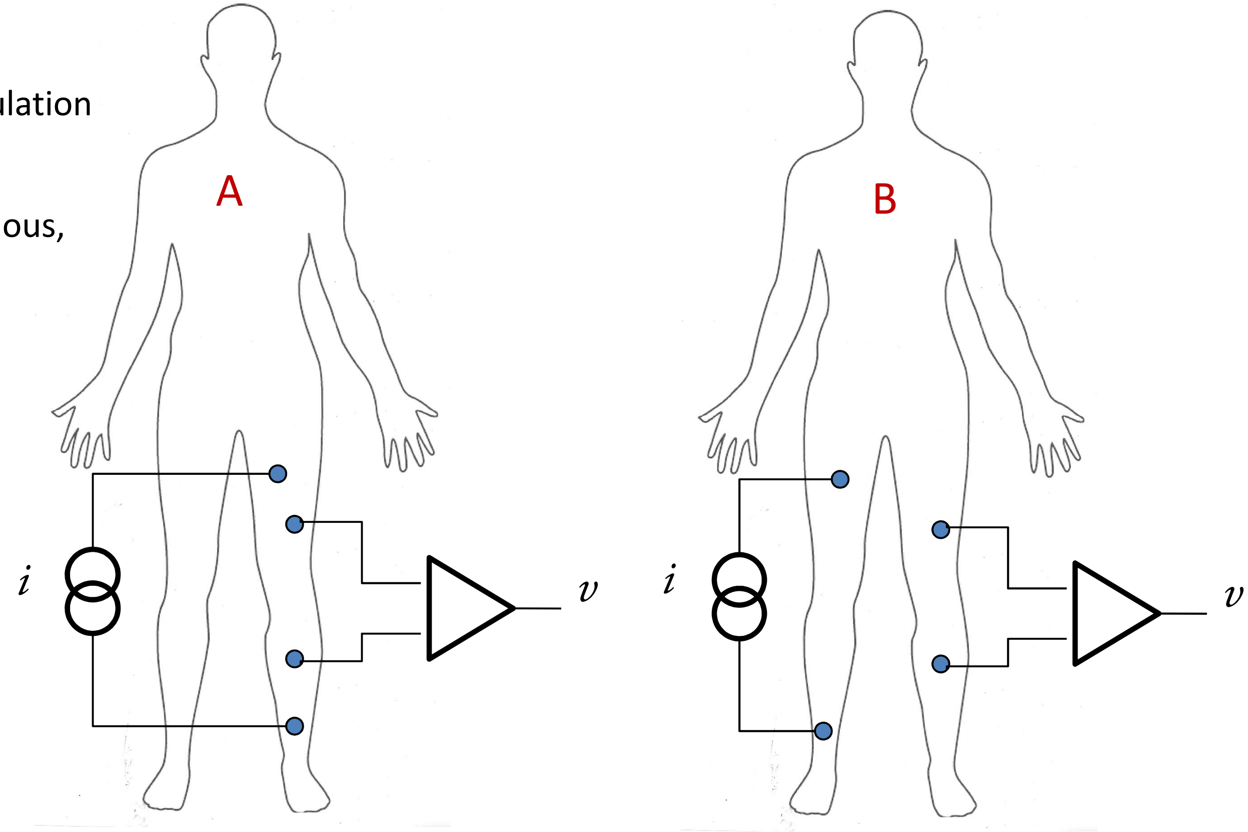
$R = \frac{1}{G}$ only if $\varphi = 0^\circ \left(\cos\varphi = \frac{1}{\cos\varphi}\right)$ and $X = \frac{1}{B}$ only if $\varphi = 90^\circ \left(\sin\varphi = \frac{1}{\sin\varphi}\right)$

Four-electrode system



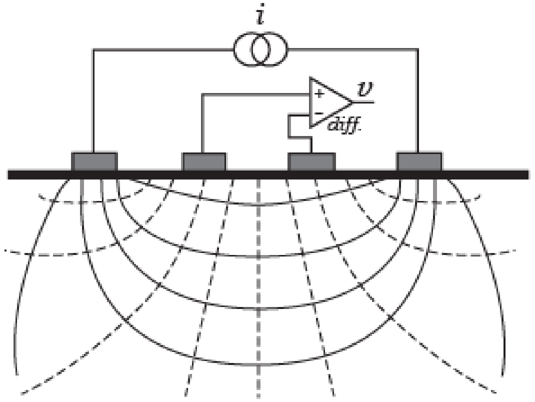
Transfer impedance

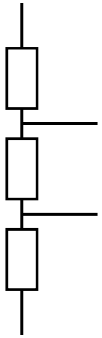
- Input: i , output: v , transfer function: $\frac{v}{i} \equiv Z$
- This is transfer impedance, not impedance
- Cannot use for calculation of σ, ρ or ε
- Except for homogenous, uniform material



Four electrodes – be aware:

- Measures <u>transfer</u> impedance
- Current shunt paths through the pick-up electrodes (⇒ over-estimation of Z)
- Multiple current paths (often ⇒ false positive phase angle)
- Common mode problems
- What happens if the frequency dependence is not the same?



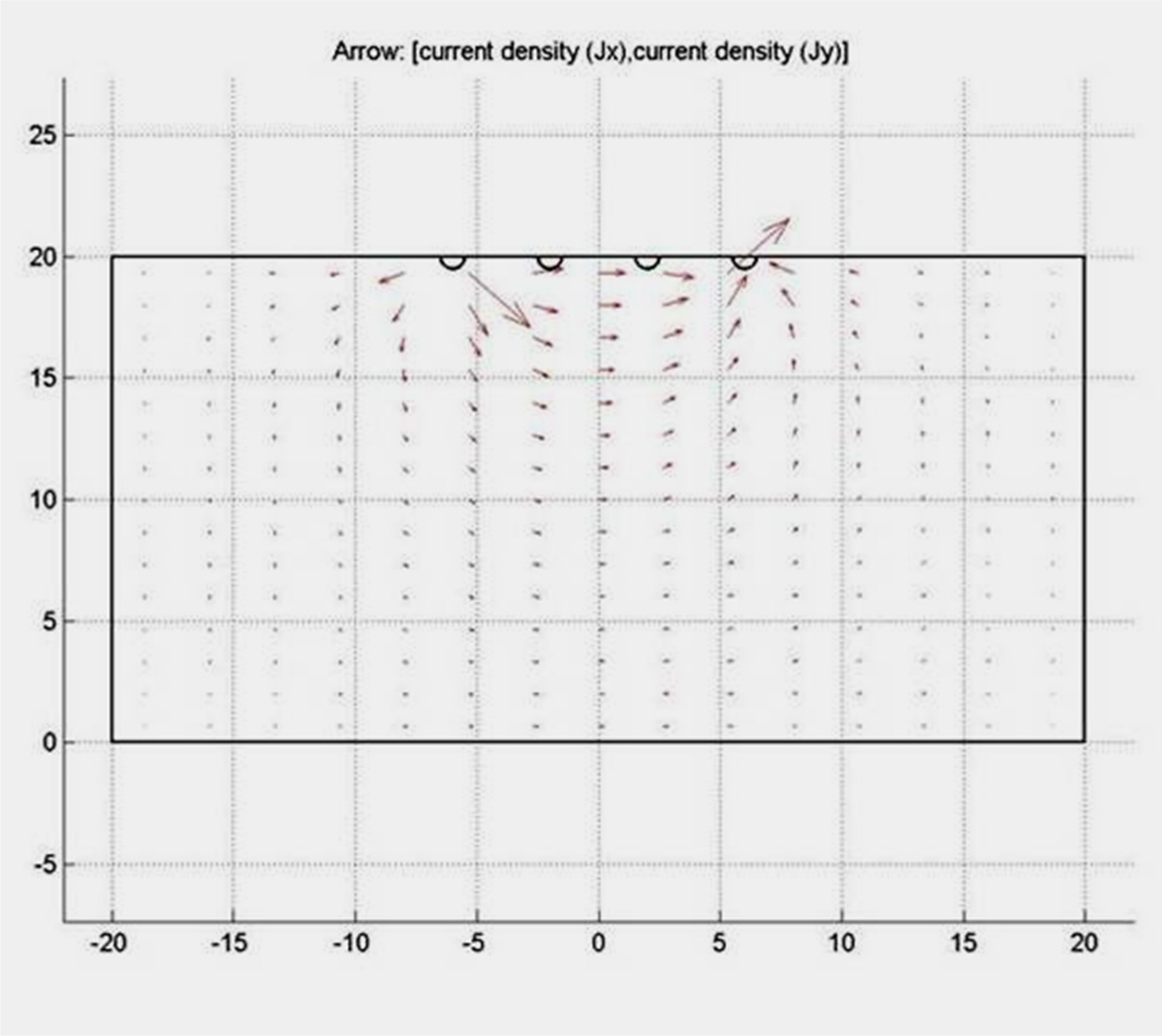


Sensitivity field calculations

- Simple and very powerful tool, but not used very much
- Example: Direct current resistance measurement with a four-electrode system on a homogeneous medium

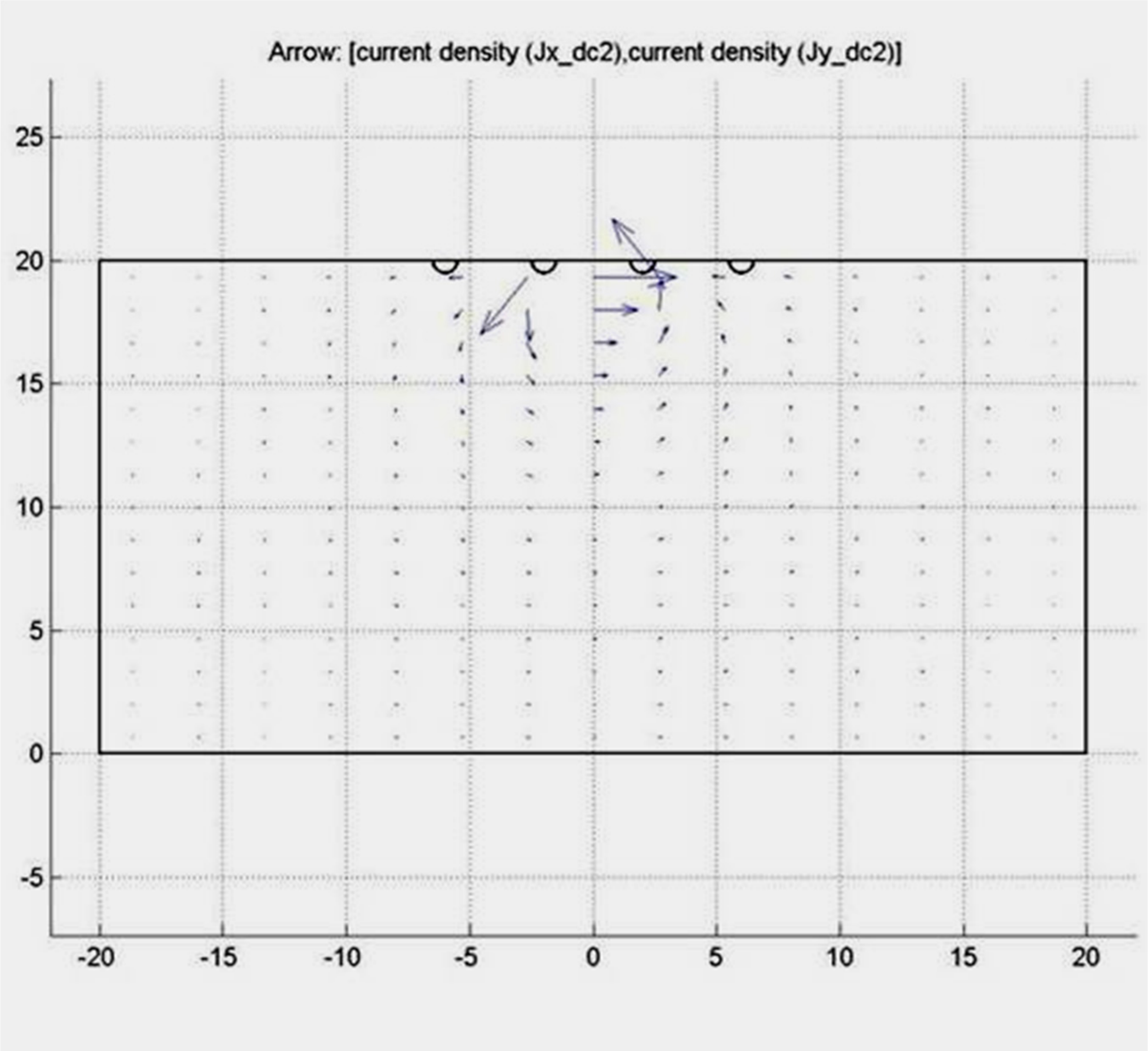
Sensitivity field calculations #1

Imagine that you inject a current *I* between the two current electrodes, and compute the current density $\mathbf{J}_1$ in each small volume element in the material as a result of this current



Sensitivity field calculations $^{\#2}$

Imagine that you instead inject the same current between the voltage pick-up electrodes, and again compute the resulting current density $\mathbf{J}_2$ in each small volume element.



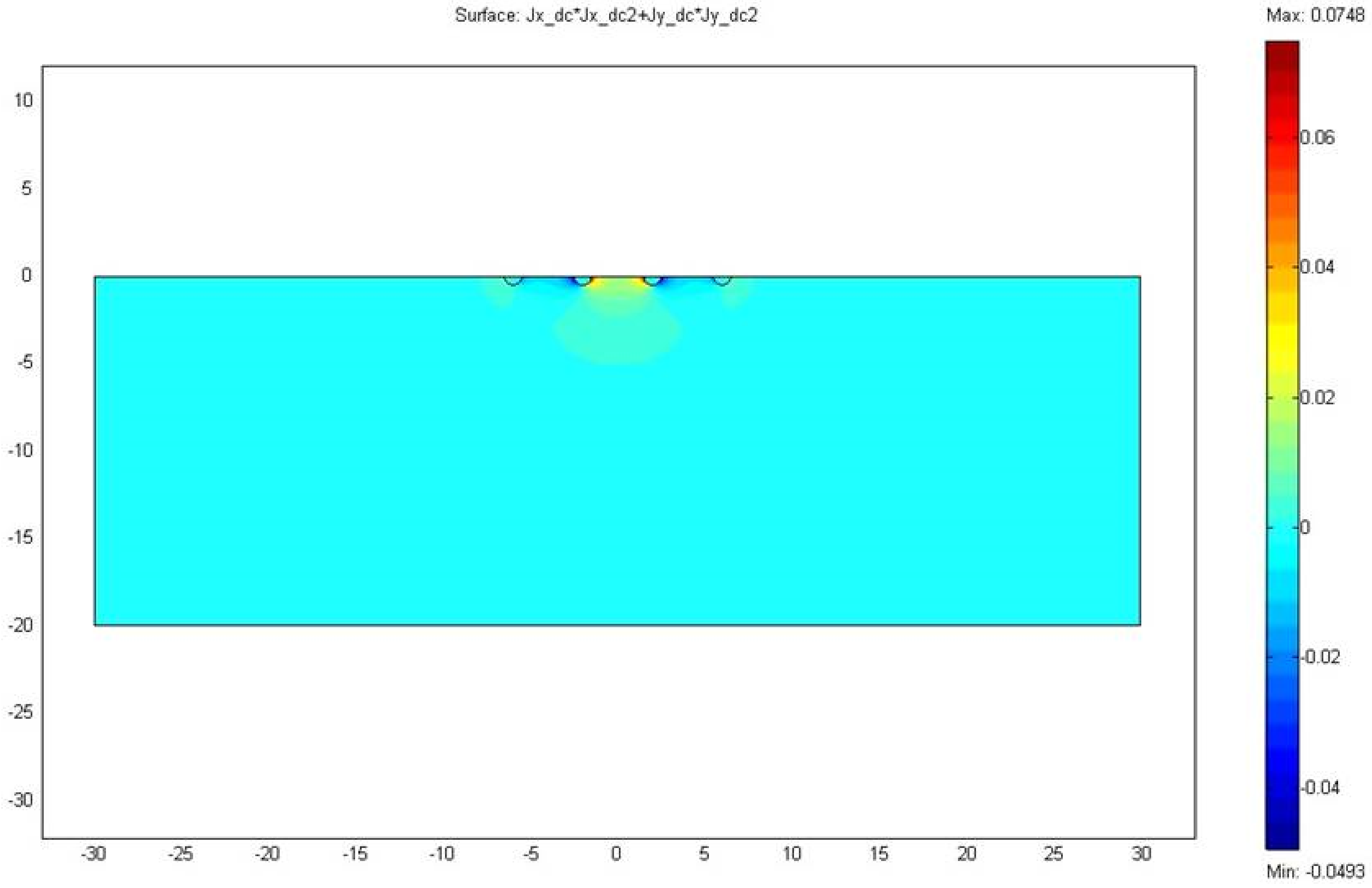
Sensitivity field calculations $^{\#3}$

- The sensitivity S and total measured resistance R are then (reciprocal system):

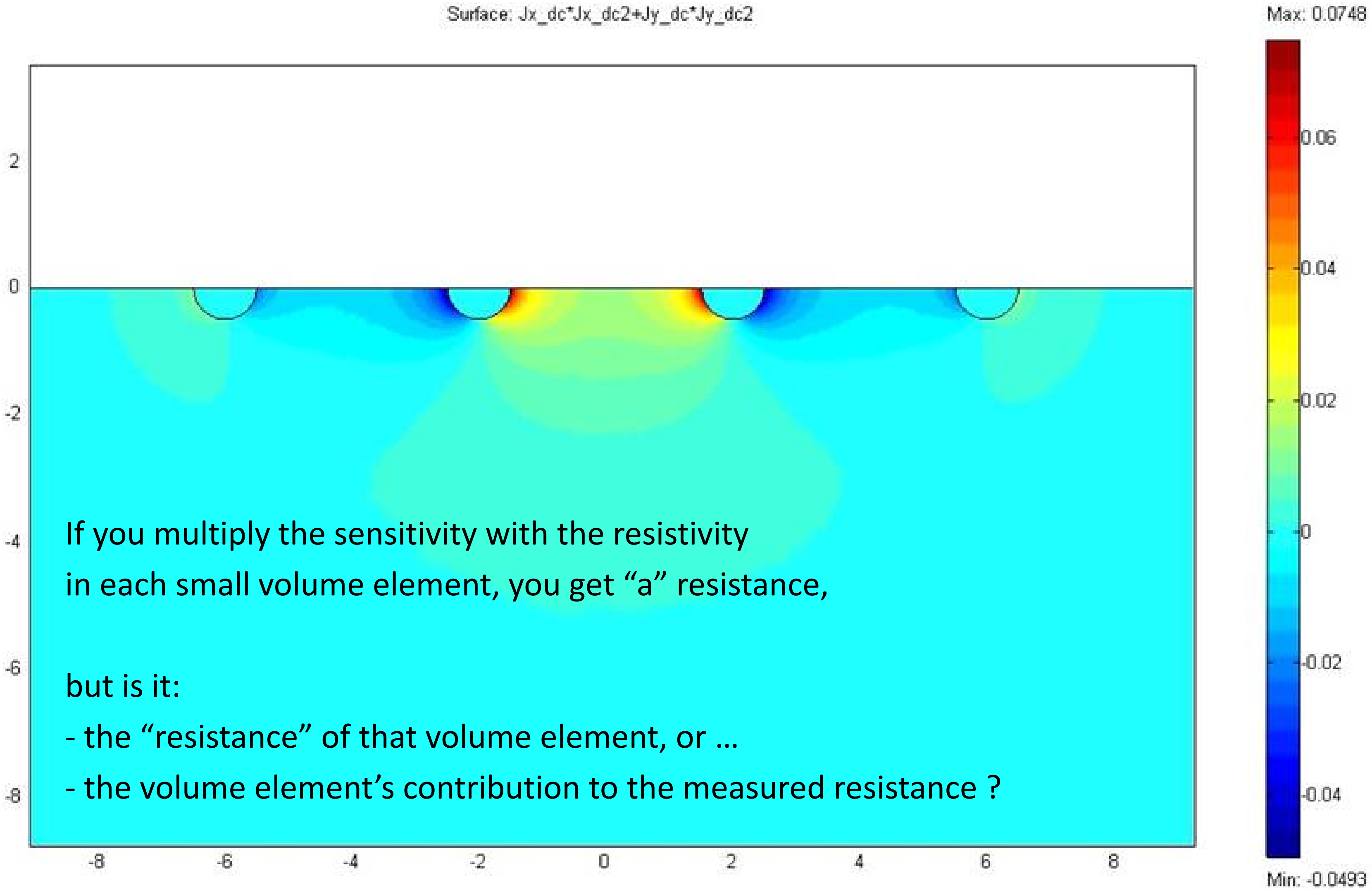
$$S = \frac{\mathbf{J}_1 \cdot \mathbf{J}_2}{I^2} \quad \text{and} \quad R = \int_V \frac{\rho \mathbf{J}_1 \cdot \mathbf{J}_2}{I^2} dv$$

- **Positive S:** Increased resistivity in this area → higher total measured resistance
- **Negative S:** Increased resistivity in this area → lower total measured resistance
- High absolute value of S: Very sensitive to changes in resistivity

Four-electrode system



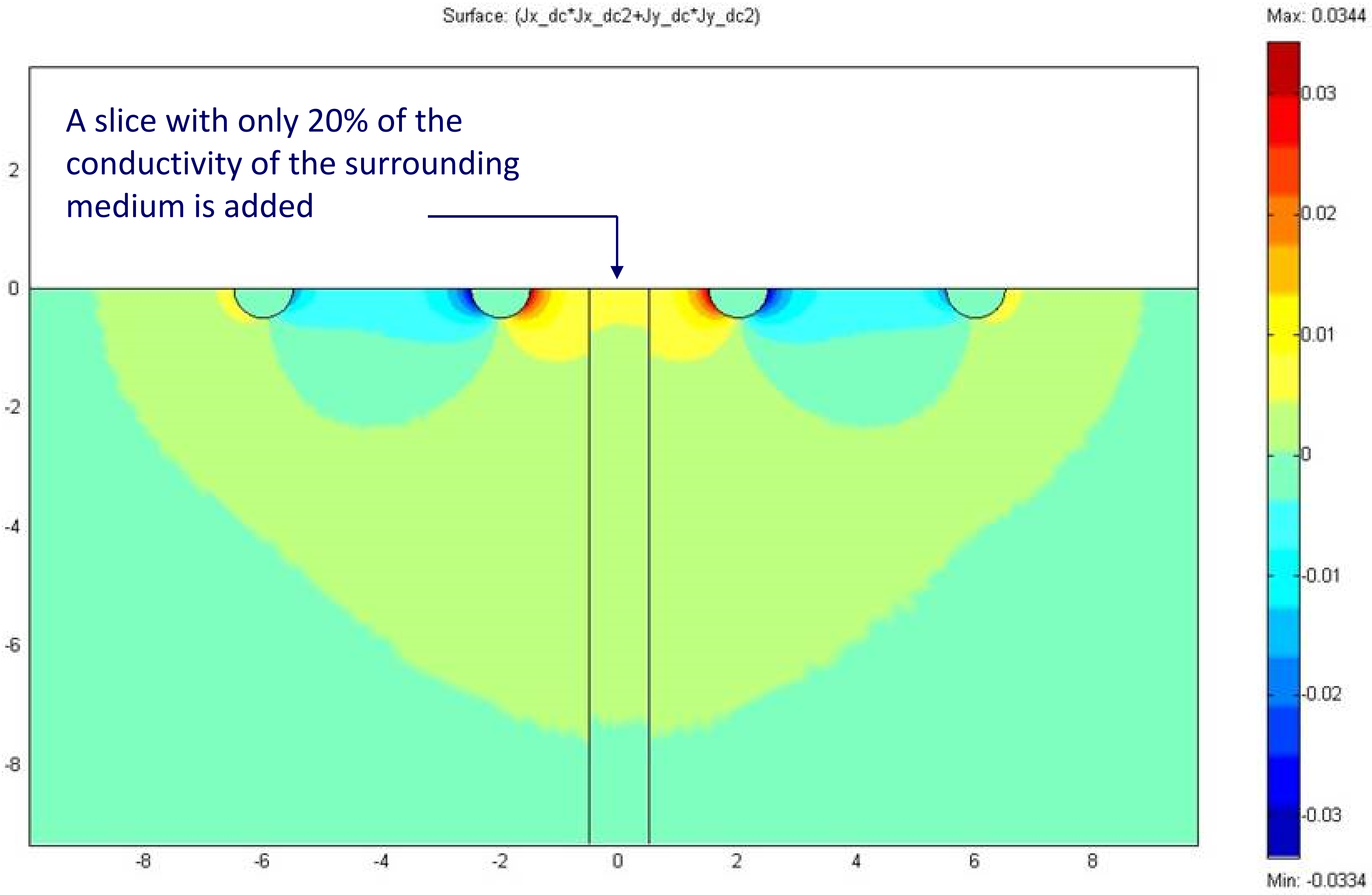
Closer look …



If you multiply the sensitivity with the resistivity
in each small volume element, you get “a” resistance,

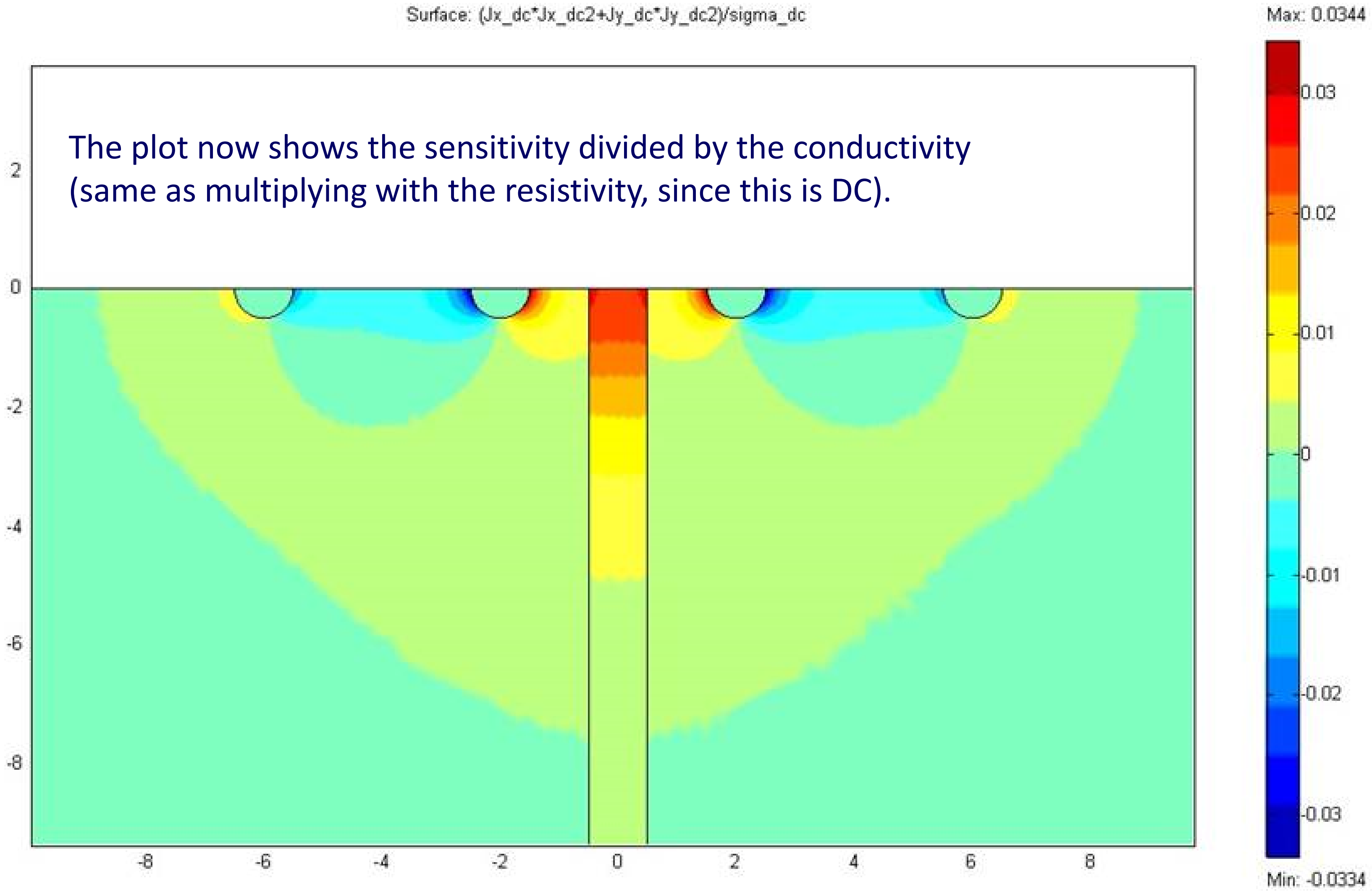
but is it:
- the “resistance” of that volume element, or …
- the volume element’s contribution to the measured resistance ?

Adding a low-conducting slice



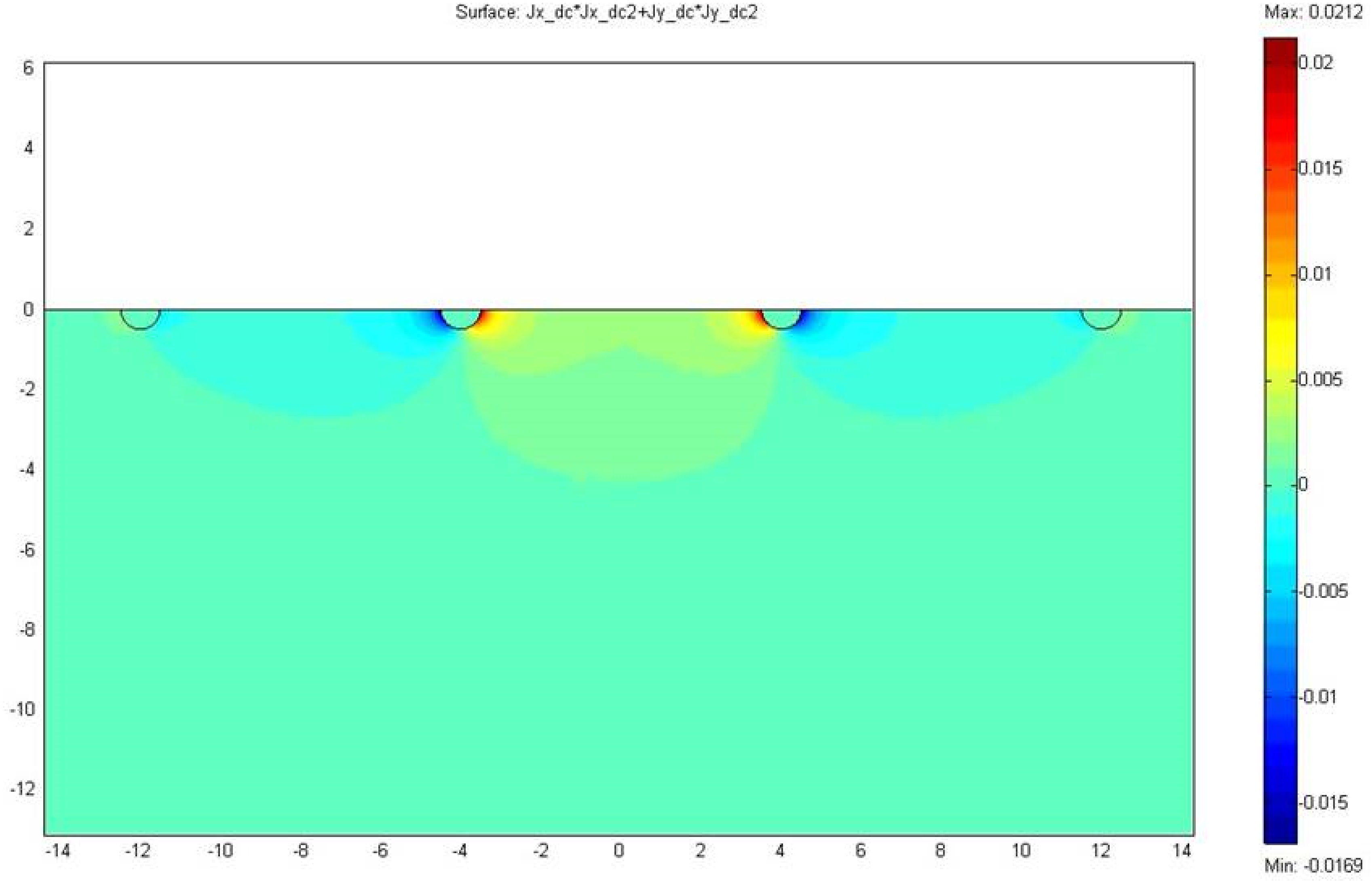
A slice with only 20% of the conductivity of the surrounding medium is added

Volume impedance density

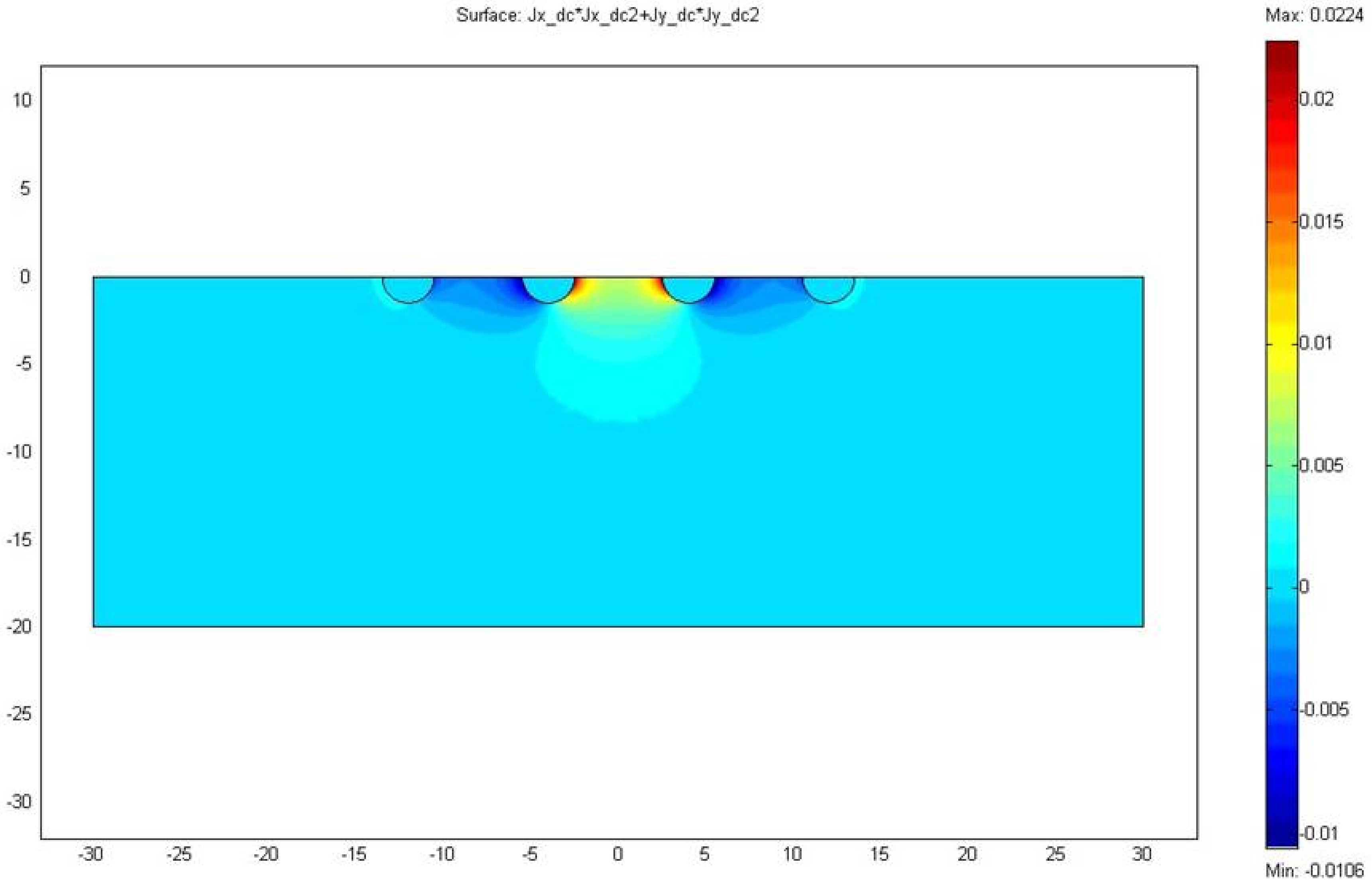


The plot now shows the sensitivity divided by the conductivity (same as multiplying with the resistivity, since this is DC).

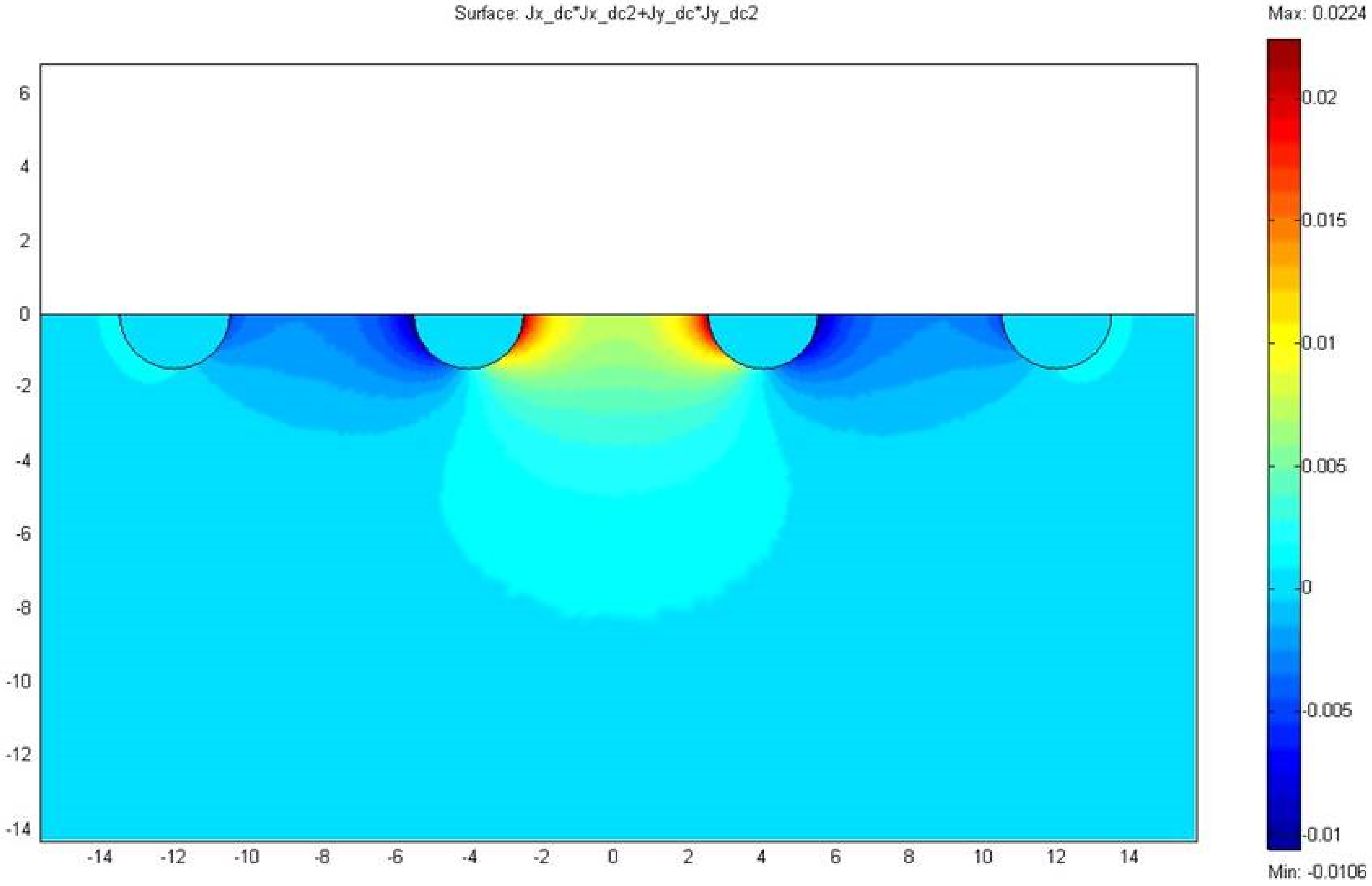
Electrodes further apart



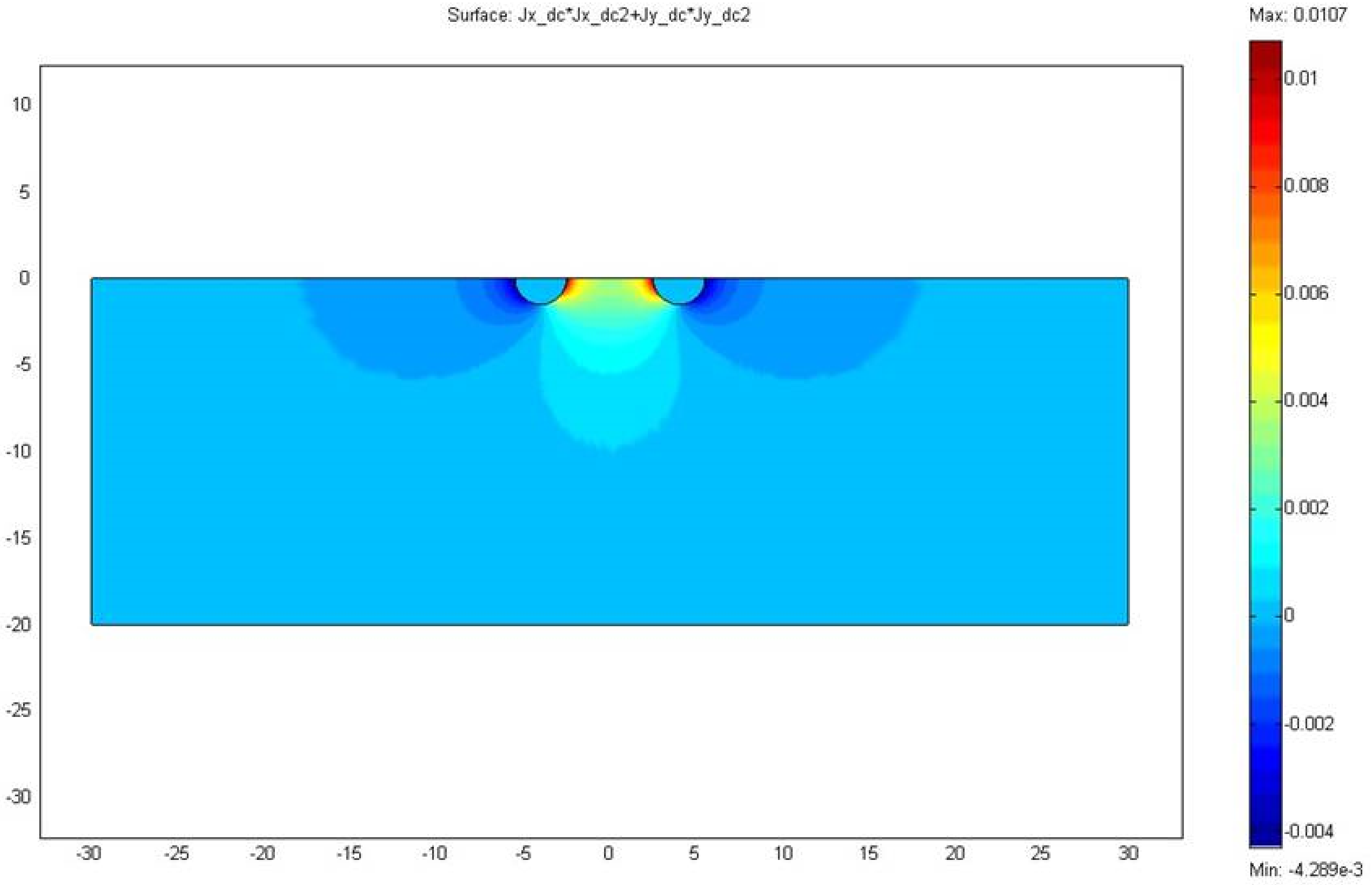
Larger electrodes



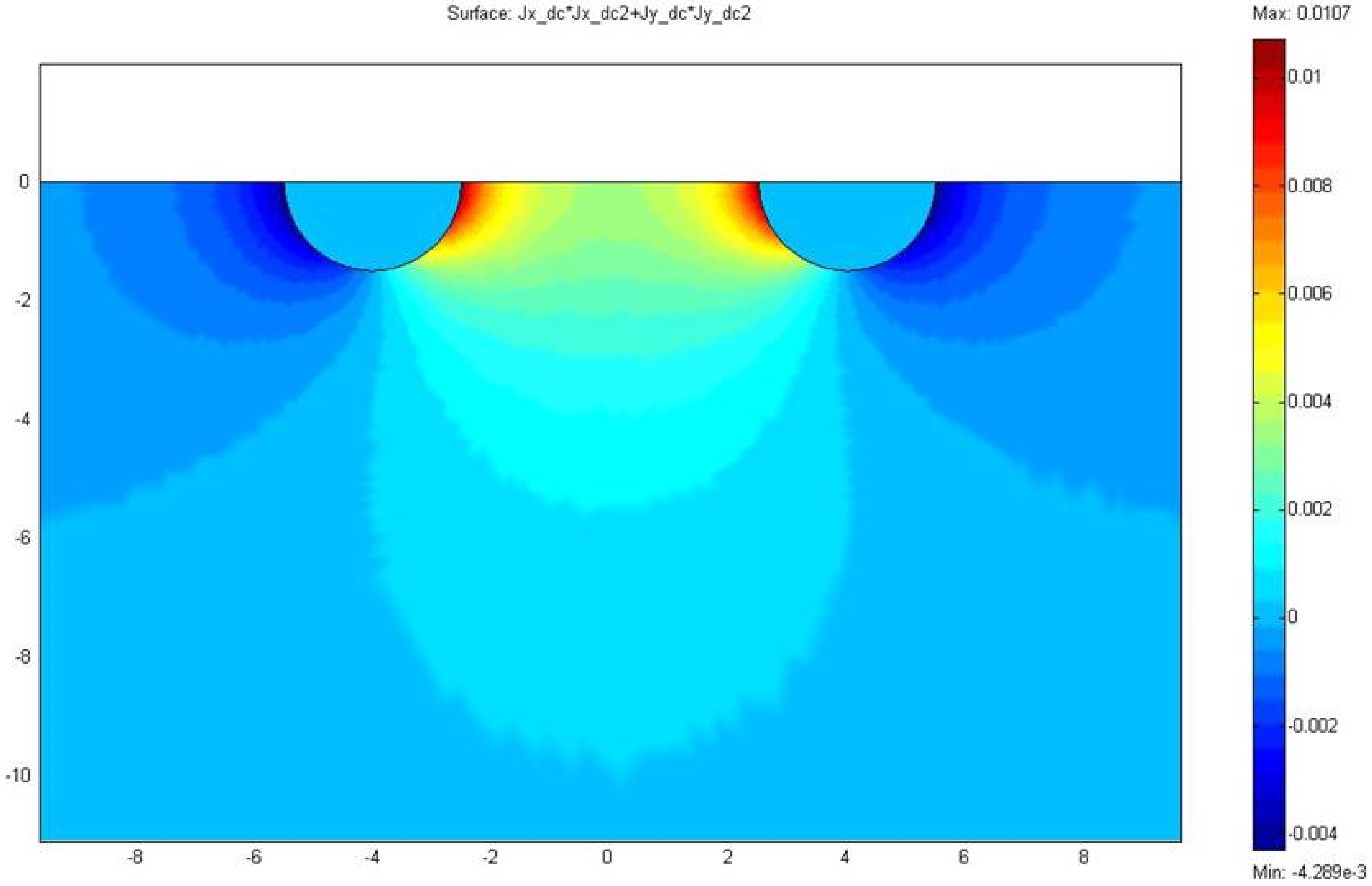
Closer look …


Surface: Jx_dc*Jx_dc2+Jy_dc*Jy_dc2
Max: 0.0224
Min: -0.0106
0.02
0.015
0.01
0.005
0
-0.005
-0.01
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-14
-12
-10
-8
-6
-4
-2
0
2
4
6
8
10
12
14

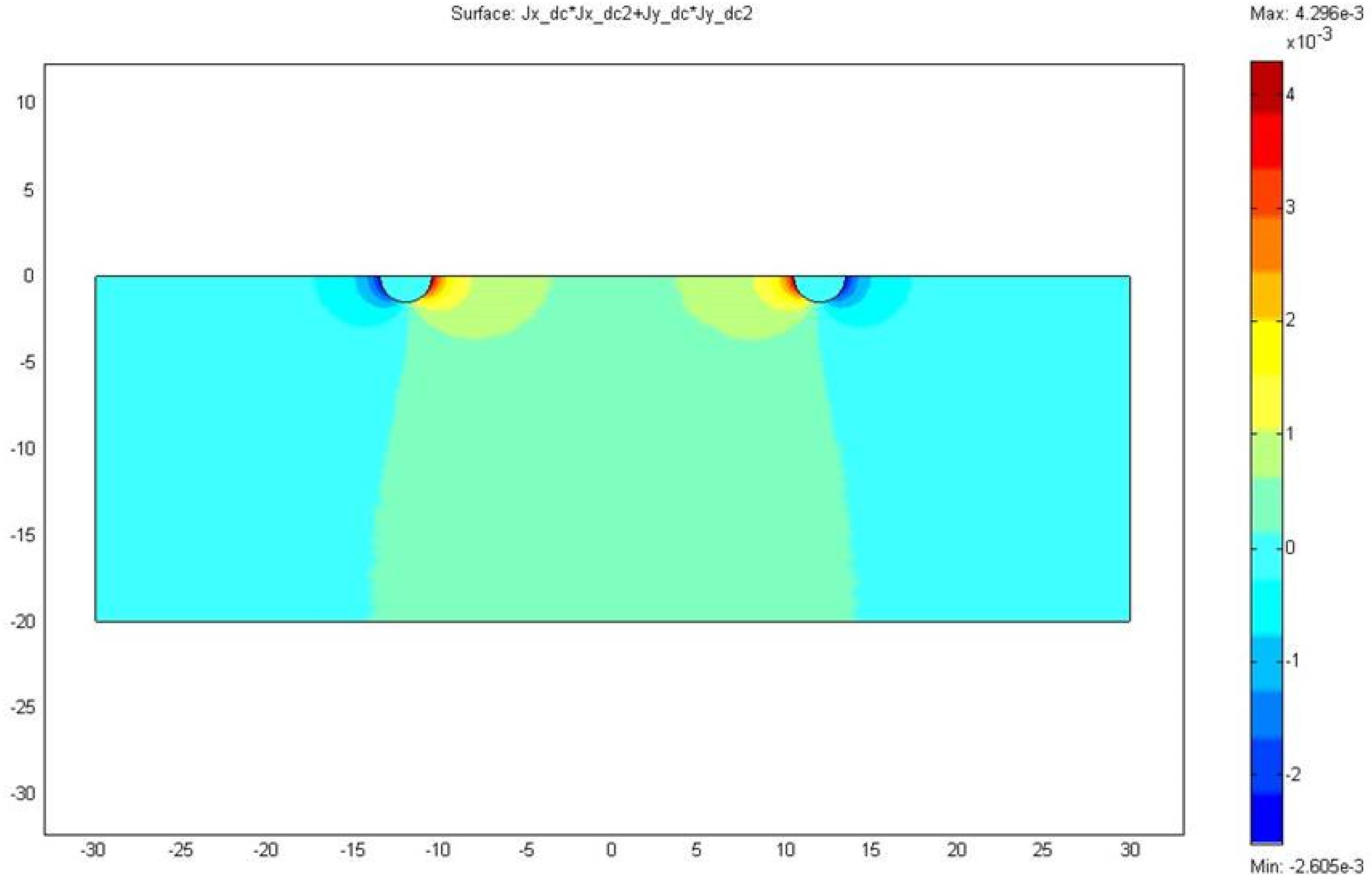
Two electrodes on the sides



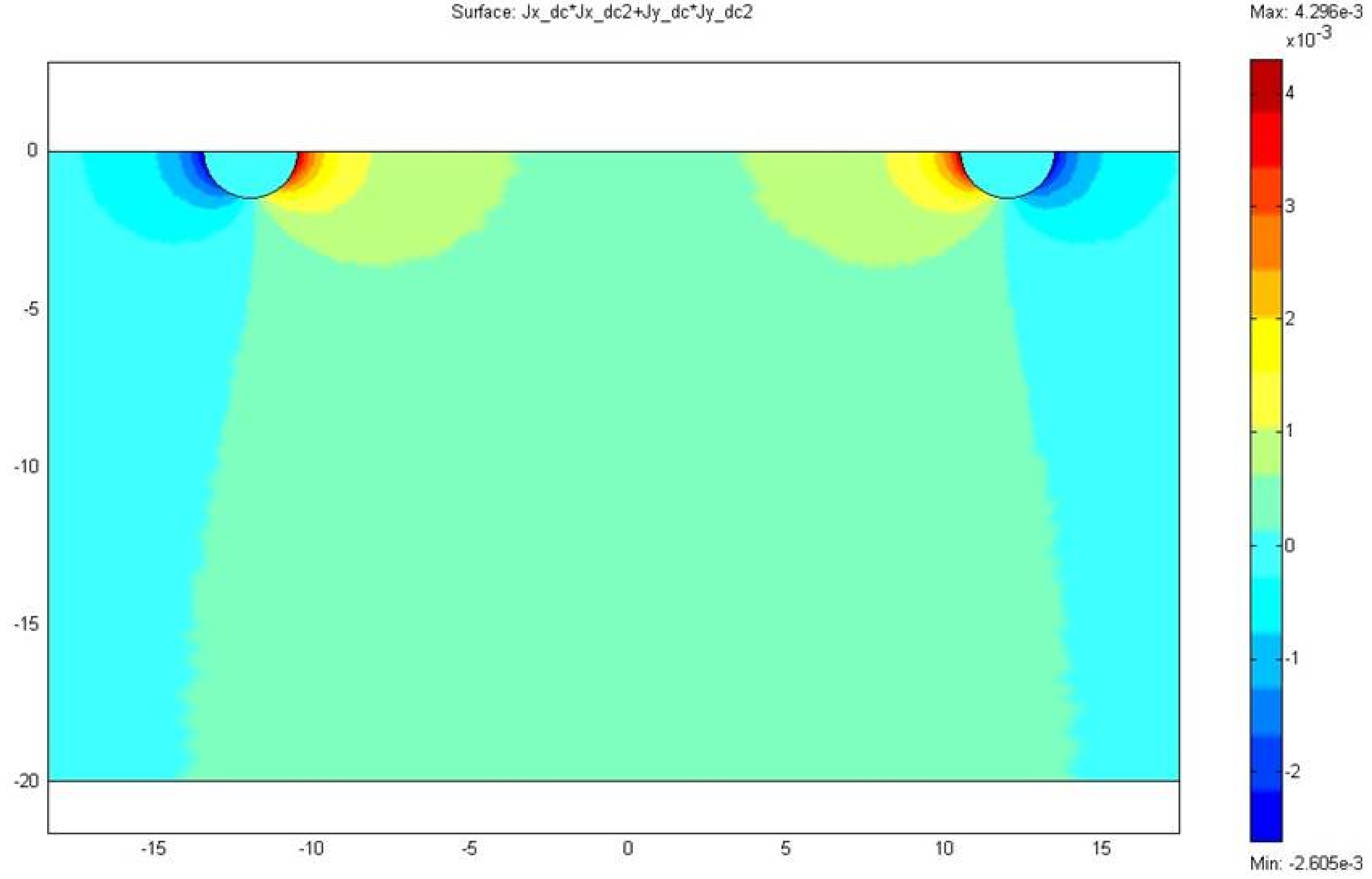
Closer look …


Surface: Jx_dc*Jx_dc2+Jy_dc*Jy_dc2
Max: 0.0107
0.01
0.008
0.006
0.004
0.002
0
-0.002
-0.004
Min: -4.289e-3
0
-2
-4
-6
-8
-10
-8
-6
-4
-2
0
2
4
6
8

Increased electrode separation

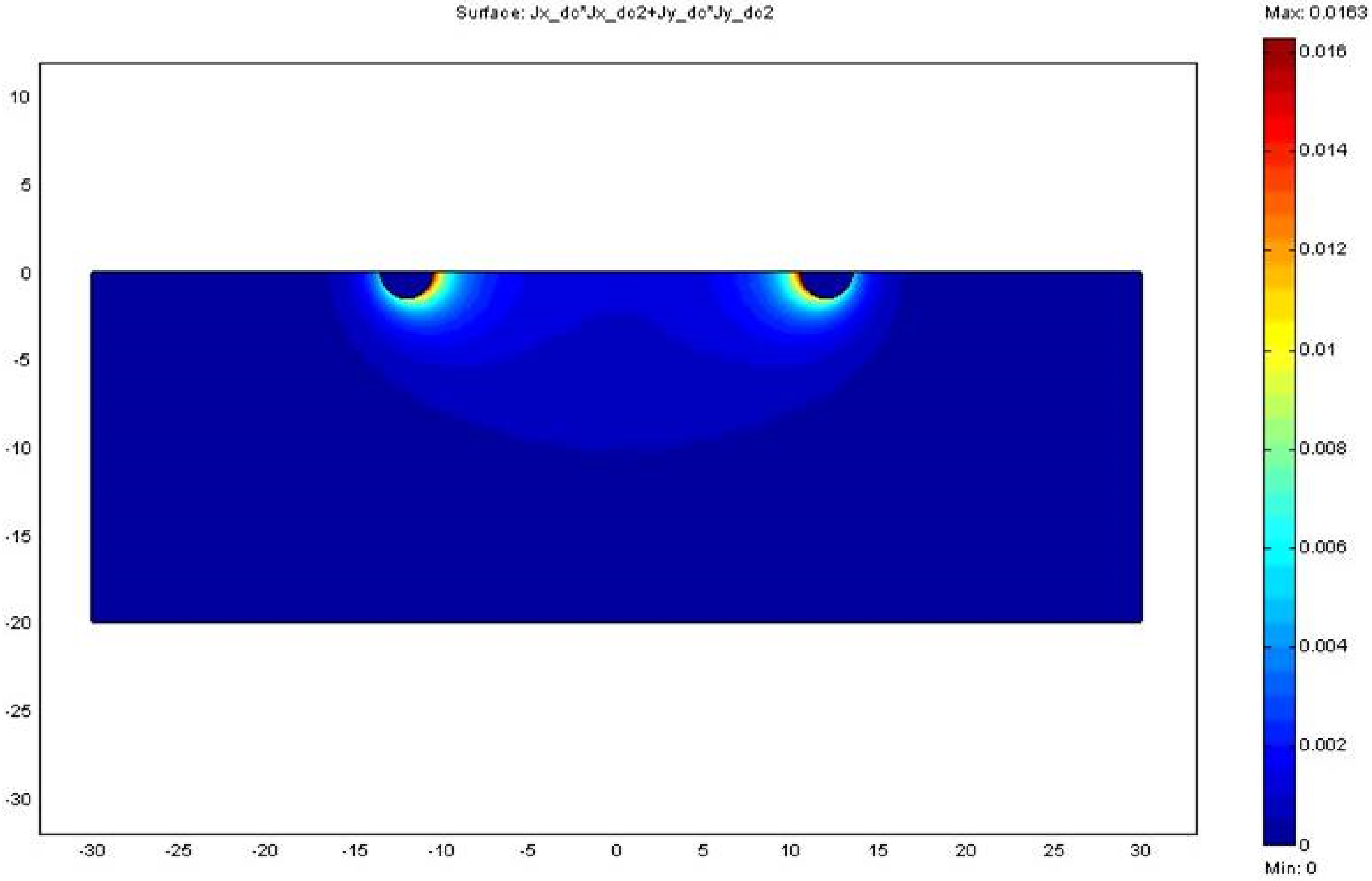


Closer look …

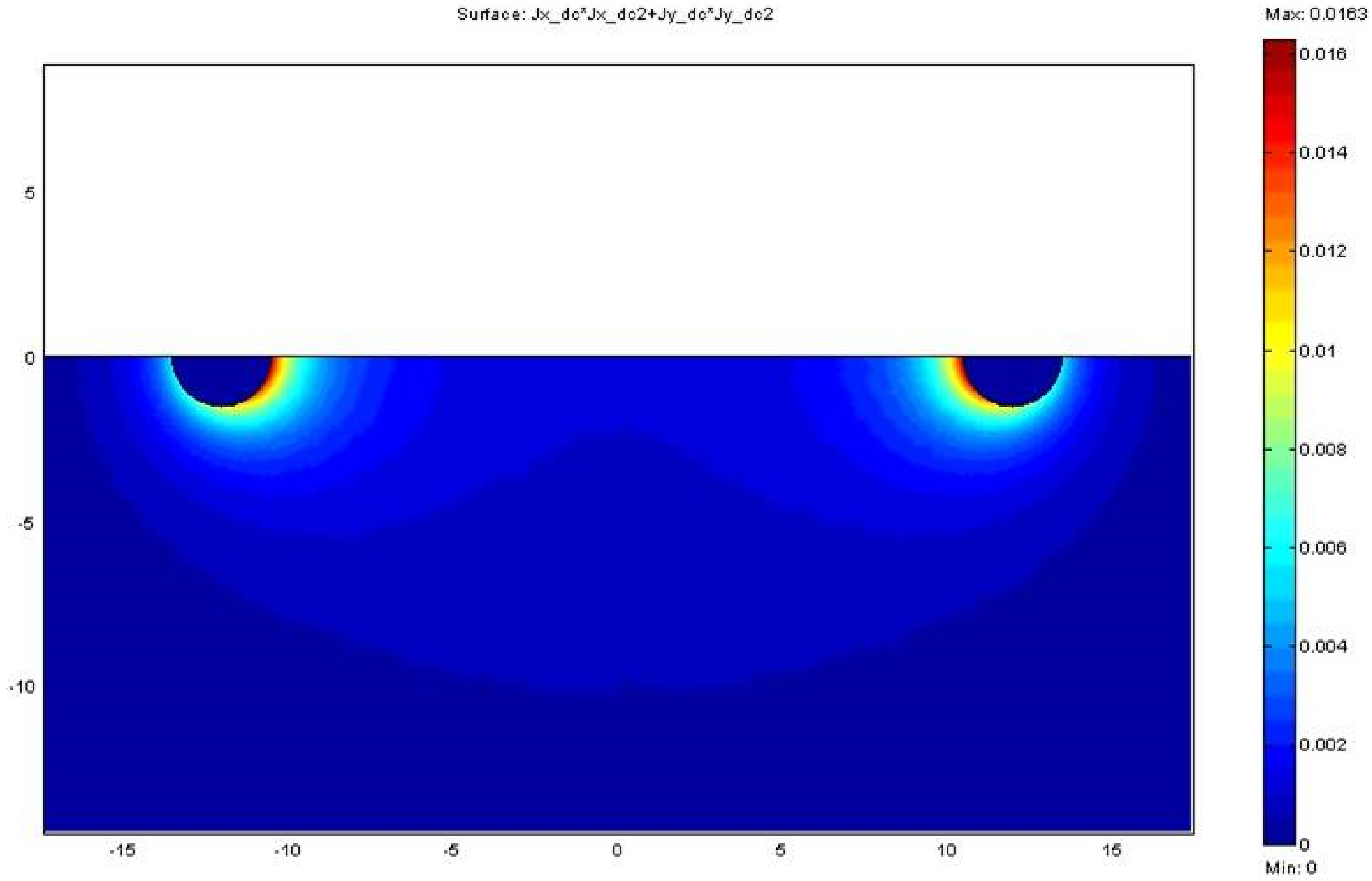


Surface: Jx_dc*Jx_dc2+Jy_dc*Jy_dc2
Max: 4.296e-3
x10^{-3}
4
3
2
1
0
-1
-2
Min: -2.605e-3
0
-5
-10
-15
-20
-15
-10
-5
0
5
10
15

Two-electrode system

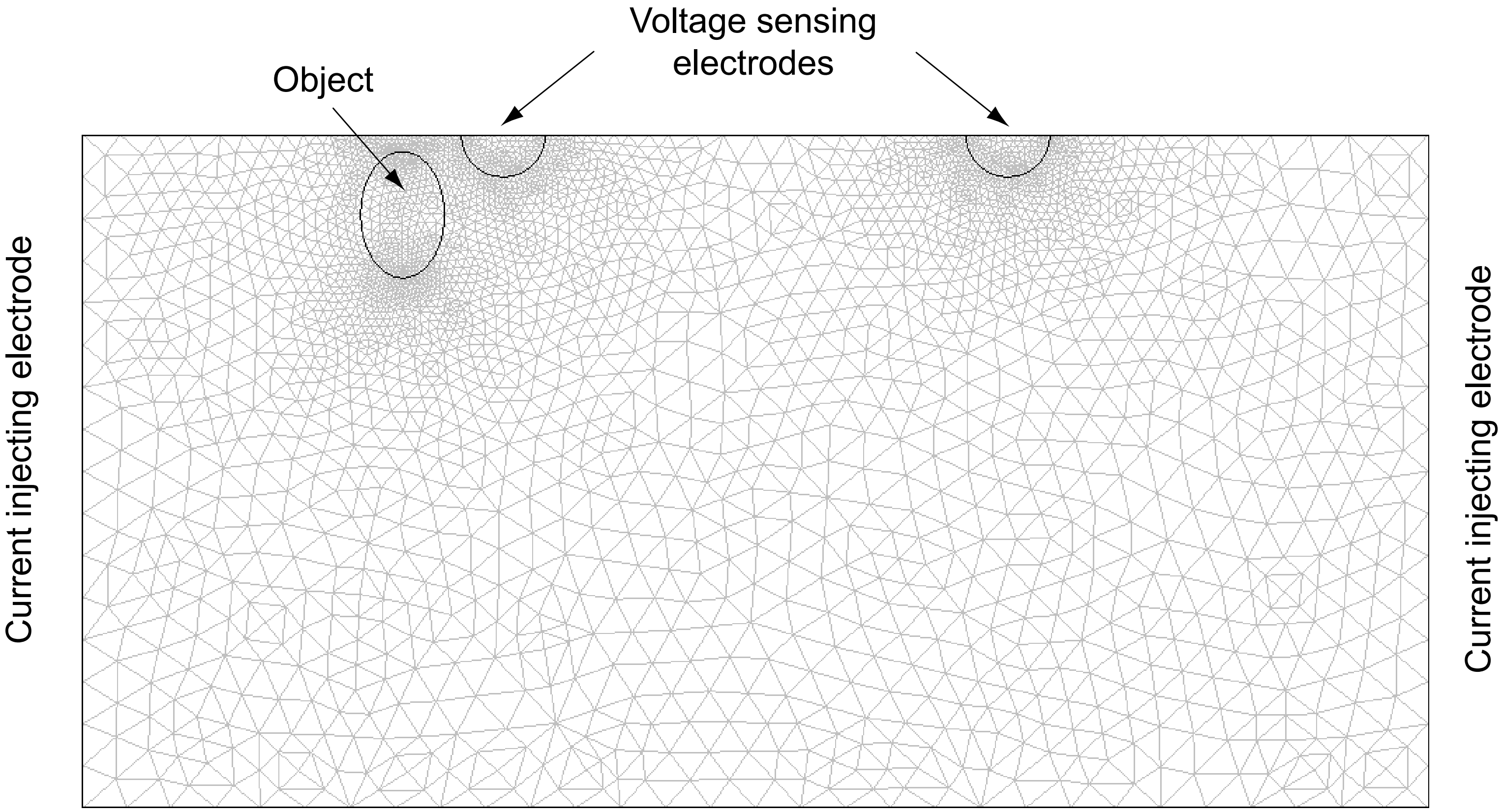


Closer look …

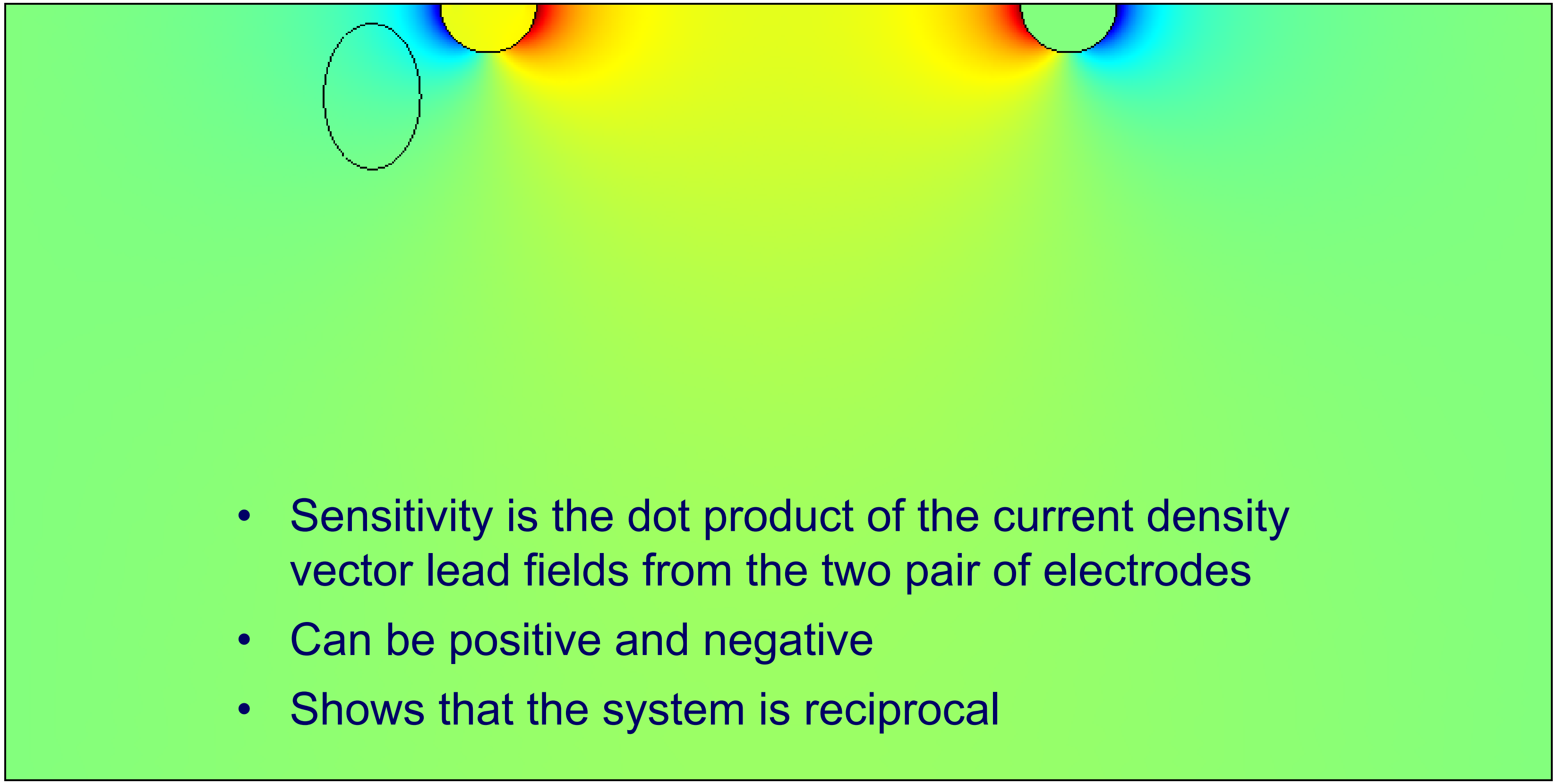

Surface: Jx_dc*Jx_dc2+Jy_dc*Jy_dc2
Max: 0.0163
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
Min: 0
5
0
-5
-10
-15
-10
-5
0
5
10
15

Simple four-electrode FEM model

Comsol Multiphysics - 2D, DC conductive media



Sensitivity field – no object

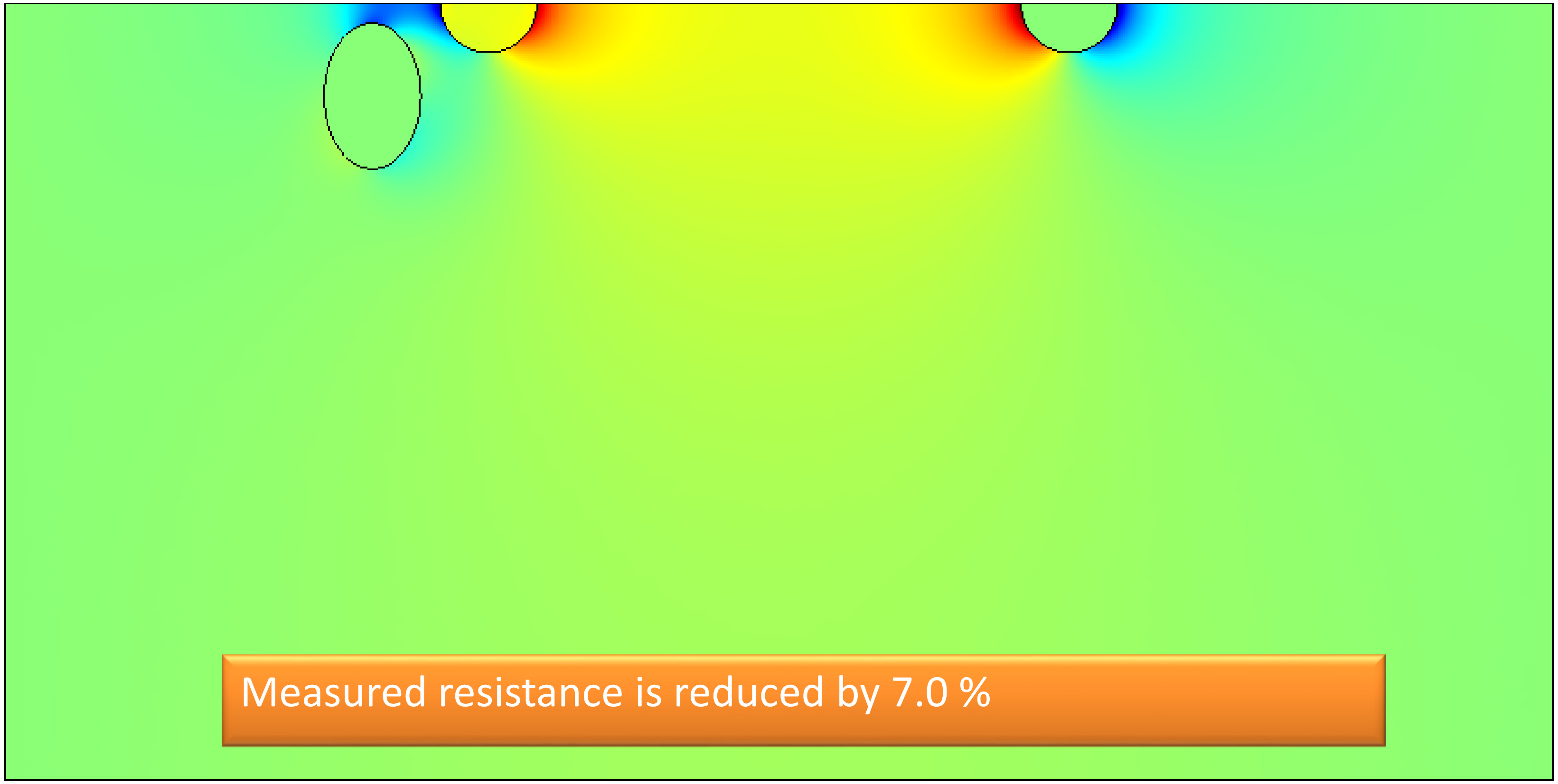


- Sensitivity is the dot product of the current density vector lead fields from the two pair of electrodes
- Can be positive and negative
- Shows that the system is reciprocal

Sensitivity field – metal object

Measured resistance is increased by 7.3 %

Sensitivity field – insulating object



Measured resistance is reduced by 7.0 %

Two popular skin surface ECG electrode designs

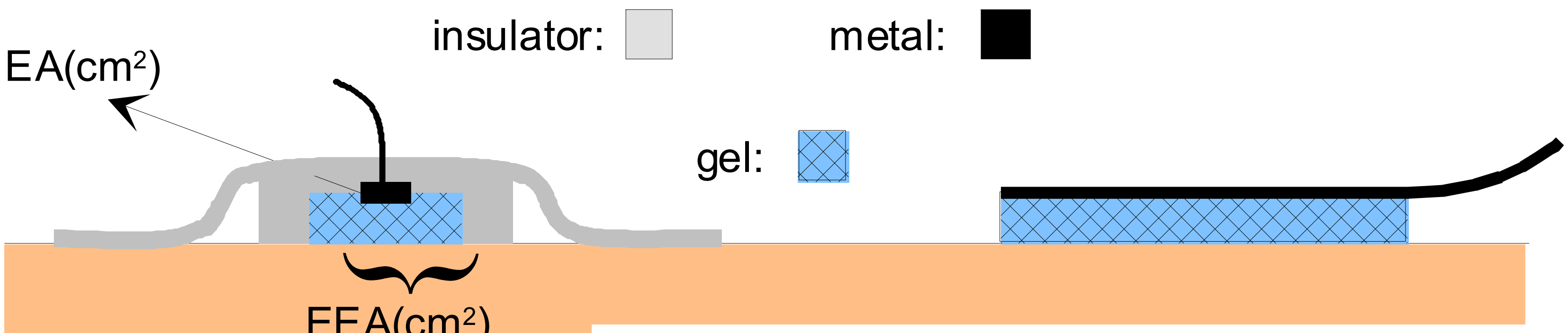
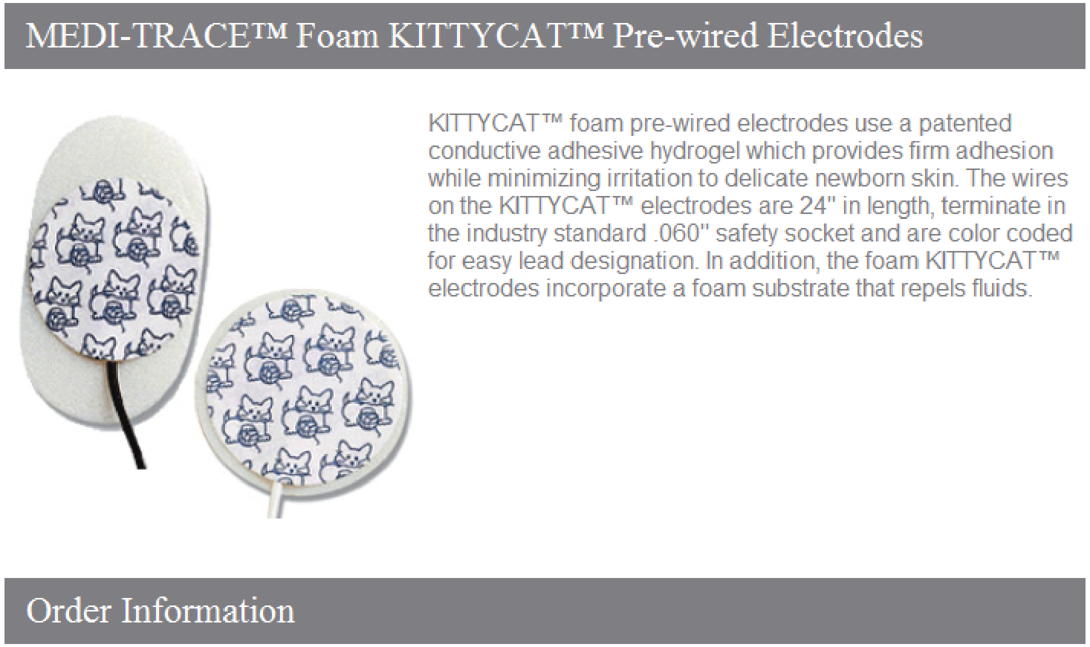


Fig. 8.10

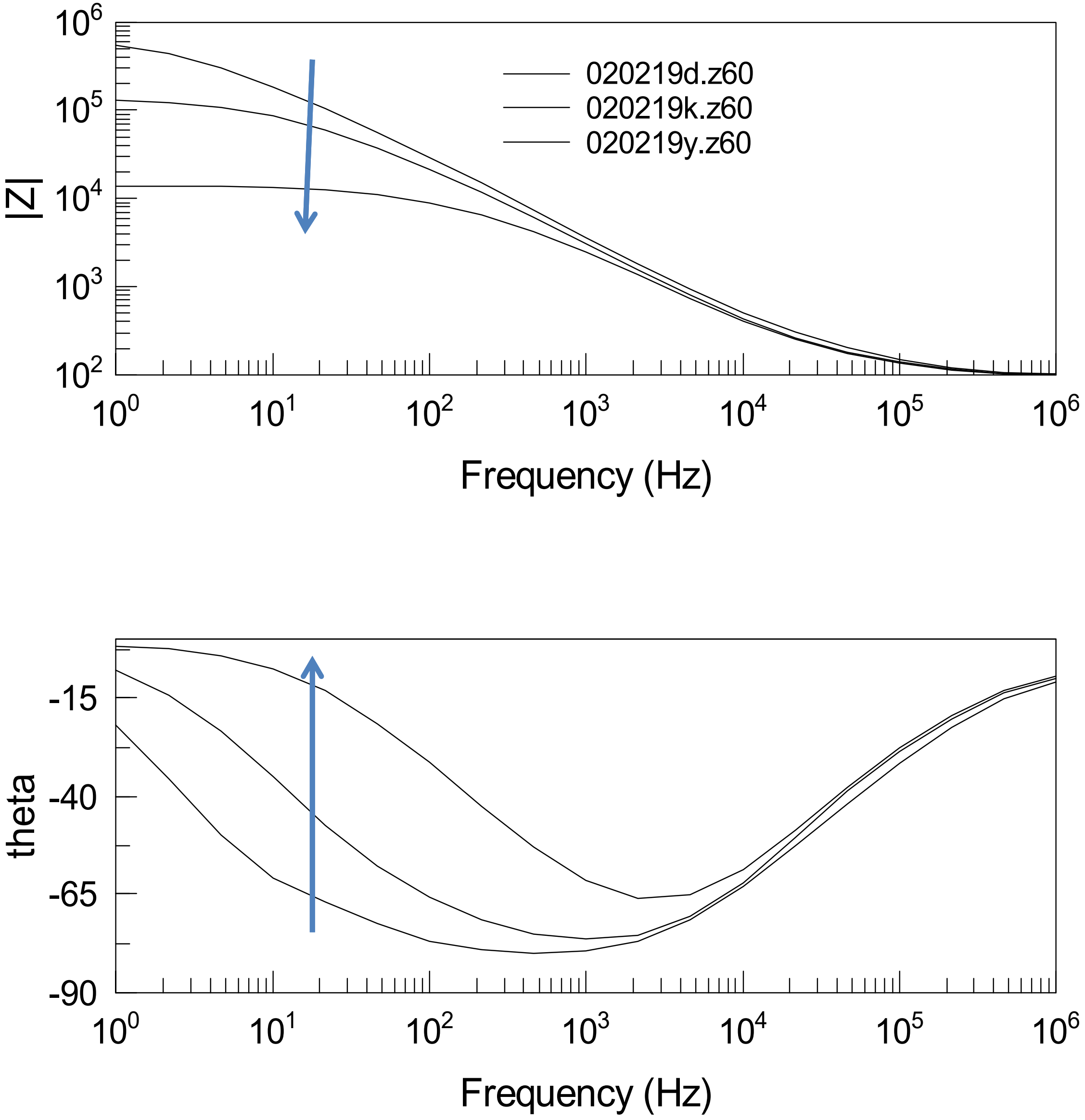

MEDI-TRACE™ Foam KITTYCAT™ Pre-wired Electrodes

KITTYCAT™ foam pre-wired electrodes use a patented conductive adhesive hydrogel which provides firm adhesion while minimizing irritation to delicate newborn skin. The wires on the KITTYCAT™ electrodes are 24" in length, terminate in the industry standard .060" safety socket and are color coded for easy lead designation. In addition, the foam KITTYCAT™ electrodes incorporate a foam substrate that repels fluids.

Order Information

Wet gel or solid gel (hydrogel)?

Gel penetration



Monopolar skin impedance spectrum as a function of gel penetration.

No significant influence from electrode polarization impedance.

1. **Onset**
2. **1 hour**
3. **4 hours**

IOP PUBLISHING PHYSIOLOGICAL MEASUREMENT

Physiol. Meas. 31 (2010) 1395–1410 doi:10.1088/0967-3334/31/10/008

A study on electrode gels for skin conductance measurements

Christian Tronstad[1], Gorm Krogh Johnsen[2], Sverre Grimnes[1,2]
and Ørjan G Martinsen[1,2]