SENSING CAPABILITIES OF MULTIFUNCTIONAL COMPOSITE MATERIALS USING CARBON NANOTUBES

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www.esa.int

15th September 2010

European Space Agency

7th ESA Round-Table on Micro and Nano-technology for Space Applications
ESA/ESTEC, Noordwijk, The Netherlands

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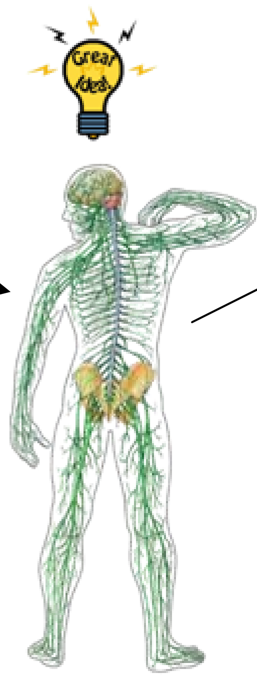
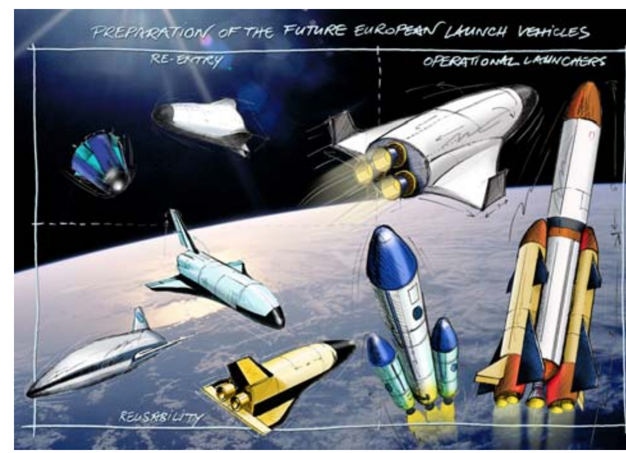
Introduction

How we envision multifunctional smart structures?





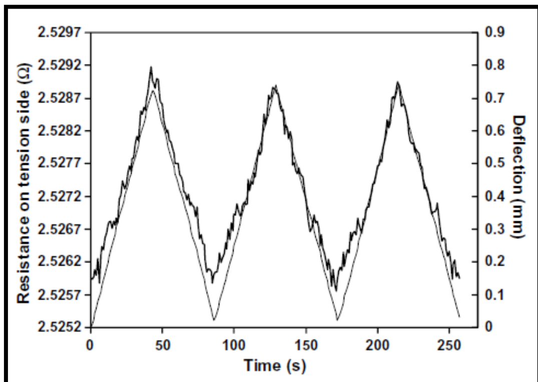
- Structure with self-sensing and diagnostic capabilities
- Smart System - Level 1: Solely sensory

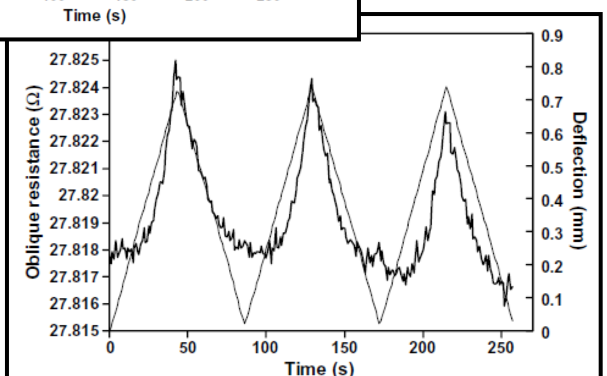
Carbon NanoTubes (CNT)
Sensing and NDI

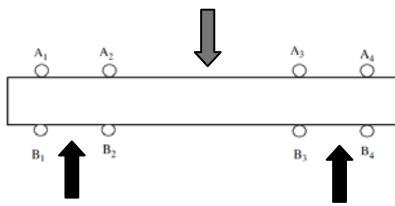
<u>Sensing:</u> identify changes in or around a system through monitoring its properties

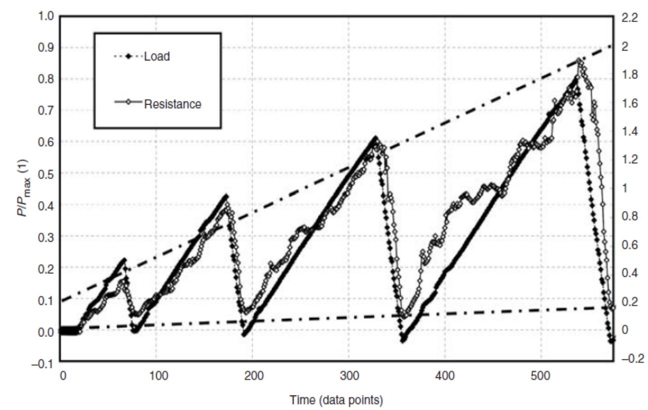
→ **Self-sensing**: to describe the material's health state through monitoring non-structural properties of it

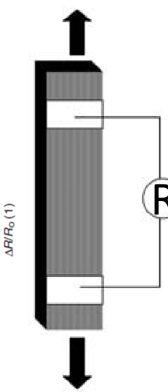
<u>Damage:</u> anything that disrupts the continuity of the material and can effectively decrease the load bearing capability of the structure











Why not use CNTs to locate a damage?
...is there any way?

Description of work

Motivation for Electrical Tomography

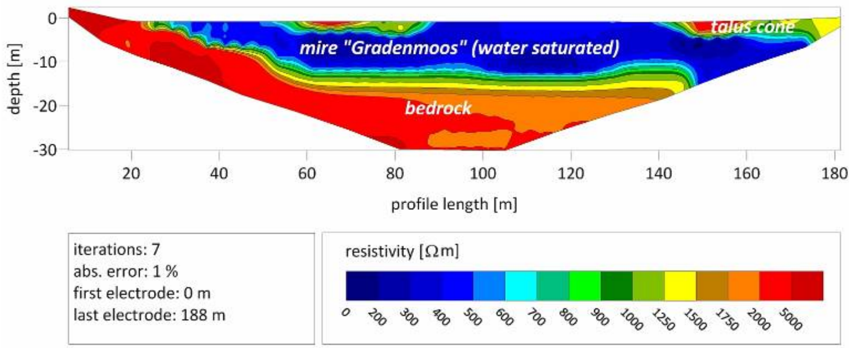
- Develop a health monitoring system
- Utilizing inherent material properties
- Capable of locating damage

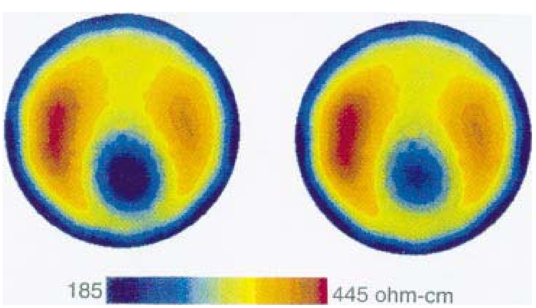
$\boxed{\text{Electrical Tomography}}$

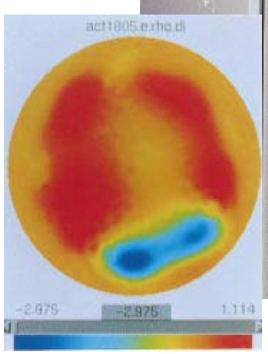
Background

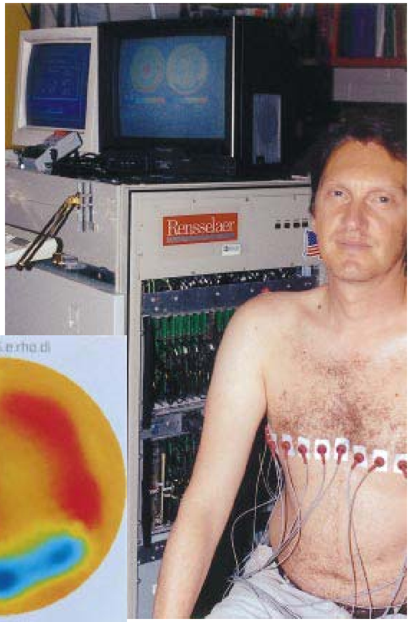
Electrical Tomography
Origins and applications

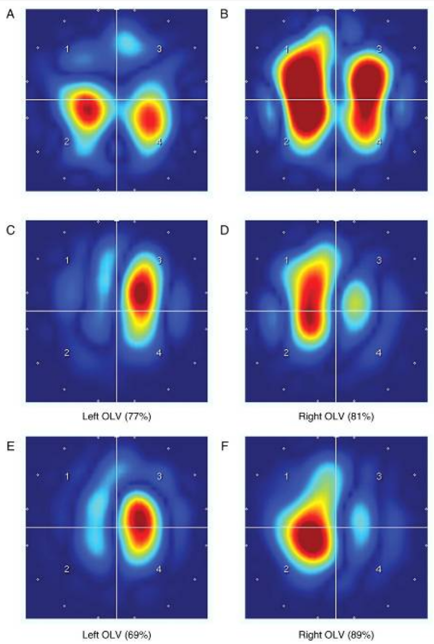
- Origins & Applications of ET
  - Geology:
    - Since the ‘30s
    - Detection of sub-surface water and oil
    - Example
  - Medical:
    - Since mid-’80s
    - Monitoring Pulmonary activity
    - Examples







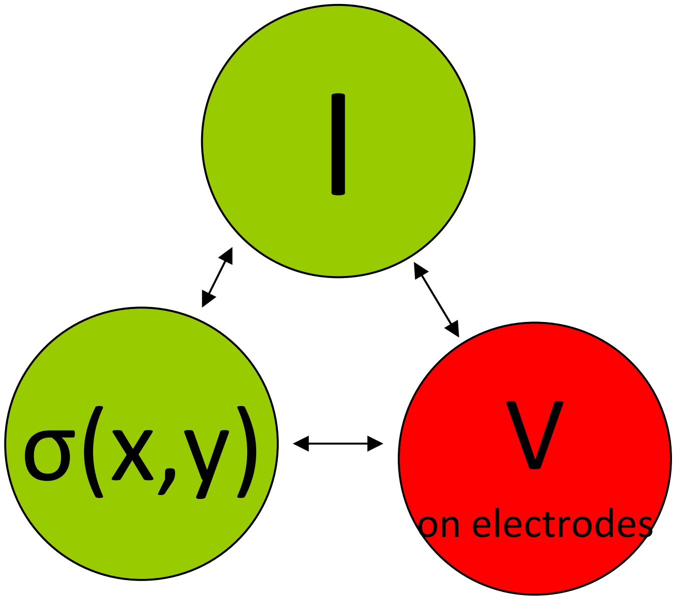




European Space Agency

Electrical Tomography
Forward Problem

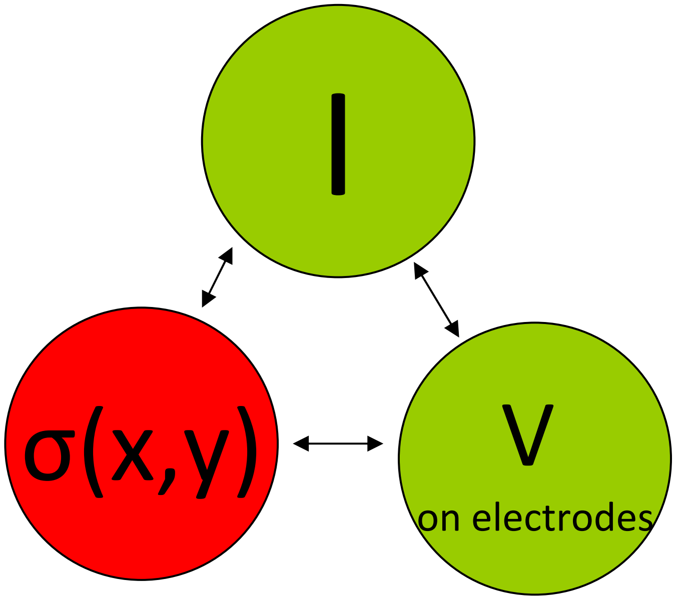
- Given (green):
  - I : points of current input
  - σ(x,y) : conductivity distribution
- Calculate (red):
  - u(x,y) : voltage
    - Extract voltage on electrodes



...things seem OK up to now

Electrical Tomography
Inverse Problem

- Given (green):
  - I : points of current input
  - Voltage on electrodes
- Calculate (red):
  - σ(x,y) :conductivity distribution

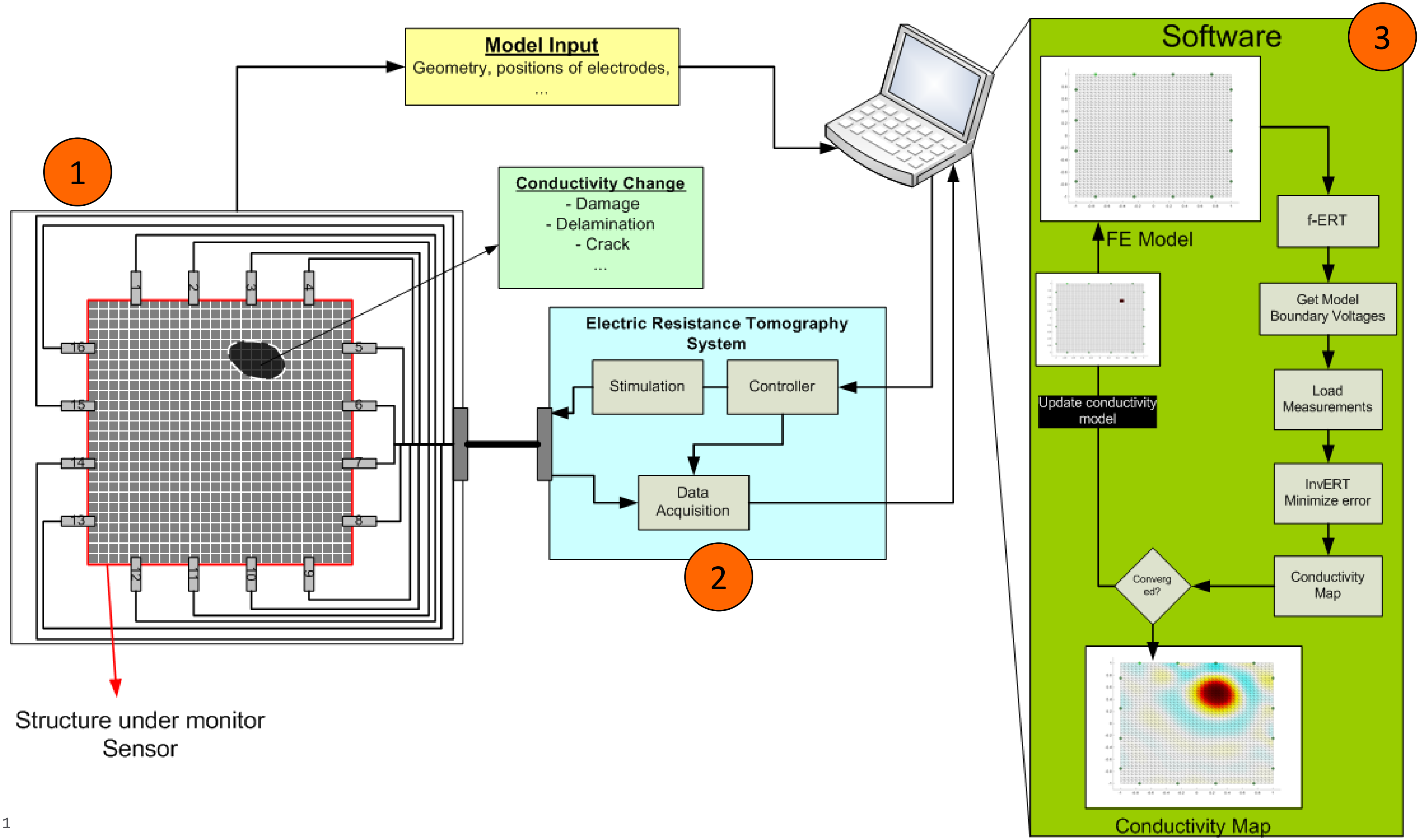


…not straight forward!

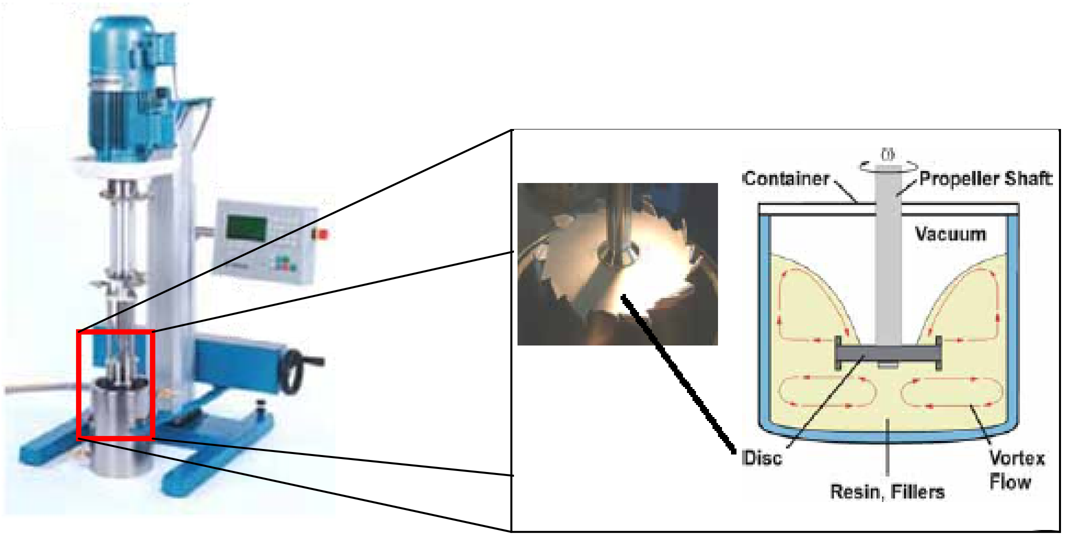
There is some information “missing”.

Application

ERT concept applied to structural materials



Manufacturing of CNT-GFRP



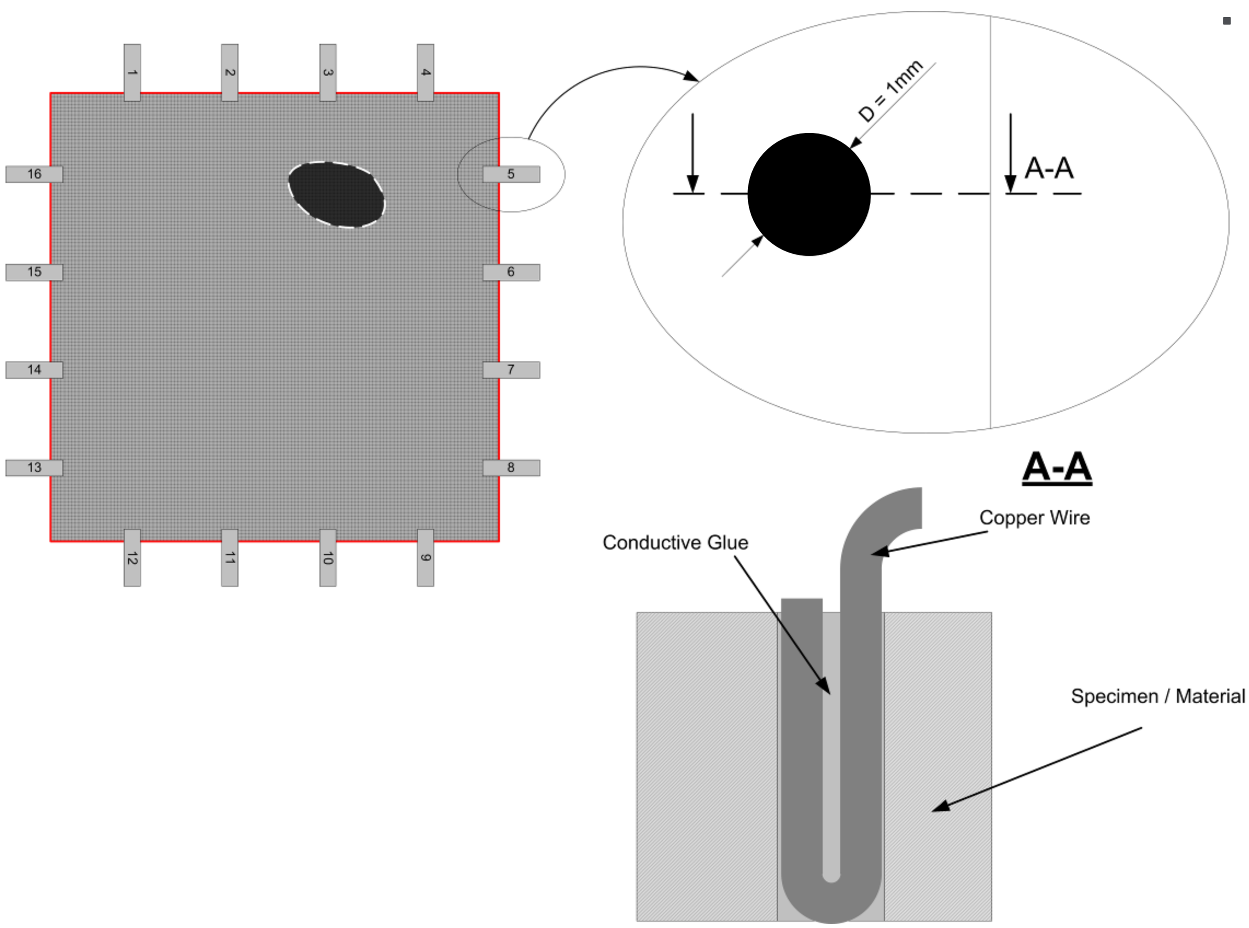
Dispersion of MWCNT into the resin system using Dissolver Technology

→ Specimens cut from plate: 10cm x 10cm

Materials and processes

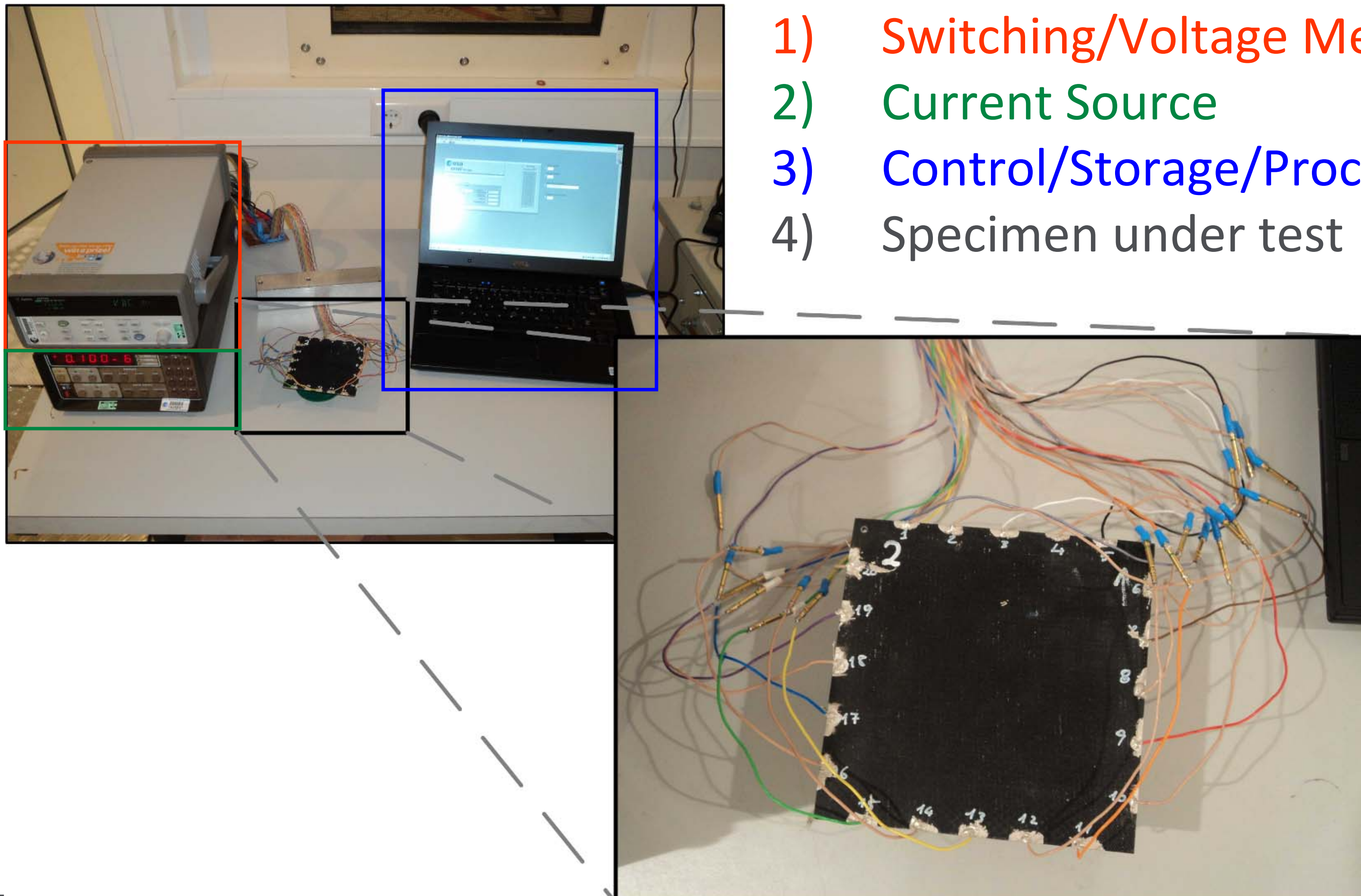
- MWCNTs
  - *ARKEMA, France*
- Epoxy
  - *Standard Wind Turbine*
  - *L1100 from R&G, Germany*
- Glass fibres
  - *Aerospace grade*
  - *Woven*
  - *160gr/m2*
- 0.5%wt MWCNT in resin
- 12 layers
- Hand-layup
- Vacuum Bag

Specimen preparation



- **Electrode positioning**
  - <u>20 electrodes</u> evenly distributed on the perimeter
  - 1mm hole drilling
  - Silver paint hole
  - Conductive Epoxy
  - Cure for 4hrs@55oC

Developed ERT setup

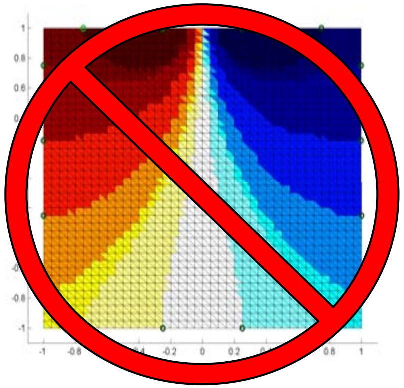


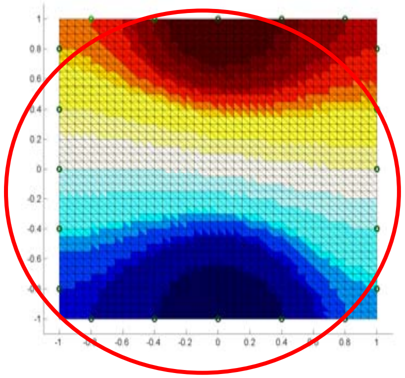
1) Switching/Voltage Measurement
2) Current Source
3) Control/Storage/Processing unit
4) Specimen under test

ERT in practise
Current injection and measurement protocol

Current injection

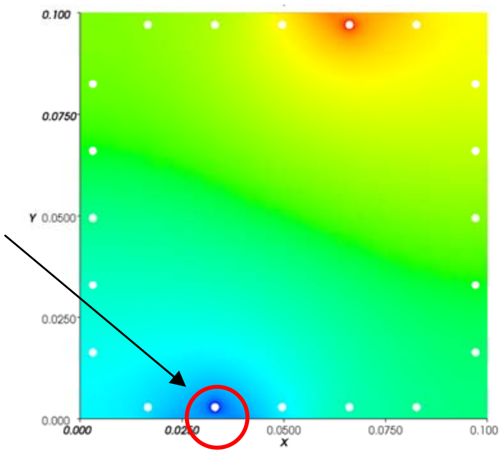
→ Opposite





Measurement

→ Absolute: all measurements with reference to the ground



ET Protocol

*1 frame

- Current: el.1; Ground: el.11
- Voltage Measurement: el.1, 2, .., 20
- Current: el.2; Ground: el.12
- Voltage Measurement: el.1, 2, .., 20
- …
- Current: el.10; Ground: el.20
- Voltage Measurement: el.1, 2, .., 20

Total 200 meas.p.fr. → 160 "useful" meas.p.fr.

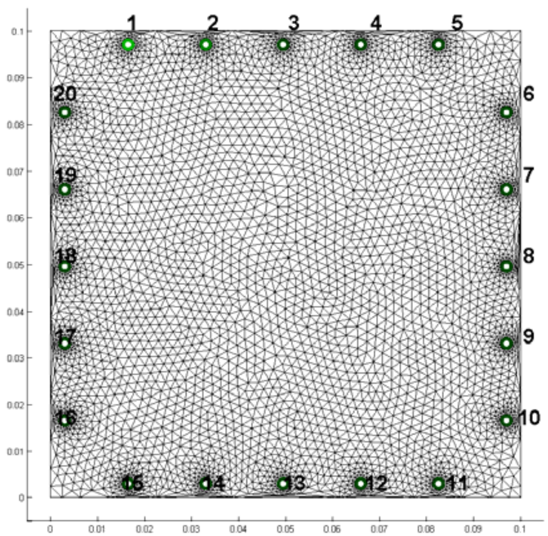
30 fr.→ mean values →Absolute/ Adjacent

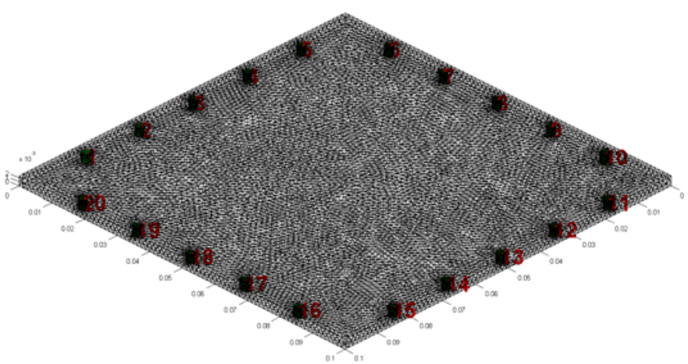
Introduction of damage

- Damage/discontinuity characteristics:
  - Reproducible and known
  - Size
  - Position: (X,Y)
- Damage in this study: drilling a hole
  - D=3mm
  - @(4cm, 2.2cm)
- Second damage: another hole
  - D=3mm
  - @(6cm,6cm)

Results

Simulation
Formation of Finite Element Model

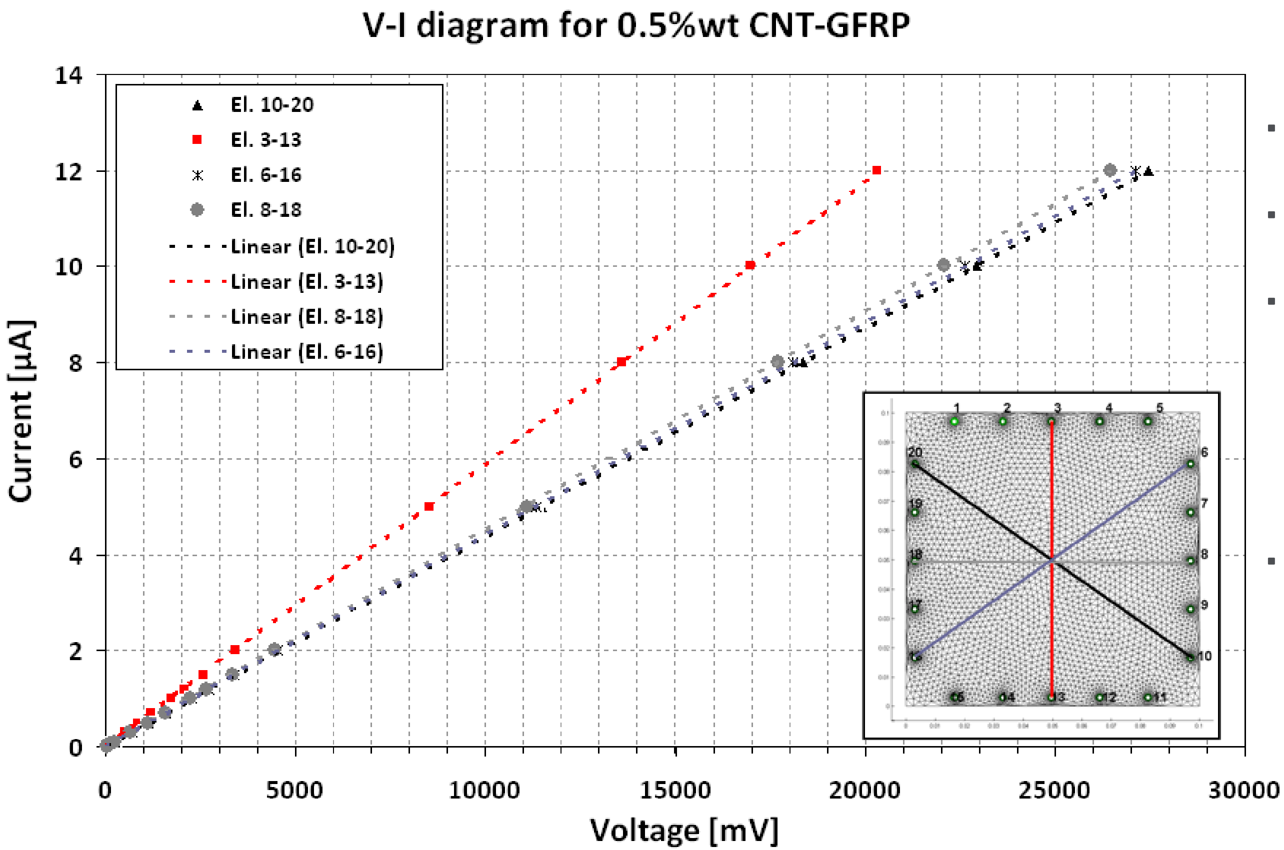




- Complete Electrode Model
- 2D and 3D
  - Equivalence?
  - Computational performance?
- Final mesh characteristics
  - Linear triangular elements
  - Nodes: 4154
  - Elements: 7982
- Conductivity?
  - Experiment
  - Simulation

Experimental

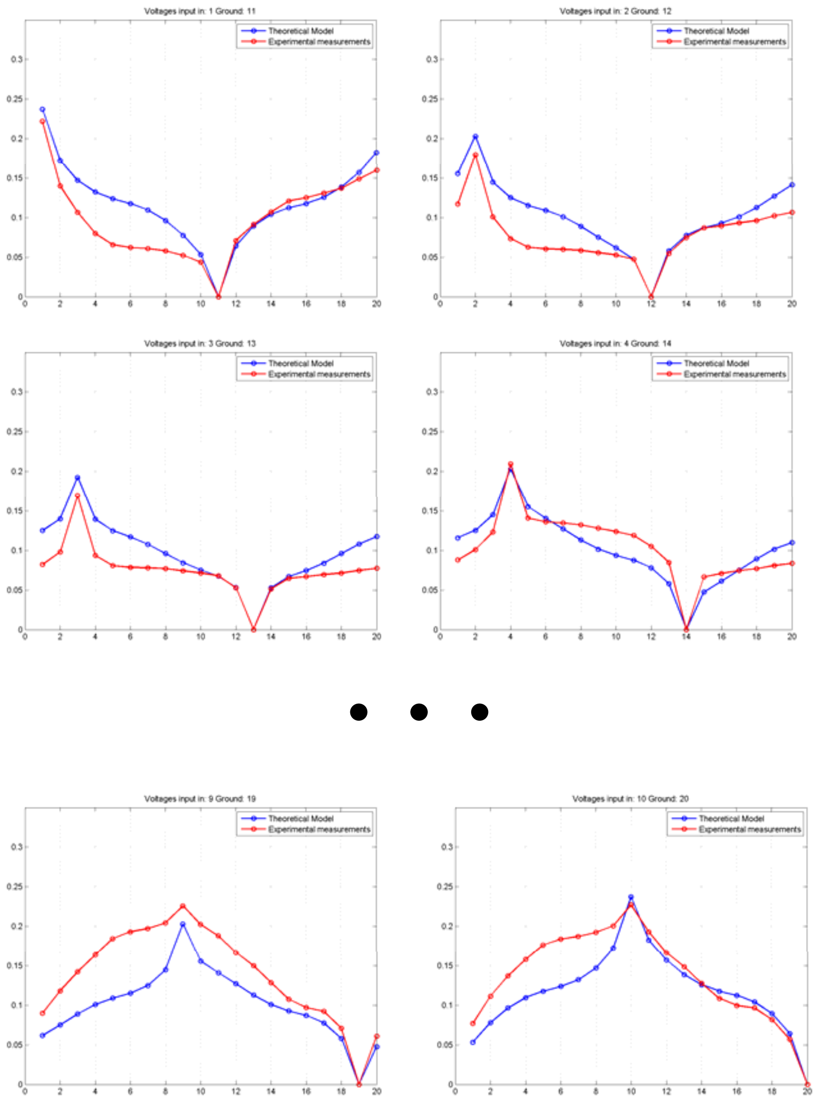
Conductivity determination



- Controlled current input
- Record voltage
- 4 angles
  - -45/0/45/90
  - Anisotropy?
- Electrically linear (resistor)

$$\sigma = 4.89*10^{-4}\ S/m$$

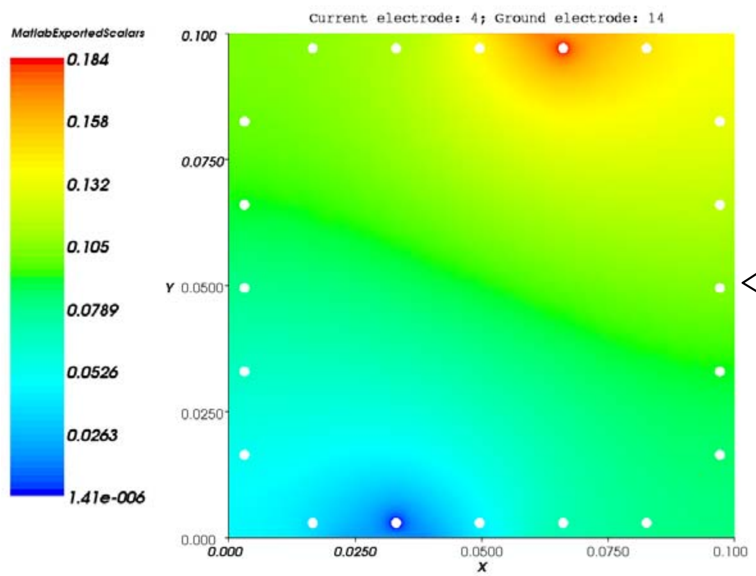
Simulation
Conductivity determination



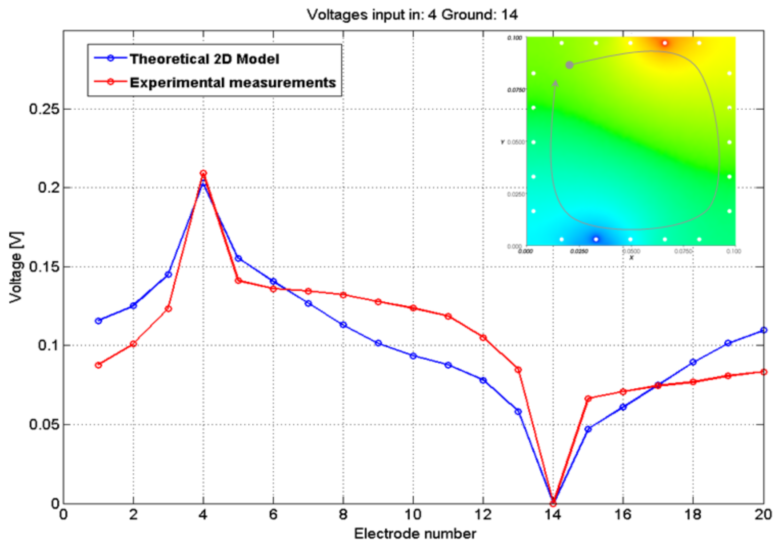
- Model with unit conductivity
- Simulate measurements
- Linear system
- Compare to experimental
- Least square fit of conductivity
  - minimize the error between simulated and experimental curves

$$\boxed{\sigma = 4.479*10^{-4} \text{ S/m}}$$

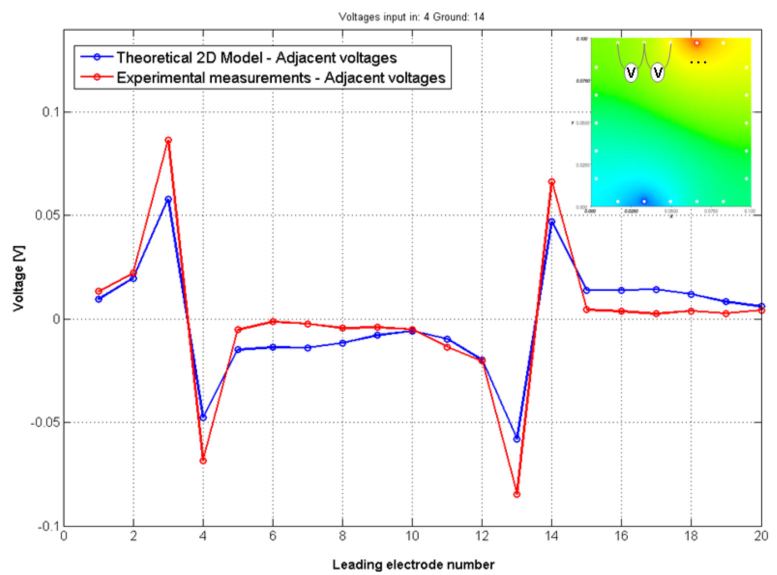
Saying the same thing…differently



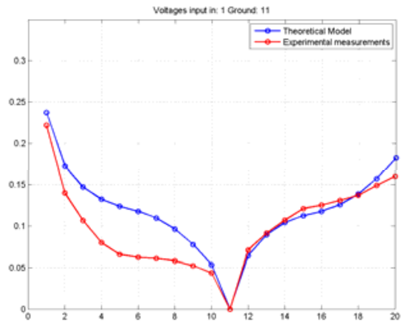
Absolute

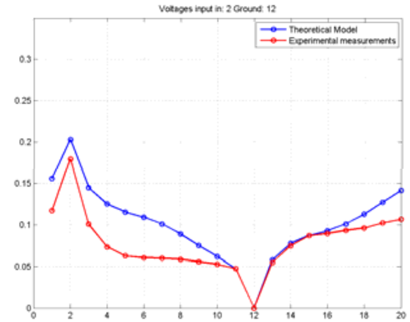


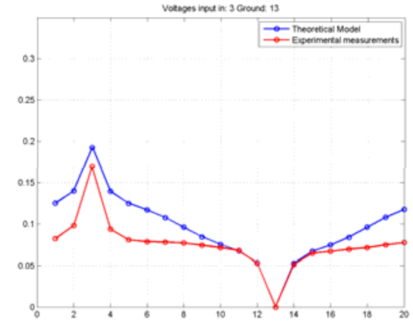
Adjacent

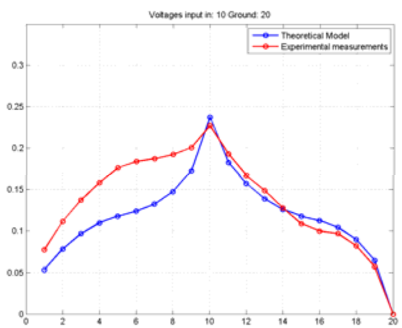


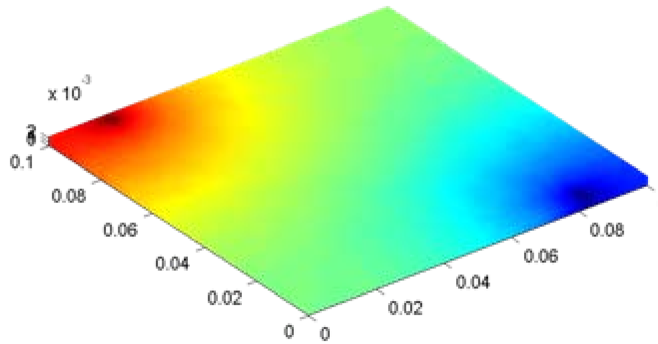
Simulation Vs. Experimental

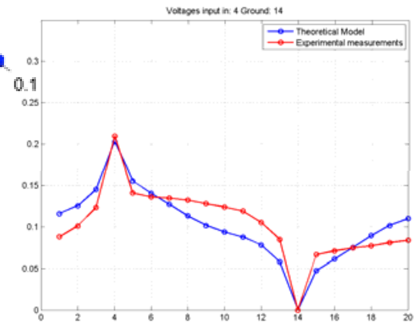


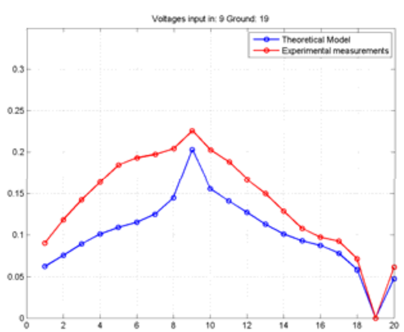






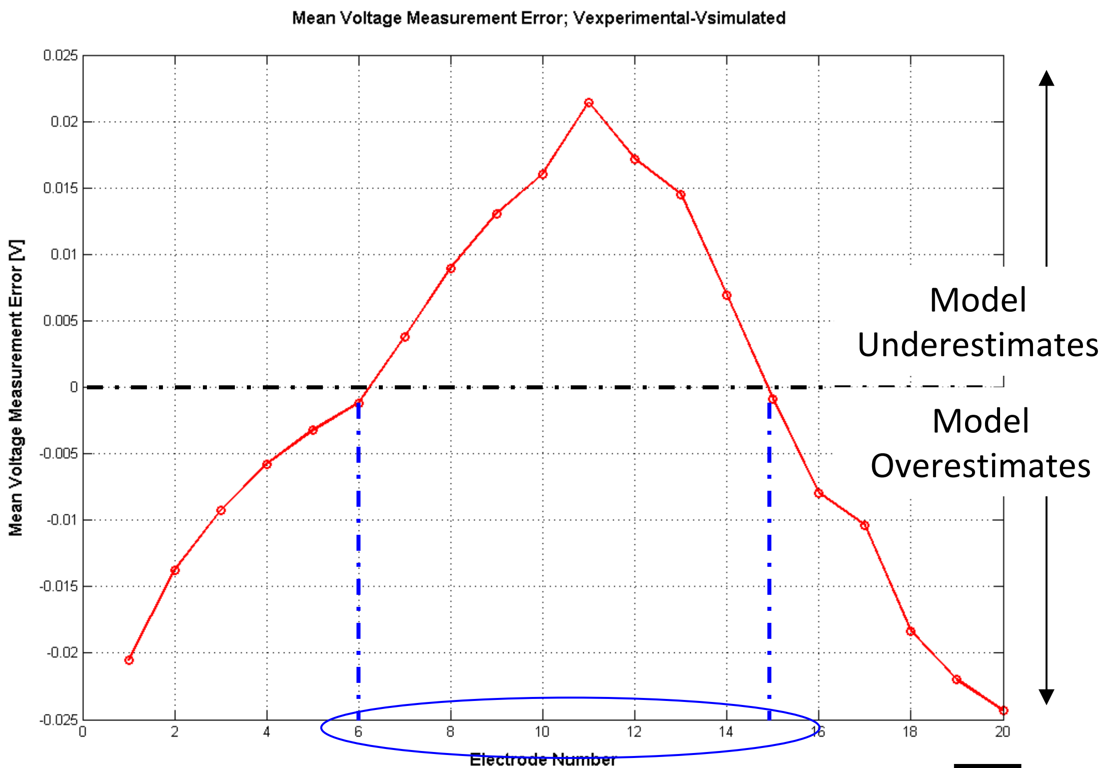




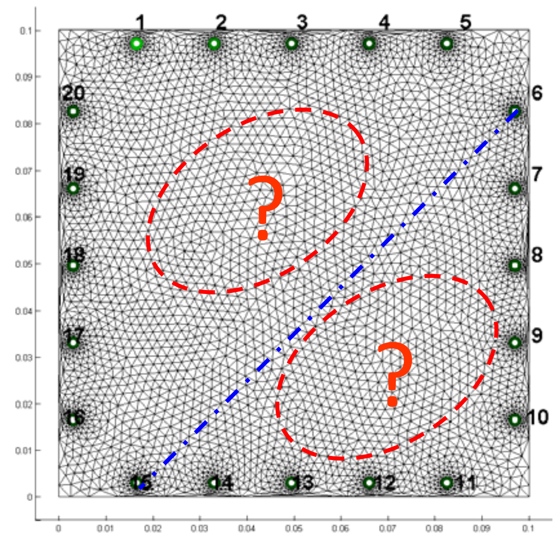


…deviations between experimental and simulation

Forward Problem
First observations

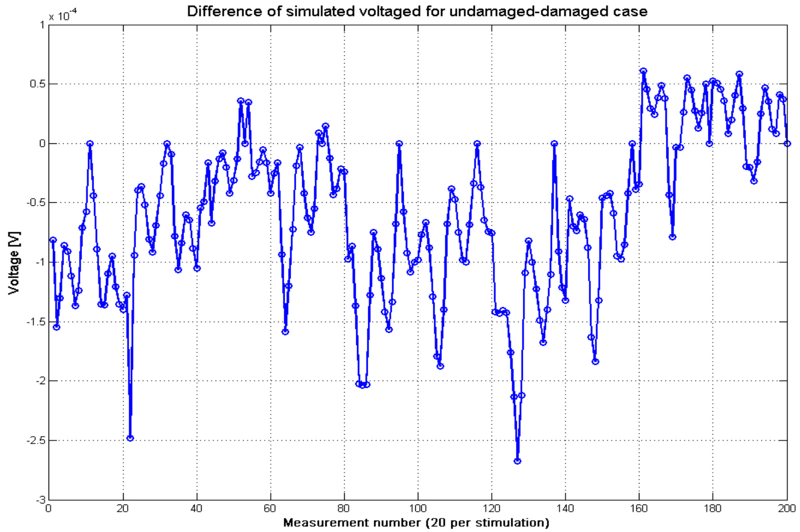


- Mean error per electrode:
  - Vexp–Vsim
  - El. 6-15: underestimated
  - → Higher experimental voltage
  - → Lower conductivity…locally
  - El. 1-5, 16-20: overestimated
- Inhomogeneous conductivity?
- Manufacturing parameters*



Any indication from C-scan?...

Measurements of Damaged Specimen



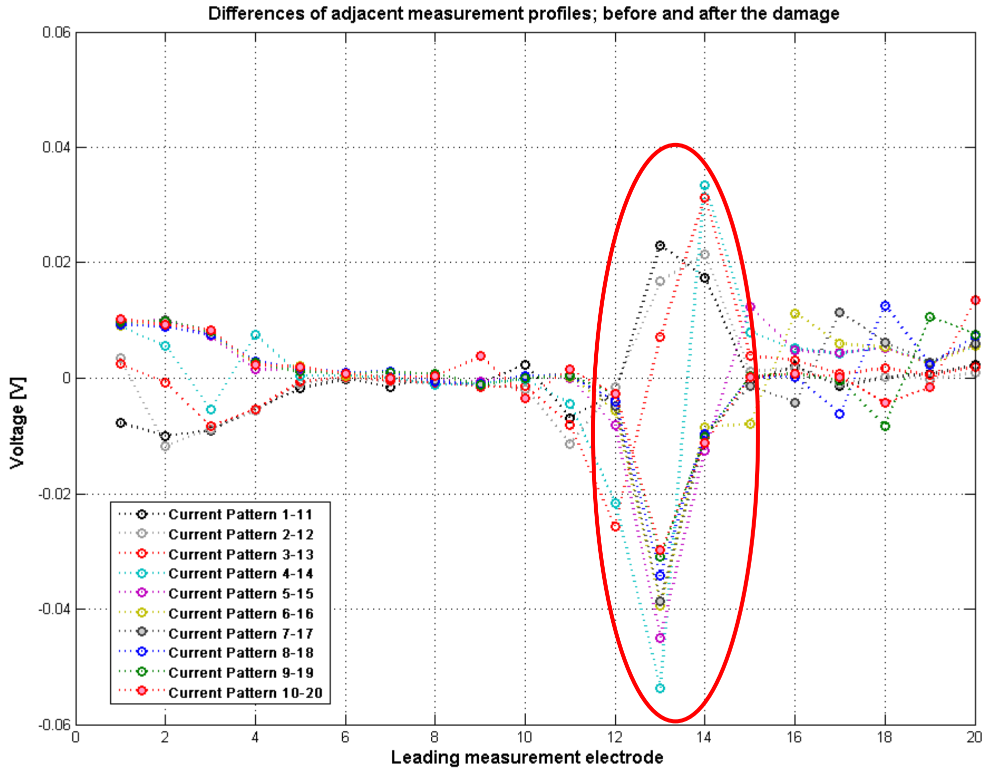
Theory*

(full measurements vector)

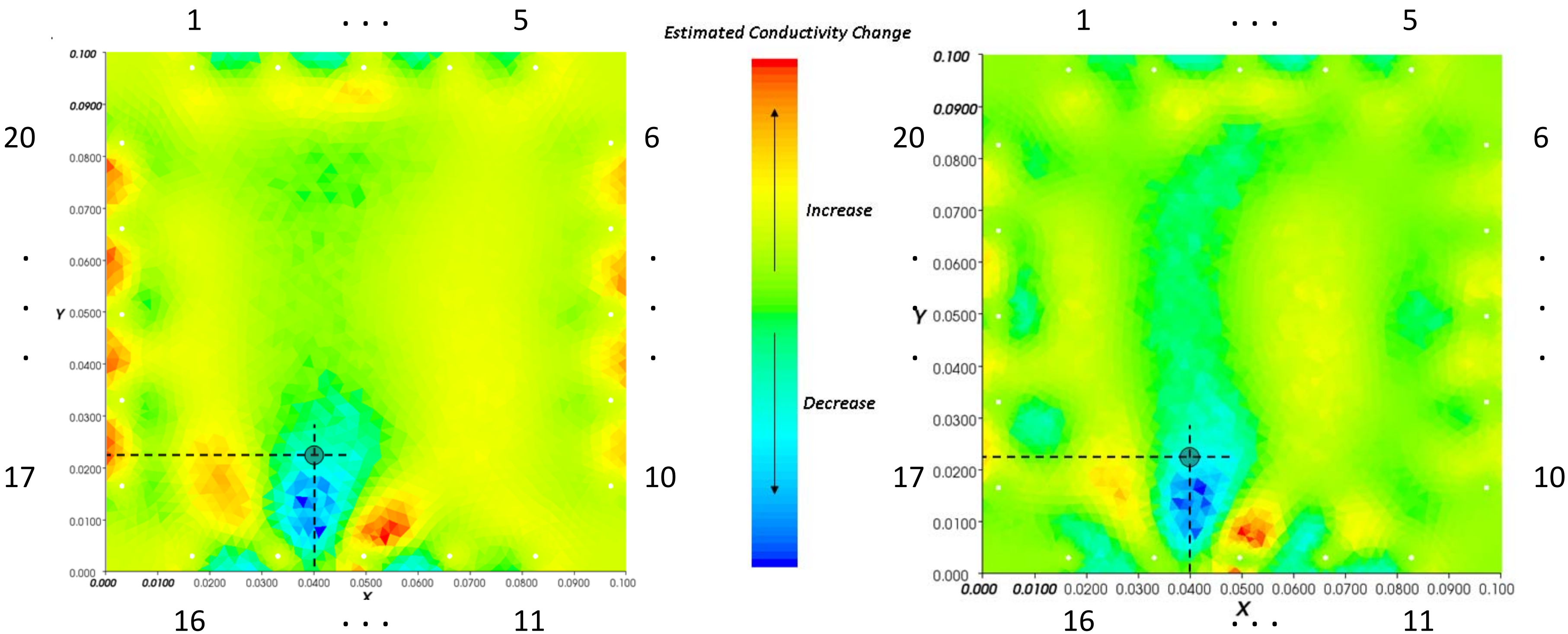
*this is what we should be able to detect with confidence

Experimental

(per current pattern)



Inverse Problem
Estimating conductivity maps



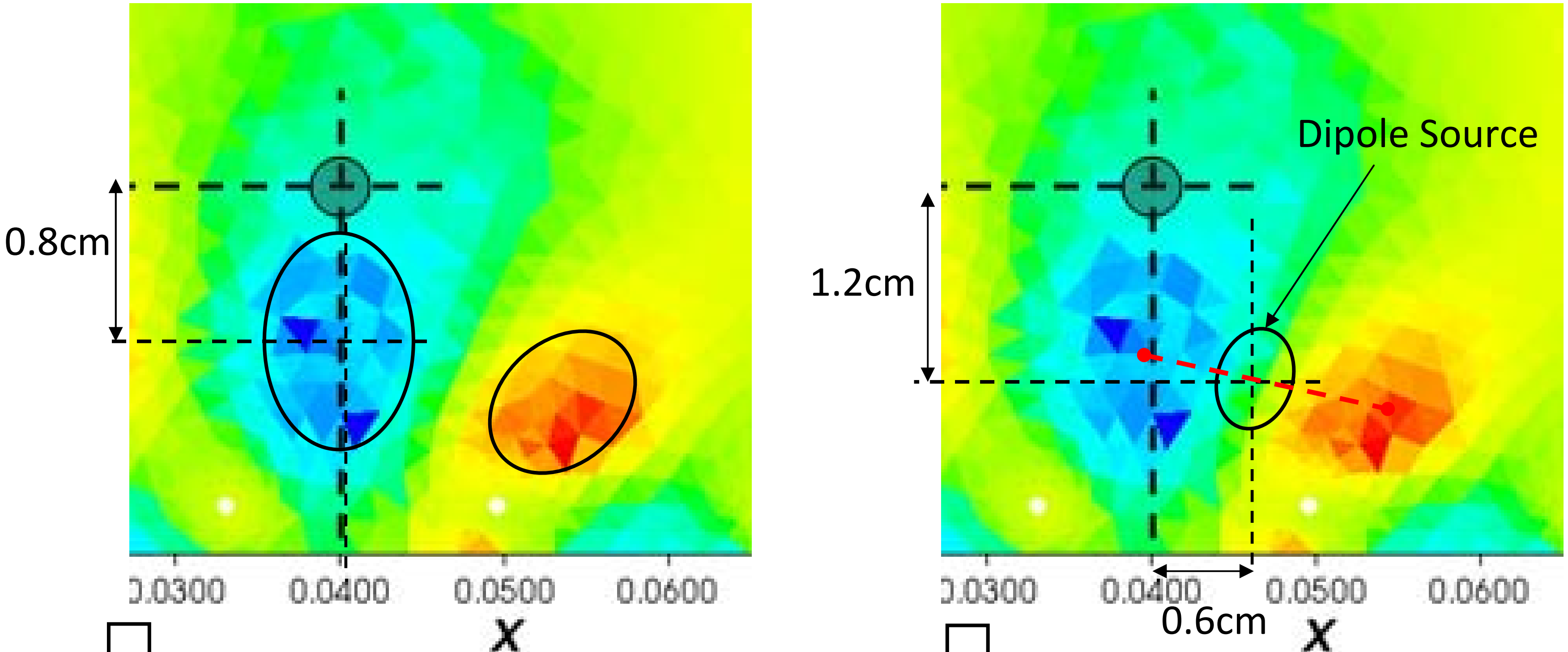
$\lambda = 10^{-6}$

$\lambda = 10^{-7}$

Regularization parameter

Inverse Problem
Estimating conductivity maps

Zoom in...



8% error

14% error

Conclusions

- Online structural health monitoring system
  - Proposed
  - Developed
  - Presented
- Application
  - CNT-GFRP
  - Experimental Vs. Simulation
    - First results show agreement
    - Calibration is possible
    - Verification of manufacturing
- Outcome – damage detection
  - Noticeable changes (before inversion)
  - Success in extracting estimation maps
  - Successful indication of damaged area
  - Small errors in the exact location

Future Outlook

- For the setup:
  - Optimization for lower noise
  - Current injection-measurement strategy
- Can we apply it to other materials and structural configurations?
  - Carbon Fibre Reinforced Composites
  - Aluminium (?)
  - Other structural materials
  - Other structural configurations (e.g. cylinders)
  - Scale-up
- Can we distinguish different damage modes?
  - Delamination
  - (micro-)cracking
- Electrical Impedance Tomography

Acknowledgements

Michele Muschitiello of ESA/ESTEC laboratories for his support and ideas on the development of the ERT setup

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