Aalto University
School of Engineering

Päällysteen tyhjätilan mittausmenetelmän ja laatuvaatimusten kehittäminen

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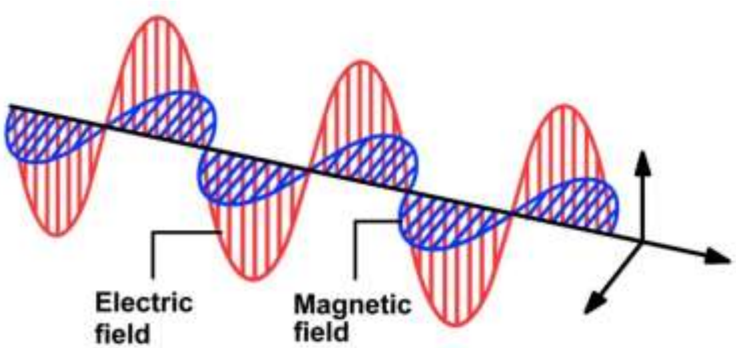
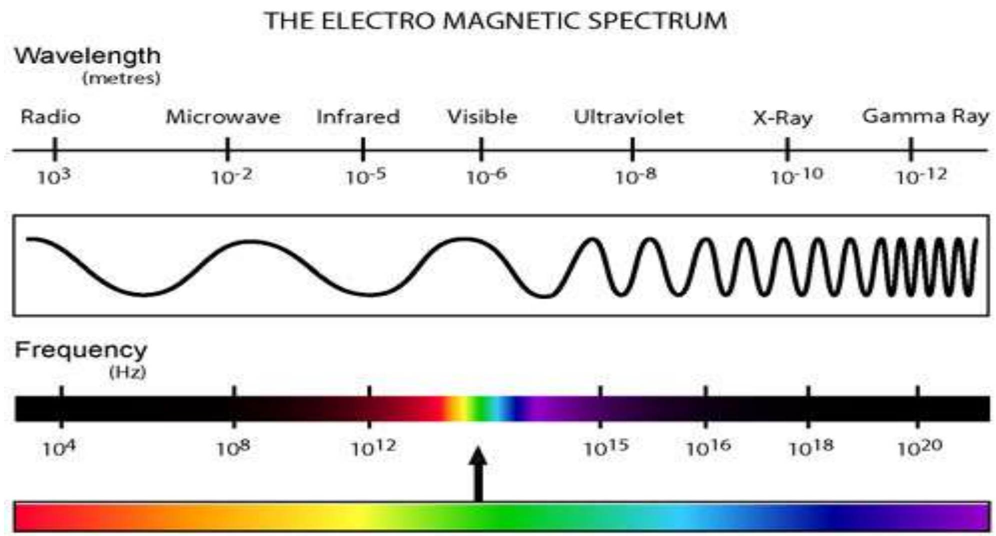
Objective

- Is to investigate if existing GPR technique is accurate enough to be used as QC/QA tool in assessing compaction of asphalt pavements.

Radio frequency (RF) and microwaves

- Electromagnetic radiation
- Microwaves are on the short side of radio wavelengths
  - 300 MHz to 300 GHz (1 m to 1 mm)
- Electromagnetic wave has both electric and magnetic field components





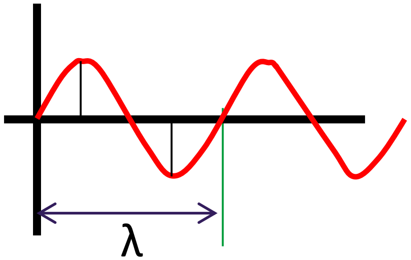
Microwaves

- For microwave signals asphalt is a lossy dielectric material
- If asphalt surface is illuminated with a microwave source, first some energy is reflected back from the air/asphalt interface
- In the asphalt the signal is attenuated (its amplitude gets smaller) due to losses (imaginary part, ε'' , of dielectric constant >0)
- At the same time, the phase angle of the signal changes, because the speed of propagation in asphalt is lower than in air (dielectric constant of asphalt, real part $\varepsilon' >> 1$)

- At the asphalt/air interface, (or in GPR measurements at the asphalt/supporting layer interface) again some reflection occurs
- Unfortunately signal phase shift is slightly connected to the imaginary part of epsilon as well

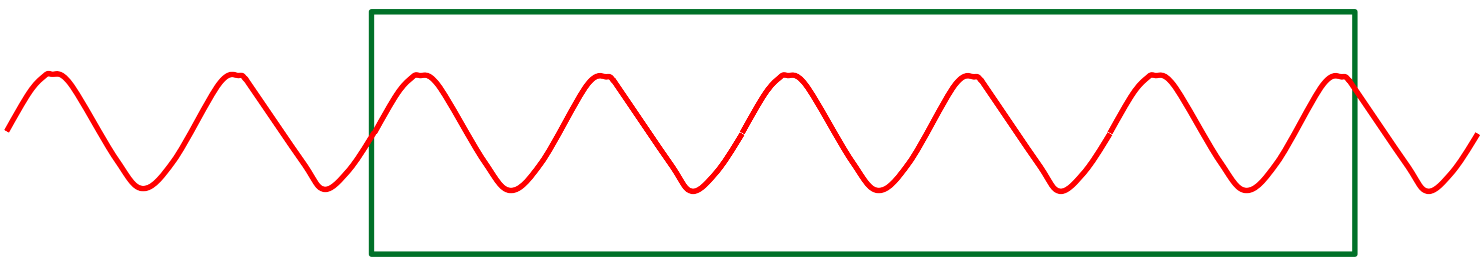
Wavelength and frequency

amplitude



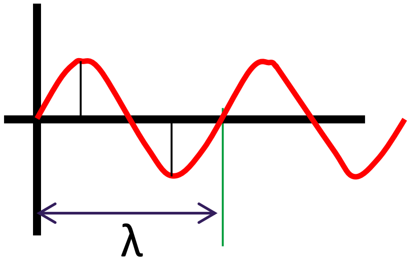
$$\lambda = \frac{v}{f}$$

f = frequency, Hz
v = velocity, m/s
λ = wavelength, m



Wavelength and frequency

amplitude



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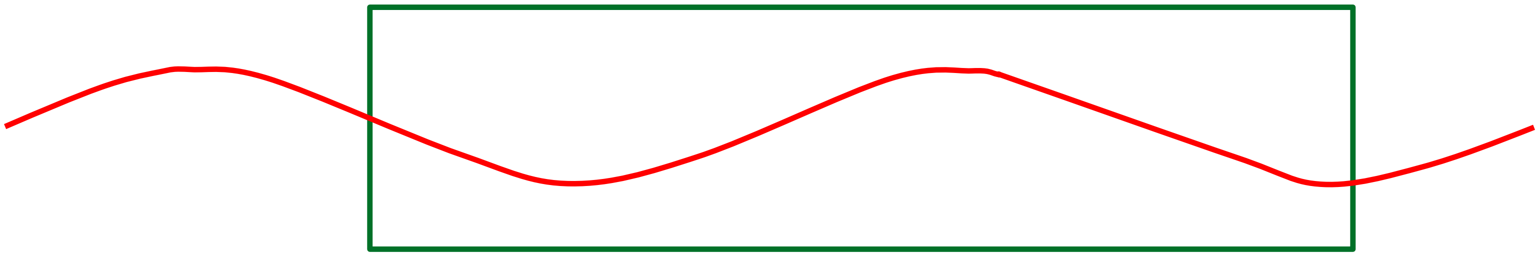
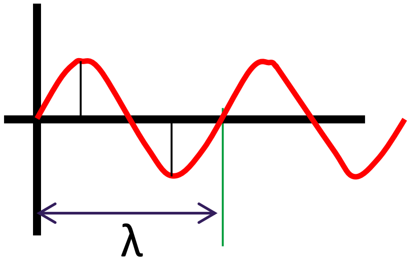


If λ is much lager than sample thickness, signal has not enough time to interact with the medium

Wavelength and frequency

amplitude



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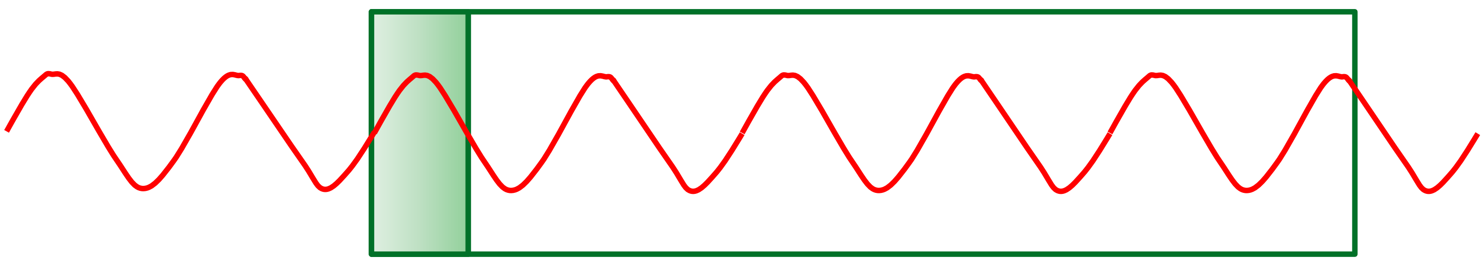
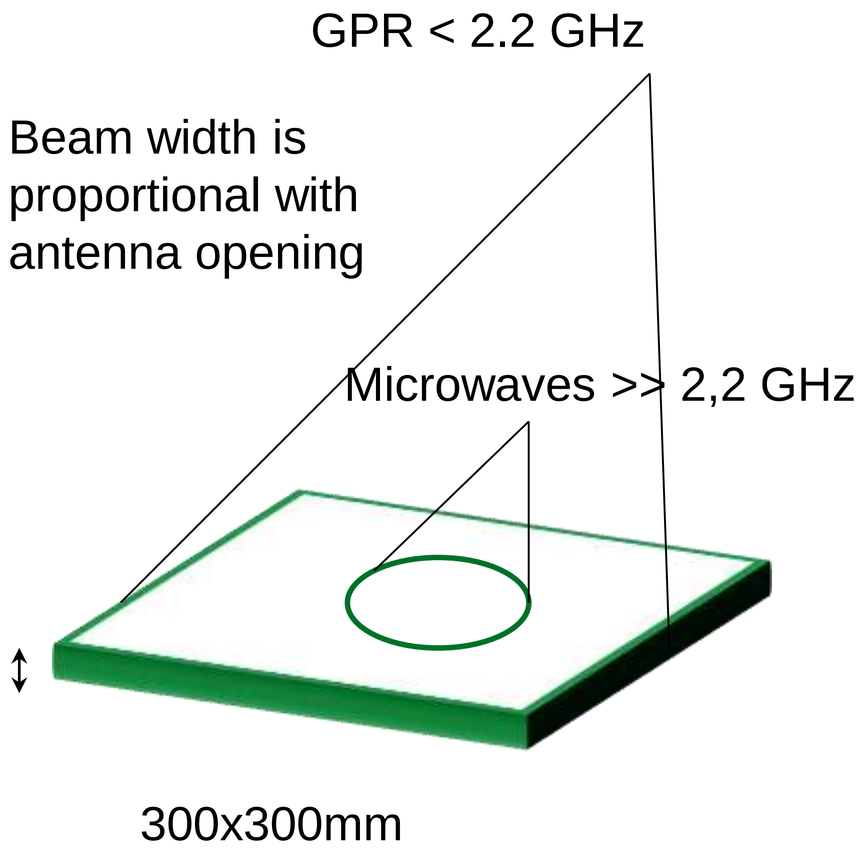


If λ is much lager than sample thickness we are interested in, signal has not enough time to interact with the medium

Beam width



- The wavelength of the microwave signal must be much shorter than the sample thickness in order to be able to distinguish between multiple reflections etc.

- If asphalt is 50 mm thick, the GPR should operate >> 5 GHz.

- As a bonus we get very good spatial resolution along the surface.
- For example, the granularity of asphalt can be seen at frequencies above 10 GHz.

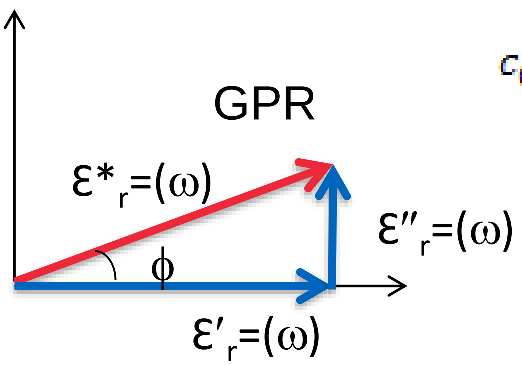
Relative Permittivity (dielectric constant)

- Relative permittivity is a material property
- Study of reflected waves allows detection of boundaries between material layers having different wave velocities (different dielectric constants).
- Reflection intensities allow estimation of dielectric constants and these combined with knowledge about time intervals between different reflections make layer thickness estimation possible.

$$c_0 = \sqrt{\frac{1}{\varepsilon_0 \mu_0}} \approx 3 \times 10^8 \, m/s$$

$$\varepsilon_r^*(\omega) = \frac{\varepsilon(\omega)}{\varepsilon_0}$$

$$\varepsilon_r^*(\omega) = \varepsilon_r'(\omega) + i\varepsilon_r''(\omega)$$



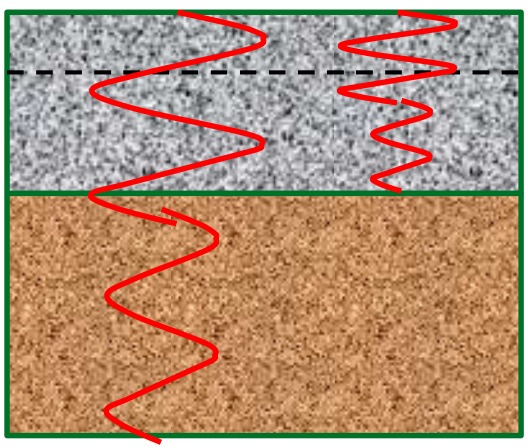
$$v = \frac{Co}{\sqrt{\varepsilon_r}}$$

Relative Permittivity (dielectric constant)

$$\overset{*}{\varepsilon}_r(\omega) = \varepsilon'_r(\omega) + i\varepsilon''_r(\omega)$$

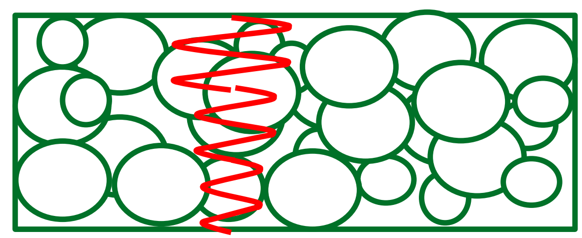
$$c_0 = \sqrt{\frac{1}{\varepsilon_0 \mu_0}} \approx 3 \times 10^8 \, m/s$$

$$v = \frac{Co}{\sqrt{\varepsilon'_r}}$$



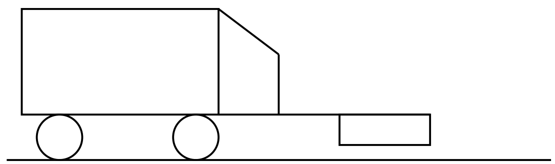
50 mm

λ >> 5 GHz

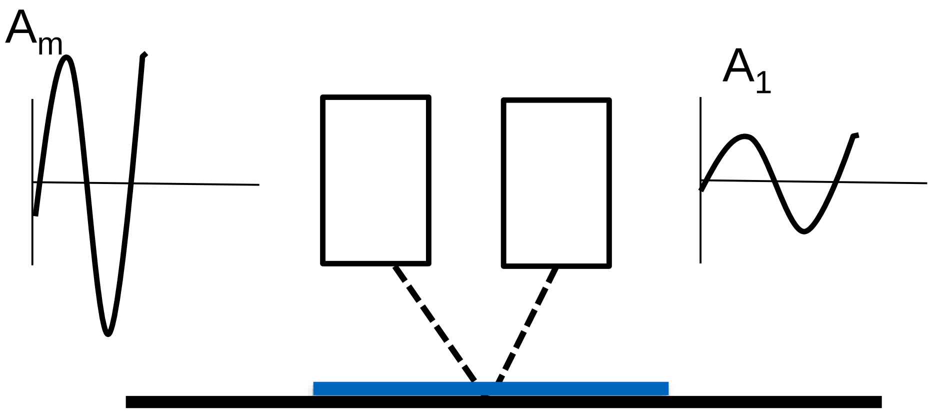


λ > 10 GHz

Ground Penetrating Radar (GPR) technique



All reflected in A_m

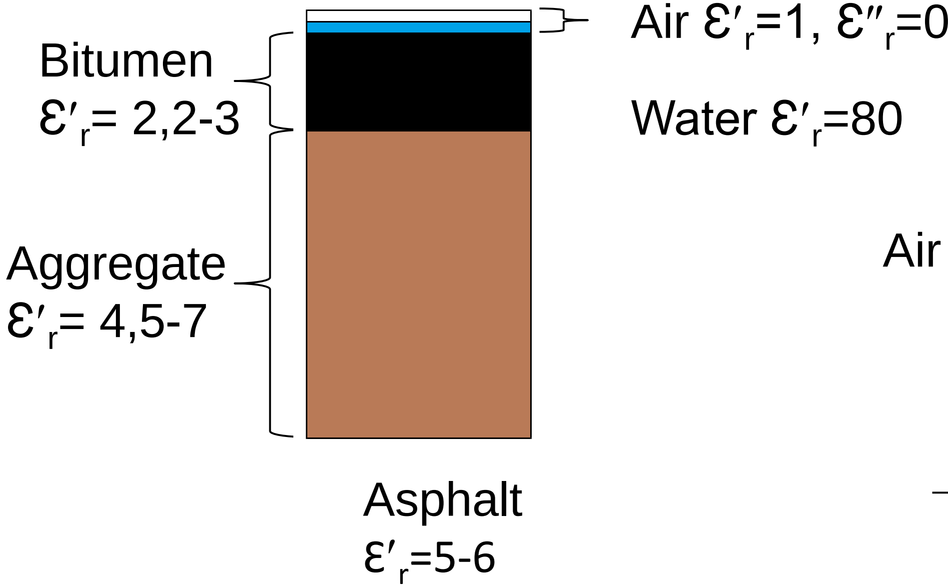


$$\varepsilon'_r = \left[\frac{1 + A_1/A_m}{1 - A_1/A_m} \right]^2;$$

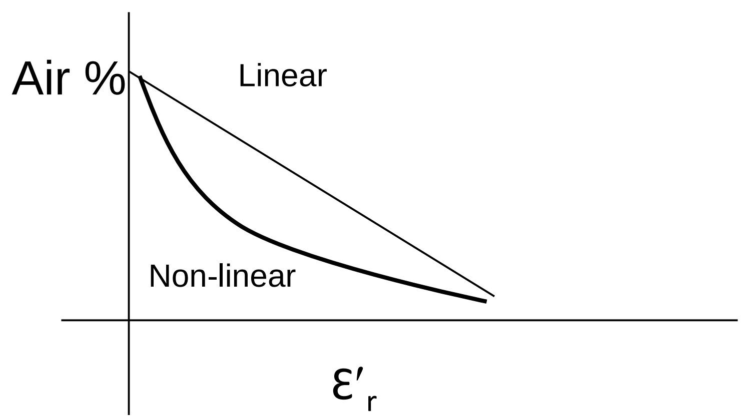
Modeling of relative permittivity

$$G_{mb} = \frac{\dfrac{\varepsilon_{AC}-\varepsilon_b}{3\varepsilon_{AC}+(u-2)\varepsilon_b} - \dfrac{1-\varepsilon_b}{1+(u-2)\varepsilon_b+2\varepsilon_{AC}}}{\left(\dfrac{\varepsilon_s-\varepsilon_b}{\varepsilon_s+(u-2)\varepsilon_b+2\varepsilon_{AC}}\right)\left(\dfrac{1-P_b}{G_{se}}\right) - \left(\dfrac{1-\varepsilon_b}{1+(u-2)\varepsilon_b+2\varepsilon_{AC}}\right)\left(\dfrac{1}{G_{mm}}\right)}$$

Al-Qadi model, based on volumetric components



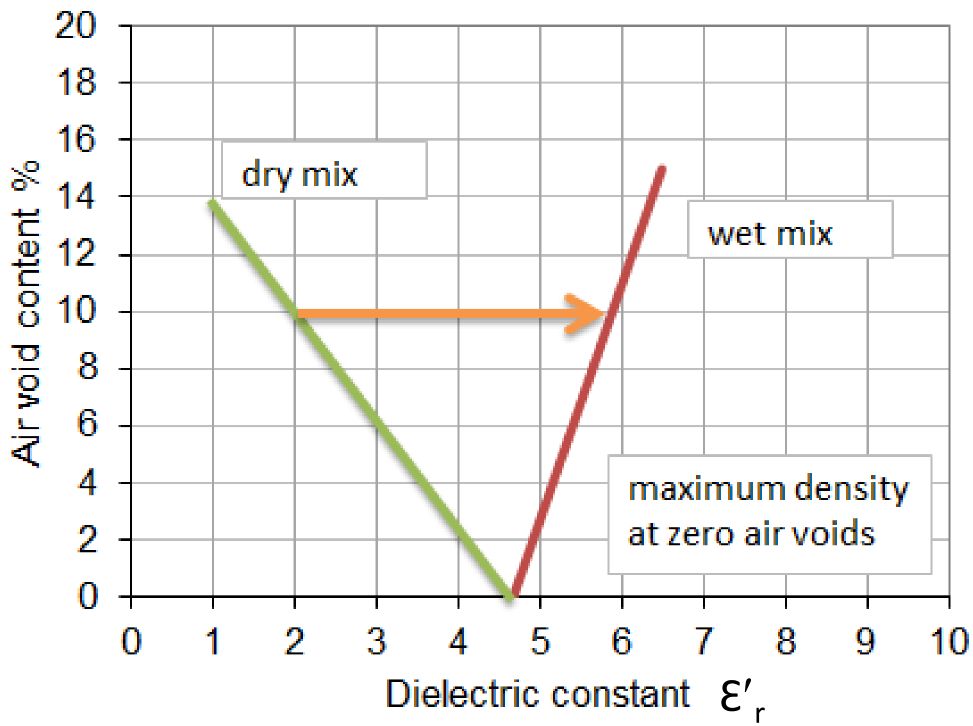
Volumetric or gravimetric relation?

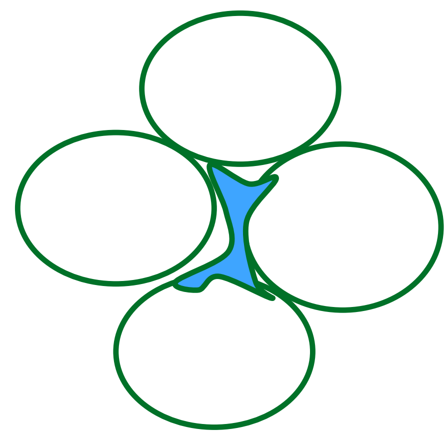


Moisture effect

Air $\varepsilon'_r=1$ Water $\varepsilon'_r=80$

Moisture will increase ε'_r



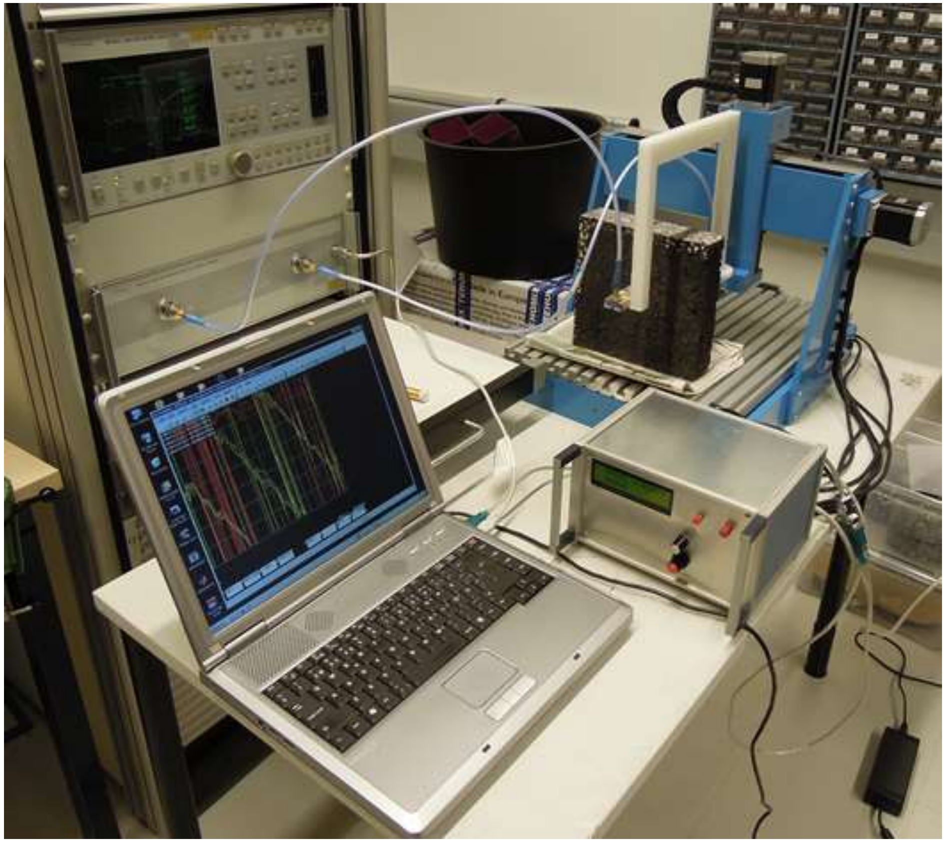


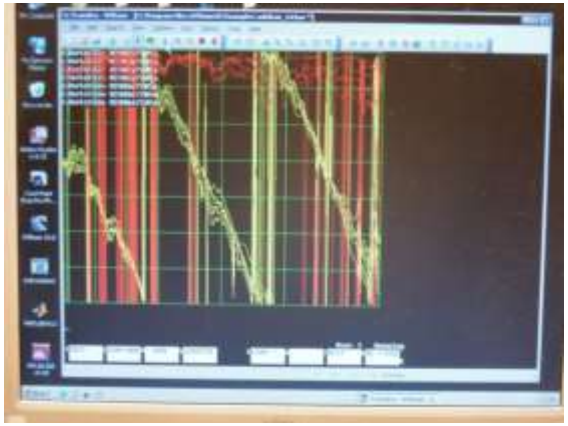
Vector Network Analyzer (VNA)

- Vector network analysis is a method of accurately characterizing signal deformations by measuring their effect on the amplitude and phase of swept-frequency (and sometimes swept-power) test signals.

- The VNA through- measurements can be then considered to give the “true” asphalt layer dielectric values and therefore they give the baseline to evaluate the GPR measuring technique.

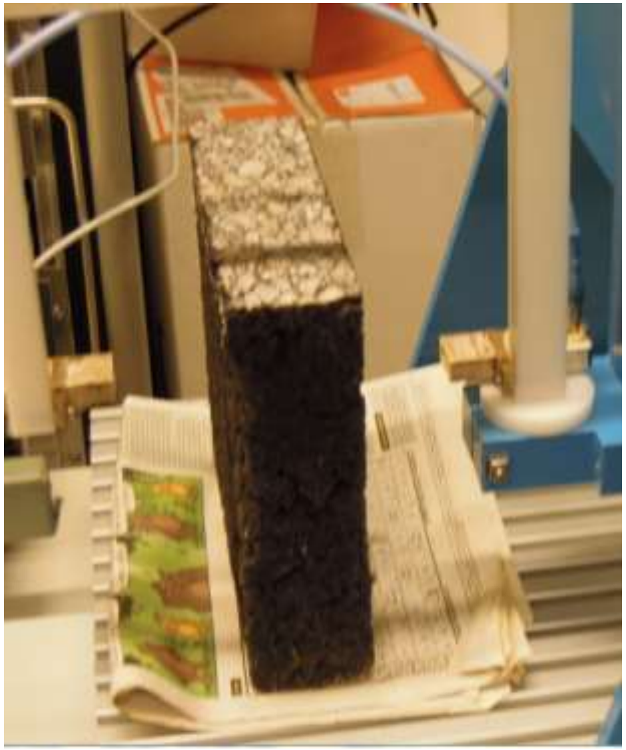
Vector Network Analyzer (VNA) with computerized scanner



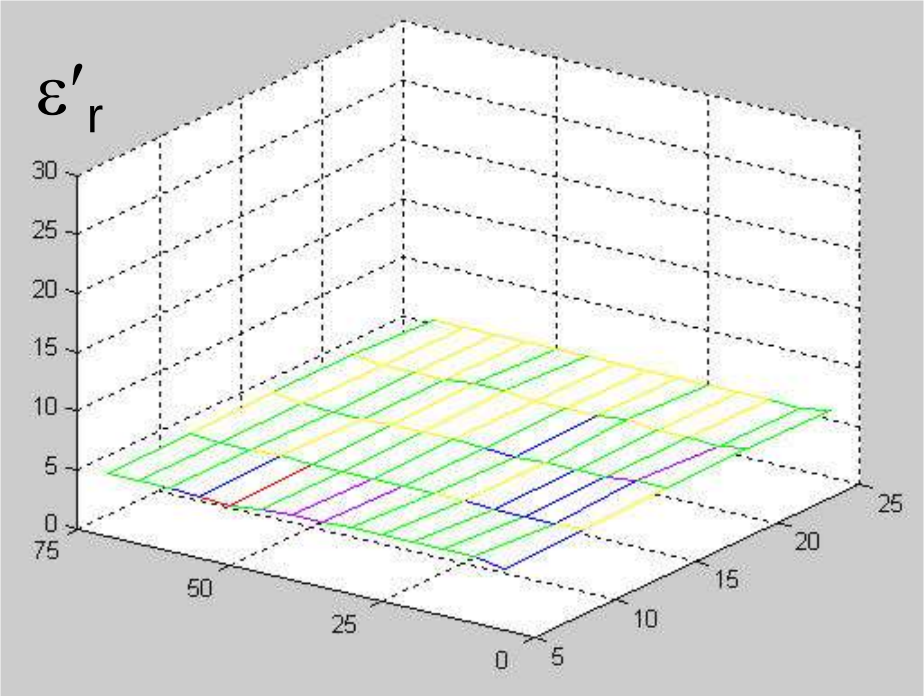


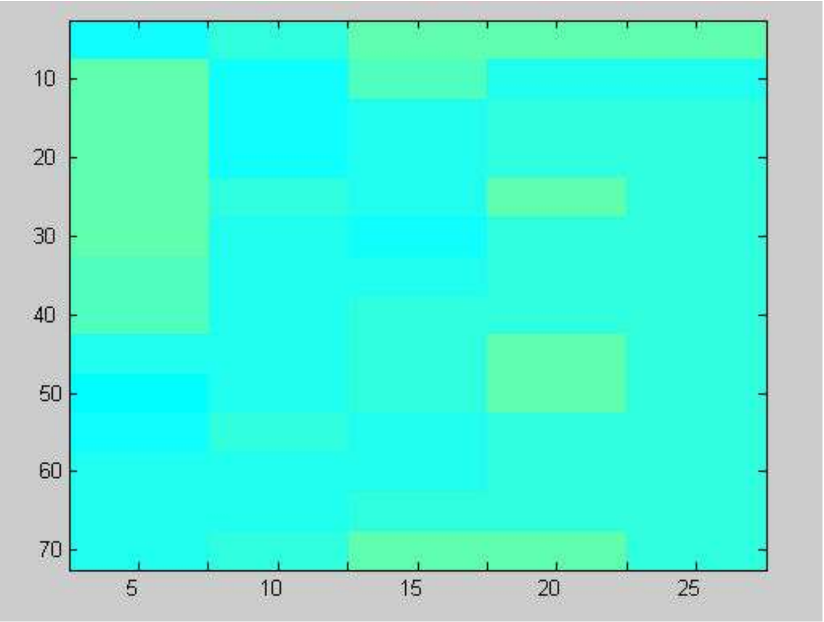
VNA measurements

- Vector Network Analyzer through-measurements utilizes air calibration (nothing but air between antennas) and constant transmitted signal amplitude.
- Then, after inserting the test sample, signal phase shift is recorded as a function of microwave frequency.

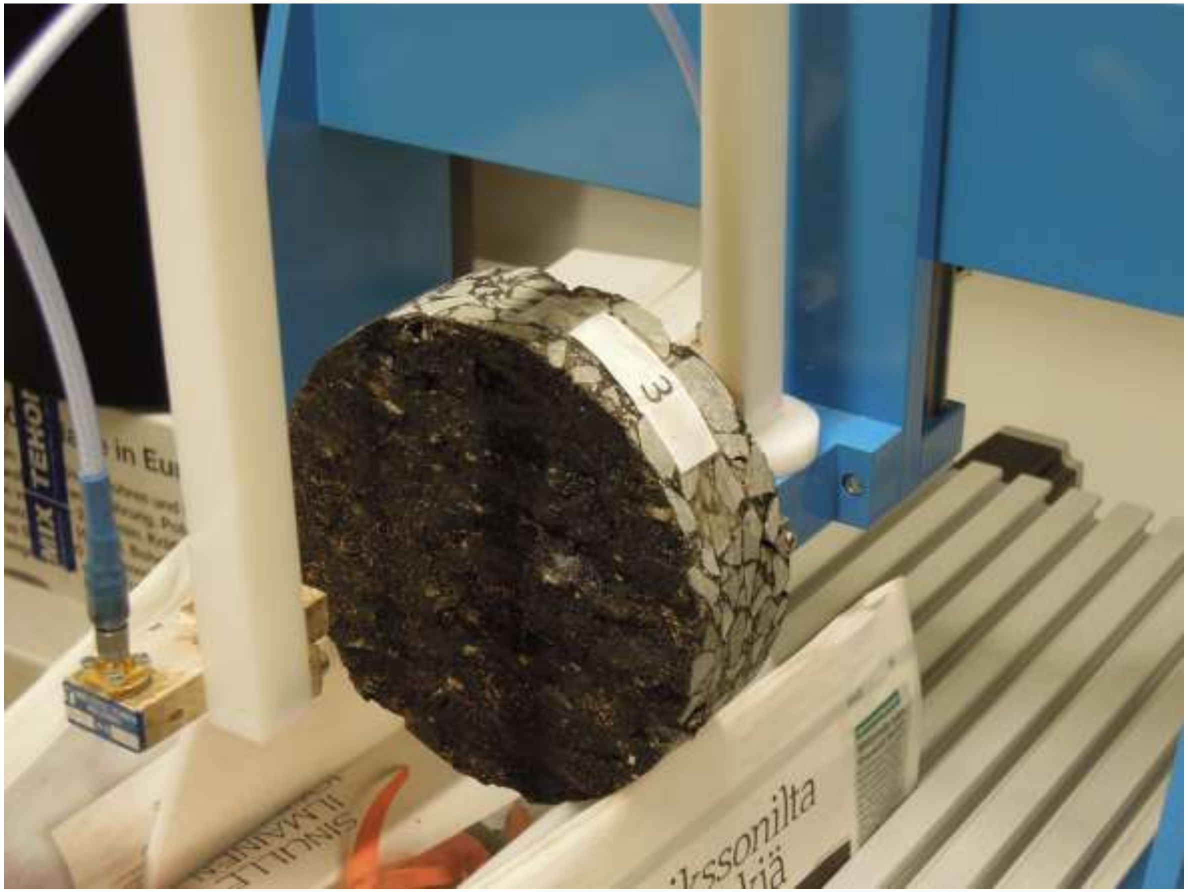


Preliminary measurements of the real part ε'_r of complex dielectric constant $\varepsilon*$ (laboratory fabricated slab with zero air voids), xy-dimensions in mm

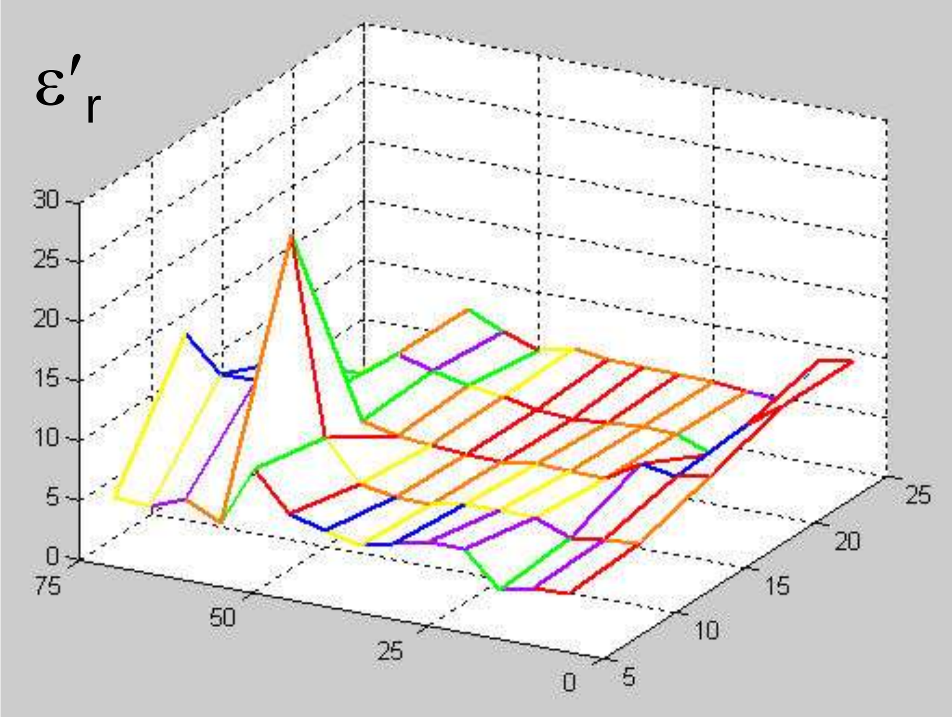


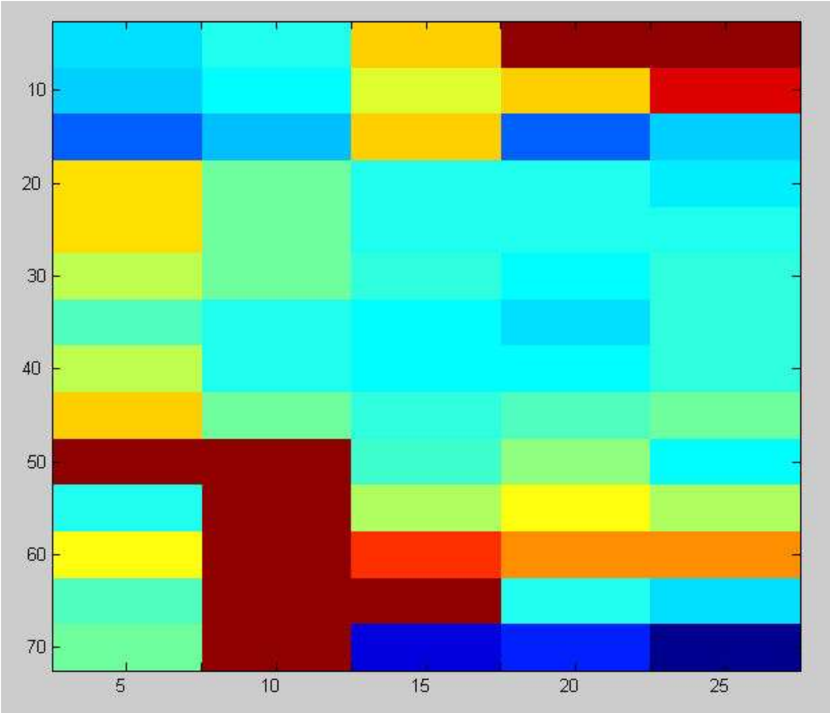


Field core measurements through the sample with VNA and computerized scanner, 7-17 GHz



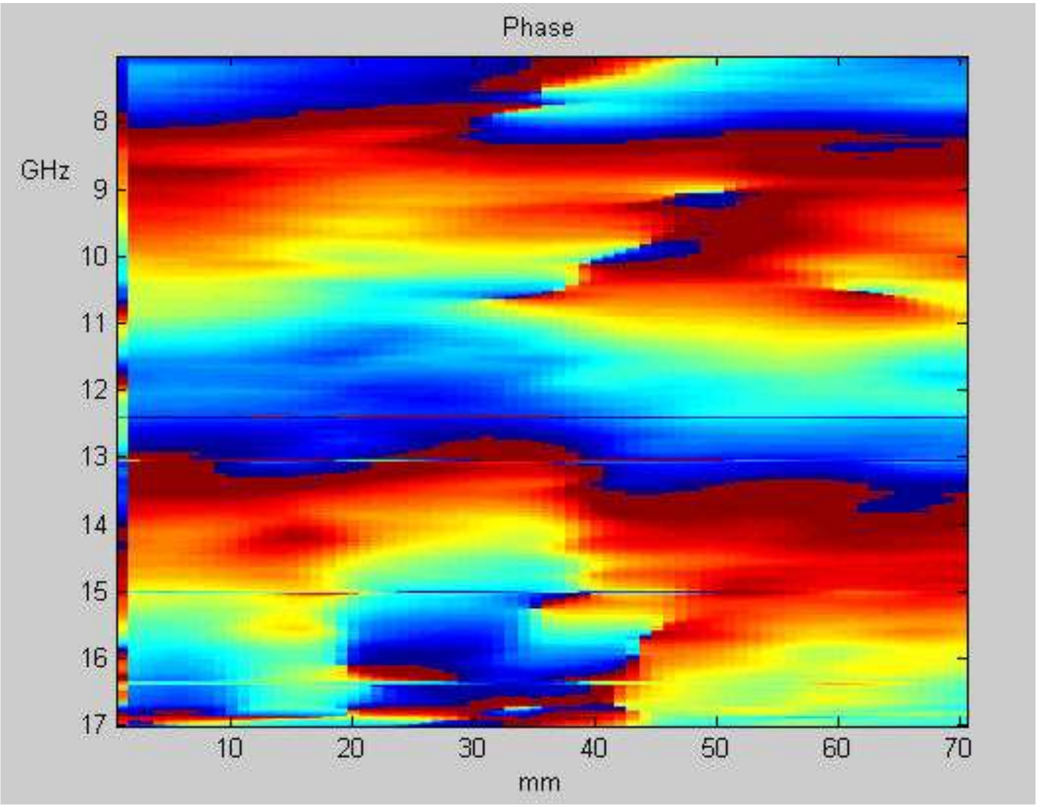
Preliminary measurements (field core with 7 % air voids) with VNA and computerized scanner, 7-17 GHz





xy-dimensions in mm

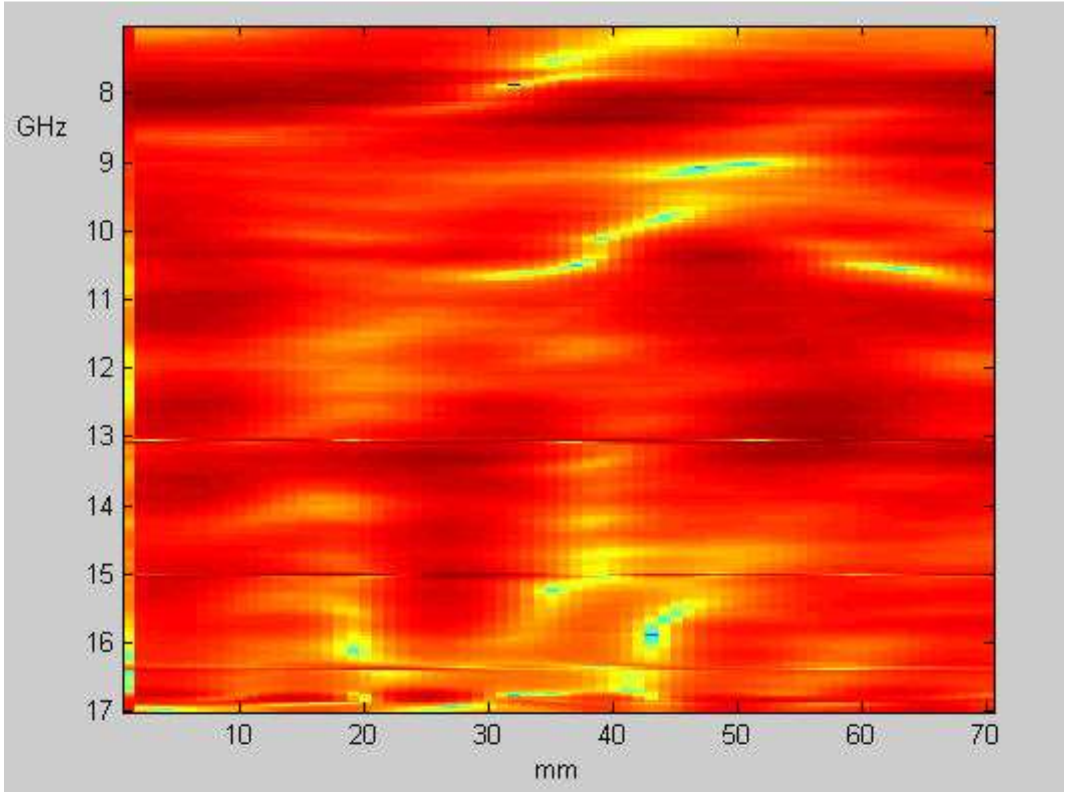
Preliminary measurements (field core with 7 % air voids), with VNA and computerized scanner



Linear scan
Along x, 0-70 mm
In 1 mm increments
y=0

Phase as color, proportional to changes in ε'

Preliminary measurements (field core with 7 % air voids), linear scan with VNA



Scan along
x- direction
0-70 mm in 1 mm increments

Attenuation as color, proportional to ε''

Research Tasks

- Sampling and field measurements
  - Coring and taking slabs
  - GPR measurements
- Testing
  - VNA
  - Pavement and maximum density of mixture
- Data processing
  - VNA and GRP data processing
- Analysis
  - GPR calibration and enhancements for measurement technique

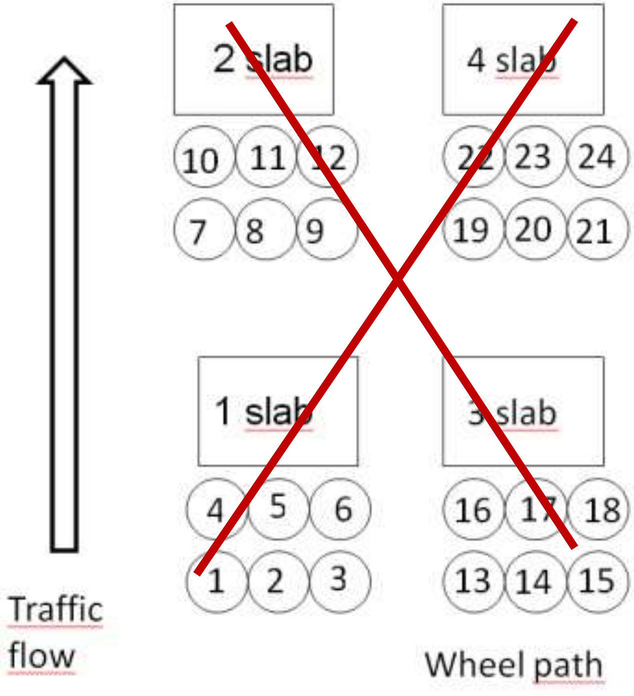
Research approach

- We had two test roads, Vt3 and Vt12
  - Both had SMA16 mixture from the same asphalt plant
- Slabs are needed for the GPR comparisons
- We also took cores for verification
  - Mixture homogeneity
  - Air void content
  - Calibration

Sampling: Vt3

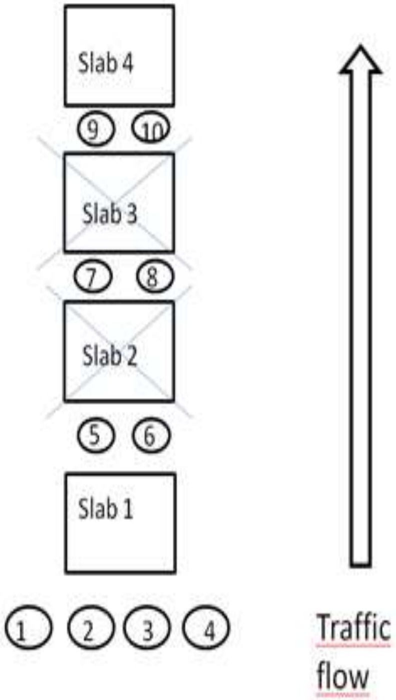
All slabs broke and we only took cores from GPR measurement locations

150 mm cores



Sampling: Vt12

100 mm cores

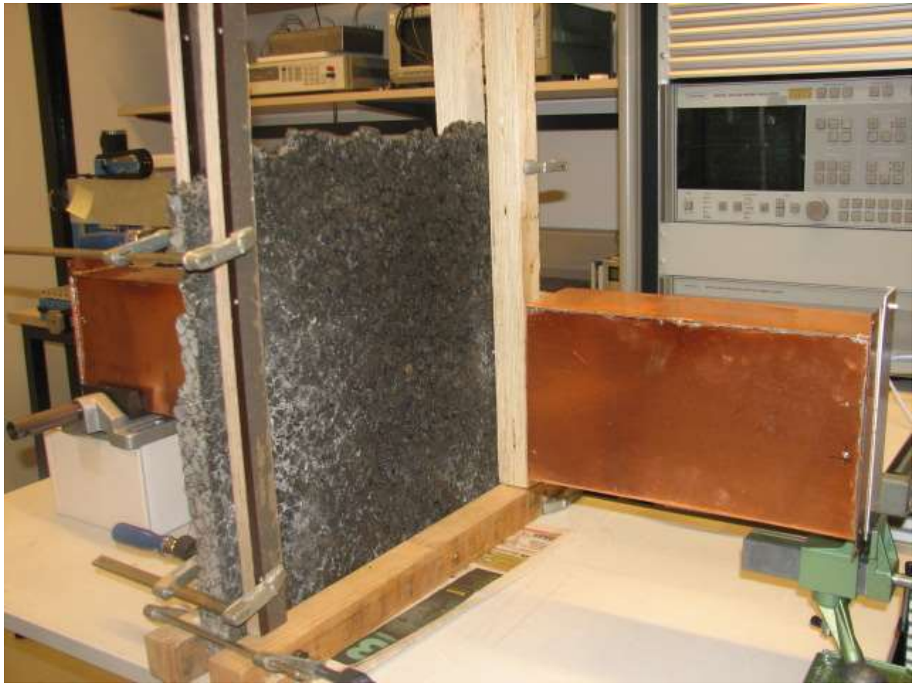


Lessons learned from sampling

- Plywood plates were reflected to the pavement surface, and layer thickness became too small
- Compaction was affected by the stiffness of base layer
- A better way of obtaining representative slabs should be developed

Slab measurements

- Slab measurements have started.

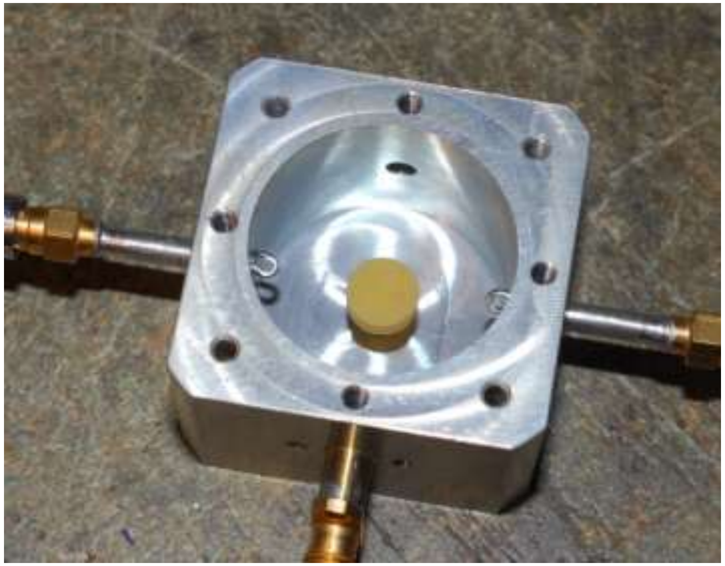


Raw material measurements: Bitumen

Raw material measurements: Bitumen

Raw material measurements: aggregates

- Cylindrical cavity resonator is used to find out dialectical properties of aggregates
- Center frequency is proportional to ε'_r
- Quality factor is proportional to ε''_r



Raw material measurements: aggregates

- We collect rocks from the quarry. Minerals we want to study are granites and quartz.

Lessons learned from measurements

- 150 mm cores are fine for 7 to 17 GHz, but too small for the GPR comparison
- 100 mm cores are too small for ε'_r measurements
- Difficult to prepare bitumen samples and avoid having air in the sample
- Measuring filler will be very difficult

Study of water effects

- Compact asphalt mixture to 0%, 4% and 8% air voids
- Measure ε'_r
- Saturate samples and measure ε'_r again

Timetable

TASKS	Q1-Q3 2013	Q4 2013	Q1 2014	Q2 2014	Q3 2014	Q4 2014
Preliminary investigation	■	■				
Sampling		■				
Testing		■	■			
Analysis			■	■	■	
Dissemination					■	■

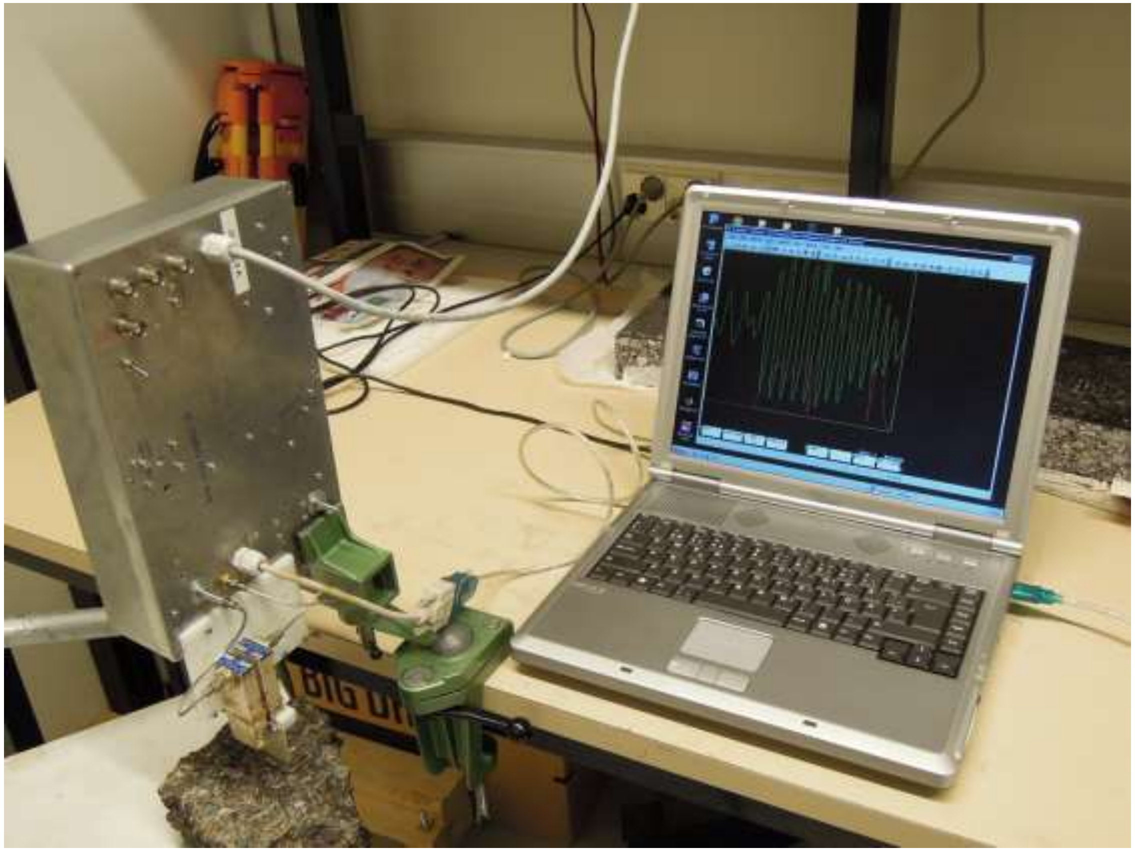
<u>Data to be collected:</u>

GPR measurements results

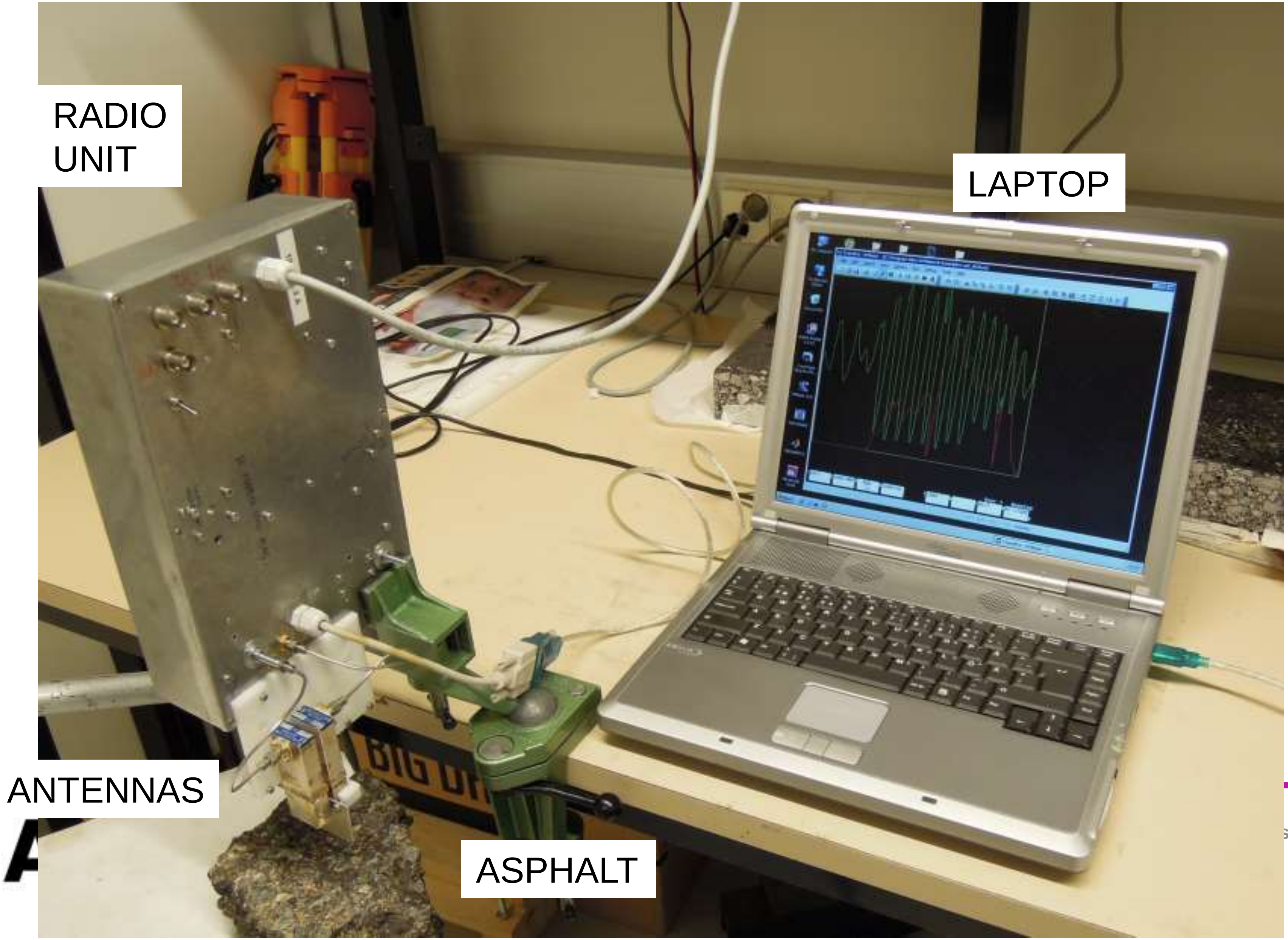
QC information on mixtures

-air voids, mixture quality

Proposed: New field measuring device for microwave frequencies



CONSTRUCTION



FEATURES

- Frequency agile, sweeps 13-17 GHz
- Quasi-monostatic construction with two antennas
- Depth resolution adequate for ≥4 cm asphalt layer
- Can find successive layers as well
- Spatial (x-y) resolution 20-25 mm
- Portable (radio unit 1 kg)
- Battery powered (12 V/ 1A)
- Direct laptop interface
- Suitable for road analysis in hand-portable, bicycle mounted or van mounted configuration

DATA OUTPUT

- Signal amplitude and phase from simple data acquisition software in the laptop
- Post-processing further yields real part of permittivity, layer granularity and layer thickness etc.

WHAT NEXT

- Radar hardware and basic software ready and functional
- Scale calibration (in progress)
- Field experiments and laboratory tests in 2014
  – Comparison with current GPR, coring
- Salary funding needed for 2014