Exploring New Microwave Measurements

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by

Roger Stancliff

CTO, Microwave Measurements
Agilent Technologies
Santa Rosa, California, USA

Exploring New Microwave Measurements

1) Microwaves, Measurements, and Vector Network Analyzers

- What are Microwaves?
- What is a Network Analyzer?
- History and Evolution of this Fundamental Measurement Instrument

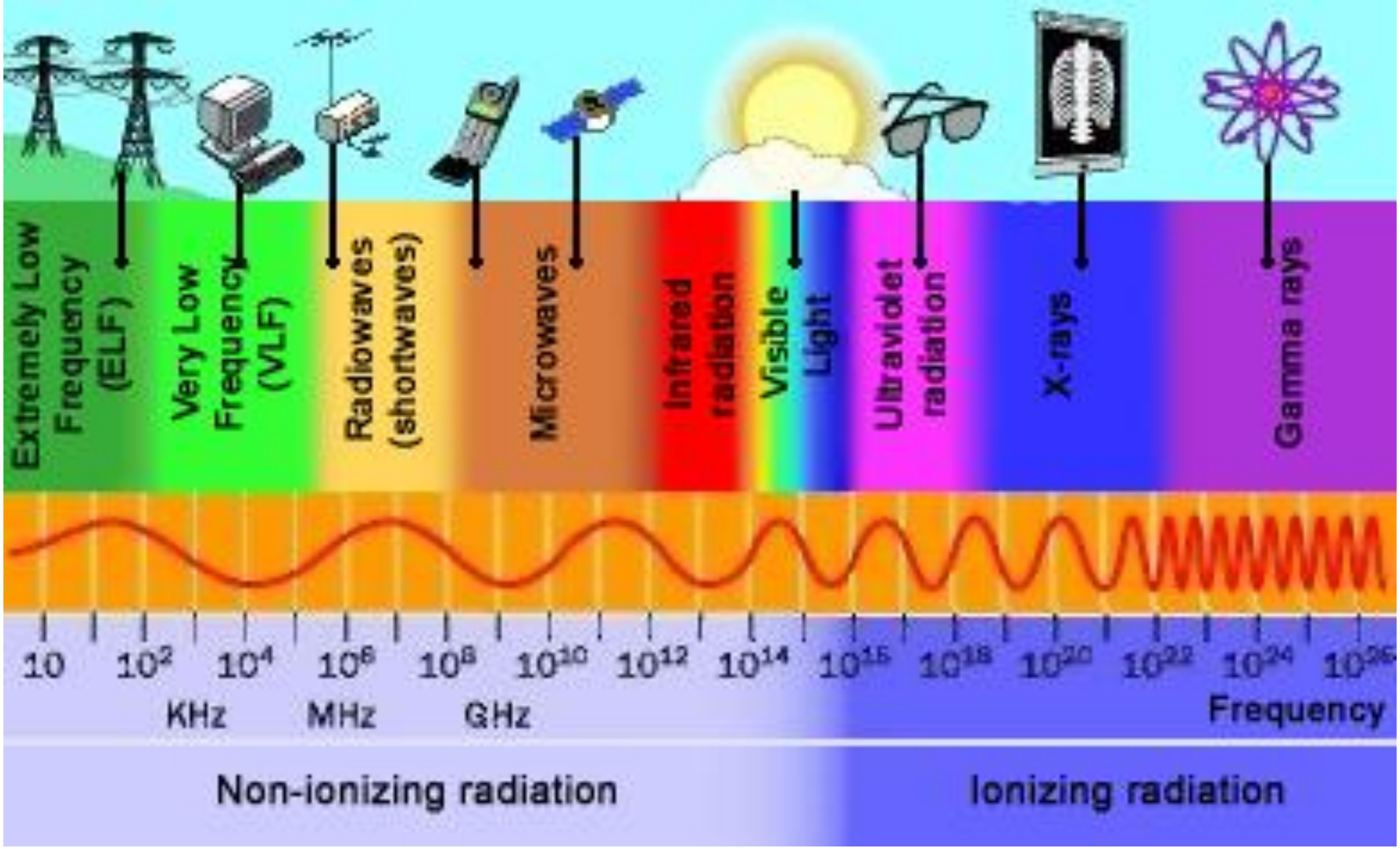
2) **New Measurements for Microwaves: small, wet, changing**

3) **Major Application Focus Areas**

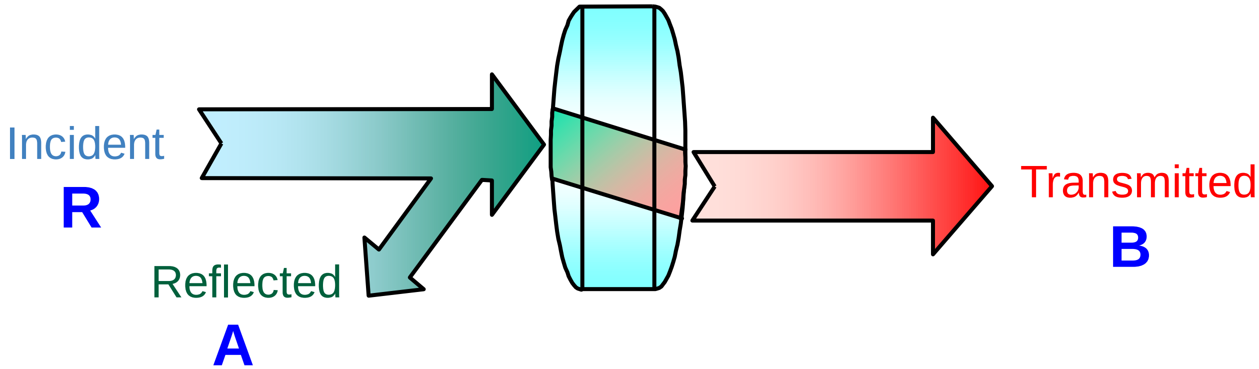
- Medical Diagnosis and Therapy
- Homeland Security
- Process Analytics & Enhancement
- Nano scale measurements and imaging

4) **Summary**

The Electromagnetic Spectrum



Network Analyzers: an Analogy



REFLECTION

$$\frac{\text{Reflected}}{\text{Incident}} = \frac{A}{R}$$

- SWR
- S-Parameters S_{11}, S_{22}
- Reflection Coefficient Γ, ρ
- Impedance, Admittance R+jX, G+jB
- Return Loss

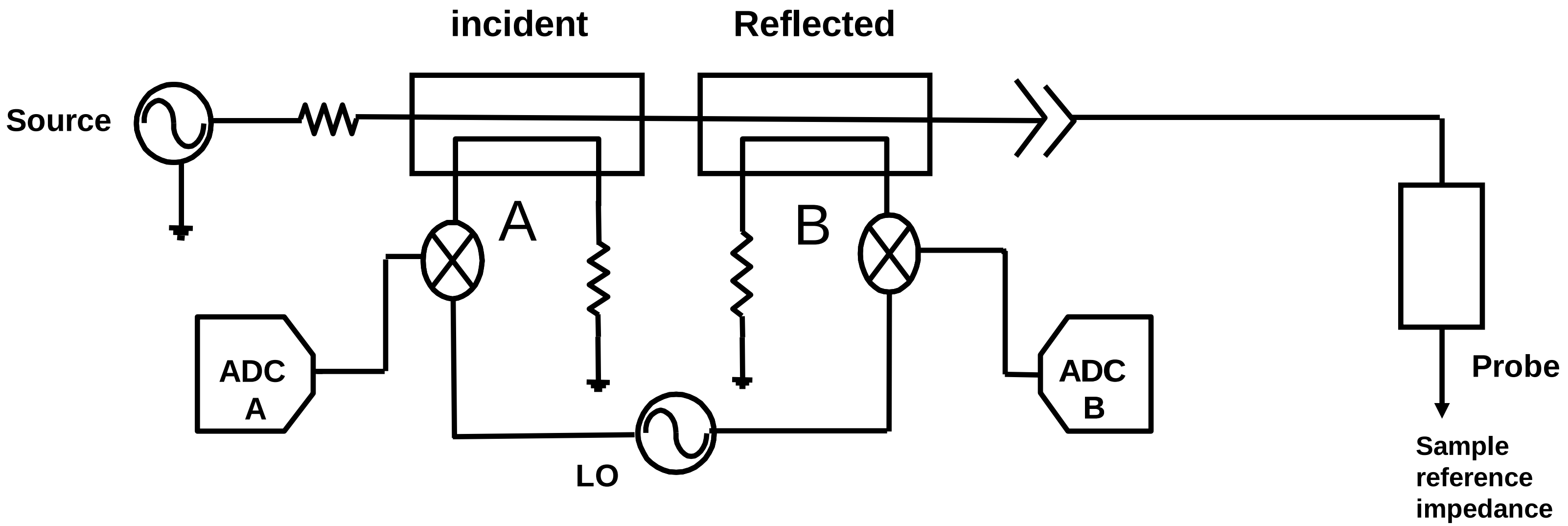
TRANSMISSION

$$\frac{\text{Transmitted}}{\text{Incident}} = \frac{B}{R}$$

- Gain / Loss
- S-Parameters S_{21}, S_{12}
- Transmission Coefficient T, τ
- Insertion Phase
- Group Delay

Standard Network Analyzer

Reflection Only



$$S_{11} = \frac{Z_L - Z_0}{Z_L + Z_0}$$

= B/A

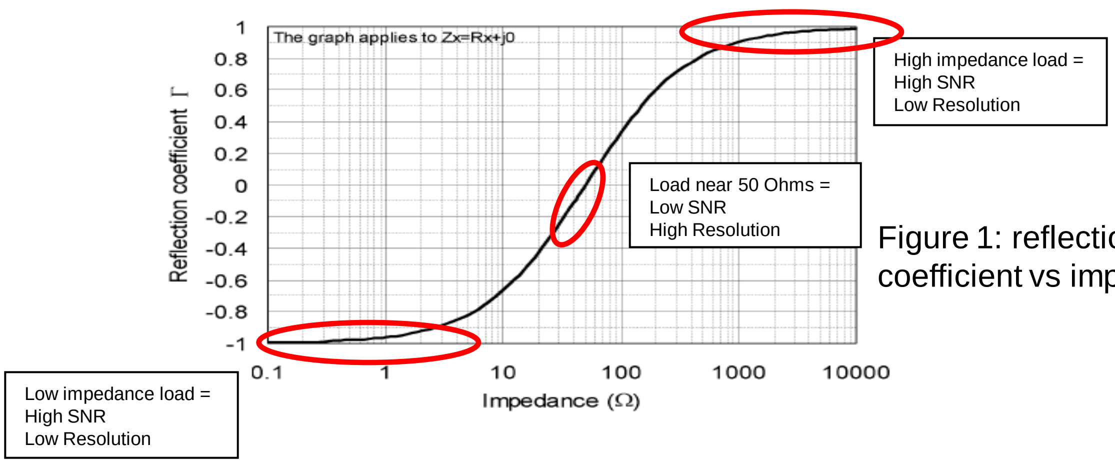


Figure 1: reflection coefficient vs impedance

Network Analyzers

The Network Analyzer products perform stimulus - response testing of RF and MW components such as filters, amplifiers, and converters.

Key Markets

- Cellular PCS
- Broadcast
- Defense Aviation

Applications

•Component Manufacturing - Automated and manual testing

•R&D - Component design and development with CAE tools

•Field Service - Base station and video cable testing

Agilent Technologies
40 Years of Network Analyzer Innovations

1967
8410A

Figure 1. 8410 network analyzer

1975
8542A Automation V

Figure 2. 8542 automatic network analyzer system

1984
8510A set the industry standard

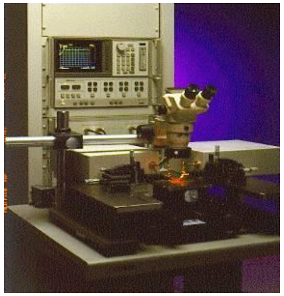
Figure 3. 8510 network analyzer

1986
8753 Series New economy entry into RF market

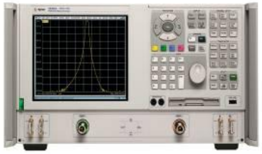
1988
8720 Series New economy entry into the Microwave

1991
8711 Series Low Frequency

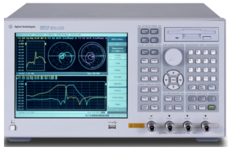
1996
8510XF Single sweep up 110GHz



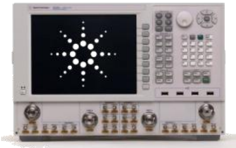
2000
PNA: New standard of performance



2001
ENA



2007
PNA-X



PNA Applications

Amplifier test
Single connection:
Gain compression,
IMD, noise figure,
harmonics,
true differential,
PAE, hot S_{22}

Load-pull Noise parameters

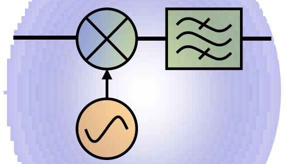
T/R module test

Satellite payload test

Antenna test

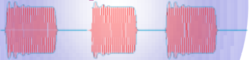
Lightwave component analysis

Mixer test



Scalar/vector Cal
absolute group delay
embedded LO

High Power Devices & Components



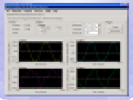
2 THz & beyond
500 GHz
110 GHz
67 GHz
50 GHz
43 GHz
26 GHz
13.5 GHz
6 GHz
300 kHz

PNA-X
PNA-L
PNA

Millimeter & Terahertz research

Materials measurements

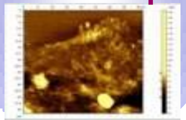
Non-linear Modeling
Characterization
X-parameter* extraction
pulse envelope domain



Metrology
Primary standards/
calibration & repair

Signal integrity

Atomic Force Scanning microscope



www.agilent.com/find/pna

**X-parameters is a trademark of Agilent Technologies.*

What are X-Parameters?

Superset of s-parameters that enable complete device characterization in linear and non-linear domains

What is an NVNA?

The New Industry Paradigm for Non-Linear Measurement and Design

- **Based on standard PNA-X (add NVNA options)**
- **New phase reference enables measurement of a signals fundamental and harmonics in both amplitude and phase**
- **IF you know a signal and its harmonics, with both amplitude and phase, you can reconstruct the time waveforms**
- **X-Parameter measurement**
- **Fast RF-Pulse Measurement (Pico-seconds of time resolution)**
- **Enables more accurate modeling at device and system level**

High Performance Millimeter Wave Solutions

Single Sweep 10 MHz to 110 GHz

N5250C

- 1.0 mm coax connector interface
- Industry leading calibration choices for coax, in-fixture or on-wafer devices
- Optional Kelvin bias tees at the port
- Optional mechanical attenuator

Single Sweep

THz Network Analysis Solution

PNA-X 2 or 4 Port OML Based Banded Waveguide System

26.5 GHz
43.5 GHz
50 GHz

Measurement Applications

WR15	50 – 75 GHz
WR12	60 – 90 GHz
WR12E	54 – 92 GHz
WR10	75 – 110 GHz
WR6	110 – 170 GHz
WR5	140 – 220 GHz
WR3	220 – 325 GHz
WR2.2	325 – 500 GHz
WR1.5	500 – 750 GHz
WR 1.2	600 – 900 GHz
WR 1.0	750 – 950 GHz

PNA-X 2 Port VDI Based Banded Waveguide System.

THz Imaging

26.5 GHz
43.5 GHz
50.0 GHz

The "Physics" of Microwave Sensing: How Microwave Measurements apply to Material Science and Biology

What can we measure or see with microwaves?

-Things that are small

(e.g. cells, viruses)

-Things that are wet

(e.g. tumors (vascularized), moist pharma powders, mined ore moisture, foods)

-Things that are changing

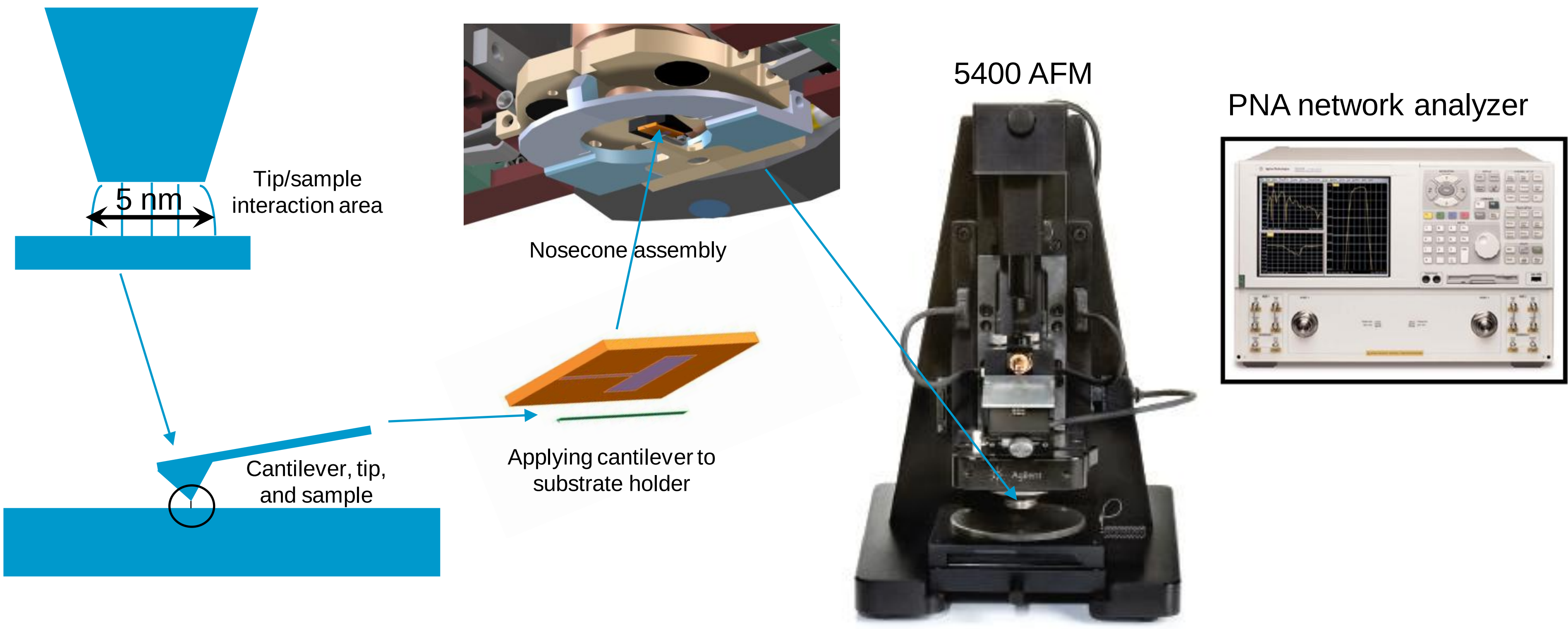
(e.g. chemical reactions, microwave chemistry, ion channel kinetics in cells)

How do we measure small things?

-SMM is a near field system. The resolution is determined by the Electric field interaction area with the sample. This is on the order of 5-10 nm

-SMM uses a network analyzer to measure the vector reflection coefficient caused by the tip-sample interaction; this gives information about the material properties (dielectric properties)

-While an AFM needs “contact” to make a measurement the SMM can measure without contact. You can be 1-10 nm away from the sample and still have good sensitivity



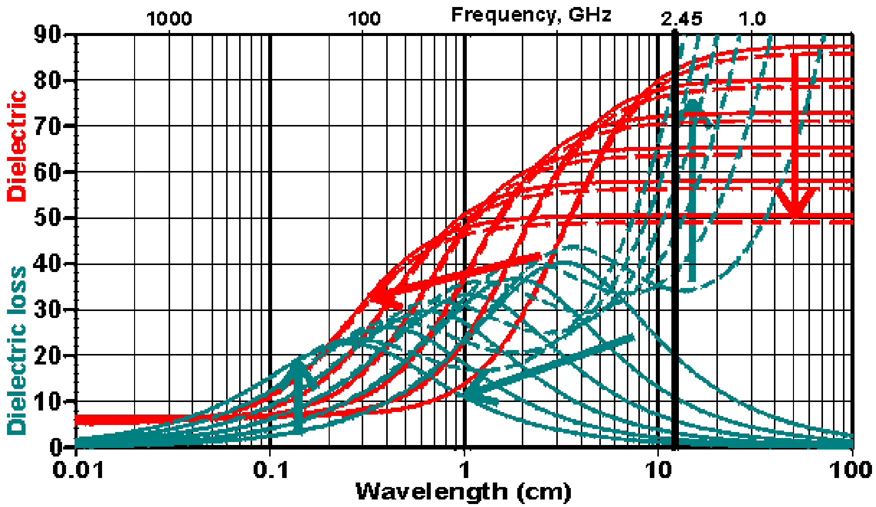
How do we measure wet things?

-Dielectric constant is the measure of polarizability and dissipation of a substance in an E field

-Water has a very high dielectric constant until it approaches a dielectric relaxation resonance between 8-50 GHz range depending on temperature (17 GHz at room T)

-Ionized water has high loss (good conduction) below 1 GHz; sweet spot for measuring moisture is 1-3 GHz. Moisture measurement depends on the relatively low dielectric constant of the "host" material compared to water and the measurement of the mixture's dielectric constant

-Tumor detection depends on the wetness (vascularization) of the tumor compared to surroundings

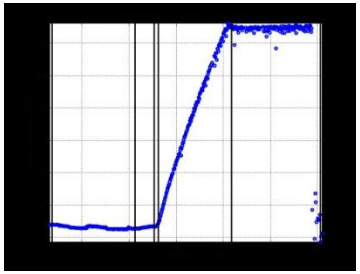


Arrows: direction of increasing temperature from 0 – 100 C

Agilent Technologies

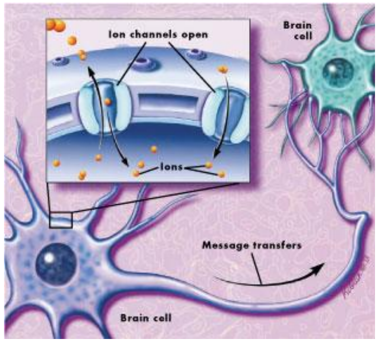
How do we measure things that are changing?

-Dielectric properties of materials change as they change state or composition. An example of this is a chemical reaction



-Microwave chemistry is the acceleration of dissolution and chemical reactions through the addition of microwave energy. We can monitor this in real time by measuring dielectric changes

-Cells (small and changing) regularly open their membrane walls to allow ions and other molecules to flow in and out. These are called ion channels. If an ion channel opens near the SMM probe, the change in dielectric constant should be visible. Also, molecules flowing through will modulate the dielectric constant, making them visible as well. We may be able to induce a channel opening with bias voltage applied to the tip



Major Markets and Application Areas for Microwave Sensing and Imaging

-Medical

-Homeland Security

-Process Analytics

-Nano Scale Imaging and Device Measurements

Microwave Medical Applications

Breast Tissue Characterization:

U of Wisconsin and U of Calgary had a joint project to characterize the dielectric properties of excised breast tissue to build a database for normal tissue and look for contrast with cancerous tissue (**M. Lazebnik, D. Popovic, L. McCartney, C. B. Watkins, M. J. Lindstrom, J. Harter, S. Sewall, T. Ogilvie, A. Magliocco, T. M. Breslin, W. Temple, D. Mew, J. H. Booske, M. Okoniewski, and S. C. Hagness, "A large-scale study of the ultrawideband microwave dielectric properties of normal, benign, and malignant breast tissues obtained from cancer surgeries,"** ***Physics in Medicine and Biology*****, vol. 52, pp. 6093-6115, 2007.**)

Breast Surgery Intra-Operative Probe (Real time Biopsy)

Dune Medical is in clinical trials with an instrument which uses dielectric contrast to help surgeons define the tumor margins during surgery.(http://dunemedical.com/)

Microwave Breast Imaging:

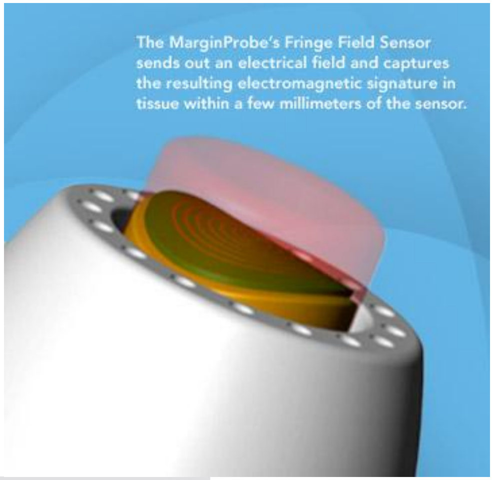
A number of Universities, research labs, and a start-up company have programs in microwave imaging for breast tumor detection.

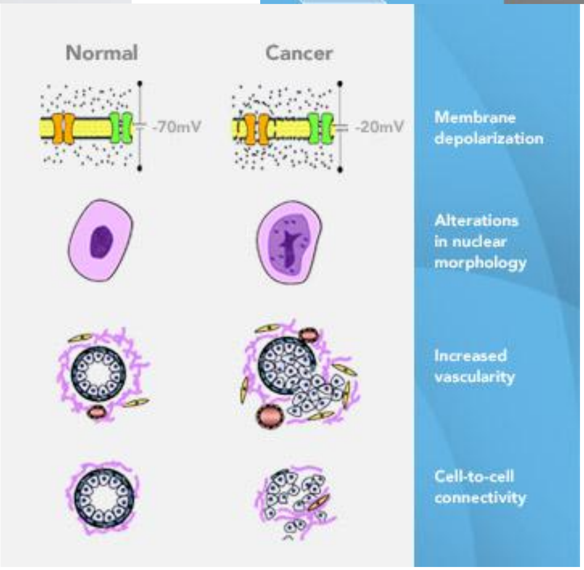
http://www.engr.wisc.edu/ece/faculty/hagness_susan.html (she has a very rich set of publications)

http://www.ucalgary.ca/sacri/node/207

http://www.micrima.com/

Dune’s Technology





Dune Medical's recent progress

FDA Accepts MarginProbe PMA and Grants Expedited Review

FDA Formally Accepts Dune Medical's MarginProbe™ System Pre-Market Approval (PMA) Application and Grants Expedited Review Status Download PDF

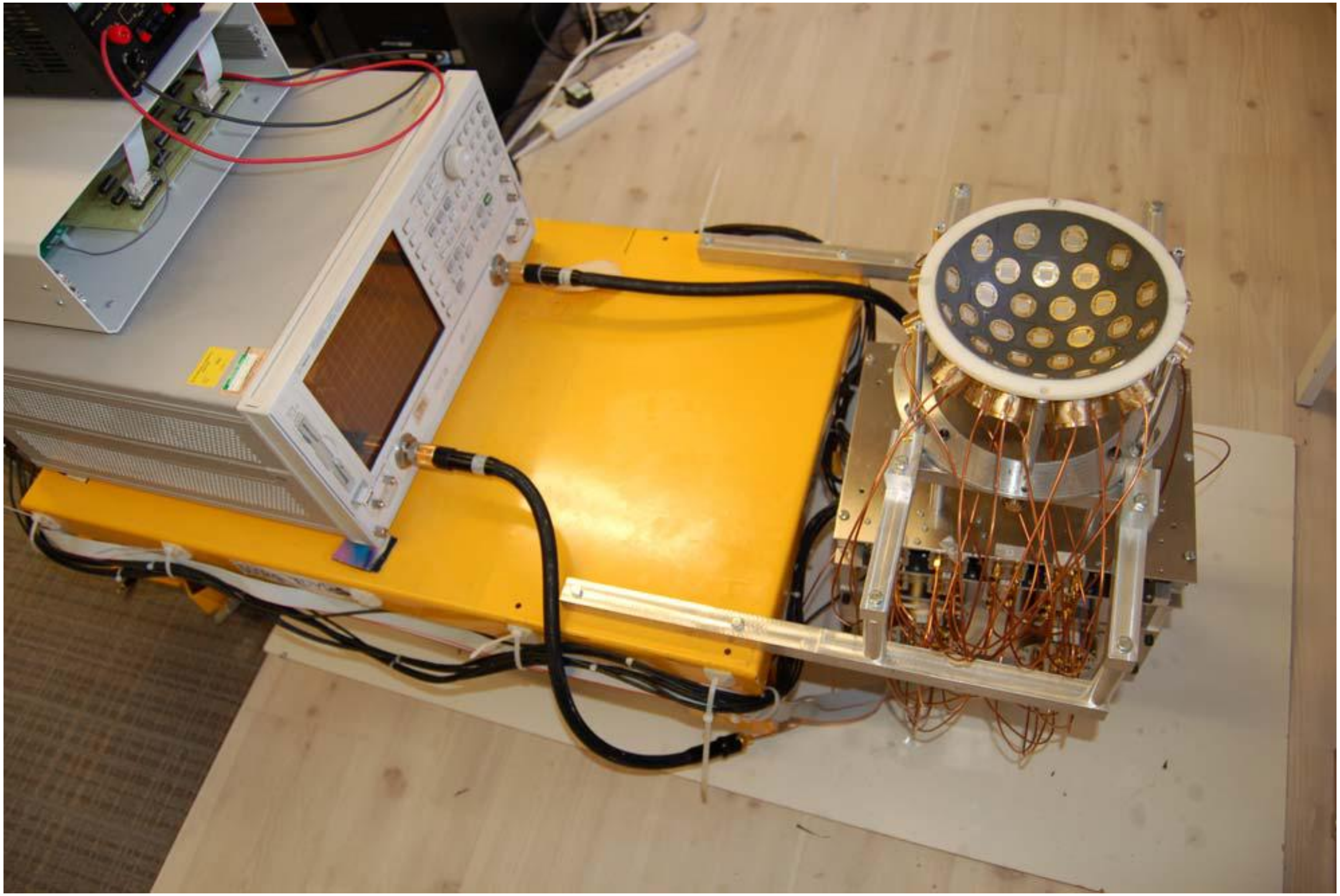
May 16th, 2011

Landmark Trial Shows Reduction in Patients Indicated for Re-excision

Dune Medical's MarginProbe™ Demonstrates Increased Positive Margin Identification Leading to Reduction in Patients Indicated for Re-excision in Landmark Lumpectomy Surgery Trial Download PDF

April 28th, 2011

Micrima (U of Bristol) Breast Imaging Prototype



Microwave Medical Applications (2)

Brain Imaging

LLNL did some early work here. Keele University and Medfield Diagnostics are building tomography systems currently

http://www.medfielddiagnostics.com/

http://www.keele.ac.uk/research/istm/semenov.html

Lung Moisture Measurement and Vital Signs Monitoring

U of Hawaii (Magdy Iskander) and others are working on this topic

On the development of a low-cost real-time remote patient monitoring system using a novel non-invasive microwave vital signs sensor Celik, N.; Gagarin, R.; Baker, J.; Youn, H.; Iskander, M.F.; Wireless Information Technology and Systems (ICWITS), 2010 IEEE International Conference on Publication Year: 2010 , Page(s): 1 - 4

News from Medfield Diagnostics

Great interest for Medfield Strokefinder study

PRINT

Medfields first clinical study with Strokefinder R10 has started with a high pace with 10 patients included within about a month. The study aims to further verify the techniques ability to distinguish between stroke caused by bleeding from stroke caused by clot. Further studies will verify the techniques ability to be an alarm during nighttime for TIA patients. During the last weeks have both the Swedish Minister of Enterprise Maud Olofsson tested the stroke helmet, as well as Jan Björklund, Minister of Education.

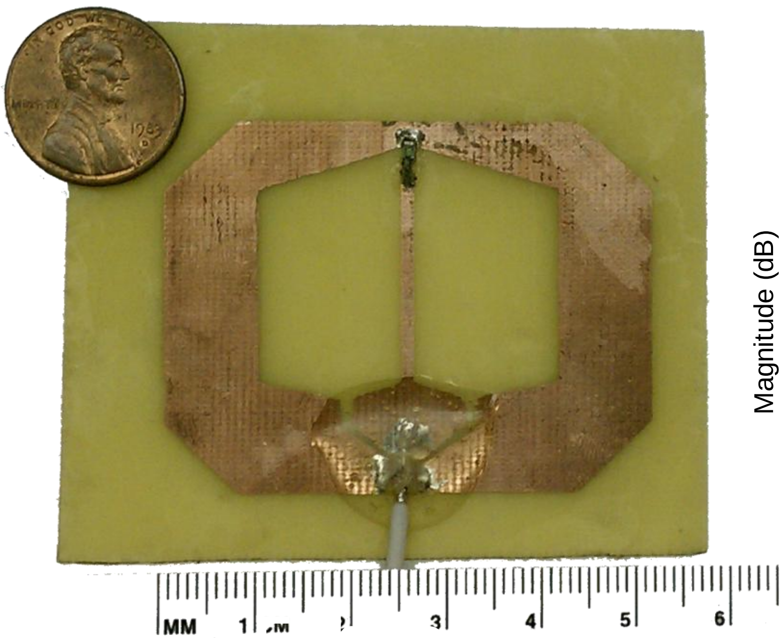
Medfield Diagnostics Brain Imaging System

Microwave Stethoscope: A New Method for Measuring Human Vital Signs

Ruthsenne Gagarin, Nuri Celik , Hyoung-sun Youn, and Magdy Iskander

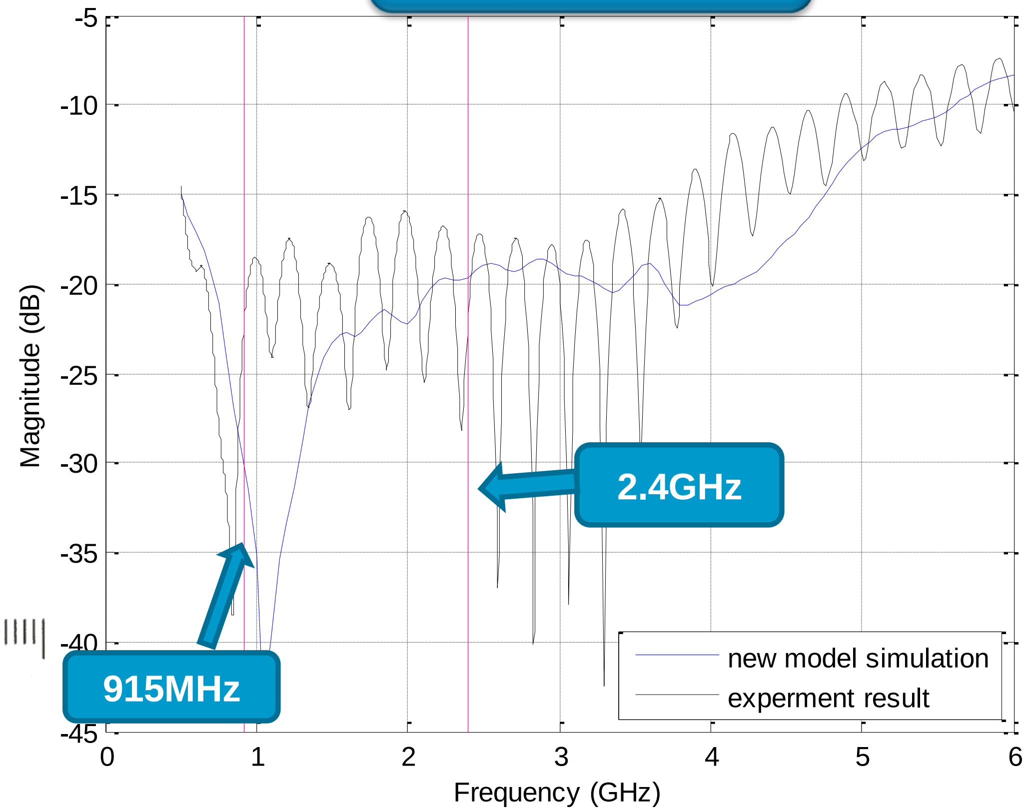
Hawaii Center for Advanced Communications
University of Hawaii,
Honolulu, HI, USA

New Applicator Design



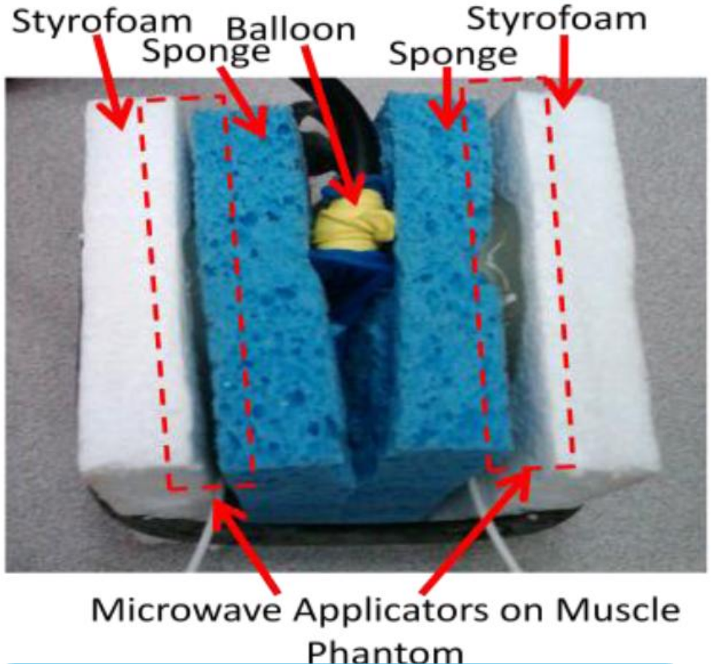
New

S11 Magnitude

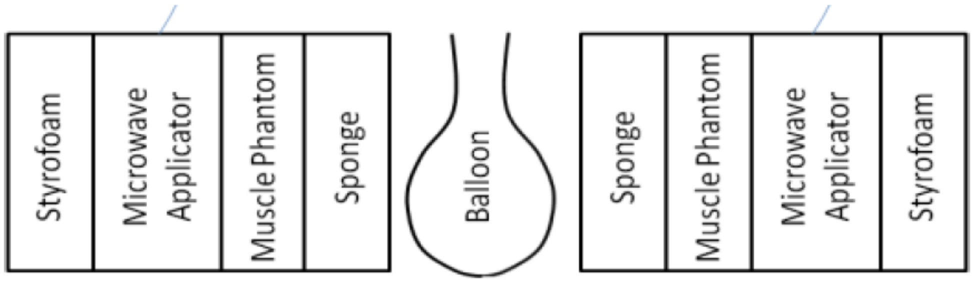


Simulation vs. Experimental

Phantom Thorax-model



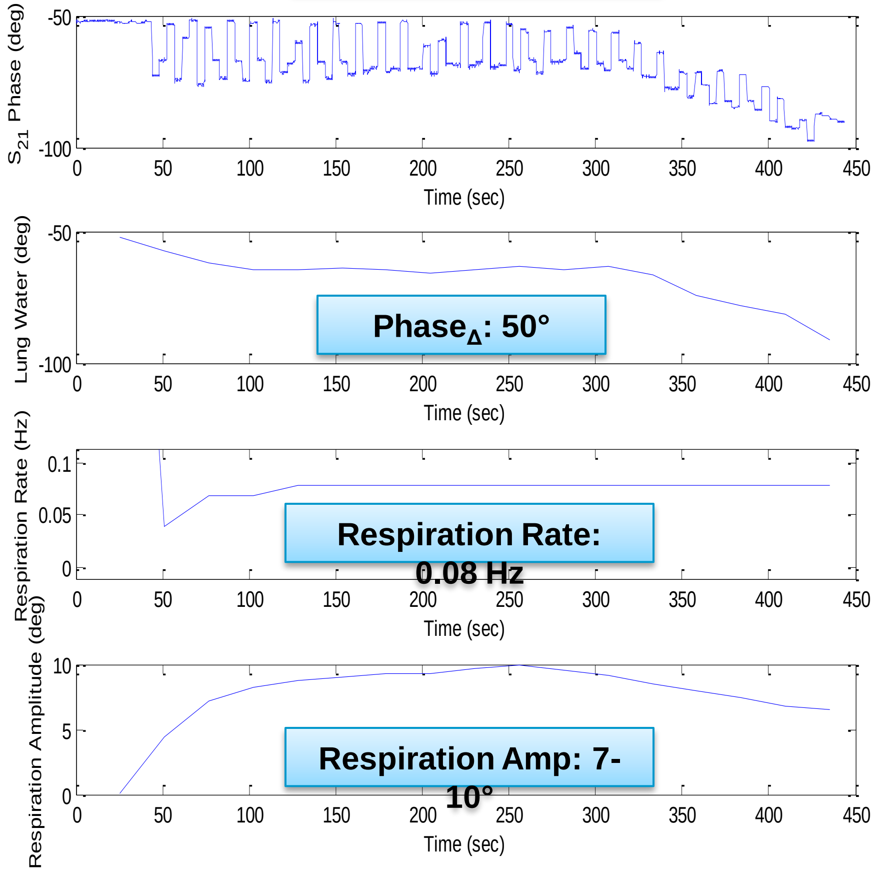
(a) Photo of the experimental setup with the Thorax-model phantoms. The overall dimensions of the model is 10cm x 10cm x10cm,



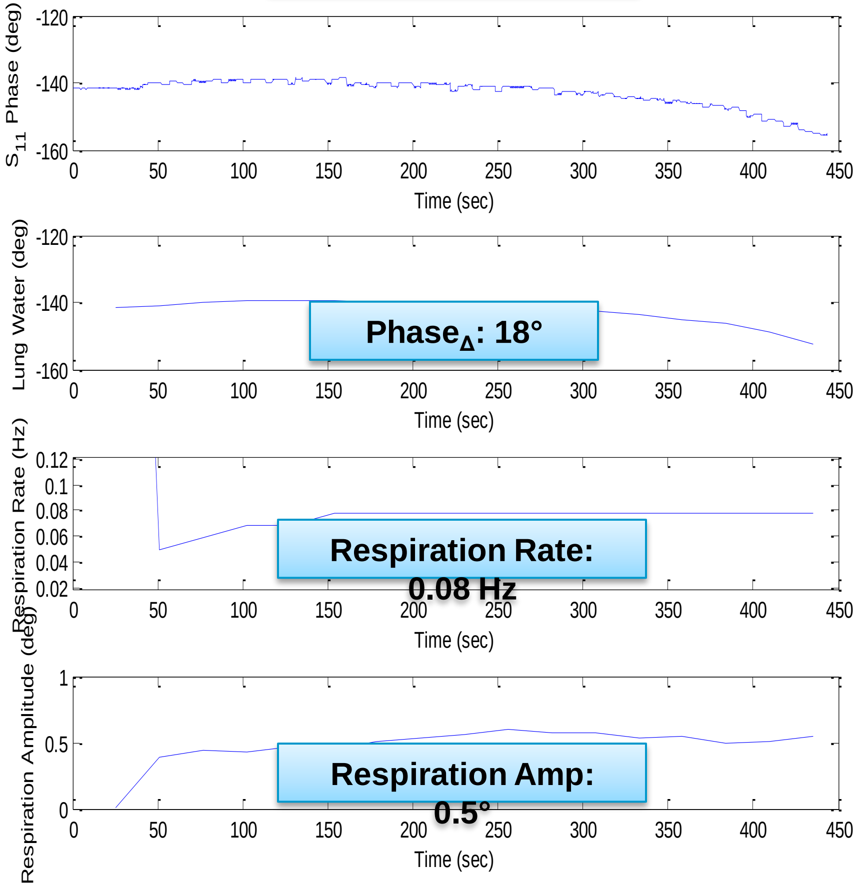
(b) Schematic of the layered structure of the Thorax-based phantom model. The microwave applicator is placed in direct contact with the muscle layers.

Vital Signs Extraction
Phantom Thorax-model Experiment

S21 Phase

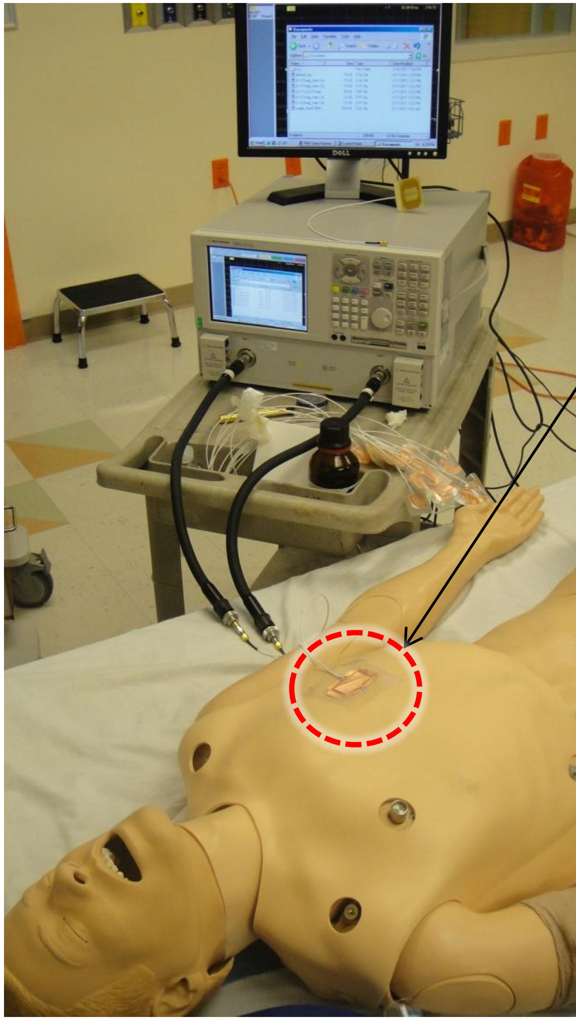


S11 Phase

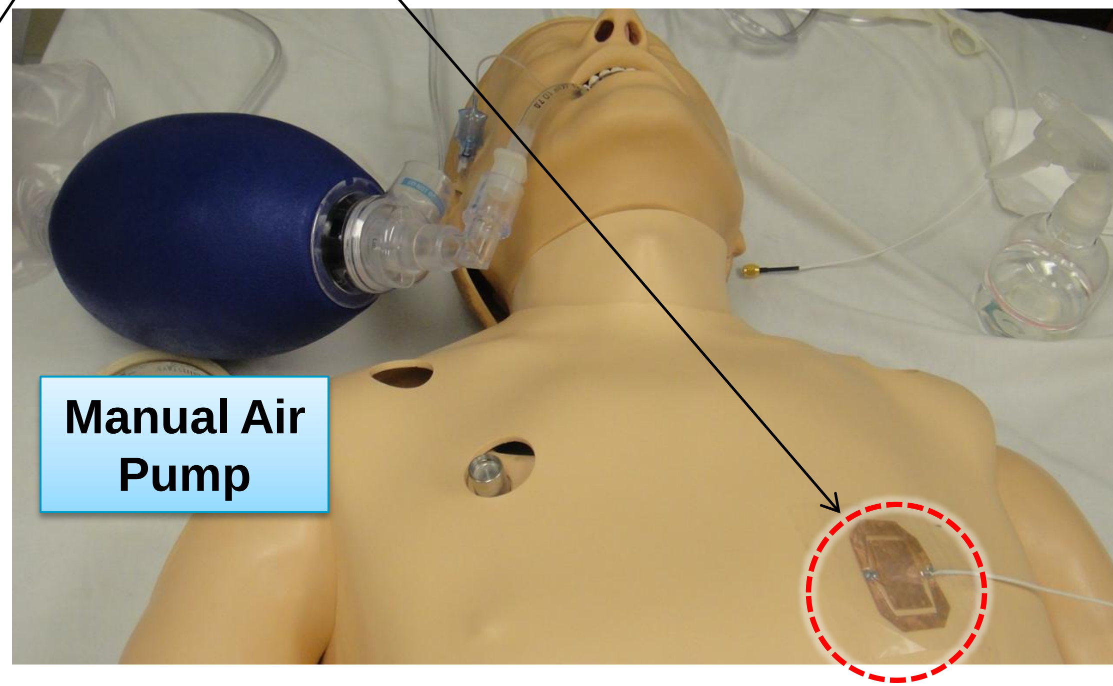


Breathing Rate Set-Up

Two Experimental Set-Ups:
1) Manual Air Pump
2) Computer Controlled Breathing Rate

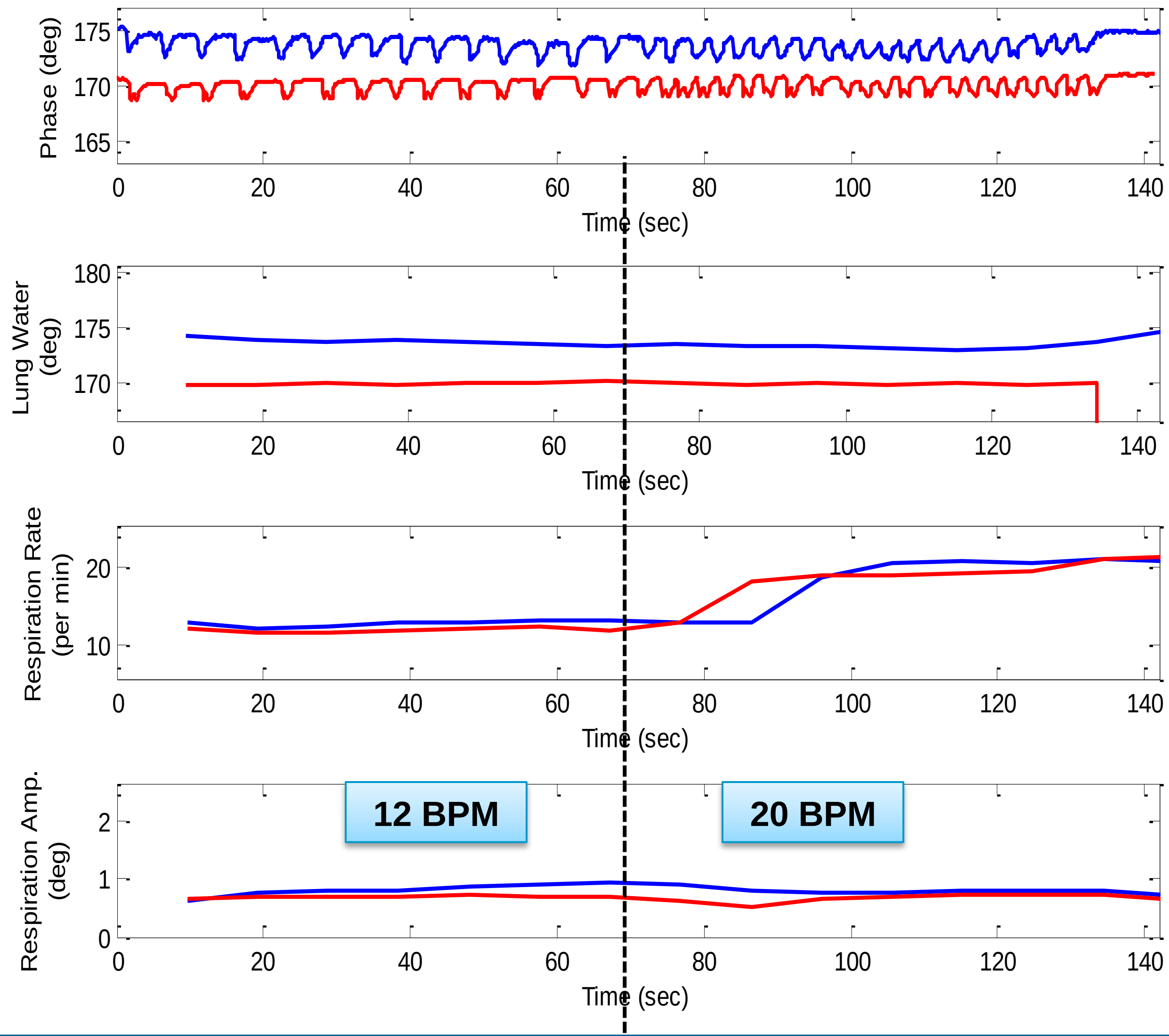


Applicator



Manual Air Pump

Vital Signs Parameter Extraction



RED: S_{11}

BLUE: S_{21}

Concluding Remarks

Significant progress has been made in developing the Microwave Stethoscope Integrated Vital Signs measurement. This includes:`

New ultra wideband microwave applicator has been designed and experimentally tested

Obtained Institutional Review Board Approval (IRB)for human trials

Experimentally validated a computationally efficient DSP algorithms for extracting breathing, heart rate and changes in lung water content from a single microwave measurement

Conducted phantom experiments both in engineering labs and in collaboration with colleagues in the medical school on computer controlled manikin.

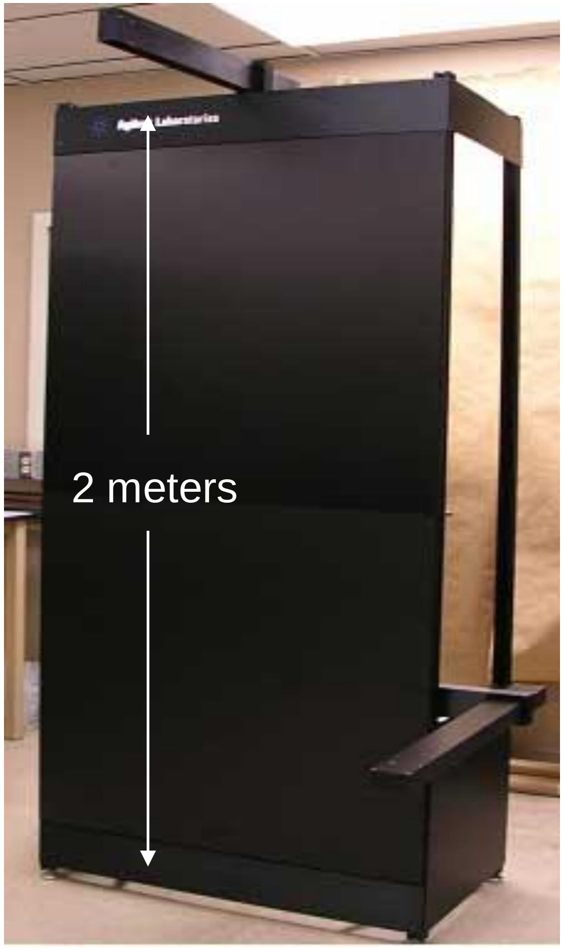
Efforts are underway to prepare for the human trial. These experiments will be conducted at laboratories in the medical school.

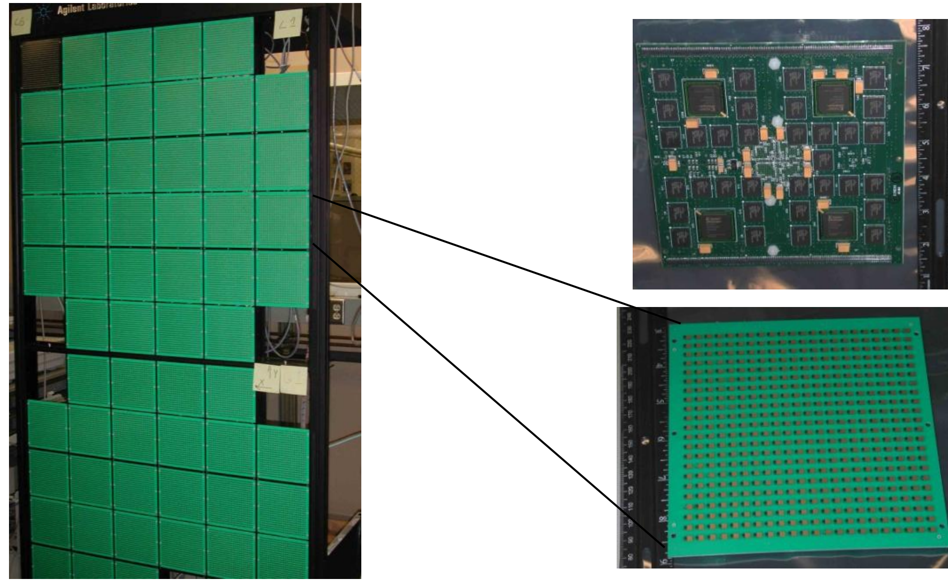
Homeland Security Applications

Millimeter waves have been applied to people screening as in airport walk through portals; the dielectric contrast of various non-metallic “threat” objects image well at these frequencies. These systems have “active” as well as “passive” versions.

Stand-off explosives imaging is also possible at mm frequencies though the spectral signatures for most of these compounds are in the low Terahertz region? An imager could see the materials but a Terahertz wand might be necessary to identify them?

Planar, Confocal Lens
Millimeter Wave Imaging System





PROTOTYPE SYSTEM

Footprint: 10 cm deep, 1 meter wide

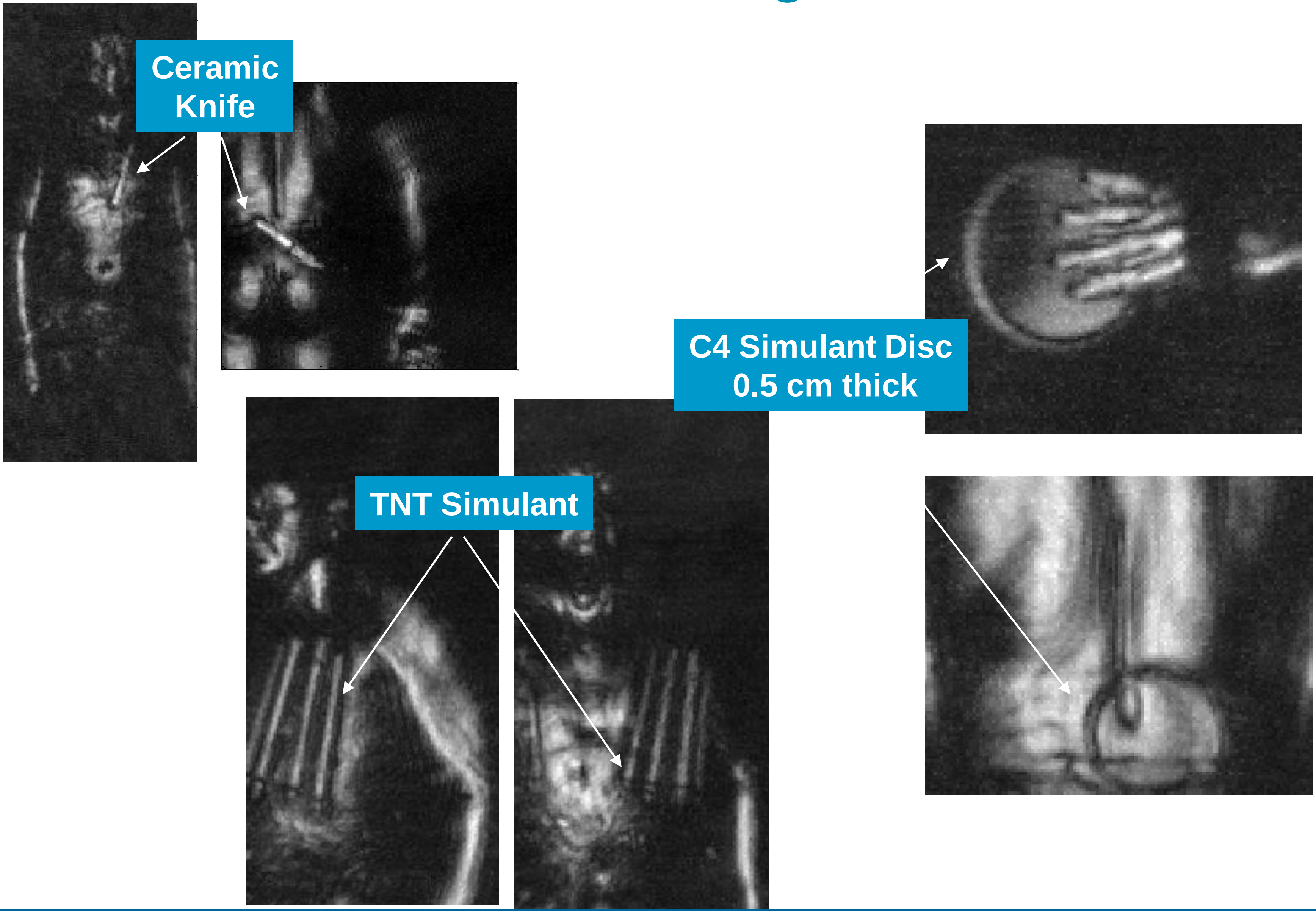
Speed: Real time imaging (20 frames/sec)
Scanning 10 Million voxels/sec.

Safety: RF exposure intensity 1/100,000 of typical cell phone.

No Moving Parts: Digital electronic architecture.

Cost: Off-the-shelf digital components.

Threat Images



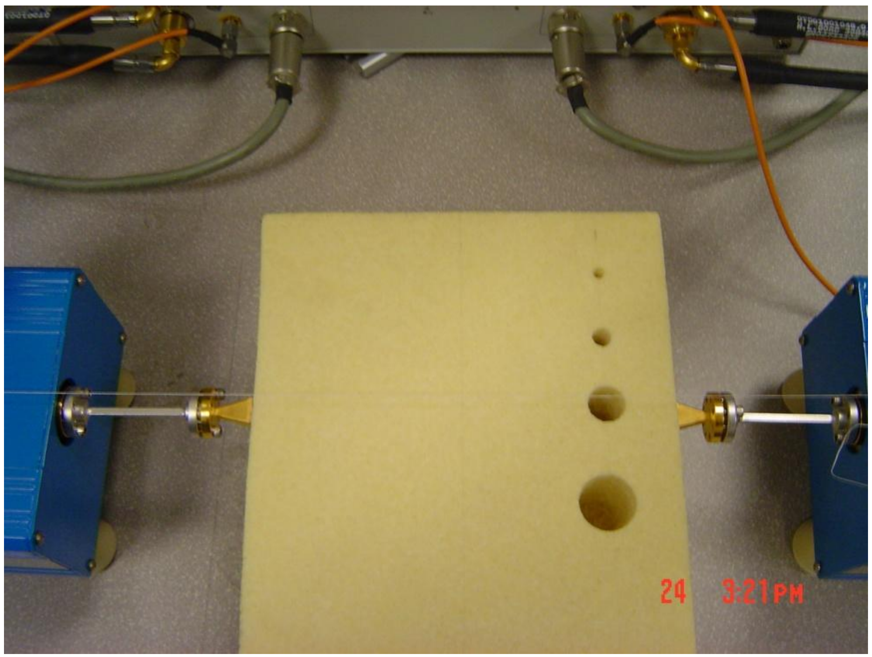
Microwave “Near to Sample” Measurements: Real Time, Non-Invasive Process Information

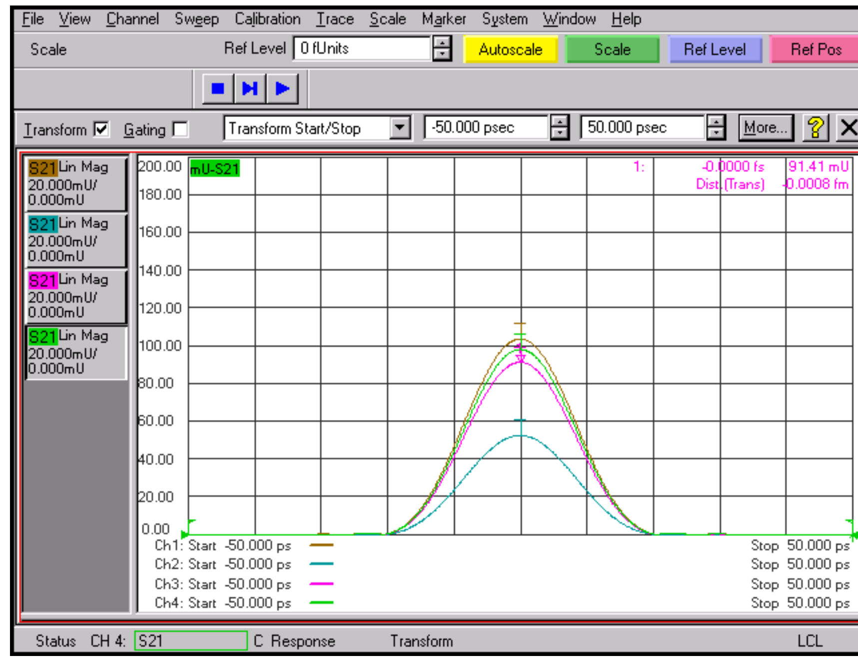
- Non-destructive test for space shuttle external tank foam quality (looking for voids, cracks, etc that weaken adhesion)

  (with NASA)

- Pharmaceutical process monitoring (PAT)
- Cement/Water ratio for strength pre-determination (Baylor)
- Microwave chemical reaction acceleration (CEM company)

NASA space shuttle external tank foam experiments





Pharmaceutical Tablet Moisture Measurements

Microwave resonance method for moisture measurement of single tablets using a multi-product calibration

Lubomir Gradinarsky, Margareta Fondelius, Jonas Johansson

Pharmaceutical Development, AstraZeneca R&D, Pepparedsleden 1, 43183 Mölndal, Sweden;
Email: Lubomir.Gradinarsky@astrazeneca.com

Presented at the 2011 Microwave Aquametry Conference

ISEMA

International Society for Electromagnetic Aquametry

Correlation Between KFT & Microwave Resonance Methods

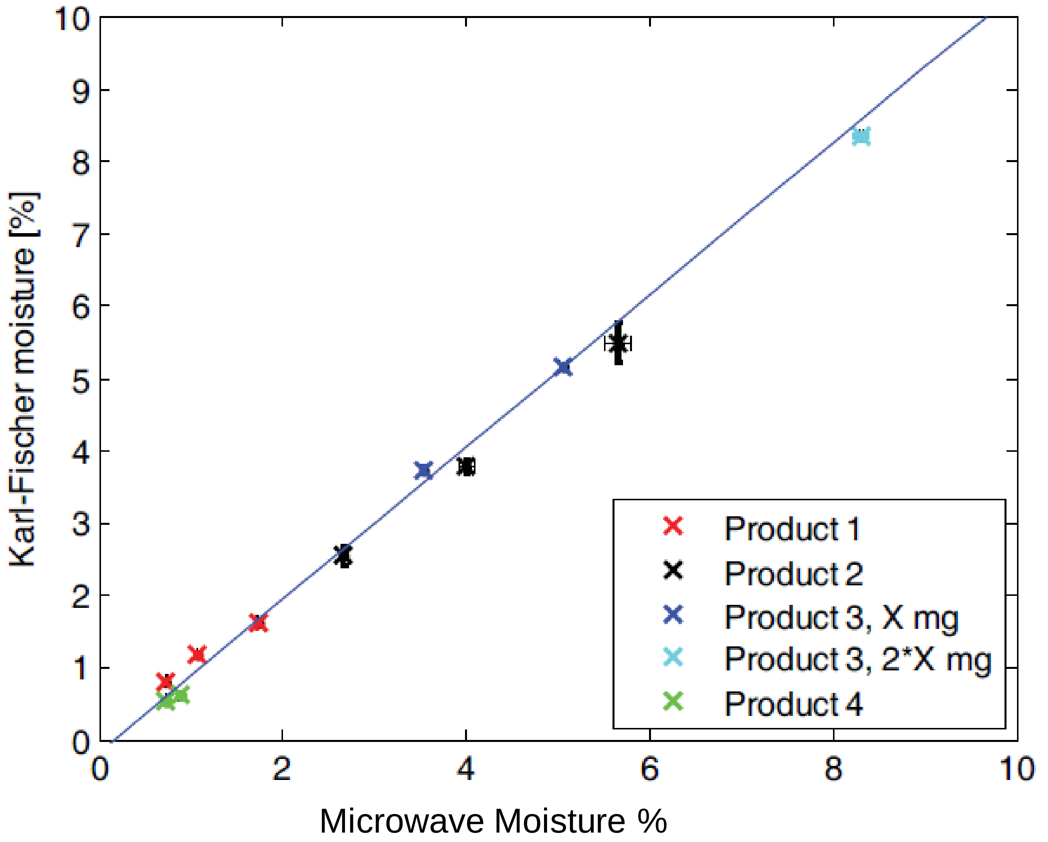
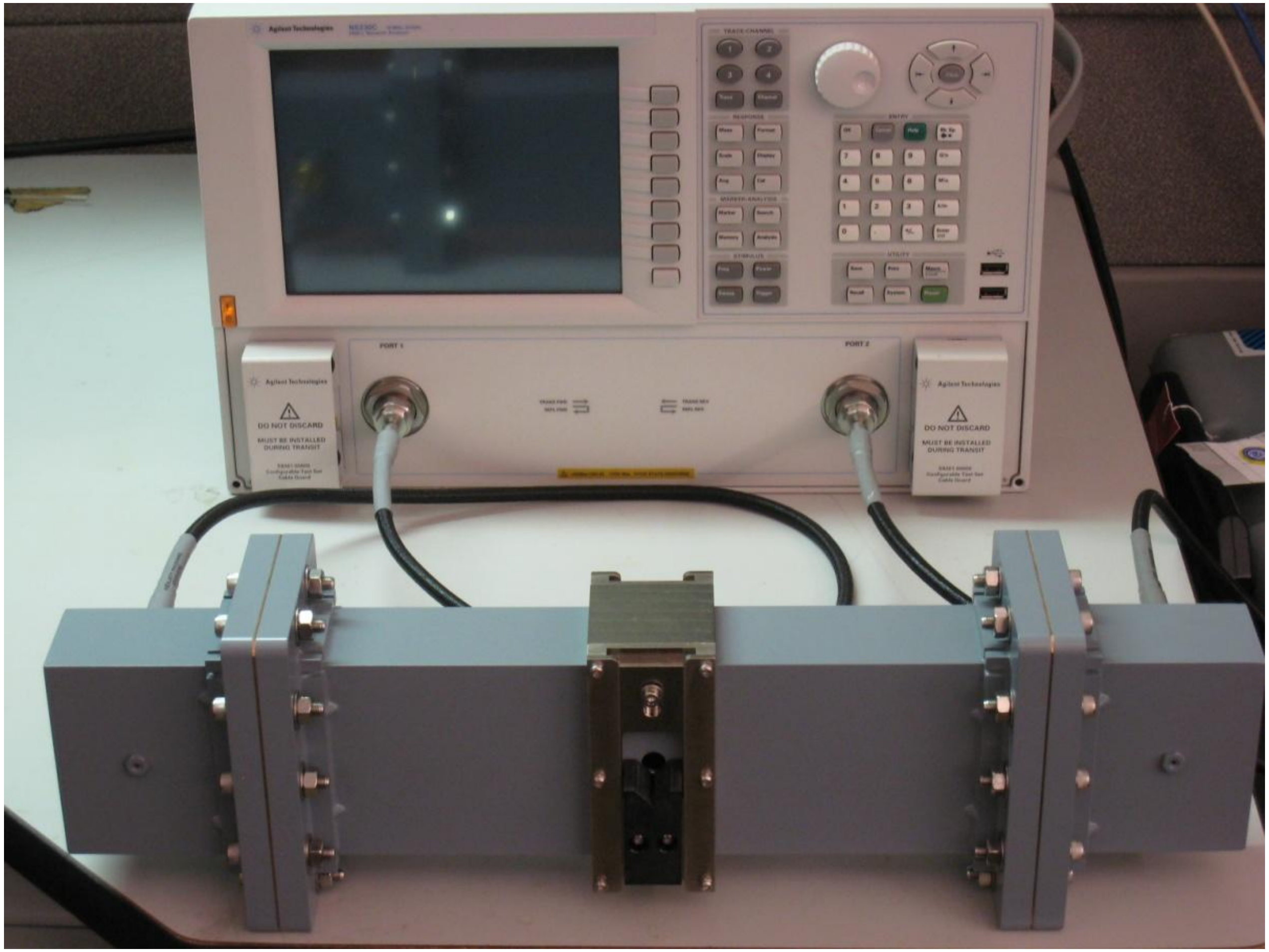
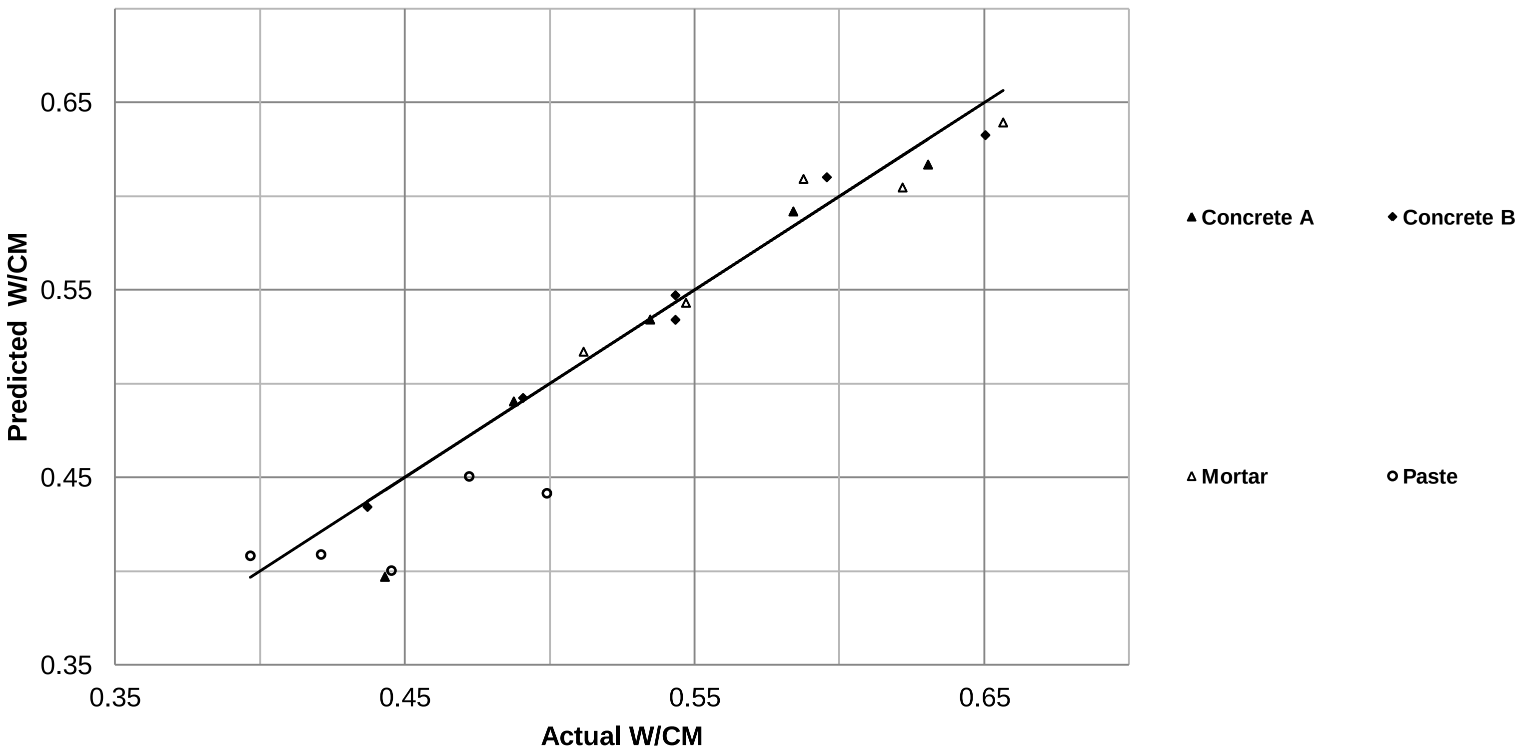


Fig. 3: The multi-calibration method linearity, based on independent samples not included in the calibration. The total RMS difference between the MW and the KF methods is 0.16% w/w.

Pharmaceutical Tablet Measurement System



Water to Cement ratio (an indicator of cured strength)-Baylor University (to be published in the IEEE I&M journal)



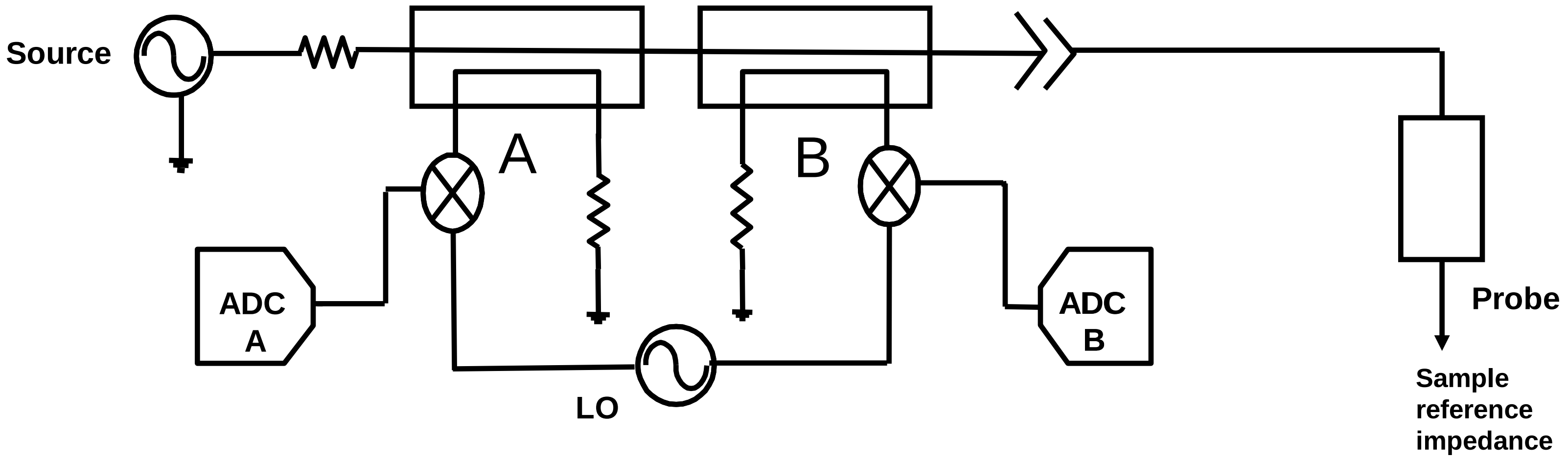
Microwave Chemistry (CEM peptide synthesis system)

Vector Network Analyzers: Problems of Measurement and Calibration at the Nano-scale

- Nanoscale devices are typically very high impedance; Network Analyzers are optimized at 50 ohms
- Probing solutions for the nanoscale do not exist but Atomic Force Microscopes (AFM) can provide a platform for approaching this issue
- Calibration standards other than shorts, opens, and 50 ohms do not exist
- The beginning of a solution: The Arbitrary Impedance Network Analyzer and the Scanning Microwave AFM (these bring forward their own issues)

Standard Network Analyzer

Reflection Only



$$S_{11} = \frac{Z_L - Z_0}{Z_L + Z_0}$$

= B/A

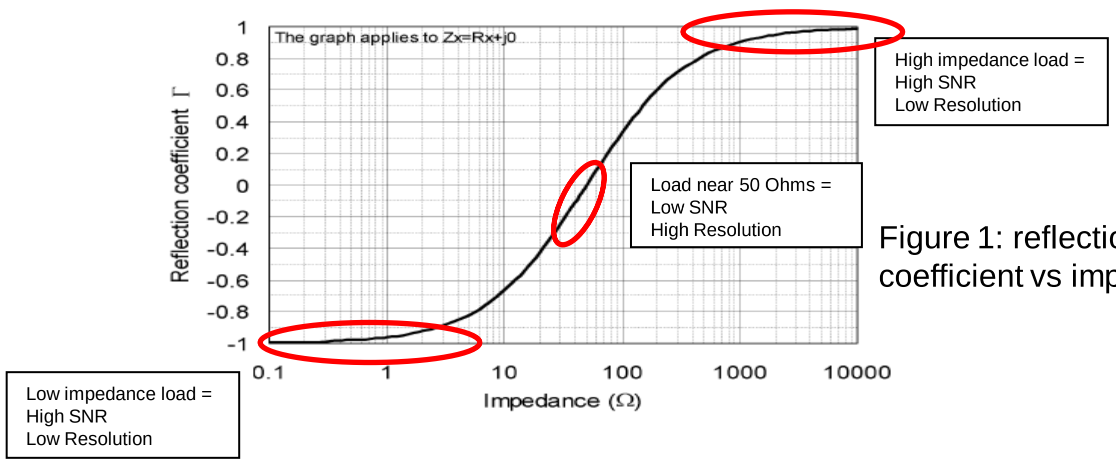
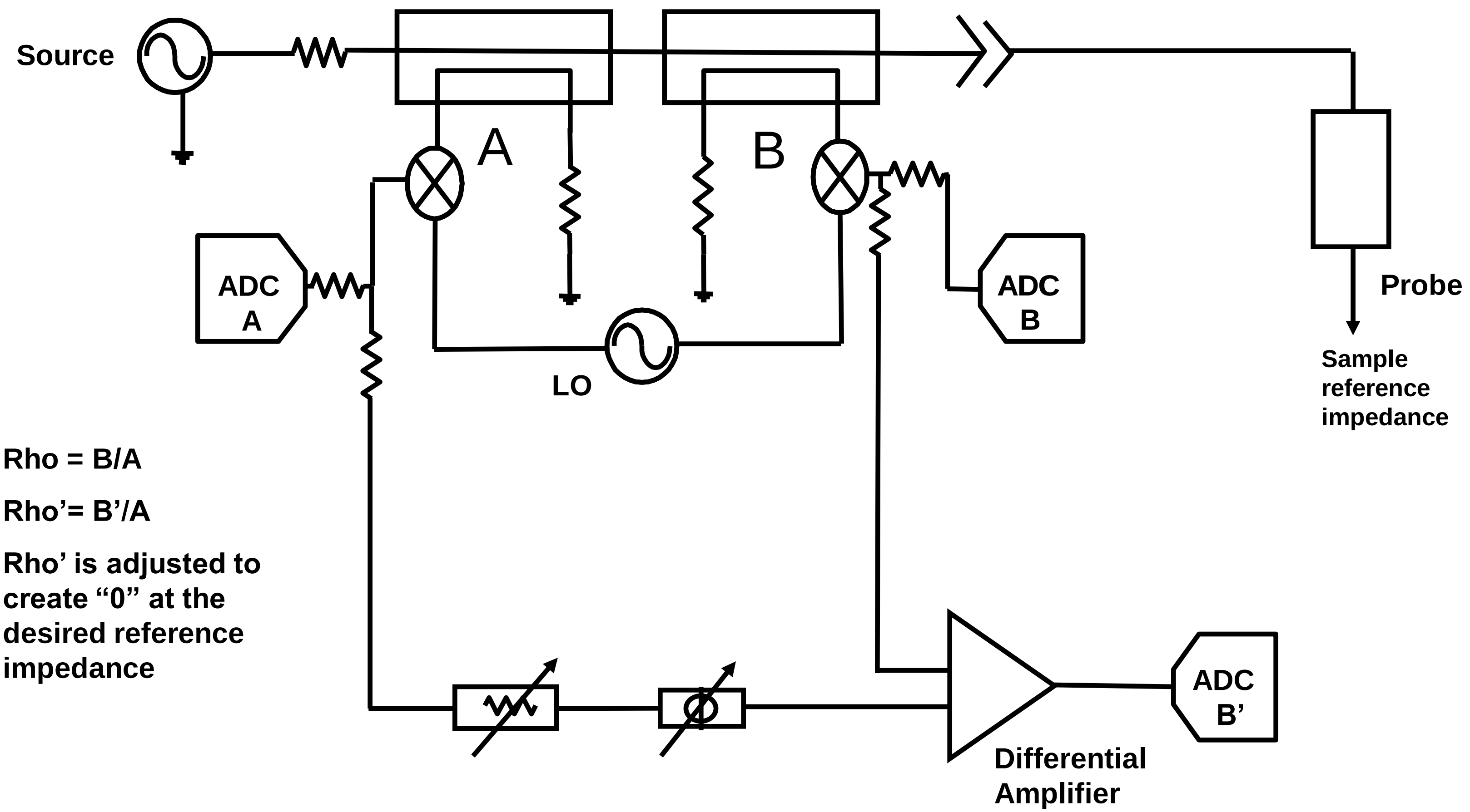


Figure 1: reflection coefficient vs impedance

Arbitrary Impedance Network Analyzer

Reflection Only

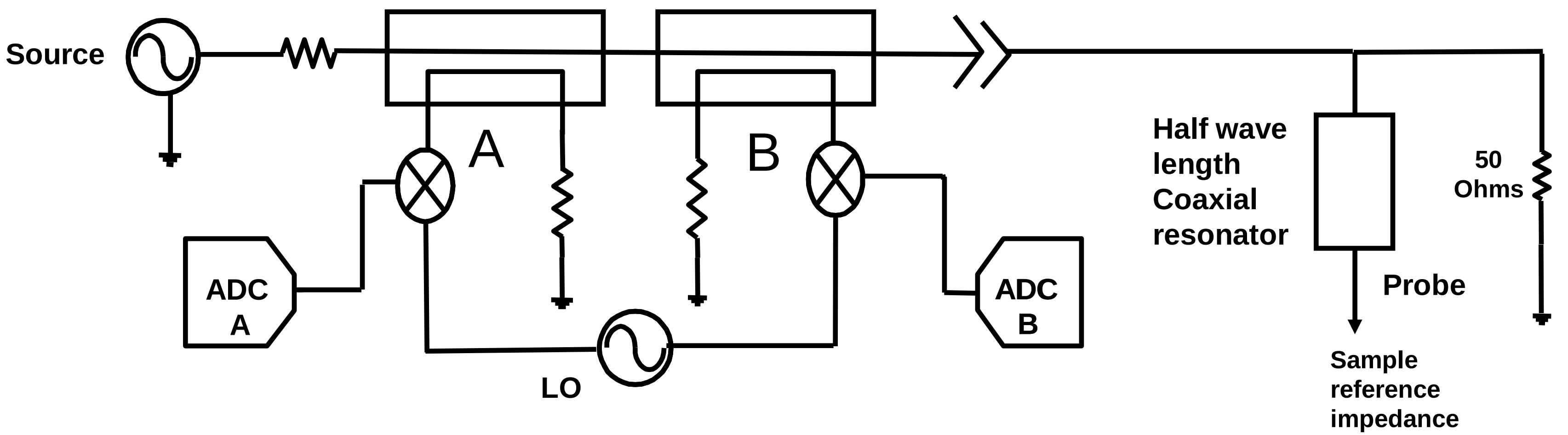


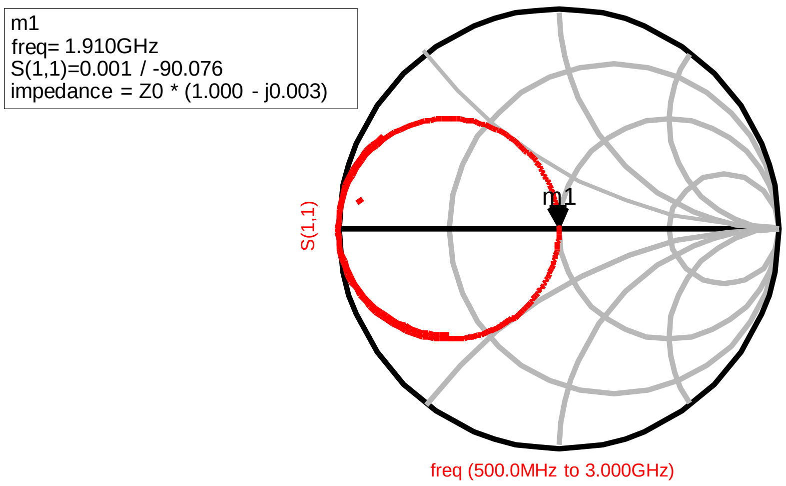
Rho = B/A

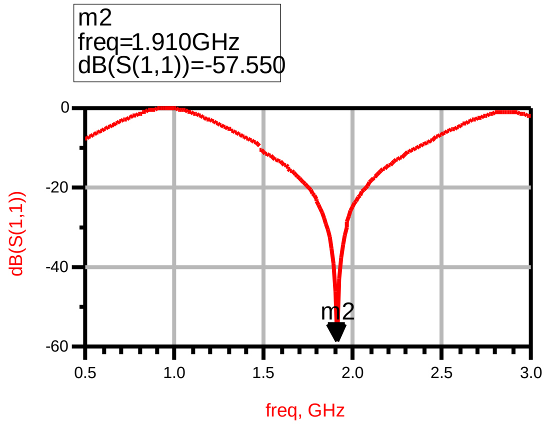
Rho’= B’/A

Rho’ is adjusted to create “0” at the desired reference impedance

Simplified Single Frequency Solution





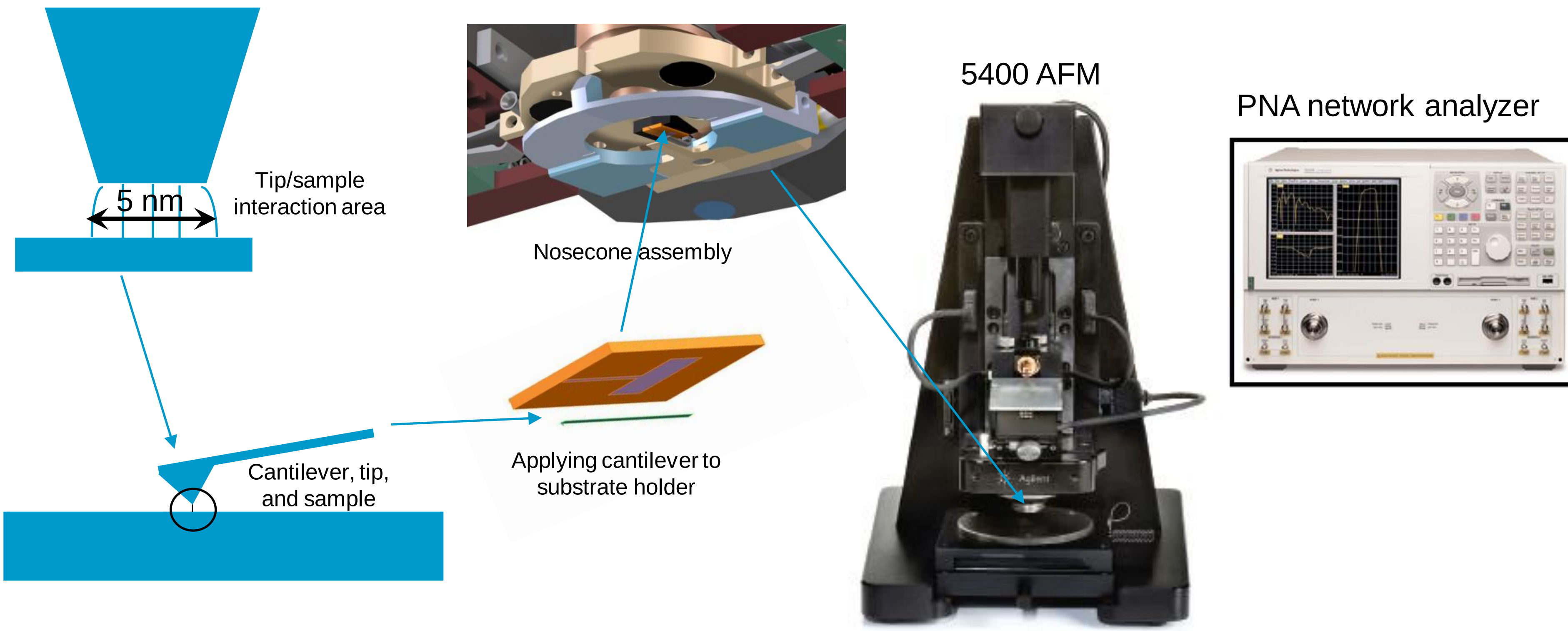


How do we measure small things?

-SMM is a near field system. The resolution is determined by the Electric field interaction area with the sample. This is on the order of 5-10 nm

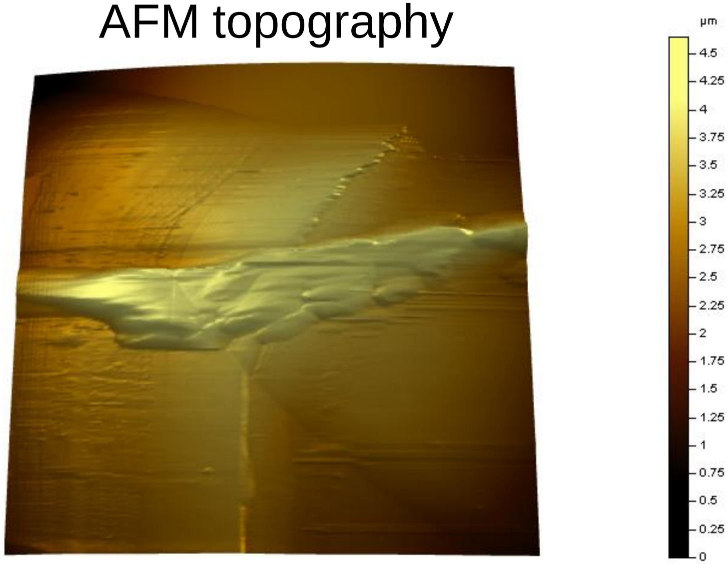
-SMM uses a network analyzer to measure the vector reflection coefficient caused by the tip-sample interaction; this gives information about the material properties (dielectric properties)

-While an AFM needs “contact” to make a measurement the SMM can measure without contact. You can be 1-10 nm away from the sample and still have good sensitivity

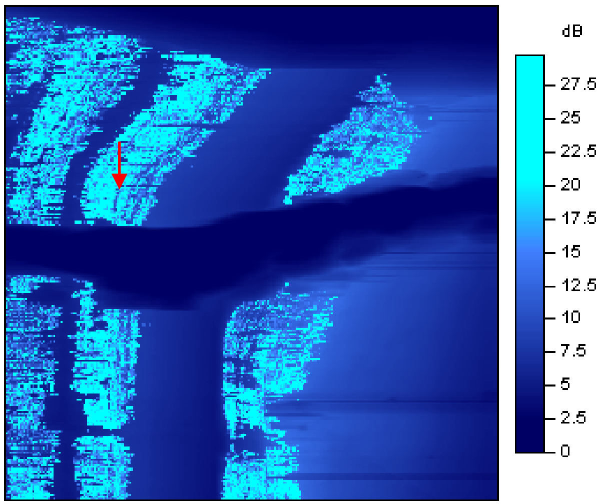


Zinc-chrome alloy

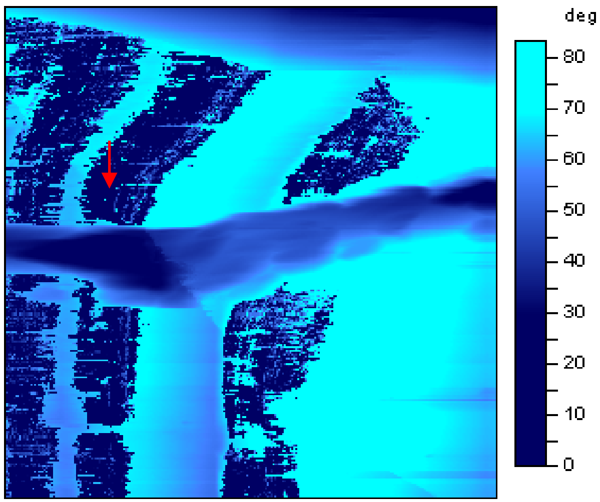
AFM topography



Impedance (amplitude)

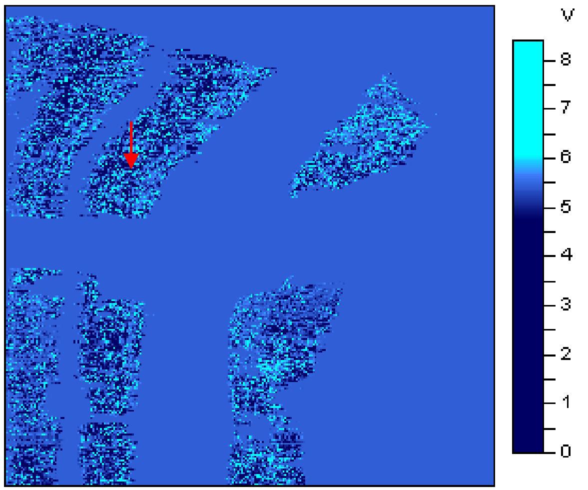


Impedance (phase)

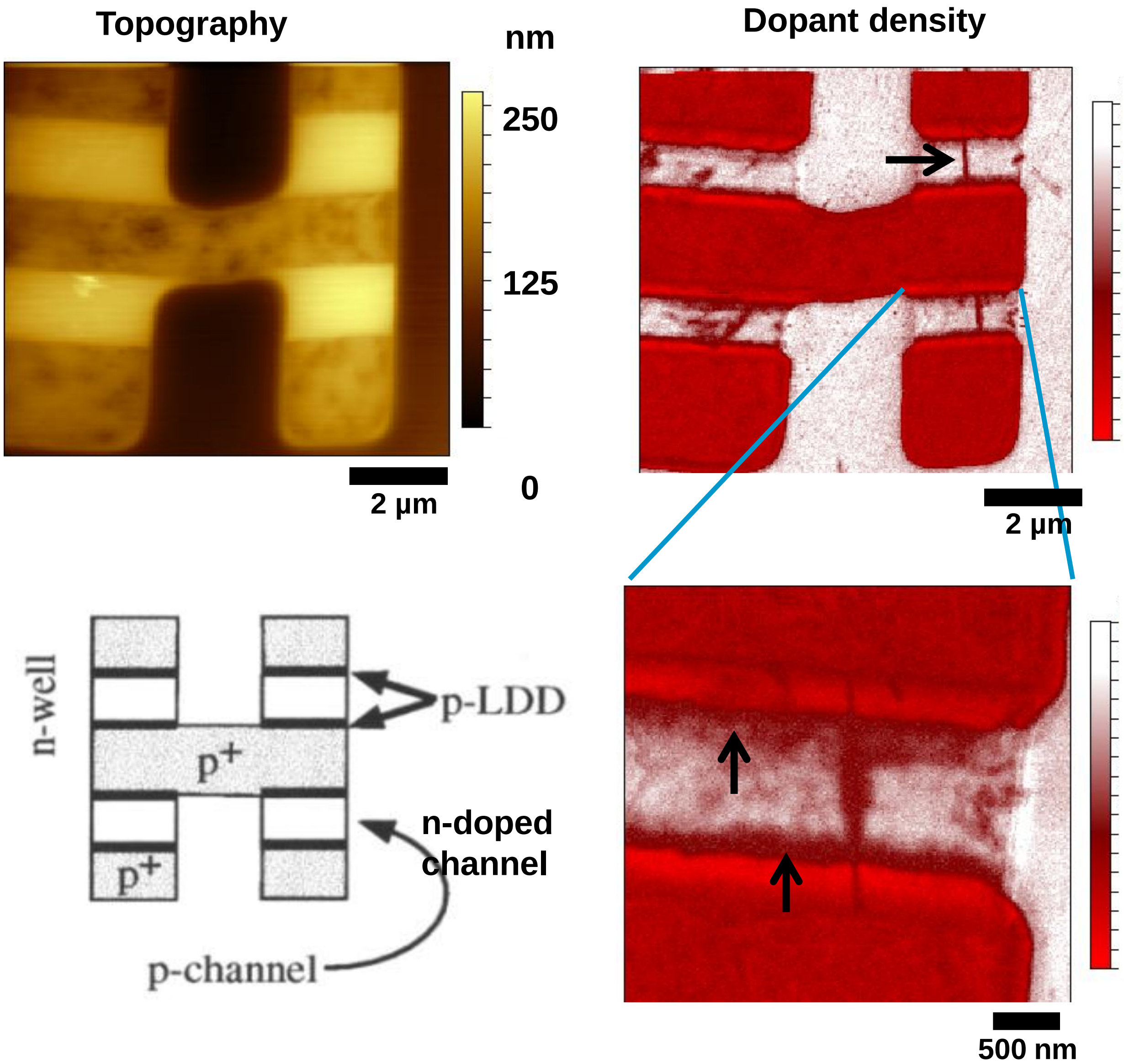


Scan size 100 x 100 µm

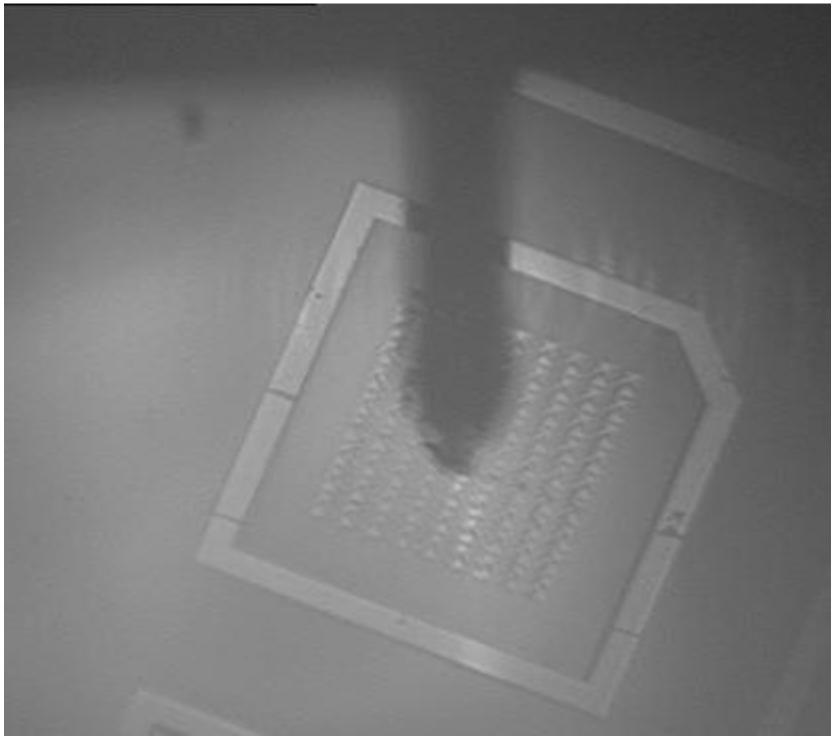
dC/dV



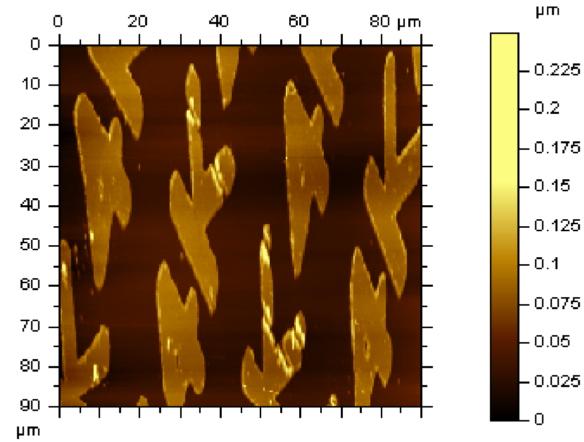
Dopant profiling application: SRAM II



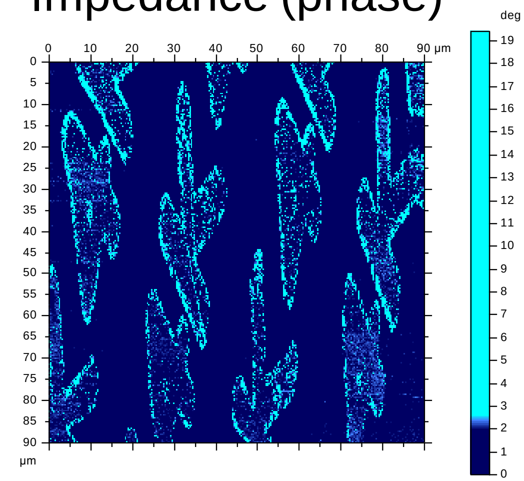
Analysis of human Rhinovirus on Gold-Patterned Glass Substrates



Topography

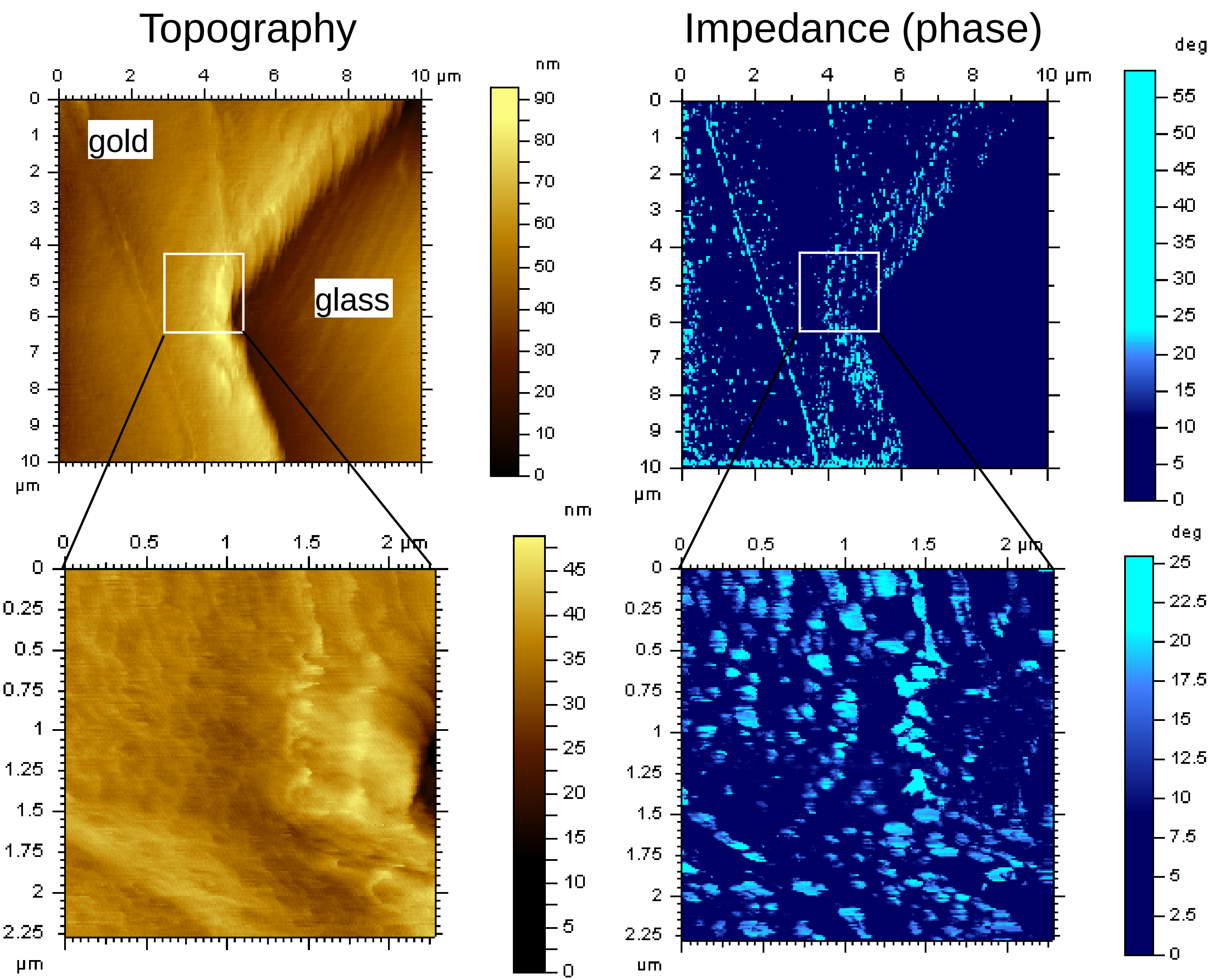


Impedance (phase)



Viruses bind specifically to gold island
→SMM phase image resolves viruses from inorganic substrate better than AFM topography

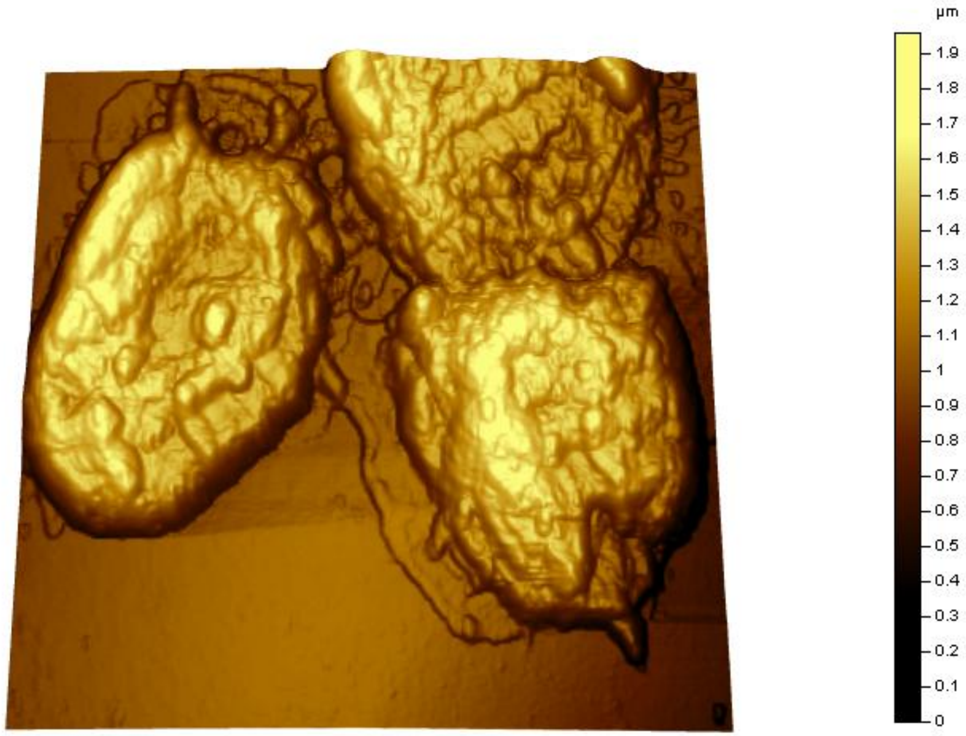
Analysis of human Rhinovirus on Gold-Patterned Glass Substrates



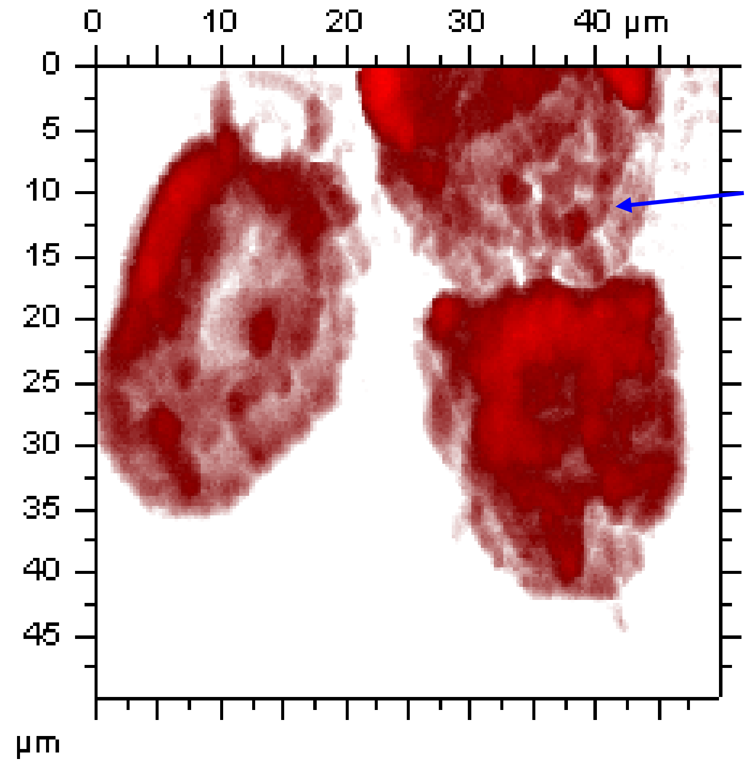
→ Background-free (gold and glass do not give an SMM signal) detection of biological matter (single viruses) without cross-talk from topography information !

THP1 cells (leukemia) adsorbed on gold

Topography



Impedance (PNA Phase)



→increased contrast in PNA phase image compared to the topography image, different membrane layers can potentially be distinguished in the PNA Phase image (blue arrow)

Calibration of the SMM

-We now have capacitance calibration developed through collaborations.

See: REVIEW OF SCIENTIFIC INSTRUMENTS **81**, 113701 2010: **Calibrated nanoscale capacitance measurements using a scanning microwave microscope**

-We have recently published the results of our collaboration on doping measurements: JOURNAL OF APPLIED PHYSICS **108**, 064315 2010: **Scanning microwave microscopy/spectroscopy on metal-oxide semiconductor systems**

-Calibration for life science measurements will probably be based on capacitance and some fixture de-embedding. Our first publication in this area will be in Ultramicroscopy this summer: **High-frequency electromagnetic dynamics properties of THP1 cells using scanning microwave microscopy** Yoo Jin Oh, Hans-Peter Huber, Markus Hochleitner, Memed Duman, Bianca Bozna,Markus Kastner, Ferry Kienberger, and Peter Hinterdorfer

Semiconductor Dopant Profiling

Calibrated nanoscale dopant profiling using a scanning microwave microscope

H. P. Huber, I. Humer, M. Hochleitner, M. Fenner, M. Moertelmaier et al.

Citation: J. Appl. Phys. **111**, 014301 (2012); doi: 10.1063/1.3672445

View online: http://dx.doi.org/10.1063/1.3672445

View Table of Contents: http://jap.aip.org/resource/1/JAPIAU/v111/i1

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Summary

-Microwave Network Analyzers perform a fundamental measurement which has many uses in the electronics industries (communications, semiconductor, aerospace/defence)

-Microwaves have many sensing and imaging application possibilities based primarily on dielectric properties and the physics of water

-We have identified four key new applications areas for microwave measurements. These are Medical, Homeland Security, Process Analytics, and Nano Scale/Nano Device Measurements

-We are working with some of the key research groups and start-up companies in these areas around the world to help move these ideas forward.