TOLMI LECTURE

DEMAND DRIVEN R&D
OF
NONDESTRUCTIVE METHODS
FOR RELIABILITY ENGINEERING

R & D DRIVEN BY DEMAND

Our Dream of Continuing Improvements

Knowledge Visions Creativity	Innovation	Competitiveness Profit Social Processes

Services – Technologies – Products

How to Manage Innovations?

Knowledge	Marketing	Competence	Management
Culture	**Visions**	**Realization**	**Profit**
Technology	Viability	Ressources	Market

or

The Modern Challenge of Science & Education

TOLMI LECTURE

WHAT'S THAT,

NDT?

TOLMI LECTURE

TOLMI

NONDESTRUCTIVE TESTING (NDT):

Concerned with all methods of detecting and evaluating material flaws.
The essential feature of NDT is that the test process itself
produces no deleterious effects on the material or structure under test

BINDT (The British Institute of Non-Destructive Testing, UK)

NONDESTRUCTIVE EVALUATION (NDE):

Measurements that are more quantitative in nature.
For example, a NDE method would not only locate a defect,
but it would also be used to measure something about that defect
such as its size, shape, and orientation.
NDE may be used to determine material properties
such as fracture toughness, formability, and other physical characteristics

CNDE (Center for NDE, Iowa State University, USA)

TOLMI LECTURE

STRUCTURAL HEALTH MONITORING (SHM):

Damage detection and characterization strategy for engineering structures .
Changes to the material and/or geometric properties of a structural system, which adversely affect the system's performance are monitored.
The SHM process involves the observation of a system over time using periodically sampled or continuously observed measurement data.
The extraction of damage-sensitive features from these measurements, and their statistical analysis determine the current state of system health.
SHM systems are usually an integral part of structures and thus a matter of automation.

DGzfP (Deutsche Gesellschaft für zfP, Germany)

PROCESS MONITORING & CONTROL (PMC):

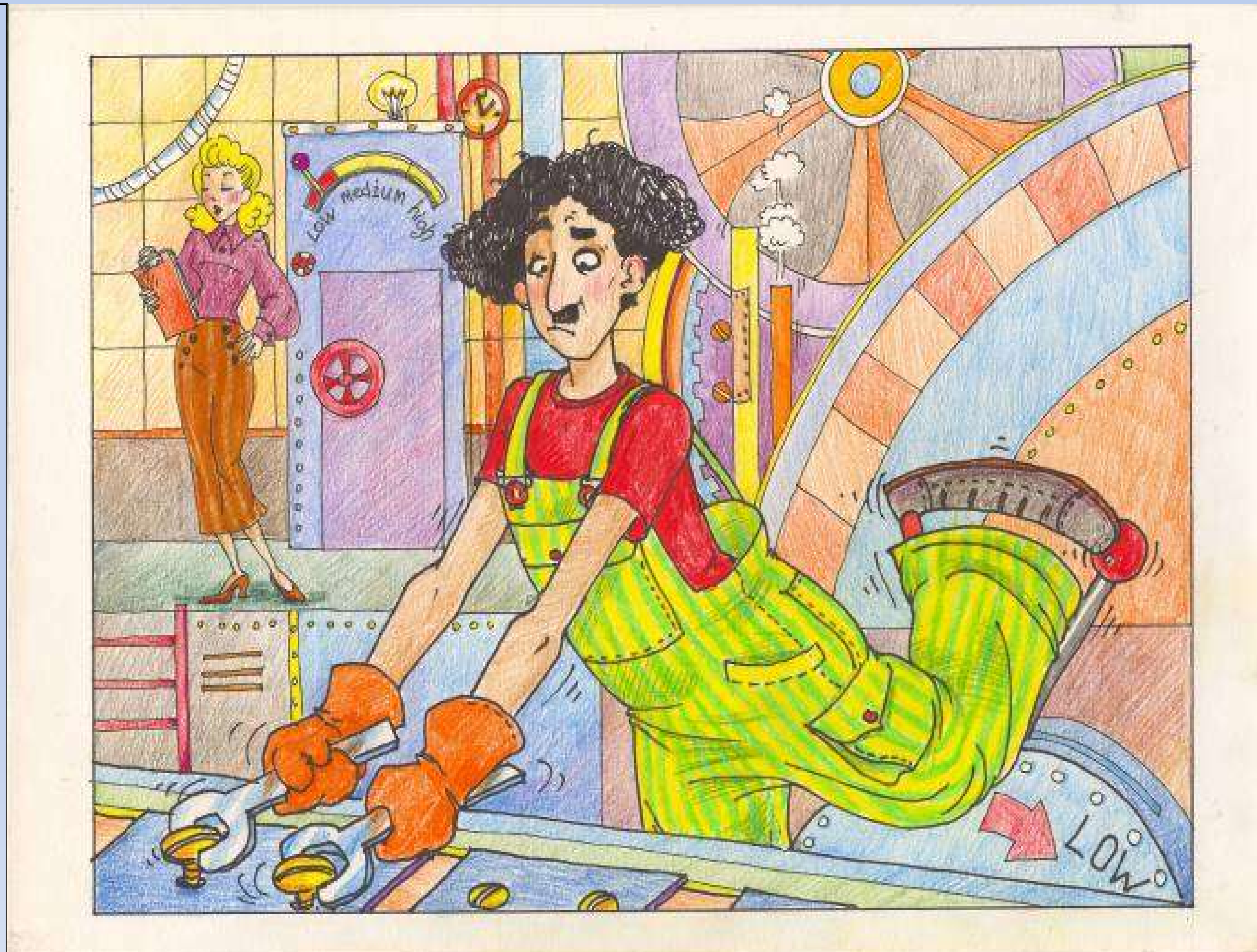
In-process sensors play a significant role in assisting manufacturing systems in producing quality products at a reasonable cost and are used to generate control signals to improve both the control and productivity of manufacturing systems. Advanced integrated process control systems are part of automated processes improving the manufacturing effectiveness.

David A. Dornfeld

TOLMI LECTURE

WHAT'S IT GOOD FOR,

THAT NDT?



TOLMI

TOLMI LECTURE

RESEARCH & DEVELOPMENT → DESIGN → Manufacturing & Production → Maintenance → (Waste Disposal)

INNOVATION DYNAMICS

QUALITY COSTS

STRUCTURAL INTEGRITY

(New) MATERIALS & JOINING TECHNOLOGIES → Components & Structures → Systems & Plants

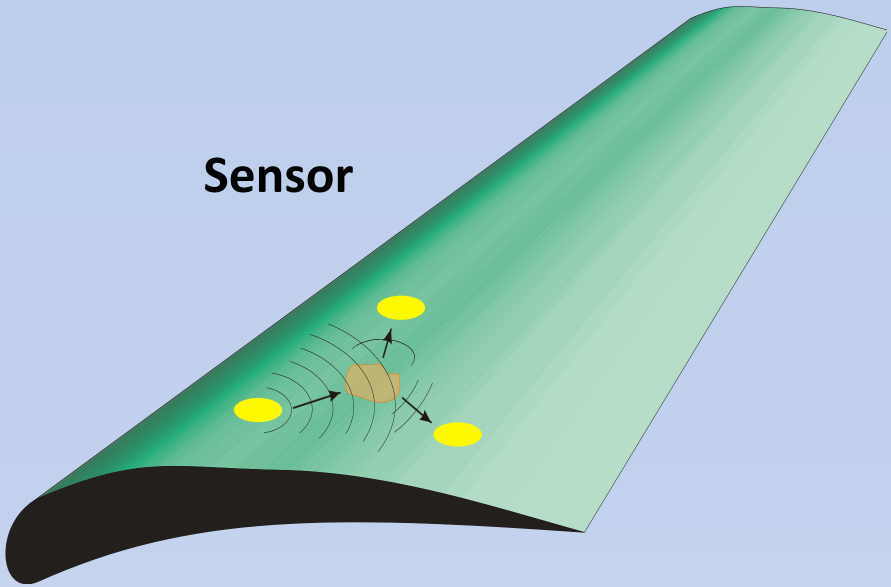
FEATURE BASED CONTROL OF AUTOMATED PROCESSES

TOLMI LECTURE

INNOVATION DYNAMICS

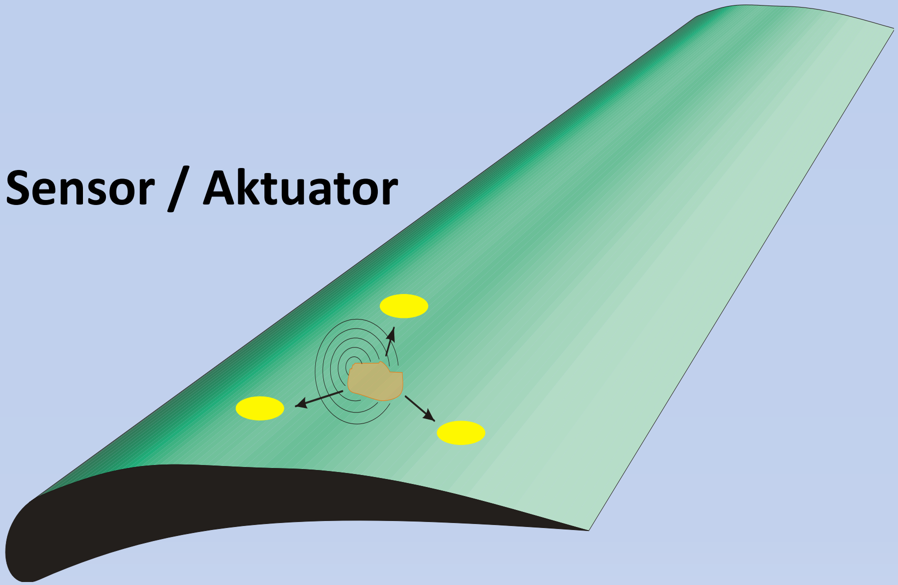
HEALTH MONITORING

Condition Based Maintenance



passive (acoustic emission)

SHM with guided waves



active (ultrasound pulse echo)

Structure Integrated Sensor System

Plastics with embedded piezoelectric fibers

Fiber thickness < 100µm

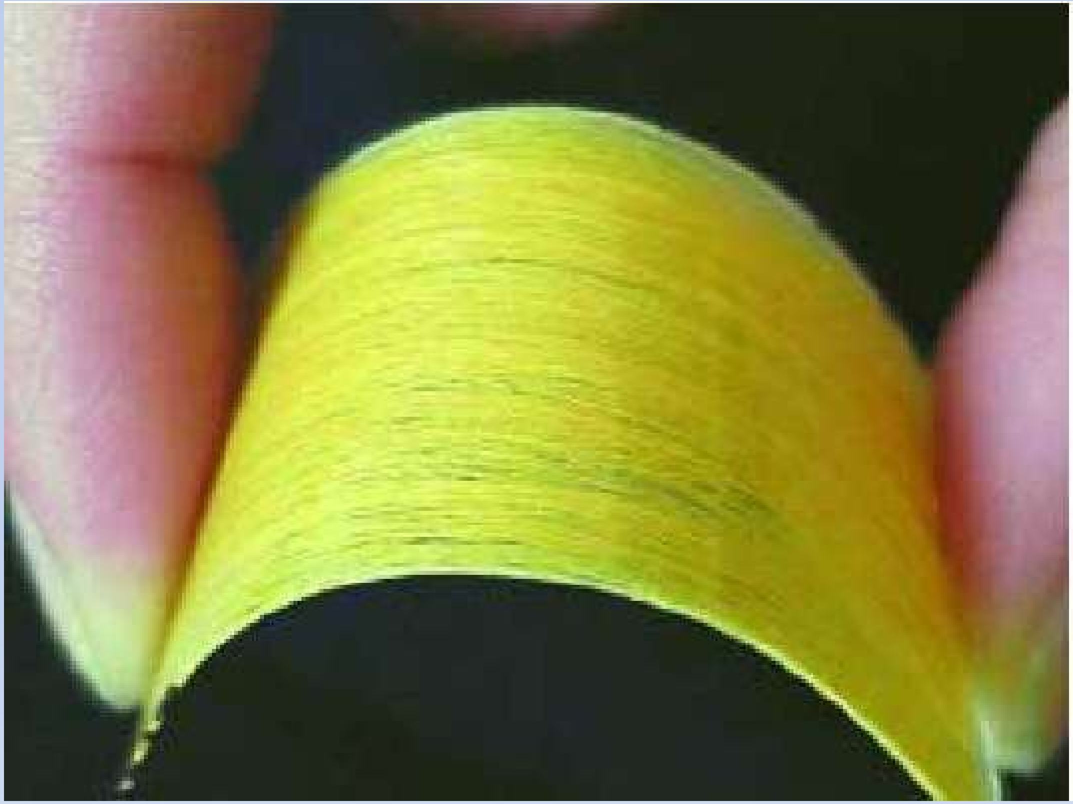
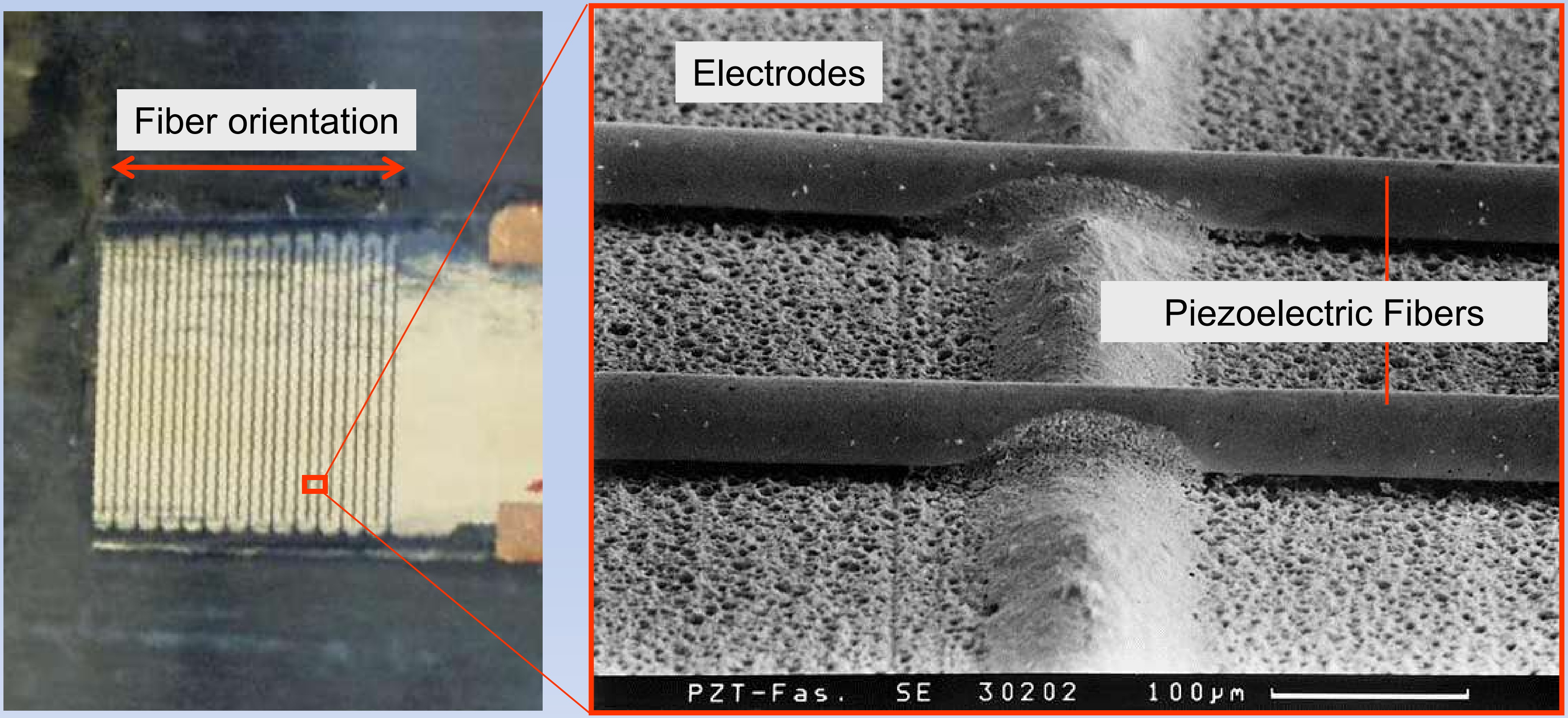


Image courtesy of Fraunhofer-ISC, Würzburg

ULTRASONIC PIEZOFIBER SENSOR STRUCTURE

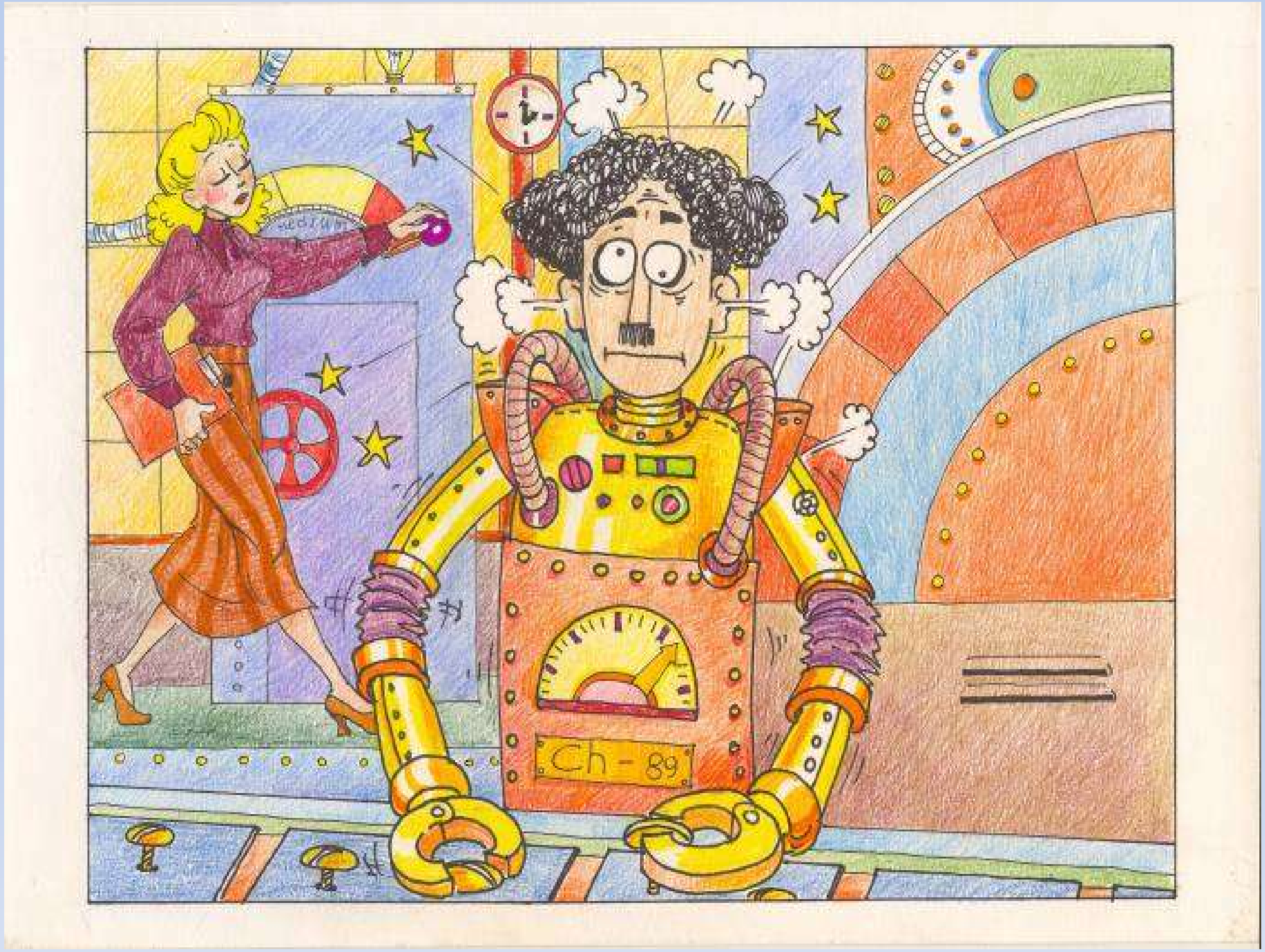


TOLMI LECTURE

Controlled Mass Production

HOWEVER,

WHAT ABOUT QUALITY OF MASS PRODUCTION

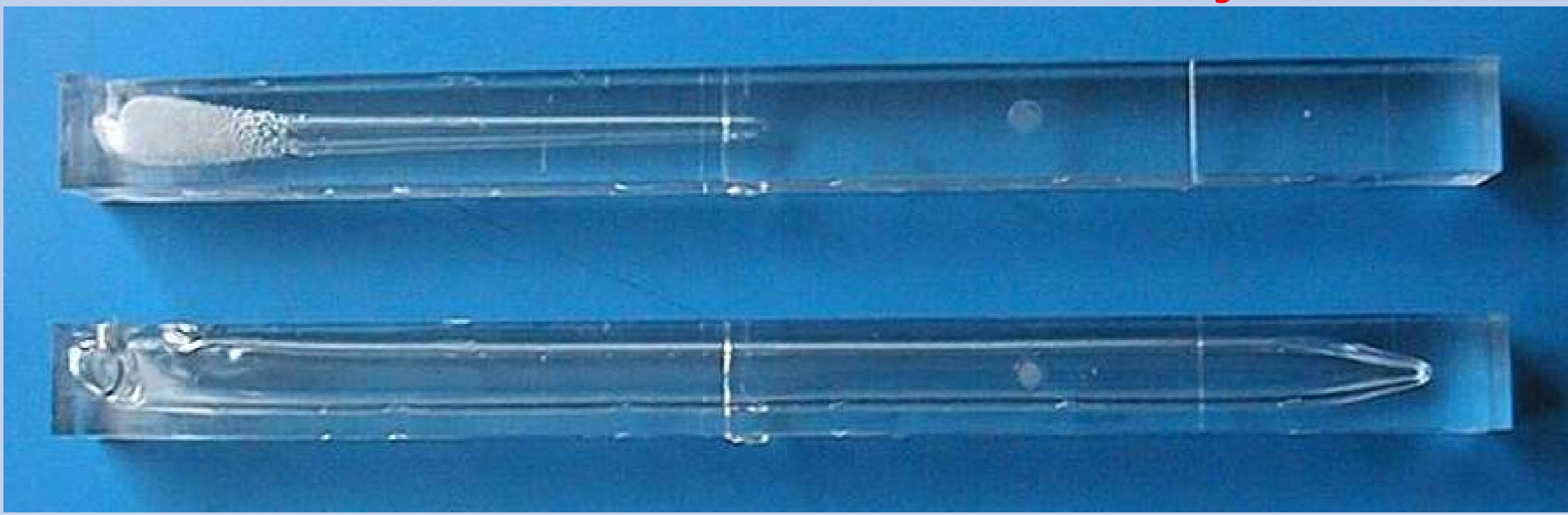


TOLMI LECTURE

Controlled Mass Production

QUALITY COSTS

reject

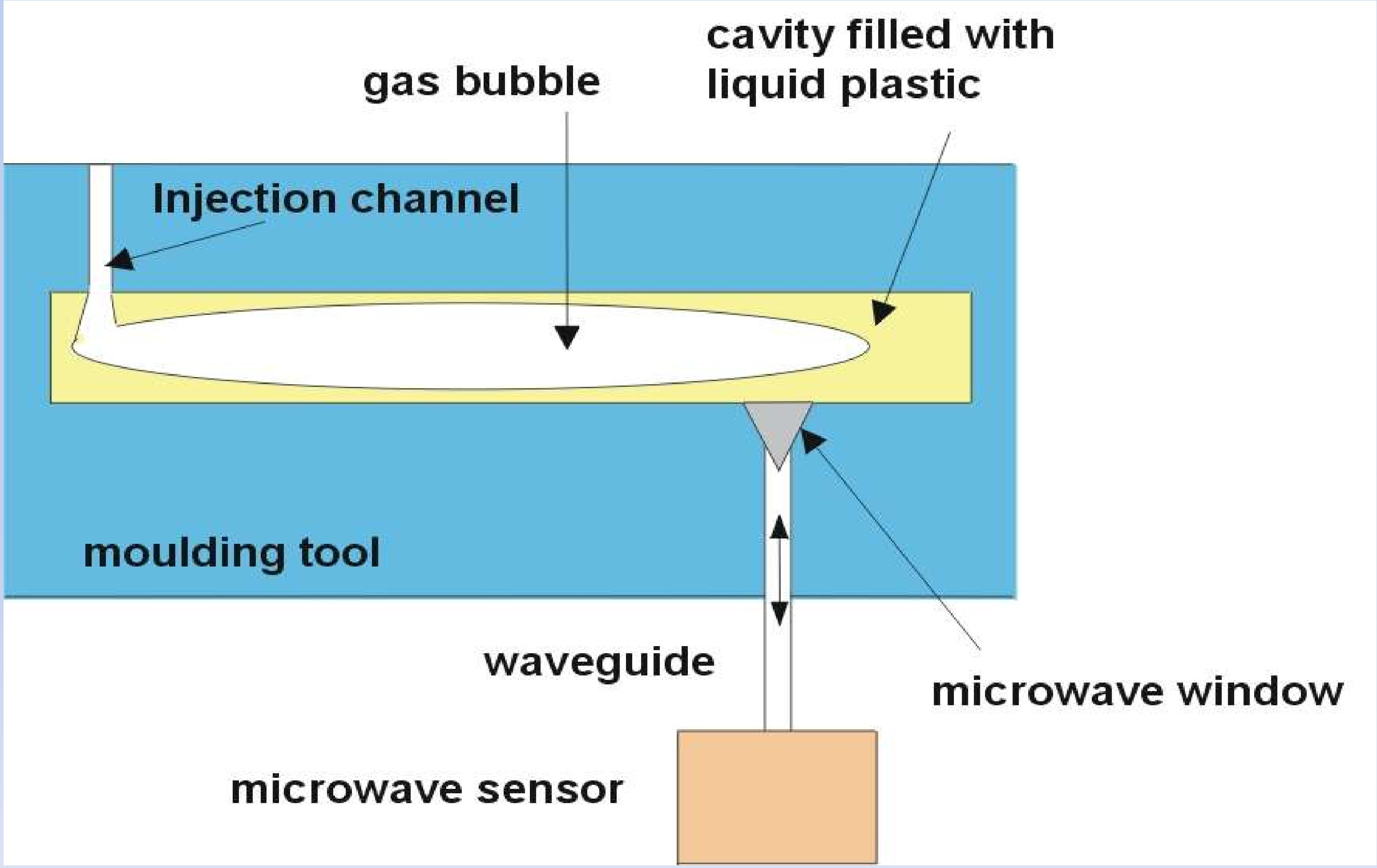


accept

TOLMI LECTURE

Controlled Mass Production

Injection molding of plastics with gas injection (GIT)

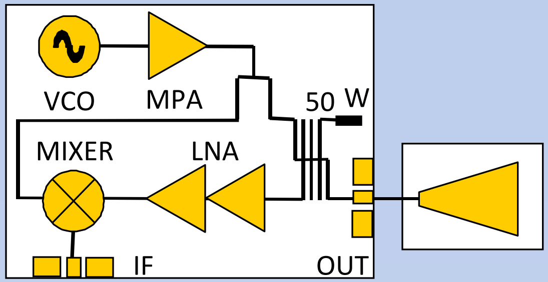


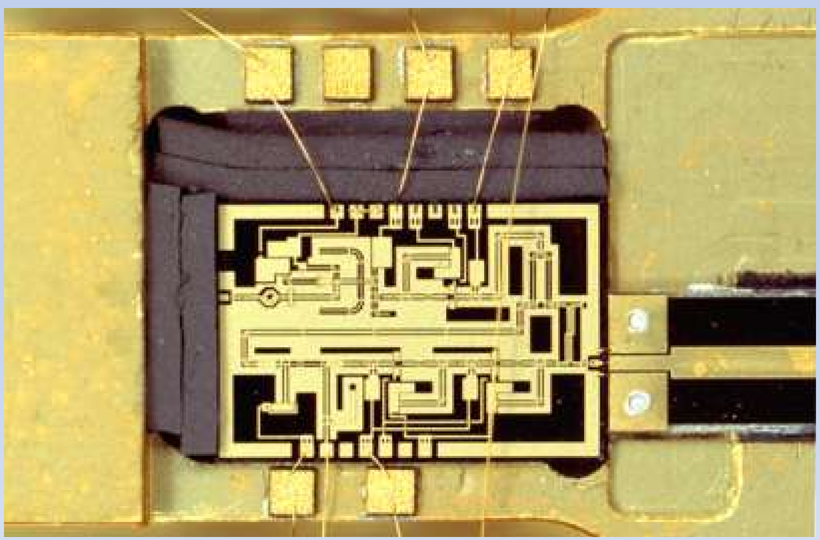
TOLMI LECTURE

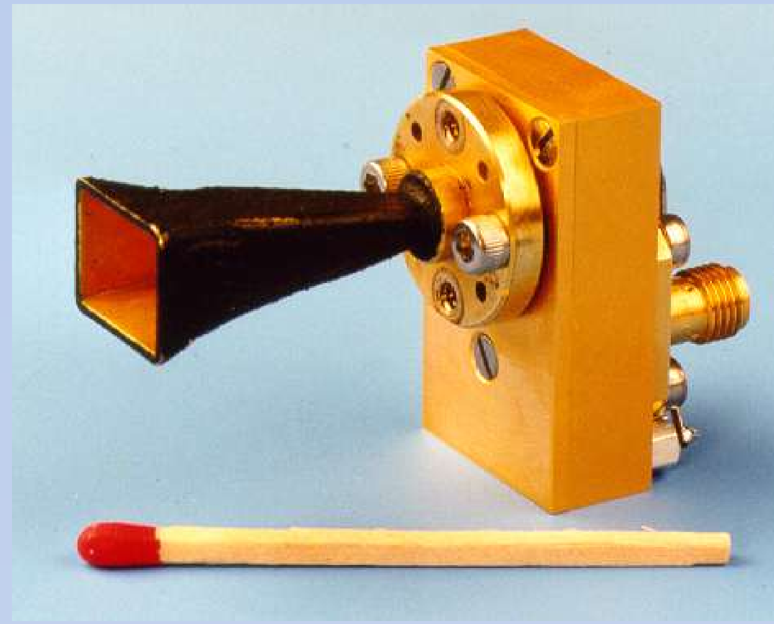
Controlled Mass Production

Monolithically Integrated 94 GHz FMCW Radar Chip

VCO – Voltage Controlled Oscillator
MPA – Medium Power Amplifier
LNA – Low Noise Amplifier
IF – Intermediate Frequency

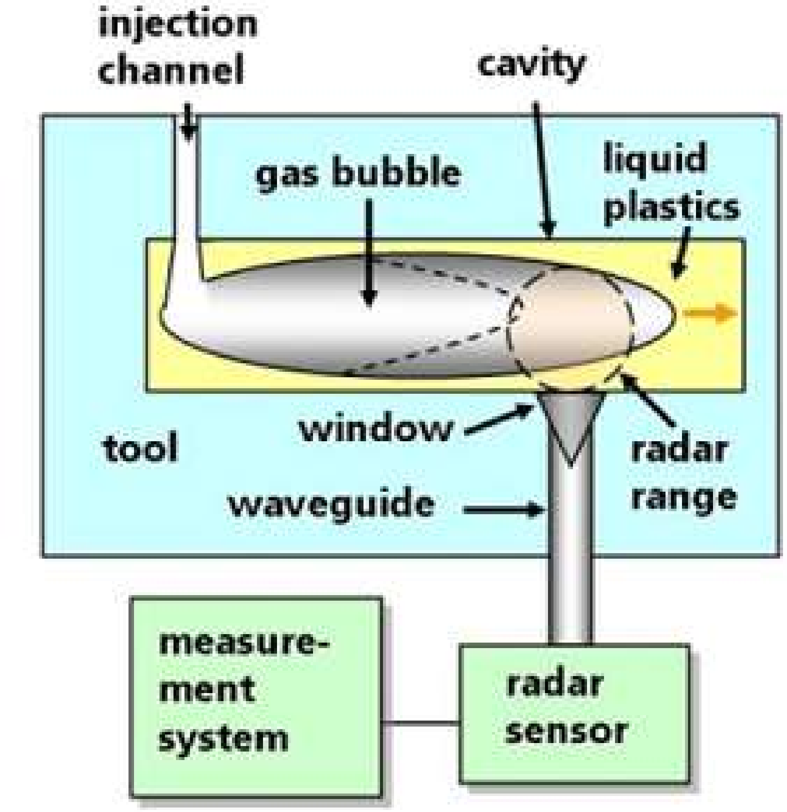


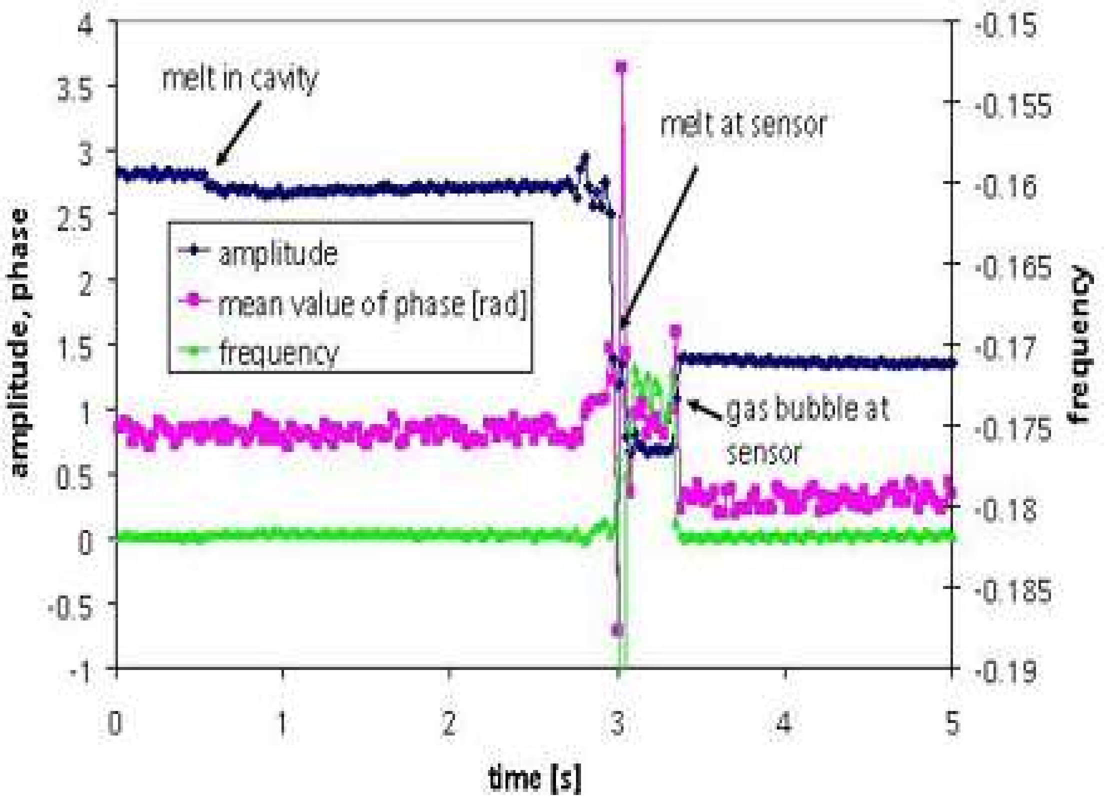




94 GHz radar module, frequency-modulated, (developed by Fraunhofer IAF)

Controlled Mass Production





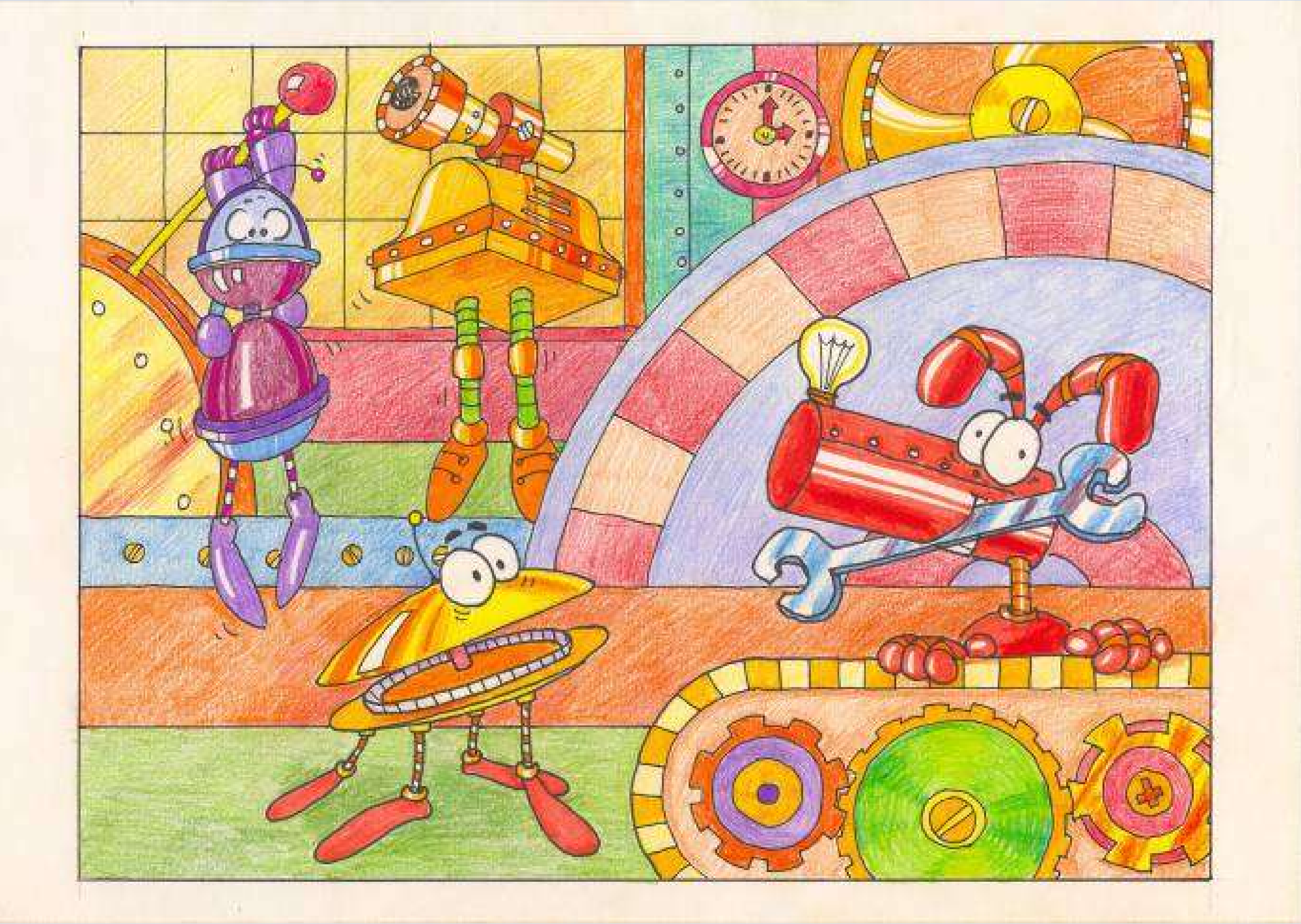
Layout of GIT process monitoring with radar sensor

Process steps identified by characteristic signal changes

TOLMI LECTURE

HOW TO
MANAGE
ALL THIS?

WE NEED
A MISSION!



TOLMI LECTURE

TOLMI LECTURE

PARADIGM CHANGE

by

AUTOMATION (Robotics)

MICROELECTRONICS (Instruments)

COMPUTING (Real-time advanced signal processing)

IT(Asset management; distributed systems;

NDT – DRIVEN BY QUALITY MANAGEMENT

TOLMI LECTURE

TOLMI MISSION

EXCELLENT & RELEVANT APPLIED SCIENCE

THROUGH

NATIONAL & INTERNATIONAL

KNOWLEDGE AND TECHNOLOGY MANAGEMENT
MARKET AND PRODUCT DRIVEN R&D PROJECTS
FUNDAMENTAL & PROFESSIONAL STUDENT EDUCATION

FOR

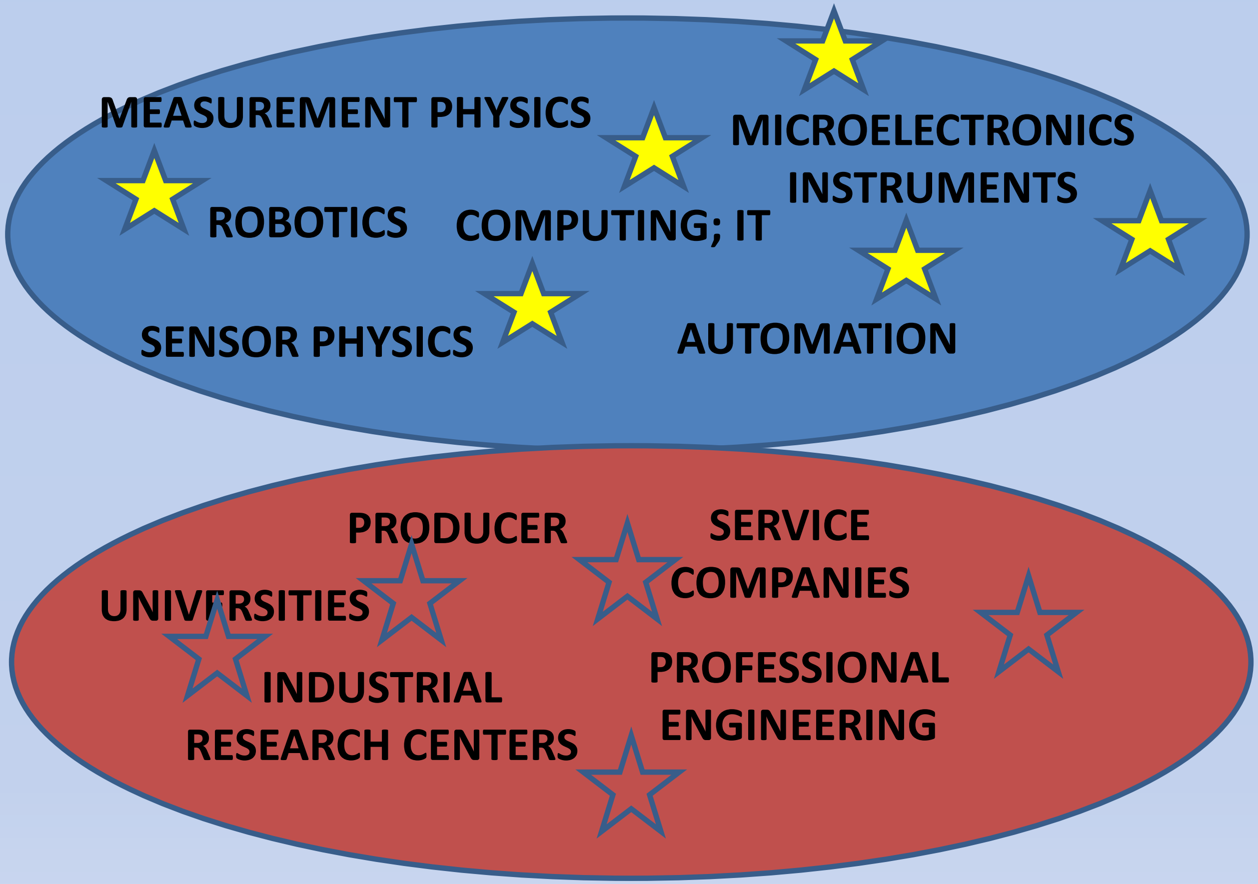
INNOVATIVE PRODUCTS:

INSTRUMENTS, SYSTEMS, SERVICES

APPLIED IN INDUSTRY

SAFE TECHNICAL STRUCTURES – CERTIFIED QUALITY PRODUCTION

TOLMI LECTURE



STRATEGIC NETWORKS
FOR PROFESSIONAL and COMPETENT
DEMAND DRIVEN DEVELOPMENT

TOLMI LECTURE

TPU, TOMSK
POLYTECHNIC UNIVERSITY
INSTITUTE NONDESTRUCTIVE
TESTING
RUSSIA

APPLIED
SCIENCE

IzfP, SAARBRÜCKEN
FRAUNHOFER GESELLSCHAFT
INSTITUTE NONDESTRUCTIVE
TESTING
GERMANY

CNDE

IIT, MADRAS
INDIAN INSTITUTE of TECHNOLOGY
CENTER for NONDESTRUCTIVE
EVALUATION
INDIA

CNDE

ISU, AMES IA
IOWA STATE UNIVERSITY
CENTER for NONDESTRUCTIVE
EVALUATION
UNITED STATES

TOLMI LECTURE

MOTIVATION

STRUCTURAL INTEGRITY

(Probabilistic) Fracture Mechanics

(Risk based)
STRUCTURAL INTEGRITY ASSESSMENT

MATERIAL

LOAD

DEFECT STATE

Advanced UT Systems

TOLMI LECTURE

(Quantitative)
ULTRASONIC TESTING

Contrast Sensitivity

DETECTION & EVALUATION
of
PLANAR FLAWS

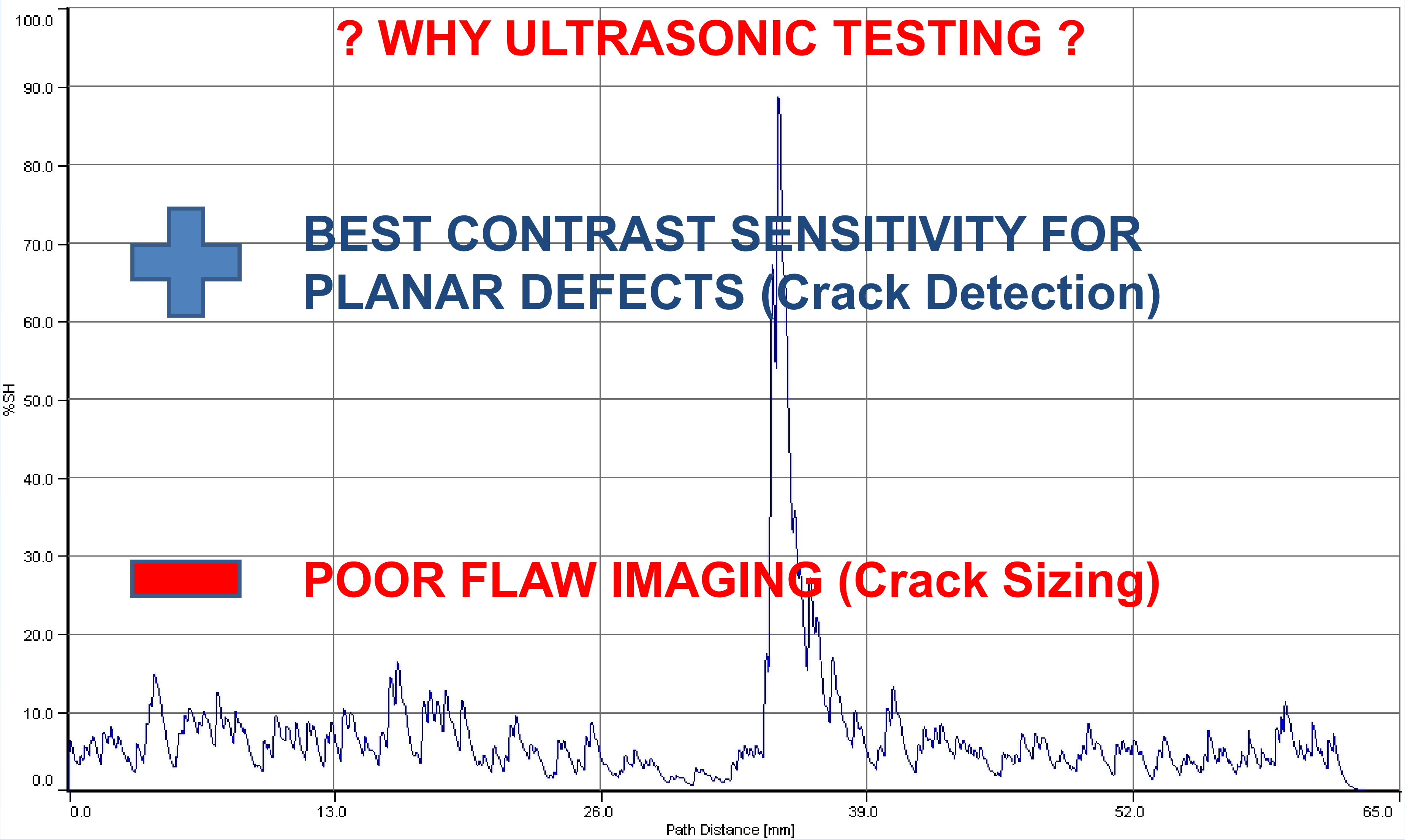
Resolution Sensitivity

DEFECT STATE

Advanced UT Systems

TOLMI LECTURE

? WHY ULTRASONIC TESTING ?

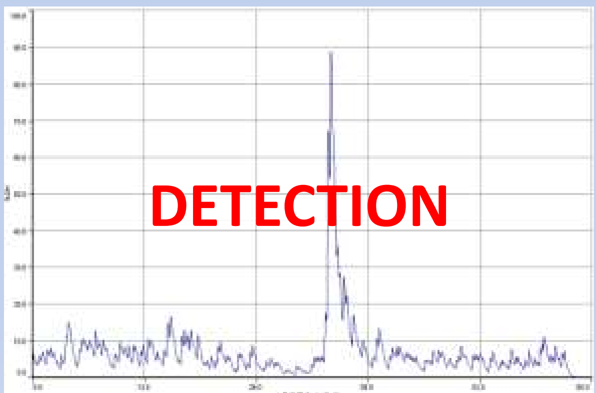


BEST CONTRAST SENSITIVITY FOR PLANAR DEFECTS (Crack Detection)

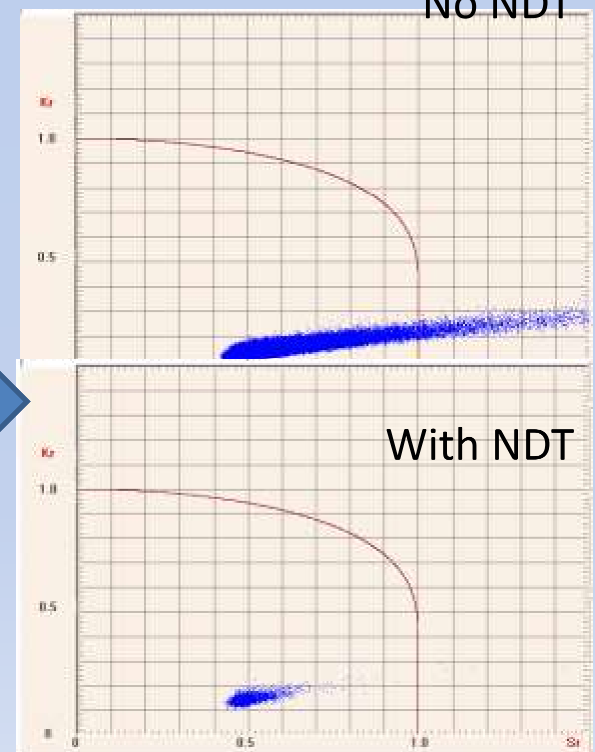
POOR FLAW IMAGING (Crack Sizing)

TOLMI LECTURE

QUT
- QUANTITATIVE ULTRASONIC TESTING -
A Preventive Action for the Integrity of Structures under Load



SIZING



POD
(Probability of Detection)

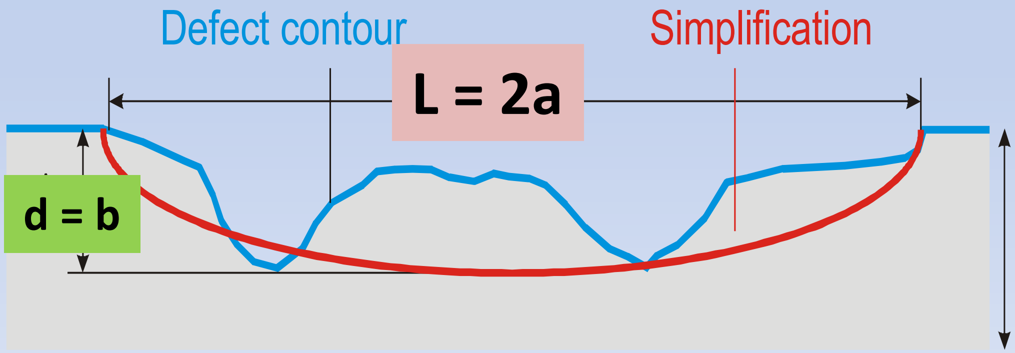
TOLMI LECTURE

45°/4 MHz A-scan
ID Crack Signal

STATE OF ENGINEERING

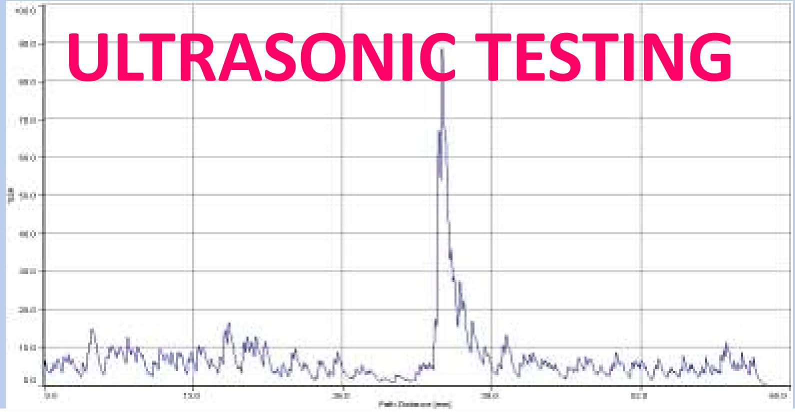
STATE OF PHYSICS

FRACTURE MECHANIC
MODEL CRACK



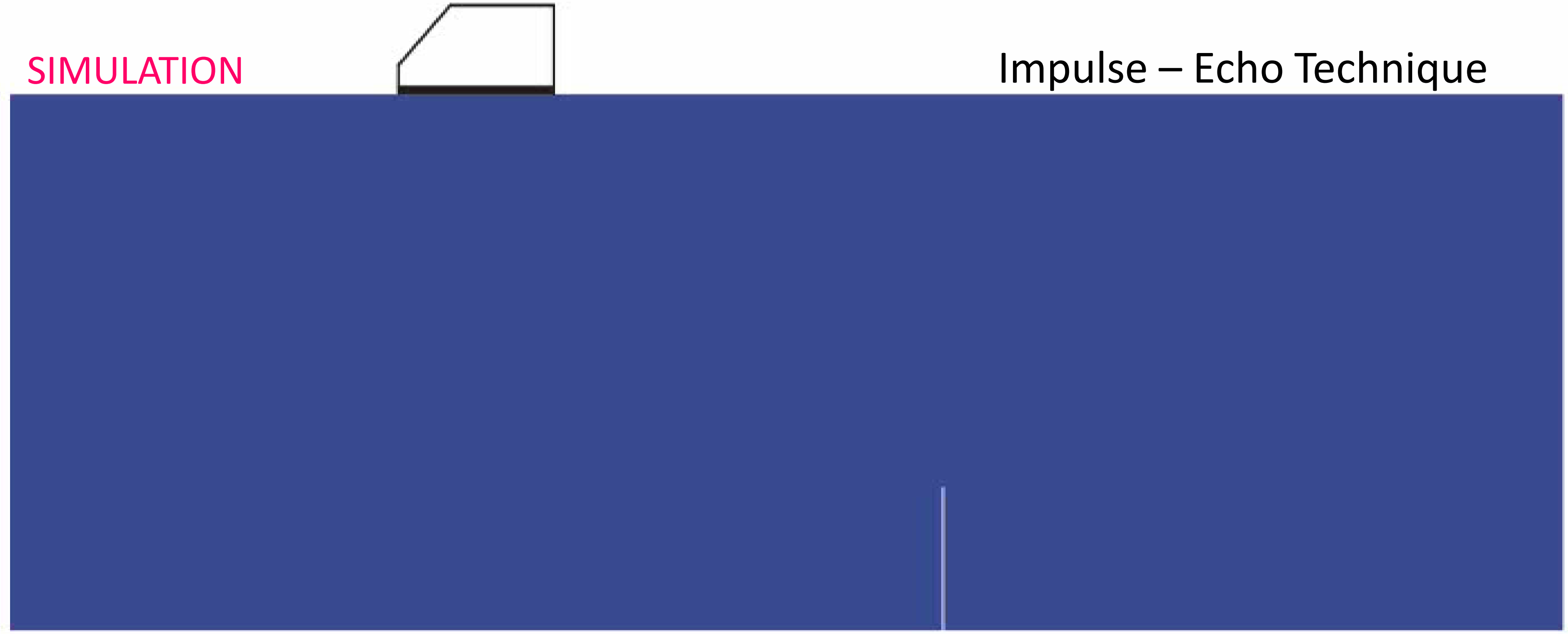
TOLMI LECTURE

ULTRASONIC TESTING



SIMULATION

Impulse – Echo Technique



Applicable Principles of Measurement Physics

PROBABILITY OF DETECTION

PoD (planar flaws) = f(Performance) X f(Contrast)

VALIDATION

f(Performance)	f(Contrast)
HUMAN ERROR	FLAWS & MATERIAL
AUTOMATION	ULTRASOUND
SCAN COVERAGE	ORIENTATION COVERAGE

Scan Index & Beam Spread

Direction of Incidence

Advanced UT Systems

FLAW EVALUATION

There are many experts and procedures
We rely on ultrasonic high resolution imaging

HUMAN ERROR

VALIDATION

INDEPENDENT EXPERT EVALUATION

AUTOMATION

WAVE PHYSICS (MIGRATION)

FLAW COVERAGE

HIGH RESOLUTION FLAW SCAN

All Flaws are imaged

3-D Scan and 3-D imaging

Advanced UT Systems

CHALLENGE

Contradicting Requirements

High Contrast Sensitivity	High Resolution Sensitivity
Space Coverage of Intromission Angles	Resolution in Space 3-D Imaging
Large Beam Spread	3-D Focussing

DEFECT STATE

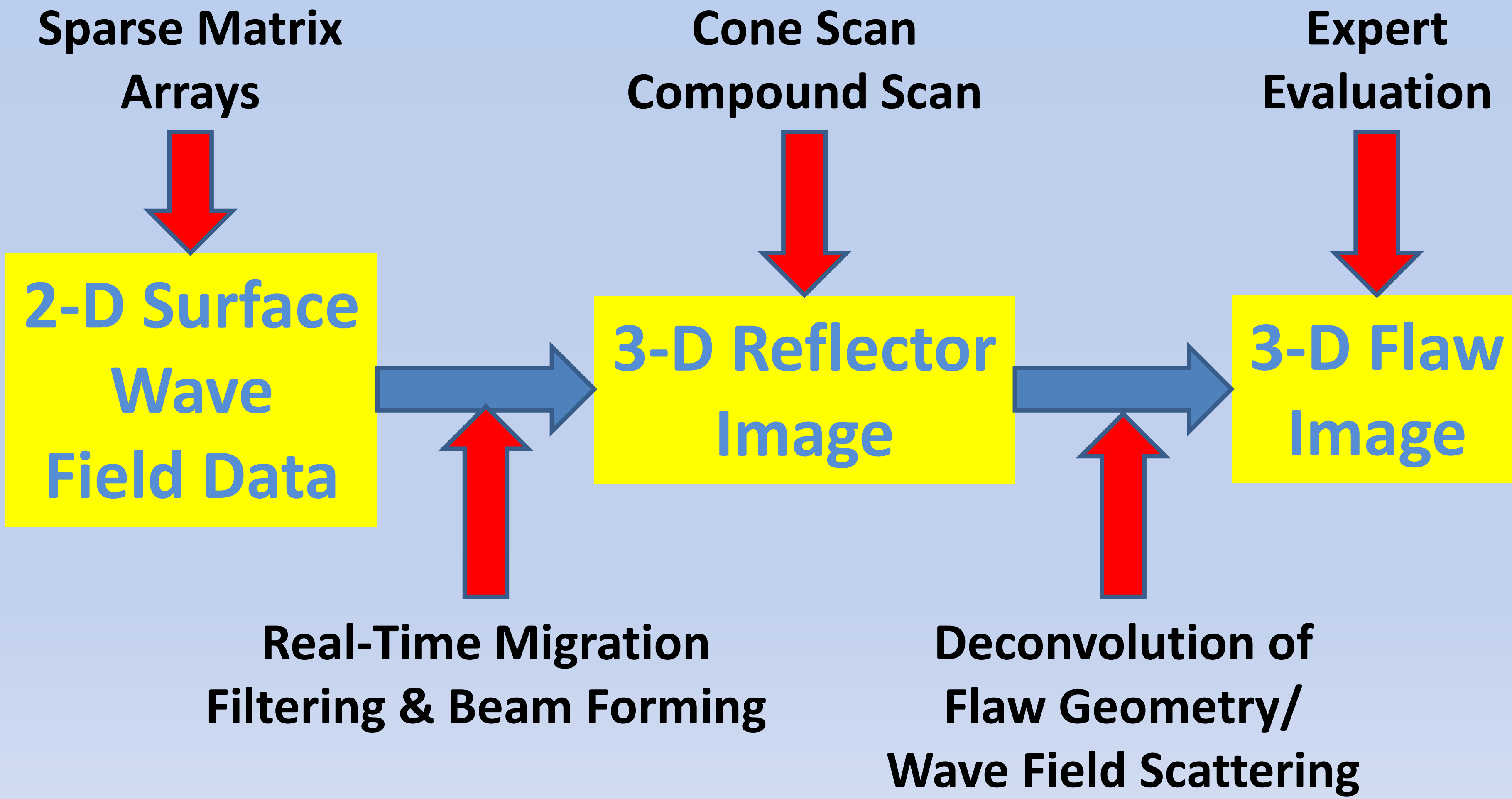
(Quantitative)

ULTRASONIC TESTING

Advanced UT Systems

TOLMI LECTURE

R&D OBJECTIVES



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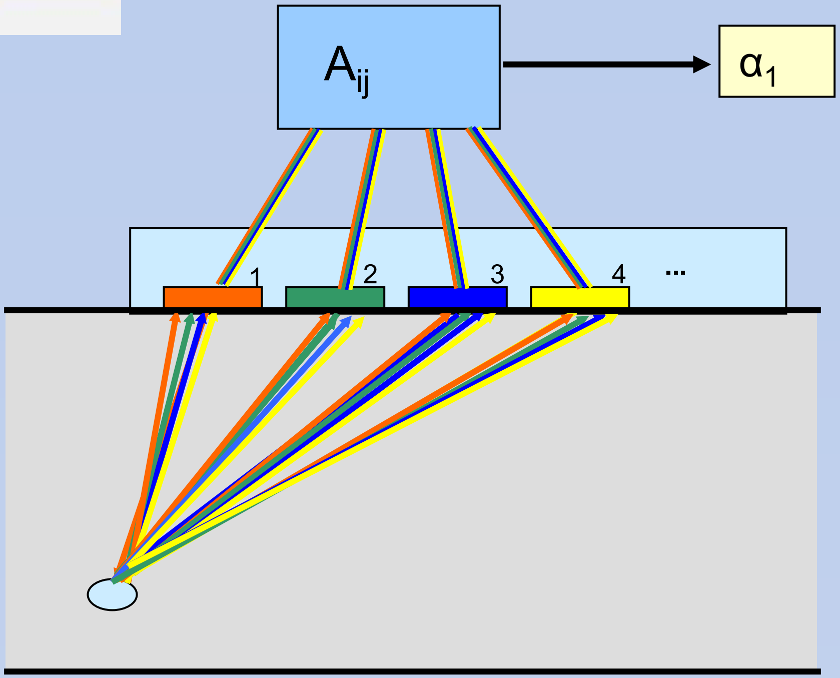
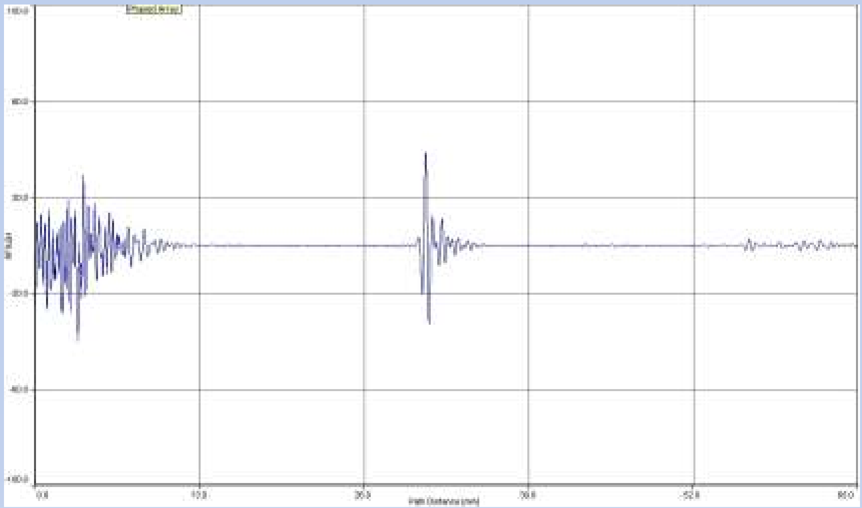


A-SCAN: $A_\alpha(t)$

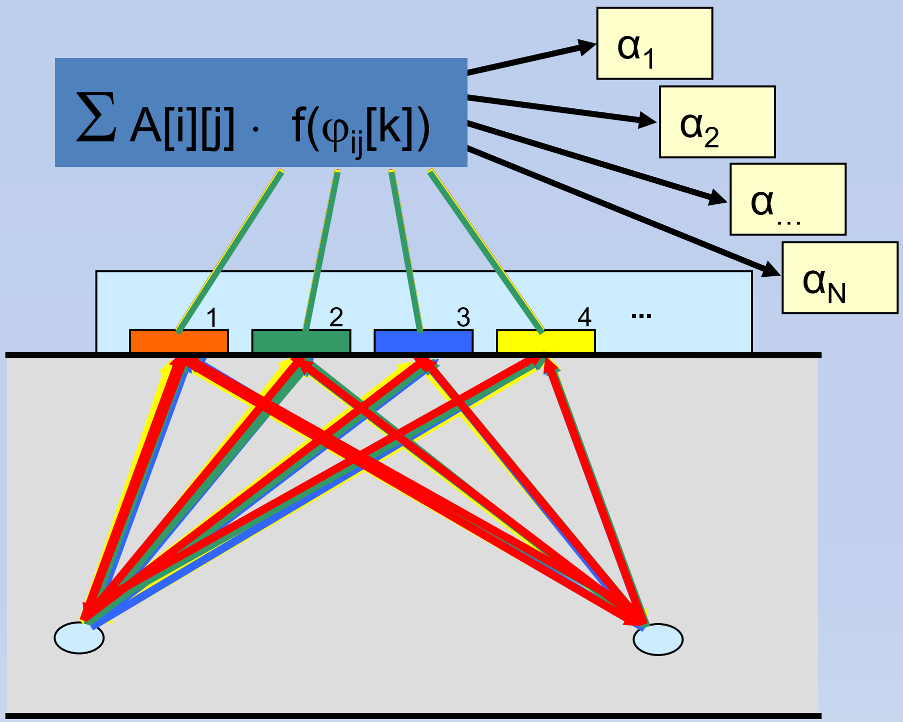
α – Beam Angle



Signal Generation Using Conventional PA

Advanced UT Systems

$\varphi_{ij}[k]$ **– corresponding phase delay for beam angle α**



Information Matrix A_{ij}

i – transmitter number
j – receiver number

A_{11}	A_{12}	A_{13}	A_{14}
A_{21}	A_{22}	A_{23}	A_{24}
A_{31}	A_{32}	A_{33}	A_{34}
A_{41}	A_{42}	A_{43}	A_{44}

Notation: **m** x **n**
m – number of active transmitters
n – number of active receivers

Sampling PA Signal Generation

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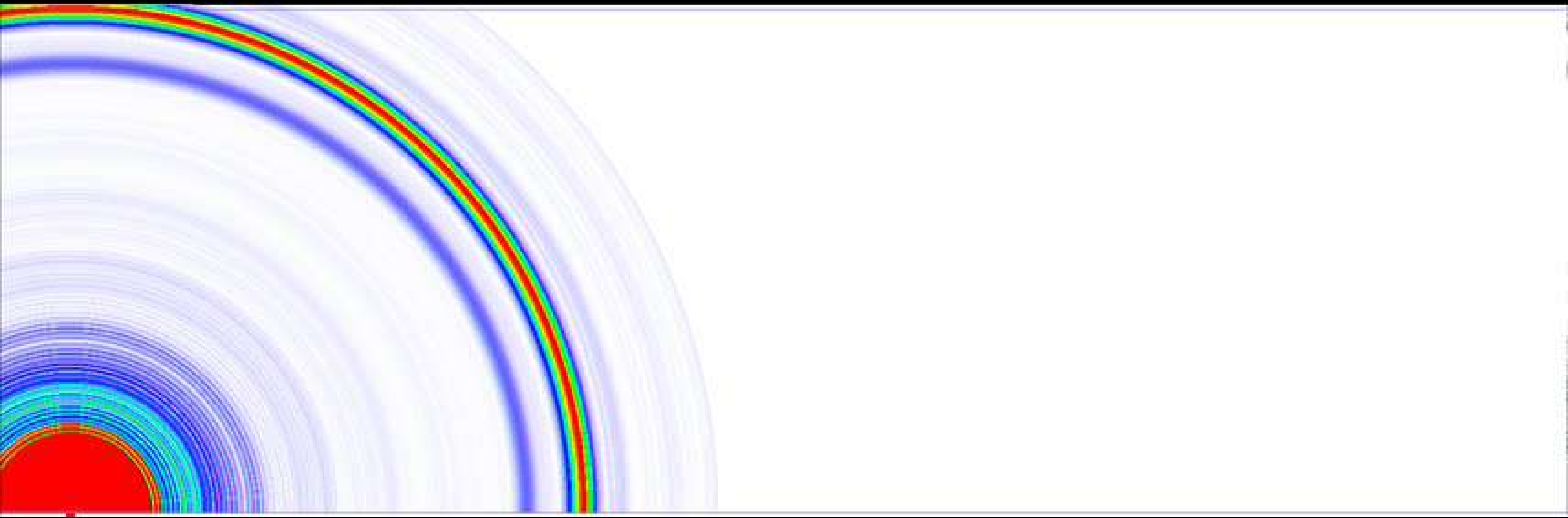
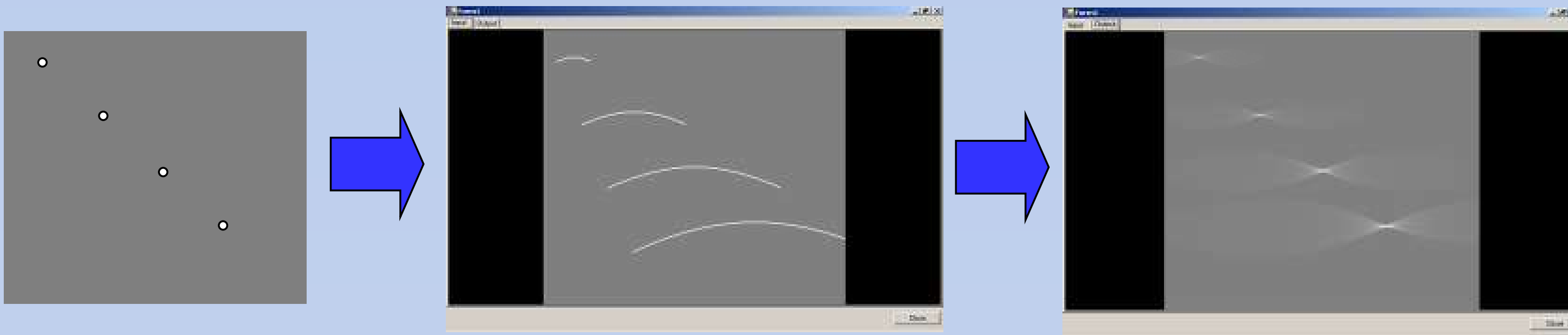
A Virtual SAFT Experiment



TOLMI LECTURE

Synthetic Aperture - SAFT

SAFT Reconstruction



A_{11}	A_{12}	A_{13}	A_{14}
A_{21}	A_{22}	A_{23}	A_{24}
A_{31}	A_{32}	A_{33}	A_{34}
A_{41}	A_{42}	A_{43}	A_{44}

Advanced UT Systems

TOLMI LECTURE

SAFT

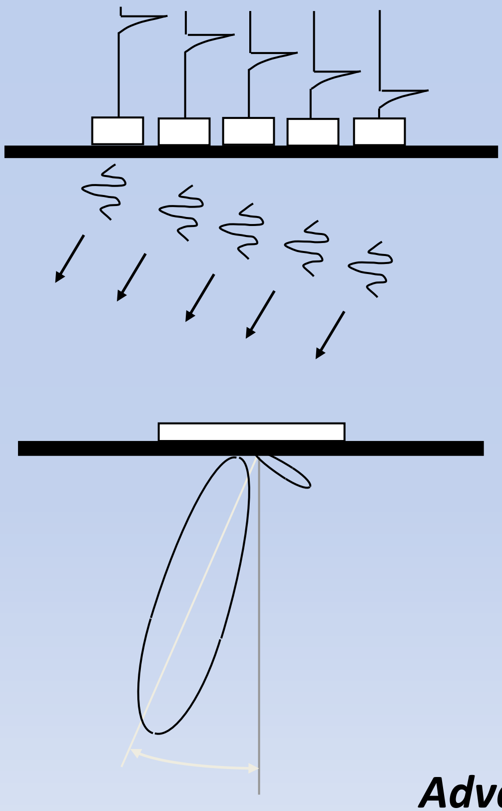
Advanced UT Systems

TOLMI LECTURE

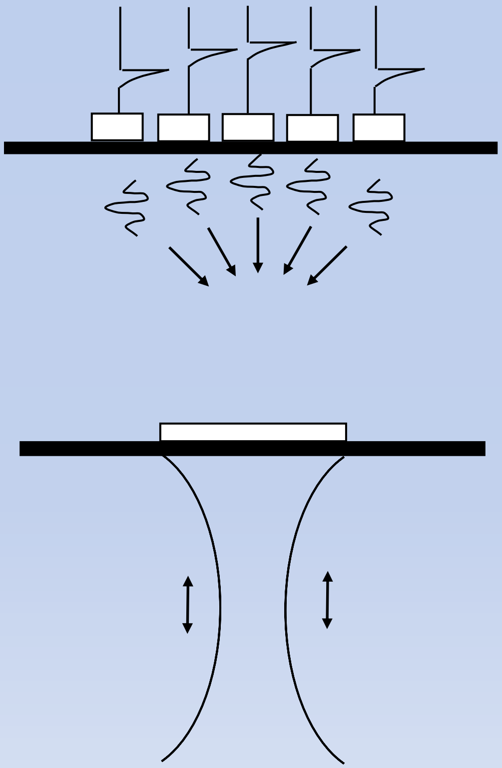
Phased Array Principle

Phase Controlled Measurement

Sweeping

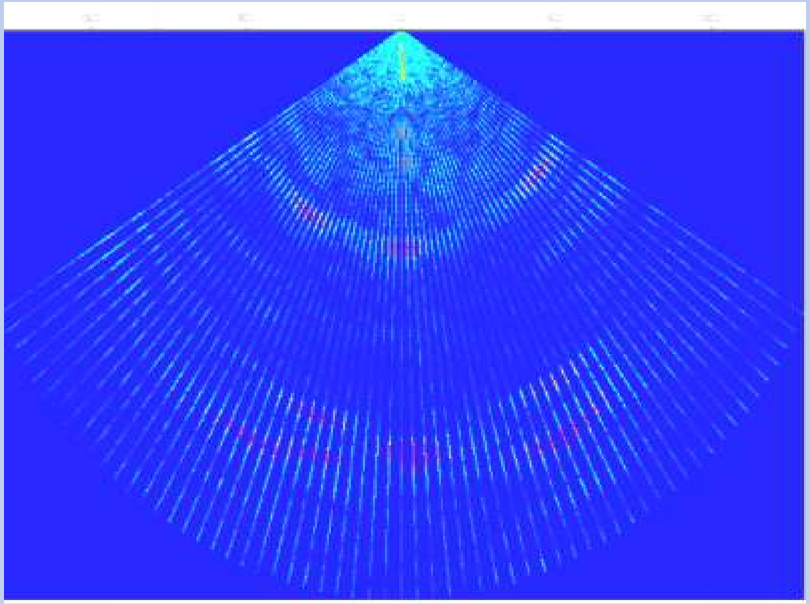


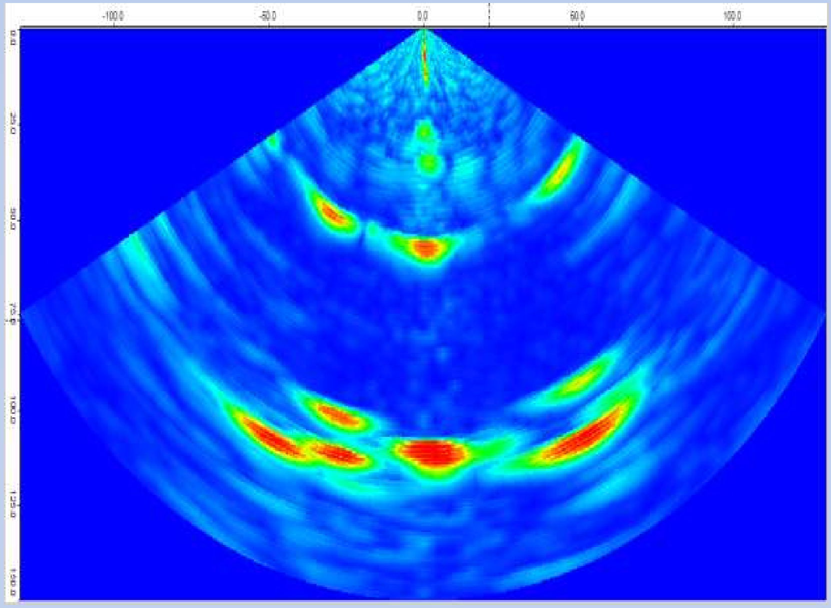
Focusing



Advanced UT Systems

Sector Scans





Ray Image | Processed Image

Sector Scan composed by 71 A-Scans (sweep: -70° to +70° in steps of 2°)

No focussing

Advanced UT Systems

PHASED ARRAY

Some (well-known) Statements

- Phase controlled measurement
- Array aperture determines nearfield with focussing capacity
- Resolution depends on array aperture
- Long measurement times for complete angle sweep and focussing

However: Excellent Contrast Sensitivity (until today for 2 – D Imaging)

Migration Arrays

{SAFT , PHASED ARRAY}

Name

We measure position controlled the acoustic field by elements of an array and migrate the field from the surface through the volume of interest and find the acoustic sources (reflectors). This is called inverse migration.

Meaning

Used for reflector reconstruction (geophysics).

Advanced UT Systems

MIGRATION ARRAY

Some (new) Statements

- Position Controlled Measurement
- Array aperture determines nearfield with synthetic focussing
- Resolution depends on Element Aperture
- One set of A-Scan data of array elements received in parallel allows full and complete image reconstruction with:

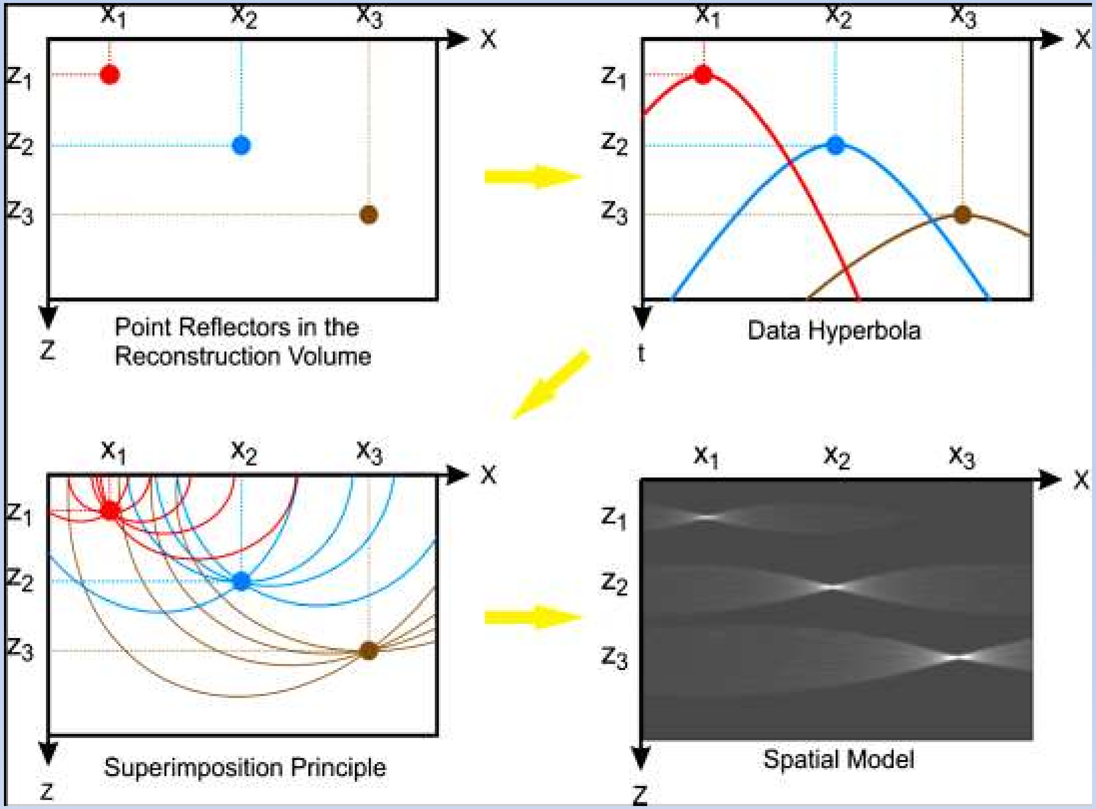
Excellent Contrast Sensitivity (all space angle of incidence)
Highest possible Resolution Contrast through synthetic focussing

Advanced UT Systems

ACOUSTIC MIGRATION

Kirchhoff Ansatz:

$$C(t) = G\sum_{i} w_i A_i(t - t_i)$$



x_i : element position

z_j : depth position

C(*t*) : computed RF echo return

$A_i(t)$: returned signal

w_i : weight assigned to $A_i(t)$

t_i : time delay for element i.

G: goodness of fit enforcement (SynFoc© by LucidSoft)

Advanced UT Systems

THAT'S WHAT WE WANT!

Resolution Sensitivity:

- depends on the element aperture in the near field of the array aperture (synthetic focusing)
- is close to the Rayleigh limit for λ/2 element apertures
- can be increased by super resolution techniques

Contrast Sensitivity:

- Matrix arrays:
  sensitive to all space directions within the chosen cone angle
- Linear Arrays:
  covers all angle of incidence of the chosen sector scan angel including angles beyond the first critical angle (shear mode)

ACOUSTIC MIGRATION
(As Realized for NDT Applications)

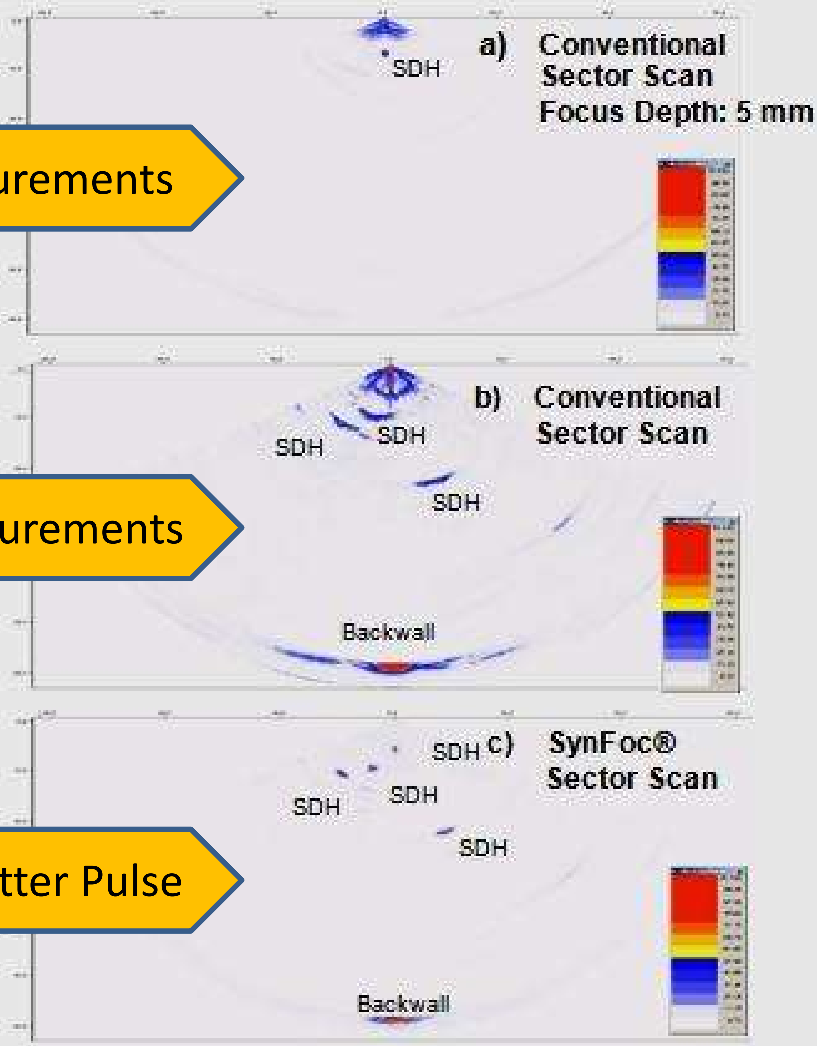
Advanced UT Systems

TOLMI LECTURE

71 Measurements

71 Measurements

1 Transmitter Pulse



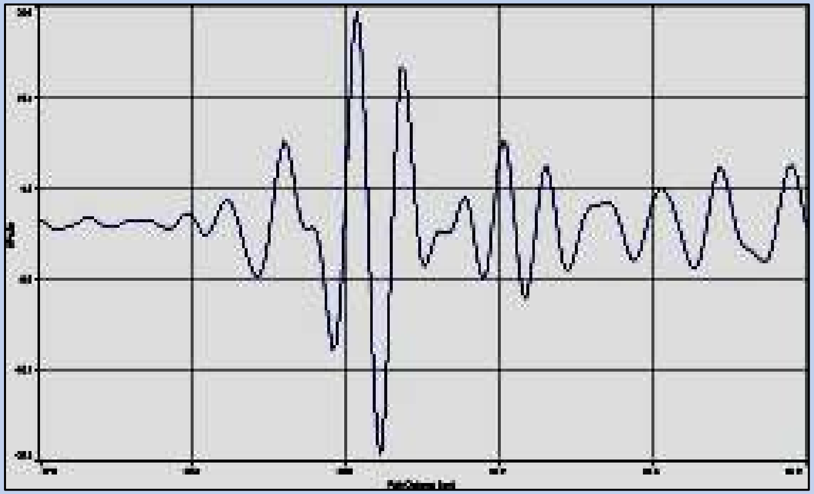
Experimental Data:

Test Specimen: Steel 55 mm thick
SDH Ø: 1mm
Linear Array Transducer:
F = 5 MHz; 16 Elements

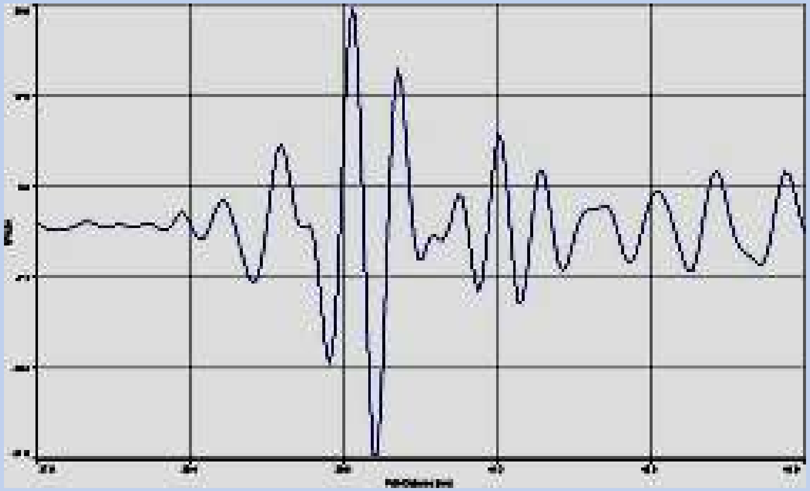
Partial View of Test Specimen with Transducer

TOLMI LECTURE

Zoomed Crack Tip Signals



Phased Array Mode

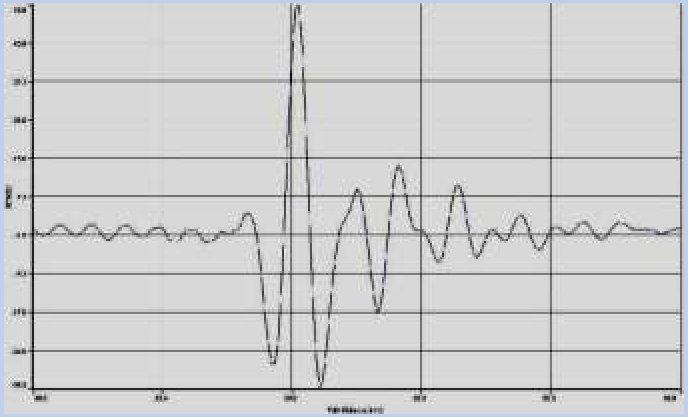


Migration Mode

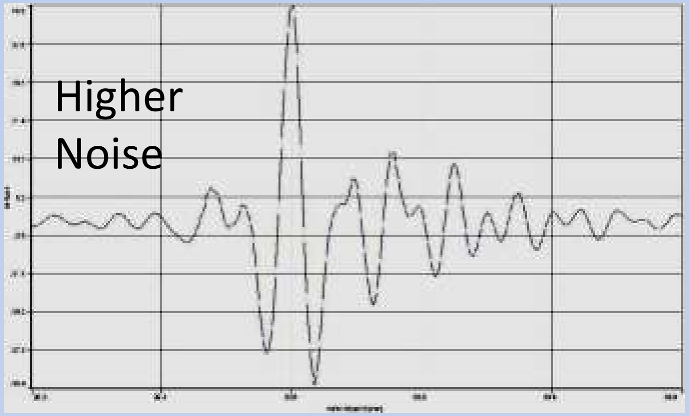
Advanced UT Systems

REAL-TIME MIGRATION

All 16 elements used as transmitter in sampling mode by multiplexing



Only 1 element used as transmitter in 1 transducer position



All 16 elements used as receiver simultaneously in parallel mode

Transducer:
5 MHz Linear Array
64 elements
with 16 used

POINT REFLECTOR SIGNALS
(Reconstructed A-Scans 45° long)

Advanced UT Systems

Just a Simple Consideration

Frequency		f: 3 MHz
Wavelength		λ: 2 mm
Array Apertures		
	8 by 8	A: 8mm by 8mm
	64 by 64	A: 64mm by 64mm

The Sampling Theorem does not allow the design of reasonable matrix transducers

MIGRATION ARRAY

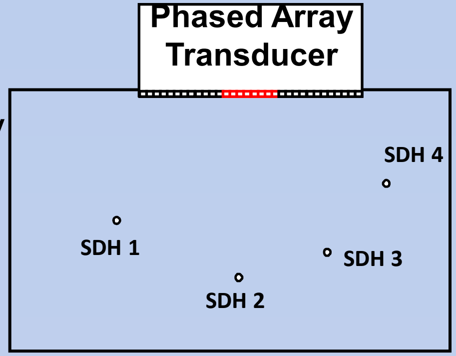
SPARSE APERTURES

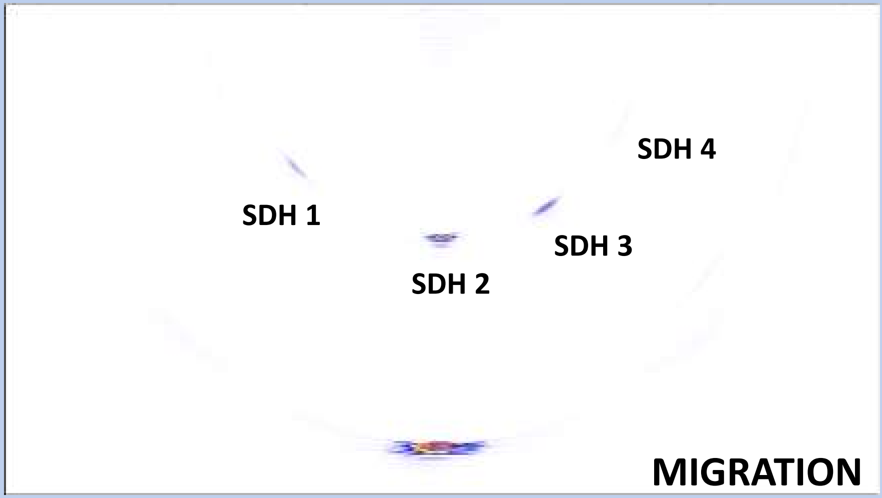
Sparse Migration Array Experiment

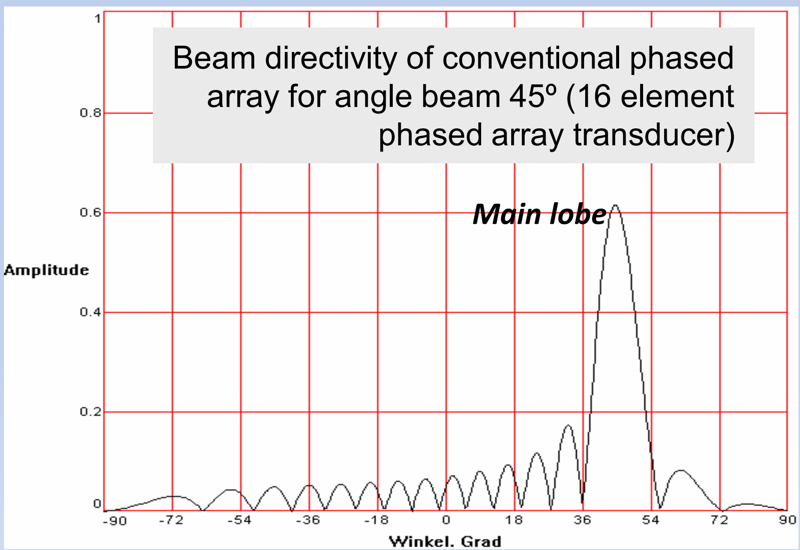
8 Elements with skips of 4 wavelengths

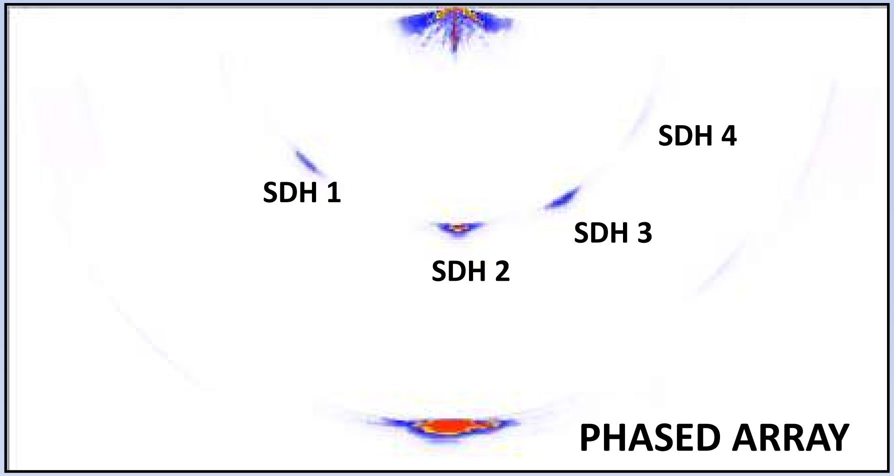
TOLMI LECTURE

64-element Linear Array
16 active elements
frequency 5 MHz,
λ =1.2 mm





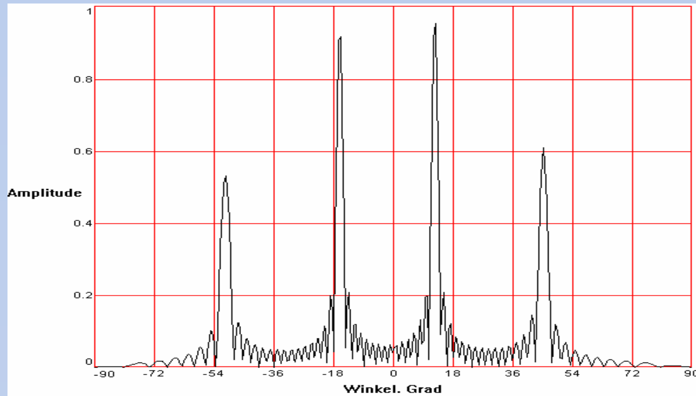




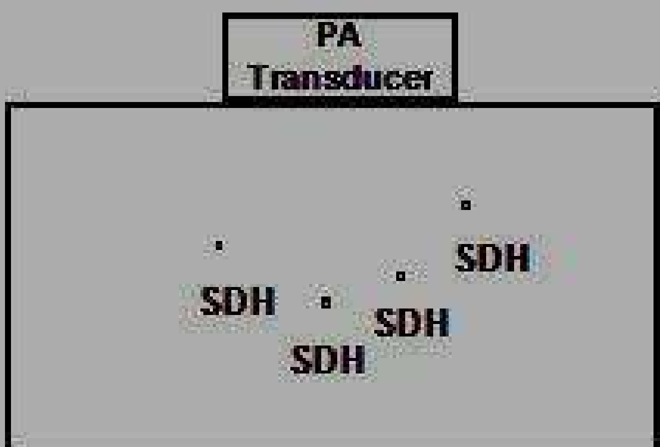
The Sampling Theorem

TOLMI LECTURE

TRANSDUCER:
64 element linear array
16 elements used
f = 5 MHz
Distribution Factor: 4
(Element Skip: 2λ)



BEAM PROFILE
Phased Array mode
Phase control: 0°



Test specimen

Phased Array sector scan

Migration image

SPARSE ARRAY SECTOR SCANS

Definition
of
Migration Array Transducer

Linear or Matrix Array Transducer with
sparse element arrangement,
not in compliance with the sampling theorem.

This type of transducers cannot be used with
Phased Array Instruments

TOLMI LECTURE

Challenge: Optimized Element Arrangement

Small Element Number
&
Large Aperture

⟷

No Artifacts
&
No Noise

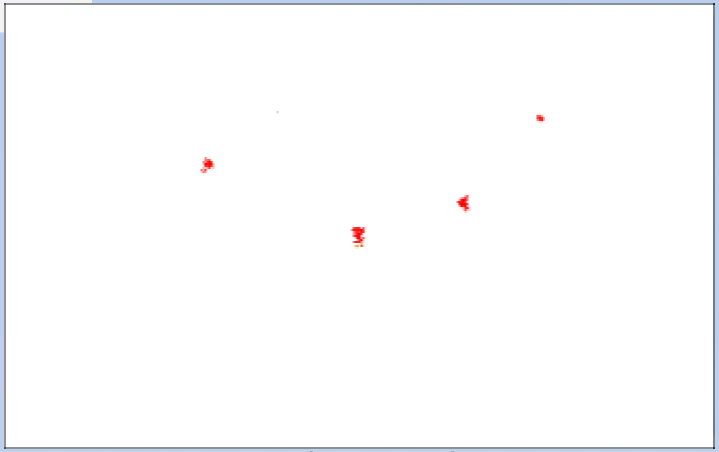
Definition: Distribution Factor ◐

◐ = 2S/λ

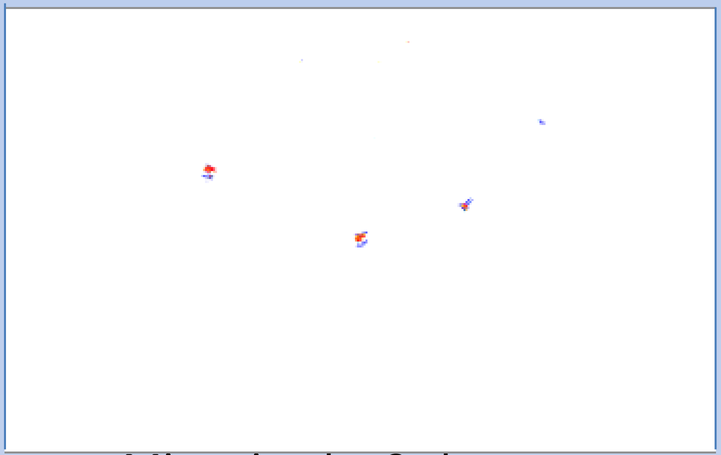
S: Skip; λ: Wavelength

(Distribution Factor for Phased Array Transducers, ◐ = 1)

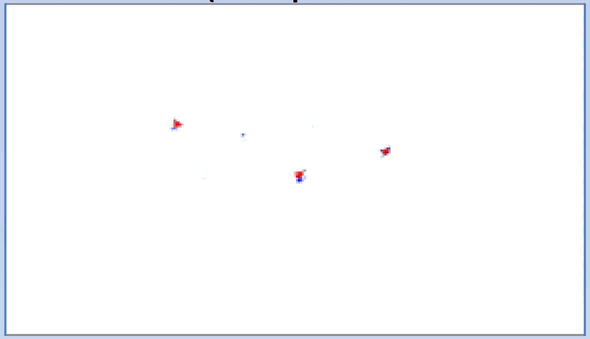
TOLMI LECTURE



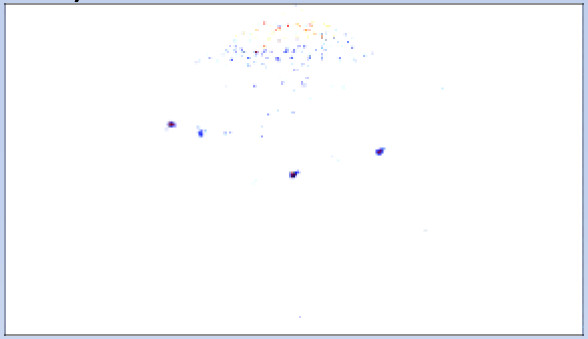
Migration by 64 elements
(full possible information)



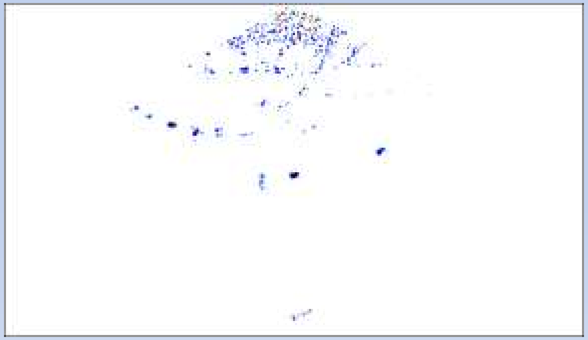
Migration by 6 elements
stochastic distribution



Migration by 16 elements
homogeneous, DF = 4



Migration by 8 elements
homogeneous, DF = 8



Migration by 6 elements
homogeneous, DF = 10

SPARSING LIMITS

TOLMI LECTURE

Arrangement Rule № 1

◐ ≤ 4

uniform element distribution,

advanced migration code

No artifacts and reasonable low noise levels

Arrangement Rule № 2

◐ > 4

Non-uniform element distribution,
advanced migration code

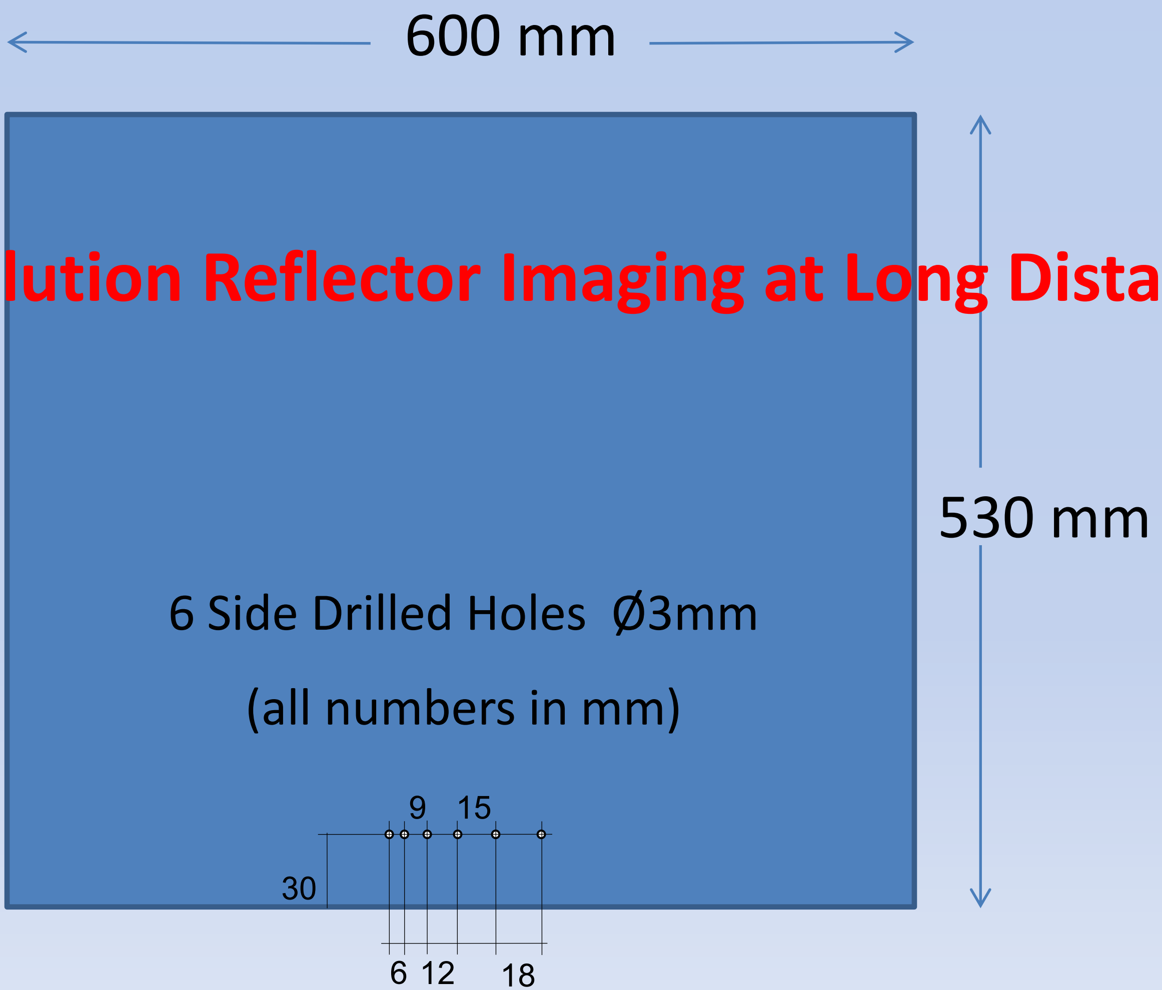
No artifacts and reasonable noise levels

Limits have to be investigated

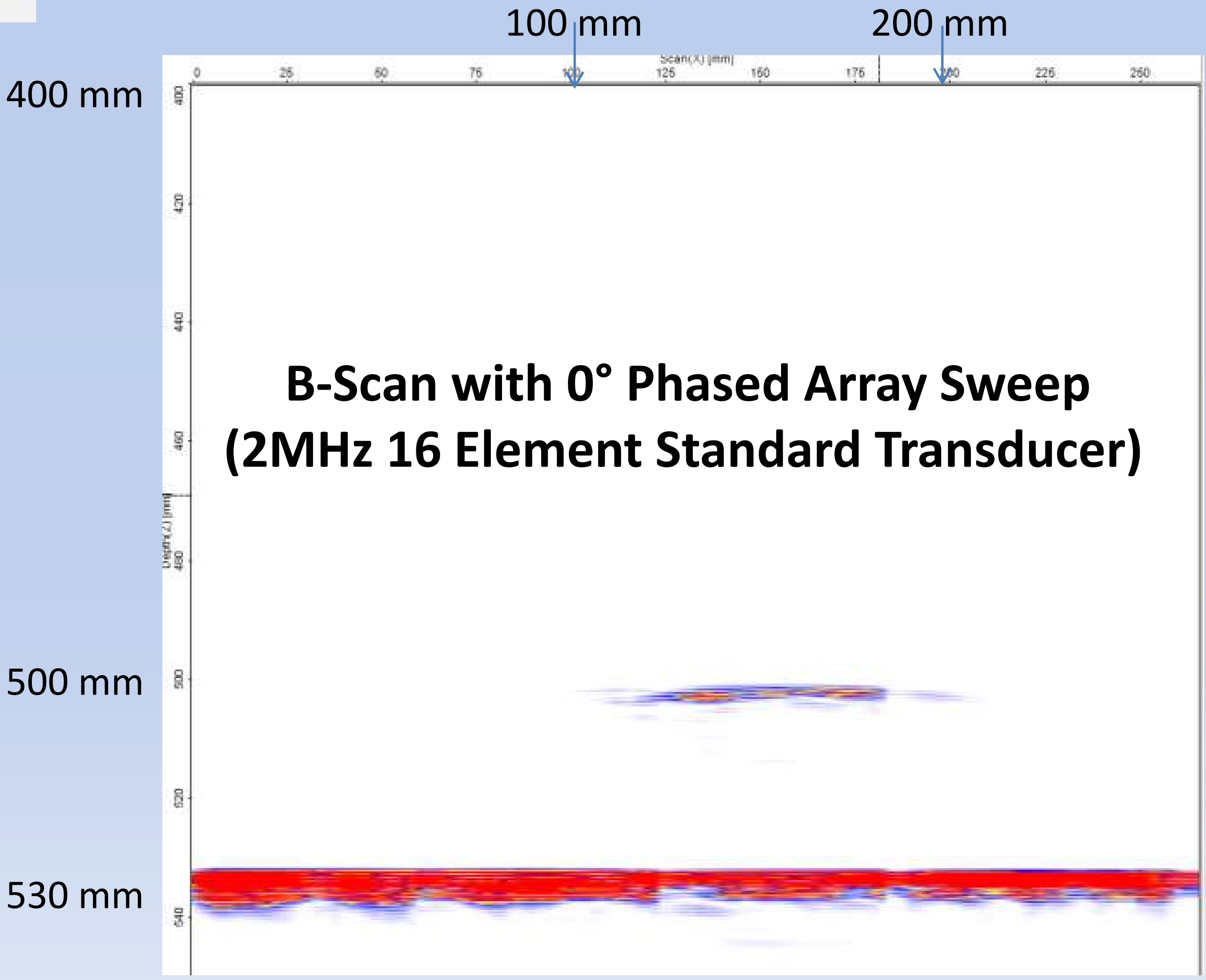
TOLMI LECTURE

CASE STUDY

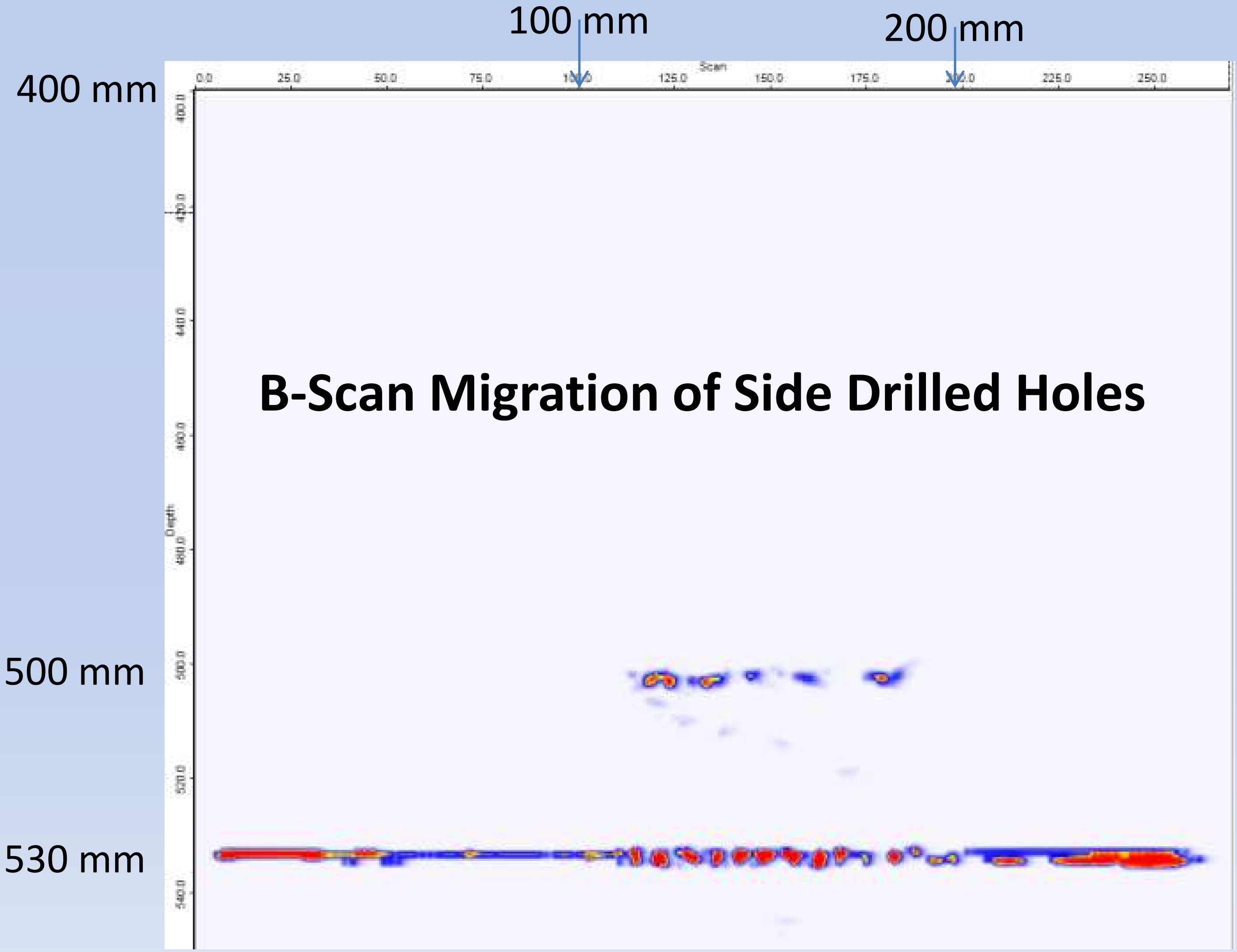
High Resolution Reflector Imaging at Long Distances



TOLMI LECTURE



TOLMI LECTURE



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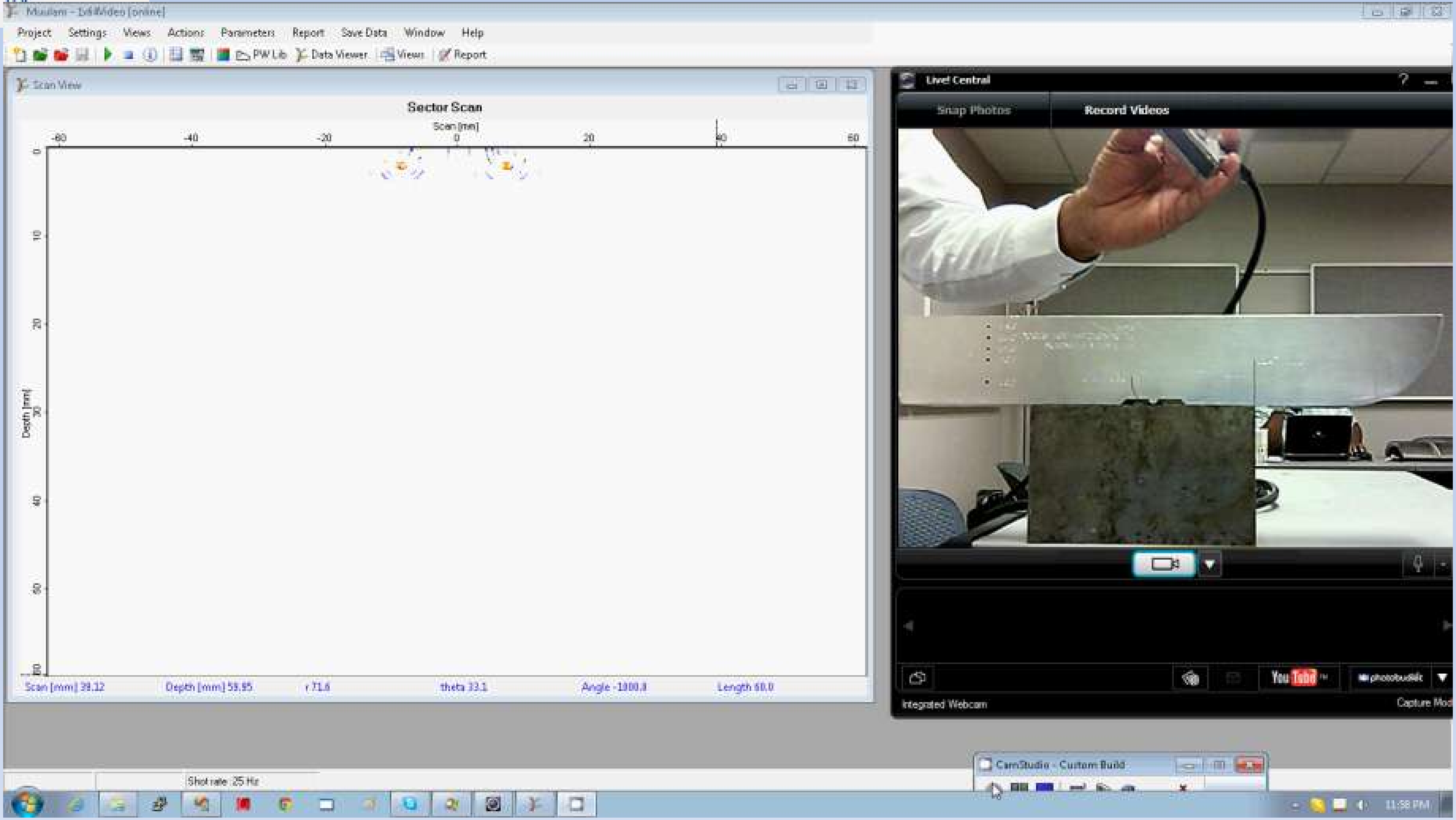
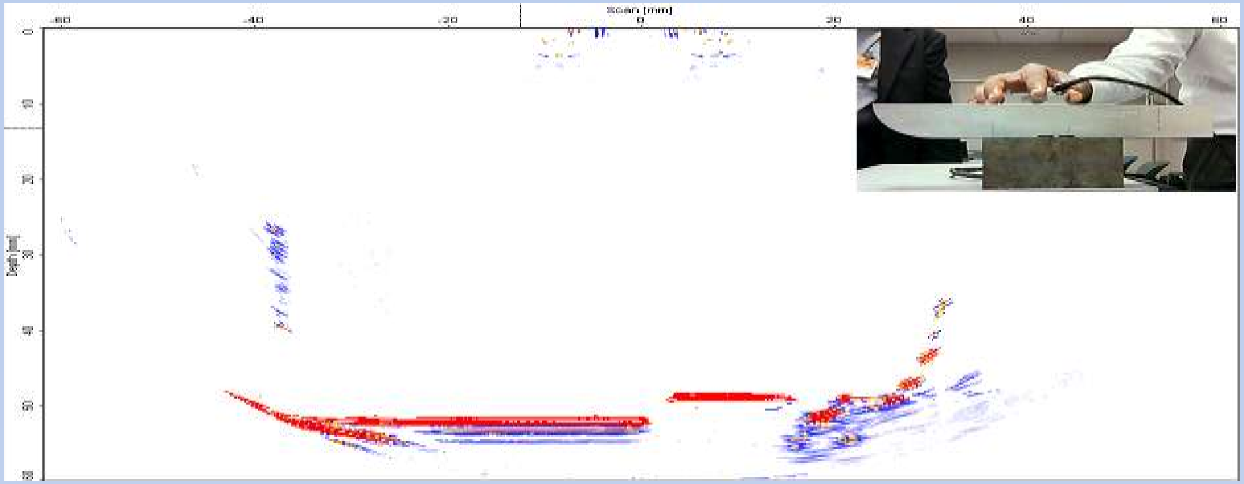
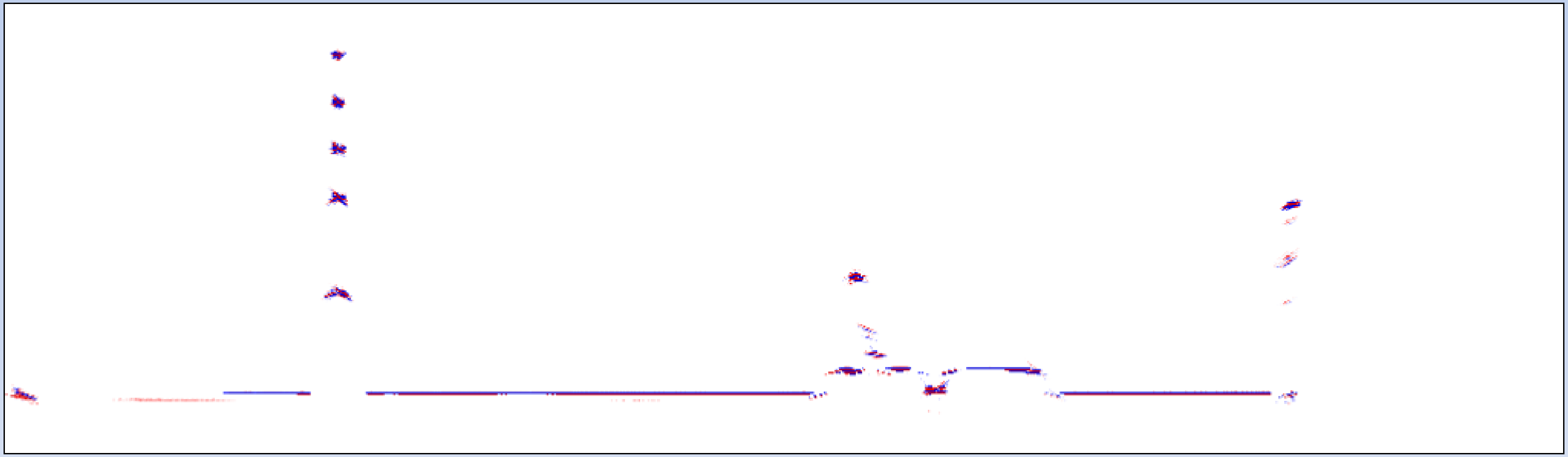


TOLMI LECTURE

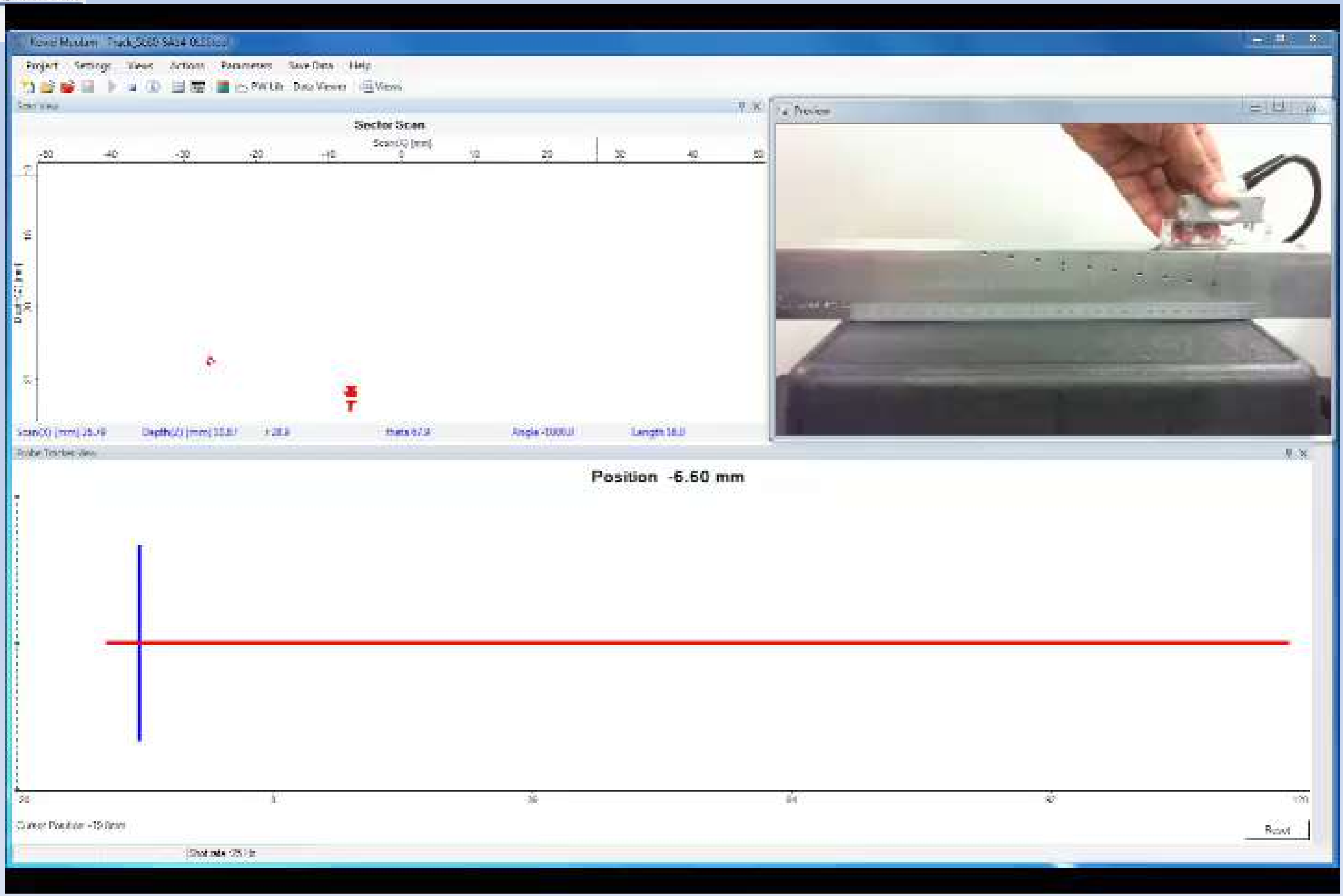


Sector scan reconstruction of Alu block with side drilled hole

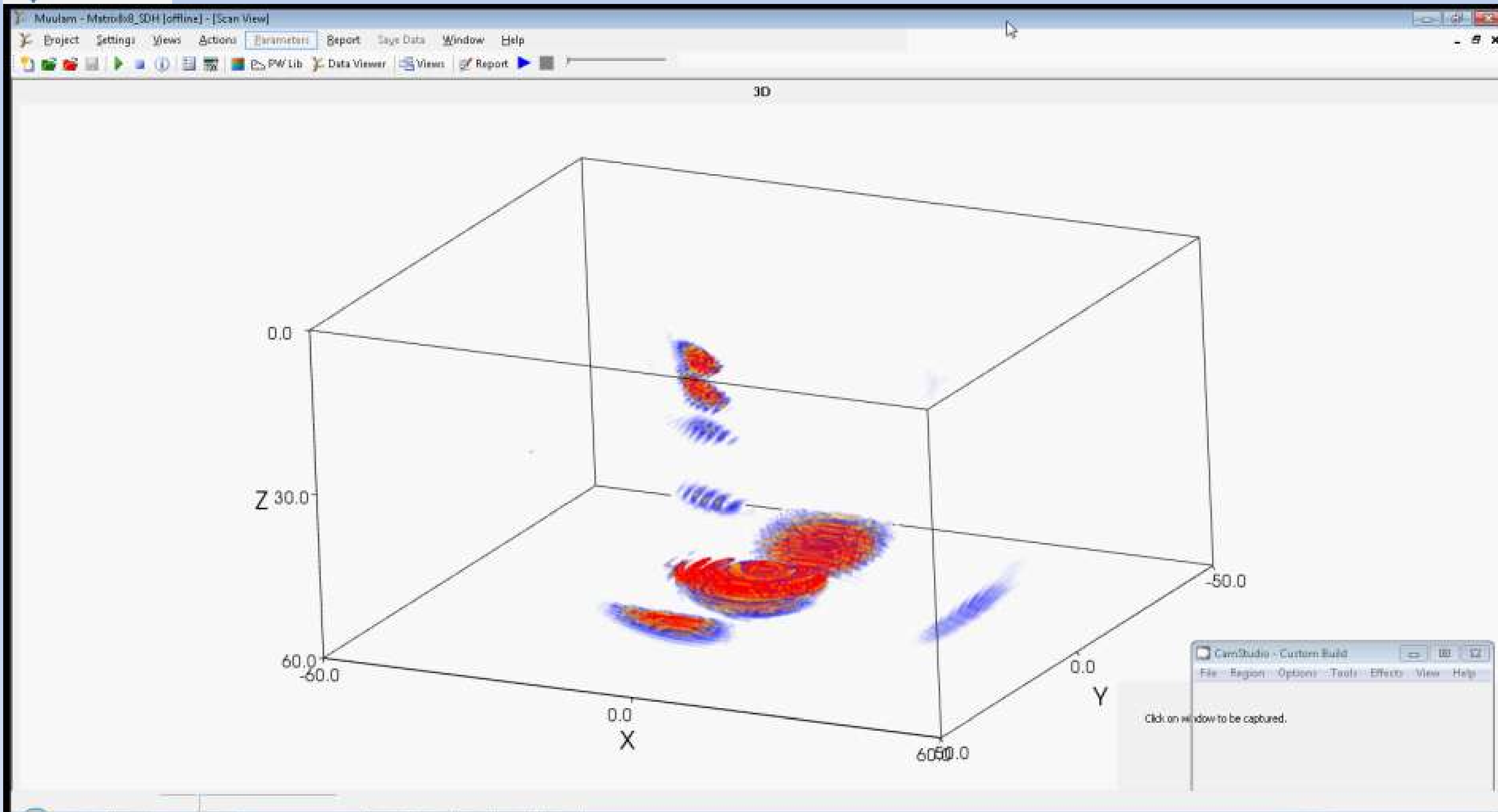


B-Scan reconstruction of Aluminium block

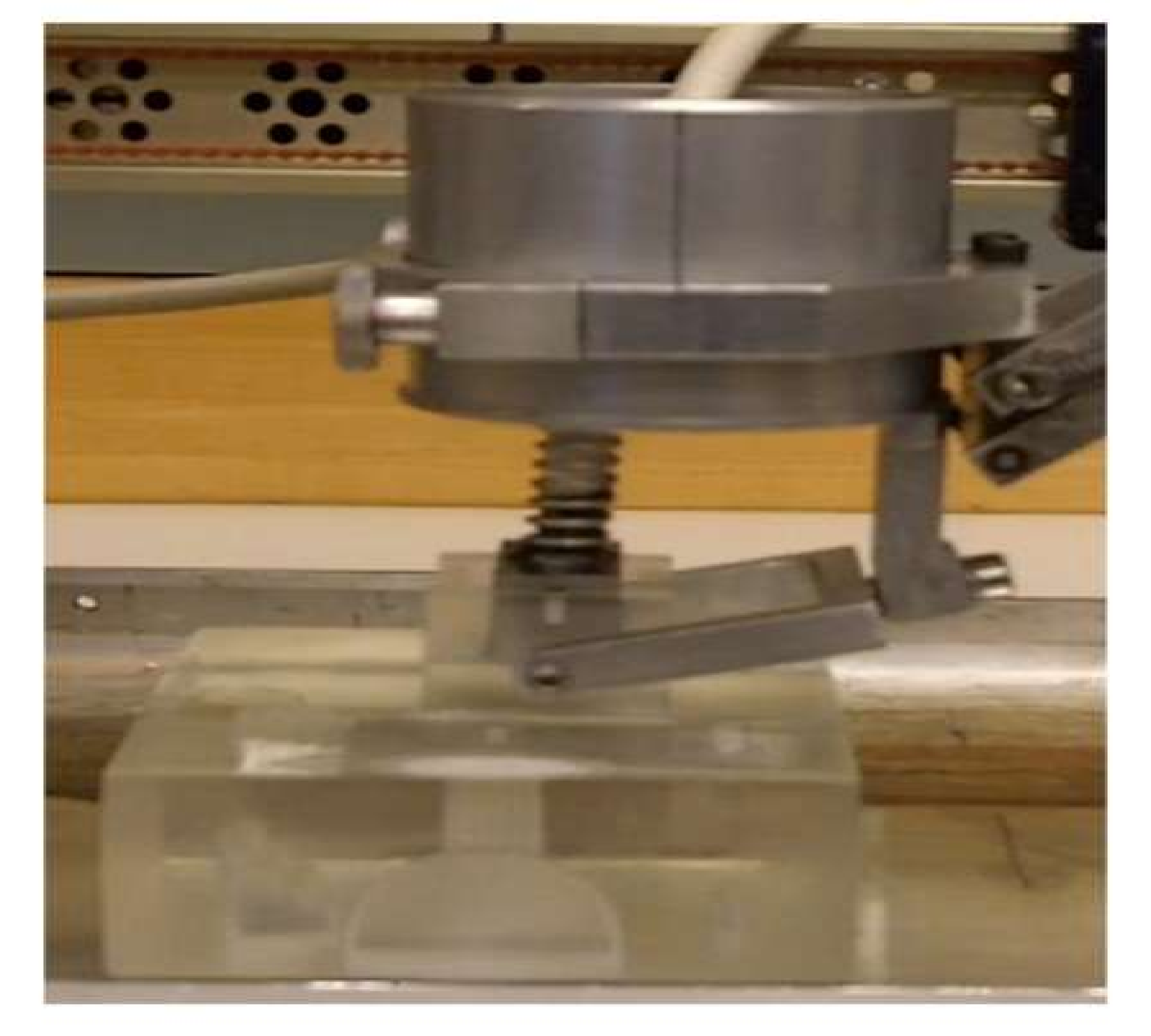
TOLMI LECTURE



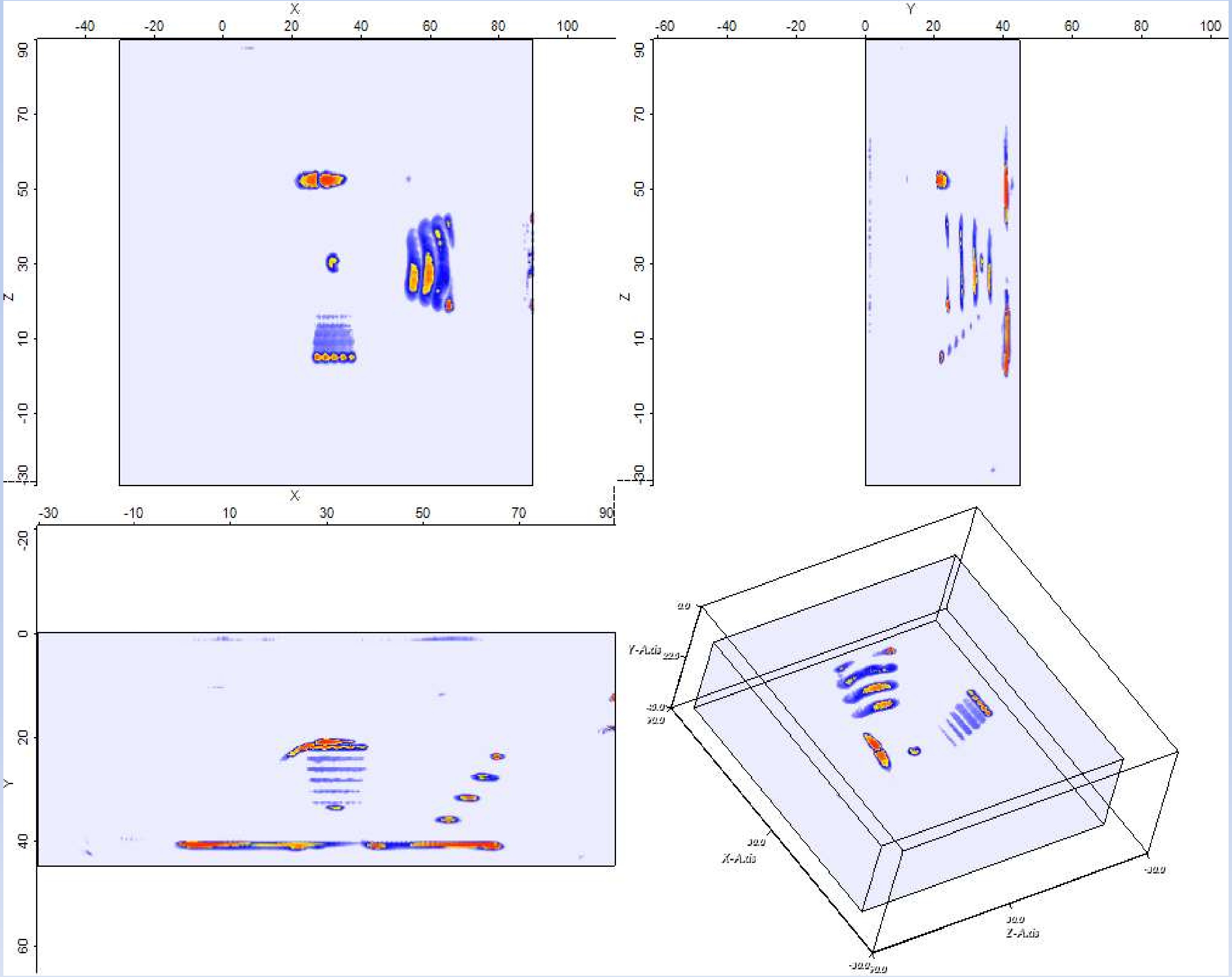
TOLMI LECTURE



TOLMI LECTURE



TOLMI LECTURE



TOLMI LECTURE

SCREEN KNOWLEDGE

FEEL THE MARKET

FIND COMPETENCIES

PUSH TECHNOLOGY

BROAD WAY TO YOUR SUCCESS