

# **Innovative Ultrasonic Testing (UT) of Nuclear Components by Sampling Phased Array with 3D Visualization of inspection results**

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## **Abstract**

Unlike other industrial branches, nuclear industry - when performing UT – is not only asking for a reliable detection, but also for an exact sizing of material defects. Under these objectives ultrasonic imaging plays an important role in practical testing of nuclear components, in the data evaluation process as well as for documentation of the inspection results.

2D and 3D sound-field steering by means of phased array technology offers great opportunities for spatially correct visualization of ultrasonic indications. Thus, by use of modern phased array inspection systems UT of objects with complex geometries can be performed more effective and flexible.

Tomographic reconstruction methods, e.g. Synthetic Aperture Focusing Technique, can significantly improve the spatial resolution of UT indications and allow - as best possible prediction - the quantitative evaluation of the defect size. However, this reconstruction technique has not found a wide spread use in practice in the past due to its effort in numerical computing and processing time especially when 3-D-reconstruction is asked for.

The Fraunhofer Institute for Non-Destructive Testing - IZFP has recently developed a Sampling Phased Array technology (SPA), which combines both, Phased Array and SAFT techniques. One of the advantages of the SPA-approach is the real-time three-dimensional visualization of the inspection volume with on-line quantitative evaluation of the inspection findings.

The current report demonstrates and discusses the potential of spatial imaging for accurate defect sizing, especially when welds in thick walled nuclear components are inspected.

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## **Introduction**

Nuclear components, e.g. primary recirculation system components, must satisfy severe requirements on safety and reliability. For that reason the non-destructive testing of those components has always been on the highest technological level in comparison to other branches. E.g. the phased array technology is widely applied for ultrasonic testing during the construction and operation of NPP since more than 20 years, while in the other industrial sectors it's becoming available just now.

The ultrasonic testing of nuclear components is mandated by construction and manufacturing codes and regulations to verify finished product quality and assure detection of all conceivable discontinuities with a high degree of reliability. The scope of ultrasonic testing (UT) is intended to guarantee that all detectable material discontinuities are well below the critical flaw sizes and will not affect the capability of the components to withstand design and operational loads or degrade the design safety margins. Thus the basic requirement to UT consists in quantitative character of material flaw evaluation. After detection of a registrable indication the defect size must be determined with highest possible precision.

The phased array testing offers significant advantages for UT of nuclear components due to its extended informational content provided by beam steering capability. Thus the combination of mechanical scanning and electronic beam steering increases the flaw detectability, since it's being insonified from various angles of incidence. Evaluation of diffraction signals, e.g. from a crack tip, allows quite accurate sizing of material flaws by means of corresponding projection images.

Nevertheless the phased array technique has its limitations in respect to spatial resolution in the far field of phased array transducer, inspection speed while beam steering over big angle range and finite signal-to-noise ratio of the system in certain applications, e.g. UT of coarse grain materials.

Synthetic Aperture Focus Technique (SAFT) developed in 1980-s has implemented principles of time-of-flight tomography by building of synthetic aperture while ultrasonic data acquisition and using diverse off-line image reconstruction algorithms for spatial overlapping the ultrasonic echo-signals obtained over the scanning area. Despite SAFT technique could offer improved sensitivity and resolution in comparison e.g. to common pulse-echo UT techniques as well as 2D and 3D imaging features, the

technique didn't find wide application in the inspection practices. The main reasons were inconsistency with most of the valid UT codes and standards as well as necessity of rather expert knowledge for conducting the testing and interpretation of inspection results.

Sampling Phased Array technology developed by Fraunhofer-IZFP combines advantages of SAFT and Phased Array. On the one side the technique is capable of fast synthesis of phased array ultrasonic signals for arbitrary angles of incidence with focusing in all the depths within the probe near field. On the other hand the back projection and overlapping in the volume the elementary wavelets obtained by SPA according to SAFT principles offers the best possible image reconstruction quality by SAFT due to small array element size ( $\sim \lambda/2$ ) and relative large effective transducer aperture compared to "typical" SAFT probes.

Thus SPA offers following practical advantages:

- 1) Fast virtual beam sweep for arbitrary angle range
- 2) Improved sensitivity and resolution in the near field of the transducer
- 3) Improved SAFT due to optimal transducer characteristics
- 4) Fast 2D / 3D imaging

Particular advantage of SPA consists in applying the Reverse Phase Matching technique for taking into account anisotropic material properties while image reconstruction. The present paper describes principles of SPA technique incl. reverse phase matching and demonstrates several application examples on nuclear components.

### Sampling Phased Array

Usually in a single transmitter-receiver act of conventional phased array every element of the PA transducer takes part as transmitter and as receiver. By considering the informational content of obtained ultrasonic signals received by single array elements [1] one can notice that the most of information gets lost while phased controlled addition according to phased array principle.

Though today's prospects of fast data acquisition, saving and processing allow measuring the single wavelets – every ultrasonic signal of information matrix. Technically it is implemented by excitation of single array elements and parallel receiving by all available array elements in all inspection positions. Thus the transmitting with  $i^{\text{th}}$  element corresponds to elements  $A_{ij}$  of information matrix with  $j = 1..N$  (Fig. 1), where  $i$  – number of transmitting element,  $j$  – number of receiving element,  $N$  – amount of array elements. After  $N$  inspection tacts the information matrix is complete and contains time signals from all combinations of array elements as transmitters and receivers.

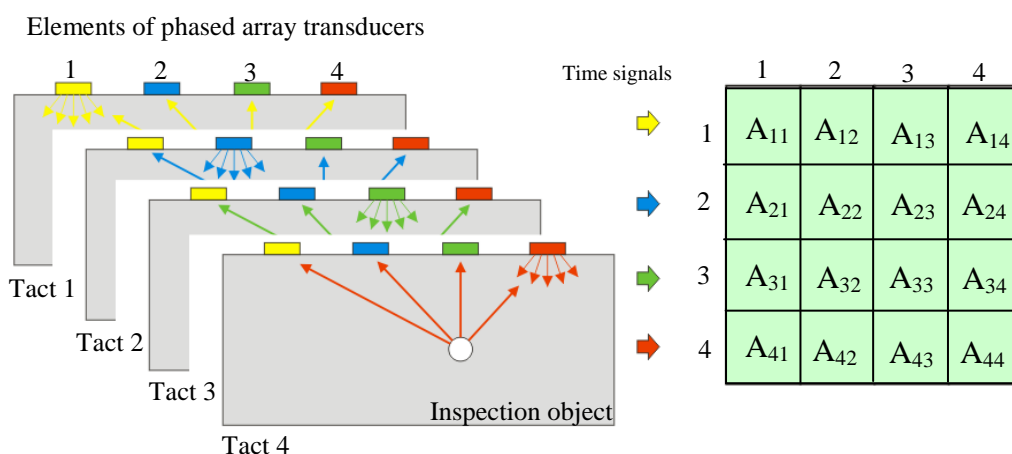


Figure 1: Principle of SPA data acquisition and the information matrix of an array with four elements

The ultrasonic signals acquired and saved in each probe position for every single array element serve as input data for 2D and 3D image reconstruction. The reconstruction occurs according to SAFT algorithm [2]. Since the sound field of array elements is very divergent, every received time signal (A-scan) contains overlapped echo-signals from available reflectors in different volume positions. The reconstructed image in one position of linear array visualizes a cut plane perpendicular to insonification

surface, so called sector-scan. For every point within this plane the propagation times from the transmitting elements and back to the receiving elements are calculated. The amplitude values from all A-scans with matching propagation times are added up in each image point [3].

Thus all angles of incidence and focal depths within the near field of the transducer can be realized even after one single transmitting/receiving act. Since the sound beam steering to each volume point, i.e. for all angles of incidence and focal depth, is performed not physically but virtually by computer, a significant increase in inspection speed can be achieved by implementation of SPA principle. Furthermore the synthetic focusing in the near field of UT transducer by SAFT principle improves sensitivity and resolution (Figure 2).

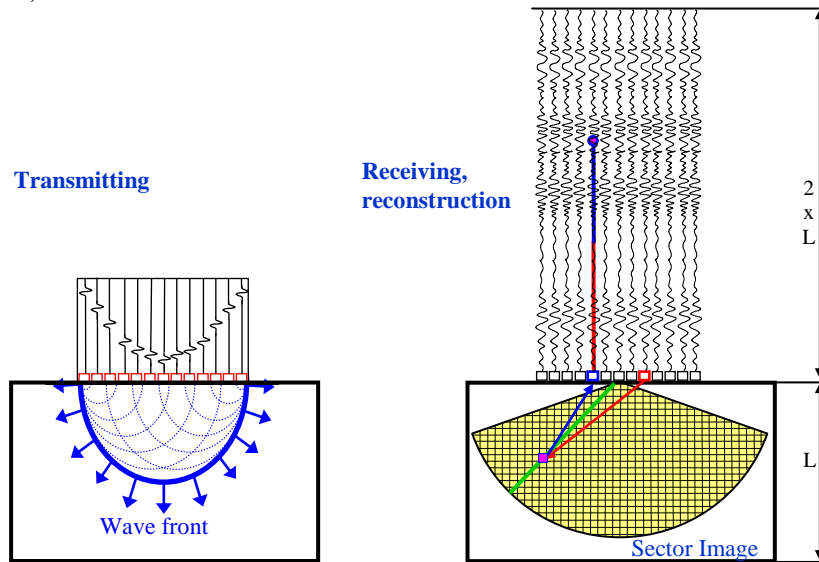


Figure 2: Defocused transmission and sector image reconstruction by SPA

For inspection of solid components the effective aperture of an array transducer can be increased and ultrasonic information from different positions can be overlapped in order to extend the SPA advantages on entire inspection volume.

Thus the focus area while inspection can be increased (Figure 3). Unlike the classical SAFT reconstruction, the SPA method overlaps not single time signals (A-scans), but two-dimensional sector images. By building the two-dimensional aperture, the interslice-tomography can be performed for better spatial resolution in three-dimensional space [4].

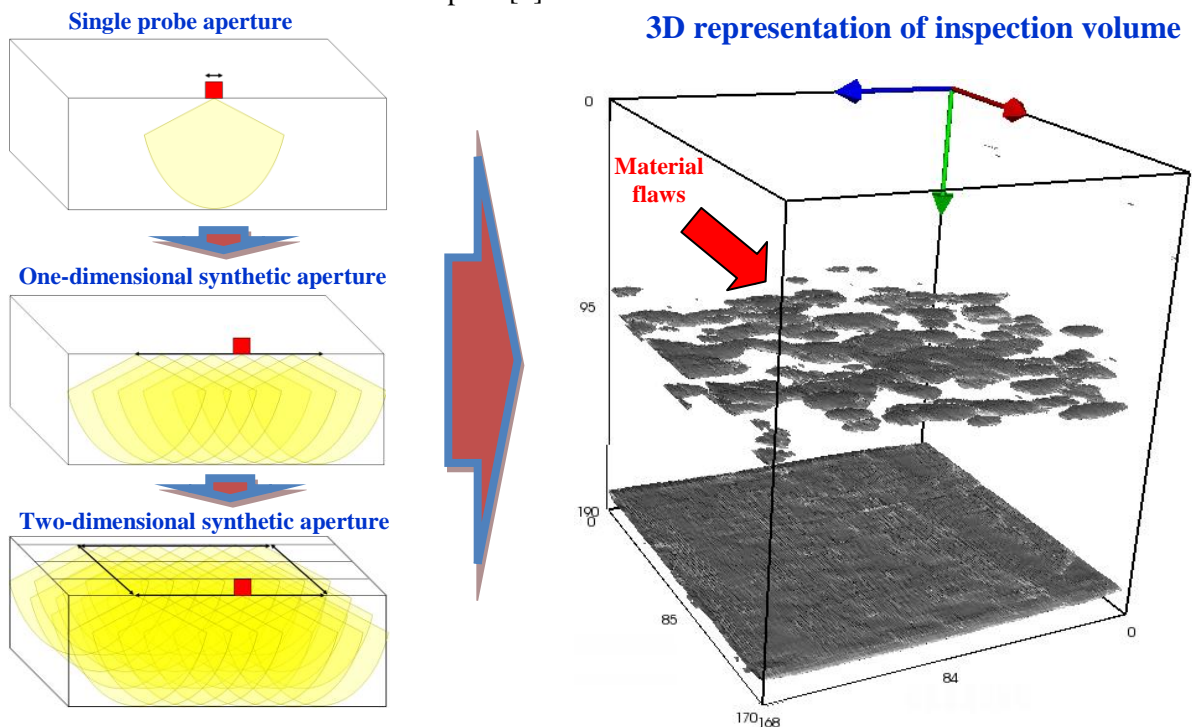


Figure 3: 3D imaging by SPA

Thus the Sampling Phased Array technique with its improved imaging capabilities can be considered in the current state of the art as the advanced technique for quantitative evaluation of material flaws by means of ultrasonic testing (Figure 4).

Single channel flaw detector  
(Image: Karl Deutsch)

Phased Array flaw detector  
(Image: GE inspection Technologies)

Sampling Phased Array  
(Image: ACSYS)

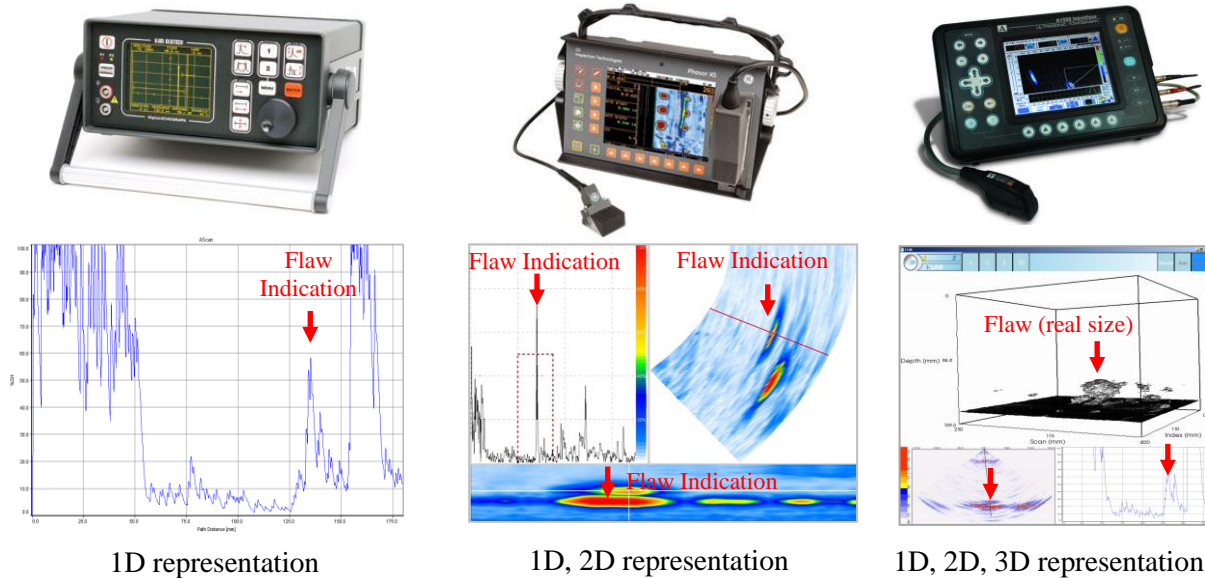


Figure 4: Ultrasonic flaw detectors

### Reverse Phase Matching

Besides increasing inspection speed and improved sensitivity and resolution in the transducer near field SPA technique has one more significant advantage. The measurement principle makes possible acquisition of „pristine“ ultrasonic wavelets generated by small array elements. Simulation of sound propagation in an inhomogeneous and/or anisotropic media allows accurate focusing and flaw evaluation in those types of materials. The technique called „Reverse Phase Matching“ (REPHAMAT) improves flaw detectability in materials with known anisotropy [5].

Acoustic properties of an anisotropic media are characterized by two sound velocity values for every wave type. The phase of an ultrasonic wave propagates in the material with so called phase velocity  $C_{ph}$  at angle of incidence  $\theta$ . The acoustic energy propagates with group velocity  $C_{gr}$  at the group angle  $\phi$ . The values and propagating angles of both sound velocities depend on the stiffness matrix values of the material.

By back projection of time signals acquired in SPA mode according to SAFT principle a sector scan image with synthetic focusing in each volume point can be obtained. The REPHAMAT consists in taking into account the direction dependencies of acoustic properties. In the simplest case of homogeneous anisotropy (e.g. in unidirectional carbon fiber structures with or metallic monocrystals) REPHAMAT means a relative simple adjustment of sound velocity value while computing the propagation time to every volume point.

### Reverse Phase Matching in inhomogeneous materials

Although the most of anisotropic materials in the UT practice are featured by both anisotropic properties and inhomogeneous structure. The typical examples are austenitic and dissimilar welds. Columnar crystals built while welding have growth direction, which depends on joint type, heat abstraction, gravity force etc. Thus an inhomogeneous anisotropic structure with characteristic texture arises.

Unlike in homogeneous materials ultrasonic waves propagate in those structures not linearly, since the wave fronts experience refraction on the columnar crystal boundaries. For computing correct propagation time values from each array element to each volume point (x, y) both sound pathway and sound velocity along this pathway are required (Figure 5).

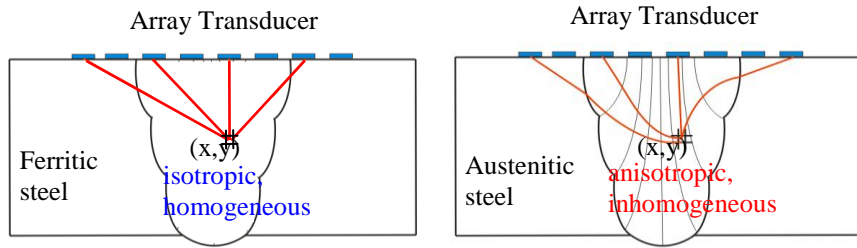


Figure 5: Schematic representation of sound pathways for computation of propagation times to pixel  $(x, y)$  in ferritic and austenitic weld

### Ray-tracing simulation of sound propagation in austenitic welds

In the case of known elastic properties (stiffness matrix) and weld structure the propagation times of ultrasound through the weld joint can be calculated via simulation. There are different modeling approaches such as elastodynamic finite integration technique (EFIT) [6], Generalized Point Source Synthesis (GPSS) [7] et al.

One of the simplest and fastest simulation techniques – ray-tracing method – considers refraction of sound waves on the interfaces and provides sufficient accuracy for sound travel time calculation. In combination with other techniques [8] it can be applied for REPHAMAT.

For this purpose we have developed a ray-tracing algorithm, which allows fast computation of phase and group velocities under consideration of beam refraction at columnar crystal boundaries. Following assumptions underline the fast simulation engine:

- Columnar crystals are considered as a transverse-isotropic medium (TI). The number of independent elastic constants for describing the medium is reduced from 27 to 5. If these five constants are known the phase and group velocities  $C_{ph}$  and  $C_{gr}$  dependent on the phase angle  $\theta$  and the group angle  $\varphi$  can be calculated (Figure 6).

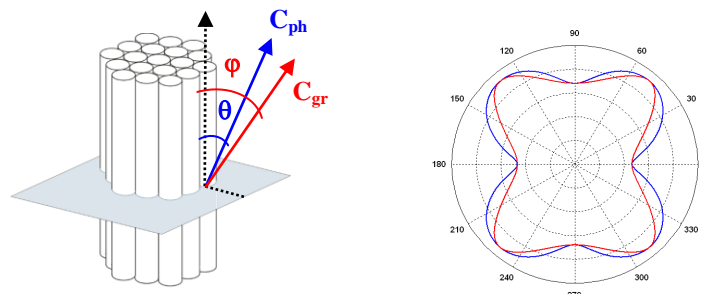


Figure 6: Direction dependency of the phase and group velocities on the phase and group angles in a TI-Medium

- The second assumption postulates that the inhomogeneous structure of the anisotropic area to be inspected can be divided („clustered“) into zones with roughly similar orientation of columnar crystals (Figure 6). Those zones are considered as TI-medium. The crystals differ only in orientation of their acoustic axes. The values of elastic constants remain constant. Computation of phase and group velocities and refraction angles at crystal boundaries is performed according to [9].

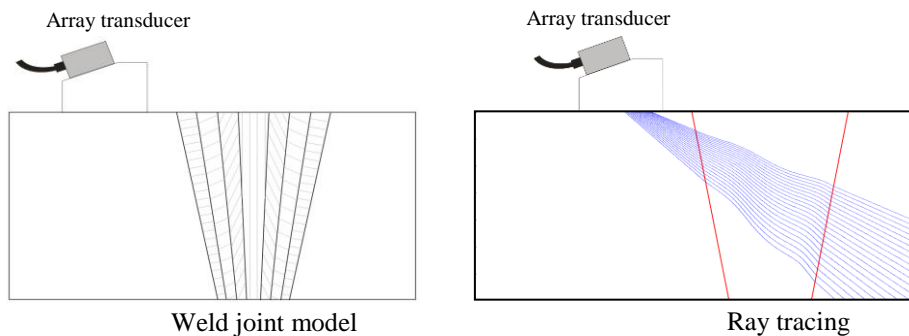


Figure 7: Ray-Tracing simulation of sound propagation in anisotropic weld joint

Thus all propagation time values from all array elements to all volume points can be computed under taken into account anisotropy of material, saved in form of Look-Up tables and used for real-time 2D and 3D image reconstruction by SPA.

**Sampling Phased Array with Reverse Phase Matching on weld joints with unknown anisotropy Gradient Elastic Constants Descent Method (GECDM)**

The correct reconstruction of ultrasonic image of anisotropic component by SPA is only possible if both material structure and elastic properties are known. While material structure can be “deviated” from the manufacturing process or determined by metallography, the elastic constants are as a rule unknown. Fraunhofer-IZFP has developed Gradient Elastic Constants Descent Method (GECDM), which allows determination of elastic constants in austenitic or dissimilar weld joints with assumed material structure. The approach consists in iterative adjustment of material properties. As an optimization criterion we take correct reconstruction of a model reflector in reference specimen with similar acoustic properties. At first the simulation of wave propagation with initial (wrong) elastic constant set is performed. In the next step reconstruction of a sector-image based on calculated propagation times occurs. Since the assumed values are wrong, the reference reflector appears at wrong position and badly resolved. Iteratively elastic constants are varied by GECDM (Figure 8) till the flaw indication appears at correct position (from A to B) with highest amplitude and best localization.

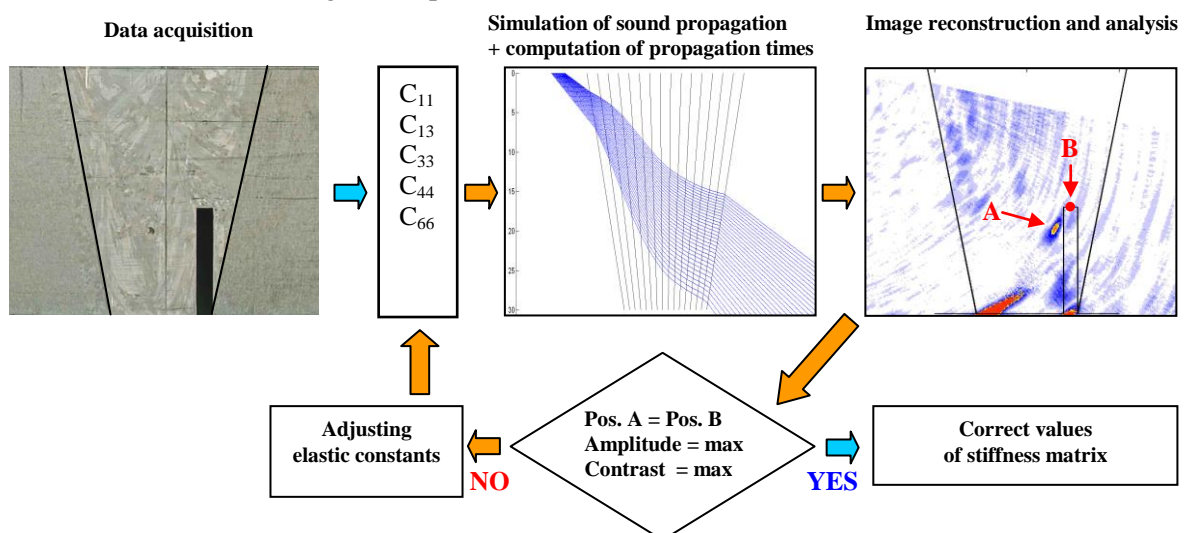


Figure 8: Iterative Gradient Elastic Constants Descent Method

The GECDM has been validated by means of divers weld structures with artificial defects of different types and positions, whereby the obtained values of elastic constants by GECDM were compared with the values obtained by mechanical examination.

Figure 6 shows the sector-images of one of examined austenitic weld with a notch. The Figure 6b represents UT inspection results by conventional phased array with assumption of a constant sound velocity in the weld joint. For better understanding the weld contour and the notch are indicated. Figure 6c shows sector image reconstructed by taking into account elastic constants obtained by GECDM algorithm. Thus the technique allows accurate sizing of the material flaw.

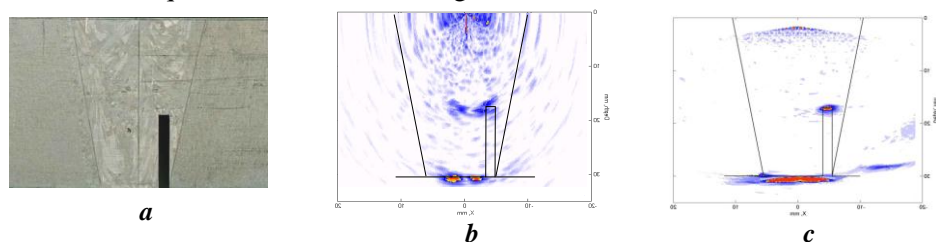


Figure 9: Sector images by Phased Array (b) and Sampling Phased Array (c) with REPHAMAT

### 3D imaging of weld joint

2-dimensional scanning of inspection object (meander scan) and building the synthetic aperture extend the physically realizable focus area of SPA and allows quantitative defect estimation an all three space directions. In an anisotropic medium the local sector image reconstruction must be performed under consideration of simulation results for every probe position (Figure 10).

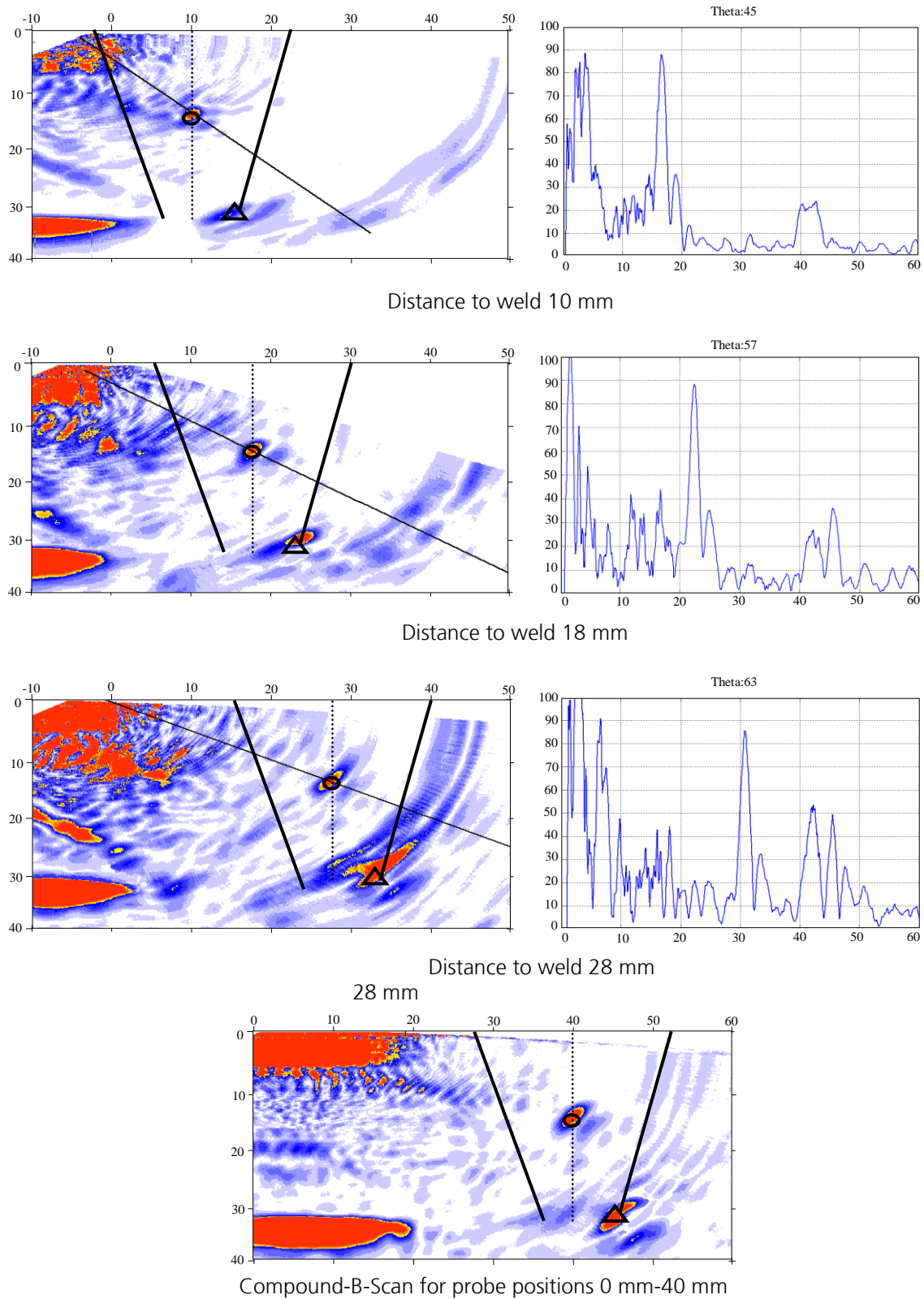


Figure 10: Reconstruction of Compound-scan by overlapping the local sector images

The so called look-up tables containing propagation time values can be calculated and saved before inspection procedure starts. In this case the 3D reconstruction can be performed in real time while scanning the component.

The Ultrasonic inspection and analysis system is based on SPA consists of 2-axes manipulator, the UT electronics and the motion control system as well as testing, visualization and analysis software for real-time 3D imaging. Figure 11b shows inspection results on a weld joint of thick walled component with lack of fusion. The system allows quantitative evaluation of material flaws in industrial facilities.

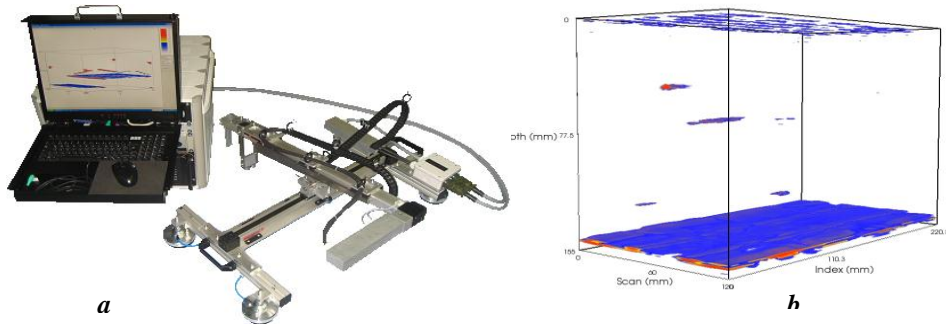


Figure 11: SPA system with 3D visualization of inspection results

## Summary

The Sampling Phased technique with Reverse Phase Matching offers an approach for quantitative ultrasonic testing of objects with unknown elastic properties.

The **Gradient Elastic Constants Descent Method** allows finding of correct elastic constants for following Reverse Phase Matching procedure for reconstruction of sector images of inspection volume.

Through building the synthetic aperture and taking into account the elastic properties, determined by GECDM, a three-dimensional representation of inspected components can be performed with quantitative evaluation of inspection results.

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