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Finnish-Korean Symposium on Inverse Problems

April 2-4, 2009
Sangsan Mathematical Building 101
Seoul National University

Organized by

Seung Yeal Ha (Seoul National University)
Hyeonbae Kang (Inha University)
Lassi Päivärinta (University of Helsinki)
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Finnish-Korean Symposium on Inverse Problems

Sangsan Mathematical Building 101, Seoul National University

April 2, Thursday, 2009

9:20-9:30, Dohan Kim (President, Korean Math. Soc.)
Opening Remark

9:30-10:20, Lassi Päivärinta
Invisibility challenges inverse problems

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Coffee Break
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10:50-11:30, Jeong-Rock Yoon
Arrival time in wave equation model of transient elastography

11:40-12:20, Markku S. Lehtinen
Statistical Inversion in Radar

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Lunch
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2:00-2:40, Nuutti Hyvönen
An inverse backscattering problem in electric impedance tomography

2:50-3:30, Hyundae Lee
Reconstruction of biological tissues elasticity using MRE measurements

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Coffee Break
****

4:00-4:40, Oh In Kwon
Shear modulus imaging in MRE

4:50-5:30, Jenni Heino
Anisotropies and inaccurately known boundary shape in optical tomography

9:30-10:20, Jin Keun Seo
Recent progress on Multi-Frequency Electrical Impedance Tomography

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Coffee Break
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10:50-11:30, Heikki Haario
Adaptive MCMC for statistical inversion

11:40-12:20, Eung Je Woo
High-resolution conductivity imaging of animal and human subjects using MREIT

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Lunch
****

2:00-2:40, Chang-Ock Lee
Conductivity Imaging based on Harmonic Algorithms for Magnetic Resonance Electrical Impedance Tomography (MREIT)

2:50-3:30, Tapio Helin
Data segmentation in Bayesian inverse problems

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Coffee Break
****

4:00-4:40, June-Yub Lee
Numerical Methods for Magnetic Resonance Imaging using Non-Uniform Fast Fourier Transformation

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6:00-8:00, Dinner
all participants are invited
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9:30-10:20, Matti Lassas
Statistical inverse problems and discretization of continuous inverse problems

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Coffee Break
****

10:50-11:30, Jeehyun Lee
Frequency Difference EIT using and Equivalent Homogeneous Conductivity Weighted Difference

11:40-12:20, Jari Kaipio
Nonstationary inversion and reduced order flow modelling

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Lunch
****

2:00-2:40, Mikko Kaasalainen
Reconstructing a body with optimal combination of boundary curves and volumes of generalized projections

2:50-3:30, Mikyoung Lim
Reconstructing Small Perturbations of an Interface from modal measurements

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Coffee Break
****

4:00-4:40, Sungwhan Kim
Numerical algorithm for tracking grounded conductor using capacitance sensor

4:50-5:30, Samuli Siltanen
Regularized D-bar method for the inverse conductivity problem
Closing Workshop

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Closing
****

Adaptive MCMC for statistical inversion

Heikki Haario

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Abstract.

Anisotropies and inaccurately known boundary shape in optical tomography

Jenni Heino

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Abstract. Near infrared optical tomography is a medical imaging modality that can be used to monitor processes that affect blood volume and oxygenation state in living tissue. Most biological tissues are strong scatterers of near infrared light, and hence light propagation in tissue is commonly modelled using the diffusion approximation to the radiative transfer equation. The related inverse problem is to estimate the internal spatial distribution of the optical parameters.

In a practical measurement situation, the boundary shape of the body and the optode positions can be known only up to a certain accuracy. If the reconstruction is done using a fixed model for the geometry, the discrepancies between the model and reality may lead to artefacts in the obtained estimates. We see that geometric mismodelling in an isotropic case may correspond to an anisotropic model. By allowing the domain to be anisotropic and taking the unknown anisotropic structure into account during the estimation using a statistical approach, the quality of the obtained estimates for the optical parameters of interest may be improved.

These results are joint work with Erkki Somersalo and Jari Kaipio.

Data segmentation in Bayesian inverse problems

Tapio Helin

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Abstract. A crucial part of solving a statistical inverse problem with Bayesian approach is constructing prior probability distributions that depict our a priori beliefs. In this talk we introduce novel ideas how to construct prior distributions that prefer sharp edges. By this we mean that estimating posterior distribution produces Mumford-Shah -type segmentations. The key aspects to this research is to show that the limiting infinite-dimensional probability distributions are well-defined and to prove so-called discretization invariance phenomenon, i.e. nothing bad happens when discrezation gets finer.

An inverse backscattering problem in electric impedance tomography

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Abstract. We consider (two dimensional) electric impedance tomography with very sparse data that resembles the so-called backscatter data of inverse scattering. Such data arises if a single (infinitely small) pair of electrodes is used to drive currents and measure voltage differences subsequently at various neighboring locations on the boundary of the object of interest. We prove that this data uniquely determines an insulating (or ideally conducting) inclusion within the object.

Reconstructing a body with optimal combination of boundary curves and volumes of generalized projections

Mikko Kaasalainen

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Abstract. We show that the boundary curves (profiles) of the generalized projections of a body uniquely determine a large class of shapes, and that sparse profile data, combined with brightness data, can be used to reconstruct both the spin state and the shape of a body. We also present an optimal strategy for the relative weighting of the data modes in the inverse problem. We present a solution method well suitable for adaptive optics data in particular, and discuss various choices of regularization functions.

Nonstationary inversion and reduced order flow modelling

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Abstract. Nonstationary inversion is a subfield of Bayesian paradigm for inverse problems. The most common formulation is based on the state space representation, or the evolution-observation representation, for the underlying problem. The stochastic convection-diffusion equation is the most common evolution model in industrial problems. This model contains the flow field as a vector-valued distributed parameter, and this parameter is commonly not known exactly. The simultaneous estimation of the state variable (typically conductivity or concentration) and the flow field is an unidentifiable problem with measurement models that correspond to inverse problems. It is possible, however, to estimate a low-dimensional approximation of the flow field simultaneously. We discuss the numerical and computational aspects of this problem.

Numerical algorithm for tracking grounded conductor using capacitance sensor

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Abstract. Electrical Capacitance Tomography can be applied to real time monitoring of moving grounded conductive object with electric field measurement. We apply voltage on each electrode in order to induce an electric field in the sensing region. In case the grounded conductive objects enter the sensing region, the induced electric field is distorted. The distortion of the electric field depends on the geometric properties, such as shape and location, of the grounded conductive object. The inverse problem is to identify the geometric properties of the grounded conductive object from the electric field measurement, that is, capacitance measurement on each electrode. In this talk, we present a new non-iterative method for tracking conductive water in a pipeline using a single excitation pattern from an Interleaved Electrical Capacitance Tomography system. The problem arises, for example, in the oil industry where brine is often mixed with oil in a pipeline. If the size of the body of brine is very large compared with the size of electrodes attached to the pipeline, the corresponding electric potential in the region of brine is close to zero. This model leads to the inverse problem of identifying the dynamic change of the cross-section of a grounded conducting region in a pipeline. Unfortunately, standard iterative reconstruction algorithms in ECT associated with the sensitivity matrix do not work in this case. Furthermore, due to unavailability of the Neumann data at drive electrodes, the previously published layer potential methods for capturing the inhomogeneity are not applicable to this system. In this work, we derive a formula providing a concrete relation between the capacitance change in each receive electrode and the dynamical change in a grounded conducting region inside the pipeline. The proposed method successfully reconstructs feature information such as rough shape of the cross section of the water region. We demonstrate the performance of our method in numerical simulations.

Bayesian multiresolution method for local X-ray tomography

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AA Bayesian multiresolution model for local tomography is proposed. In this model a wavelet basis is used to represent the x-ray attenuation density of the tissues and the prior information is modeled in terms of Besov norms. The number of unknowns in the local tomography problem is reduced by abandoning fine-scale wavelets outside the region of interest (ROI). This multiresolution approach allows significant reduction in the dimensionality of the image reconstruction problem without loss of reconstruction accuracy inside the ROI. The feasibility of the proposed method is tested with two-dimensional (2D) examples of local tomography in dental radiology.

Shear Modulus Imaging in MRE

Oh In Kwon[†], Chunjae Park[†], Hyunsoo Nam[†],
Eung Je Woo[‡], and Jin Keun Seo[§]

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Abstract. Magnetic resonance elastography (MRE) is an imaging modality to visualize the elastic properties of an object using MRI-measurement of transverse acoustic strain waves in an imaging object induced by a harmonically oscillating mechanical vibration. Various algorithms have been designed to determine the mechanical properties of the object under the assumptions of linear elasticity, isotropic and local homogeneity. One of the challenging problems in MRE is to reduce the noise effects and to maintain contrast in the reconstructed shear modulus images. We introduce a new algorithm designed to reduce the degree of noise amplification in the reconstructed shear modulus images without the assumption of local homogeneity. Investigating the relation between the measured displacement data and the stress wave vector, the proposed algorithm uses an iterative reconstruction formula based on a decomposition of the stress wave vector. Numerical simulation experiments and real experiments with agarose gel phantoms and human liver data demonstrate that the proposed algorithm is more robust to noise compared to standard inversion algorithms and stably determines the shear modulus.

Statistical inverse problems and discretization of continuous inverse problems

Matti Lassas

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Abstract. In this talk we consider the question how inverse problems posed for continuous objects, for instance for continuous functions, can be discretized. This means the approximation of the problem by finite dimensional inverse problems.

We will consider a linear inverse problem $m = Au+\epsilon$. Here function m is the measurement, A is a ill-conditioned linear operator, u is an unknown function, and ϵ is random noise. The inverse problem means determination of u when m is given. The traditional solutions for the problem include the generalized Tikhonov regularization and the estimation of u using Bayesian methods. To solve the problem in practise u and m are discretized, that is, approximated by vectors in a finite dimensional vector space. We show positive results when this approximation can successfully be done and consider problems that can surprisingly appear. As an example, we consider the total variation (TV) regularization and the Bayesian analysis based on total variation prior.

The results presented in the talk [1,2] have been done in collaboration with Eero Saksman (University of Helsinki) and Samuli Siltanen (Tampere University of Technology).

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Related material can be found from

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Conductivity Imaging based on Harmonic Algorithms for Magnetic Resonance Electrical Impedance Tomography (MREIT)

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Abstract. Magnetic Resonance Electrical Impedance Tomography (MREIT) is a late medical imaging modality visualizing static conductivity images of electrically conducting subjects. When we inject current into the object, it produces internal distributions of current density $\mathbf{J}$ and magnetic flux density $\mathbf{B} = (B_x, B_y, B_z)$. By using an MRI scanner, we can measure B_z data where z is the direction of the main magnetic field of the scanner. Conductivity images are reconstructed based on the relation between the injection current and B_z data. Recently, MREIT has rapidly progressed in its theory, algorithm, and experiment technique and now reached to the stage of *in vivo* animal experiments. In this talk, we present the basic concept of MREIT, a recent MREIT algorithm called *local harmonic B_z-algorithm*, and a software named CoReHA. Furthermore, we discuss problems in the area of scientific computation, image processing, and mathematical medeling, which arise in MREIT.

Reconstruction of Biological Tissues Elasticity Using MRE Measurements

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Abstract. Magnetic Resonance Elastography (MRE) is an approach to measuring material properties using external vibration in which the internal displacement measurements are made with magnetic resonance. A variety of simple methods have been designed to recover mechanical properties by inverting the displacement data. Currently, the remaining problems with all of these methods are that in general the homogeneous Helmholtz equation is used and therefore it fails at interfaces between tissues of different properties. The purpose of this work is to propose a new method for reconstructing both the location, the shape and the shear modulus of a small anomaly with Lamé parameters different from the background ones using internal displacement measurements.

This is a joint work with Habib Ammari, Pierre Garapon, and Hyeonbae Kang.

Frequency Difference EIT using Weighted Difference and Equivalent Homogeneous Conductivity

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Abstract. A new method of frequency-difference electrical impedance tomography (fdEIT) has been lately suggested to produce frequency-difference images of a complex conductivity distribution inside an imaging object. The most distinct feature was the use of weighted voltage differences at two different frequencies. In this paper, we explain why the weighted difference is essential in fdEIT. Based on a relationship between a sequence of injection currents at two different frequencies and corresponding weighted differences of complex voltages, we establish an fdEIT image reconstruction algorithm. To deal with more realistic cases, we elaborate the algorithm using the concept of an equivalent homogeneous complex conductivity. To validate the algorithm, we performed numerical simulations and phantom imaging experiments using a 16-channel multi-frequency EIT (mfEIT) system KHU Mark1. Reconstructed real- and imaginary-part images show changes of complex conductivity distributions with respect to frequency. Results indicate that reconstructed frequency-difference images using weighted voltage differences are comparable with time-difference EIT (tdEIT) images in terms of the image quality. This means that numerous common errors are effectively canceled out in the new fdEIT method. We propose using the new fdEIT method for applications where tdEIT cannot be used due to the lack of a time-referenced data set.

Numerical Methods for Magnetic Resonance Imaging using Non-Uniform Fast Fourier Transformation

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Abstract. The MRI hardware is able to acquire the Fourier transform of proton density of a specimen such as human body at selected points in the frequency domain. Under the assumption of a perfectly homogeneous magnetic field, the signal produced during the "readout phase" at time t is given by

$$s(t) = \int \rho(\mathbf{x}) e^{-i2\pi \mathbf{k}(t)\cdot \mathbf{x}}\, d\mathbf{x}. \tag{1}$$

where $\mathbf{x} = (x^1, x^2)$ is a point in the two-dimensional image plane. In other words, $s(t)$ is precisely the value of the Fourier transform $\tilde{\rho}$ at the location $\mathbf{k}(t) = (k^1(t), k^2(t))$. In most clinical systems, the device is designed to acquire data $\tilde{\rho}(k^1_{m_1}, k^2_{m_2})$ on a uniform Cartesian mesh, from which a standard FFT can be used for image reconstruction.

$$\rho(x^1_{n_1}, x^2_{n_2}) = C \sum_{m_1=0}^{M-1} \sum_{m_2=0}^{M-1} e^{2\pi i \frac{m_1 n_1}{M}} e^{2\pi i \frac{m_2 n_2}{M}} \tilde{\rho}(k^1_{m_1}, k^2_{m_2})$$

For a variety of technical reasons, however, nonuniform data sampling techniques are much better suited for fast data acquisition, motion correction, and functional MRI [1, 7]. In order to demonstrate a fast MRI reconstruction method using a non-uniform fast Fourier transformation(NUFFT), we create simulated MRI data by using a type 2 transformation in two dimensions:

$$F(s^1_k, s^2_k) = \sum_{j_1} \sum_{j_2} f(j_1, j_2)\, e^{-i(j_1,j_2)\cdot(s^1_k, s^2_k)}\,,$$

followed by a type 1 transformation to reconstruct the image,

$$\tilde{f}(j_1, j_2) = \sum_{k=0}^{N-1} F_k\, e^{i(j_1,j_2)\cdot(s^1_k, s^2_k)}. \tag{2}$$

Once the decision has been made to use (2) for reconstruction, one still has a number of degrees of freedom to work with. Engineering considerations determine the selection of points $\{(s^1_k, s^2_k)\}$ which will certainly affect the image

quality. One must also select quadrature weights W_k so that, in the transform (2), $F_k \equiv W_k \, F(s_k^1, s_k^2)$. The values $\{W_k\}$ can be considered quadrature weights, and it is shown in [2, 5] that an optimal set of weights is given by the formula

$$\frac{1}{W_k} = \sum_m \text{sinc}^2((s_m^1, s_m^2) - (s_k^1, s_k^2)). \tag{3}$$

Here, $\text{sinc}(k) \equiv \frac{\sin(\pi k)}{\pi k}$ and, in d dimensions, we define $\text{sinc}(\mathbf{k}) = \text{sinc}(k_1) \cdot \text{sinc}(k_2) \cdots \text{sinc}(k_d)$, where $\mathbf{k} = (k_1, k_2, \ldots, k_d)$.

Following the discussion of [8], the minimum-norm least-squares solution to this problem, denoted by $\hat{\rho}(x)$, can be found by applying the pseudo-inverse of the operator $\mathcal{H}$ to the signal,

$$\hat{\rho}(x) = \mathcal{H}^{+}\mathbf{s} = \mathcal{H}^{\dagger}(\mathcal{H}\mathcal{H}^{\dagger})^{+}\mathbf{s}, \tag{4}$$

where $\mathcal{H}^{\dagger}$ is the adjoint of $\mathcal{H}$ and $(\mathcal{H}\mathcal{H}^{\dagger})^{+}$ is the pseudoinverse of $\mathcal{H}\mathcal{H}^{\dagger}$. Note that the process involved in (2) can be written as

$$\rho(\mathbf{r}) \approx \mathcal{H}^{\dagger} W \mathbf{s}$$

where W is the diagonal matrix of quadrature weights. Thus, the quadrature approach based on the inverse Fourier transform can be viewed as a diagonal approximation ($W\mathbf{s}$) of the pseudoinverse construction ($(\mathcal{H}\mathcal{H}^{\dagger})^{+}\mathbf{s}$).

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Statistical Inversion in Radar

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Abstract. Statistical inverse problems development in Finland had it's original motivation in the solution of the statistical inverse problems for the EISCAT radars meant for scientific research of the plasmas of the earth ionosphere. Various ionospheric layers have widely different characteristics as radar targets, with Doppler properties ranging from nearly stationary to severely range-Doppler overspread. As the EISCAT radars were designed to be extremely versatile in waveforms, they were an ideal platform to develop new radar measurement methods, especially after legacy signal processing systems were replaced by our own electronics facilitating inverse methods of radar signal processing in a computer.

This talk is a review of our development of radar techniques, starting from modification of legacy techniques through invention of more general, but anyway ad hoc techniques, to recent theoretical results in rigorous comparison of radar experiments. The new methods can be and have been applied to different kinds of radars, including weather radar, synthetic aperture sonar, planetary radars, meteor radars and space debris detection. It is highly probable that most other radar applications could significantly benefit from some of the methods developed by us.

We will also discuss our plans for further research. Our rigorous results are valid for time-stationary range distributed radar targets for any signal-to-noise ratio (SNR) and we have also been able to rigorously optimize radar coding for severely non-stationary range distributed targets, but only for very low SNR. We believe the recent results in radar experiment comparison will eventually enable us to cover all the possible variants of range spread targets, with any SNR and any kind of Doppler spread.

Reconstructing Small Perturbations of an Interface from modal measurements

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Abstract. We consider the problem of determining the boundary perturbation of inclusions from measurements of eigenvalues and eigenfunctions associated with the transmission problem for the Laplacian. We derive asymptotic formula for the perturbations in the measurements data due to small changes in the interface of the inclusion. Numerical experiments to reconstruct the inclusion based on the asymptotic expansion will be presented.

Invisibility challenges inverse problems

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Abstract. The general common point in the vast area of inverse problems is that one attempts to retrieve information of unaccessible parameters from indirect measurements. Recently striking advances and breakthroughs have been achieved in geometric and analytical inverse problems. On the other hand some new phenomena have revealed the limits of these methods. In this talk, based on joint research with Kari Astala, Matti Lassas we discuss these phenomena in context of the electrical impedance tomography problem (Calderón problem). In particular, we raise up the question about the possibility of invisible cloaking in two dimensional EIT, where methods of geometric complex analysis turn out to be very useful. Finally we discuss the limits of visibility and optimal conditions for unique solvability of the Calderón problem.

Recent progress on Multi-Frequency Electrical Impedance Tomography

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Abstract. Last three decades, static imaging in EIT which aims to provide absolute conductivity has suffered from its fundamental ill-posedness combined with technical difficulties caused by a forward modeling error; any reconstruction problem is highly sensitive to discrepancies of boundary geometry and electrodes positions, while boundary voltage data is insensitive to local perturbation of conductivity. Numerous experiences toward this issue have shown that it seems to be difficult or infeasible to alleviate effects of these modeling error enough for the static EIT imaging to even roughly work out. To deal with this issue in the static EIT, some researchers have considered multi-frequency EIT system with a view of alleviating forward modeling errors. In this talk, we explain mfEIT system with its mathematical theories and phantom experiments and human experiments.

Regularized D-bar method for the inverse conductivity problem

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Abstract. A strategy for regularizing the inversion procedure for the two-dimensional D-bar reconstruction algorithm for the ill-posed inverse conductivity problem is presented. The strategy utilizes truncation of the boundary integral equation and the scattering transform. It is shown that this leads to a bound on the error in the scattering transform and a stable reconstruction of the conductivity; an explicit rate of convergence in appropriate Banach spaces is derived as well. Numerical results are also included, demonstrating the convergence of the reconstructed conductivity to the true conductivity as the noise level tends to zero. The results provide a link between two traditions of inverse problems research: theory of regularization and inversion methods based on complex geometrical optics. Also, the procedure is a novel regularized imaging method for electrical impedance tomography.

High-resolution conductivity imaging of animal and human subjects using MREIT

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Abstract.

Arrival Time in Wave Equation Model of Transient Elastography

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Abstract. The arrival time concept has been successfully utilized to show the uniqueness and to devise an efficient reconstruction algorithm in transient elasography, which aims to make a high resolution stiffness image of cancerous tissue from interior displacement measurements.

In the (anisotropic) wave equation model of transient elastography, the arrival time of a wave front is defined as the first arrival of the wave front at each interior point. An efficient algorithm, the arrival time algorithm, is mainly based on eikonal equation that provides a simple direct relation between the stiffeness parameter and the arrival time. As the eikonal equation contains a derivative of the arrival time, we require at least a Lipschitz regularity of the arrival time in order for the eikonal equation to make a sense.

It turns out that the arrival time is in fact Lipschitz continuous in general, and furthermore the arrival time becomes a viscosity solution of the eikonal equation. In this talk, a clear mathematical proof of these facts are presented based on a unique continuation principle for the wave equation.