Conference on Modern Challenges in Imaging

In the Footsteps of Allan MacLeod Cormack
On the Fortieth Anniversary of his Nobel Prize

August 5-9, 2019, Tufts University, Medford, Massachusetts

Organizing Committee
Eric Todd Quinto  Tufts University
Fulton Gonzalez  Tufts University
Bernadette Hahn  University of Würzburg
Misha Elena Kilmer  Tufts University
Eric Miller  Tufts University
Gaël Rigaud  University of Würzburg

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Gordon Foundation
Jay A. Stein, Chief Technology Officer, Hologic, Inc., Marlboro, Massachusetts

More Information  http://go.tufts.edu/Cormack2019
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I.1 Tribute to Allan McLeod Cormack

From 1957 to 1995, Allan MacLeod Cormack was a professor at Tufts, ending as a University Professor, which is awarded to only the most distinguished colleagues. His pioneering work published in 1963 and 1964 provided the mathematical foundations of computerized tomography (CT) and thereby the first practical method to “see into” an object without physically breaking it open. Along with the engineer Godfrey Newbold Hounsfield, he won the 1979 Nobel Prize in Physiology or Medicine for this work.

Forty years later, the international conference on Modern Challenges in Imaging will honor the achievements of Tufts only Nobel Laureate and keep his thriving legacy up by gathering top international researchers in mathematics, engineering, science, and medicine. A broad range of tomographic modalities, mathematics, and applications will be presented to provide an overview of the different aspects and foster new collaborations.

I.2 Tufts and Historical Talks

Tufts is a leader in American higher education, distinctive for its success as a moderately sized university that excels at research and providing students with a personal experience. Our unique combination of research and liberal arts attracts students, faculty and staff who thrive in our environment of curiosity, creativity and engagement.

Three talks on Wednesday will highlight the impact of Tufts in the scientific world.

I.3 Conference dinner

The conference dinner will be held on Wednesday between 19:00 and 22:00 in Breed Hall, 51 Winthrop St. for signed up participants only.

The cash bar opens at 18:30.

I.4 Administrative information

Accessibility:

The Office of Equal Opportunity has information about accessibility and all rooms should be wheelchair accessible. To contact them go to https://oeo.tufts.edu/ or e-mail oeo@tufts.edu, Phone: or call 617-627-3298.
Resources for family care:

Tufts is a family friendly university, and we will provide specific information in the registration documents. For example, Tufts has nursing rooms and there are many playgrounds nearby. The Tufts campus is a safe area for children and families to stroll, and there are pleasant and historic parks in a short walk. There are nursing rooms in various locations on campus (Θ). Children can stay with parents in dorm rooms or in hotels. We will provide detailed information in all registration packets as well as the number of the Tufts Conference bureau for specific questions.

We will provide a map with all gender and single stall bathrooms at the conference and on the “General→Information” tab on the website.

1.5 Lightning talks and Poster Session

Students will have the opportunity on Tuesday to introduce their work thanks to a lightning talk. The posters will then be displayed during the coffee breaks in the afternoons.

1.6 Minisymposia

MS1. Applied Mathematics in Tomography  
*Todd Quinto*  
[Mon] [Thu]

MS2. Dynamic Tomography  
*Bernadette Hahn, Alexander Katsevich*  
[Tue]

MS3. Generalized Radon Transforms and Applications in Imaging  
*Gaik Ambartsoumian, Venky Krishnan*  
[Tue] [Tue] [Thu]

MS4. Integral Geometry in Tomography  
*Fulton Gonzalez*  
[Mon] [Tue]

MS5. Mathematics and Machine Learning  
*Ge Wang, Todd Quinto*  
[Wed] [Thu]

MS6. Recent Advances in Algorithms and Software for Tomographic Reconstruction  
*Julianne Chung, Jim Nagy*  
[Tue] [Wed]

MS7. Regularization  
*Ronny Ramlau, Otmar Scherzer*  
[Mon] [Tue]

MS8. Security Applications  
*Eric Miller, Clem Karl*  
[Wed] [Thu]

MS9. Spectral Imaging  
*Gaël Rigaud, Fatma Terzioglu*  
[Mon]

MS10. Tomographic Image Reconstruction in Medical Imaging  
*Xiaochuan Pan, Emil Sidky*  
[Mon] [Tue]
<table>
<thead>
<tr>
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<th>Monday</th>
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<th>Wednesday</th>
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<tr>
<td>8:45-9:00</td>
<td>Welcome (B01)</td>
<td>Plenary talk (B01)</td>
<td>Plenary talk (B01)</td>
<td>Coffee Break (B01)</td>
<td>Lunch</td>
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<tr>
<td>9:00-9:40</td>
<td>Frank Natterer</td>
<td>Per Christian Hansen</td>
<td>Charles Epstein</td>
<td>Ge Wang</td>
<td>Todd Quinto</td>
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<tr>
<td>9:40-10:20</td>
<td>Peter Kuchment</td>
<td>Bernadette Hahn</td>
<td>Misha Kilmer</td>
<td>Simon Arridge</td>
<td>Lunch</td>
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<td>10:20-10:50</td>
<td>Coffee Break (CR)</td>
<td>Lightning Talks (B01)</td>
<td>Industrial Panel (R253)</td>
<td>Lunch</td>
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<td>10:50-11:30</td>
<td>John Schotland</td>
<td>John Schotland</td>
<td>Lightning Talks (B01)</td>
<td>Lunch</td>
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<td>11:30-12:10</td>
<td>Gunther Uhlmann</td>
<td>Industrial Panel (R253)</td>
<td>Lightning Talks (B01)</td>
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<td>Plenary talk (R253)</td>
<td>Lightning Talks (B01)</td>
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<td>14:30-15:30</td>
<td>Carl Crawford</td>
<td>Plenary talk (R253)</td>
<td>Lightning Talks (B01)</td>
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<td>15:30-16:00</td>
<td>Coffee Break (SA)</td>
<td>Coffee and Poster (SA)</td>
<td>Lightning Talks (B01)</td>
<td>Lunch</td>
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<td>16:00-18:00</td>
<td>Tufts and Historical Talks (R253)</td>
<td>Coffee and Poster (SA)</td>
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<td>19:00-21:30</td>
<td>Conference dinner (BH)</td>
<td>Conference dinner (BH)</td>
<td>Lightning Talks (B01)</td>
<td>Lunch</td>
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1.8  Tufts Map

1.9  Rooms

B01  Braker 01

BH  Breed Hall, 51 Winthrop St. – Conference dinner

CR  Crane Room – Coffee breaks M-Th mornings

SA  SEC Atrium – Coffee breaks in the afternoons and Friday

R253  Robinson 253

112  Anderson 112-Nelson Auditorium

206  Anderson 206

210  Anderson 210

211  Anderson 211

Anderson, Robinson, and SEC are parts of the same building
### Conference Program

#### II.1 Monday, August 5

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<td>MS7. Regularization (206)</td>
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<td>MS10. Medical Tomography (112)</td>
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<td>Mark Agranovsky</td>
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<td>Arpad Kurusa</td>
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<td>Otmar Scherzer</td>
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<td>15:30-16:00</td>
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<td>MS1. Appl. Math. in Tomography (112)</td>
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<td>MS7. Regularization (206)</td>
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<td>MS9. Spectral Imaging (210)</td>
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<td>Venky Krishnan</td>
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<td>Anuj Abhishek</td>
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<td>Jurgen Frikel</td>
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<td>Yang Yang</td>
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<td>Lothar Reichel</td>
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Frank Natterer  
*University of Muenster, Germany*

**Sonic reflection imaging in the time domain**

In sonic imaging one has to solve the inverse problem for the wave equation. If the sources contain enough low frequencies, this can be done by standard methods. Often these low frequencies are not available. We use Fourier analysis to show that the linearized problem can be solved provided reflectors are used or the aperture is large. We demonstrate by numerical simulations of mammography and falling weight deflectometers what can be achieved in practice.

Peter Kuchment  
*Texas A&M University, College Station, TX*

**Mathematics arising from some recent imaging challenges**

The talk will present a brief survey of three recent (some more recent than others) approaches in medical and homeland security imaging:

1. hybrid (coupled physics) techniques, trying to combine different modalities to get simultaneously good contrast and high resolution;

2. problems with internal information, where one creates and uses a signal that is labeled by internal locations throughout the object to stabilize highly unstable modalities;

3. cone transforms and Compton (type) camera imaging, which avoids collimation when detecting low SNR data.

*Coffee Break*

John Schotland  
*Department of Mathematics, University of Michigan, Ann Arbor, MI*

**Superresolution and inverse problems with internal sources**

I will discuss a method to reconstruct the optical properties of a scattering medium with subwavelength resolution. The method is based on the solution to the inverse scattering problem with internal sources. Applications to photoactivated localization microscopy are described.
Gunther Uhlmann  
*University of Washington*  

**Generalized Radon Transforms and Applications**

We will consider the problem of inverting Radon transforms defined by integrating functions, or tensors, over curves, surfaces or higher dimensional manifolds. These generalized Radon transforms arise in several fields of science and technology including geophysics, medical imaging and astrophysics. We will consider some of these applications in this talk.

*Lunch*

Carl Crawford  
*Cspectwo 6577 N. Crestwood Drive, Glendale, WI 53209*  

**Achieving and Relaxing The Assumptions Posed by Cormack**

Cormack and others in the early days of x-ray CT made explicit and implicit assumptions that the object being interrogated was stationary during data collection and that a sufficient number of perfect line integrals could be acquired to allow the inverse Radon transform to be performed. Artifacts such as rings, streaks and noise are present in images when these assumptions are not met. The artifacts are due in part to sampling, quantum statistics, polychromatic x-ray spectra, patient motion, mechanical instabilities and electrical imperfections. Additional sources of artifacts are caused by the scanning methods required by the clinical need to acquire the integrals more quickly and scan more anatomy. A number of methods developed by the speaker will be shown to meet these assumptions and to increase the clinical efficacy of CT. The methods include single and multi-slice helical scanning, patient motion compensation, high-speed iterative bone correction, dual-energy reconstruction and automated image interpretation. These methods were developed when the speaker was affiliated with Purdue University, University of Washington, Elscint, GE Healthcare, Analogic and Tribogenics. A list of collaborators will be shown in the presentation.
Mark Agranovsky  
*Bar-Ilan University and Holon Institute of Technology*

**On single and paired shifted Funk transform**

The classical result due to Funk is about the reconstruction of even functions on the unit sphere in $\mathbb{R}^n$ from their integrals over the cross-sections by the hyperplanes with the common point at the origin. In recent works of several authors, the Funk type transforms with arbitrary common points inside the unit sphere were studied. The kernels of such transforms were described and the inversion formulas were obtained. A key point was the reduction of the shifted Funk transform to the classical one. We consider the shifted Funk transform with an arbitrary center, either inside or outside of the unit sphere and, using the hyperbolic automorphisms of the unit ball, construct an universal intertwining operator between the shifted and standard Funk transforms. This implies corresponding kernel characterization and inversion formulas. While single shifted Funk transform is non-injective and therefore does not determine the function, a collection of Funk data might have trivial common kernel and hence be sufficient for the unique reconstruction of functions. Recently, the authors proved that the kernels of two Funk transforms with two different centers inside the unit sphere have zero intersection. The reconstruction procedure was proposed for this case. However, this is not always the case for arbitrarily located centers, and we give necessary and sufficient conditions for the mutual location of the centers which provide uniqueness of reconstruction of functions from the corresponding pair of Funk transforms. An interesting feature is a relation of the injectivity problem for the paired Funk transform with the behavior of a certain dynamics of Moebius transformations of the unit circle and sphere.

This is joint work with Boris Rubin, Louisiana State University.
Identifying X-ray transforms: the boundary-distance rigidity of projective metrics

Identifying and characterizing unknown generalized Radon transforms by some knowledge about there behavior is a classical subject (see for example only some works of E. T. Quinto, A. Hertle, D. C. Solmon, F. Natterer, J. Boman, etc.). Identifying the Radon transform that integrates appropriate functions on the geodesics of a compact, simple Riemannian manifold with boundary, is a subject researched for a long time (see for example only some works of G. Herglotz, Ju. E. Anikonov, V. G. Romanov, R. G. Mukhometov). It revived nowadays in some important new results, called the boundary-distance rigidity of Riemannian manifolds, due to the works of R. Michel, C. Croke, G. Uhlmann, A. Vasy, P. Stefanov, etc..

Contemplating these results the feeling comes that the properties of the system of the domains over which the integration is performed probably play more important role than what differentiability allows to see. This feeling motivated the investigation of the boundary-distance rigidity of projective metrics.

A **projective metric** is a continuous metric defined on a convex, not necessarily proper subset $M$ of the Euclidean space such that the geodesics are the chords of $M$. The class of these metrics is really huge (this was observed by H. Busemann), but, by Beltrami’s theorem, the only Riemannian projective metrics are those that have constant curvature.

**Theorem.** (Á. K. & T. Ódor, 2018) Let $M$ be a compact convex non-empty domain in the plane. If a continuous bounded metric $\delta: \partial M \times \partial M \to \mathbb{R}_+$ satisfies the quadrangle inequality

$$\delta(P, R) + \delta(Q, S) - \delta(P, S) - \delta(Q, R) \geq 0$$

for any convex non-degenerate quadrangle $\square(PQRS)$, then $\delta$ uniquely extends to a projective metric $d: M \times M \to \mathbb{R}_+$.

The proof basically follows Busemann’s integral geometric idea to generate all projective metrics from measures on the Grassmannian by the Crofton formula. Then the uniqueness comes from the uniqueness part of Carathéodory’s extension theorem. It turns out that the boundary-distance rigidity of the Riemannian manifolds follows from the boundary-distance rigidity of the projective metrics if the set of geodesics satisfies the Desargues property.
Peter Maass  
*Center for Industrial Mathematics, University of Bremen, Germany*

**Regularization properties of neural networks for inverse problems**

Machine learning and in particular deep learning using multilayer neural networks are presently used for solving some of the most complex problems in scientific computing. The success of these methods is surprising - as much as the almost complete lack of theoretical foundation. In the field of inverse problems, partial results for explaining certain features of neural networks are just emerging.

This talk adds along this line by considering trivial neural networks for inverse problems in its first part. We will show that attacking inverse problems by neural networks requires specific architectures, which however allow to obtain a link to classical regularization theory. In the second part of the talk we analyse deep prior networks and relate them to variational regularization methods for inverse problems. Finally we cannot resist to present - without proof - some numerical experiments for magnetic particle imaging.

Otmar Scherzer  
*Computational Science Center, University of Vienna, and Johann Radon Institute for Computational and Applied Sciences, Linz, Austria*

**Multi-Modal OCT and PAT**

In this talk we show who the combined use of optical coherence tomography and photoacoustics can bring more insight on physical parameters. We present a three-step approach consisting of tomographic reconstructions, displacement estimation, and quantitative estimation of elasticity parameters.

This is joint work with Wolfgang Drexler, Simon Hubmer, Lisa Kainz, Julian Schmid, Ekaterina Sherina.

Coffee Break

James Nagy  
*Emory University*

**Regularization via Krylov Subspace Methods**

In this talk we describe Krylov subspace based regularization approaches that combine matrix factorization methods and variable preconditioning with iterative solvers. The methods are very efficient for large scale inverse problems. Some approaches can also incorporate methods to automatically estimate regularization parameters and enforce sparsity and nonnegative constraints. We will illustrate the effectiveness of the methods using examples from tomography. This is joint work with Silvia Gazzola (University of Bath) and Per Christian Hansen (Technical University of Denmark).
Denise Schmutz  
*Computational Science Center, University of Vienna, Austria*

**Three-dimensional Motion Reconstruction from Parallel-Beam Projection Data**

We consider optical tomography of an object that is being moved with optical and acoustical tweezers. In this setup the sample is undergoing an unknown non-uniform rigid motion during the illumination. We propose a simplified time-dependent model based on the parallel-beam transform and will characterize conditions under which it is possible to reconstruct the object’s motion from a time series of projections. This constitutes a first step towards the reconstruction of the object itself.

Lothar Reichel  
*Department of Mathematical Sciences, Kent State University*

**Linearized Krylov subspace Bregman iteration with nonnegativity constraint**

Bregman-type iterative methods have attracted considerable attention in recent years due to their ease of implementation and the high quality of the computed solutions they deliver. However, these iterative methods may require a large number of iterations and this reduces their attractiveness. This talk describes a linearized Bregman algorithm defined by projecting the problem to be solved into an appropriately chosen low-dimensional Krylov subspace. The projection reduces both the number of iterations and the computational effort required for each iteration. A variant of this solution method, in which nonnegativity of each computed iterate is imposed, also is described. The talk presents joint work with A. Buccini and M. Pasha.
Towards the numerical quantification of source conditions

We consider linear ill-posed problems with possibly noisy data $y$ and exact solution $x^\dagger$. A classical assumption in the theory of inverse problems are source conditions of the type $x^\dagger \in \text{range}(\text{range}(A^*A)^\mu)$ for some $\mu > 0$. This allows to bound the worst-case error between approximate solutions and $x^\dagger$ as the noise goes to zero, and it yields rules for an appropriate choice of the regularization parameter. In the real-world situation where a fixed operator $A$ and a datum $y$ are given, a good approximation to $\mu$ is only available in specific cases, while in general $\mu$ is unknown, rendering in particular a-priori parameter choice rules unfeasible. Moreover, practical computations are performed in a discretized setting, such that the role of the source condition is less clear. In this talk, we make a first attempt of breaking the disconnection between theory and practice. Based on the Kurdyka–Łojasiewicz inequality and the Landweber method, we develop an algorithm that allows to approximate $\mu$ as long as the noise in the data is not too large. We show several numerical examples including the tomography data sets of the Finnish Inverse Problems Society. We also discuss implications of our result.
Verification studies in inverse problems

In this talk, we focus on discussing verification (i.e., inverse-crime) studies that are a hallmark of solving inverse problems. In tomographic imaging, a data model is devised that relates the model data and image of interest. The inverse problem refers to the reconstruction of the image from knowledge of the model data. We feel that it is necessary to review and define what is meant by solving an inverse problem in the context of tomographic image reconstruction in the current research climate where so-called "data-driven algorithms" claim to address inverse problems in imaging. We consider two types of linear data models: the first type is referred to as the continuous-to-continuous (CC)-data model in which the spaces upon which the model data and image are defined are continuous. Examples of CC-data models include the Radon transform (RT), the Fourier transform (FT), and the X-ray transform (XRT); whereas the second type is referred to as the discrete-to-discrete (DD)-data model in which the model data and image are discretized, and the linear DD-data model takes the form of matrix-vector multiplication. Examples of linear DD-data include discrete RT, discrete FT, and discrete XRT. Algorithms for solving or inverting either CC-data or DD-data models are developed based upon the respective data models. A necessary step of algorithm development in an inverse problem comprises analytic or/and numerical verifications for making sure that the algorithm does solve or invert the data model. Verifications take analytic and numerical forms. Consider, for example, the RT and its inverse – the filtered back-projection (FBP) algorithm. Analytic verification involves demonstrating that FBP inverts the complete Radon transform. In many situations of relevance, inverting a linear DD-data model is formulated as a convex optimization program from which an iterative algorithm can be derived. Analytic verification involves showing that the iterative algorithm recovers the discrete image from the discrete data in the limit of infinite iteration number; or devising some other means to demonstrate analytically that the optimization solution is the true image that generates the data. Numerical verification is another important aspect of inverse-problem studies especially involving a linear DD-data model. It demonstrates with empirical, numerical studies that the error between true discrete image and reconstructed discrete image decreases with increasing iteration number. In the presentation, we will use examples to illustrate analytic and numerical verifications of existing algorithms for inverse problems of interest and to reveal the current lack of verification evidence of data-driven algorithms. In summary, an algorithm must be verified to solve an inverse problem in analytic or/and numerical verification studies if it is claimed to solve inverse problems in tomographic imaging. This is joint work with Emil Y. Sidky (University of Chicago).
Venky Krishnan  
*TIFR Centre for Applicable Mathematics, Bangalore, India*

**Range characterization of momentum ray transforms in Euclidean space**

Momentum ray transforms are certain weighted transforms that integrates symmetric tensor fields over lines in Euclidean space with weights that are powers of the integration parameter. This is a generalization of the standard longitudinal ray transforms which has attracted significant attention due to its several tomographic applications. We first present an inversion algorithm recovering the full symmetric tensor field of rank $m$ from its first $m + 1$ momentum ray transforms. We then characterize the range of such transforms.

Anuj Abhishek  
*Drexel University, Philadelphia*

**Support theorem for transverse ray transform of tensor fields**

Let $(M, g)$ be a simple, real analytic, Riemannian manifold with boundary and of dimension $n \geq 3$. In this work, we prove support theorem for the transverse ray transform of tensor fields of rank $m$ defined over such manifolds. First of all we prove that, given a symmetric tensor field $f$ of rank $m$, if the transverse ray transform of $f$ vanishes over an appropriate open set of maximal geodesics of $M$, then the support of $f$ vanishes on the points of $M$ that lie on the union of the aforementioned open set of geodesics. We also show that the method of the proof can be adapted to prove such a support theorem for arbitrary tensor fields.
Jürgen Frikel  
*OTH Regensburg, Germany*

**Characterizations of singular artifacts in limited data CT**

In this talk, we present characterizations visible and added singularities for the general limited data problem for the 2D Radon transform. In particular, we analyze FBP type reconstructions from data where an arbitrarily shaped region in the sinogram is missing. Our results cover classical and well studied problems such as limited angle tomography, interior and exterior tomography, but they also extend to novel data acquisition methods. In particular we show that, depending on the geometry of the boundary of the missing sinogram region, two types of artifacts can arise: object-dependent and object-independent artifacts. Object-dependent artifacts are generated by singularities of the object being scanned, and these artifacts can extend along lines. They generalize the streak artifacts observed in limited-angle tomography. Object-independent artifacts, on the other hand, are essentially independent of the object and take one of two forms: streaks on lines if the boundary of the data set is not smooth at a point and curved artifacts if the boundary is smooth locally. This talk is based on joint work with Leise Borg (University of Copenhagen, Denmark), Jakob Sauer Jørgensen (University of Manchester, UK), Eric Todd Quinto (Tufts University, USA).

Yang Yang  
*Michigan State University*

**Fluorescence Ultrasound Modulated Optical Tomography in the Diffusive Regime**

Fluorescence optical tomography (FOT) is an imaging technology that localizes fluorescent targets in tissues. FOT is unstable and of poor resolution in strongly scattering media where the propagation of multiply-scattered light is highly diffusive. We study a hybrid imaging modality called fluorescent ultrasound-modulated optical tomography (fUMOT). It combines FOT with acoustic modulation to produce high-resolution images of optical properties. The principle of fUMOT is to perform multiple measurements of photon currents at the boundary as the optical properties undergo a series of perturbations by acoustic radiation, then the internal information of the optical field can be extracted from the measurement. We set up a mathematical model for fUMOT, prove well-posedness for certain choices of parameters, and present reconstruction algorithms and numerical experiments for the well-posed cases. This is joint work with Wei Li and Yimin Zhong.
Markus Haltmeier  
*Department of Mathematics, University of Innsbruck*

**Deep Learning in Image Reconstruction**

Recently, deep learning and neural network based algorithms appeared as new paradigm for solving inverse problems. We propose and analyze NETT, naming Tikhonov regularization using a neural network as regulariser. We present a convergence analysis, derive convergence rates, and propose a possible training strategy. Additionally, we discuss regularizing two-step networks. Numerical results for tomographic inverse problems are presented demonstrating good performance of the proposed deep-learning based method even for unknowns very different from the training data.

Voichiţa Maxim  
*CREATIS, University of Lyon, France*

**Challenges in Compton camera imaging for medical applications**

Compton cameras are a promising alternative to collimated cameras in single particle emission computed tomography (SPECT). They meet the challenge of imaging sources having poly-chromatic spectrum and low photon yields. Currently used SPECT cameras rely on mechanical collimation, imposing a trade-off between efficiency and resolution. As the photon energy increases, the radiation can penetrate the collimator and thus degrade the resolution. A solution is then to increase the thickness of the septa which further reduces the detection efficiency. Based on a coincidence detection system and on the kinematics of Compton scattering, Compton cameras restrict to a half-cone the set of possible origins of a detected photon. They allow an increase in efficiency of one or two orders of magnitude, at the cost of more complex image reconstruction techniques. Specific tomographic algorithms capable to invert conical Radon transforms are then required to produce the image of the source.

In this talk we focus on iterative reconstruction methods. We will first highlight the importance of choosing a data model well adapted to the measurement uncertainties. Then we will discuss some regularization strategies in statistical image reconstruction. In particular we will present a fast and convergent algorithm for the non-differentiable total variation prior. We will illustrate its performances on low-statistics data issued from a complex-shaped mono-energetic source. In addition, this example will allow us to compare the performances of collimated and Compton cameras. We will end with an example from proton-therapy, where treatment monitoring could be realized by imaging the secondary prompt-gamma radiation. In this application, extremely low photon counts are expected in a wide energy range.
Xiaochuan Pan  
*University of Chicago*

**Multi-Spectral Computed Tomography with Non-Standard Configurations**

There has been renewed interest in research on and application of multi-spectral (or photon-counting) CT on academic and industrial sides, as multi-spectral CT is expected to be of a potentially high degree of task-specific utility for medical, security, and other imaging applications. In current development of multi-spectral CT, significant hardware modifications or additions are required relative to conventional CT, and accurate image reconstruction remains challenging because its appropriate data model is highly non-linear due to the polychromatic nature of X-ray spectra used. In the presentation, recent advances in the development of methods will be discussed, with a focus on a non-convex optimization-based image reconstruction (OBIR) method, for accurate image reconstruction in multi-spectral CT, and more importantly, for enabling multi-spectral CT capability on conventional CT with virtually no hardware modification or addition. Following the discussion of the method design, the effectiveness of the OBIR method will be demonstrated for image reconstruction from data collected with current multi-spectral CT, and the potential of the OBIR method for enabling new multi-spectral CT will be revealed with innovative scanning configurations designed for accommodating scans of workflow significance, lowering hardware cost, and/or reducing imaging dose/time. This is joint work with Emil Y. Sidky (University of Chicago).

Alexander Meaney  
*University of Helsinki, University of Helsinki, Finland*

**Structural Priors in Multi-Energy CT Reconstruction**

A significant limitation of conventional computed tomography is that no bijective relation exists between the composition of the material and the attenuation coefficient value in the reconstruction. More information on the material composition of the object can be obtained with multi-energy imaging, which involves obtaining projections using different X-ray energies, and then computing reconstructions for each energy. Simultaneous dose reduction and improved image quality in the multi-energy reconstructions can be obtained through exploitation of data redundancies: although the attenuation values will differ at each energy, it is reasonable to assume that the underlying structural properties of the imaged object, i.e., its boundaries and interfaces, will remain in the same locations at each energy. We investigate various structural priors in joint reconstruction of multi-energy CT images. In this approach, all of the data is combined into one inverse problem that is solved simultaneously for all of the X-ray energies, and the priors promote structural similarities the reconstructions. The multi-energy reconstructions can then be used to compute a material decomposition into basis materials.
### Tuesday, August 6

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Efficient parametric model reduction for tomographic reconstruction

Nonlinear inversion for forward models based on partial differential equations with many measurements requires a large number of expensive solves in each optimization step. This can make the solution of such problems extremely expensive. Parametric reduced order models reduce these large systems to small ones, drastically reducing the solution cost. However, building accurate reduced order models itself is quite expensive, and we discuss randomized methods to further reduce the costs of nonlinear inversion. This overall approach leads to drastic reductions of computational cost.

Dynamic Tomography: Modelling, Analysis and Algorithms

Motion compensation represents an important time-dependent problem in tomography. Most modalities record the data sequentially, i.e. temporal changes of the object lead to inconsistent measurements. Consequently, suitable models and algorithms have to be developed in order to provide artefact free images.

In this talk, we discuss two reconstruction approaches incorporating different types of motion information. Using an explicit motion model, we derive suitable algorithms of filtered backprojection type by exploiting results on microlocal analysis. We further present an iterative strategy which treats the dynamic behavior as uncertainty in the forward model. Both strategies are validated for data sets from computerized tomography with different dynamic behavior.
Misha Kilmer  
*Tufts University, Department of Mathematics*

**Image Reconstruction from Limited Data**

In this talk, we consider image reconstruction from limited data. Limited angle CT is a prime example of such a problem: there are fewer values in the sinogram data array than the number of pixels in the image you wish to reconstruct. We present two methods for enhancing the quality of the reconstructions which are computationally efficient and demonstrate the algorithms on examples. In the first approach, we propose to learn enhanced edge information via an iterative process. This allows us to specify a new regularized problem per iteration for which we can automatically find an appropriate regularization parameter as well as specify the corresponding solution in a computationally efficient manner. In the second method, we discuss the use of non-negative tensor patch dictionaries for restoration.

This work is joint with several investigators: Eric Miller, James Nagy, Oguz Semerci, Per Christian Hansen, Sara Soltani and Elizabeth Newman.

Lightning Talks

*Lunch*

Jennifer Mueller  
*Colorado State University*

**Electrical impedance tomography: Modern advances and challenges**

Electrical impedance tomography (EIT) has posed a challenge for mathematicians, engineers, and applied scientists for over four decades now as a nonlinear and severely ill-posed inverse problem. This challenge has required new mathematical techniques and reconstruction algorithms, but at the same time has arguably been responsible for its slow progress to widespread clinical acceptance for medical applications. In this talk, a brief introduction to the EIT problem is provided, several state-of-the-art reconstruction algorithms are surveyed, and the role of modern techniques such as deep learning and 3-D algorithms are discussed. Results for several clinical applications are shown, and we speculate on what the future holds for EIT imaging.
François Monard
UC Santa Cruz

The X-ray transform on constant curvature disks
We will review recent results on range characterizations and the singular value decomposition of the geodesic X-ray transform over functions on constant curvature disks.
Such results give the first non-Euclidean generalization of some of the Euclidean articles "Efficient Tensor Tomography in Fan-Beam Coordinates" [Inv. Probl. Imaging, 2016, 2018], whose main aim is to produce explicit statements for X-ray transforms and the tensor tomography problem.
Joint work with Rohit Kumar Mishra.

Manmohan Vashisth
Beijing Computational Science Research Center, Beijing

A uniqueness result for a light ray transform of two tensor fields
We study light ray transform of symmetric 2-tensor fields defined on a time-space domain in $\mathbb{R}^{1+n}$ with $n \geq 3$. Let $\lambda$ be a scalar function, $g$ denote the Minkowski metric and $dv$ stand for the symmetrized covariant derivative of a vector field $v$. Then one has that the symmetric 2-tensor field $\lambda g + dv$ lies in the kernel of the light ray transform. In this talk, we show that kernel of the light ray transform is of the form mentioned above. Specifically, we show unique determination of symmetric 2-tensor fields (modulo the kernel mentioned above) from the knowledge of its light ray transform given in some open neighbourhood of a fixed light-like geodesic.
Ronny Ramlau
Institute for Industrial Mathematics, Kepler University Linz, and Johann Radon Institute for Computational and Applied Mathematics, Linz, Austria

Singular value decomposition for atmospheric tomography

In atmospheric tomography, light originating from guide stars travels through the atmosphere. Its recorded wavefronts are used to reconstruct the turbulence in the atmosphere. The information on the turbulence is then used to obtain sharp images from astronomical telescopes. Taking into account the layered structure of the turbulent atmosphere, the properties of the guide stars as well as the geometric structure of the telescope, we present singular value decompositions of the underlying tomography operators for different telescope settings. This is joint work with Simon Hubmer and Andreas Neubauer.

Tatiana A. Bubba
Department of Mathematics and Statistics, University of Helsinki, Finland

Learning the Invisible: Limited Angle Tomography, Shearlets, and Deep Learning

We present a hybrid reconstruction framework that fuses model-based sparse regularization with data-driven deep learning in the contest of limited angle computed tomography, a severely ill-posed inverse problem in which entire boundary sections are not captured in the measurements. Our method is reliable in the sense that we only learn the part that can provably not be handled by model-based methods, while applying the theoretically controllable sparse regularization technique to the remaining parts. Such a decomposition into visible and invisible segments is achieved by means of the shearlet transform that allows to resolve wavefront sets in the phase space. Furthermore, this split enables us to assign the clear task of inferring unknown shearlet coefficients to the neural network and thereby offering an interpretation of its performance in the context of limited angle computed tomography. Our numerical experiments show that our algorithm significantly surpasses both pure model- and more data-based reconstruction methods. This is joint work with G. Kutyniok, M. Lassas, M. März, W. Samek, S. Siltanen and V. Srinivasan.
Mark A. Anastasio  
*University of Illinois at Urbana-Champaign*

**Deep learning-enabled task-based image quality assessment in medical imaging**

It is widely accepted that optimization of medical imaging systems should be guided by task-based measures of image quality (IQ). Task-based measures of IQ quantify the ability of an observer to perform a specified task such as detection or estimation of a signal (e.g., a tumor). For binary signal detection tasks and joint signal detection-localization tasks, the Bayesian Ideal Observer (IO) sets an upper limit of observer performance and has been advocated for use in optimizing medical imaging systems and data-acquisition designs. In this work, we propose and investigate supervised learning-based methods to approximate IO test statistics. Namely, convolutional neural networks (CNNs) are employed to approximate the IO test statistic for both a binary signal detection task and a joint signal detection-localization task. Additionally, we apply autoencoders (AEs) to design efficient channels by learning a reduced-dimensionality embedding of a signal-of-interest that can increase the robustness of IO computations when few data samples are available. We also investigate an augmented generative adversarial network (GAN) architecture named AmbientGAN for learning the statistical distributions of objects from raw imaging measurements, which can further enable the optimization of imaging system designs for specific diagnostic tasks.

Georges El Fakhri  
*Massachusetts General Hospital and Harvard Medical School*

**PET/MR: from Quantitative Reconstruction to Molecular Imaging**

In this talk, recent developments in Positron Emission Tomography (PET) and Magnetic Resonance Imaging (MRI) are explored and the challenges of simultaneous imaging as well as the opportunities afforded by the two modalities are discussed. The unique sensitivity of PET (picomolar) and its quantitative capabilities can be associated with the superb spatial and temporal resolution of MR as well as its excellent soft tissue contrast to provide an ideal imaging modality for many cancers as well as cardiac and brain explorations. Improvements in image quality and diagnostic accuracy are illustrated in specific patient studies and synergies between PET and MR spectroscopy are discussed in the context of guiding radiotherapy. Beyond oncology, applications in cardiac (viability, perfusion) and brain imaging (neurodegenerative disease, traumatic brain injury) are presented including mapping of mitochondrial membrane potential and simultaneous PET/fMRI for mapping dopaminergic and serotoninergic neurotransmission.
Guang-Hong Chen  
*Dept. of Medical Physics & Dept. of Radiology, University of Wisconsin-Madison*

**An Enhanced SMART-RECON Algorithm for Time-Resolved Cone-beam CT Imaging**

Temporal resolution in time-resolved cone-beam CT (TR-CBCT) imaging is often limited by the time needed to acquire a complete data set for image reconstruction. With the recent developments of performing nearly limited-view artifact free reconstruction from data in a limited-view angle range and a prior image, temporal resolution of TR-CBCT imaging can be improved. One such an example is the use of Simultaneous Multiple Artifacts Reduction in Tomographic RECONstruction (SMART-RECON) technique. However, with SMART-RECON, one can only improve temporal resolution up to 1 frame per second (fps) which is an improvement of 4.5 times over that of the short-scan FBP reconstruction. In this work, a new technique referred to as enhanced SMART-RECON (eSMART-RECON) was introduced to enhance the temporal performance of SMARTRECON in a multi-sweep CBCT data acquisition protocol. Both numerical simulation studies with ground truth and in vivo human subject studies using C-arm CBCT acquisition systems were conducted to demonstrate the following key results: for a multi-sweep CBCT acquisition protocol, eSMART-RECON enables 4-7.5 fps temporal resolution for TR-CBCT which is 4-7.5 times better than that offered by the original SMART-RECON, and 18-34 times better than that offered by the conventional FBP reconstruction. This is joint work with Yinsheng Li, John W. Garrett, Ke Li, Charles Strother, and Guang-Hong Chen.

Salla-Maaria Latva-Äijö  
*University of Helsinki, Finland*

**Modified Space Time Level Set Method in Dynamic Tomography**

Dynamic tomography is of great interest in modern X-ray tomography, mainly because imaging of dynamic systems is a challenge for medical CT-imaging. Level set (LS) method algorithms are in wide use in the inversion and segmentation of data. The modified level set (MLS) method is a reconstruction technic, which is able to pick the greatest changes from the image, for example boundaries between different materials. Because MLS method does regularization in both spatial and temporal direction, it works well with time-dependent targets. We tested the MLS reconstruction approach with a self-made time-dependent phantom and got good results even with extremely sparse data. Our next aim is to combine MLS method to multi-energy X-ray tomography. This is a way to increase the number of information available from one X-ray-scan. Materials attenuate X-rays differently, depending on the energy of the X-ray spectrum used. By using several level set functions in reconstructions, we can differentiate several materials and use the mathematical model to determine the amount of materials in the target.
Jiahua Jiang  
*Department of Mathematics, Virginia Tech*  

**Hybrid Projection Methods with Recycling for Large Inverse Problems**

Iterative hybrid projection methods have proven to be very effective for solving large linear inverse problems due to their inherent regularizing properties as well as the added flexibility of being able to select regularization parameters adaptively. However, the main disadvantage of hybrid methods compared to standard iterative methods is the need to store the basis vectors for solution computation. In this work, we present a framework that uses recycling approaches with the Golub-Kahan bidiagonalization to efficiently compute an accurate solution, even after the solution space has been compressed. Various techniques for subspace selection/compression can be incorporated, and the proposed recycling techniques can be coupled with a hybrid projection method for automatic regularization parameter selection. Numerical examples from image processing show the potential benefits of using recycling in hybrid methods for solving problems.

Marta M. Betcke  
*University College London, Centre for Inverse Problems, Centre for Medical Image Computing, Department of Computer Science, UK*  

**Dynamic tomography of foot & ankle using optical flow**

The advances in clinical treatment of the highly complex foot & ankle structure hinge upon improving the understanding of the underlying biomechanics. The state of the art models are derived from visual measurements of the gait cycle and hence are limited to the motion assessable by eye. This limitation can be overcome using 4D tomography of a load bearing foot & ankle if such can be acquired at a reasonable dose. Such a dynamic image of foot & ankle would provide the orthopaedic surgeon with a patient specific information to facilitate the diagnosis and selection of the best treatment including opening new treatment options such as replacement of joints which are currently unavailable.

In this work we propose to obtain such a dynamic image of foot & ankle by acquiring in addition to a static load bearing foot & ankle scan a fully dynamic scan at the same dose. To stably solve such a highly undersampled dynamic inverse problem we make use of the joint image reconstruction and motion estimation framework. The motion of individual bones of foot & ankle can be assumed rigid, which justifies imposing the optical flow constraint with total variation regularization of the motion field to favour piecewise constant motion reflective of the structure dynamics and a total variation regularization of the linear attenuation of the bones.

The resulting dynamic inverse problem is posed in a variational framework and subsequently cast in a form amiable to solution with Proximal Alternating Linearized Minimization (PALM) algorithm. We present results for both simulated and phantom experiment data.

This is joint work with Nargiza Djurabekova, Andrew Goldberg, Andreas Hauptmann, David Hawkes, Felix Lucka, and Guy Long.
Eric Grinberg  
*University of Massachusetts Boston, MA 02125 USA*

**Integral Geometry over Finite Fields—cataloging inadmissibility**

Standard models of tomography are built over the real numbers. The ambient space is usually euclidean, functions are assumed to have regularity properties and families of lines or planes are endowed with some structure. By replacing the reals by a finite field and the ambient space by a vector or projective space over it, we can dispense with all regularity and structural assumptions and aim to answer "all" tomography questions. We will focus on I.M. Gel’fand’s "admissibility" question: which families of lines are minimally sufficient for inversion. The contrapositive, inadmissible families of lines, lead to rich geometries and counting problems. The resulting scrapbooks and catalogs of inadmissible line complexes, produced by hand, may be amenable to replication and generalization by recently developed artificial intelligence theorem provers. This work includes collaboration with Mehmet Orhon and with David Feldman.

Jan Boman  
*Department of Mathematics, Stockholm University, 116 91 Stockholm, Sweden*

**Radon transforms supported in hypersurfaces**

If the Radon transform of a compactly supported distribution is supported in the set of tangent planes to a bounded, convex domain $D$, then the boundary of $D$ must be an ellipsoid. This fact and a number of related phenomena will be discussed in the talk.

Fulton Gonzalez  
*Tufts University Department of Mathematics, 503 Boston Avenue, Medford, MA 02155, USA*

**Surjectivity of Convolution Operators**

In the 1950’s Leon Ehrenpreis introduced the idea of slowly decreasing functions to describe the Fourier transforms of compactly supported distributions $\mu$ on $\mathbb{R}^n$ for which the convolution operator $C_\mu: T \mapsto T \ast \mu$ has a fundamental solution and is surjective on various function and distribution spaces. We will discuss this criterion in detail and some of its applications, as well as some recent related results on noncompact symmetric spaces.
Tomoyuki Kakehi
Division of Mathematics, University of Tsukuba, Ibaraki, 305-8571, Japan
Mean value Operators on Noncompact Symmetric Spaces
We will talk about the surjectivity of mean value operators on noncompact symmetric spaces and related results. This is a joint work with Fulton Gonzalez, Jens Christensen, and Jue Wang.

MS 6 : Recent Advances in Algorithms and Software for Tomographic Reconstruction (P1)

Organizers: Julianne Chung, Jim Nagy
Room: 206

Ioannis Sechopoulos
Department of Radiology and Nuclear Medicine, Radboud University Medical Center
Beyond anatomic imaging: More, not less, time
The last 40 years of advances have made computed tomography the workhorse of the radiology department of today. Since the introduction of CT, developments in hardware have driven images to be acquired faster, with acquisition times dropping from minutes to under one second, with higher spatial resolution and lower dose than ever before. This has resulted in the capture of images with exquisite detail, even in moving organs, such as the heart. However, CT has traditionally been used as an anatomical imaging modality, providing information on only the size, location, and make-up of tissues and organs. However, the next step forward in CT imaging should takes us beyond simple morphology to depict organ and tissue function. It is no longer enough to find pathology, what we need is to find clinically-relevant pathology. It is also no longer enough to see if a tumor is shrinking during treatment, but if it is dying. Is this embolus decreasing lung function? Is this tumor responding to treatment? The answers to these questions will not be reliably found using morphological imaging. For CT to stay at the forefront of radiological imaging for the next 40 years, we need to develop CT into a functional imaging modality. This will require the introduction of dynamic, 4D imaging, to query the perfusion properties of tissues and pathologies. For this, we need to develop and introduce the algorithms that allow for extended, or continuous, image acquisition at radiation doses and image noise levels that are clinically viable. This will require improvements in noise filtering, reconstruction, motion correction, and quantitative analysis. This presentation will discuss the current status of functional CT imaging and how this technology needs to be moved forward.
Emil Sidky
Dept. of Radiology, The University of Chicago

An optimization framework for one-step spectral CT image reconstruction and current challenges

Photon-counting X-ray detector technology developed over the last decade has reignited interest in energy-resolved computed tomography (CT), also known as spectral CT. This technique is a generalization of a decades-old CT configuration called dual-energy CT (DECT), where X-ray transmission data is acquired with two energy windows, implemented either by changing the X-ray source spectrum or altering the detection sensitivities. With photon-counting detectors, it is possible to extend DECT to include transmission data for many energy-windows for a single X-ray source spectrum. This multi-energy transmission data can be exploited for quantitative imaging, artifact reduction, and novel scan configurations. As hardware developments have been driving the recent surge of interest in spectral CT, they have also present imaging scientists with new challenges for image reconstruction. In this talk, standard spectral CT image reconstruction techniques that process the data in two steps will be discussed along with their limitations. The optimization framework for one-step spectral CT image reconstruction, which we have been developing, will then be presented. Its practical advantages in terms of flexible data acquisition will be explained. A number of challenges that remain will be toured: multi-material decomposition, calibration/auto-calibration, parameter selection, and nonconvexity. This is joint work with Taly Schmidt, Rina Barber and Xiaochuan Pan.

William Lionheart
School of Mathematics, University of Manchester

Histogram tomography

In conventional tomographic imaging problems the data consist of integrals along lines or curves. Increasingly we encounter "rich tomography" problems where the quantity imaged is higher dimensional than a scalar per voxel, including vectors, tensors, and functions. The data can also be higher dimensional and in many cases consists of a one or two dimensional spectrum for each ray. In many such cases the data contain not just integrals along rays but the distribution of values along the ray, when binned this is a histogram. In this talk we will discuss scalar and tensor histogram tomography problems. For the scalar case we see that bins in the cumulative histogram correspond to the Radon transform of the characteristic function of the sublevel. On the other hand moments of the histograms give Radon transforms of powers of the desired function. We go on to consider strain tomography using neutron and x-ray diffraction. In particular we show that for Bragg edge strain tomography a moment approach gives information about a compatible strain that is not available from the integral approach.
Silvia Gazzola  
*Department of Mathematical Sciences, University of Bath, Bath BA2 7AY, United Kingdom*  

**Flexible Krylov Methods for \( \ell_p \) Regularization**  

This talk is about new flexible Krylov methods that efficiently approximate regularized solutions to large-scale linear inverse problems with a "\( p \)-norm" penalization term, for \( 0 < p \leq 1 \). These new strategies can handle both under- and over-determined linear systems, together with penalization terms that involve a transformation of the solution (such as wavelets or total variation). To achieve this, the flexible Golub-Kahan algorithm is introduced, and convenient standard form transformations, as well as iterative reweighting, are exploited within a flexible Krylov-Tikhonov hybrid framework. The key benefits of the new approach are that efficient projection methods replace classical inner-outer iteration schemes, and expensive regularization parameter selection techniques can be avoided. Theoretical insights and numerical results from realistic test problems in computed tomography are provided. This is a joint work with Julianne Chung (Virginia Tech) and Malena Sabaté Landman (University of Bath).
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<td>15:30-16:00</td>
<td>Coffee Break and Poster Session</td>
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<td>16:00-18:00</td>
<td>Tufts and Historical Talks (R253)</td>
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<td>Linda Abriola (16:00-16:40)</td>
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<td>Sergio Fantini(16:40-17:20)</td>
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<td>George Read (17:20-18:00)</td>
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<td>19:00-21:30</td>
<td>Conference dinner (BH)</td>
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<td>(bar opens at 18:30)</td>
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Plenaries

Rooms: B01, R253 (afternoon)

Jeff Fessler
EECS Department, University of Michigan, Ann Arbor, MI

CT image reconstruction using adaptive signal models

When X-ray CT data is collected with low source intensity or with sparsely sampled views, image reconstruction methods require regularization to improve image quality. The regularizers used in clinical model-based image reconstruction methods for X-ray CT are based on a very simple mathematical model, namely that neighboring image voxels tend to have similar intensity values. Pursuing lower X-ray doses or sparser view sampling requires stronger forms of regularization, and the current trend is to use methods that are adaptive to the image properties of the patient being reconstructed or learned from training images from a population of similar patients. This talk will give an overview of data-adaptive regularizers for X-ray CT image reconstruction, focusing on methods that use sparsifying transform learning, learned convolutional operators, and variational neural networks.

The methods and results presented will be based on joint work with Yong Long, Sai Ravishankar, Il Yong Chun, Xuehang Zheng, Siqi Ye, and Zhipeng Li.

Linh Nguyen
University of Idaho, 875 Perimeter Dr, Moscow, ID 83844

Time reversal methods for thermoacoustic tomography

Thermoacoustic tomography (TAT) is a hybrid method of imaging. It combines the high contrast of microwave imaging and high resolution of ultrasound imaging. There are several inversion methods for TAT, such as closed-formed formulas, iterative methods, and time reversal methods. The time reversal methods have proved to be both efficient and mathematically interesting. In this talk, we will survey the methods in three scenarios: the standard setting of TAT, TAT in elastic media, and TAT in a reflecting cavity.

Coffee Break

Alexander Katsevich
Department of Mathematics, University of Central Florida, Orlando, FL 32816

On reconstruction of functions with discontinuities from discrete Radon transform data
In this talk we consider the question:

- Why and how well do Radon transform inversion formulas work with discrete data?

The question is easier if the function $f$ to be reconstructed is sufficiently smooth. It is harder if $f$ is not smooth, e.g. has jump discontinuities. The question has two parts:

1. What does reconstruction look like near the jumps of $f$?

2. Do the jumps of $f$ create non-local artifacts in the reconstruction?

We obtain the behavior of the reconstructed image in a neighborhood of an edge singularity of $f$. The neighborhood shrinks appropriately as the sampling rate increases. We call it "transition behavior or edge response." Both 2D and 3D classical and generalized Radon transforms are considered. We show also that under some generic conditions, the jumps of $f$ do not lead to non-local artifacts in the reconstruction. In all the obtained results a connection with the theory of uniform distribution turns out to be essential.

Simon Arridge  
Dept. Computer Science, University College London, UK

Tomography with Sound and Light

Several different techniques exist for indirectly recovering the optical absorption and/or scattering coefficients of biological objects, and from there to inferring concentrations of chromophores of interest, from observations of transmitted and reflected light at multiple wavelengths; these include diffuse optical tomography, fluorescence optical tomography, and bioluminescence tomography. These modalities exhibit a tradeoff between greater contrast against lower resolution due to increased scattering. Acoustic waves also have a long tradition in imaging with both qualitative and quantitative interpretations. These concepts are combined in photo-acoustic tomography (PAT) which generates contrast with optical photons and develops resolution using ultrasound.

In this talk I review some recent progress in these areas including the acceleration of PAT using Compressed Sensing and Machine Learning techniques.

Lunch

Industrial Panel
**MS 3 : Generalized Radon Transforms and Applications in Imaging (P2)**

Organizers: Gaik Ambartsoumian, Venky Krishnan

**Ralucă Faleza**
*Rochester Institute of Technology*

**Generalized Radon Transforms with cusp singularities**

We will describe some microlocal properties of Generalized Radon Transforms over curves $\gamma(t) = (t, t^n, t^m)$. Under some restrictions for $n$ and $m$, these are Fourier integral operators (FIOS) with singularities. We will focus on the case of cusp singularities and we will consider the composition calculus of these operators. We will show how these results can be extended to more complicated FIOs using the weak normal form. Such operators appear in inverse problems related to seismology (in the presence of cusp caustics) and to Synthetic Aperture Radar imaging (when the flight track has simple inflection points).

**Peter Kuchment**
*Texas A&M University*

**Detecting presence of emission sources with low SNR - 'Analysis' vs deep learning**

The talk will discuss the homeland security problem of detecting presence of emission sources at high noise conditions. (Semi-)analytic and deep learning techniques will be compared. This is a joint work with W. Baines and J. Ragusa.

**MS 5 : Mathematics and Machine Learning (P1)**

Organizers: Ge Wang, Todd Quinto

**Gustav Zickert**
*Department of Mathematics, KTH Royal Institute of Technology, Sweden*

**Machine learning for cryo-EM**

In this talk I will present some recent results on using methods from machine learning in cryo-electron microscopy (cryo-EM). In particular, I will describe a new greedy variational method for sparse representations of cryo-EM images using Gaussian mixtures.

**Xiaojing Ye**
*Department of Mathematics and Statistics, Georgia State University, Atlanta*

**Deep Image Reconstruction Network**
Variational models and associated optimization solvers are the keys to a concise and elegant mathematical framework for image reconstruction. On the other hand, the emerging deep learning technique has shown its transcendent power in extracting complex latent features from large datasets. To combine the best of both worlds, we build a deep reconstruction network by integrating multilayer convolutional neural networks as feature-exploiting operations into an accelerated proximal gradient algorithm. This network is then trained to learn local and nonlocal image features during the offline training process and can then produce high quality images for online reconstruction tasks. We show a number of promising results generated by the proposed method on synthetic and real datasets.

**MS 6 : Recent Advances in Algorithms and Software for Tomographic Reconstruction (P2)**

**Organizers:** Julianne Chung, Jim Nagy

**Room:** 206

**14:30-15:00 Chris Jacobsen**

*Advanced Photon Source, Argonne National Laboratory, and Department of Physics and Astronomy, Northwestern University*

**X-ray nanotomography: seeing subcellular structure in 3D**

The brightness of synchrotron light sources has been increasing at a rate beyond that of Moore’s law in electronics. Along with advances in x-ray optics, cryogenic specimen preparation and imaging methods, and advances in phase retrieval algorithms, this is making it possible to obtain images of subcellular structure at sub-20 nm resolution in 2D and sub-50 nm resolution in 3D. One practical challenge is how to align 2D projections to each other when using rotational stages that are imperfect at this length scale; this is accomplished using iterative reprojection methods. Another challenge involves the fact that the depth of focus (necessary for satisfying the pure projection approximation) decreases as the square of improvements in transverse resolution. We address this challenge by accurate modeling of the forward problem using multislice wave propagation, and using numerical optimization methods to find the object based on the data recorded. Together, these advances are giving us new 3D views of the world at the nanoscale.
Efficient marginalization-based MCMC approaches for Hierarchical Bayesian inverse problems

Hierarchical models in Bayesian inverse problems are characterized by an assumed prior probability distribution for the unknown state and measurement error precision, and hyper-priors for the prior parameters. Combining these probability models using Bayes’ law often yields a posterior distribution that cannot be sampled from directly. We propose different Markov Chain Monte Carlo (MCMC) algorithms for efficiently sampling the posterior distribution that exploit the structure of the problem, efficiently sample the posterior distribution, and quantify the uncertainty associated with the reconstruction and the prior parameters. We provide a detailed analysis of the acceptance rates and computational costs associated with our proposed algorithms, and compare their performances on numerical test cases—image deblurring, computerized tomography, and inverse heat equation. This is joint work with Johnathan Bardsley, D. Andrew Brown, Alen Alexanderian and Sarah Valle’lian.
Unified Reconstruction Framework for Multi-Modality Neutron Imaging

Neutron transmission imaging provides object information that complements information obtained from X-ray imaging. In addition, neutron interactions in the object may produce secondary particles that can be detected and identified, enabling elastic-scatter and induced-fission imaging. We describe a total variation (TV) constrained weighted least squares (WLS) framework that unifies reconstruction of these neutron imaging modalities. Applications of neutron imaging include non-destructive measurement or verification of the distribution of nuclear material in a closed container. A portable deuterium-tritium (DT) neutron source and an array of pixelated neutron detectors are used to acquire the data. Detection of the alpha particle that accompanies every neutron in the DT reaction facilitates electronic neutron collimation as well as time-of-flight techniques. Reconstruction is based on applying an incremental proximal gradient algorithm to solve the TV-WLS problem given by

$$x^* = \arg \min \frac{1}{2} \| Ax - y \|_W^2 + \beta \frac{1}{2} \| x \|_2^2 \quad \text{s.t.} \quad \text{TV}(x) \leq \epsilon.$$  

The only difference between elastic-scatter and induced-fission reconstruction is with respect to the physics incorporated into the system matrix which also accounts for the imaging geometry in a manner that allows for upsampling of the projection data. Attenuation is estimated from a transmission reconstruction which also serves to produce a density map that can be used to visualize the object(s) being imaged. Variance weighting allows higher certainty measurements to exert greater influence on the solution. Tikhonov regularization is used to compensate for undersampling. Total variation plays a similar role but also serves to produce uniform material regions. Free parameters, such as $\beta$ and $\epsilon$, are determined semi-automatically. A modified version of SIRT is used to solve the WLS sub-problem. Ordered subsets accelerate convergence and multi-threading supports multi-core computation. The TV constraint is satisfied by mapping the image to the closest point on the corresponding L1-ball using the Chambolle-Pock algorithm combined with a projection method by Duchi et al. This computation is also multi-threaded.
Iterative sparse-view X-ray Tomography Fusing Attenuation and Compton Scatter Data: Approach, Simulation and Experimental Results

X-ray inspection systems are critical in medical, non-destructive testing, and security applications, with systems typically measuring attenuation along straight-line paths connecting sources and detectors. Computed tomography (CT) systems can provide higher-quality images than single- or dual-view systems, but the need to measure many projections leads to greater system cost and complexity. Typically, off-angle Compton scattered photons are treated as noise during tomographic inversion. We seek to maximize the image quality of sparse-view (few-view) systems by combining attenuation data with measurements of Compton-scattered photons, exploiting the fact that the broken-ray paths followed by scattered photons provide additional geometric sampling of the scene. We describe a single-scatter forward model for Compton-scatter data measured with energy-resolving detectors, and demonstrate a reconstruction algorithm for density that combines both attenuation and scatter measurements. The potential for imaging improvement is evaluated using both high-fidelity Monte Carlo simulations and an experimental testbed system. Both simulation and experimental results suggest that including Compton-scattered data in the reconstruction process can improve image quality for density reconstruction using few-view systems. This is joint work with Abdulla Desmal, Hamideh Rezaee, Eric Miller, Jeffrey Schubert, Jeffrey Denker, Aaron Couture, Sherman Kisner, and Peter Roschild.
Linda M. Abriola  
*University Professor* Tufts University Medford, MA 02155

**Subsurface Contaminant Source Zone Characterization and Uncertainty Quantification Using Discriminative Random Fields**

Contamination of groundwater by separate phase organic solvents (a.k.a. nonaqueous phase liquids (NAPLs)) is a common problem at thousands of industrial and government sites throughout the US. Research has demonstrated that the quantity and spatial distribution of entrapped NAPL in the subsurface controls contaminant plume persistence and the long-term performance of most remediation technologies. Unfortunately, our ability to estimate the spatial distribution and total mass of contaminant in the field remains severely limited. In this work, a novel statistical approach is developed and implemented for the reconstruction of chlorinated solvent source zone realizations and the quantification of associated distribution metrics and their uncertainty. The approach employs discriminative random field (DRF) models, originally introduced for computer vision applications, to model the spatial distributions and relationships among source zone properties (i.e. permeability, NAPL saturation and aqueous concentration distributions), consistent with commonly collected field data. A limited number of full-scale finite difference model simulations of NAPL release, migration, and dissolution are used to train the model parameters. Monte-Carlo sampling methods based on these trained models then provide an efficient method to generate contaminant mass realizations conditioned on measured borehole data. Post-processing of these realizations yields approximations of uncertainty to inform further sampling for characterization and remediation. Model performance is evaluated through comparisons of predicted mass distribution metrics with those obtained from the ‘true’ values generated with validated flow and transport models. These comparisons demonstrate that the trained DRF model can reconstruct realistic, borehole-conditioned, saturation and concentration fields for a range of spill scenarios.

Co-authors:  
Masoud Arshadi, Clara De Paolis Kaluza, Jack L. Elsey, Eric L. Miller
Diffuse optical imaging of biological tissue

Light in the near-infrared spectral region (wavelength range of about 700-1000 nm) is weakly absorbed in most biological tissues, thus allowing for large optical penetration depths of the order of centimeters. This feature allows for non-invasive optical imaging of macroscopic tissue, with a variety of applications including diagnostic, functional, and physiological studies of the human brain, breast, and skeletal muscle. While near-infrared light is weakly absorbed in tissue, it is also highly scattered, with photon mean free paths for scattering that are orders of magnitude shorter than photon mean free paths for absorption. This property results in a strongly diffusive nature of light propagation in tissue, which is a major challenge both for quantitative spectroscopy and for imaging. In this presentation, I will provide an overview of diffuse optical studies of biological tissue, including applications to breast imaging (for cancer detection and monitoring of individual response to neoadjuvant chemotherapy) and brain imaging (for functional activation studies and monitoring of brain perfusion). I will also present a recent development in my lab, which is based on dual-slope measurements of the phase of photon-density waves that enhance the depth sensitivity of diffuse optical imaging. The issue of extracerebral tissue contributions to the optical signal is a major open question in the field of non-invasive functional imaging of the brain, and the ability to enhance the optical sensitivity to deeper tissue can provide optical signals that are more specific to brain tissue. Diffuse optical imaging of the brain is a growing field, and effective approaches to image reconstruction can significantly augment its impact and enhance the value of its research and clinical applications.
## II.4 Thursday, August 8

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<th>Time</th>
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<td>Per Christian Hansen</td>
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<td>9:40-10:20</td>
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<td>Coffee Break</td>
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<td>10:50-11:30</td>
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<td>Ge Wang</td>
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<td>11:30-12:10</td>
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<td>Andreas Rieder</td>
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<td>12:10-13:40</td>
<td>Lunch</td>
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<td>Charles Bouman</td>
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<td>14:30-15:00</td>
<td>MS1. Appl. Math. in Tomography (206)</td>
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<td>15:30-16:00</td>
<td>Coffee Break and Poster Session</td>
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<td>16:00-16:30</td>
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<td>MS5. Machine Learning (112)</td>
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<td>17:00-17:30</td>
<td>MS3. Gen. Radon transforms (210)</td>
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<td>17:30-18:00</td>
<td>Ming Jiang</td>
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<td>Mikhail Zaslavsky</td>
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Plenaries

**Per Christian Hansen**  
*Technical University of Denmark*

**Convergence and Non-Convergence of Algebraic Iterative Reconstruction Methods**

Algebraic iterative reconstruction methods - such as ART (Kaczmarz), SART, and SIRT - produce good results for underdetermined X-ray CT problems, and they can easily incorporate non-negativity and box constraints. Hence they are quite popular alternatives to filtered back projection. When these iterative methods are implemented on GPU-accelerated systems with a focus on computational efficiency, different discretization schemes are used for the forward projection and the backprojection. In the underlying "language" of linear algebra, this means that there is a mismatch between the backprojection matrix B and the transposed of the forward projection matrix A. The use of such an unmatched A,B-pair has two consequences: the accuracy (compared to when using a matched pair) deteriorates, and the iteration may fail to converge. In this talk we illustrate these issues with recent theoretical and computational results, and we present a novel approach to "fixing" the non-convergence with only a small computational overhead.

**Charles Epstein**  
*Department of Mathematics, University of PA, Philadelphia, Center for Computational Mathematics, Flatiron Institute, New York, NY*

**Geometry of the Phase Retrieval Problem**

In several imaging modalities the measured data can be interpreted as the modulus of the Fourier transform of a function describing the unknown object. To reconstruct this object one needs to use some auxiliary information to recover the un-measured phase of the Fourier transform. This is a notoriously difficult problem. I will discuss the underlying geometric reasons for these difficulties, approaches to improving the performance of standard algorithms, as well as entirely new approaches.

*Coffee Break*
Ge Wang

*Biomedical Imaging Center, Polytechnic Institute, Troy, NY, USA*

**Tomography with Deep Learning**

Currently, deep learning is the mainstream of machine learning and a most active area of artificial intelligence. Computer vision and image analysis are great application examples of deep learning. While computer vision and image analysis deal with existing images and produce related features (registration, segmentation, classification, etc.), tomography produces images of internal structures from externally measured features (line integrals, k-space samples, etc.) of underlying images. Recently, deep learning techniques are being actively developed worldwide for tomographic image reconstruction. We believe that “image reconstruction is a new frontier of machine learning” (IEEE Transactions on Medical Imaging 37 (2018) 1289) and promises major impacts on the development of solutions to many inverse problems. Over the past years, we have been working on data-driven CT, MRI and optical image reconstruction algorithms for superior imaging performance. In this presentation, we report our representative deep learning results, including both important applications and methodological innovations. We welcome collaborative opportunities.

Andreas Rieder

*Karlsruhe Institute of Technology D-76131 Karlsruhe, Germany*

**Seismic imaging with the elliptic Radon transform**

The elliptic Radon transform (eRT) integrates functions over ellipses (2D) and ellipsoids of revolution (3D). It thus serves as a model for linearized seismic imaging under the common offset scanning geometry where sources and receivers are offset by a constant vector. As an inversion formula of eRT is unknown we propose certain imaging operators (generalized backprojections) which allow to reconstruct some singularities of the searched-for function from seismic measurements. We analyze these imaging operators as pseudo-differential operators to understand how they map, emphasize or de-emphasize singularities. Numerical examples illustrate the theoretical findings.

*Lunch*
Machine Learning in Imaging and Reconstruction: Where is it Going?

Machine learning (ML) and AI promise to bring the next wave of change and innovation to every corner of society. But how will ML methods such as deep neural networks (DNNs) change scientific imaging in areas such as material science, geoscience, and healthcare? This talk explores a number of important recent directions in the integration of AI with scientific imaging problems, and also speculates on some directions these innovations might take in the future. We discuss three different approaches to the integration of ML models with more established physical models for the reconstruction of quantitative images from sensor data. In the first approach, we show how physical models of sensors can be integrated with data-driven ML models using a general framework which we refer to as Plug-and-Play methods. Next, we provide examples of how ML methods can be used as fast approximations to established reconstruction approaches that are highly computationally expensive. Finally, we describe direct approaches to reconstruction using ML/DNN methods. Throughout the talk, we present state-of-the-art examples using imaging modalities including computed tomography (CT), transmission electron microscopy (STEM), synchrotron beam imaging, optical sensing, scanning electron microscopy (SEM), and ultrasound imaging. In each of these examples, we show how key advantages result from the integration of sensor, data, and physics models using emerging ML methods.
Anne Wald
Saarland University, Saarbrücken, Germany

A fast iterative method for inverse problems with inexact forward operator

For most inverse problems $Ax = y$, the available data $y$ is corrupted by noise, which can be compensated by regularization. In addition, the forward operator $A : X \to Y$ is based on a mathematical model that is often inexact or subject to uncertainties. Since the forward operator significantly influences the reconstruction itself, this inexactness may lead to artefacts or even useless results. A well-known example is dynamic computerized tomography: If the object is even slightly moving in time, a reconstruction based on the static forward model often leads to inconclusive results. If the motion of the object is known or can be estimated, it can be compensated. In applications, however, the motion is often unknown.

We present a fast iterative method, based on sequential subspace optimization, that allows us to incorporate a (local) model inexactness

$$\|Ax - A^\eta x\| \leq \eta$$

in the reconstruction to obtain a stable solution. In particular, the inexactness parameter $\eta$ may depend on additional system parameters $k \in K$ such as space, state, or time, if the inverse problem can be written as a semi-discrete problem $A_kx = y_k$.

In the case of dynamic computerized tomography, the motion of the object in time can be reinterpreted as an inexactness in the static model with respect to a fixed time point $t_0$. The parameter $\eta$ can be chosen as a function of time without requiring precise information on the motion itself. We present some numerical experiments for different types of motion to evaluate our method.

This is joint work with Stephanie Blanke and Bernadette Hahn (University of Würzburg)
Ngoc Do  
*Missouri State University*

**Theoretically exact solution of the inverse source problem for the wave equation with spatially and temporally reduced data**

The inverse source problem for the wave equation arises in several promising emerging modalities of medical imaging. Of special interest here are theoretically exact inversion formulas, explicitly expressing solution of the problem in terms of the measured data. Almost all known formulas of this type require data to be measured on a closed surface completely surrounding the object. This, however, is too restrictive for practical applications. I will present an alternative approach that, under certain restriction on geometry, yields explicit, theoretically exact reconstruction from the data measured on a finite open surface. Numerical simulations illustrating the work of the method will be presented. This is joint work with Leonid Kunyansky.

**Coffee Break**

Ming Jiang  
*School of Mathematical Sciences, Peking University, Beijing, China*

**FPGA Acceleration for 3D Low-Dose CT**

In this presentation, I am to talk about our recent progress on accelerating the image reconstruction for low dose X-ray CT with field-programmable gate array (FPGA) devices. Low-dose CT (LDCT) is to provide CT images of clinical quality with reduced cumulative radiation dose. Iterative image reconstruction methods with effective regularization are used for LDCT but generally induce higher computation load than the conventional filtered back-projection methods. The high computational demand of iterative image reconstruction methods with notably increased reconstruction time precludes its routine clinical application and makes it unacceptable in emergency. FPGA is highly programmable and enables optimizing the usage of computing resources at logic gate level. In our work, we formulate an iterative reconstruction algorithm by the Mumford-Shah regularization functional with beam-based asynchronous parallelism. In the implementation, because of the beam-based approach, we can use the pipelining and tiling techniques to increase the computational efficiency and reduce the memory I/O. The implementation is evaluated with a physical phantom and has image quality comparable with the vendor’s result. Relevant aspects of the asynchronous parallelism and implementation are also discussed. This is a joint work with Yong Cui, William Hsu, Guojie Luo, Linjun Qiao, and Wentai Zhang.
Judit Chamorro-Servent  
*PhySense Group, BCN-MedTech, Universitat Pompeu Fabra, Barcelona*

**Microwave Inverse Scattering for Colorectal Cancer Detection**

Colorectal cancer (CRC) is the third leading cause of cancer-related deaths. When CRC is found at an early stage, the 5-year relative survival rate is about 90%. However, only about 4 out of 10 CRC are found at the early stage with the current screening techniques. My co-workers, M. Guardiola, M.A. González-Ballester and O. Camara, all three from BCN-MedTech at the University Pompeu Fabra, together with G. Fernández-Esparrach at the Hospital Clinic of Barcelona and J. Romeu at the Antenna Lab at the University Politecnica of Catalonia, have recently proposed a novel microwave imaging (MWI) pre-prototype for endoscopic explorations and interventions. This pre-prototype is a small endoscope head composed by an array of antennas that transmits and receives microwave signals that interact with colon tissues. MWI exploits the possibility of a significant dielectric contrast between healthy and disease-affected tissues to detect pathological condition. In addition, MWI has been previously employed in other medical imaging applications such as breast cancer, brain cancer, monitoring of brain stroke, etc. However, unlike in the medical imaging applications cited, where the MWI system and their antennas were surrounding the region to observe, the novel MWI pre-prototype situates its antennas inside the region to observe (colon tissue). Furthermore, the endoscope and colon sizes severely limits the number of antennas to eight transmitters and eight receivers. These two facts bring new challenges during the reconstruction imaging process. Then, efficient and accurate real-time inverse problems algorithms are necessary to bring this pre-prototype to the clinical scenario. In this work, we present first a finite difference time domain simulating the microwave signal transmission and reception processes for the MWI pre-prototype. Then, we present a three-step reconstruction algorithm aiming to detect CRC. The first step consists in a temporal filtered backprojection algorithm; the second step aims to reduce the ill-posedness of the problem by choosing a region-of-interest that decreases the degrees of freedom; and the third and final step reconstruct the reduced problem. The algorithm is tested for different frequencies and tumor’s scenarios. Results demonstrate that the first step detects the angular position of the tumors and its approximate size around 8GHz, while the second and third step may help to improve the tumor localization. To conclude, novel inverse methods, some adapted from quite different fields of computer science and mathematics, could help to transfer the new MWI pre-prototype to the clinical scenario.

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Gaik Ambartsoumian  
*University of Texas at Arlington*

**Lines, broken lines and stars in tomography**

The talk will discuss recent results on some generalized Radon transforms that map a function to its integrals along piecewise linear trajectories. The list of such transforms includes the broken-ray transform, broken-line (V-line) transform and the star transform. We will present several results on inversion of these transforms, their properties and connections to tomographic applications.
Jong Chul Ye  
*Dept. of Bio and Brain Engineering, KAIST, Republic of Korea*

**Understanding Geometry of Deep Neural Networks for CT Reconstruction**

Encoder-decoder networks using convolutional neural network (CNN) architecture have been extensively used in deep learning literatures thanks to its excellent performance for various inverse problems such as x-ray computed tomography. However, it is still difficult to obtain coherent geometric view why such an architecture gives the desired performance. Inspired by recent theoretical understanding on generalizability, expressivity and optimization landscape of neural networks, as well as the theory of deep convolutional framelets, here we provide a unified theoretical framework that leads to a better understanding of geometry of encoder-decoder CNNs. Our unified framework shows that encoder-decoder CNN architecture is closely related to nonlinear frame representation using combinatorial convolution frames, whose expressivity increases exponentially with the depth. We also demonstrate the importance of skipped connection in terms of expressivity, and optimization landscape. Motivated by the theoretical understanding of encoder-decoder CNNs, we review several encoder-decoder CNN architectures of low-dose CT, sparse view CT, interior tomography, and cone beam CT. In particular, we introduce recent development on the unsupervised learning methods and differentiated backprojection domain learning as a new research frontier.
Dictionary Learning based Image-domain Material Decomposition for spectral CT

The potential huge advantage of spectral computed tomography (CT) is its capability to provide accuracy material identification and quantitative tissue information. This can benefit clinical applications, such as brain angiography, early tumor recognition, etc. To achieve more accurate material components with higher material image quality, our team developed a dictionary learning based image-domain material decomposition (DLIMD) for spectral CT. First, we reconstruct spectral CT image from projections and calculate material coefficients matrix by selecting uniform regions of basis materials from image reconstruction results. Second, we employ the direct inversion (DI) method to obtain initial material decomposition results, and a set of image patches are extracted from the mode-1 unfolding of normalized material image tensor to train a united dictionary by the K-SVD technique. Third, the trained dictionary is employed to explore the similarities from decomposed material images by constructing the DLIMD model. Fourth, more constraints (i.e., volume conservation and the bounds of each pixel within material maps) are further integrated into the model to improve the accuracy of material decomposition. Finally, both physical phantom and preclinical experiments are employed to evaluate the performance of the proposed DLIMD in material decomposition accuracy, material image edge preservation and feature recovery. This is joint work with Weiwen Wu, Haijun Yu, Peijun Chen, Fulin Luo, Fenglin Liu, Qian Wang, Yining Zhu, Yanbo Zhang and Jian Feng.

Coffee Break

NETT regularization for inverse problems

Deep learning has recently become an important tool in solving inverse problems. One particular approach is to use neural network to learn the proper regularization term. This method has been coined Network Tikhonov (NETT) regularization. In this talk, we discuss the developments of NETT regularization. This is a joint presentation with Markus Haltmeier (University of Innsbruck).
Klaus Mueller  
*Stony Brook University (State University of New York)*

**Medical CT Image Generation with Style**

We propose the use of a conditional generative adversarial network (cGAN) to anatomically generate accurate full-sized CT images. Our approach is motivated by the recently discovered concept of style transfer and proposes to mix style and content of two separate CT images for generating a new image. We argue that by using these losses in a style transfer based architecture along with a cGAN, we can increase the size of clinically accurate, annotated datasets by multiple folds. Our framework can generate full-sized images with novel anatomy at spatial high resolution for all organs and only requires limited annotated input data of a few patients. The expanded datasets our framework generates can then be utilized within the many deep learning architectures designed for various processing tasks in medical imaging.

Quanzheng Li  
*Massachusetts General Hospital Boston, MA USA*

**Deep Learning in Iterative Image Reconstruction Framework**

Iterative image reconstruction has established a mature framework over years, including data model, image model, system model, cost function and optimization algorithms. In last several years, deep learning has been applied in various methods of image reconstruction, and demonstrated impressive performance in many tasks. In this talk, we will put deep learning based image reconstruction algorithms in the framework of iterative image reconstruction, and illustrate the essential differences of these algorithms. We will also demonstrate our work on applying deep learning based image reconstruction algorithms in PET, CT and MR recon.
Mikhail Zaslavsky  
*Schlumberger-Doll Research. 1 Hampshire st., Cambridge, MA 02139, USA*

**Distance preserving model order reduction of graph-laplacians for cluster imaging**

Graph-Laplacians play an important role in multiple areas of machine learning directly related to imaging, such as image segmentation and, in general, discovering structure of large data sets that may not have explicit geometric interpretation. Spectral imbedding of graph-Laplacians provides a low dimensional parametrization of the data manifold which makes the subsequent task (for example, clustering, with k-means or any of its approximations) much easier. However, despite of reduced data dimensionality, the overall computational cost may still be prohibitive for large data sets due to two factors. First, computing the partial eigendecomposition of the graph-Laplacian typically requires a large Krylov subspace. Second, after the spectral imbedding is complete, the application in mind still has to operate with the data set of full size, and that may ruin the efficiency of the approach. For example, clustering of the imbedded data is typically performed with various relaxations of k-means which computational cost scales poorly with respect to the size of data set. Also, they become prone to getting stuck in local minima, so their robustness depends on the choice of initial guess.

In this work we present two-level approach for big data clustering. On the first stage we split the entire dataset into some randomly (or conveniently) chosen subsets and then cluster them independently. On the second stage we perform clustering on the dataset composed from the obtained clusters on the first stage for all subsets. Obviously, the dataset on the second stage is significantly smaller than the original one. We also note that the first stage is embarrassingly parallel. However, the crucial part of our approach is efficient clustering of each data subset (target subset) on the first stage while making sure that clustering result for each of them is consistent with the spectral clustering of the full data set if one would perform such. We develop novel algorithm for such low-dimensional representation of the original graph that it preserves important global distances between nodes of the target subset. That was achieved thanks to properly parametrized graph-Laplacian reduced-order model (ROM) approximating accurately the diffusion transfer function of the original graph for inputs and outputs restricted to the target subset. Working with a small target subset reduces greatly the required dimension of Krylov subspace and allows to exploit the conventional algorithms (like approximations of k-means) in the regimes when they are most robust and efficient. It was verified by the numerical clustering experiments with both synthetic and real data.

Besides being building block of two-level (or multi-level) approach, there are several other uses for ROM-based algorithm. First, it can be employed on its own for representative subset in cases when handling the full graph is either infeasible or simply not required. Second, it may be used for quality control. Third, as it drastically reduce the problem size, it enable the application of more sophisticated algorithms for the task under consideration (like powerful approximations of k-means like those based on semidefinite programming (SDP) instead of the conventional Lloyd’s algorithm). We present application to ultrasound imaging for oilwell integrity applications.
MS 8: Security Applications (P2)

Organizers: Eric Miller, Clem Karl

James Webber
Department of Electrical and Computer Engineering, Tufts University, Medford, MA USA

Microlocal analysis of a Compton tomography problem

Here we present a novel microlocal analysis of a new toric section transform which describes a two dimensional image reconstruction problem in Compton scattering tomography and airport baggage screening. By an analysis of two separate limited data problems for the circle transform and using microlocal analysis, we show that the canonical relation of the toric section transform is 2–1. This implies that there are image artefacts in the reconstruction. We provide explicit expressions for the expected artefacts and demonstrate these by simulations. In addition, injectivity proofs are given for smooth functions which are compactly supported on an annulus and we present simulated reconstructions using a discrete approach with varying levels of added pseudo random noise.

MS 3: Generalized Radon Transforms and Applications in Imaging (P3)

Organizers: Gaik Ambartsoumian, Venky Krishnan

Plamen Stefanov
Purdue University

Semiclassical Sampling and Discretization of Linear Inverse Problems

We study sampling of functions $f$ and their images $Af$ under Fourier Integral Operators $A$ at rates $sh$ with $s$ fixed and $h$ a small parameter. We show that the Nyquist sampling limit of $Af$ and $f$ are related by the canonical relation of $A$ using semiclassical analysis. We apply this analysis to the Radon transform in the parallel and the fan-beam coordinates. We explain and illustrate the optimal sampling rates for $Af$, the aliasing artifacts, and the effect of averaging (blurring) the data $Af$. We prove a Weyl type of estimate on the minimal number of sampling points to recover $f$ stably in terms of the volume of its semiclassical wave front set.
Fatma Terzioglu  
*The University of Chicago*

**Compton Camera Imaging and the Cone Transform**

The talk addresses the cone (or Compton) transform that integrates a function over the surfaces of circular cones. It arises in a variety of imaging techniques, e.g. in astronomy, optical imaging, and homeland security imaging, especially when the so called Compton cameras are involved. Several analytic inversion formulas for the cone transform and the results of their numerical implementation will be presented.

Mohammad Latifi Jebelli  
*University of Arizona*

**Star Radon Transform**

The Star Radon Transform is a natural generalization of the V-Line Radon transform, which has been applied recently to some imaging problems, where the scattering plays an important role. The Star Radon transform of a given function on the plane is defined as the sum of integrals of that function along a collection of rays emanating from the given input point. In this talk, we discuss the Star Radon transform and prove an inversion formula relating this transform to the classical Radon transform in a geometric way.

Yiran Wang  
*Stanford University*

**Quantitative analysis of metal artifacts in X-ray tomography**

In X-ray CT scan with metallic objects, it is known that direct application of the filtered back-projection (FBP) formula leads to streaking artifacts in the reconstruction. These are characterized mathematically in terms of wave front sets in Seo et al 2017. In this talk, we give a quantitative microlocal analysis of such artifacts. For strictly convex metal regions, we show that the streaking artifacts are conormal distributions to straight lines tangential to at least two boundary curves. For metal regions with piecewise smooth boundaries, we analyze the streaking artifacts especially due to the corner points. Finally, we discuss the reduction of the artifacts using appropriate filters. This is a joint work with B. Palacios and G. Uhlmann.
Plenaries

Room: R253

Rosemary Renaut
School of Mathematical and Statistical Sciences, Arizona State University, Tempe, AZ 85282

Improving LSQR with oversampling application for inverse problems

The LSQR iterative method has been a standard for the solution of an ill-posed linear problem. The Krylov space used for the solution of the problem yields a surrogate space that inherits the ill-conditioning of the original problem. Modern techniques employ a randomized singular value decomposition (RSVD) to find the dominant subspace for the solution, hence providing an alternative surrogate which in this case inherits the dominant properties of the original problem. For ill-posed problems the surrogate is usually of a sufficient size that its spectral properties still provide a problem that is ill-conditioned. In both cases hybrid methods in which regularization is applied at the subspace level are still required. In this work we demonstrate pros and cons of the old and new, through consideration of the underlying spectral space approximations that are obtained. Ultimately, the results are relevant within the context of large scale data science applications, when the accuracy of dominant spectral terms is used to infer dominant and significant features of the underlying model. Here we present numerical examples from image restoration and inversion of three dimensional magnetic data to support the analysis in the context of solving practical least squares applications.

Leonid Kunyansky
University of Arizona, 617 N Santa Rita Ave, Tucson AZ 8721

Magnetoacoustic and magnetoelectric hybrid imaging modalities

Several magnetic imaging modalities were introduced recently, with the goal of reconstructing the conductivity distribution within an object. All these techniques couple strong magnetic fields and electric currents with either ultrasound or nuclear magnetic resonance. Such a coupling provides spatial information needed to stabilize the underlying inverse problems and to reconstruct a sharp image. In spite of the differences in physics, all these modalities are closely related mathematically. We will review the physical and mathematical foundations of these techniques, common challenges, and the methods and algorithms that can be used to overcome them.

Coffee Break
Gaël Rigaud  
*Institute of Mathematics, University of Würzburg, Germany*

**A reconstruction strategy in 3D Compton scattering imaging**

Compton scattering imaging (CSI) is an arising imaging concept exploiting the measured spectrum by focusing on the scattered radiation while an object of interest is illuminated by an ionising source. Known as the Compton effect, the phenomena describes the collision/scattering of a photon with an electron leading to a loss of energy of the photon and a change of trajectory. The photon is measured by a camera in terms of energy delivering a precious information on the electron density. The measurement consists then in detecting the scattered photons for different detector positions and different level of energies. The complexity of the involved physical phenomena induces models for the measurement hard to handle when recovering the electron density. Under certain assumptions, we show that the model can be modeled by generalized Radon transforms.

Our work analyses the operators modeling the scattered radiation and addresses the problem of inverting the measured spectrum in order to reconstruct (or at least extract features of) the electron density.

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Todd Quinto  
*Tufts University, Medford, MA USA*

**Allan Cormack and Limited Data Tomography**

Allan Cormack introduced me to tomography, in particular, limited data X-ray CT. This was the start of two main themes of my research—understanding what can be seen in limited data and developing and analyzing reconstruction algorithms.

I will start with of our shared history and then what I’ve learned about these themes. I will describe a general paradigm to determine object features that will be (stably) visible in reconstructions as well as features that will be difficult to reconstruct along with artifacts that can be added in reconstructions. These are, in part, determined by the specific limited data, and good algorithms must address these limitations. Examples will be given from general limited data X-ray CT and, if time, photoacoustic tomography and dynamic CT.

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*Lunch*
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