Modified spacetime level set method in dynamic tomography

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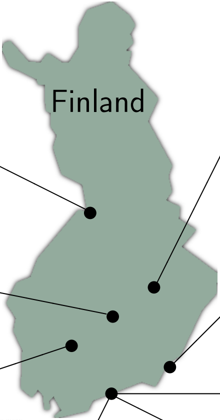
ACADEMY OF FINLAND



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FINNISH METEOROLOGICAL INSTITUTE

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The structure of my talk

- Previous dynamic tomography research
- Modified Level Set (MLS) method
- Production of datasets and results with MLS
  - Dynamic cross phantom
  - Heart imaging project
  - Data collection in CWI
- Future visions

Outline

Previous dynamic tomography research

Modified level set (MLS) method

Production of dynamic datasets

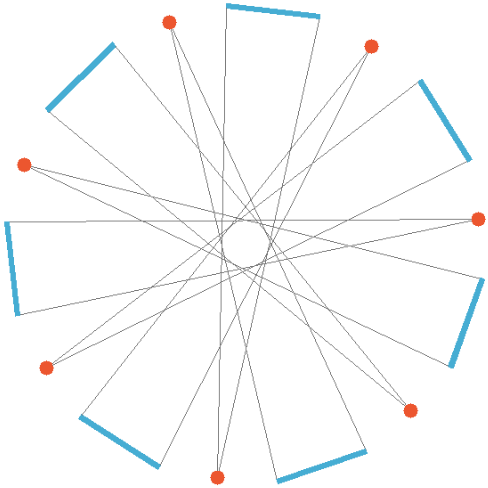
1. Dynamic Cross phantom
2. Heart imaging project
3. Data collection in CWI

Next step in our research

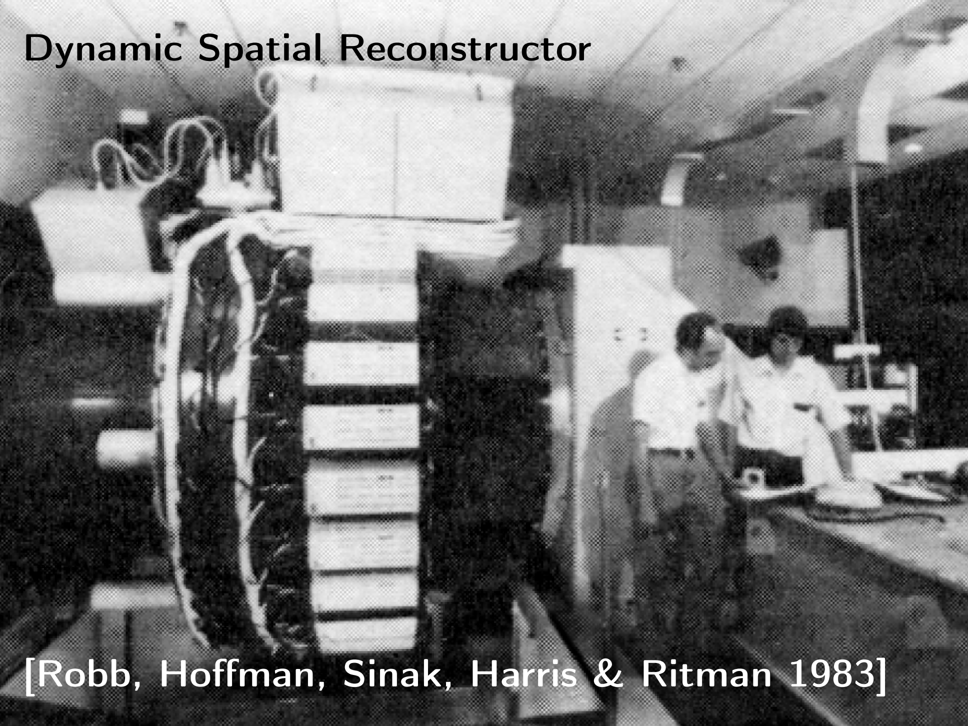
We study a tomographic imaging modality based on fixed multiple source-detector pairs

- High-frame rate detectors monitor a moving object from several directions
- X-ray projection data is gathered from all directions at the same time
- We reconstruct dynamic 3D X-Ray movies!

- Plenty of applications: **cardiac imaging, biotechnology research, veterinary medicine, nondestructive testing**



Dynamic Spatial Reconstructor



[Robb, Hoffman, Sinak, Harris & Ritman 1983]

Very brief overview of multi-source tomographic studies, all based on FBP-type algorithms

- **1980** **Berninger & Redington**: Multiple purpose high speed tomographic x-ray scanner (patent)
- **1983** **Robb, Hoffman, Sinak, Harris & Ritman**: High-speed three-dimensional x-ray computed tomography: The dynamic spatial reconstructor
- **1993** **Stiel, Stiel, Klotz & Nienaber**: Digital flashing tomosynthesis: a promising technique for angiocardiographic screening
- **2001** **Liu, Liu, Wang & Wang**: Half-scan cone-beam CT fluoroscopy with multiple x-ray sources

Static multi-source arrangements have received very little attention in the literature. Filtered back-projection type methods are not well-suited for the resulting sparse datasets.

Reconstruction methods for dynamic tomography

- **1997** **Baroudi & Somersalo**: Gas temperature mapping using impedance tomography
- **2002** **Lu & Mackie**: Tomographic motion detection and correction directly in sinogram space
- **2003** **Bonnet *et al.***: Dynamic X-Ray Computed Tomography
- **2004** **Roux *et al.***: Exact reconstruction in 2D dynamic CT: compensation of time-dependent affine deformations
- **2006** **Kindermann & Leitão**: On regularization methods for inverse problems of dynamic type
- **2010** **Katsevich**: An accurate approximate algorithm for motion compensation in two-dimensional tomography
- **2014** **Hahn**: Reconstruction of dynamic objects with affine deformations in computerized tomography
- **2015** **Hahn**: Dynamic linear inverse problems with moderate movements of the object: Ill-posedness and regularization

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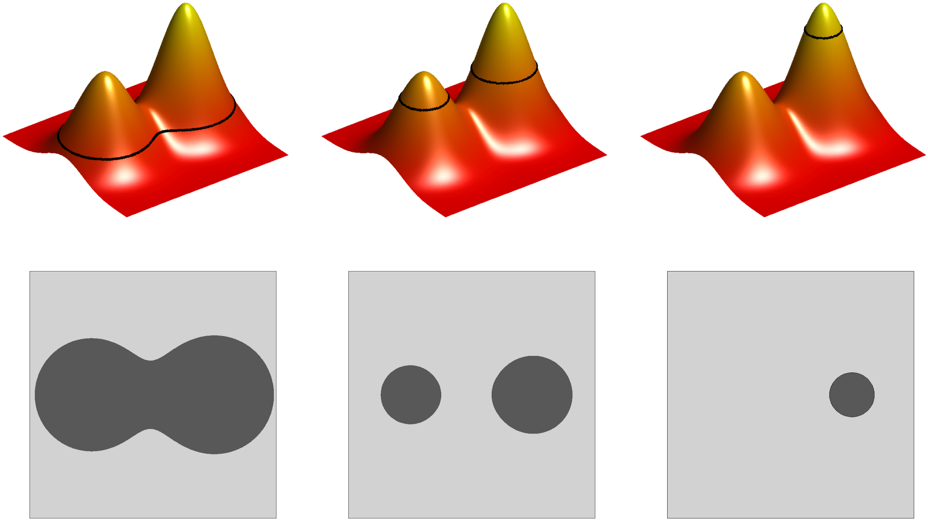
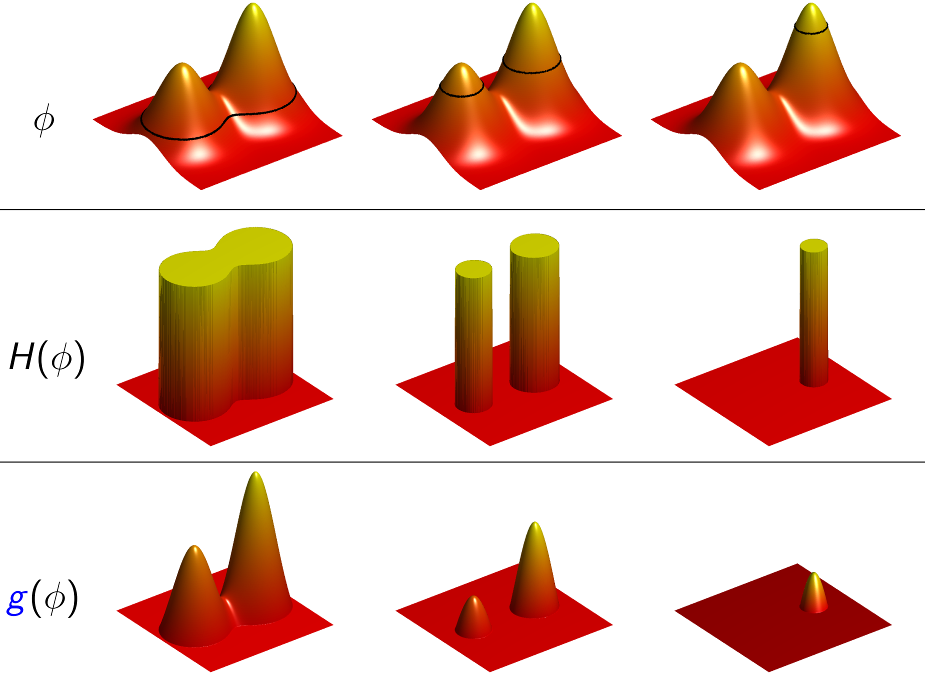
The level set method [Osher, Sethian] parametrizes curves and surfaces in a flexible way




ϕ
$H(\phi)$
$g(\phi)$

There exists at least one minimizer for our generalized level set functional

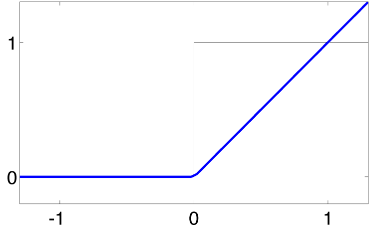
Theorem: Let $\mathcal{A}$ be an operator modeling 2D Radon transforms measured at several times. If $\alpha > 0$ satisfies an upper bound involving the signal-to-noise ratio, then the nonlinear functional

$$F_n(\phi) := \frac{1}{2}\|\mathcal{A}g(\phi) - m\|_2^2 + \frac{\alpha}{2} \sum_{1 \leq |\beta| \leq n} \|D^\beta \phi\|_2^2$$

has a **global minimizer**. The minimizer is unique for $n = 1$.

We model the X-ray attenuation function as $g(\Phi(x, y, t))$, where

$$g(\tau) = \begin{cases} \tau, & \text{if } \tau \geq 0 \\ 0, & \text{if } \tau < 0. \end{cases}$$



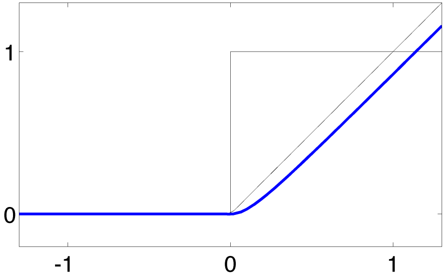
[Niemi, Lassas, Kallonen, Harhanen, Hämäläinen and S **2015**]

Numerical minimization in the case $n = 2$

We smooth out the nondifferentiability of the objective functional by replacing $g : \mathbb{R} \to \mathbb{R}$ by the differentiable approximation

$$g_\delta(\tau) = \begin{cases} \sqrt{\tau^2 + \delta^2} - \delta, & \text{if } \tau > 0, \\ 0, & \text{if } \tau \leq 0, \end{cases}$$

where $\delta > 0$ is small.



Now we can use a gradient-based optimization method for computing the minimizer of

$$\|\mathcal{A}g_\delta(\phi) - m\|_{L^2}^2 + \alpha\|\nabla\phi\|_{L^2}^2 +$$
$$+\alpha(\|\partial_x^2\phi\|_{L^2}^2 + \|\partial_y^2\phi\|_{L^2}^2 + \|\partial_t^2\phi\|_{L^2}^2).$$

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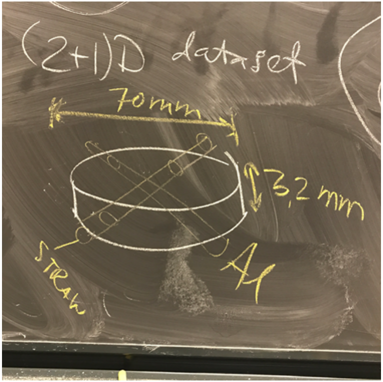
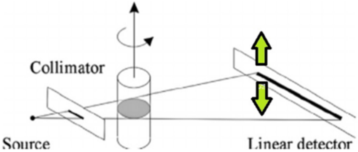
Plans for new time-dependent phantom

- More experimental data for testing dynamic sparse data algorithms!
- We dont have multiple detectors and sources
- We have simulated the multi-source system with stop-motion animation imaging, which takes a lot of time
  Emoji video
- New idea: crossed sticks in tilted angles!



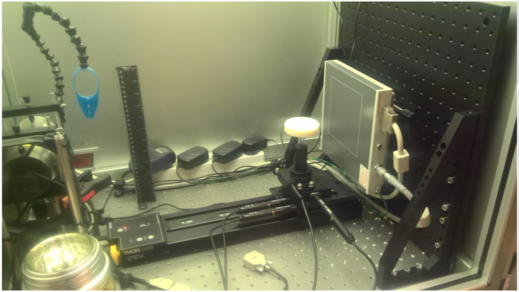


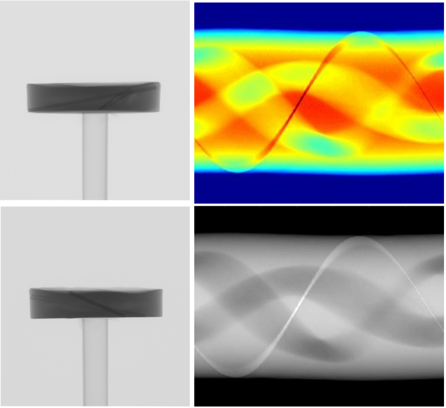
Manufacturing of the phantom

X-ray measurements of the cross phantom

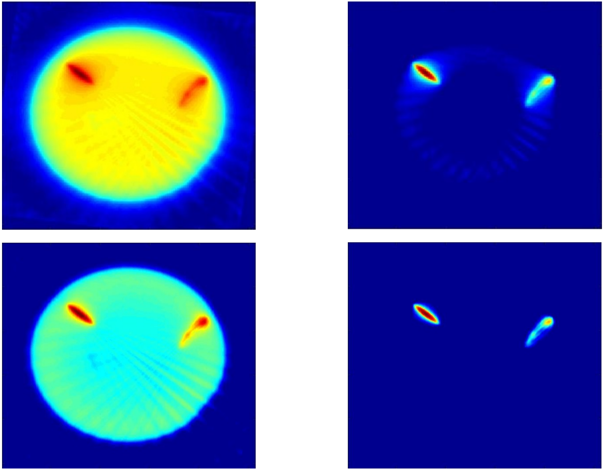
- 360 cone-beam projections (angular step one degree)
- original resolution 2240×2368
- X-ray exposure time 1000 ms
- tube acceleration voltage 50 kV
- tube current 0.9 mA

ASTRA FDK reconstruction



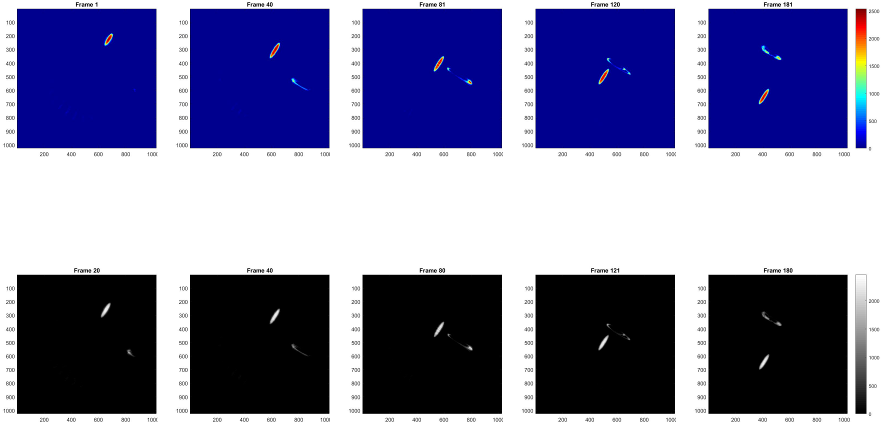


Non-negativity constrained Tikhonov vs. MLS



- one example frame made from downsampled 60 angle sinogram
- level set method finds the greatest change in the image (boundary)
- everything outside the level set is put to zero

MLS reconstructions of the time-dependent cross phantom



Modified Level Set reconstruction of the dynamic cross phantom

- 60 angles, 230 timesteps, regularization parameter $\alpha = 0.5$
- ht=20 (adjusts the amount of regularization in temporal direction)
- number of iterations is 10 with $n = 2$ and 3 with $n = 1$

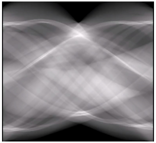
Final reconstruction results

Color X-rays are coming!

Dynamic tomography of cardiac imaging

- Rupturing of a cholesterol plaque (soft or calcified) in aortic vessels often causes a heart attack, which is a very common cause of death
- The ambitious aim of the project was to develop a cardiac CT application for regognizing the people at greatest risk
- Anatomically and functionally realistic phantom was produced with XCAT software
- We searched the optimal (low dose) reconstruction approach and I made tests with MLS

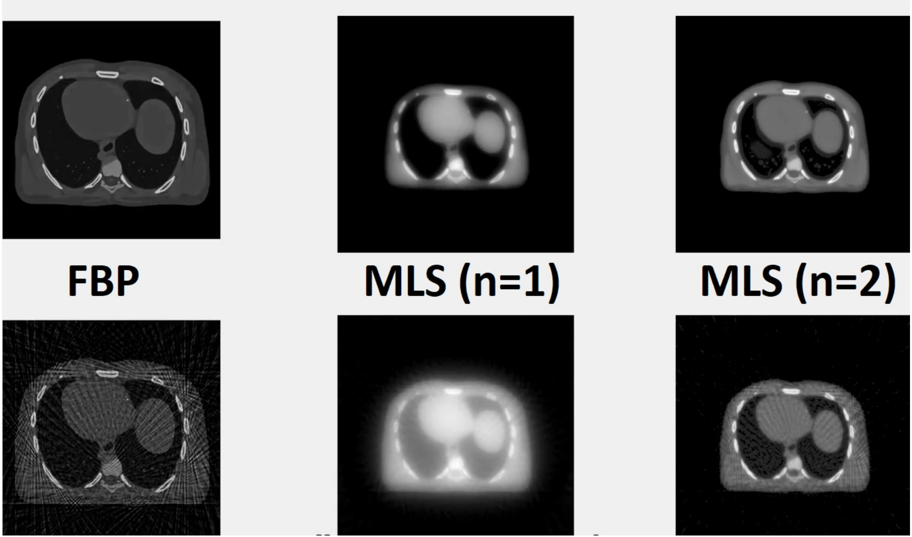
XCAT target



Movement in sinogram space

XCAT reconstruction results (360 and 36 angles)

360 angles

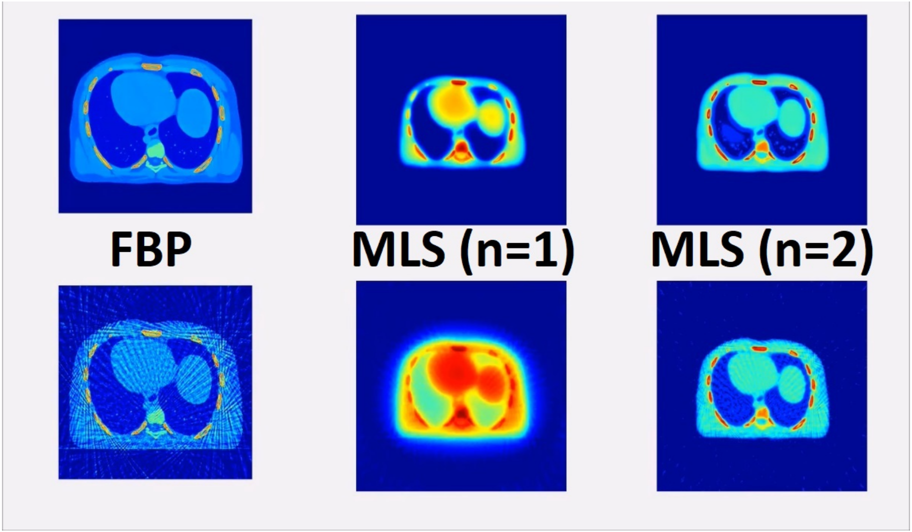


36 angles

Watch as a video

Results in highlighting colors (360 and 36 angles)

360 angles



36 angles

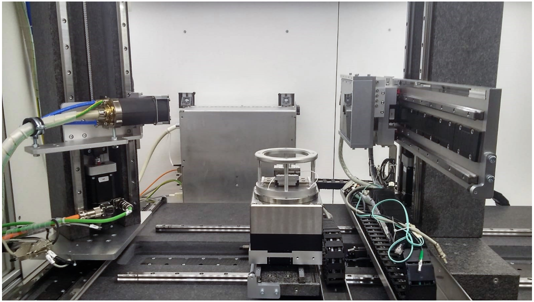
Watch as a video

Collaboration with Centrum Wiskunde & Informatica (CWI)

- National research institute for mathematics and computer science in the Netherlands
- Research group of computational imaging (lead by professor Joost Batenburg), is developing methods for real-time 3D X-ray imaging

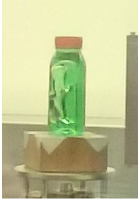
State-of-the-art Flex-Ray scanner

- High resolution X-ray CT system
- Very flexible scanning geometries
- Possibility to observe the target almost in real time

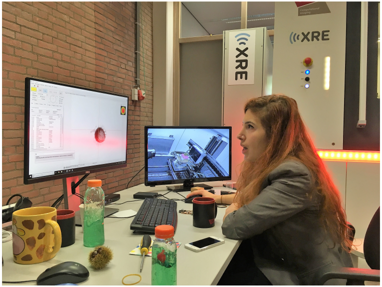


Two X-ray datasets produced

- Spiky chestnut
  - challenging shape for testing reconstruction algorithms
- Dynamic hair gel phantom
  - for dynamic 3D reconstruction algorithms

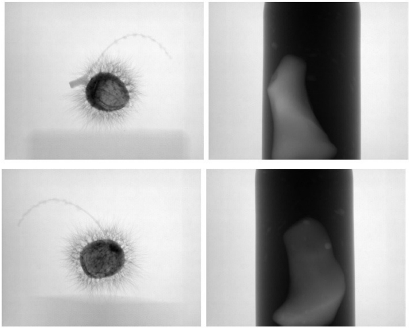


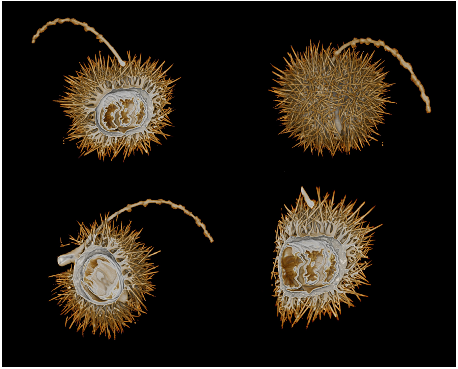
The speed of the movement was crucial for successful scanning!

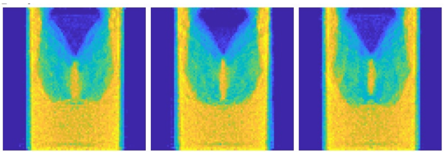


Flex-Ray results

- Dynamic reconstructions were made by using the ASTRA-toolbox [1,2] and an iterative accelerated gradient method (AGD), which is a faster variant of the standard gradient descent method







Links to open computational resources

Open CT datasets:

- Finnish Inverse Problems Society (FIPS) dataset page

Matrix-based parallel-beam reconstruction algorithms:

- Truncated SVD
- Total Variation regularization
- Modified Level Set Method

Matrix-free large-scale reconstruction algorithms:

- Matlab page of Mueller-S 2012 book
- ASTRA toolbox
- TVReg: Software for 3D Total Variation Regularization

For some of the slides see:
http://www.siltanen-research.net/talks.html

Dataset

- two Tikhonov codes, giving idea how to use the data
- 2D sinograms with 16, 30, 80 or 230 time frames
- sinogram contains 15 or 60 angles (obtained from a measured 360-projection fan-beam sinogram by down-sampling)
- original (measured) sinogram
- static and dynamic measurement matrices
- data is hosted on Zenodo: https://zenodo.org/record/1446516
- Documentation can be found also at arXiv: https://arxiv.org/abs/1809.00166

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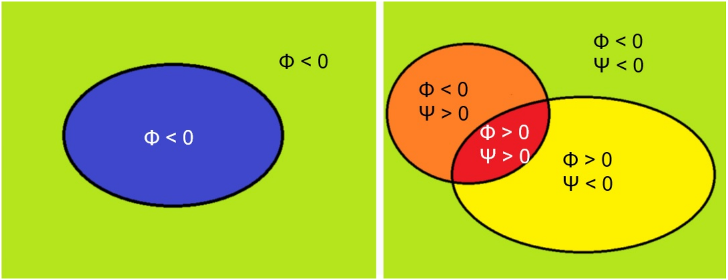
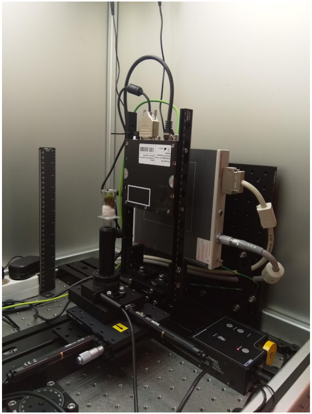
Discussion & future research

- Results with MLS and dynamic sparse data targets were promising
- Next aim is to:
  - combine MLS method to multi-energy X-ray tomography
  - use more than one level set function for determining the amount of material in the target



Multiple LS functions: One function ϕ can differentiate two materials. Two functions ϕ and ψ can determine already four materials.

New detector for multi-energy imaging!



The updated X-ray setup in the industrial math lab of Helsinki.

- CdTe photon counting detector added
- Makes multi-energy imaging possible
- Visit our lab and measure real X-ray data for free! : D

References

[1] Esa Niemi, Matti Lassas, Aki Kallonen, Lauri Harhanen, Keijo Hämäläinen, Samuli Siltanen: *Dynamic multi-source X-ray tomography using a spacetime level set method* [1] A. Chambolle, T. Pock: An introduction to continuous optimization for imaging (2016)
[2] W. van Aarle, W. J. Palenstijn, J. Cant, E. Janssens, F. Bleichrodt, A. Dabravolski, J. De Beenhouwer, K. J. Batenburg, and J. Sijbers: Fast and Flexible X-ray Tomography Using the ASTRA Toolbox (2016) [3] W. van Aarle, W. J. Palenstijn, J. De Beenhouwer, T. Altantzis, S. Bals, K. J. Batenburg, and J. Sijbers; The ASTRA Toolbox: A platform for advanced algorithm development in electron tomography (2015)
[4] A. Limaye; Drishti: a volume exploration and presentation tool. Proc. SPIE 8506, Developments in X-Ray Tomography VIII, 85060X (October 17, 2012)

Thanks for listening!