4th CoSeRa workshop 19.-22. September 2016 in Aachen

# Towards a THz stand-off Single-Pixel Camera using Compressed Sensing

Benjamin Fürsich(1), Sven Augustin(3,4), Richard Bamler(2), Xiaoxiang Zhu(1,2), Heinz-Wilhelm Hübers(3,4)

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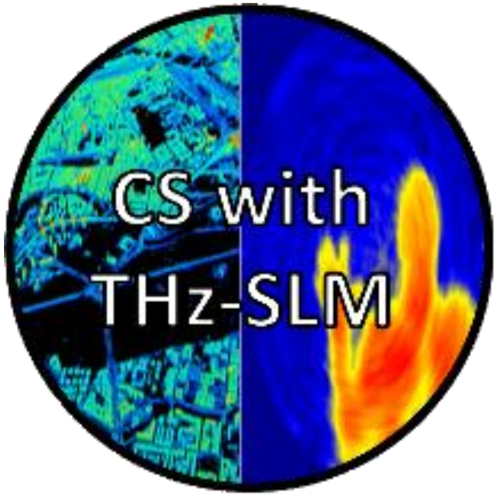
(3) Institut für Physik - Optische Systeme, Humboldt Universität zu Berlin
(4) German Aerospace Center (DLR) Berlin-Adlershof, Institute of Optical Sensor Systems

# Funding




**Goal:** *„Development of a Terahertz stand-off FMCW single-pixel camera for security imaging applications that employs CS algorithms"*

**Thanks to:**
the German Research Foundation (DFG) for funding the work presented here in the scope of the priority program SPP1798 Compressed Sensing in Information Processing (CoSIP) - within the project Compressed Sensing for Terahertz Body Scanners.

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# Talk Overview

- start by explaining the physical setting (introduction) and the resulting model

- then one approach to solve the model will be presented

THz stand-off single-pixel Camera using Compressed Sensing

① ② ③

- Terahertz (THz)
- stand-off
- single-pixel Camera
- FMCW-Radar

- electromagnetic radiation outside of the visible range

**Advantages:**

- ability to penetrate many optical obstructions (clothing, plastics, etc.)
- not harmful to people/living tissue (unlike X-rays!!!)

→ good suited tool for *„Security applications“*

- we intend to use **0.35 THz** radiation

**Disadvantages**

- invisible radiation
- difficult to generate/detect
- limited analog processing capabilities
- large optical components necessary

# Introduction: stand-off

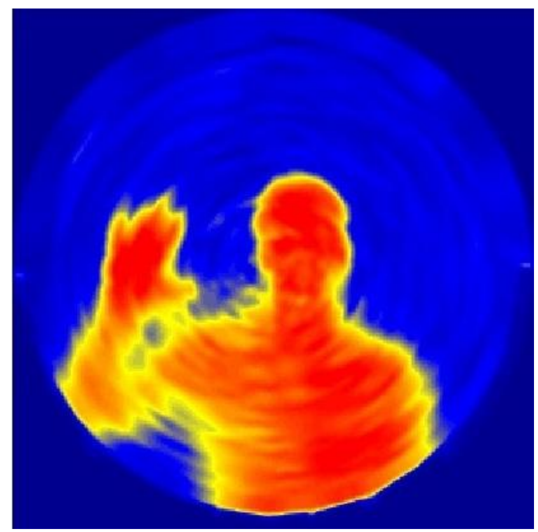
- Terahertz (THz) ✓
- stand-off
- single-pixel Camera
- FMCW-Radar

➢ image acquisition from a distance of several meters (≈10m)

THz-Body Scanner

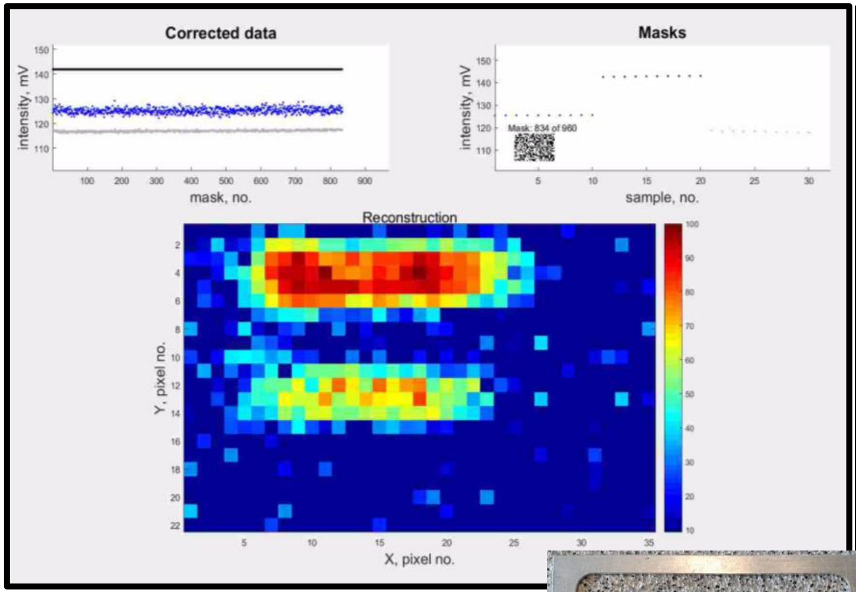
≈2m

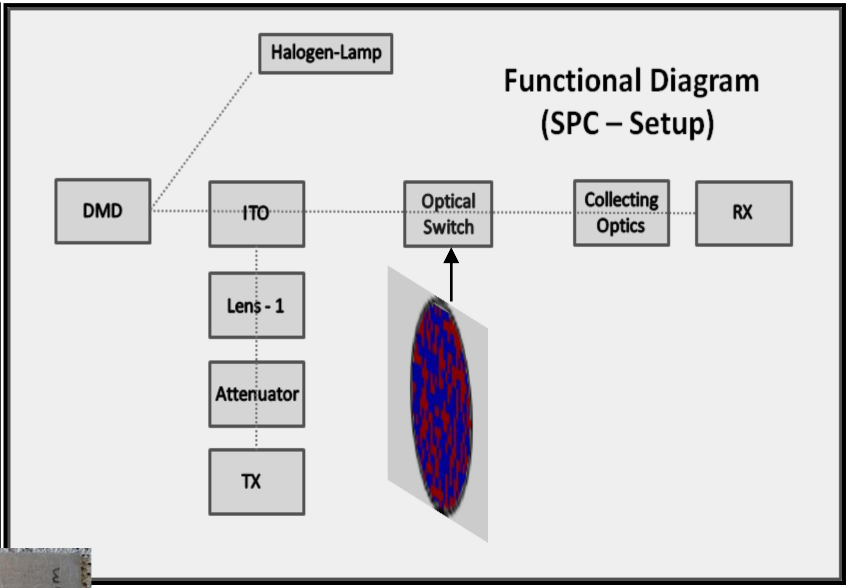
≈1.5m

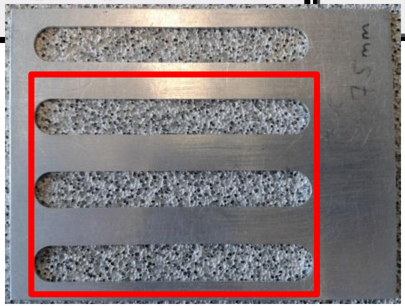


# Introduction: single-pixel camera

- Terahertz (THz) ✓
- stand-off ✓
- single-pixel Camera
- FMCW-Radar

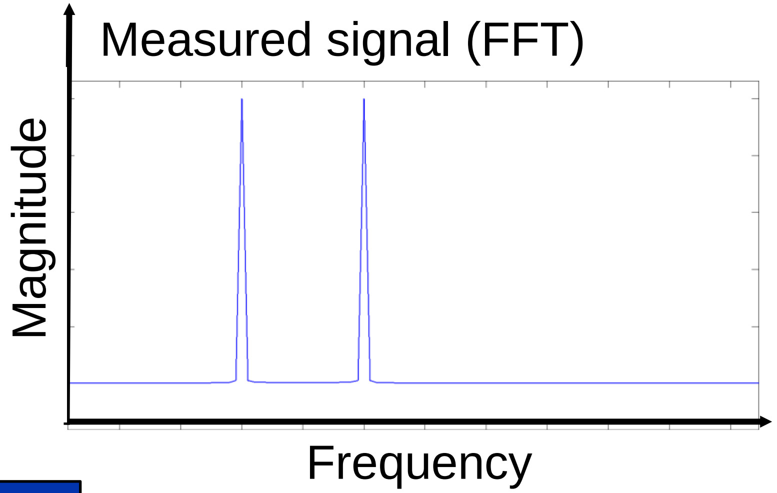


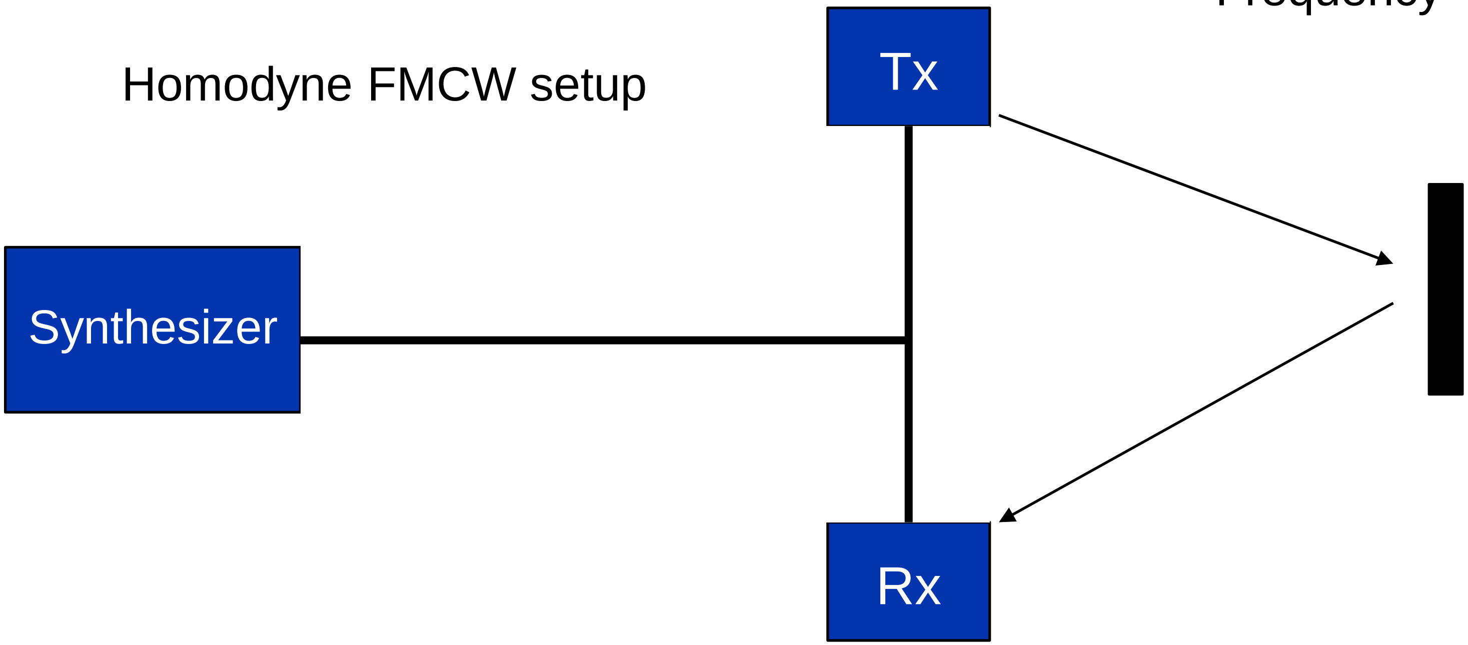



# Introduction: FMCW-Radar

- Terahertz (THz) ✓
- stand-off ✓
- single-pixel Camera ✓
- FMCW-Radar



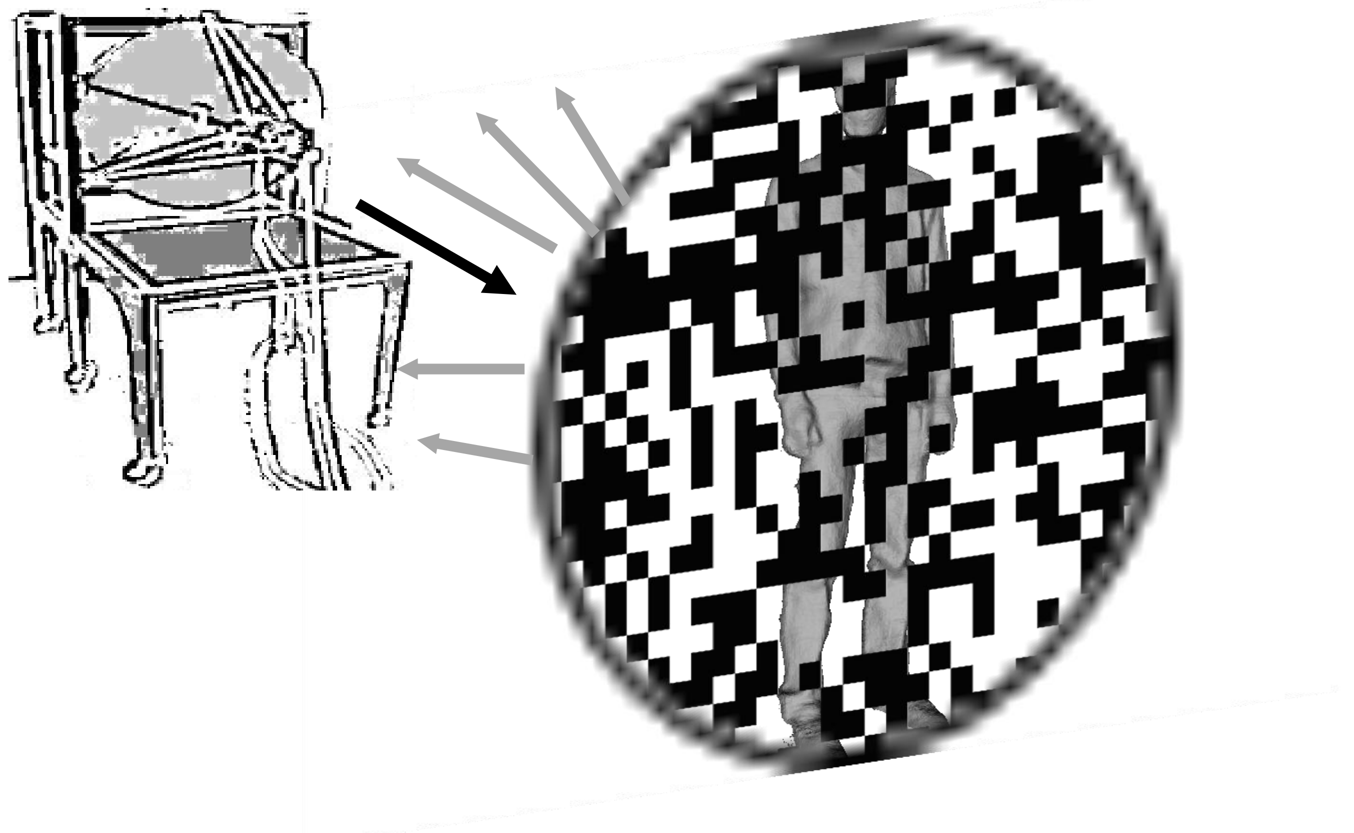

Homodyne FMCW setup



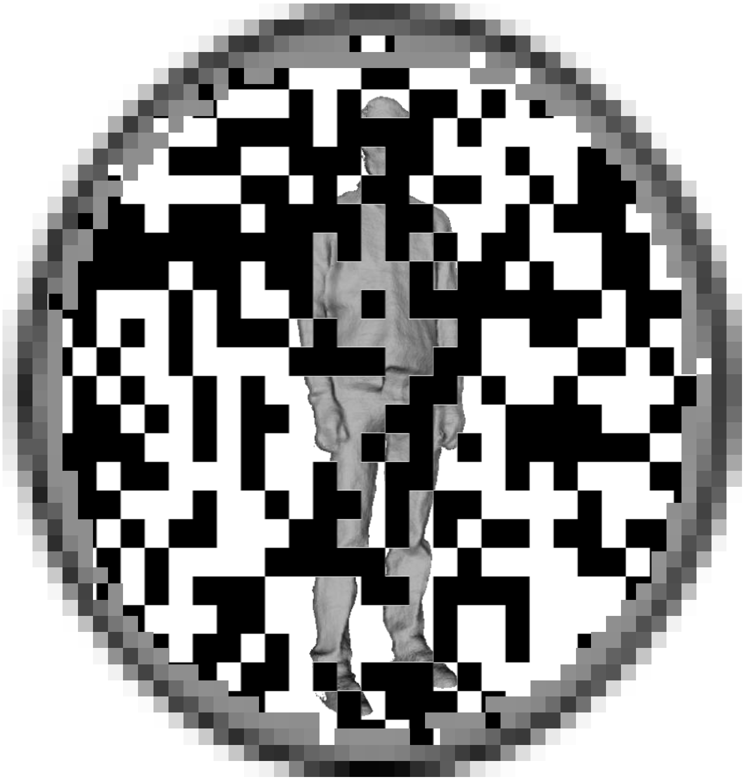
# Idea

- Terahertz (THz) ✓
- stand-off ✓
- single-pixel Camera ✓
- FMCW-Radar ✓

**combination of all aforementioned aspects**

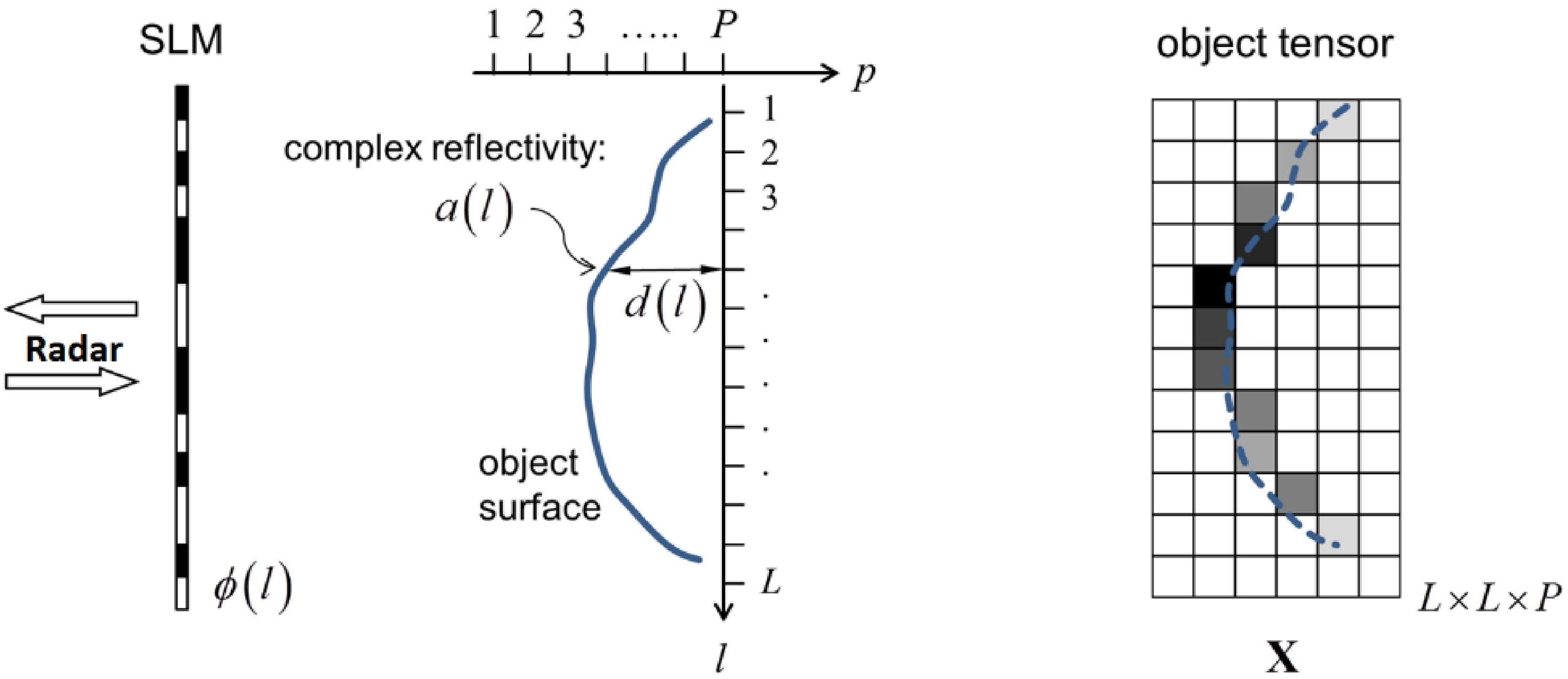


# Algorithmic Part - Outline



1. Mathematical Model
2. Reconstruction Approaches
3. Simulation Results
4. Summary & Outlook

# Model




**Measurement equation:**

$$\mathbf{Y} = \boldsymbol{\phi}\,\mathbf{X} + \mathbf{E}$$

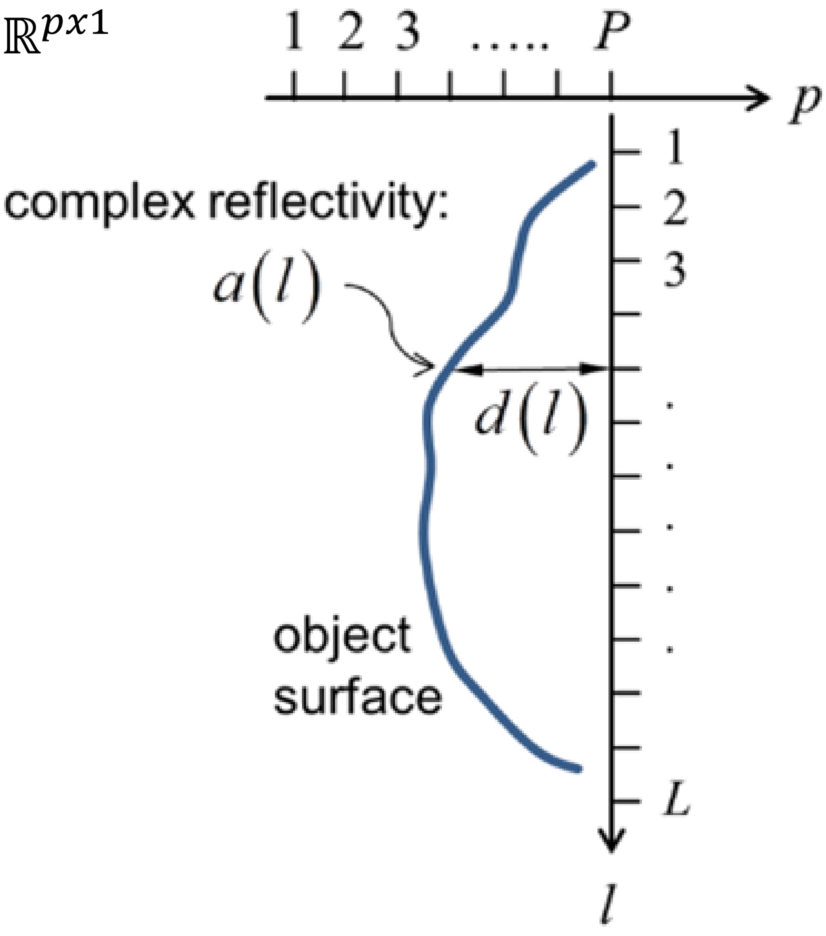
**Projection map:**

$\mathbf{a} = \mathbf{X} \cdot \mathbf{1}$, with $\mathbf{1} = [1\ 1 \ldots 1]^{\mathbf{T}} \in \mathbb{R}^{px1}$

**Depth map:**

$\mathbf{d} = \mathbf{X} \cdot \mathbf{p} \cdot \mathrm{diag}(\mathbf{a})^{-1}$,

with $\mathbf{p} = [1\ 2 \ldots \mathrm{P}]^{\mathbf{T}} \in \mathbb{R}^{px1}$



# Reconstruction approaches

- Separate slice wise

$$\mathbf{x}_{i,\text{rec}} = \underbrace{\text{argmin}}_{\mathbf{x}_i}\left\{\frac{1}{2}\|\,\boldsymbol{\phi}\,\mathbf{x}_i - \mathbf{y}_i\|_2 + \lambda_1\|\,\Psi(\mathbf{x}_i)\|_1\right\}$$

- Iterative approach using sparsity in the projection map

$$\mathbf{a}_{\text{rec}} = \underbrace{\text{argmin}}_{\mathbf{a}}\left\{\frac{1}{2}\|\,\boldsymbol{\phi}\,\mathbf{a} - \mathbf{Y}\cdot\mathbf{1}\|_2 + \lambda_1\|\,\Psi_{\text{a}}(\mathbf{a})\|_1\right\}, \text{ solve } \mathbf{X}_{\mathbf{d},\text{guess}}$$

$$= \underbrace{\text{argmin}}_{\mathbf{X}}\{\|\,\boldsymbol{\phi}\,\mathbf{X} - \mathbf{Y}\|_F\} \text{ iteratively}$$

- 3D reconstruction with additional regularizing terms

$$\mathbf{X}_{\text{rec}} = \underbrace{\text{argmin}}_{\mathbf{X}}\left\{\frac{1}{2}\|\,\boldsymbol{\phi}\,\mathbf{X} - \mathbf{Y}\|_F + \lambda_1\|\,\Psi_{\text{a}}(\mathbf{a}(\mathbf{X}))\|_1 + \lambda_2\|\,\Psi_{\text{d}}(\mathbf{d}(\mathbf{X}))\|_1 + \lambda_3\left\|\,[\nabla(\mathbf{a}(\mathbf{X})), \nabla(\mathbf{d}(\mathbf{X}))]\right\|_{1,2}\right\}$$

# Reconstruction approaches - iterative

- **using sparsity in the projection map**
- **includes the knowledge that we probably have only one element in each row:**

Step 1: solve $\mathbf{a}_{\text{rec}} = \underbrace{\text{argmin}}_{\mathbf{a}} \left\{ \frac{1}{2} \| \boldsymbol{\phi}\, \mathbf{a} - \mathbf{Y} \cdot \mathbf{1} \|_2 + \lambda_1 \| \Psi_{\text{a}}(\mathbf{a}) \|_1 \right\}$

*up to a high accuracy of a*

Step 2: $\mathbf{X}_{\mathbf{d},\text{guess}} = \underbrace{\text{argmin}}_{\mathbf{X}} \{ \| \boldsymbol{\phi}\, \mathbf{X} - \mathbf{Y} \|_F \}$

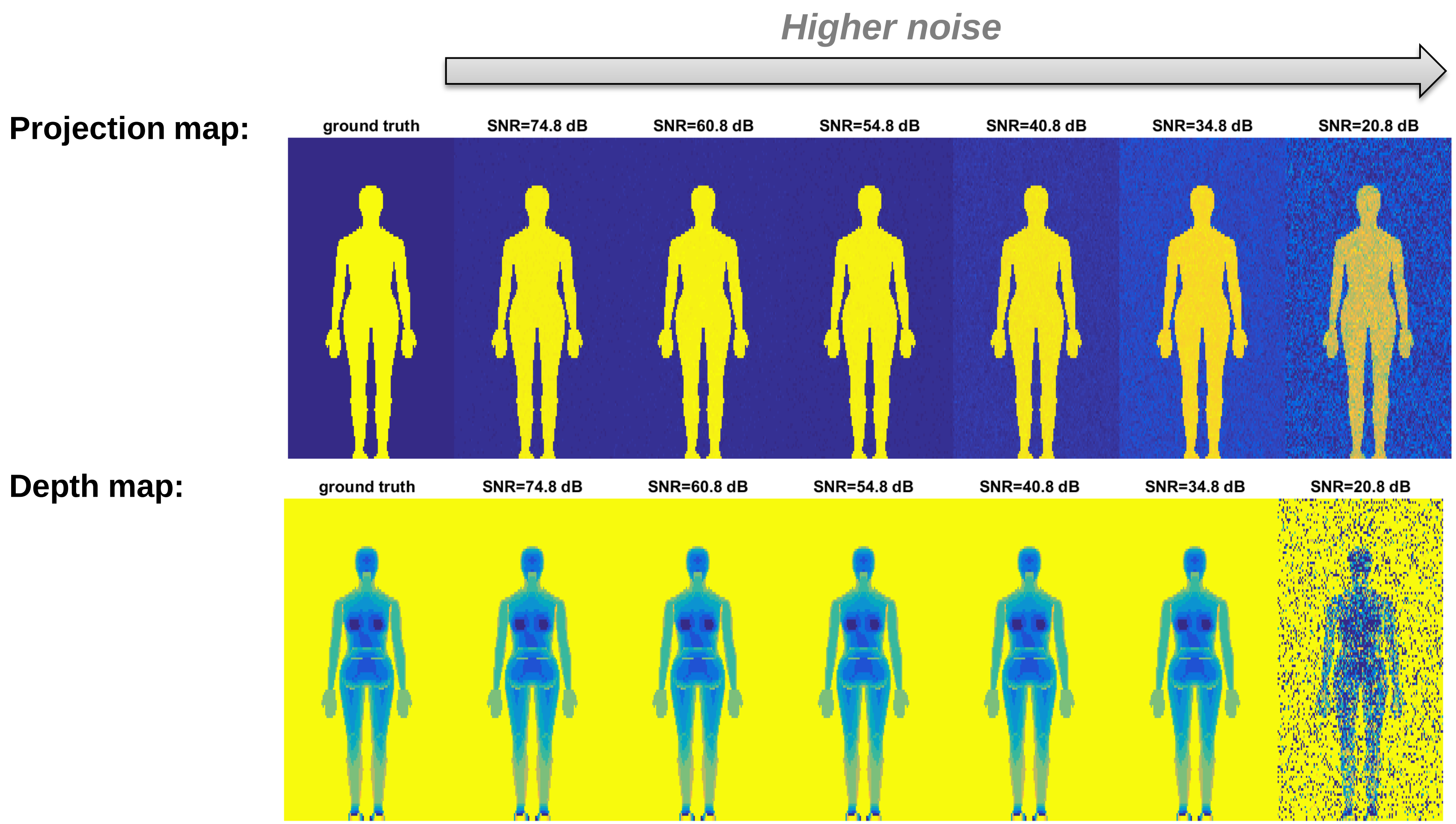
*iteratively*

Step 3: find maxima in each row of **X**

Step 4: new **X** is created with zeros and projection map coefficients at the maxima positions

Step 5: Go to step 2

## Simulation with human 3D point cloud for varying measurement noise:

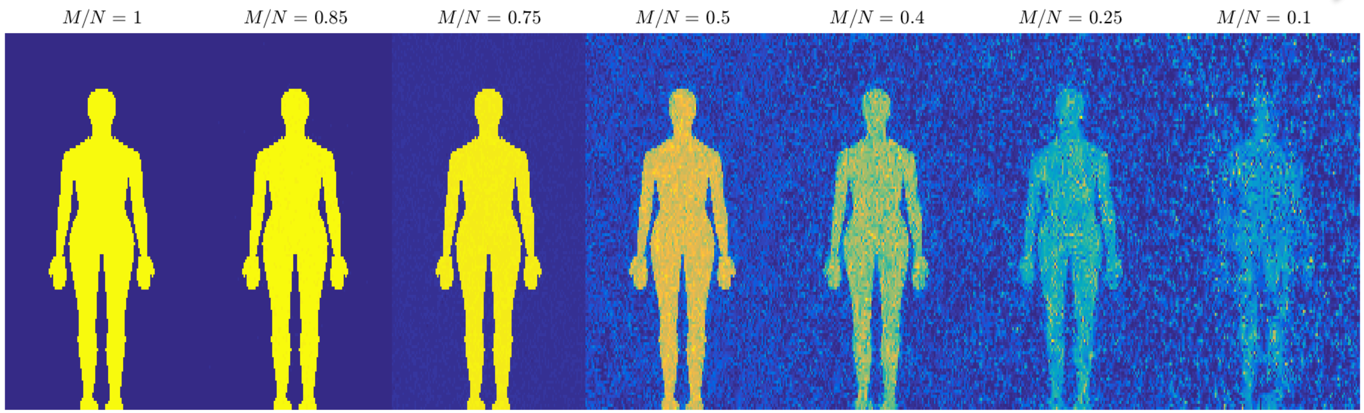



Sampling ratio: M = 0.75N

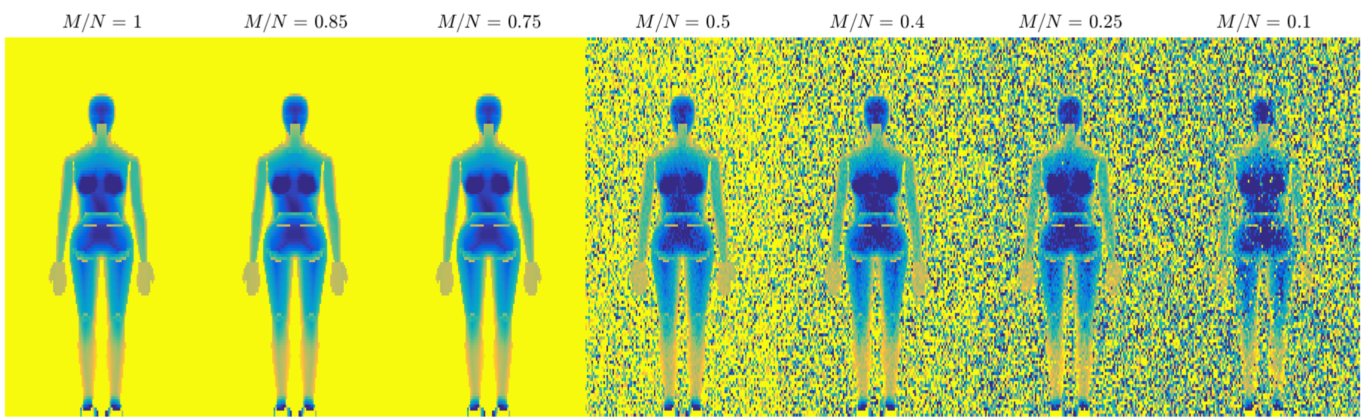
**Simulation with human 3D point cloud for varying number of measurements:**

*Lower Sampling* →

**Projection map:**




**Depth map:**



# Summary & Outlook

- novel combination of THz FMCW radar with a single-pixel measurement approach
- for the reconstruction of 3D (2.5D) images an iterative algorithm was proposed
- the presented iterative algorithm exploits sparsity in the projection map a
- next steps: Algorithm will be tested on real data
  evaluation and refinement (multiple scattering events?)
  model extensions (coherent radiation)

Thank you!