On the determination and description of fabric in natural granular materials

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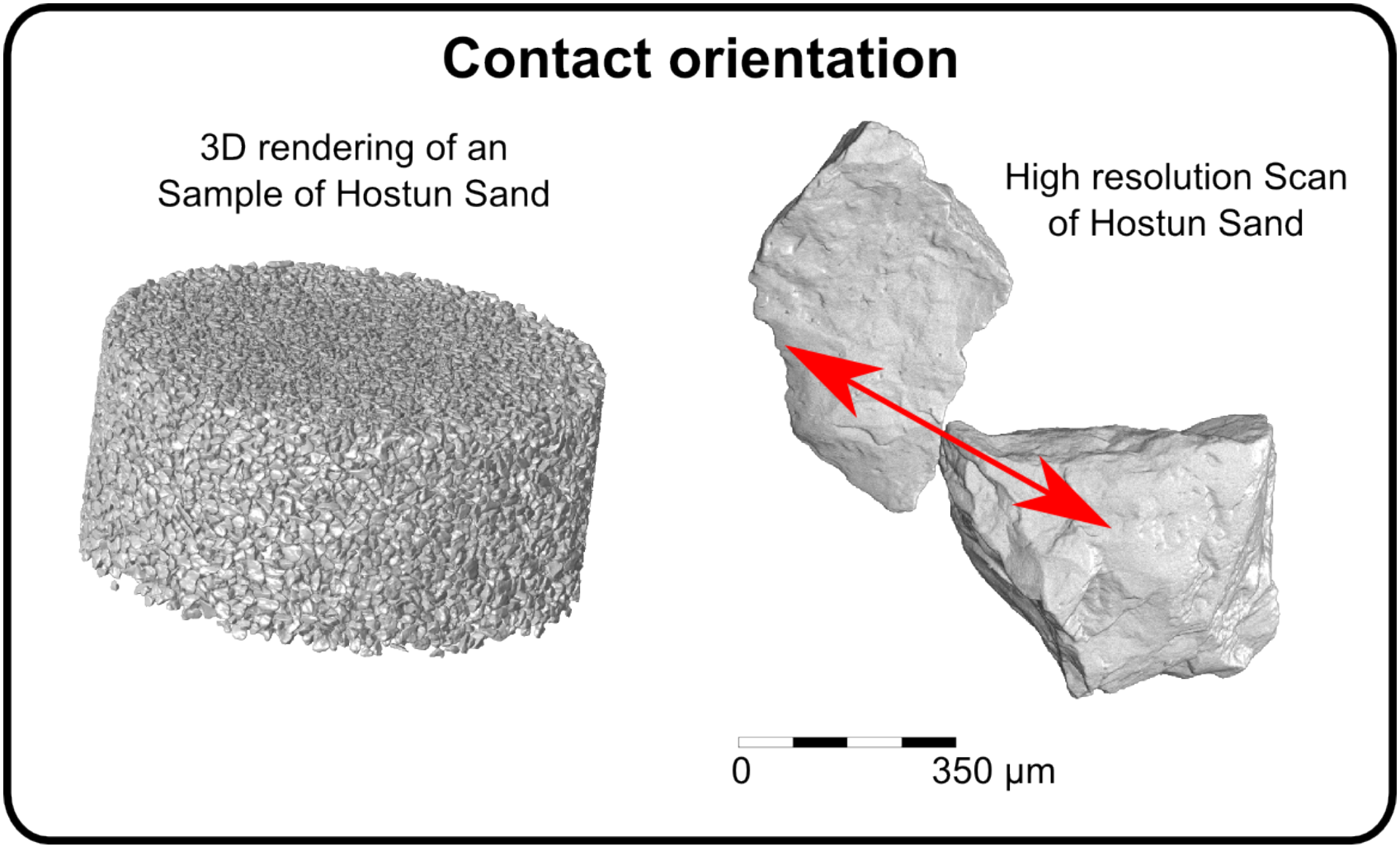
The full description of micro-mechanical behaviour may be divided into three points:

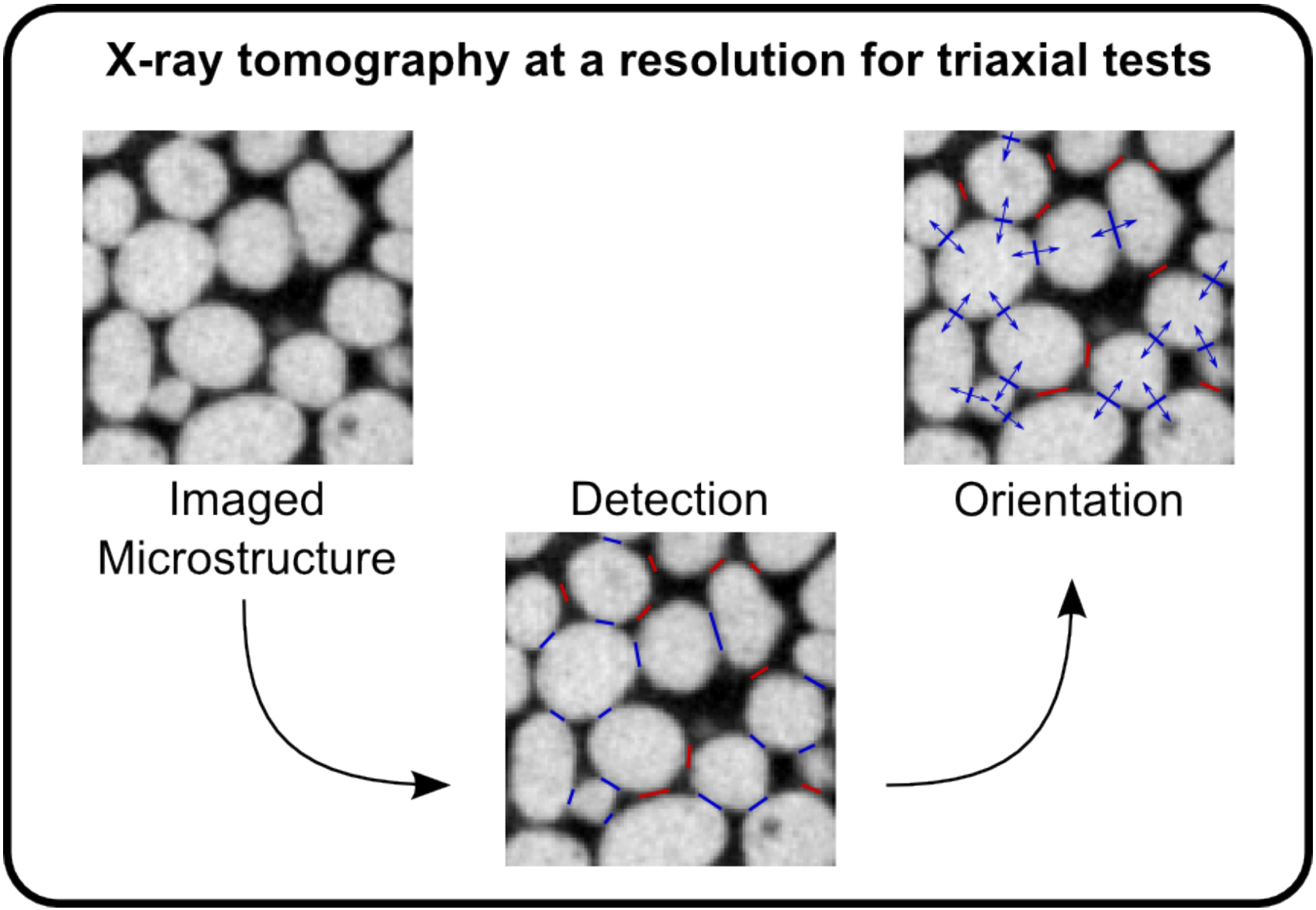
1. *Description of the structure, that is to say, positions of grains and contacts between them.*
2. *Description of the kinematics evolution: displacements, rotations, evolution of contacts.*
3. *Description of inter-granular forces.*

from: F. Calvetti, G. Combe and J. Lanier: Experimental micromechanical analysis of a 2D granular material: relation between structure evolution and loading path. *Mechanics of cohesive-frictional materials, VOL. 2, 121-163, 1997*

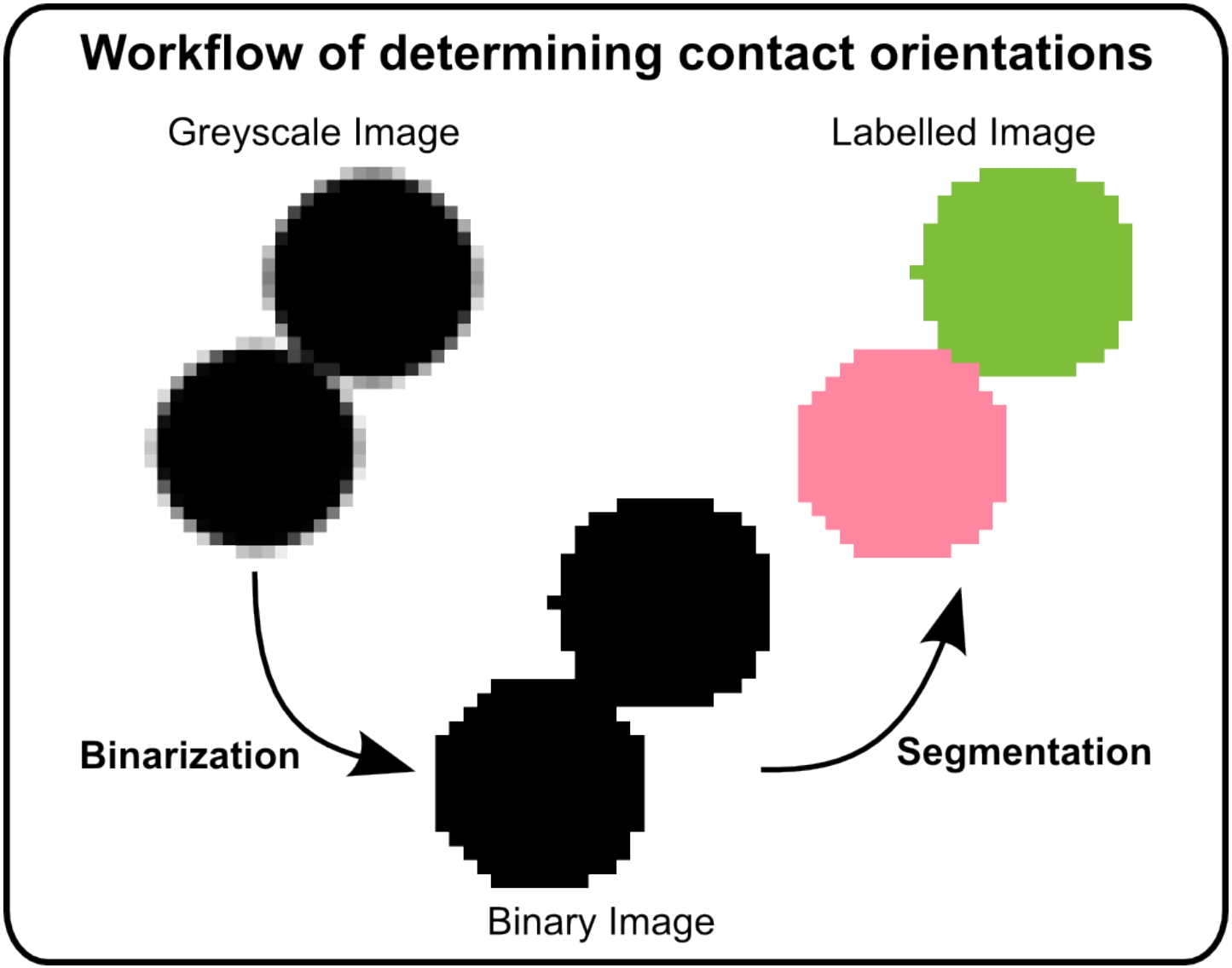
What do we want to measure?



How can we measure contact orientations?



How can we measure contact orientations?

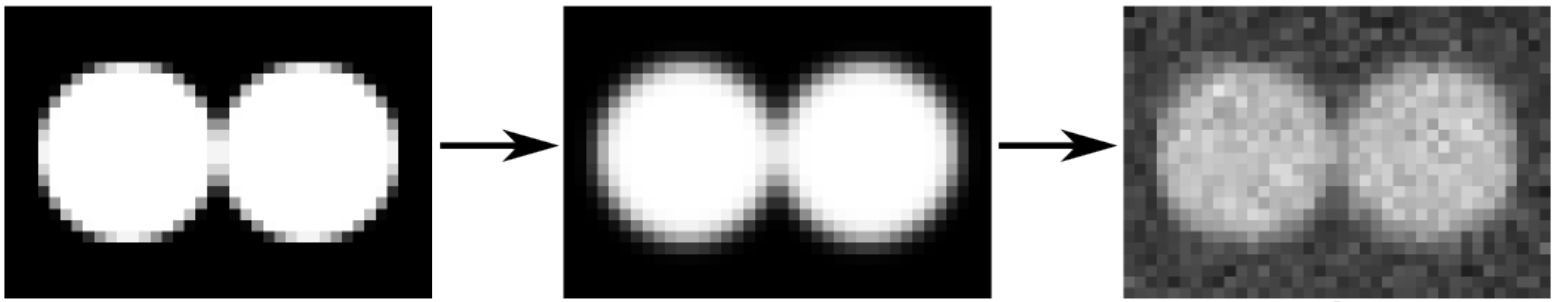


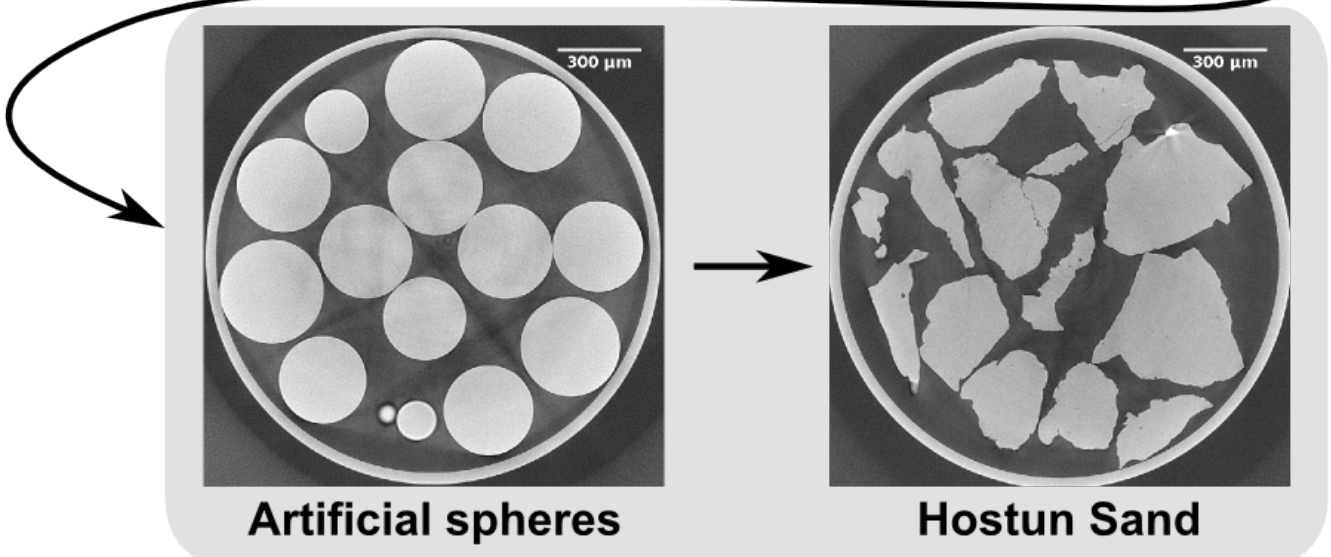
How accurate are the standard approaches to determine contact orientations?

Strategy to approach the analysis

Artificial images

Perfect spheres → Blurred spheres → Noised spheres



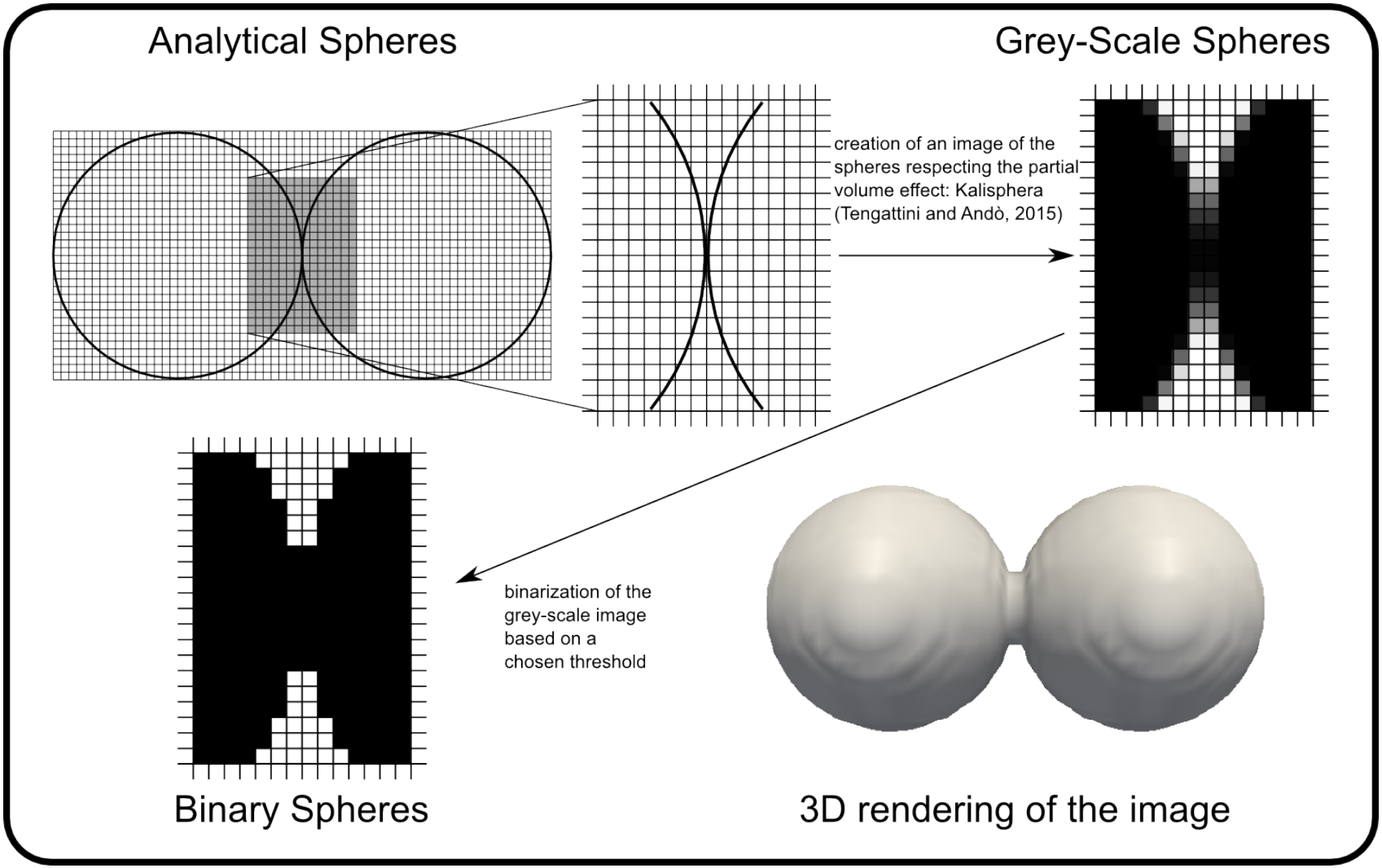


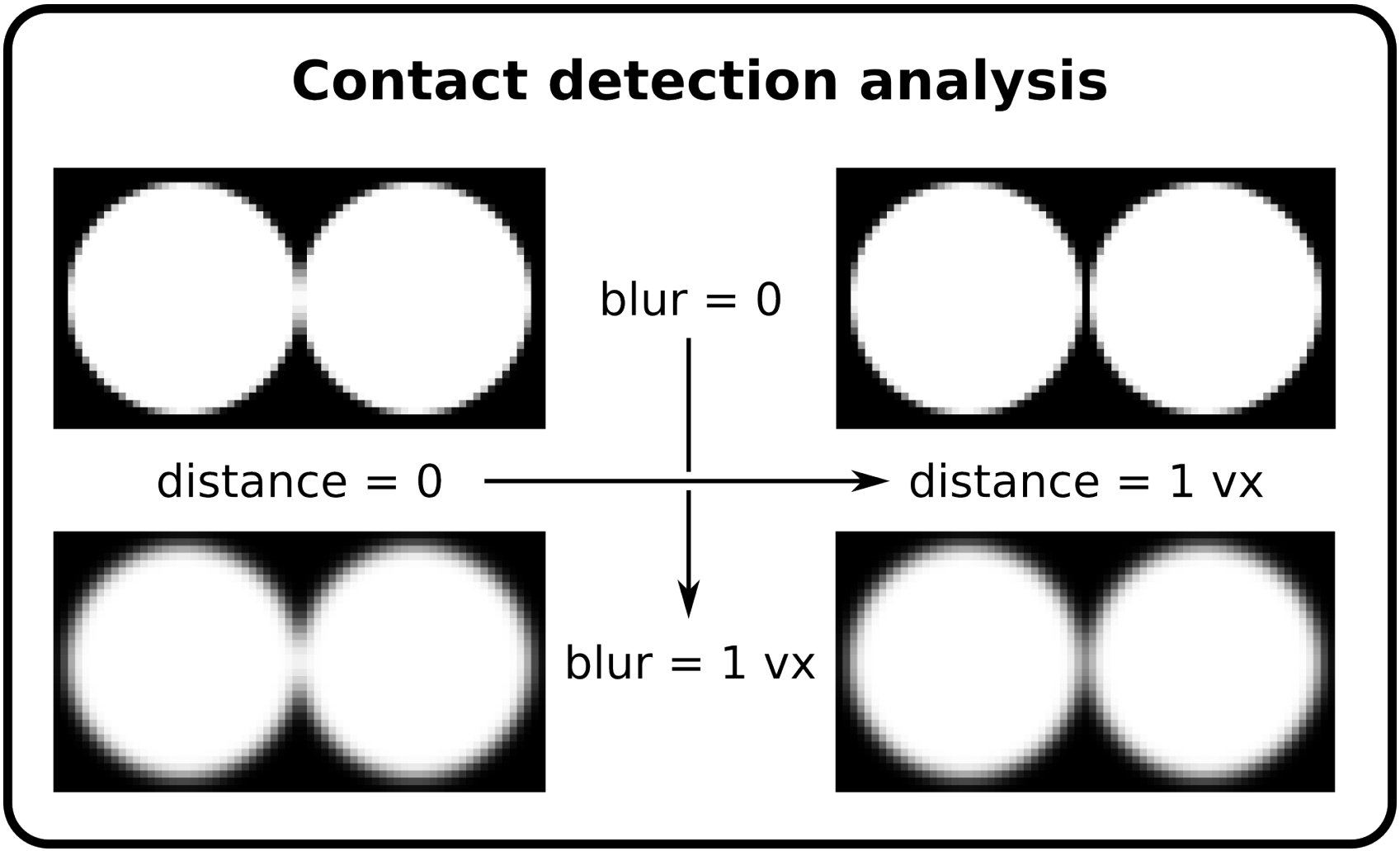
Artificial spheres → Hostun Sand

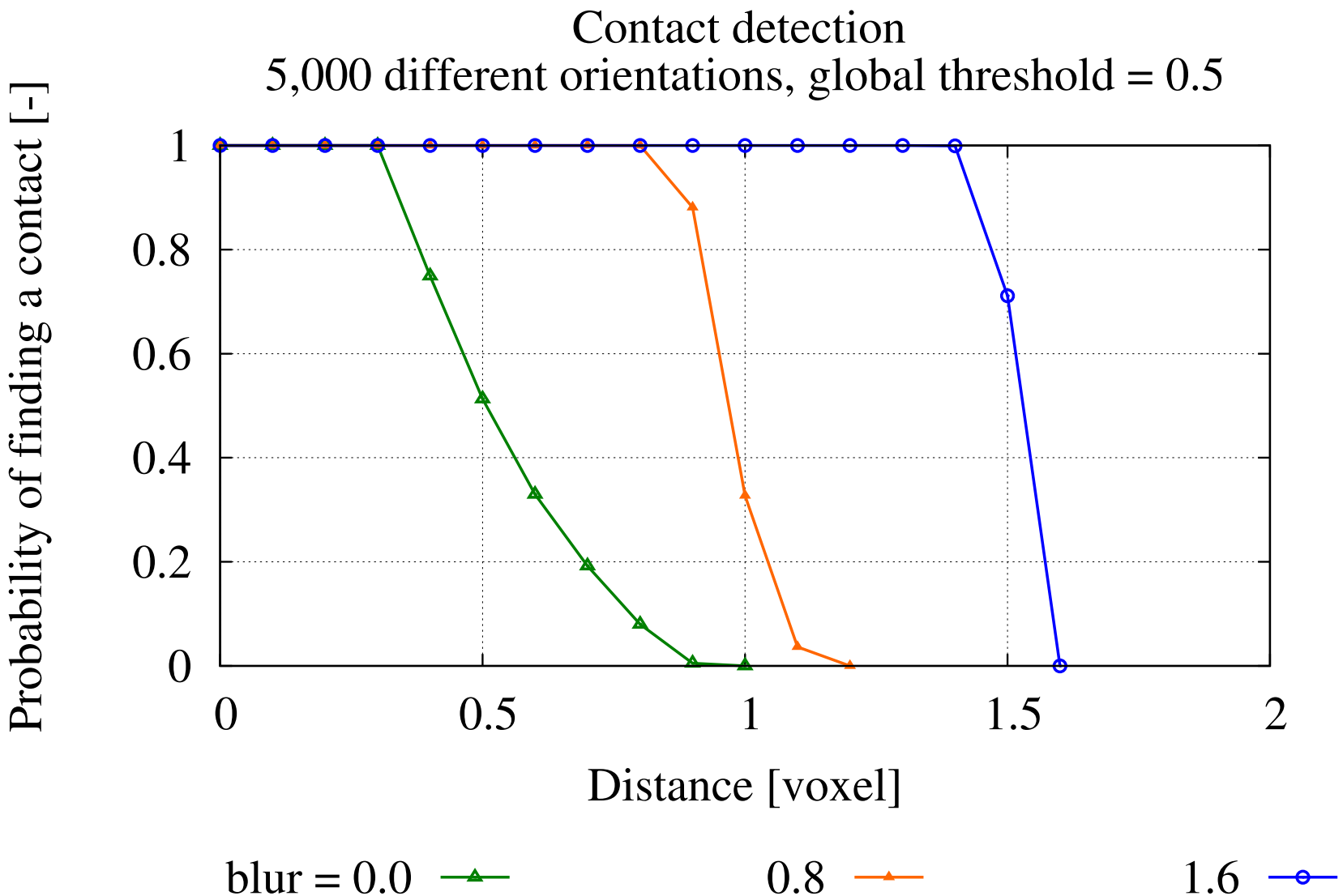
Real tomographies

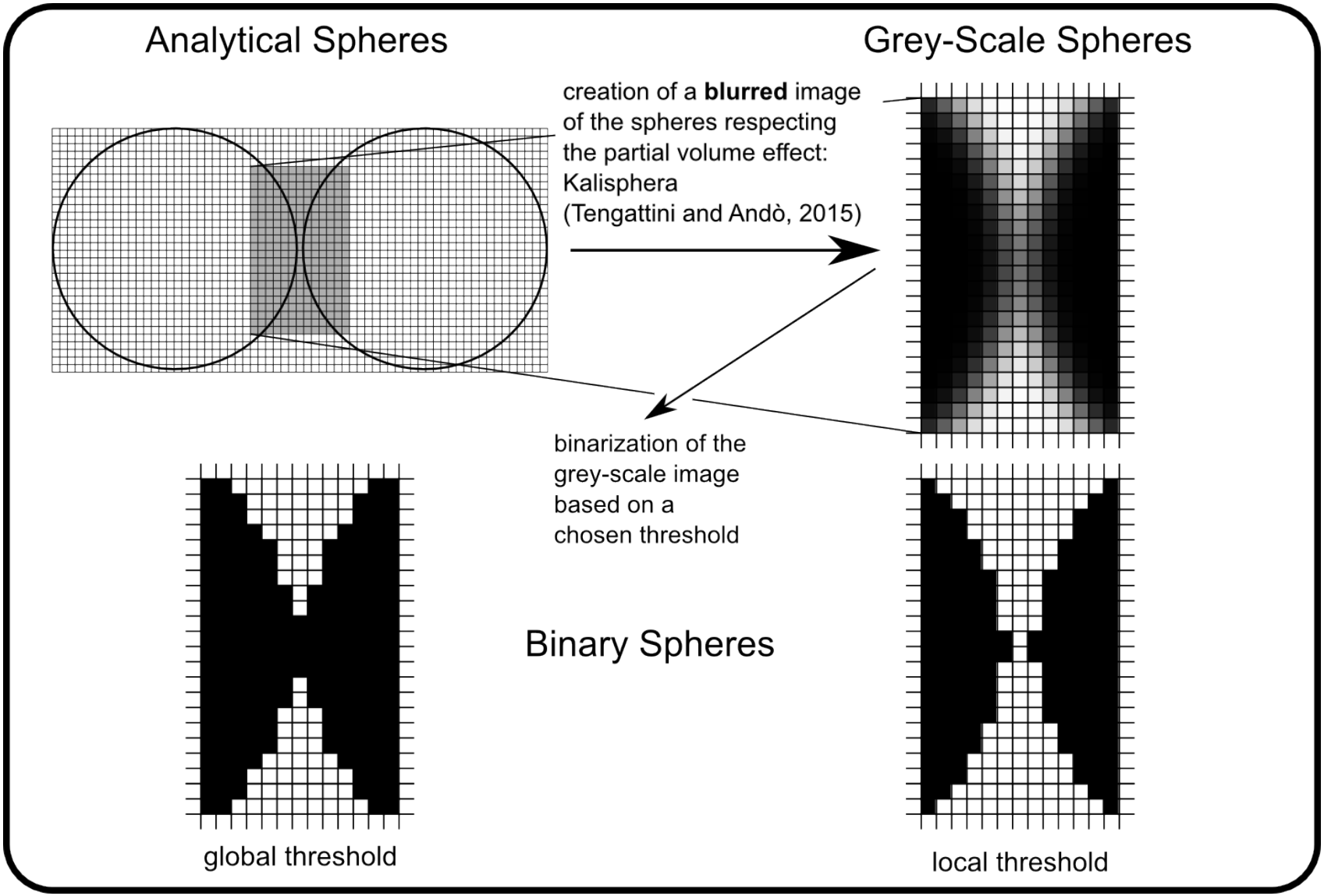
Contact detection

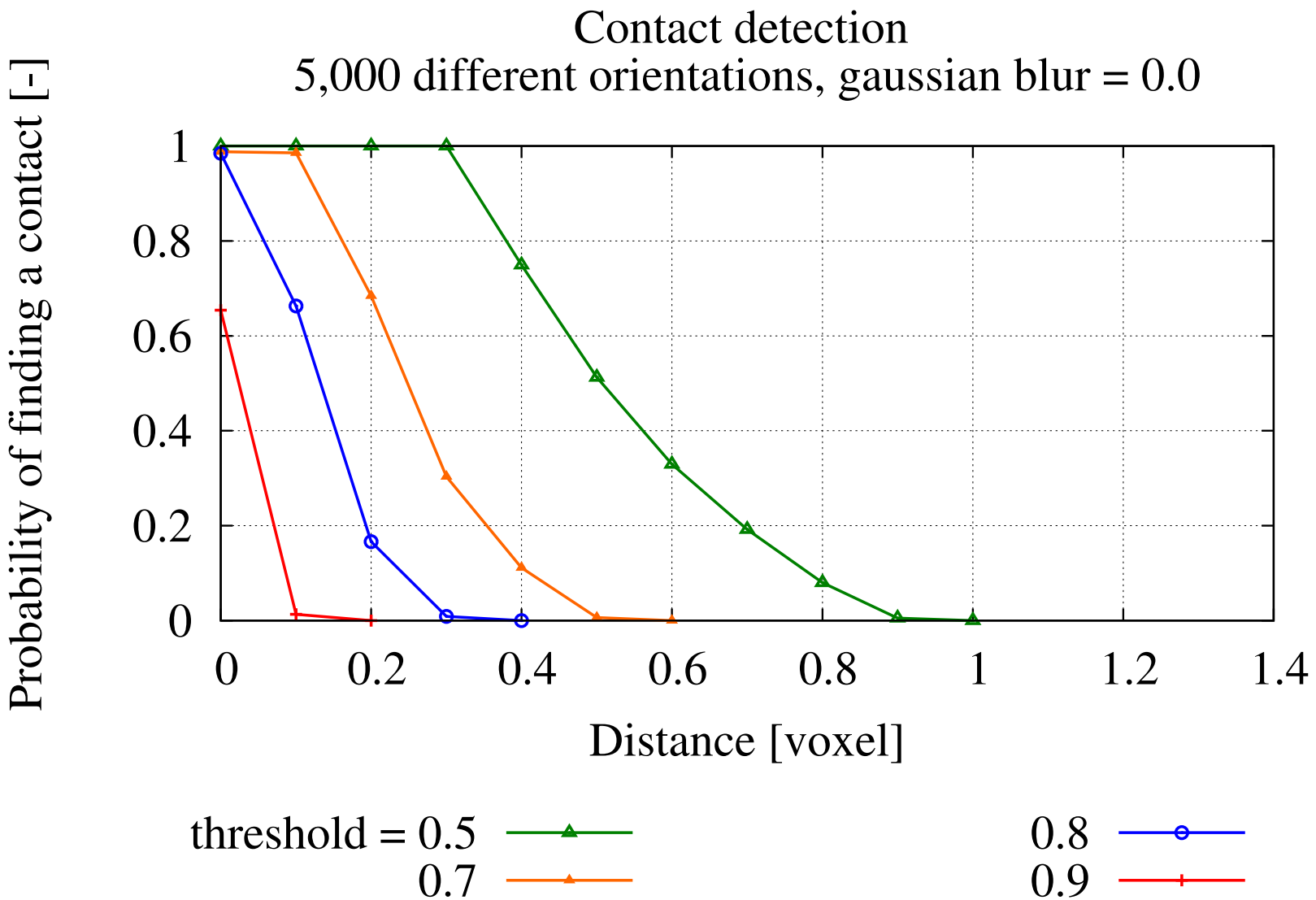
Artificial spheres

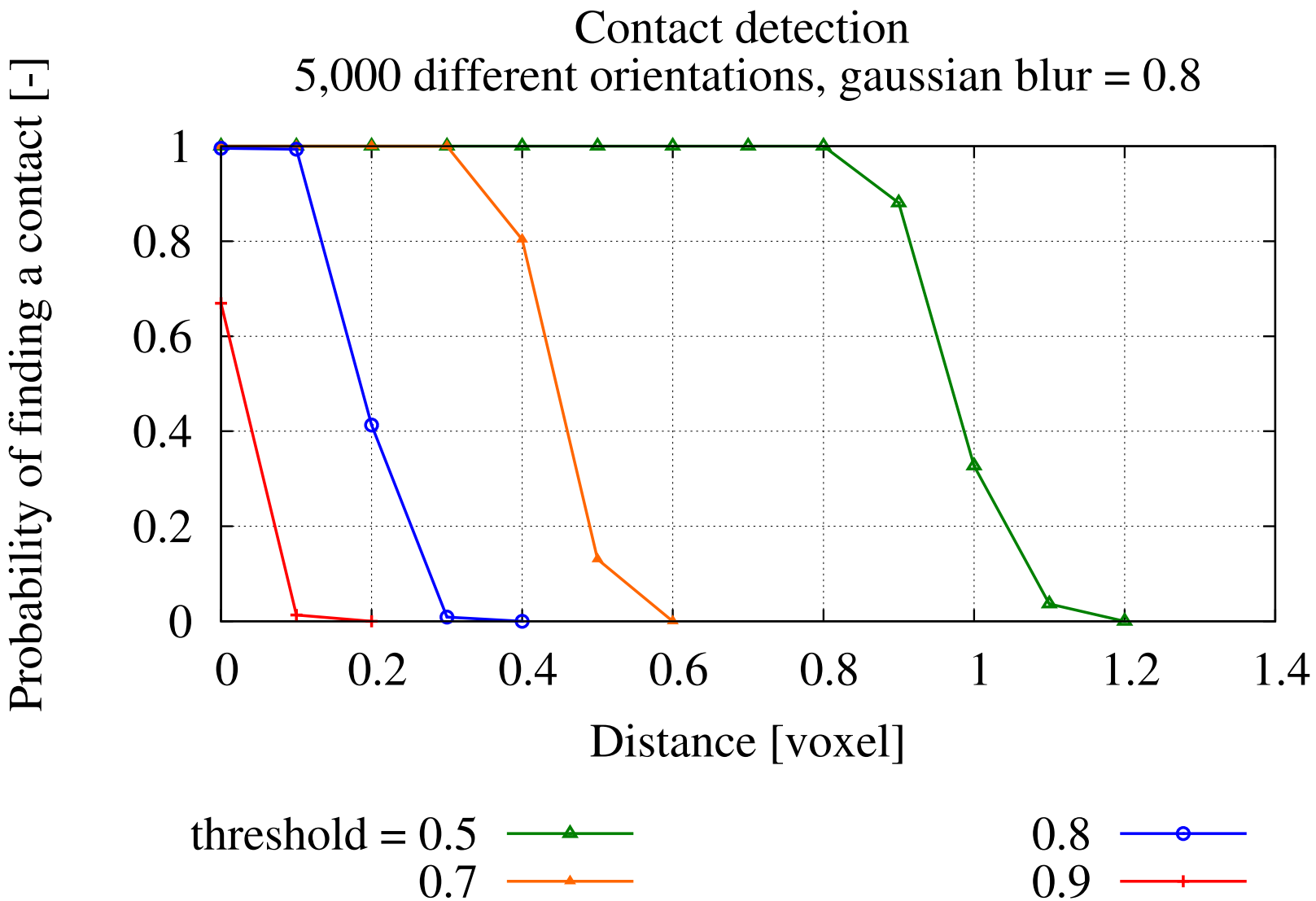

Analytical Spheres
Grey-Scale Spheres
creation of an image of the spheres respecting the partial volume effect: Kalisphera (Tengattini and Andò, 2015)
binarization of the grey-scale image based on a chosen threshold
Binary Spheres
3D rendering of the image


Contact detection analysis
blur = 0
distance = 0
distance = 1 vx
blur = 1 vx


Contact detection
5,000 different orientations, global threshold = 0.5
Probability of finding a contact [-]
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
Distance [voxel]
blur = 0.0
0.8
1.6


Analytical Spheres
Grey-Scale Spheres
creation of a **blurred** image of the spheres respecting the partial volume effect: Kalisphera (Tengattini and Andò, 2015)
binarization of the grey-scale image based on a chosen threshold
Binary Spheres
global threshold
local threshold


Contact detection
5,000 different orientations, gaussian blur = 0.0
Probability of finding a contact [-]
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Distance [voxel]
threshold = 0.5
0.7
0.8
0.9


Contact detection
5,000 different orientations, gaussian blur = 0.8
Probability of finding a contact [-]
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Distance [voxel]
threshold = 0.5
0.7
0.8
0.9

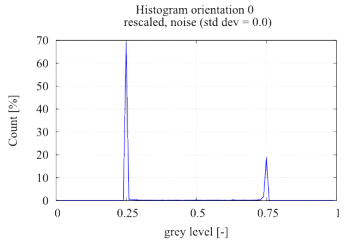
Contact detection

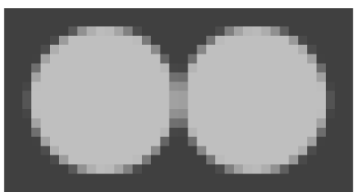
Adding noise

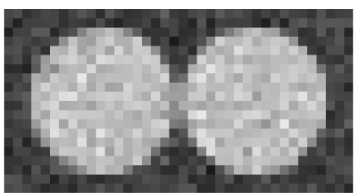
Adding noise to Kalisphera images

I added noise here with the numpy function numpy.random.normal()
it deviates (σ ... standard deviation) the value of each voxel around the given one (0.25,0.75) in the original array

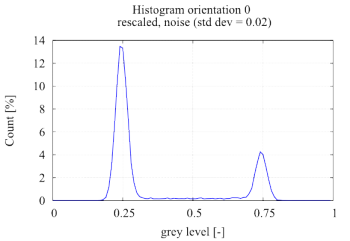
σ = 0.00

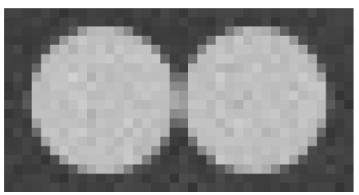


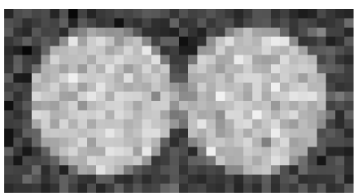




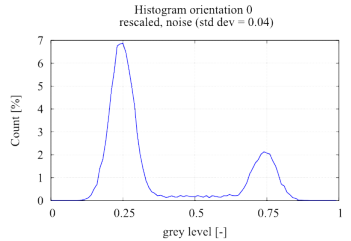
σ = 0.02

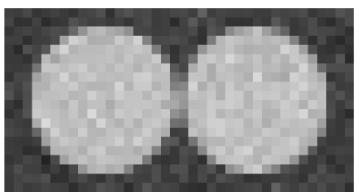


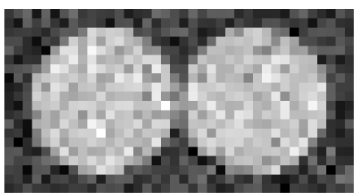


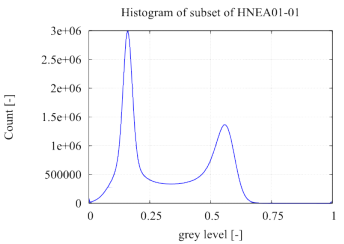


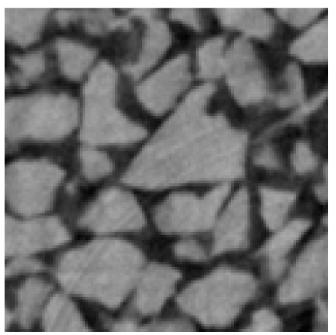
σ = 0.04



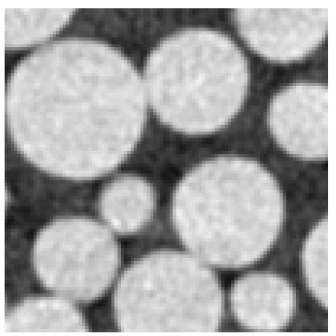




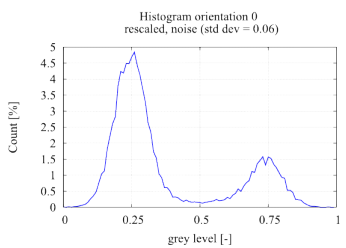




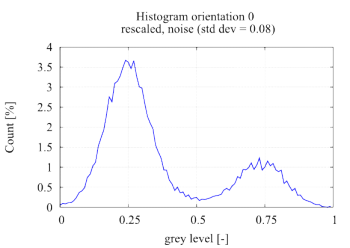
HNEA01-01



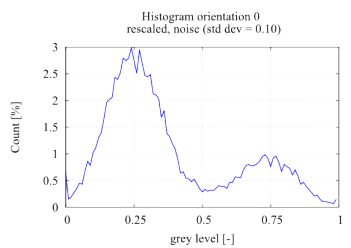
PSEA01-01



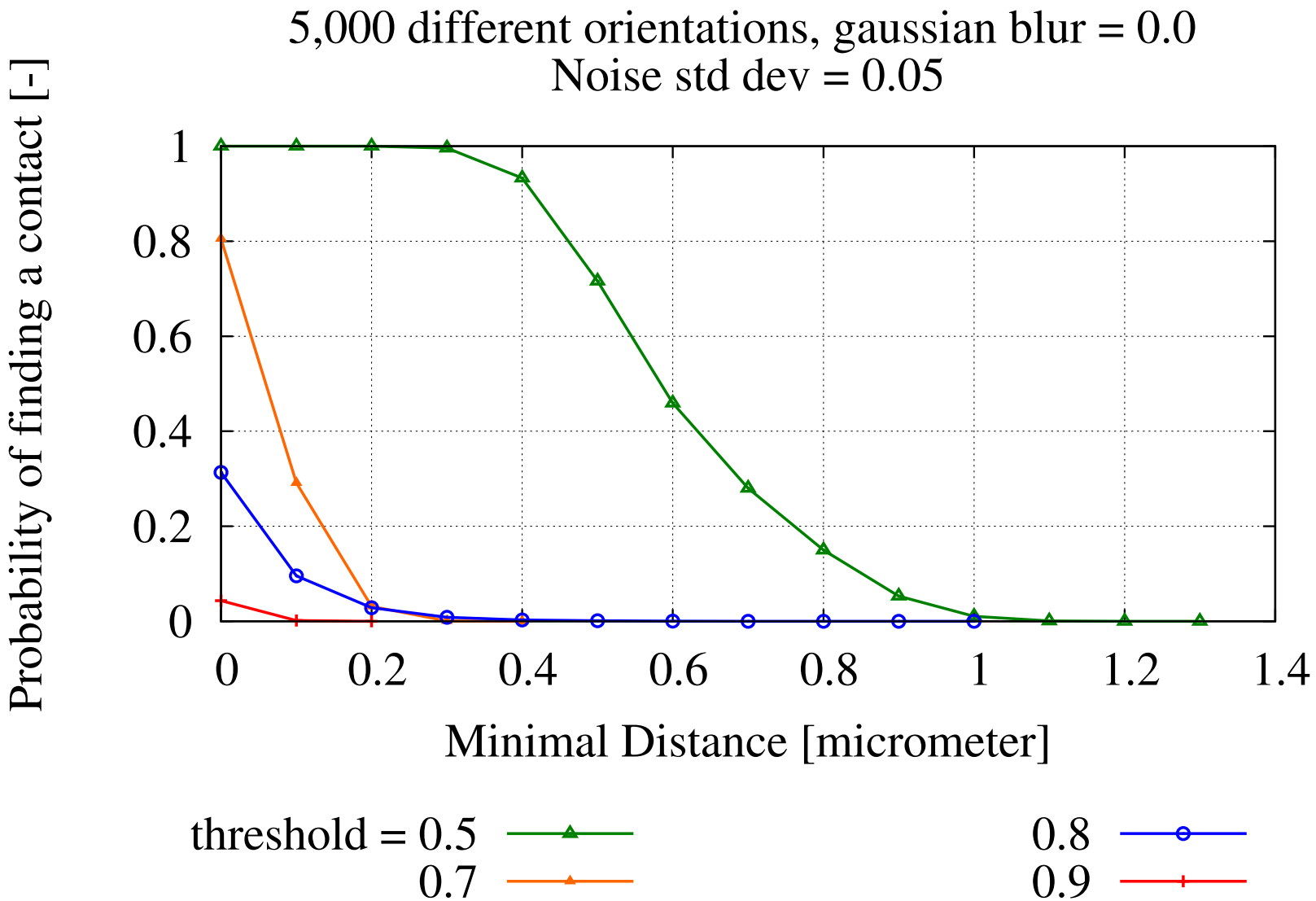
σ = 0.06



σ = 0.08



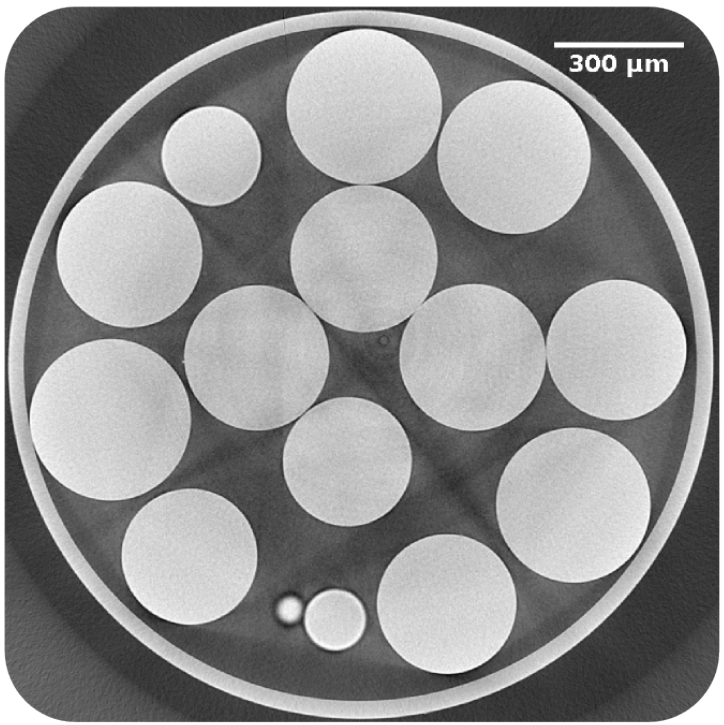
σ =0.10


5,000 different orientations, gaussian blur = 0.0
Noise std dev = 0.05
Probability of finding a contact [-]
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Minimal Distance [micrometer]
threshold = 0.5
0.7
0.8
0.9

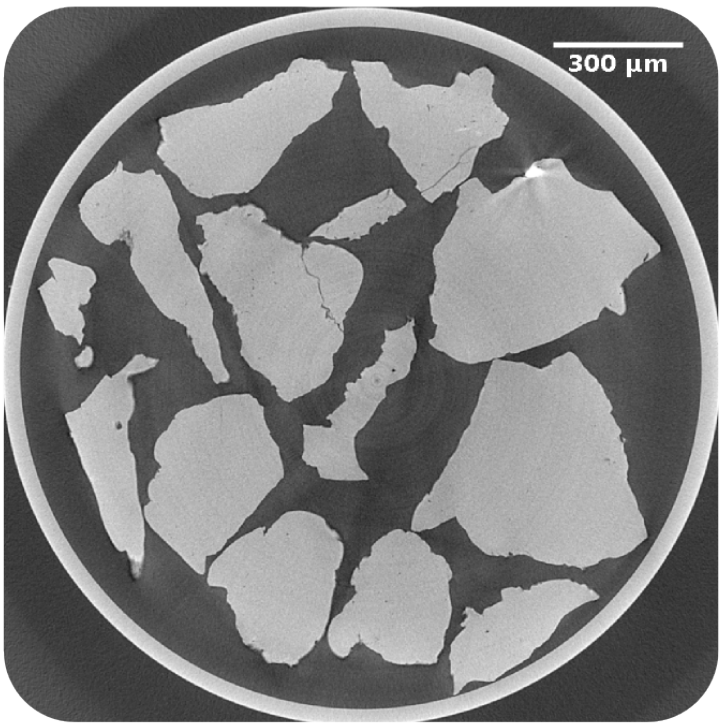
Contact detection

Getting real

Nano X-ray CT's at a resolution of 1 µm/pixel



Ruby Spheres



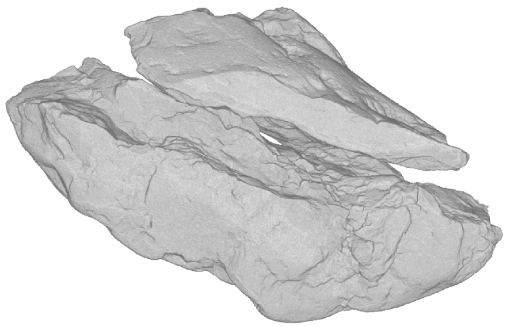
Hostun Sand

Contact detection analysis with high resolution images

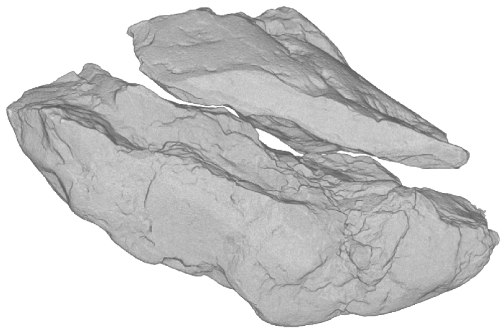
Grains in high resolution are translated away from each other and
scaled down subsequently (for every distance) until a contact can be found

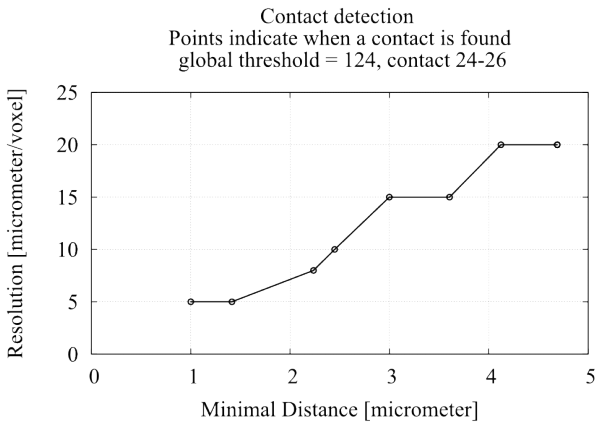
3D rendering of the grains in contact in different distances

distance = 1µm

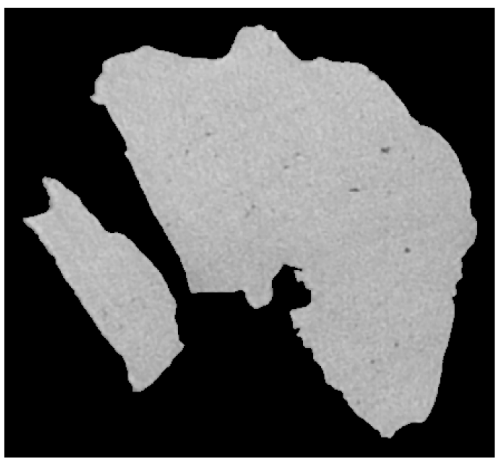


distance = 4.69µm

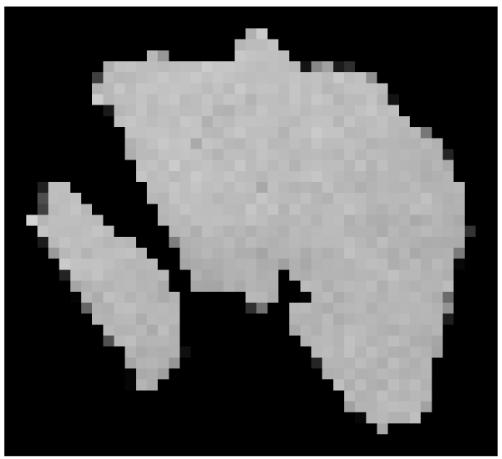




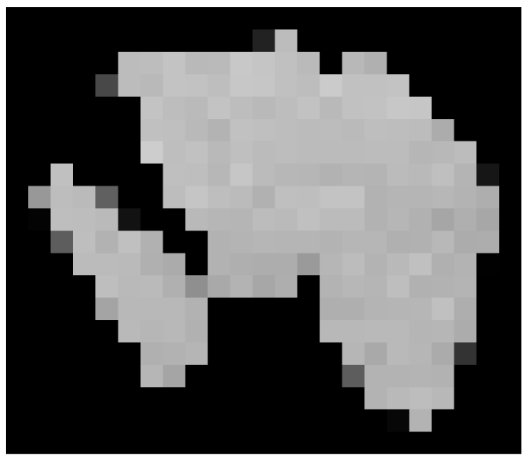
slices of the grains in contact in the distance = 4.69µm at different resolutions



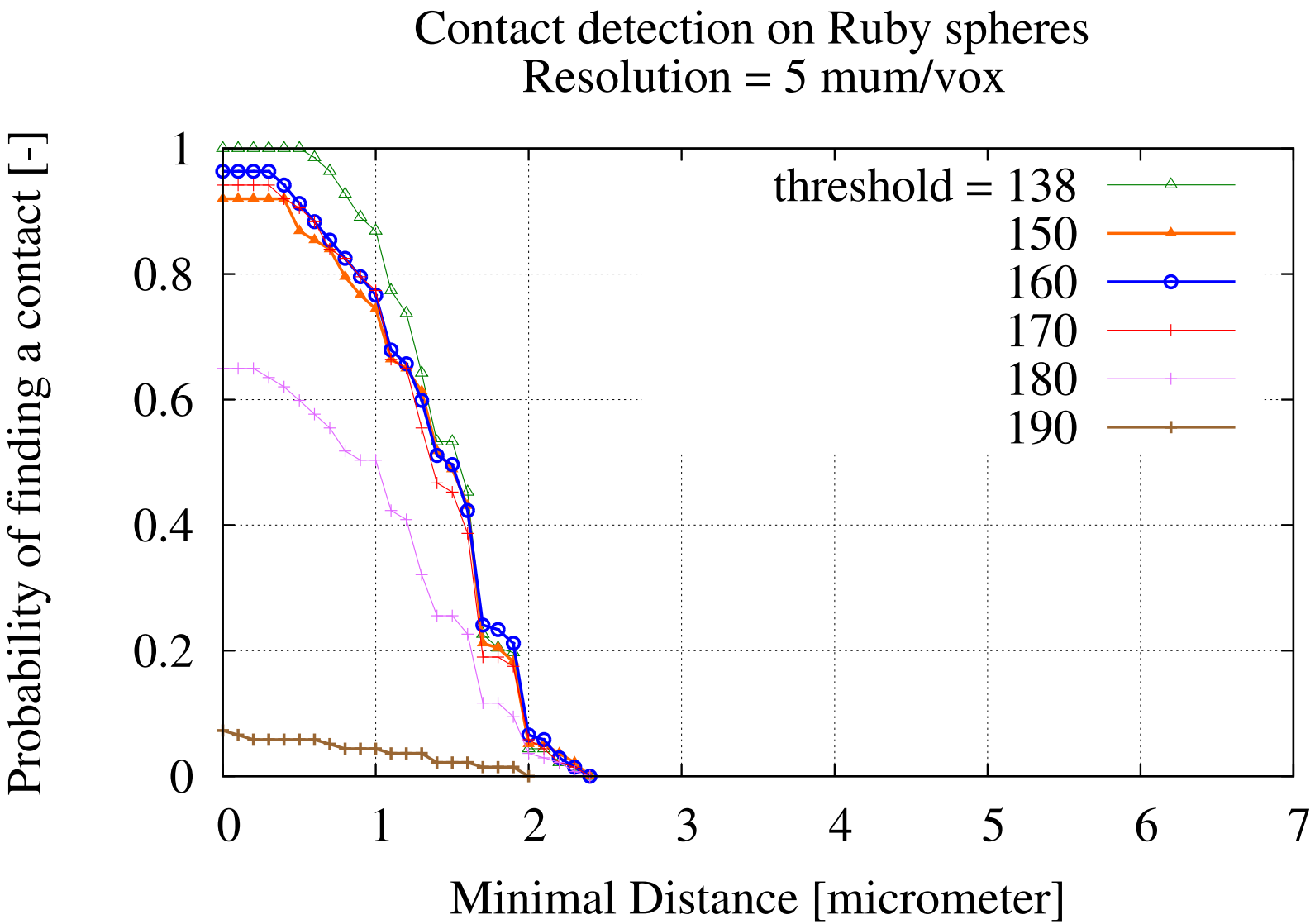
resolution = 1µm

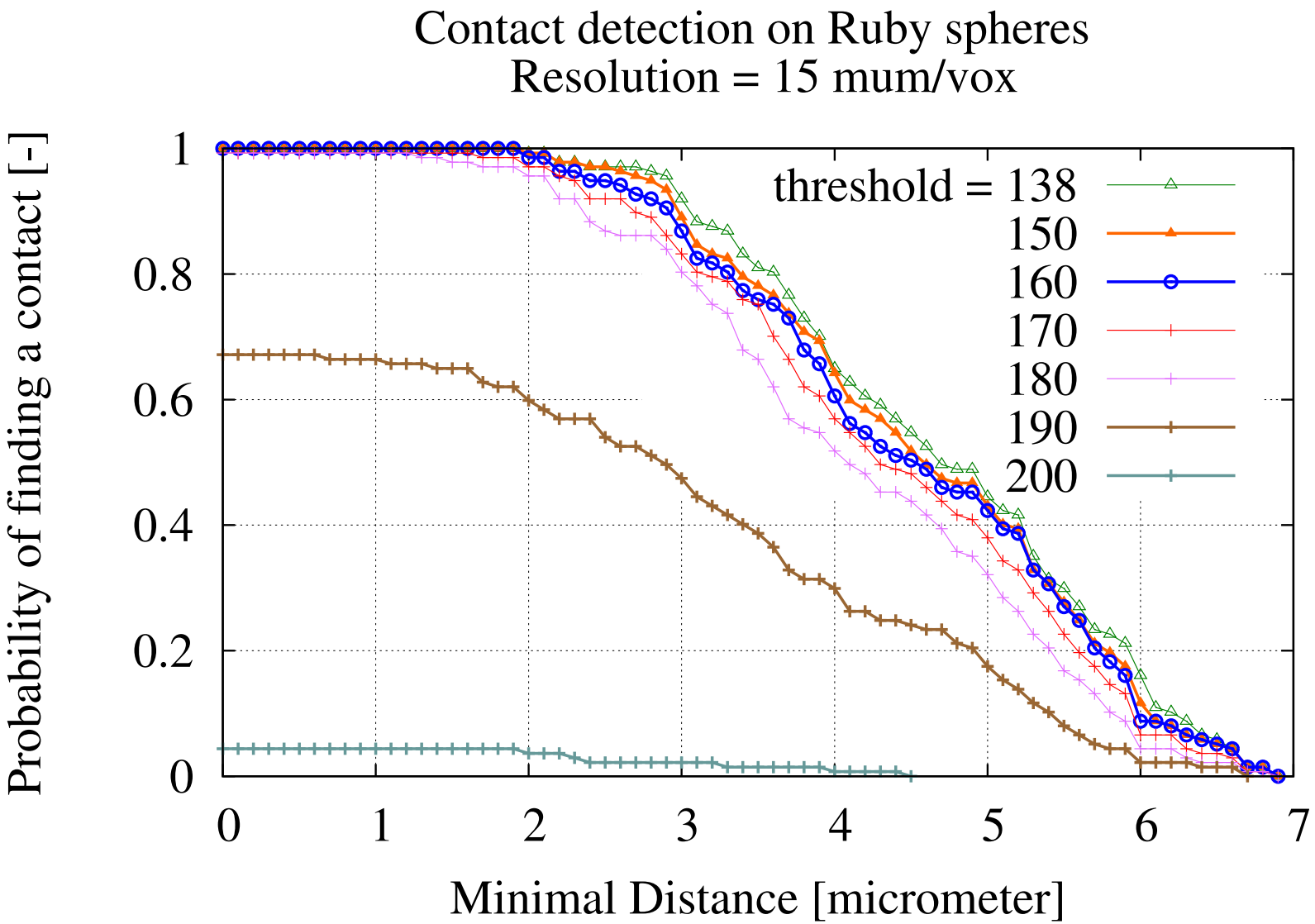


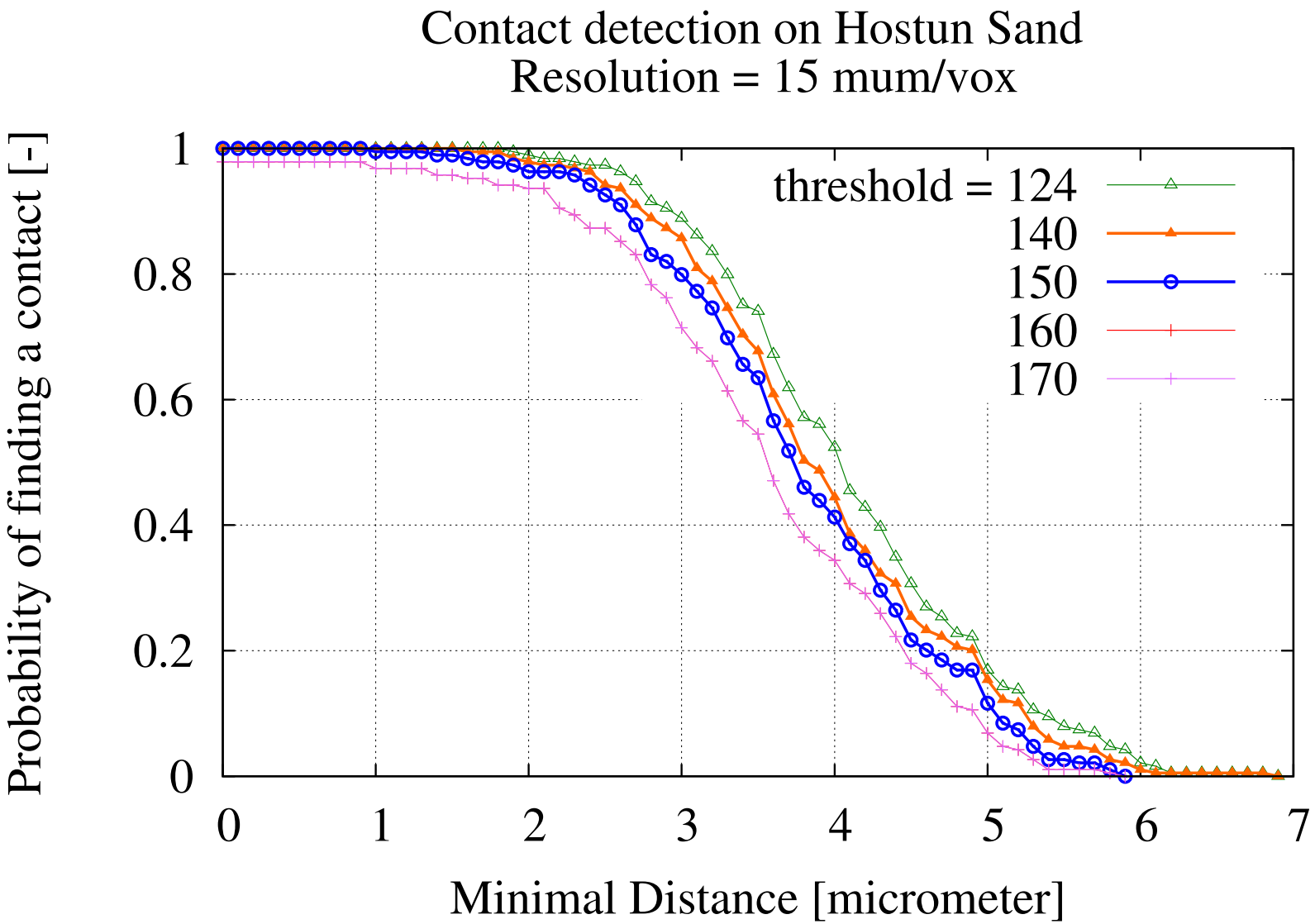
resolution = 10µm



resolution = 20µm


Contact detection on Ruby spheres
Resolution = 5 mum/vox
Probability of finding a contact [-]
Minimal Distance [micrometer]
threshold = 138
150
160
170
180
190
0
0.2
0.4
0.6
0.8
1
0
1
2
3
4
5
6
7

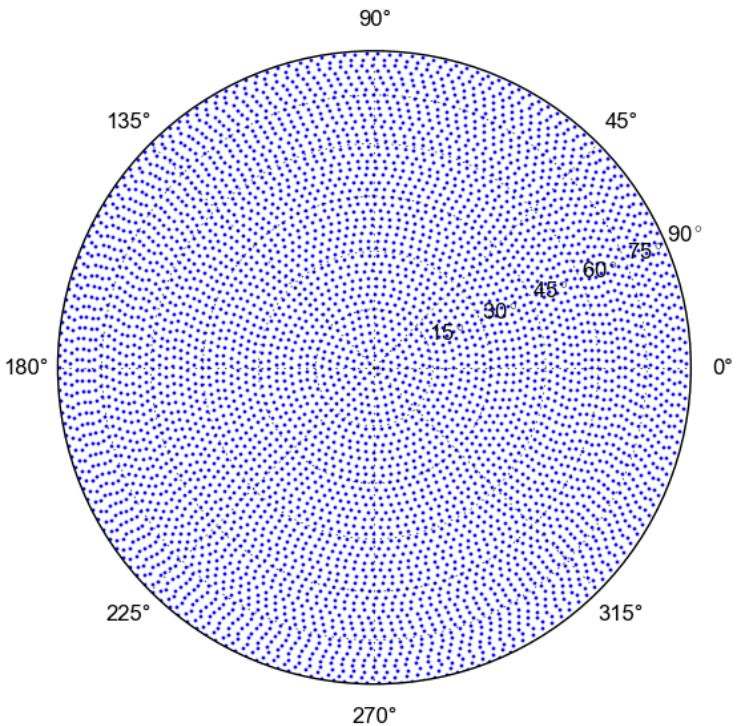

Contact detection on Ruby spheres
Resolution = 15 mum/vox
Probability of finding a contact [-]
Minimal Distance [micrometer]
threshold = 138
150
160
170
180
190
200
0
0.2
0.4
0.6
0.8
1
0
1
2
3
4
5
6
7


Contact detection on Hostun Sand
Resolution = 15 mum/vox
Probability of finding a contact [-]
Minimal Distance [micrometer]
threshold = 124
140
150
160
170
0
0.2
0.4
0.6
0.8
1
0
1
2
3
4
5
6
7

Contact orientation

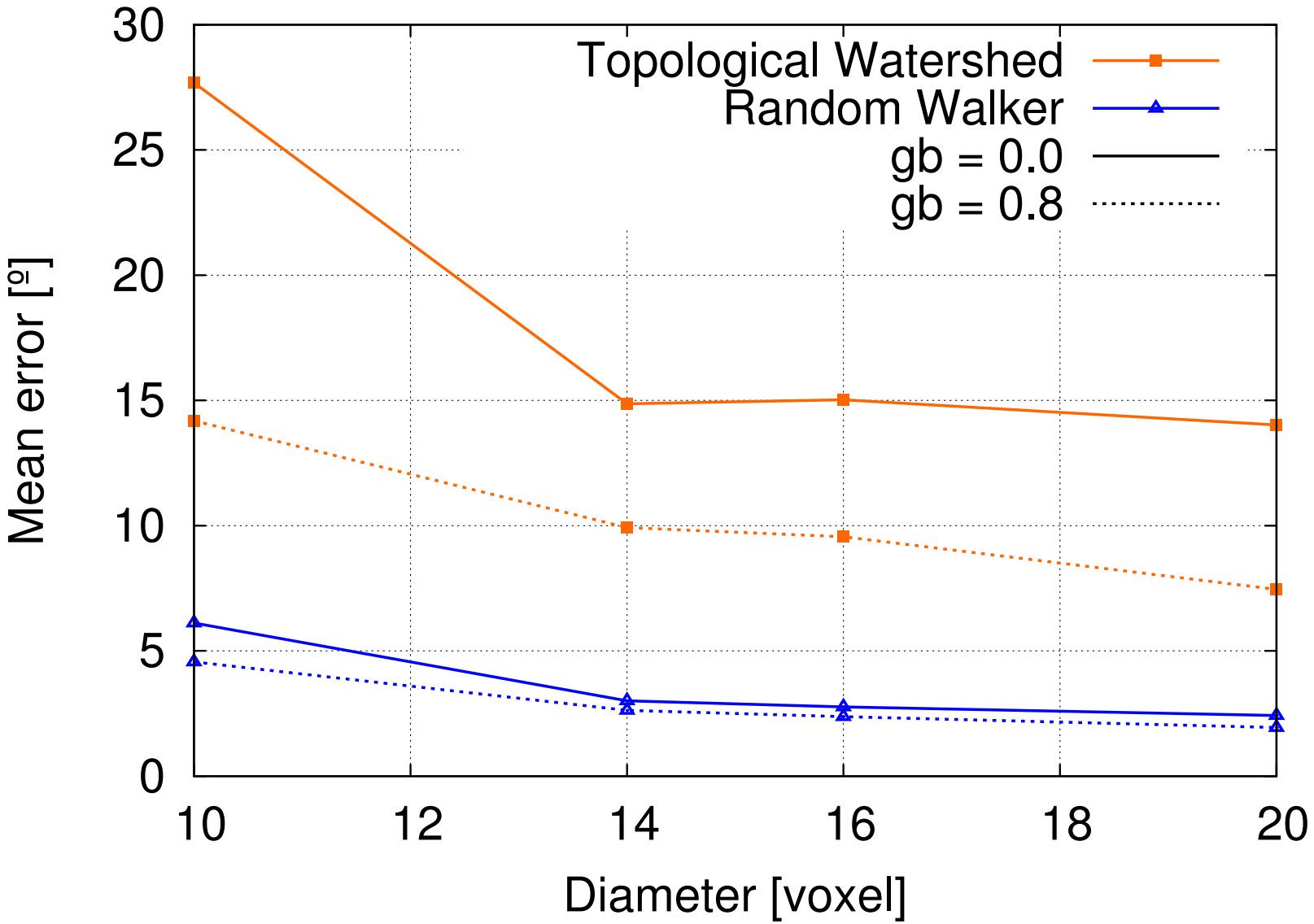
Artificial spheres

Orientation of Contacts



Lambert azimuthal equal-area projection of the imposed orientations

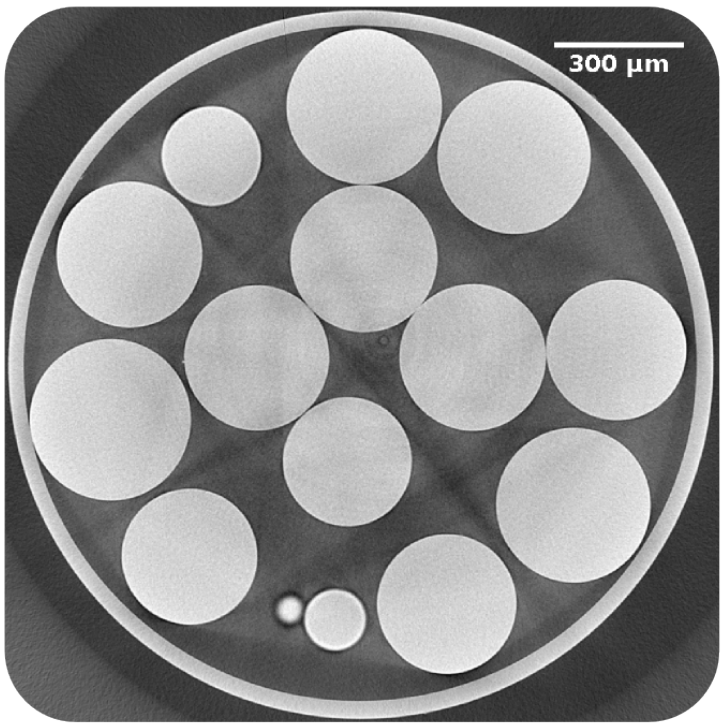
- creation of 5,000 pairs of spheres with equally distributed branch vectors
- error is defined as the angle between the orientation and the imposed branch vector


Topological Watershed
Random Walker
gb = 0.0
gb = 0.8
Mean error [º]
Diameter [voxel]
0
5
10
15
20
25
30
10
12
14
16
18
20

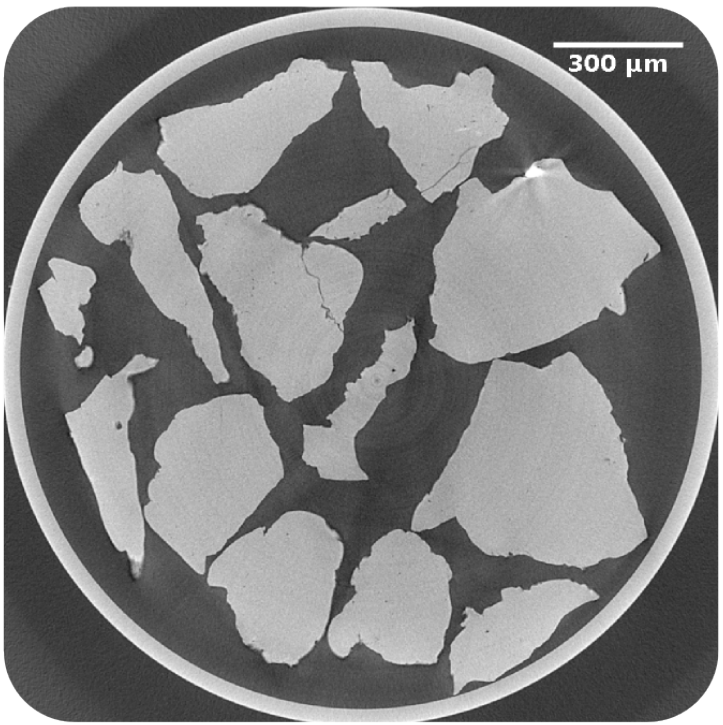
Contact orientation

Getting real

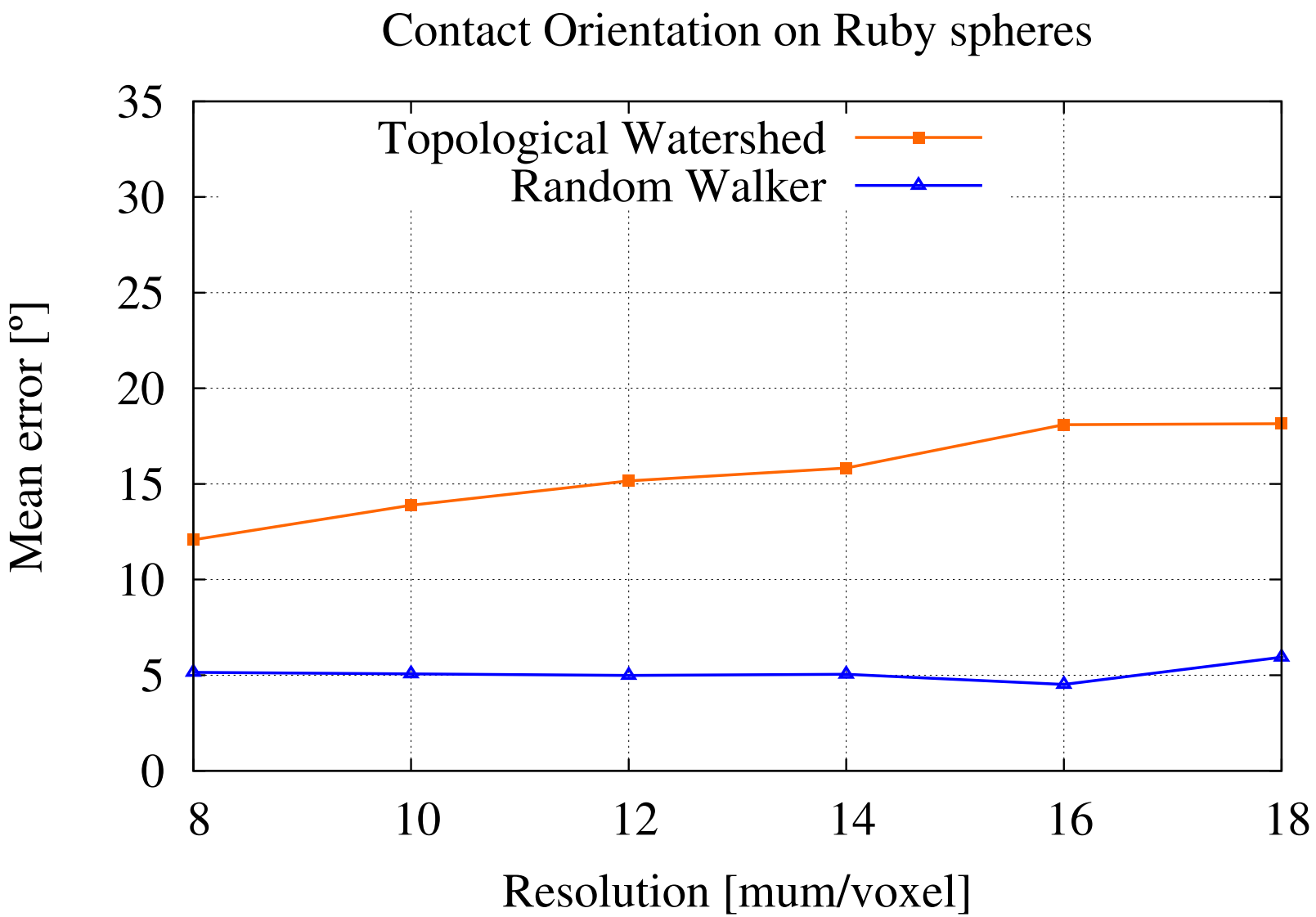
Nano X-ray CT's at a resolution of 1 µm/pixel

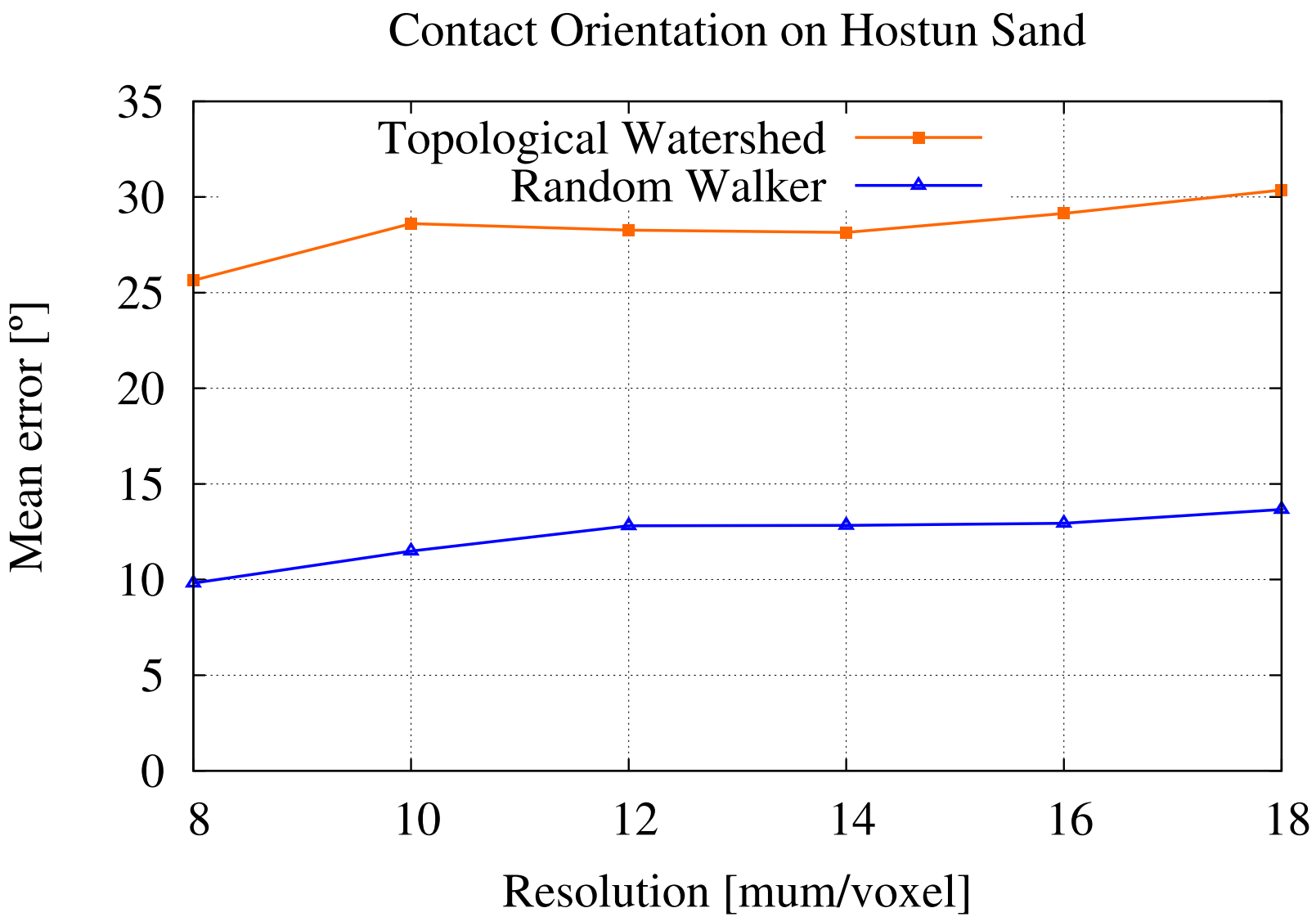


Ruby Spheres



Hostun Sand


Contact Orientation on Ruby spheres
Topological Watershed
Random Walker
Mean error [°]
Resolution [mum/voxel]
0
5
10
15
20
25
30
35
8
10
12
14
16
18


Contact Orientation on Hostun Sand
Topological Watershed
Random Walker
Mean error [°]
Resolution [mum/voxel]
0
5
10
15
20
25
30
35
8
10
12
14
16
18

Problems with natural shapes...

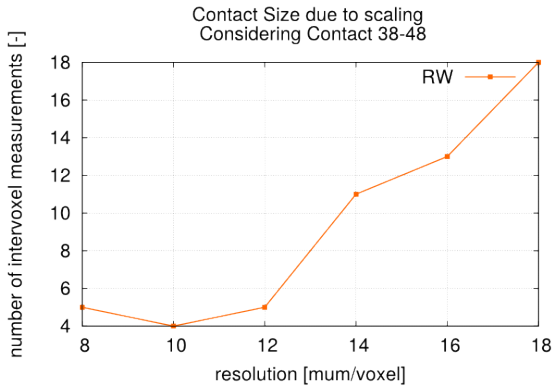
Different scaling effects on contact orientation

visible in this slice:

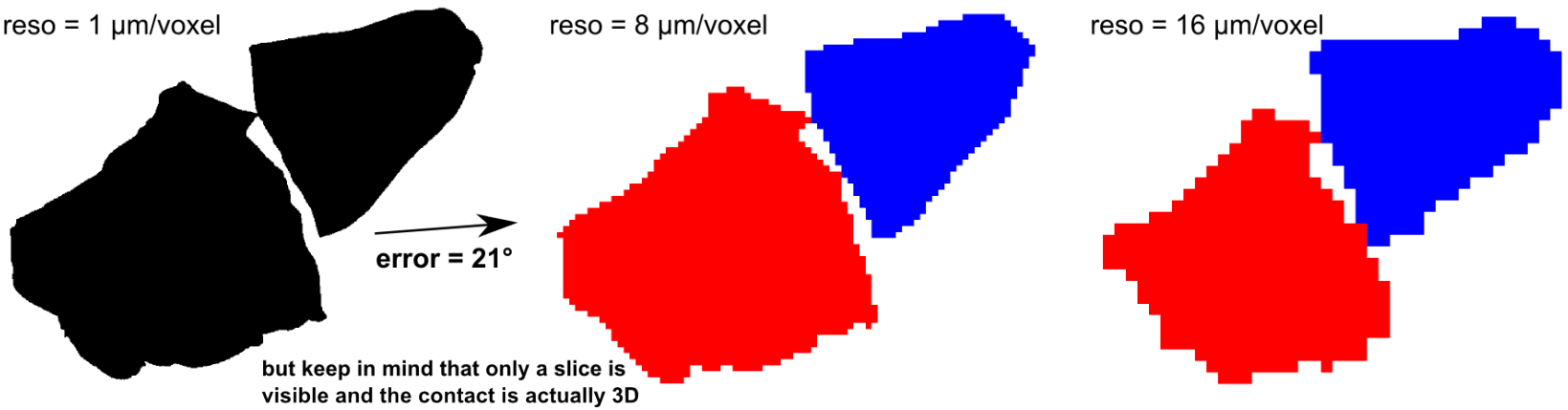
1. **creation of additional contacts** (see contact detection study)
2. contact area - the number of voxels representing a contacts seems to stay relatively constant with scaling - if few voxels serve as a fit, the fit suffers

not visible:

3. **contact merging** - if a contact between two grains consists of multiple contact regions and if they are close they might merge when scaling down



Contact 38-48



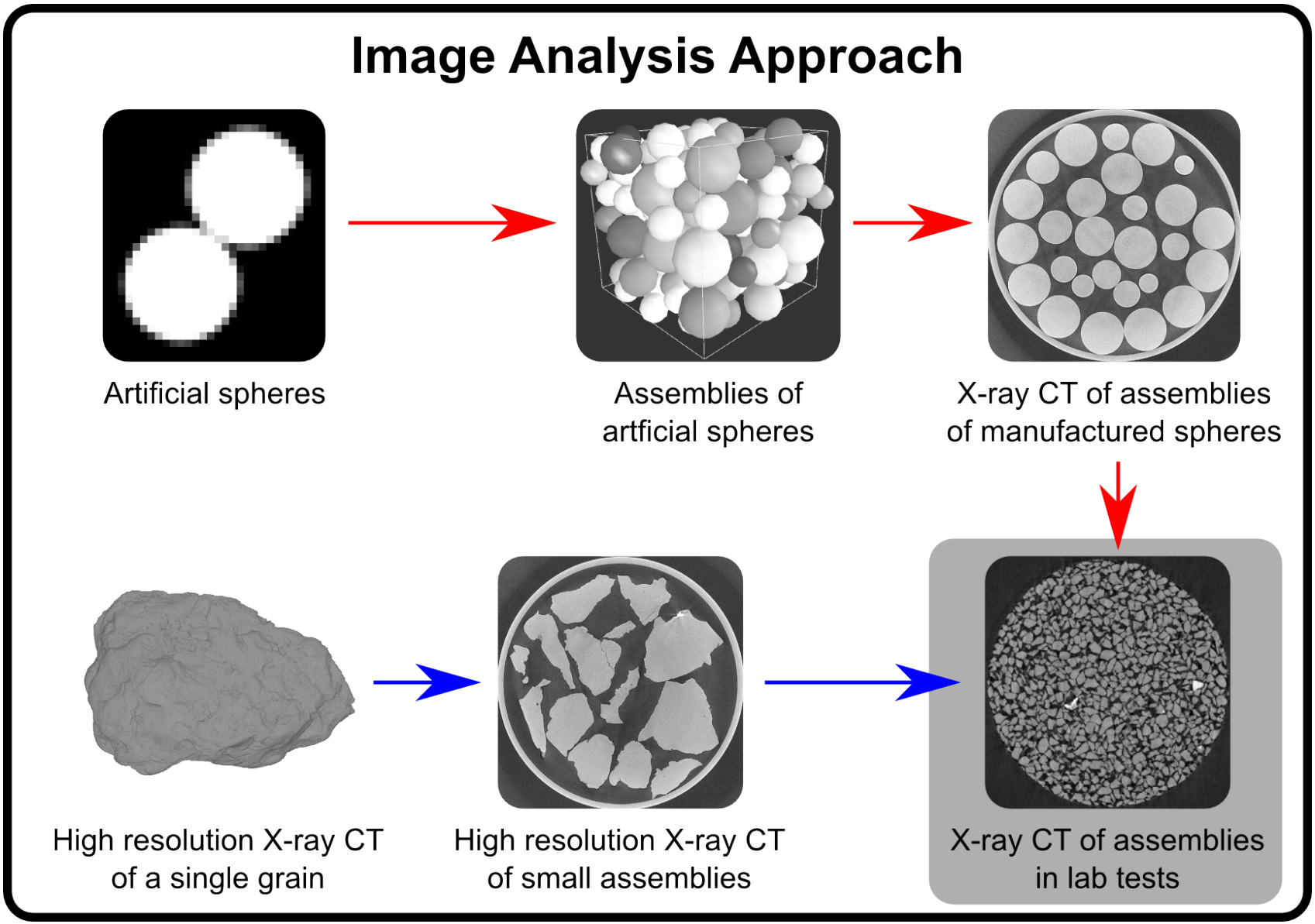
but keep in mind that only a slice is visible and the contact is actually 3D

Going further...

Summary

- The standard approach was investigated closely using the scales of interest for X-ray μCT
  - systematic over-detection of contacts
  - strong bias on contact orientations
- The following improvements were found to yield more accurate results
  - Local thresholding to improve the detection of contacts
  - Advanced watershed methods to improve the accuracy on contact orientations

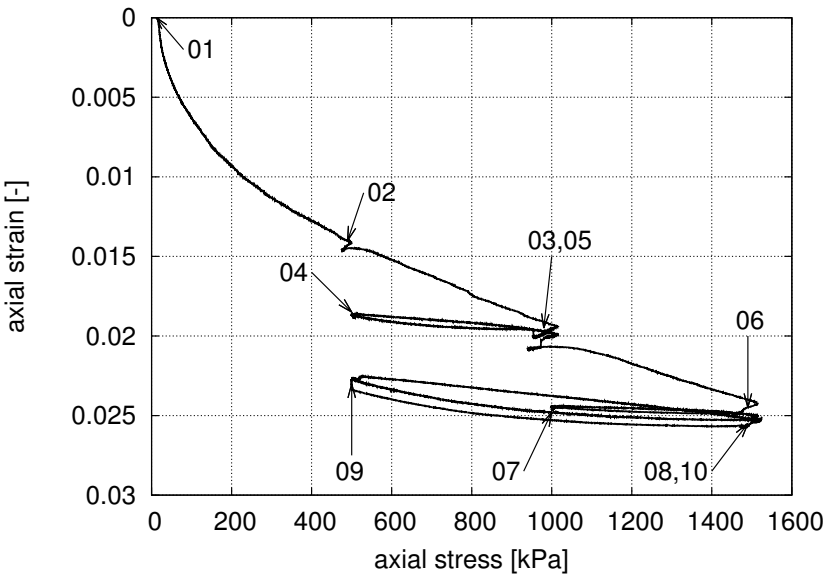
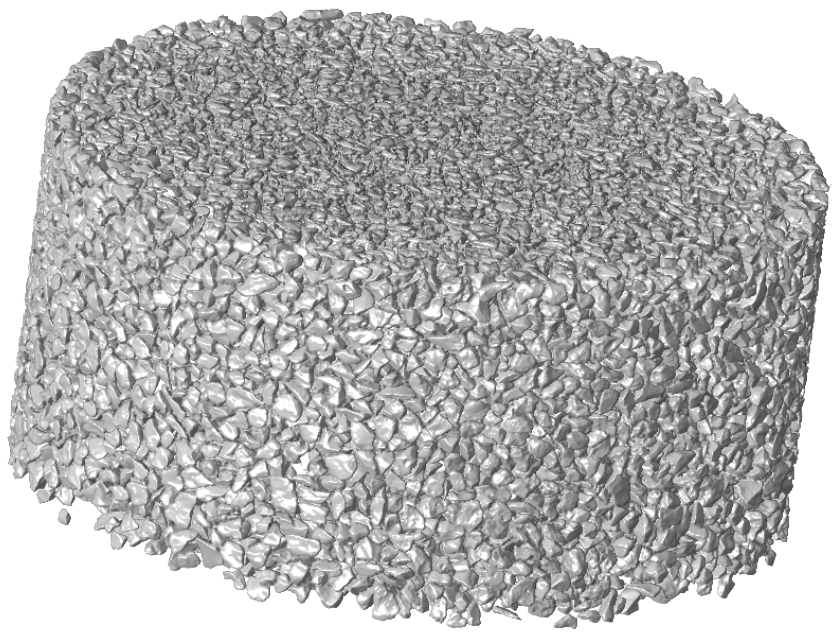
Our approach to contacts



Experiments in the x-ray CT

Oedometric compression on Hostun Sand

Macroscopic Curves



3D rendering of an image of the initial state