



Focalstacking at OBACHT

Y. Ulrich*, E. Elsen*, L. Steder*, M. Wenskat*

January 2014

Abstract

A high resolution camera and sophisticated illumination system has been mounted in a robot that facilitates the acquisition of images of the inner surface of superconducting cavities, which otherwise are hardly accessible. The OBACHT system in use at DESY has been optimized for acquisition time and resolution. This note describes the algorithm used to retrieve information on depth, i.e. surface structure.

1 Introduction

The "Optical Bench for Automated Cavity inspection with High resolution images on short Timescales" (OBACHT) [1] is a camera system developed for automatic inspection of 9-cell 1.3 GHz SRF-cavity [2] surfaces. A photograph of such a cavity is shown in figure 1. Its principle of operation is shown in figure 2. More details are described in [3]: A tube with a camera mounted inside longitudinally slides into the cavity to inspect the

*DESY, Hamburg, Germany

surface quality and to detect surface defects.

An example OBACHT picture is shown in figure 3. The three light-shaded vertical patterns are the welding seams. The ridge in the center is the actual welding seam and the lateral lines correspond to the edge of the melting zones. Due to surface treatments they may vary from picture to picture. The image is about $w_m = 12$ mm wide and about $h_m = 9$ mm tall such 1 px equals about $3.5 \mu\text{m}$ at the equator. The z -coordinate describes the camera's position relative to the mirror. The camera is controlled by a stepping motor where 255 steps focus motor steps corresponds to 1 mm.

Detailed knowledge about the cavities surface is a critical part of understanding limiting effects. Up to now it is only possible to gain surface height information using replica technique [4]. For this purpose, molding of interesting spots can be performed. The replica has to be analyzed by profilometric methods. The focal stacking algorithm allows to extract topological information from OBACHT pictures. If it is able to reproduce the replica results, it could be used as a much faster and non-invasive method to learn about the cavity surface.

The algorithm assumes that depth information can be derived from the focus motor position z : A part of an image is sharp when the distance between the camera and the surface has a specific value z_{sharp} . To gain depth information multiple pictures with different z -position z_i and hence different focal planes of the camera are taken. In each picture small regions (eg. boxes with $\Delta x = \Delta y = 100$ px edge length) are assumed to have slow variation of distance. For each region the so-called focus function F is measured. F corresponds to the sharpness of the region. The peak value $z_{x,y}$ of a Gaussian function fitted to F is used as an approximation to the best focus values and thus the local distance to the camera.

The algorithm's x - and y -resolution is related to Δx and Δy while the z -resolution is limited by the camera's depth of field (DOF). All following data was taken with a DOF of $51 \mu\text{m}$, which can be chosen at the lens of the camera.



Figure 1: A TESLA cavity at DESY [5]

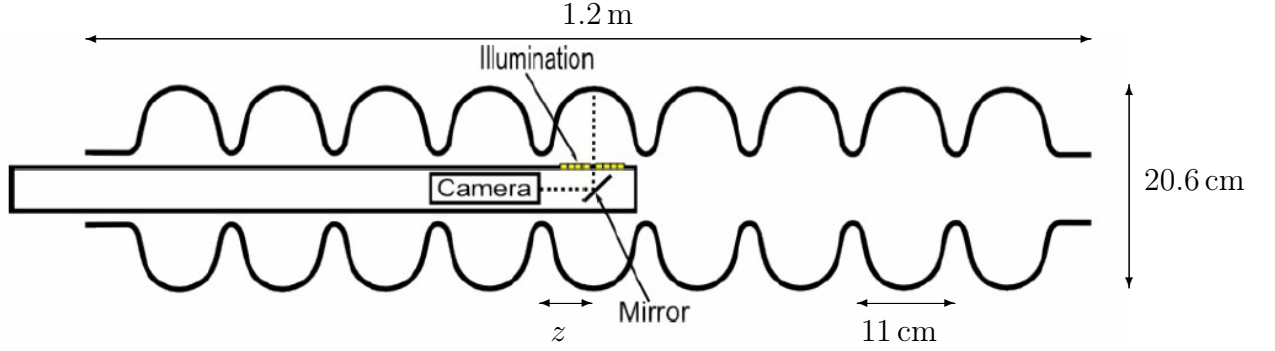


Figure 2: The principle of the OBACHT system [3]: The high-resolution camera is mounted in a tube which can be introduced into the 9-cell cavity. The focus z is adjusted by longitudinal movements of the camera inside the tube. The DOF can be chosen at the camera.

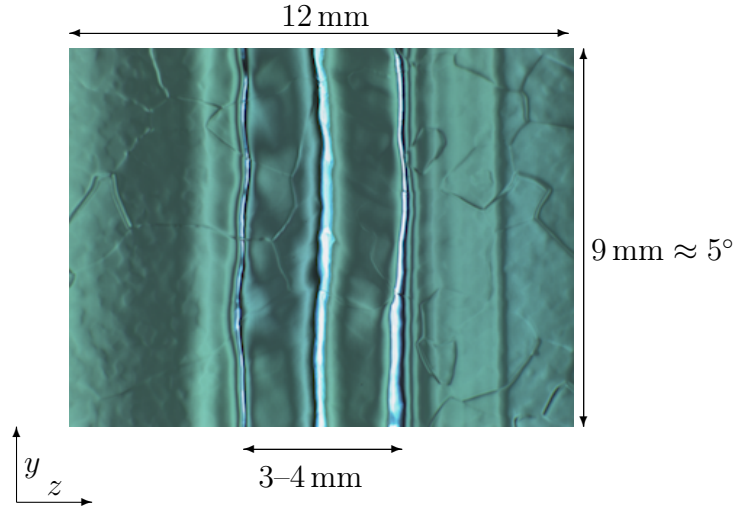


Figure 3: An OBACHT picture of a welding seam

2 Theory of operation

A color image like Fig. 3 consisting of three channels R (red), G (green) and B (blue) can be transformed into a grayscale image using [?]

$$I = 0.3R + 0.59G + 0.11B$$

which can be represented by a $\mathbf{I} \in \text{Mat}(n_y, n_x, [0, 1])$ where n_x is the image's width and n_y its height. The so-called focus function measures the image sharpness

$$F : \text{Mat}(n_y, n_x, [0, 1]) \rightarrow \mathbb{R}_+$$

$$\mathbf{I} \mapsto F(\mathbf{I}) \tag{1}$$

In figure 4 a flow chart of the algorithm is shown. The main components are:

1. Take image at z_i : The OBACHT-systems takes an image \mathbf{I}_i at focus position z_i . This is done for multiple z -values where $\Delta z = z_{i-1} - z_i$ should be about the depth of field of the camera.
2. Measure F_{x,y,z_i} : For each image \mathbf{I}_i and each region $(x + \Delta x) \times (y + \Delta y)$ the focus function F is computed:

$$F_{x,y,z_i} = F((I_{x:x+\Delta x,y:y+\Delta y})_i) \quad (2)$$

3. Gauss $z_{x,y}$: In order to find the distance of best focus, for each regions x, y the focus function $F(x, y, z)$ is maximized with respect to z using a Gaussian fit. Its peak value $z_{x,y}$ is the distance of the best focus.
4. Filtering and Adjustment: Due to illumination, the $z_{x,y}$ data may have strong outliers with a difference $z_{outlier} - \bar{z} \gtrsim 10^4$ steps. These values are removed. Furthermore the data points are fitted using for example a moving average method to smooth the data.

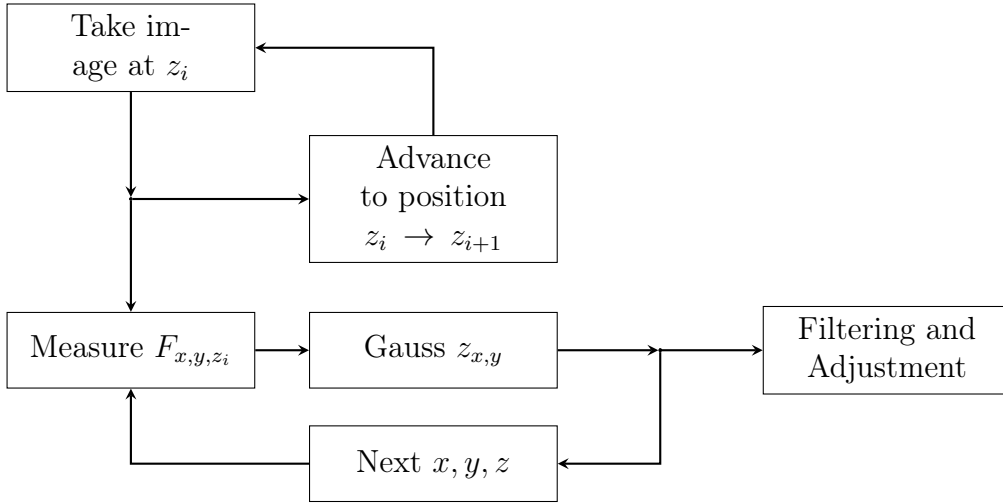


Figure 4: After taking pictures, for each regions and each picture the focus function is computed and maximized. Finally, the resulted topology is corrected.

2.1 Definition of the focus function

Let \mathbf{I} be an $n_y \times n_x$ matrix representing the gray scale image. A so-called focus function is a function measuring the sharpness of \mathbf{I} :

$$F : \text{Mat}(n_y, n_x, [0, 1]) \rightarrow \mathbb{R}_+ \\ \mathbf{I} \mapsto F(\mathbf{I}) \quad (3)$$

Multiple such measures are implemented in [6]. Focus functions yielding good results (see below) are for example:

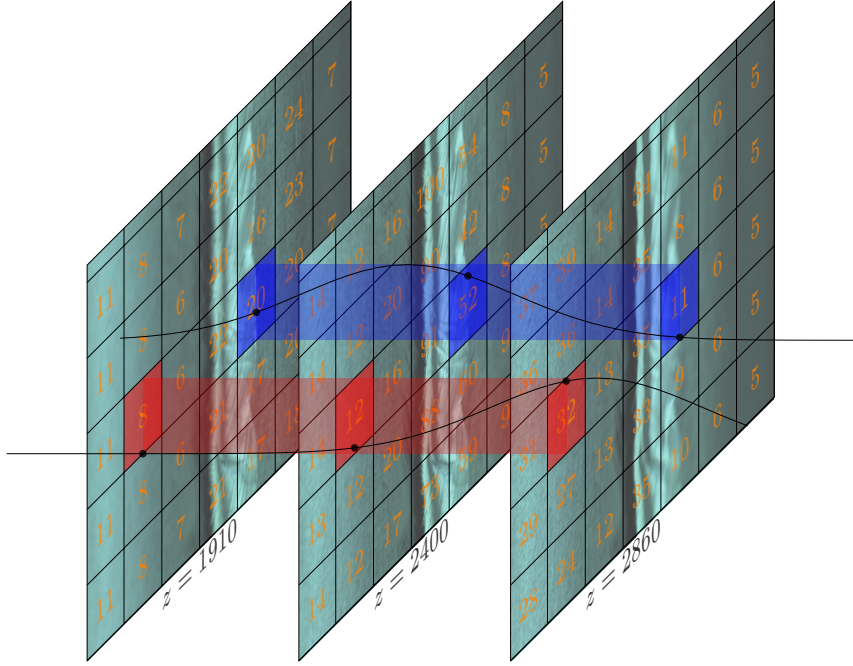


Figure 5: Example for focalstacking with three images at positions $z_i = 1910$ steps, 2400 steps, 2860 steps: In each region the (normalized) focus function $100 \cdot F/F_{max}$ is shown. F was computed using the GRAS-method. For two regions (red and blue) the Gaussian fit is shown. Its maximum is the predicted region of best focus.

- Absolute squared gradient (GRAS, [7]): This method compares two neighboring pixels:

$$F = \frac{1}{n_x \cdot n_y} \sum_x \sum_y |I_{x,y} - I_{x+1,y}|^2 \quad (4)$$

- Brenner's focus measure (BREN, [8]): This method uses the same technique. But instead using the direct neighbor the second neighbor is used:

$$F = \frac{1}{n_x \cdot n_y} \sum_x \sum_y |I_{x,y} - I_{x+2,y}|^2 \quad (5)$$

- Energy of gradient (GRAE, [9]): Instead of only comparing pixels along the image's x -axis, this method also incorporates its y -axis:

$$F = \frac{1}{n_x \cdot n_y} \sum_x \sum_y ((I_{x,y} - I_{x+1,y})^2 + (I_{x,y} - I_{x,y+1})^2) \quad (6)$$

An example for the steps 2 and 3 can be found in figure 5: For three images of a tilted welding seam with $z_i = 1910$ steps, 2400 steps, 2860 steps in each regions the (normalized) focus function $100F/F_{max}$ is shown using the GRAS-method. One can see that sharper regions correspond with greater numbers. For two of these regions, the Gaussian fit is shown. Its maximum would represent the distance of best focus and thus the local topology.

2.2 Resolution

To roughly estimate the algorithm's resolution it is assumed that the error parallel to the surface σ_{\parallel} equals the perpendicular error σ_{\perp} . Assuming a uniform pixel distribution in one lattice element, σ_{\parallel} can be approximated with $\sigma_{\parallel} = \Delta x / \sqrt{12}$. Thus for σ_{\perp} :

$$\sigma_{\perp} \approx \sigma_{\parallel} = \frac{\Delta x}{\sqrt{12}} \quad (7)$$

Of course these approximations only hold as long Δx is significantly greater than the camera's resolution. Also the resolution can not be smaller than the camera's DOF. A typical value of $\Delta x \approx 10$ px will yield an approximate resolution $\sigma_{\perp} \approx 10 \mu\text{m}$.

3 Implementation

The described algorithm was implemented in MATLAB [10] using its Image Processing Toolbox (`images`), the Parallel Computing Toolbox (`distcomp`) and the Curve Fitting Toolbox (`curvefit`). Some focus methods may also require the Wavelet Toolbox (`wavelet`). The source code contains the following files:

- `addFocalstacking.m`: This function checks the availability of all required toolboxes and makes focalstacking available in all directories by adding it to MATLAB's PATH variable
- `src/`
 - `fmeasure.m`: This code by [6] computes F for an image.
 - `fanalyze.m`: This function loops through all images \mathbf{I}_z and returns F_{x,y,z_i} and z_i .
 - `ffit.m`: In order to compute $z_{x,y}$ this function does the Gaussian peak fit of z_i vs. F_{x,y,z_i}
 - `fsmooth.m`: Before the resulted topology $z_{x,y}$ can be plotted it must be cleaned from outliers fitted which is done by this function.
 - `OBACHTconfig.m`: `OBACHTconfig.m` provides parameters for OBACHT like the image size in both pixels and millimeters.
 - `fplot3.m`: All following plots are provided by this tool.

```

1 >> matlabpool open
Starting matlabpool using the 'local' profile ... connected to 12 workers.
>> addFocalstacking
Checking toolboxes...
5 Adding to PATH...
Focalstacking is now added!
    focalstacking

Files
10    fanalyze      - Creating focusV and stepV vectors
    ffit          - Performes gaussian fit on focusV vs. stepV
    fmeasure      - This measures the relative degree of focus of
    fplot3        - T3PLOT Plots 3d topology from suitable bases
    fsmooth       - Smoothes a topological base
15    OBACHTconfig  - Returns default OBACHT config data
    parfor_progress - Progress monitor that works with parfor.

>> cd images
>> ls
20  0.jpg      -200.jpg  -320.jpg  -440.jpg  -600.jpg  -720.jpg  -840.jpg
    -100.jpg  -20.jpg  -340.jpg  -460.jpg  -60.jpg   -740.jpg  -860.jpg
    100.jpg   20.jpg   -360.jpg  -480.jpg  60.jpg    -760.jpg  -880.jpg
    -120.jpg  -220.jpg  -380.jpg  -500.jpg  -620.jpg  -780.jpg
    120.jpg   -240.jpg  -400.jpg  -520.jpg  -640.jpg  -800.jpg
25  -140.jpg  -260.jpg  -40.jpg   -540.jpg  -660.jpg  -80.jpg
    -160.jpg  -280.jpg  40.jpg   -560.jpg  -680.jpg  80.jpg
    -180.jpg  -300.jpg  -420.jpg  -580.jpg  -700.jpg  -820.jpg
>> [focusV,stepV]=fanalyze('./');
>> topological_base = ffit(focusV,stepV);
30 >> fplot3(topological_base);

```

Listing 6: Usage example

3.1 Usage

An usage example is shown in listing 6:

1. Preparing images: For focalstacking n OBACHT images with different focus motor positions z_i are required as discussed below. This can be done using the `manseek.vi`-LabVIEW program. The images acquired by the program are already named appropriate (z_i .`bmp`) and may be converted to a different image format like `jpg`.
2. Activating toolbox: To use this toolbox, it must be added to MATLAB's `PATH` variable. Therefore the `addFocalstacking`-function must be called.
3. Analyzing the images by calling `[focusV,stepV]=fanalyze(path)`. For further details like specifying a region of interest, see the technical documentation.
4. Fitting the focus values by typing `topological_base = ffit(focusV,stepV)`;
5. Visualizing the surface in 3D: `fplot3(topological_base)`

4 Results

The focalstacking toolbox has numerous options regarding used method, number of images etc. For these options a wide range of sample values (Table 7) were tested in order to find the best values. Besides computation time also a subjective quality is listed. In a good result (subjective quality 10) the surface is clearly identifiable and low-noise. Bad bad result (subjective quality 0) does not resemble the surface, i.e. certain features cannot be identified.

- **Methods:** Reasonably good results were obtained using the above described methods **GEAE**, **BREN** and **GRAS**.
- **Number of images n and step size Δz :** Due to the limited speed of the focus motor, taking fewer images with smaller Δz without loss of quality would be desirable. It turns out that even $n = 10$ and $\Delta z = 50$ steps yield reasonably good results as one can see in Table 7. It is, however, recommended to use a greater n resp. a smaller Δz for detailed analysis.
- **Lattice size:** As described in 2.2 the resolution is strongly correlated to lattice size $\Delta x = \Delta y$. But since the amount of computation grows disproportionately when Δx is decreased, a decision needs to be made. Analysis showed that for a fundamental sketch $\Delta x = 200$ is sufficient. Going below $\Delta x = 100$ seems unnecessary since the resolution does not improve significantly.

4.1 Comparison with replica method

On one cavity a comparison between the proposed focalstacking method and the already existing replica technique was possible. This can be used as a performance check since the replica technique yields resolution in the micrometer scale [4]. The results are shown in figure 8 using $\Delta y = \Delta x = 10 \text{ px} = 35 \mu\text{m}$. It can be seen that the focalstacking results (blue line) are in good agreements with the red replica data outside the defect. Even in the region of the defect rough approximation is possible. On the defect's borders at $x \approx 1250 \mu\text{m}$ and $x \approx 2200 \mu\text{m}$ an optical reconstruction was not possible since the corresponding regions in the image are black (figure 8b) eg. no surface information can be obtained.

5 Summary

The focal stacking procedure may offer a new interesting analysis method. However a sufficiently small DOF is required. In order to integrate it into the cavity inspections the OBACHT camera needs to allow the operator to change the DOF automatic if necessary. Integrating focalstacking into the day-to-day OBACHT operations may offer interesting physical insights about defects and features of the surface and their impact on the cavity

performance without using time consuming replica techniques.

For a first topological overview the following values are recommended:

$$\begin{aligned}n &= 10 \\ \Delta z &= 50 \text{ steps} \\ \Delta x = \Delta y &= 100 \text{ px} \\ \text{Method} &= \text{GRAS}\end{aligned}$$

For a detailed analysis the following values are recommended:

$$\begin{aligned}n &= 50 \\ \Delta z &= 10 \text{ steps} \\ \Delta x = \Delta y &= 10 \text{ px} \\ \text{Method} &= \text{GRAS}\end{aligned}$$

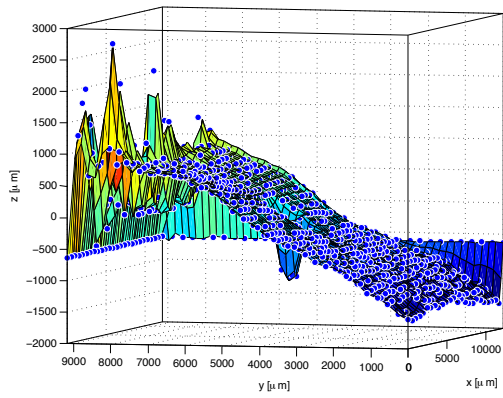
The source code can be found in the provided zip-archive.

References

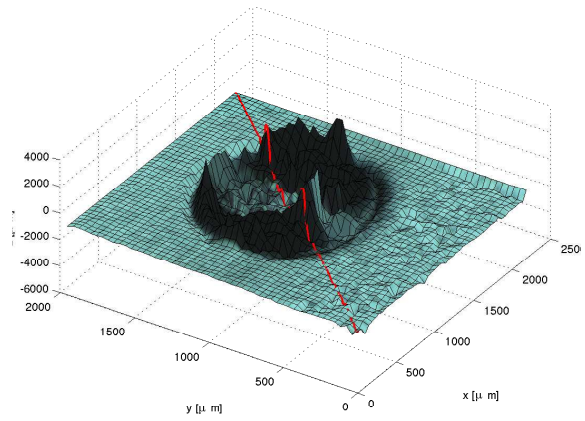
- [1] M. Lemke, et al. OBACHT - optical bench for automated cavity inspection on short time scales. ILC-HiGrade Report 001, DESY, Hamburg, Germany, 2013.
- [2] Chris Adolphsen, et al. The International Linear Collider Technical Design Report - Volume 3.I: Accelerator R&D in the Technical Design Phase. 2013.
- [3] S. Aderhold. *Study of field-limiting defects in superconducting RF cavities for electron- accelerators*. PhD thesis, DESY, Hamburg, Germany, 2013.
- [4] M. Ge, et al. Routine characterization of 3d profiles of srf cavity defects using replica techniques. *Superconductor Science and Technology*, 24(3):035002, 2011.
- [5] Lea Steder. Optische inspektion von supraleitenden cavities. Presented at the "DPG Frühjahrstagung 2013", 03 2013.
- [6] S. Pertuz, D. Puig, and M. A. Garcia. Analysis of focus measure operators for shape-from-focus. *Pattern Recognition*, 46(5):1415–1432, May 2013.
- [7] A.M. Eskicioglu and P. S. Fisher. Image quality measures and their performance. *Communications, IEEE Transactions on*, 43(12):2959–2965, 1995.
- [8] A Santos, et al. Evaluation of autofocus functions in molecular cytogenetic analysis. *J Microsc*, 188(Pt 3):264–272, Dec 1997.
- [9] M. Subbarao, T. S. Choi, and A. Nikzad. Focusing techniques. *Journal of Optical Engineering*, pages 2824–2836, Nov. 1993.
- [10] *MATLAB version 7.14 (R2012a)*. The MathWorks Inc., Natick, Massachusetts, 2012.

Method	Number of images n	Step size Δz / steps	Lattice size / px	Time / s	Subjective quality
GRAS	101	10	100	18.17	8
BREN	101	10	100	20.03	10
GRAE	101	10	100	19.54	5
SFRQ	101	10	100	21.06	5
GRAS	101	10	10	1774.00	
GRAS	101	10	25	153.70	10
GRAS	101	10	50	43.06	8
GRAS	101	10	100	18.41	9
GRAS	101	10	200	12.38	4
GRAS	101	10	500	12.07	0
GRAS	100	100	100	18.37	10
GRAS	100	10	100	18.19	10
GRAS	50	50	100	21.67	10
GRAS	10	50	100	18.16	10
GRAS	10	100	100	18.20	10

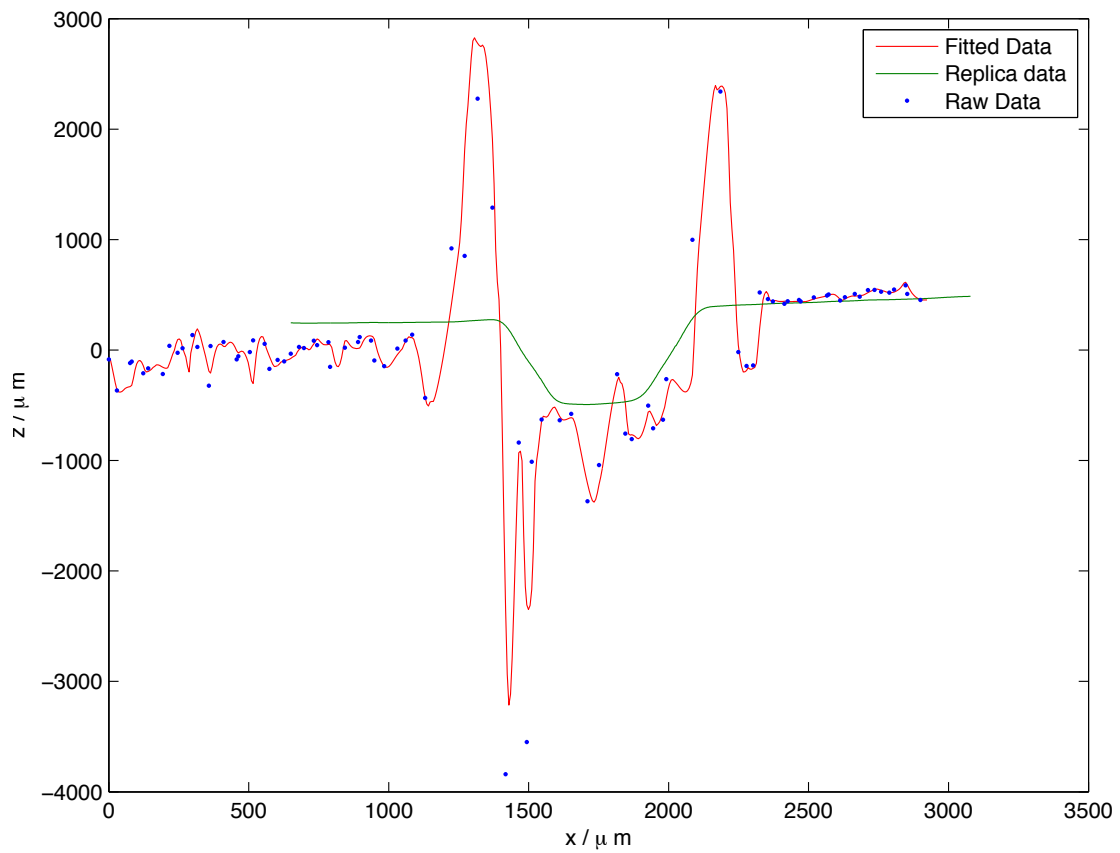
Table 7: Computation time for various options. The subjective quality of results was approximated for each group individually on a scale from 0 to 10 where 0 is worst.



(a) Surface overview



(b) Detailed surface for region of interest



(c) Cross section

Figure 8: Comparison with replica method: In the surface (a) a spot (b) has been analyzed with both the replica technique and focalstacking. Along the red line in (b) a cross section of the surface was computed. The data are shown in (c).