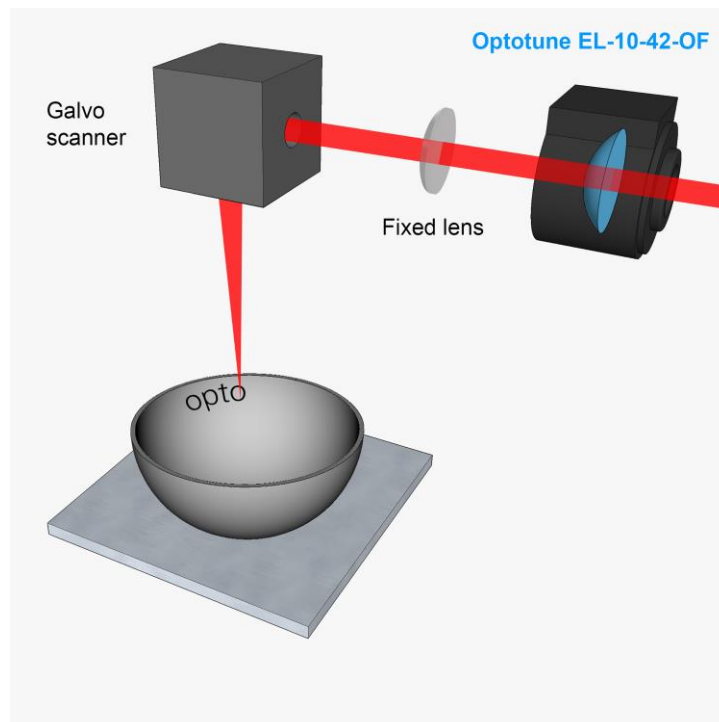


## Application note for laser processing using EL-10-42-OF tunable lens and SCAPS Optotune-DSD digital controller board



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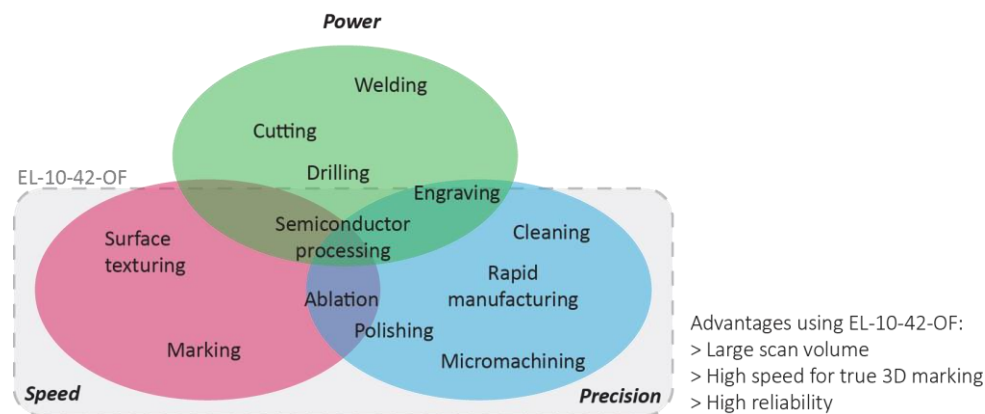
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## 1. Introduction

Nowadays, the common solution available on the market for controlling the z-coordinate in laser processing is using a mechanical translation. However, the major limitations of this approach are the slow speed and a small range in z-travel. The delicate movable parts are limited in their lifetime and require a lot of space to be integrated in an existing system. The EL-10-42-OF lens is light, compact and has a fast response time as well as a long lifetime. Therefore, it is an ideal candidate to overcome the downsides of a mechanical solution.

In this Application Note we provide general guidelines for using the Optotune's EL-10-42-OF tunable lens in combination with the digital controller board for fast 3D laser processing applications. We describe how to integrate the EL-10-42-OF lens and the Optotune-DSD controller board, developed by SCAPS GmbH, into a laser processing system.

With a special but simple optics design, a 3D laser processing system using the EL-10-42-OF lens can achieve the same spot size across the whole scan volume. The EL-10-42-OF lens, designed for pulsed lasers, comes in two wavelength options: the near infrared between 950nm and 1100nm, and the visible at 532nm. This opens the possibility of using the EL-10-42-OF lens for various laser processing applications, as illustrated below.



### 1.1. Overview of the necessary steps to integrate the EL-10-42-OF

To use the EL-10-42-OF lens in combination with the SCAPS Optotune-DSD controller for 3D laser processing, the following steps are required for the integration into a laser processing system:

- 1) Perform mechanical integration. For more details, please refer to corresponding sections in the manual provided at <http://download.scaps.com/downloads/Hardware/DSD-2-O/DSD-2-O.pdf>
- 2) Prepare the cable for the SCAPS Optotune-DSD board and the galvo scan head. For example, we use a Y-junction type cable by splitting the cable from the main controller card into two cables for which one is connected to the SCAPS Optotune-DSD controller board and the other one is connected to the galvo scan head.
- 3) Prepare the power and the heater cables plugged into the SCAPS Optotune-DSD board.
- 4) Install the software and firmware for the SCAPS Optotune-DSD board.
- 5) Calibrate the lens using SCAPS Optotune-DSD software.
- 6) Create a correction grid file if necessary. Normally for a system without an f-theta lens, the correction grid needs to be done once.
- 7) Perform the z-calibration of the laser processing system. In Section 3 and Appendix 1, you find detailed instructions for the z-calibration using SCAPS SAMLight software.
- 8) The system is ready.

## 2. System integration

### 2.1. Controlling EL-10-42-OF lens with Optotune-DSD controller board

Optotune-DSD is an FPGA-based digital controller board designed to control the EL-10-42-OF lenses. While the EL-10-42-OF lens shifts the laser spot in z- (vertical) direction, the galvo mirrors deflect the laser spot in the x-y- (horizontal) plane.

This approach is implemented in a compact laser marker presented in Appendix 3 & 4 and schematically shown in the left panel of Figure 1. The communication between the PC (the user) and the digital controller card is often established via a serial bus, for example via USB. Within the extended XY2-100 protocol, the signal used to control the z axis is already available, in addition to the x- and y-axes that control the galvo mirrors. The digital signal output from the controller card for the z-axis can be directly sent to the Optotune-DSD board, as shown on the left panel of Figure 1.

The right panel of Figure 1 shows another possible integration, where the controller board from SCAPS is used. Then, the bi-directional XY-SCAPS communication protocol can be applied.

Both situations allow for fast 3D laser processing and do not require f-theta lenses. The processing speed without f-theta lens has been demonstrated to be 6 m/s on a 45° tilted object and 15 m/s on a 2D plane with working distances comparable with a setup using a 160mm f-theta lens and the EL-10-42-OF for the z-axis.

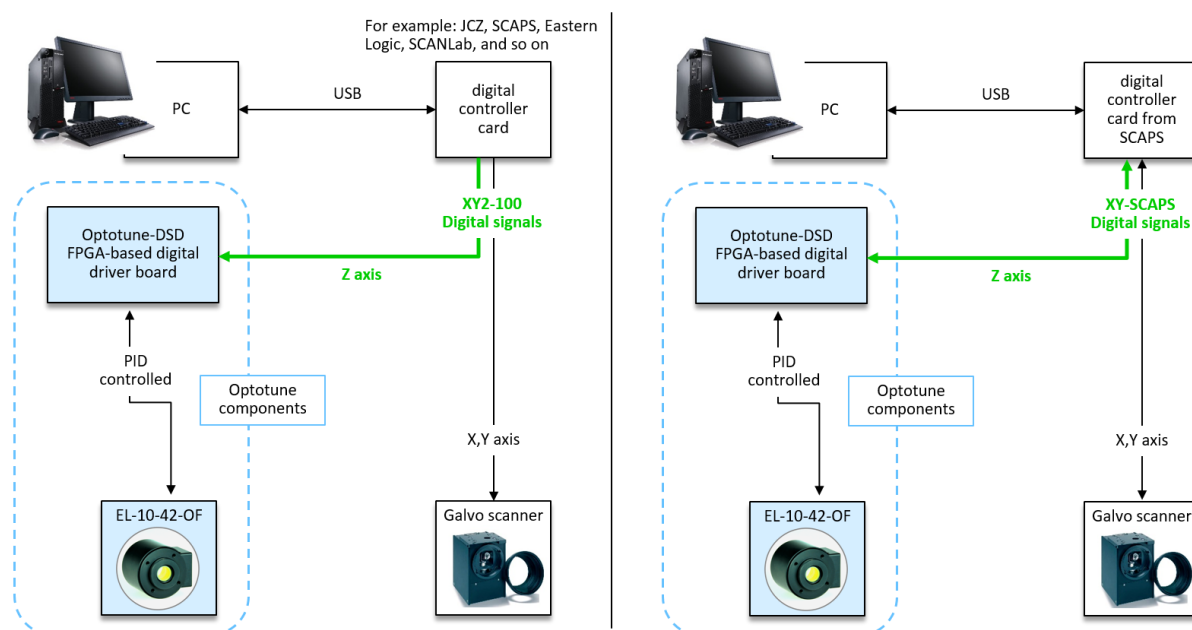


Figure 1: Integration of EL-10-42-OF lens within a digital protocol that provides x,y and z-signals. The output signal from the controller card for the z axis can be directly fed into the Optotune-DSD board for the control of EL-10-42-OF lens.

**Note:** Optotune-DSD board is especially developed to control the EL-10-42-OF lens. In laser processing applications, pulsed and high-power laser beams are used, posing considerable challenges on the precision of the optical feedback (OF) control. Tiny amounts of stray light still introduce an offset on the OF, shifting the actual set value. Although the remaining shift is canceled electronically, for efficient OF control the laser repetition rates  $\geq 20$  kHz are recommended.

## 2.2. Integration with f-theta lens

One possible integration approach is with the EL-10-42-OF lens and the digital controller in a configuration with an f-theta lens. The resulting z-tuning range in combination with different f-theta lenses is shown in Figure 2. In this particular case the output laser beam has a diameter of about 6 mm. The EL-10-42-OF lens is placed on the beam path from the laser output to the galvo scanner. The beam is then reflected by the galvo mirrors that allow beam deflection along x- and y-direction on the target. The field size shown in the simulation results from the mirror deflection angle of +/- 10°. The z-position of the laser spot is controlled by tuning the focal length of EL-10-42-OF lens. For the f-theta lens with a longer focal length, the resulting z-tuning range as well as the scan field size increases. In each configuration, the focal length of the EL-10-42-OF is tuned over the maximal range (from -2 diopter to +2 diopter). Field flattening and final focusing onto the processing plane are done by the f-theta lens. This configuration is simple to implement since the EL-10-42-OF is integrated between the laser and the scan head without additional optics.

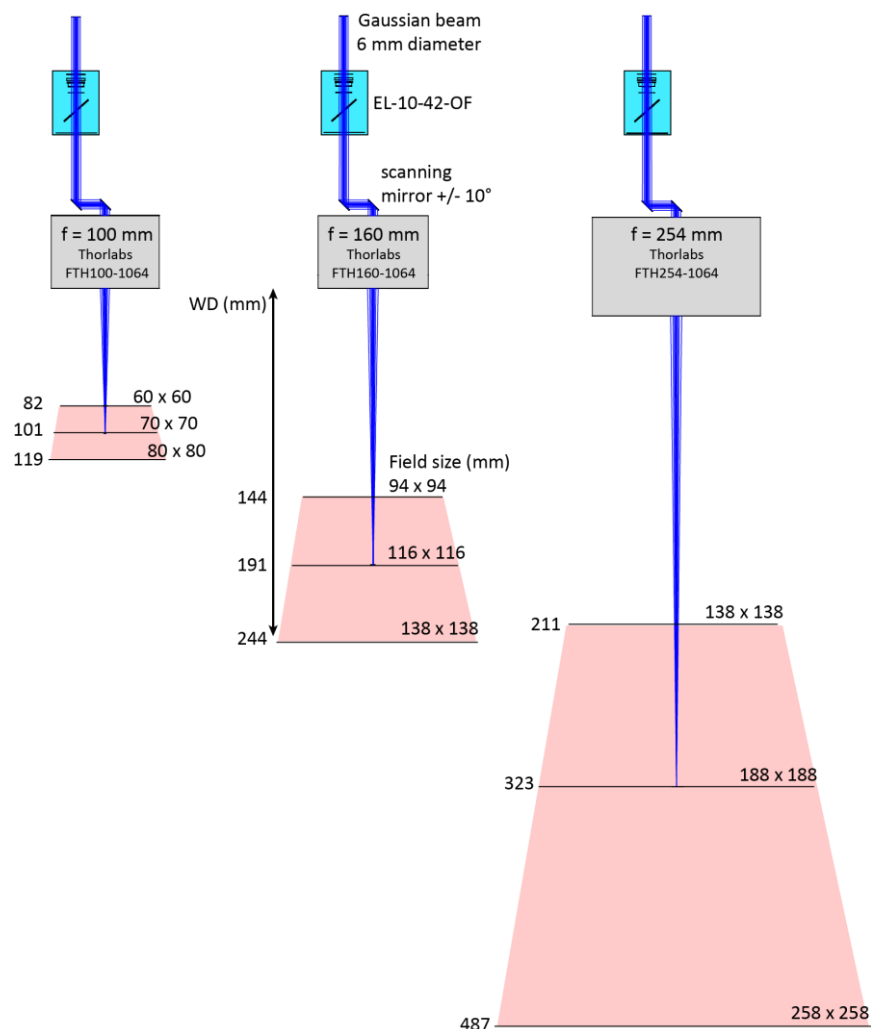


Figure 2: Laser scanning system with the EL-10-42-OF, galvo scanning mirror and different f-theta lenses  $f = 100, 160$  and  $254$  mm. The corresponding z-scanning range and change of working distance (WD) is indicated by the black arrow. The red color indicates the scan volume for the different situations.

**Note:** There are remaining field distortions due to imperfections of the f-theta optics. Those effects are slightly enhanced when operating the f-theta lens with the EL-10-42-OF because of the introduced convergence or divergence of the input beam that enters the f-theta lens. For best processing quality, this must be taken into account on the software side by, for example, introducing a correction grid.

### 2.3. Integration without an f-theta lens

Without an f-theta lens, both field flattening and tuning in z-direction is accomplished by the EL-10-42-OF lens. The major advantage of a system without an f-theta lens is the enlarged size of the scan field together with an increased z-range and minimum to no change in spot size throughout the whole scan volume. In the absence of the f-theta lens, additional optics are required between the laser and the scan head for the laser beam focusing. Depending on the position and focal length of these lenses, different working distance ranges and scan field sized can be achieved. Contact us for support with your desired configuration.

Optotune designed and tested a demo 3D module (Figure 3) with mounting for multiple fixed lenses in addition to the EL-10-42-OF (Figure 4). Standard 1-inch spherical fixed focus lenses can be used.



Figure 3: Rendering of Optotune's 3D module design

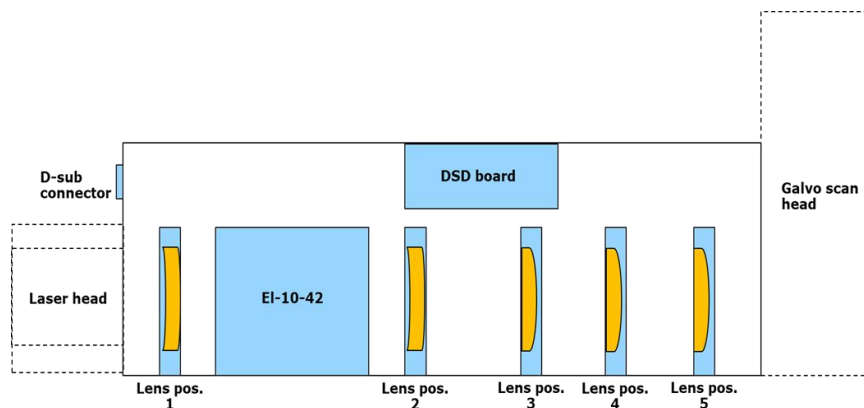


Figure 4: Schematics of Optotune's 3D module with the 5 fixed lens positions

The 3D module is placed between the laser and the scan head as illustrated in Figure 5. Depending on the fixed focus lenses used, different configurations can be achieved as illustrated in Figure 6. The STEP file of the module is available from Optotune for easy manufacturing or further tailoring to your specific optical layout.

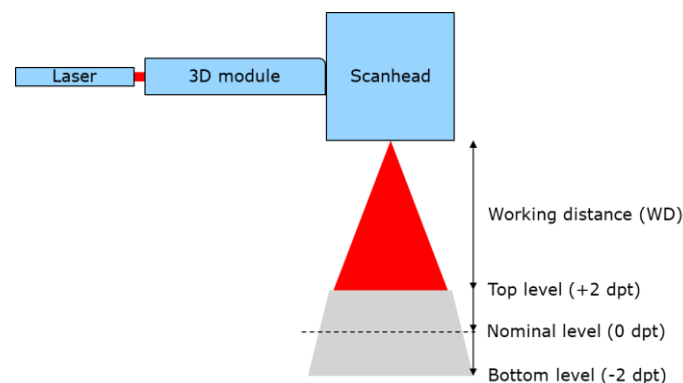


Figure 5: Integration of the 3D module in a 3D laser processing setup

Constant spot size									
3D module configuration			➔	System specification					
Lens position	Focal length (mm)	Min. scanhead aperture (mm)		Level	Scanfield (mm)	Working distance (mm)	Spot size center (um)	Spot size edge (um)	
5	175	10		Top	40 x 40	55	43	43	
				Nominal	80 x 80	102	43	43	
				Bottom	130 x 130	165	43	43	

Similar field size and working distance like with 160mm f-theta (with 1.5X beam expander)									
3D module configuration			➔	System specification					
Lens position	Focal length (mm)	Min. scanhead aperture (mm)		Level	Scanfield (mm)	Working distance (mm)	Spot size center (um)	Spot size edge (um)	
2	-100	14		Top	95 x 95	120	45	46	
3	150			Nominal	135 x 135	170	46	47	
5	250			Bottom	190 x 190	240	47	48	

Similar field size and working distance like with 160mm f-theta (with 1.66X beam expander)									
3D module configuration			➔	System specification					
Lens position	Focal length (mm)	Min. scanhead aperture (mm)		Level	Scanfield (mm)	Working distance (mm)	Spot size center (um)	Spot size edge (um)	
2	-75	14		Top	100 x 100	130	40	41	
3	125			Nominal	135 x 135	170	40.5	41.5	
5	250			Bottom	180 x 180	225	41	42	

Similar field size and working distance like with 254mm f-theta (with 1.5X beam expander)									
3D module configuration			➔	System specification					
Lens position	Focal length (mm)	Min. scanhead aperture (mm)		Level	Scanfield (mm)	Working distance (mm)	Spot size center (um)	Spot size edge (um)	
2	-100	14		Top	150 x 150	190	60	61	
3	150			Nominal	220 x 220	280	65	66	
5	350			Bottom	360 x 360	450	75	76	

Similar field size and working distance like with 254mm f-theta (with 1.66X beam expander)									
3D module configuration			➔	System specification					
Lens position	Focal length (mm)	Min. scanhead aperture (mm)		Level	Scanfield (mm)	Working distance (mm)	Spot size center (um)	Spot size edge (um)	
2	-75	14		Top	160 x 160	205	55	56	
3	125			Nominal	220 x 220	280	60	61	
5	350			Bottom	330 x 330	410	64	65	

Large field sizes									
3D module configuration			➔	System specification					
Lens position	Focal length (mm)	Min. scanhead aperture (mm)		Level	Scanfield (mm)	Working distance (mm)	Spot size center (um)	Spot size edge (um)	
1	-100	25		Top	460 x 460	550	76	79	
4	250			Nominal	680 x 680	820	92	95	
5	1000			Bottom	950 x 950	1155	117	119	

Figure 6: Fixed lens setups and corresponding optical performance achieved with Optotune's 3D module

As a comparison, the performance of the system with the EL-10-42, the DSD digital controller, an 160mm f-theta lens (and no additional optics) is shown in Figure 7.

160mm F-Theta lens									
3D module configuration			➔	System specification					
Lens position	Focal length (mm)	Min. scanhead aperture (mm)		Level	Scanfield (mm)	Working distance (mm)	Spot size center (um)	Spot size edge (um)	
		10		Top	94x94	144	26	32	
				Nominal	116x116	191	26	27	
				Bottom	138x138	244	26	58	

Figure 7: Optical performance of a typical 2D laser processing setup with a 160mm f-theta lens

## 3. System calibration

### 3.1. Lens calibration

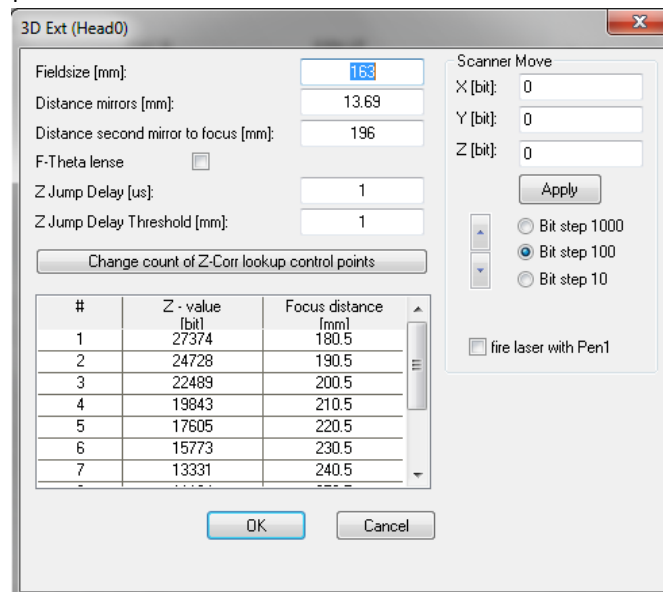
After the EL-10-42-OF lens has been installed in a laser processing machine, it has to be calibrated for its dynamic behavior in the installed orientation. This can be performed either within SCAPS SAMLight software if the SCAPS USC-3 controller card is used, or with a stand-alone lens calibration software from SCAPS for all other controller cards. The lens is compatible with any controller card that can output X-Y-Z axis through the XY2-100 interface. For details how to perform the lens calibration, please see SCAPS Optotune-DSD Manual page 16.

### 3.2. Correction grid

In order to correct the nonlinearity induced by the galvo mirrors in a laser processing system, a correction file loaded in the control software is required. Normally the correction file is provided by the scan head supplier and can be modified by a tool from the control software vendors. For a system without an f-theta lens, the correction depends on the optical layout as each optical design shows different nonlinear behavior.

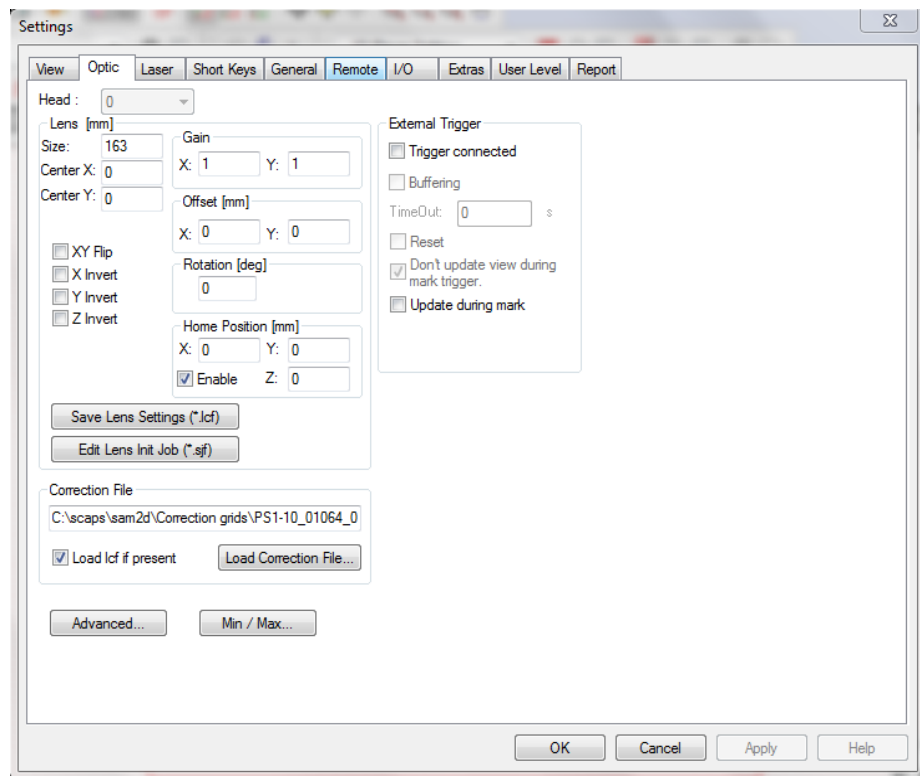
The example illustrated here uses the calibration point method using `sc_corr_table` tool from SCAPS in combination with SAMLight. Note: parts of the texts below are copied directly from SCAPS `sc_corr_table` manual.

1. Place and mount Optotune tunable lens in the laser processing system.
2. Construct the look-up table for the Z axis.



3. Make sure the target is at the position where the Z level is zero.
4. Go to SAMLight -> Settings -> System -> Optic
  - a. Apply a correction file. This can either be the neutral correction file (default one in SAMLight) or any existing correction file (\*.ucf) which need to be improved. Make sure NOT to check the box Load lcf if present.
  - b. Set X gain and Y gain to 1 and offsets and rotation to 0.
  - c. Set field size (Lens Size) to 100 mm and set Center X and Center Y to 0. Note: the following figure is the example from our marking system with a field size of 163 mm.
  - d. Make sure, all checkboxes for inversion and flip are inactive.





5. Load the job \jobfiles\100mm\_Square.sjf and mark it.
  - a. Check whether the orientation of “Left Top” is correct in the marking result.
  - b. If yes, go to Step 6.
  - c. If not, change the current state of Axes, X axis and Y axis to get the proper orientation of the coordinate system. Close SAMLight and open \tools\sc\_corr\_table. Import the currently applied correction file (\*.ucf). Go to Correction -> Orientation of coordinate system and set Axes, X axis and Y axis accordingly.



Axes: normal, X: normal, Y: normal



Axes: normal, X: inverted, Y: normal



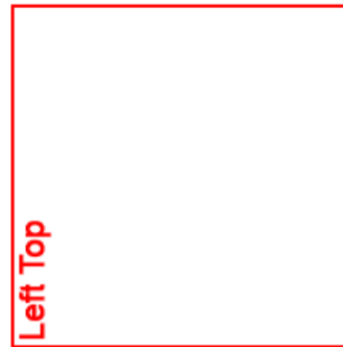
Axes: normal, X: normal, Y: inverted



Axes: normal, X: inverted, Y: inverted



Axes: flipped, X: normal, Y: normal



Axes: flipped, X: inverted, Y: normal



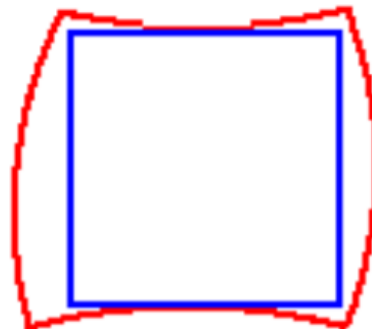
Axes: flipped, X: normal, Y: inverted



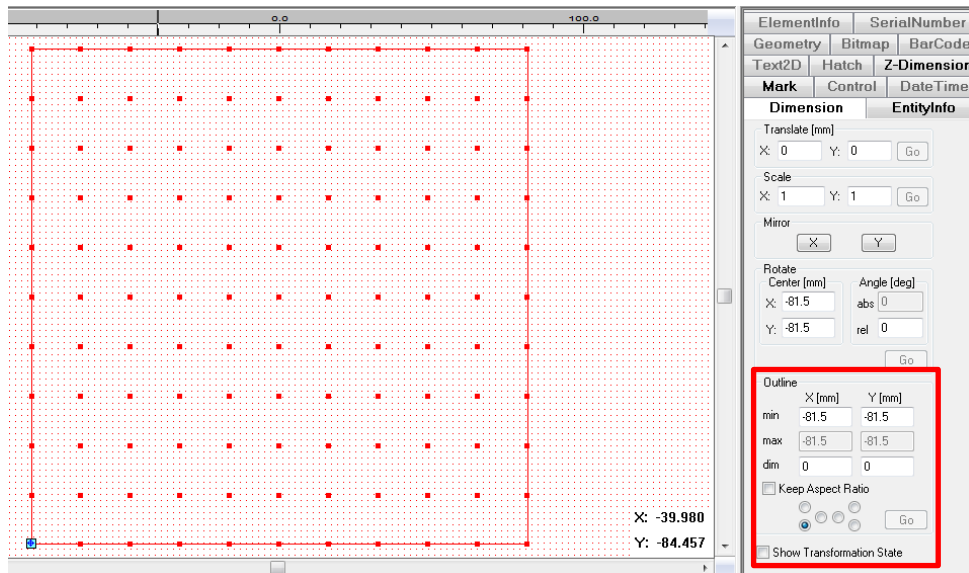
Axes: flipped, X: inverted, Y: inverted

- d. File -> Export and overwrite the existing correction file.
- e. Close sc\_corr\_table and Open SAMLight again
- f. Mark 100mm\_Square.sjf job again and check if the orientation is correct now. Note: Do not use the checkboxes XY Flip, X Invert and Y Invert in SAMLight. Repeat steps c., d. and e. until the orientation in the SAMLight is the same as the marked job.

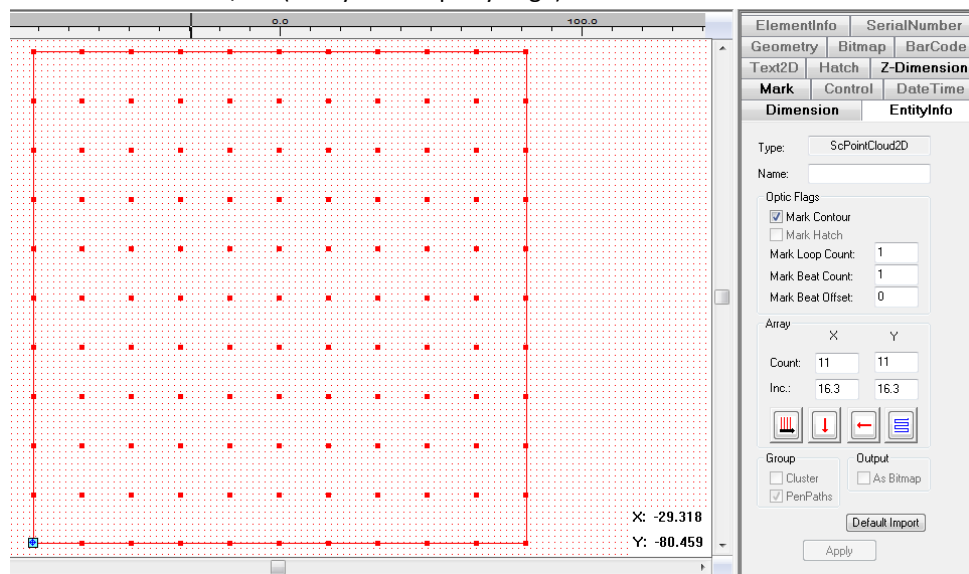
6. Find the biggest square which fits totally into the distorted square.



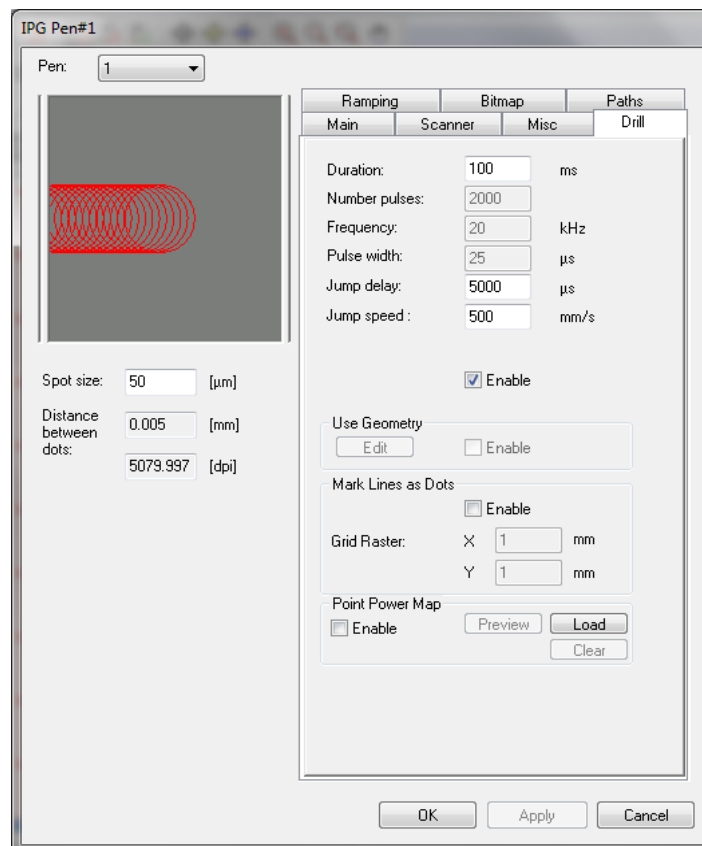
7. Set the field size to the side length of the insquare. (SAMLight -> Settings -> System -> Optic -> Lens Size).
8. Create a new job file with 11x11 (=121) centered points covering the whole field in SAMLight.
  - a. The way to create the points is the following: Create a "Point" entity and position this point to the left bottom of the field. This means, set the X and Y coordinate to -Field size/2.



- b. To generate the rest of the points, create 11x11 (=121) array copies of this point and set the increment to Field size/10. (EntityInfo Property Page)



9. Mark these points with drill mode. Set the drill jump delay to a reasonably high value to ensure the scanner is in the desired position before each mark.



To avoid temperature drifts, test processing should be done with the scanner already at working temperature.

10. Create an ASCII text file, name it "sc\_calib\_points.txt" and save it in the folder \system.
11. Measure the coordinates ( $X_{i, \text{Measured}}$  and  $Y_{i, \text{Measured}}$ ) of all these marked points. The unit is in mm. Fill the SAMLight coordinates (the setting in SAMLight) and the measured reality coordinates into the "sc\_calib\_points.txt" using the following form:
 

```
X1, SAMLight; Y1, SAMLight; X1, Measured; Y1, Measured
X2, SAMLight; Y2, SAMLight; X2, Measured; Y2, Measured
X3, SAMLight; Y3, SAMLight; X3, Measured; Y3, Measured
X4, SAMLight; Y4, SAMLight; X4, Measured; Y4, Measured
...
X121, SAMLight; Y121, SAMLight; X121, Measured; Y121, Measured
```
12. Close SAMLight (save your job) and start \tools\sc\_corr\_table.
13. Use Correction -> Show calibration points to display the measured data. For improvement of the fit result, the function Delete worst point can be used.
14. Go to Correction -> Correct UCF by calibration points and choose the desired fit order in the drop-down menu of 2D Fit-> Fit Order (Default mode: 3\_Advanced).
15. After clicking "OK", two correction files are displayed. At the same time, both the original and the newly created correction files are saved in \Correction grids folder with different names.

16. Apply the new \*.ucf file in the settings. (SAMLIGHT -> Settings -> System -> Optic)

17. Mark 100mm\_Square.sjf job again and check if the new correction file is good enough or not.

There are many different methods to calibrate the nonlinearity and generate the correction files. The customer should contact the scan head manufacturer or the control software vendor for detailed information particularly for the 3D laser processing systems without f-theta lens.

### 3.3. Z-calibration

Optotune-DSD board controls the optical power of the lens and hence allows for shifting the laser spot in z-direction (see Figure 8). It is necessary to perform a calibration between the control signal and the laser spot's physical z-position in millimeter due to a nonlinearity in the voltage applied versus optical power characteristics. The detailed steps for the z-axis calibration with EL-10-42-OF lens in SAMLIGHT are listed in Appendix 1.

After calibration, the set signal directly represents the tuning range in z-direction between  $z_{min}$  and  $z_{max}$ , as shown on the right panel of Figure 8. The actual z-tuning range depends on the optical layout in which the EL-10-42-OF lens is integrated. The calibration procedure needs to be done once and typically the data can be stored in a lookup table in the laser processing software. It is recommended to measure at least ten calibration points. More points will increase the precision of the control.

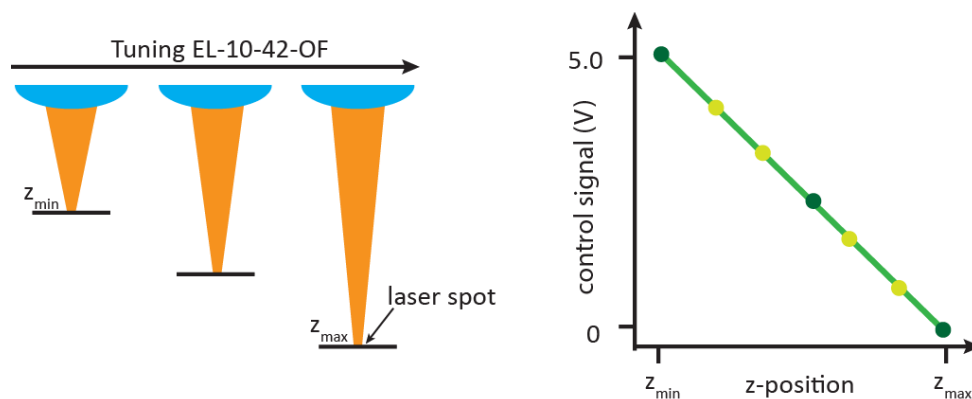


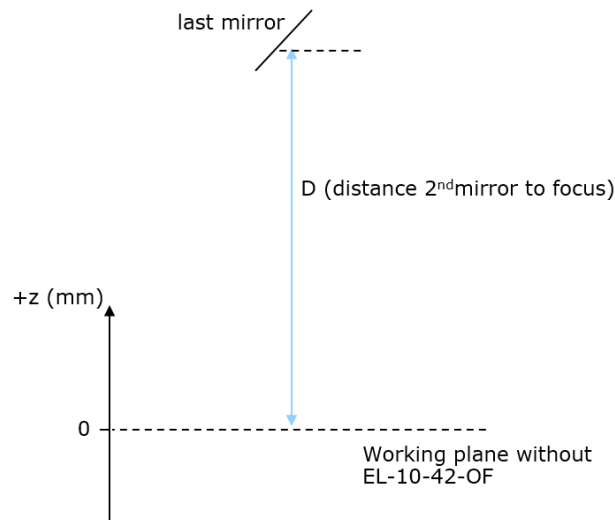
Figure 8: The left panel shows how the z-position of the laser spot is changed by tuning EL-10-42-OF. The right panel illustrates the calibration curve of control signal versus the focal positions in z axis. The light green points represent further points required to increase the precision of the calibration.

## 4. Further information & support

Our application engineers would be happy to advise you about the integration of Optotune's products into your design. Do not hesitate to contact us by e-mail at [sales@optotune.com](mailto:sales@optotune.com) or by phone at +41 58 856 3000.

## Appendix 1: How to perform z-calibration with EL-10-42-OF in SAMLight

The following procedure describes one possible way to calibrate the z-position of the processing laser spot against the control signal. The method has been successfully tested in a standard laser marking system described in Appendix 3 & 4. The laser processing software SAMLight (SCAPS) allows for easy integration of the z-calibration via a look-up table. The coordinate system is defined as:



1. It is assumed that the distance D from second mirror to the working plane is already known (in the exemplary system, D = 250 mm). Before integrating the EL-10-42-OF lens, this has to be measured precisely, for example by using a mechanical z-stage.
2. As a first step, a temporary z-correction look-up table has to be created. The measurements done with this table will be a basis to determine the final z-correction table.

**3D Ext (Head0)** ✕

Fieldsize [mm]:	<input type="text" value="130"/>	
Distance mirrors [mm]:	<input type="text" value="13.69"/>	
Distance 2nd mirror to focus [mm]:	<input type="text" value="250"/>	
<input checked="" type="checkbox"/> F-Theta lens		
Z Jump Delay [us]:	<input type="text" value="100"/>	
Z Jump Delay Threshold [mm]:	<input type="text" value="50"/>	

Change count of Z-Carr lookup control points

#	Z - value [bit]	Focus distance [mm]
1	18000	185
2	-18000	315

Scanner Move

X [bit]:

Y [bit]:

Z [bit]:

▲  
▼

Bit step 1000  
 Bit step 100  
 Bit step 10

fire laser with Pen1

The table is defined only by the two DAC end points  $DAC_1 = -18000$  and  $DAC_2 = 18000$ , which correspond to  $-1.8$  dpt and  $+1.8$  dpt respectively. This is the maximum allowed range of the lens control. The corresponding distances (mm) are calculated approximately as seen in the following table:

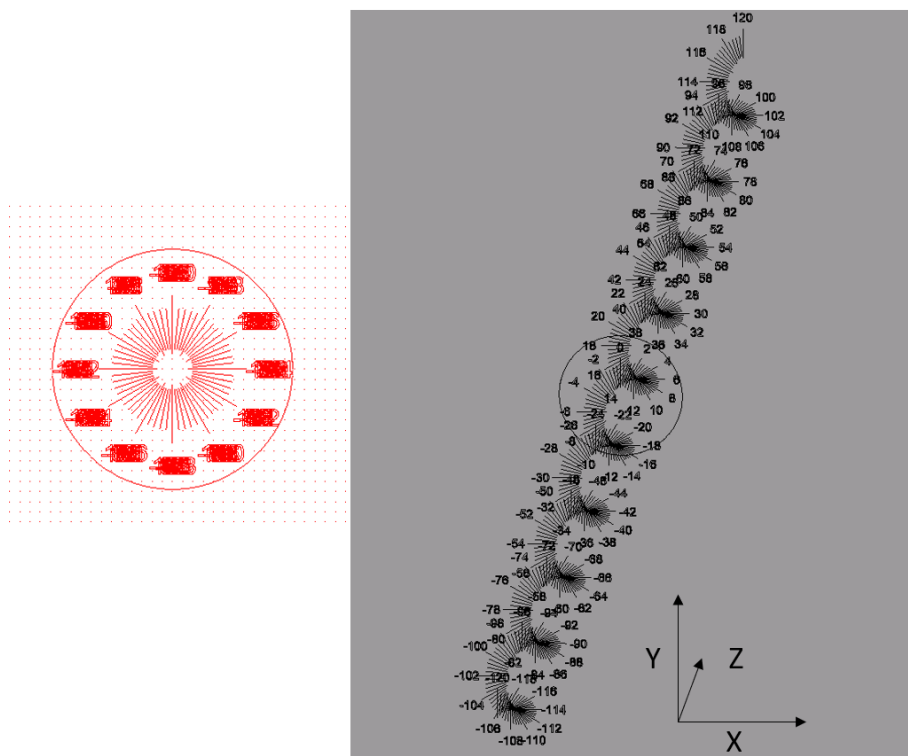
$DAC_1$	-18000	$D + (x,y\text{-working area} / 2) = D_1$
$DAC_2$	+18000	$D - (x,y\text{-working area} / 2) = D_2$

- When using an f-theta lens, the corresponding check box in SAMLight has to be enabled.

Distance 2nd mirror to focus [mm]:

F-Theta lens

- Load the pre-defined job file "Calibrate\_Optic3D\_Circle\_-120\_to\_120.sjf" in SAMLight.

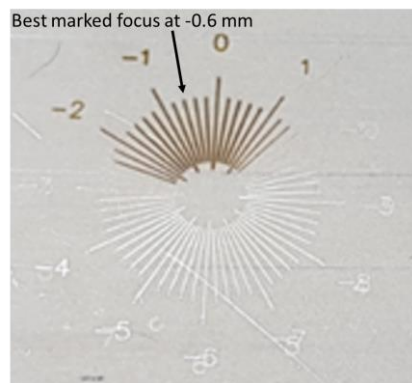


This job file serves as a vertical "ruler". It consists of lines ranging from  $-120 \dots +120$  mm in z-direction. The lines have 0.2 mm spacing in z. If your x,y-working area is smaller than this range, you have to delete a few lines in the job file such that the z-range  $<$  x,y-working area. Otherwise, the error message "Galvo out of range" will appear after starting the job with "start mark".

- Next, define the following table in a spread sheet. The points have to be within the maximum physical z-tuning range. For example:

Target height [mm]	Scanner height [mm]	Focus dist [mm]
-50.00	50.00	300.00
-40.00	40.00	290.00
-30.00	30.00	280.00
-20.00	20.00	270.00
-10.00	10.00	260.00
0.00	0.00	250.00
10.00	-10.00	240.00
20.00	-20.00	230.00
30.00	-30.00	220.00
40.00	-40.00	210.00
50.00	-50.00	200.00

- Position a sample at one point in the table (0 mm in this example). Start the job file.
- Change the z-position of the sample to the next point in the table and mark the job file again. Repeat this procedure for all z-values.
- Extract the marked z-position values  $F_z$  from the sample. To do so it is helpful to analyze the samples under a standard microscope (for example using 8x magnification). This increases the precision when locating the “best” line that was in focus.



- After the analysis, the z-correction table should look like the table shown below. At the z-value = 0 mm, the marked value on the sample is not necessarily zero due to a possible offset. The calibration will take this offset automatically into account.

-30.00	30.00	280.00	-40.00
-20.00	20.00	270.00	-28.00
-10.00	10.00	260.00	-16.00
0.00	0.00	250.00	-2.00
10.00	-10.00	240.00	12.00
20.00	-20.00	230.00	24.00
30.00	-30.00	220.00	36.00
40.00	-40.00	210.00	48.00

- Calculate the distances  $D_z = D - F_z$  ( $D = 250$  mm in this example). To establish the linear relation between the DAC values and the values  $D_z$  we have to calculate

$$DAC_z = a \cdot D_z + b$$

with the coefficients from step 2:

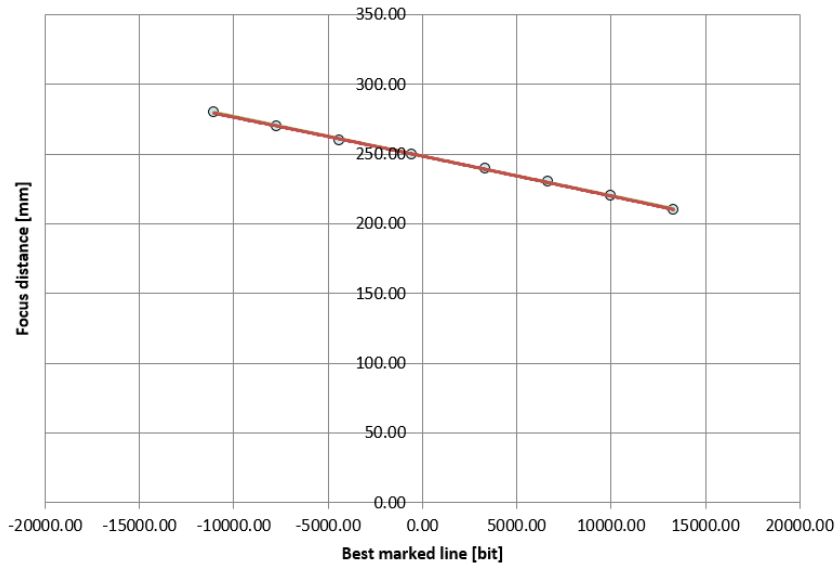
$$a = \frac{DAC_2 - DAC_1}{D_2 - D_1}, \quad b = \frac{D_2 \cdot DAC_1 - D_1 \cdot DAC_2}{D_2 - D_1}$$



The calculated values are shown in the last column of the table below:

Marking result from temporary lookup table					
Target height [mm]	Scanner height [mm]	Focus dist [mm]		Best marked line	Best line [bit]
-50.00	50.00	300.00			#N/A
-40.00	40.00	290.00			#N/A
-30.00	30.00	280.00		-40.00	-11076.92
-20.00	20.00	270.00		-28.00	-7753.85
-10.00	10.00	260.00		-16.00	-4430.77
0.00	0.00	250.00		-2.00	-553.85
10.00	-10.00	240.00		12.00	3323.08
20.00	-20.00	230.00		24.00	6646.15
30.00	-30.00	220.00		36.00	9969.23
40.00	-40.00	210.00		48.00	13292.31
50.00	-50.00	200.00			#N/A

11. In a next step, the look-up table “Best line [bit]” vs “Focus dist [mm]” is created. The second-order polynomial fit is used to account for any nonlinearity in the optical system.



Finally, substitute the given bit values into fitted equation to obtain the focus distance [mm] as a function of the z value:

Calibrated quadratic lookup table	
Z value [bit]	Focus dist. [mm]
18000	196.47
13500	209.74
9000	222.85
4500	235.80
0	248.59
-4500	261.22
-9000	273.69
-13500	286.00
-18000	298.15

These two columns are used in SAMLight as the final z-calibration look-up table. Note that in SAMLight, the “Focus distance (mm)” must be entered in ascending order.

12. *Optional:* one can perform a verification measurement. If the calibration is correct, the same values are obtained when repeating steps 5 to 8. The deviations are small and within the precision of the method described in step 8.

## Appendix 2: Lens response time

Using the Optotune-DSD board to control the EL-10-42-OF lens, we characterize the lens response by ramping the applied voltage up and down and record the optical feedback signal.

The lens response is measured to evaluate the lens settling time and quantify the speed of focus change. Through this measurement we can determine how accurate the lens position along the z-axis can be controlled as well as the tuning performance. The applied voltage at the input of Optotune-DSD board is ramped up and down with adjustable speed. In Figure 9 the cyan curve is the input signal showing 20% and 80% jump length respectively with a ramp speed of 7000 bit/ms (such a high speed is only for test purposes). The optical feedback signal of the lens is represented by the black data. One can see that during the ramp, the lens is in a controllable way following the red curve which is modeled based on the control algorithm. In both rising and falling edges, it takes about 8 ms for the 80% jump length and 4.5 ms for the 20% jump length to reach the set value. The data are acquired with the DSD software provided by Scaps.

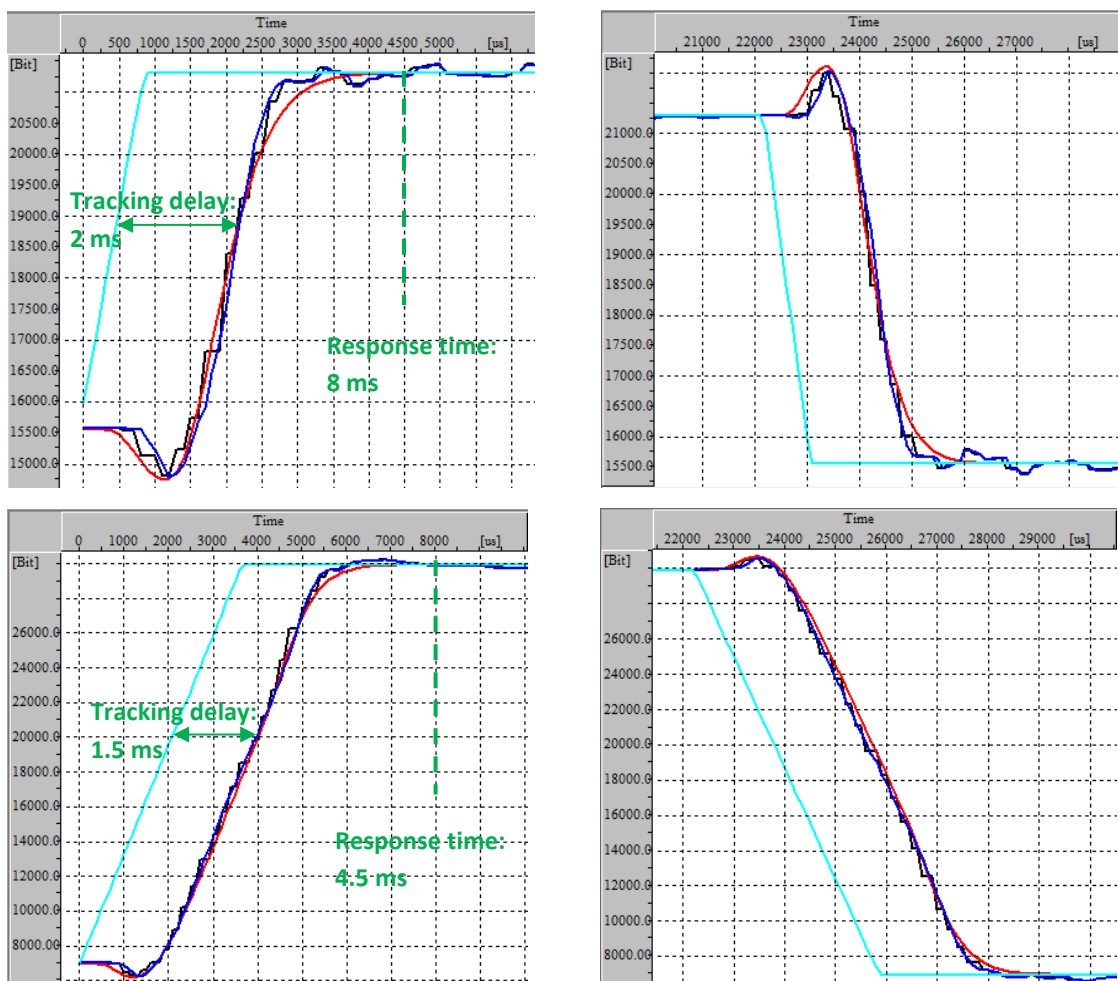


Figure 9: Response time of the EL-10-42-OF lens controlled with the Optotune-DSD board for different step sizes (20% for top two plots and 80% for bottom two plots). The optical feedback signal is shown in blue. The cyan data shows the applied voltage at the input of Optotune-DSD board. Both falling and rising edge show a very similar response time.

In a more detailed analysis, we investigate the scaling of the response time for different jump lengths using the same ramp speed. The results are depicted in Figure 10 showing that the lens response time decreases with smaller jump lengths. Compared to the results measured using an EL-E-OF-A analog controller board, the response time is about a factor of 1.5 faster.

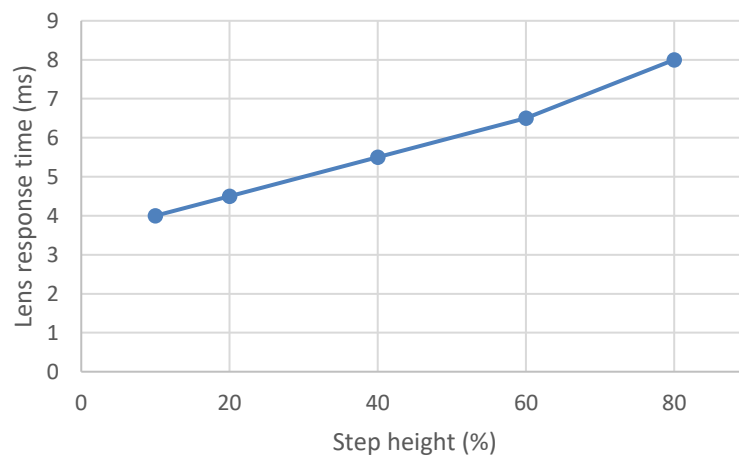


Figure 10: Response time of the EL-10-42-OF lens controlled with the Optotune-DSD board for different step sizes

### Appendix 3: Integration example with an f-theta lens

Figure 11 shows an integration example of a compact laser marking system built at Optotune. The EL-10-42-OF is a very compact lens, which can be easily mounted in the empty space between the laser output and the galvo head (see Figure 12). The mechanical holder for the EL-10-42-OF lens has been designed in a way, which ensures that the laser beam, the EL-10-42-OF lens and the aperture of the galvo head are coaxial.



Figure 11: Laser marking system using Optotune's electrically focus tunable lens EL-10-42-OF for fast z-axis focusing.

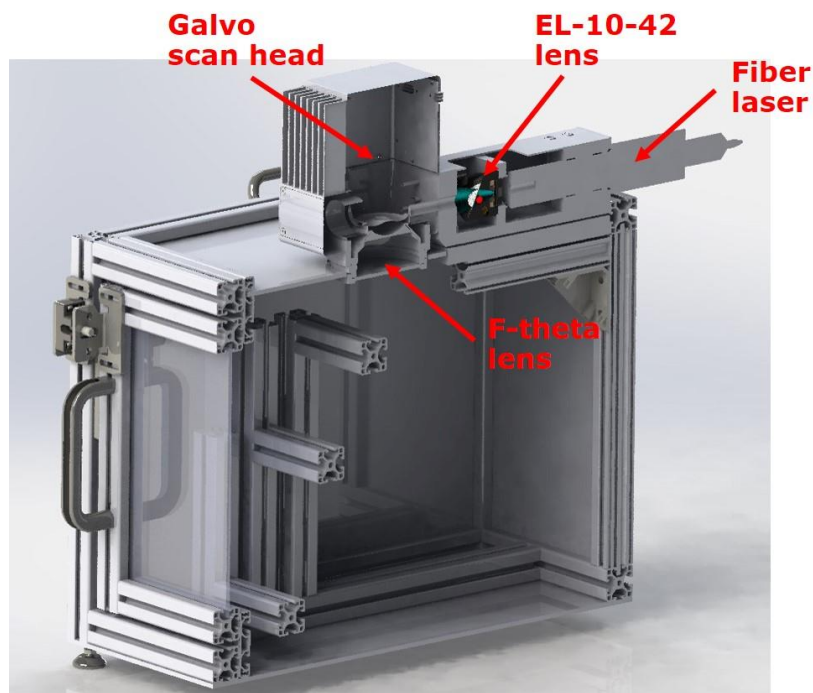


Figure 12: 3D model of the Optotune laser marking demo setup. Optotune electrically focus tunable lens EL-10-42-OF is placed between the laser head and the galvo mirrors.

The following table summarizes the main specifications of the demo marking system with a 160 mm f-theta lens.

### Basic Specifications

Outer measures	400 x 400 x 300	mm
Weight	approximately 15	kg
Marking field at central position	100 x 100	mm
Laser class	1 (with housing)	
Laser vendor	IPG / Nufern	
Maximal laser power	20 / 50	W
Laser wavelength	1064	nm
Typical spot size	approximately 60	µm
Focal length f-theta lens	160	mm
Typ. Jump speed	6000	mm/s
Z-tuning range	100	mm
Software	SCAPS SAMLight	

The typical laser marking results are shown in Figure 13. The ruler on the right-hand side is horizontally oriented, illustrating the field flattening capabilities. The left side shows a ruler marked at an inclination of 45°, representing the extreme case, where full 3D marking is required. The maximum field size at the highest z-position is 110 x 110 mm. The maximal marking speed is up to 15 m/s on a 2D plane. For marking on a 45° tilted surface, the speed of 6 m/s has been achieved.

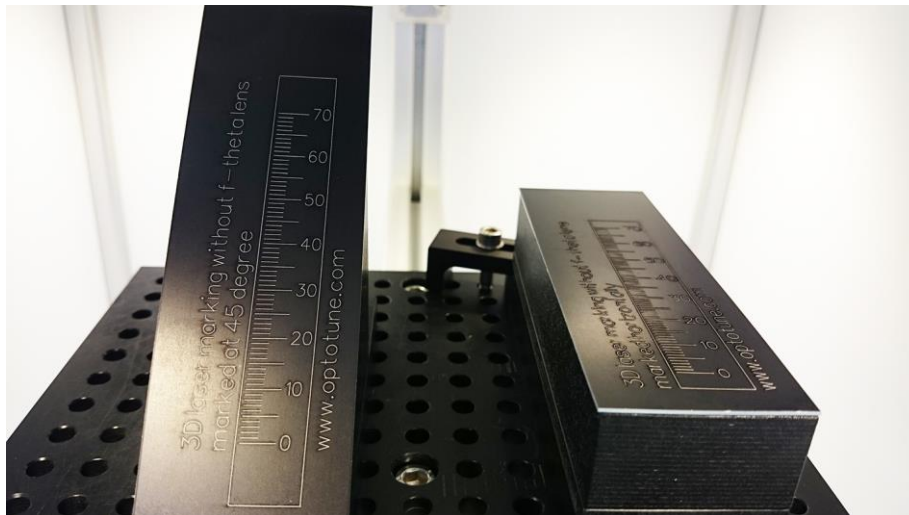


Figure 13: Real example of the 3D marking capabilities. On the right, a horizontal ruler is marked to illustrate the field flattening capabilities. The left shows a ruler marked on a 45° tilted surface.

## Appendix 4: Integration example without an f-theta lens

We have also implemented the laser marking with the EL-10-42-OF without using an f-theta lens. To account for the lack of the f-theta lens, supplementary focusing optics has to be implemented. Standard 1-inch optics, available from vendors such as Thorlabs is sufficient, as shown in Figure 14. It is recommended to use a white Teflon washer between the EL-10-42-OF and the holder plate to achieve a good thermal isolation.

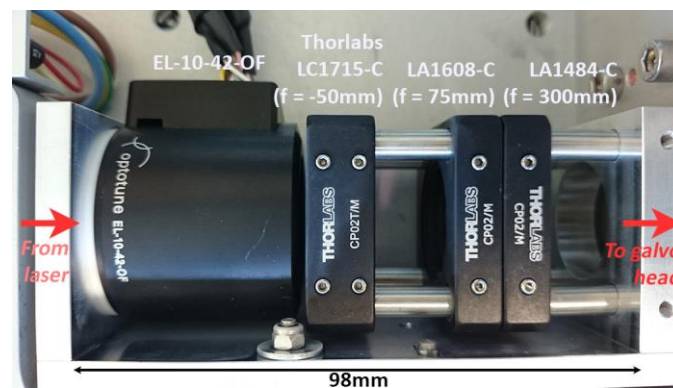


Figure 14: An example of the optical setup for laser marking system without an f-theta lens, placed between the laser and the scanning head.

The corresponding optical layout is illustrated in Figure 15. The EL-10-42-OF lens tunes the beam from -2 to +2 dpt, whereas the next two lenses ( $f = -50$  mm and  $f = 75$  mm) compose a beam expander, which enlarges the beam size. Finally, the beam is focused onto the working plane using the  $f = 300$  mm lens. The beam expansion is necessary to achieve spot sizes and marking quality comparable to those of the f-theta system ( $f = 160$  mm).

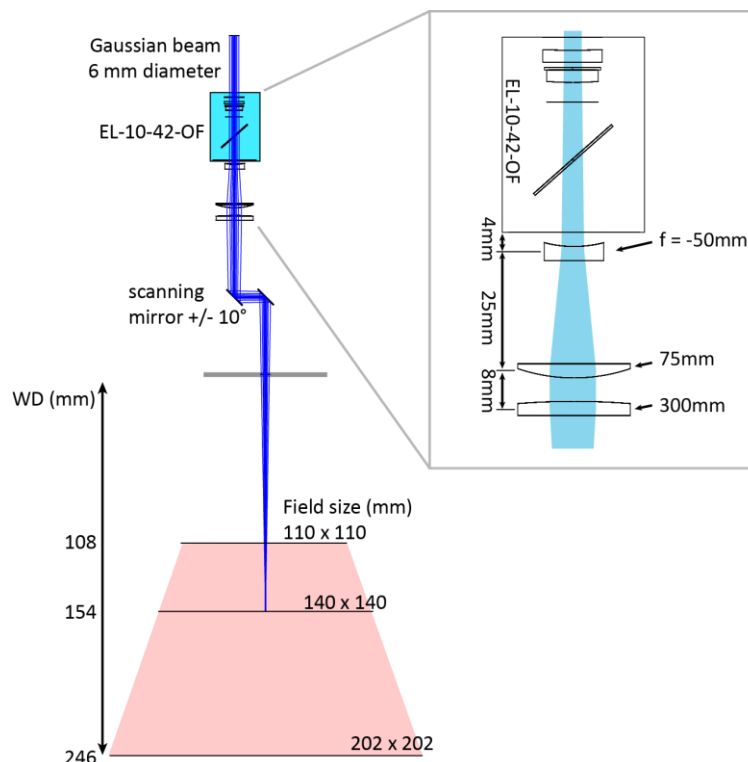


Figure 15: Optical layout of a laser marking system without the f-theta lens. The EL-10-42-OF tunes the beam divergence, the  $f = -50$  mm lens diverges the beam further to achieve a beam expansion of about a factor 1.5. The  $f = 75$  mm lens collimates the beam, which gets focused by the  $f = 300$  mm lens onto the working plane.