# *WP2*

# *D2.6 – External measurement head for high lateral resolution*

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# INTRODUCTION

## ADALAM Context

### Workpackage context

The main objective of this work package is to design and implement a complete solution for an inline topography measurement and analysis for monitoring before, during and after the laser micro machining. The following approach integrates a high-resolution optical distance measurement system in the beam path of the laser micro machine, enabling an in-line measurement of the current state of the machined micro- and macro-structures directly in machine coordinates. Based on this device an automatic and adaptive process will be enabled. The following solution uses a low coherence spectral interferometer in a Michelson-type set-up, with a measurement path through the scanning optical system and an external reference path.

One of the biggest challenges herewith are the very high axial and lateral tolerances of the process. Especially the required lateral tolerances under 10 µm demands special developments on the measurement system and on the machine optical system.

Moreover the high shape and feature variation of the workpieces to be manufactured represents a further challenge especially in regards to the numerical aperture of the optical system as well as to the measurement data processing and analysis.

Finally the overall optical effects of the scanning optics (scanning mirror and objective) represent a challenge for the measurement system regarding effects on the optical path, measurement spot diameter, laser and measurement beam coaxiality. Especially the internal dispersion properties of a telecentric scanning lens cause a wavelength and field angle dependent change in the measurement beam's focal length and beam waist diameter. Furthermore the optical path of the measurement beam is distorted by the optical aberration of the optical system. This effect is in addition position dependent, leading to a position dependent optical path.

These effects need to be characterized and compensated in the measurement system unit and integration / coupling unit. The sensing unit will rely heavily on the use of adaptive optical elements. An attractive feature of adaptive optics is that it can alleviate the extreme requirements on the scanning objective and can be tuned to the specific objective used in a setup after a calibration step.

In order to fulfill the main objective and cope with the related challenges four work areas / specific objectives were defined and subdivided on working groups, which are lead and executed by partners regarding their expertise. The work areas / specific objectives are as follows:

- Design and implementation of an **optical high-precision distance measurement system** optimized for the USP laser characteristics (high power and ultra short pulse duration), machine optical system and process axial and lateral tolerances;
- Concept and design of an optimized **scanning objective** with enhanced numerical aperture and lateral accuracy (reduced laser and measurement spots) as well as reduced focal depth and chromatic aberration regarding the measurement beam wavelength;
- Design and implementation of an **active alignment unit** for beam coupling and sensor integration based on adaptive optics;
- Design and Implementation of an **automatic point cloud analysis software** for feature detection and characterization for the generation of qualified information, which is feed back to the machine for process adaptation and control.

- Design and implementation of **evaluation and calibration methodology** to ensure high fidelity and reliable data. This work will be done in close collaboration with WP4.

As a second solution to comply in particular with the required lateral resolution, a high numerical aperture (NA) sensing head will be developed and attached to the machine scanning unit not using the optics of the scanning head. The measurement system device will address both sensing paths based on an optical switch (see picture in section 1), being able therefore to measure through the processing optics as well as through the high NA sensing head. This solution has the advantage of offering additional versatility to the machining head when measuring smaller structures, which are not measureable by the main sensing head.

## Task context

As a second solution to comply in special with the required high lateral resolution, a high numerical aperture (NA) sensing head will be developed and attached to the machine scanning unit without using the optics of the scanning head.

The sensor head will be based on an achromatic objective with high NA. This approach will lead to a high lateral accuracy associated to a high numerical aperture, which enables the measurement of steep flanks. Related to its constant spot size over the field of view, the high lateral accuracy is given for the designed focal length.

In the final machine concept, the measurement system device will address both sensing paths using an optical switch. Based on this approach, the system will be able therefore to measure through the processing optics as well as through the high NA sensing head.

# THEORY BACKGROUND

## External measurement head for high lateral resolution

### Measurement principle

The measurement system, which will be developed within WP2, is based on the spectral domain low coherence interferometry (SD-LCI), described by Schmitt et al., 2013, and is integrated on-axis into the laser processing optics for the fulfillment of inline measurements during the laser micro machining process. This integration leads to a very simple implementation and disables the need of further optics for the measurement system integration. Except those benefits, the on-axis integration is the enabler of the inline measurement concept, because the measurement beam path is the same as the laser processing beam path. In contrast to the benefits of the on-axis integration of the measurement system, the limitation in the numerical aperture (NA), which is induced by the specifications of the scanning objective, exposes a drawback of the measurement system. The limitation of the NA is a restriction of the lateral accuracy of the scanning objective. This is because the NA depends on the index of refraction *n* and the sinus of the acceptance angle *α* of the objective lens (see (1)). But not only the scanning objective is a limiting parameter for the numerical aperture, the scanner mirrors are inducing limitations too, because the mirrors always scans through a small area of the scan objective only. The acceptance angle is defined in this case as half the angular aperture of the scanner mirror.

$$NA = n \cdot \sin\alpha \tag{1}$$

To achieve a high numerical aperture, the acceptance angle has to be as big as possible. Within the goal of developing an external measurement head for high lateral resolution in Task 2.7, the integration of a second measurement head is performed, which features a shorter working distance, higher acceptance angle and therefore a higher NA than the on-axis sensor. By the integration of this high lateral accuracy sensor head, the measurement system will be able to perform off-line measurements of defects, which are beneath the lateral accuracy of the on-axis sensor. The external measurement head will not be able of inline measurements, because of its off-axis integration, but is supposed to be the back-up solution for measurements of defects, which cannot be measured with the main measurement system.

Since the measurement principle of the external measurement head is based on the same measurement principle as the main measurement solution, the integration is realized by a fiber switch. The fiber switch allows, if it is necessary, to perform off-axis measurements by using the same spectrometer as evaluation unit, than the inline measurement system uses. Only the development of an adapted reference path for the external measurement head is necessary. This is needed, because the working distance of the external head is not the same as the working distance for the inline measurement system. The combination of the two integration options of the SD-LCI measurement principles, like the inline on-axis measurement system with the external off-axis measurement head, combines the advantages of both integrated sensors, because both can feed only one evaluation unit. The external back-up solution can be used, when the preferred inline measurement systems reaches the limit of its lateral resolution.

### Literature

1. Schmitt, R., Pfeifer, T., Mallmann, G., 2013, Machine integrated telecentric surface metrology in laser structuring systems, Acta Imeko Vol. 2 Nr. 2, p. 73-77

# Concept and design of the external measurement head

## Solution concept

For scenarios of measuring defects, smaller than the lateral accuracy of the inline measurement system, an external high NA measurement head should help out for the localization and measurement of the defects as an off-axis solution. The scanning lens for the inline systems possesses a focal length of 100.2 mm, which decreases the maximal lateral resolution of the lens in terms of its minimum spot diameter on the focal plane. Due to the development of an external scanning head with a focal length of its scanning lens of 39 mm, the lateral resolution will be increased.

## Prototype system

### Simulation

The chosen concept for the design of the external measurement head is based on a small scanning lens with a working distance of 25.1 mm, to achieve a high lateral resolution, like described in the sections above. Furthermore the sensor is designed with an internal reference path and a scanning unit. To connect the optical path of the measurement beam with the optical path of the reference beam, a beam splitter is integrated between the scanning unit and the reference path, which guides 50% of the light in the direction of each optical path. In the simulation only the scanning unit and the scan lens are considered for the preparation of the spot diameters. Figure 1 illustrates the simulated design of the scanning unit and the scan lens.

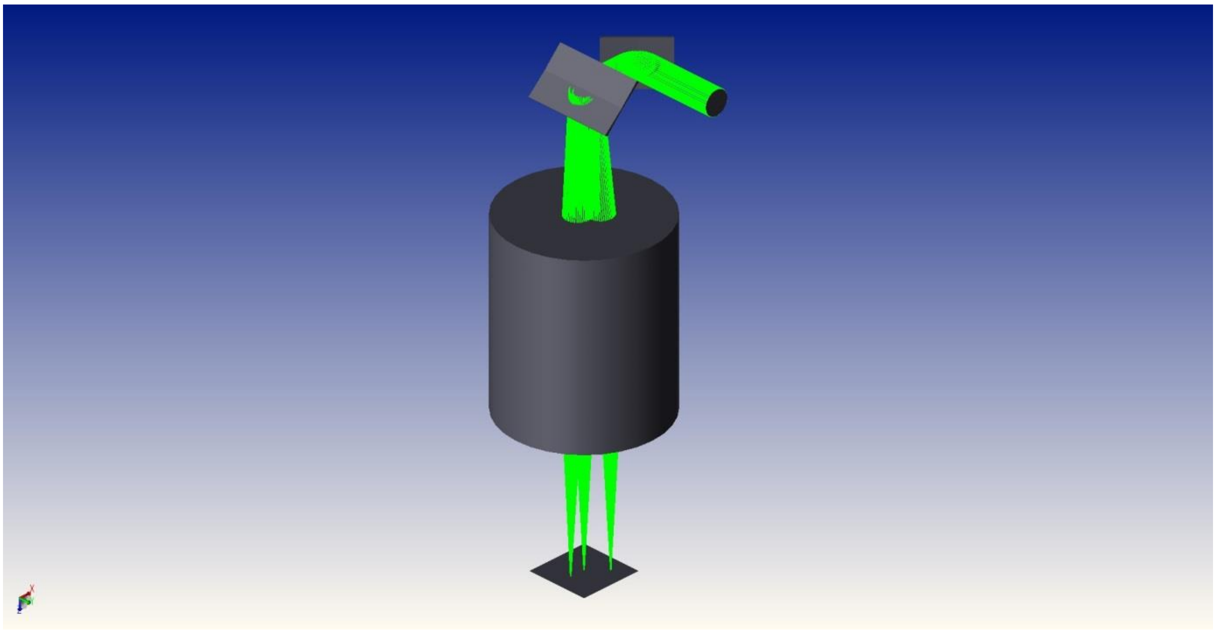
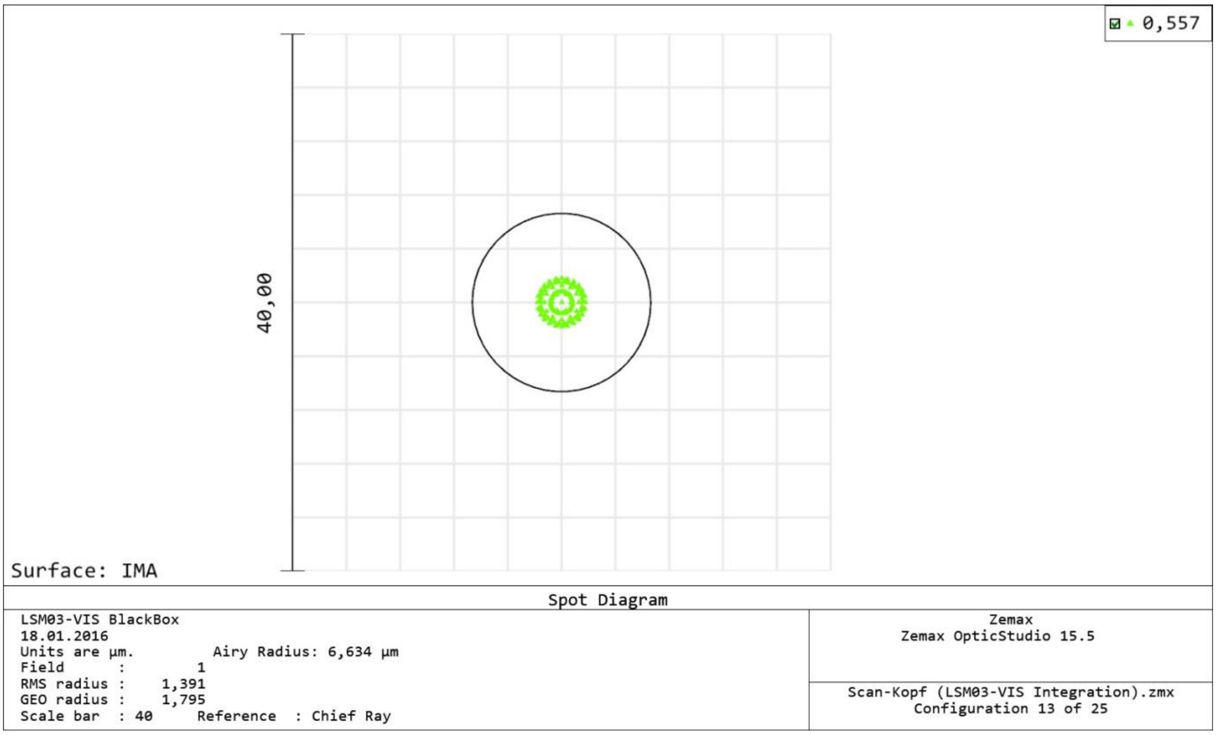


**Figure 1: Simulated design of the scanner unit and the scan lens with three different scanning angles.**

In the simulation a spot analysis with respect to three scanning angles was carried out. Only three scanning angles were considered, because these three are representative for the complete field of view with respect to the convenience of the spot size. The spot analysis was carried out to investigate the focal shift and spot diameter of the scanning lens.

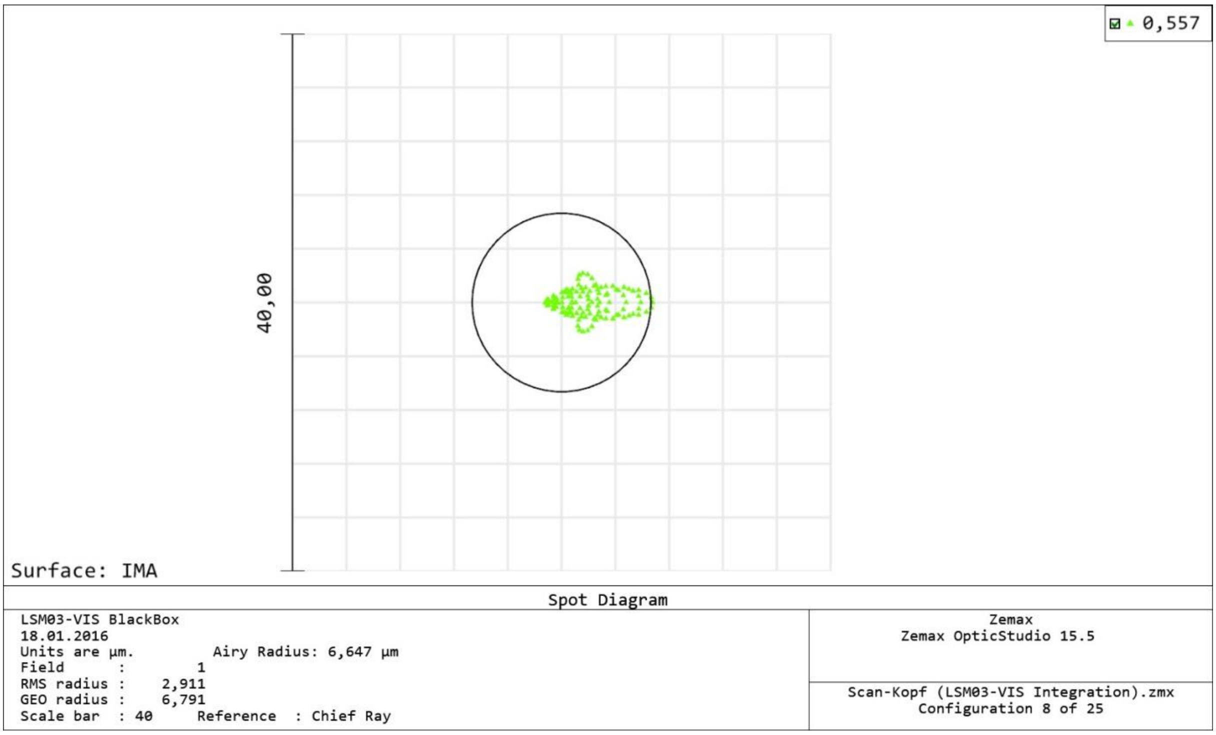
The three investigated tilting angles of the mirrors were 0° for both mirrors to investigate the spot with the beam passing through the centre of the lens. The angles of 0° for the first mirror and 2° for the second mirror was chosen to examine the spot size at the lateral edge of the field of view. At least the spot diameter, which impinges in the corner of the field of view, was examined with an angle of both mirrors of 2°. The spot diagrams for the different angles are shown in Figure 2-4.



```
LSM03-VIS BlackBox
18.01.2016
Units are µm.          Airy Radius: 6,634 µm
Field       :        1
RMS radius  :    1,391
GEO radius  :    1,795
Scale bar   : 40      Reference   : Chief Ray

Scan-Kopf (LSM03-VIS Integration).zmx
Configuration 13 of 25
```

**Figure 2: Spot diagram for the center of the field of view.**



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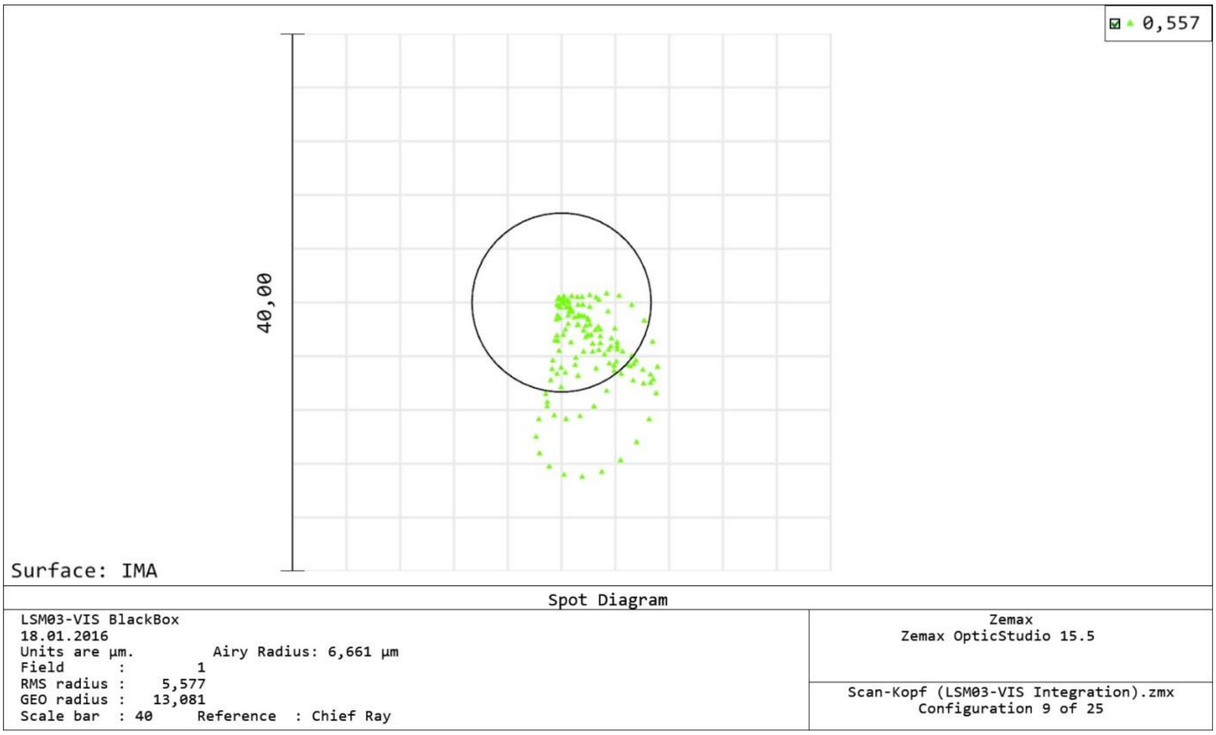
LSM03-VIS BlackBox
18.01.2016
Units are µm.          Airy Radius: 6,647 µm
Field      :         1
RMS radius :     2,911
GEO radius :     6,791
Scale bar  : 40      Reference  : Chief Ray
```

```
Zemax
Zemax OpticStudio 15.5

Scan-Kopf (LSM03-VIS Integration).zmx
Configuration 8 of 25
```

Figure 3: Spot diagram for the lateral edge of the field of view.



```
LSM03-VIS BlackBox
18.01.2016
Units are µm.          Airy Radius: 6,661 µm
Field      :         1
RMS radius :     5,577
GEO radius :    13,081
Scale bar  : 40      Reference  : Chief Ray
```

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Zemax
Zemax OpticStudio 15.5

Scan-Kopf (LSM03-VIS Integration).zmx
Configuration 9 of 25
```
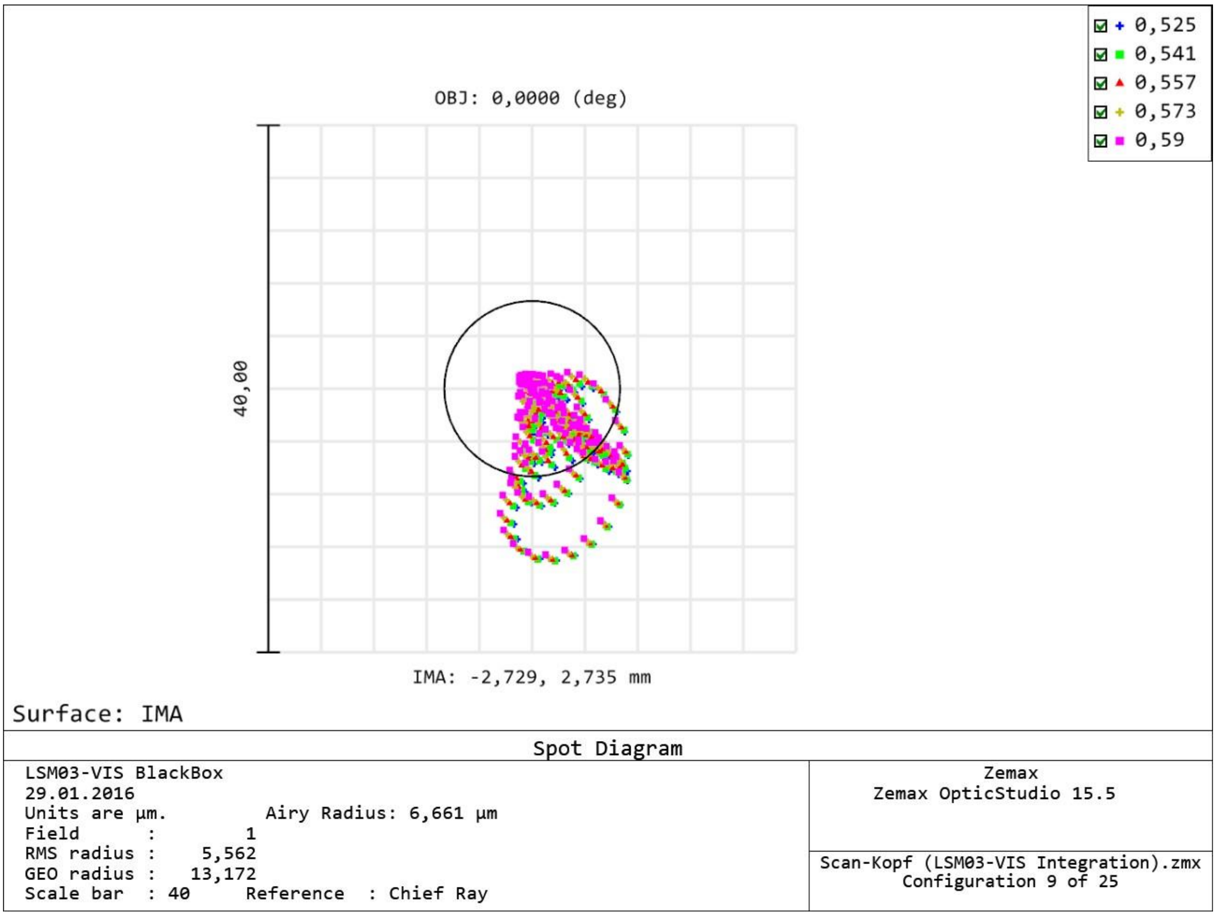

Figure 4: Spot diagram for the corners of the field of view.

The appearances of the spots for the different scan angles show an increased spot diameter for scan angles near to the edges of the field of view of the scan lens. This behaviour is induced by comatic aberration, which generates a distortion of the spots and therefore an increased spot diameter. To achieve the maximum lateral accuracy the spot diameters cannot be bigger than the airy radius, for what purpose the external measurement head achieves a field of view of 2x2 mm² with respect to the convenience of the spot size. The spots within this field of view are beneath the airy radius (RMS radius < Airy Radius), which means spots with a radius 5.577 µm per design. Further all optical elements are enhanced for the visible wavelength range. Unfortunately the color correction of the lens is not intend to work perfectly over the whole corrected spectral range, for which reason the lateral color error of the lens was analysed. The lateral color error is illustrated in Figure 5. The illustration shows, that the lateral focal shift of the lens, with respect to the wavelength and the designated scan angle, respectively field of view, is not significant within the measurement system's range. So the lateral color error can be neglected, for what reason the high NA external measurement can be declared as optimized for the wavelength range of the second generation measurement system.



```
LSM03-VIS BlackBox
29.01.2016
Units are µm.          Airy Radius: 6,661 µm
Field      :        1
RMS radius :    5,562
GEO radius :   13,172
Scale bar  : 40      Reference  : Chief Ray

Zemax
Zemax OpticStudio 15.5

Scan-Kopf (LSM03-VIS Integration).zmx
Configuration 9 of 25
```

**Figure 5: Lateral color error for the measurement wavelength range of 525 nm - 590 nm, within the designated field of view of 2x2 mm².**

## Hardware prototype

The mechanical design of the external measurement sensor integrates the optical components into a single compact housing, which is made of aluminium. The integration of the optics begins with the collimator. The collimator couples the light of the light source into the sensor. In the next step, the light is divided by the beam splitter, whereat 50% is transmitted to the scanner unit and reflected through the scanning lens to the sample surface. The other 50% of the coupled light is reflected by the beam splitter into the reference path and focused on the reference mirror by an achromatic lens. The achromatic lens prevents the reference light beam from chromatic aberration, for which reason the spot on the reference mirror is not affected by the wavelength. Only the dispersion of the scanning lens induces a focal shift on the sample surface. For the correction of the dispersion in the measurement path, a compensation element is integrated into the reference path, which compensates the shift between both paths. To feed the measurement signal back to the spectrometer, the reflected light from both, the sample surface and the reference mirror, is coupled back into the collimator by the beam splitter. Due to the coupling of both beams back together the interference is induced. The collimator feeds the light into an optical fibre, which transmits the light with the aid of a fibre switch into the evaluation unit, whereat the interference will be analysed. An overview on the positioning of the optical components within the sensing head is shown in Figure 5 and the real mechanical assembly is illustrated beneath in Figure 6.

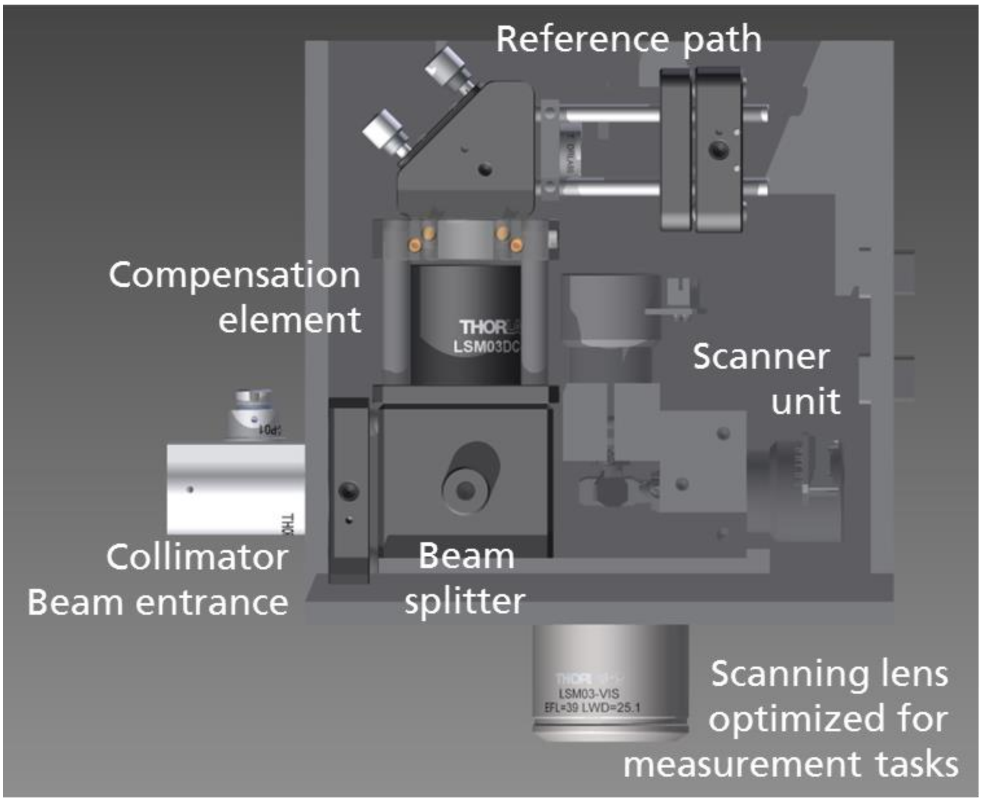


**Figure 6: Mechanical design of the external high NA measurement head.**

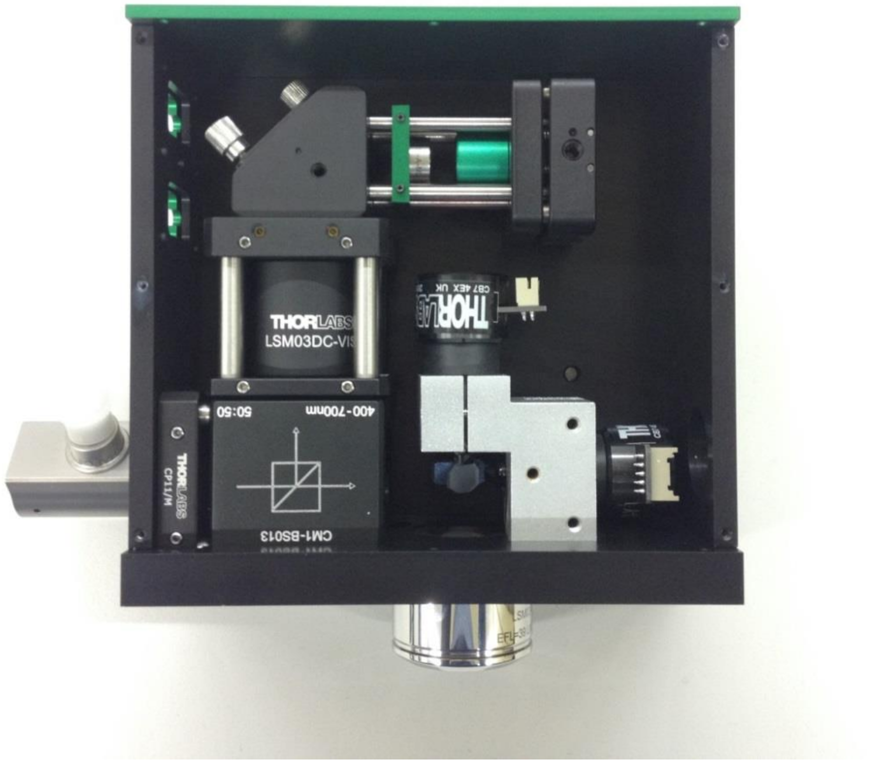


**Figure 7: Assembly of the external high NA measurement head.**

The evaluation unit is the same spectrometer as it is for the inline sensor. The spectrometer extracts information about the distance to the workpiece from the interfering measurement signal. By scanning the measurement beam over the field of view on the sample surface, the interference in the evaluated light changes slightly, for what reason defects on the sample surface could be measured. The scanner is able of 15 µrad repeatability, a scanning angle of ±12.5° and a bandwidth of 1 kHz. Accuracy and frequency are very suitable for the measurement task, but the scanning angle cannot be fully exploited, because the scan lens loses too much accuracy in the outer areas of its field of view. The collimator provides a collimated beam with a diameter of 4mm, which is chosen with regards to the other ingredient optics, which apertures are limiting the beam diameter. The ingredient optical elements were selected with regards to the limitations in size, given to the boundary conditions of developing a compact measuring sensor.

# NEXT STEPS

Once the second generation measurement system is fully developed and ready for the integration of the external measurement head for high lateral resolution, the next steps will be the following:

- Adjustment and alignment to the spectrometer of the second generation measurement unit and test measurements in a stand-alone laboratory built-up.
- The integration of this prototype in a laser micro processing machine from Lightmotif and the combination and alignment with the inline measurement sensor.

- Based on the fully integrated system, a series of testing experiments will be carried out, focusing on the system's usage as back-up high resolution measurement sensor.
- Software-sided integration in the point-cloud analysis in terms of the feedback control of the laser micro machine.

All these tasks are aligned with the WP2 and WP3 structure, the main goal is to develop the second generation measurement system by M20. Then, it will be completely evaluated and characterized by M24.