Precise topographic surface measurements of warm and cold large image detectors for astronomical instrumentation

Sebastian Deiries[1]*[a],Olaf Iwert[a], Stefan Stroebele[a]
[a]European Organization for Astronomical Research in the Southern Hemisphere,
Karl-Schwarzschild Str. 2, D-85748 Garching, Germany

ABSTRACT

This paper describes ESO's surface measurement device for large image detectors in astronomy. The machine was equipped with a sub-micrometer laser displacement sensor and is fully automated with LabView. On the example of newly developed curved CCDs, which are envisaged for future astronomical instruments, it was demonstrated that this machine can exactly determine the topographic surfaces of detectors. This works even at cryogenic temperatures through a dewar window. Included is the calculation of curvature radii from these cold curved CCDs after spherical fitting with MATLAB. In addition (and interesting for calibration of instruments) the micro-movements of the detector inside the cryostat are mapped.

Keywords: Surface topography measurement, detector characterization, curved CCDs, cryogenic movements, CCD, optical CCD, laser triangulation, LabView software

1. INTRODUCTION

Large optical detectors in Astronomy need to be precisely placed into the focal plane of the astronomical telescopes or its instruments in order to have optimum results. Therefore the detector has to be very flat or in the future may be defined curved shaped. Moreover it has to be aligned inside its cryogenic vessel. To achieve this at the European Organization for Astronomical Research in the Southern Hemisphere (ESO) an in-house designed machine using laser triangulation was constructed in order to first map topographically these detectors in space coordinates, then calculate and do the necessary alignments.

2. PRINCIPLE: LASER TRIANGULATION

2.1 Sensor

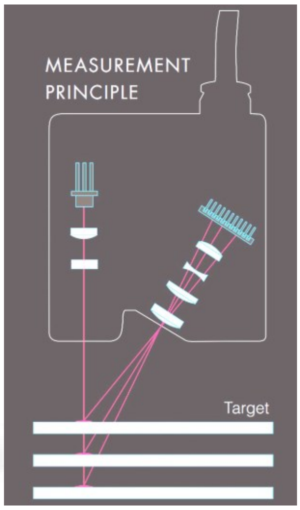

Figure 1 The laser triangulation sensor measures the distance to specular reflective surfaces

[1]*sdeiries@eso.org; phone +49 89 32006-354; fax +49 89 3202362, www.eso.org

2.2 Advantage

This method is contact-free and does not require very small working distances. Moreover it can be used through optical (cryostat) windows.

3. TOPOGRAPHIC MEASUREMENTS ON DARK LOW-REFLECTING DETECTOR SURFACES

The difficulty was to find a measurement principle, which works on very dark surfaces with a reflectivity of less than 1…4%, like coated CCD detectors, and at the same time on transparent surfaces (e.g.: cryostat windows) with anti-reflective coatings, which give a transmission of higher than 99%. Therefore a laser triangulation displacement sensor was selected, which can also handle tilted surfaces.

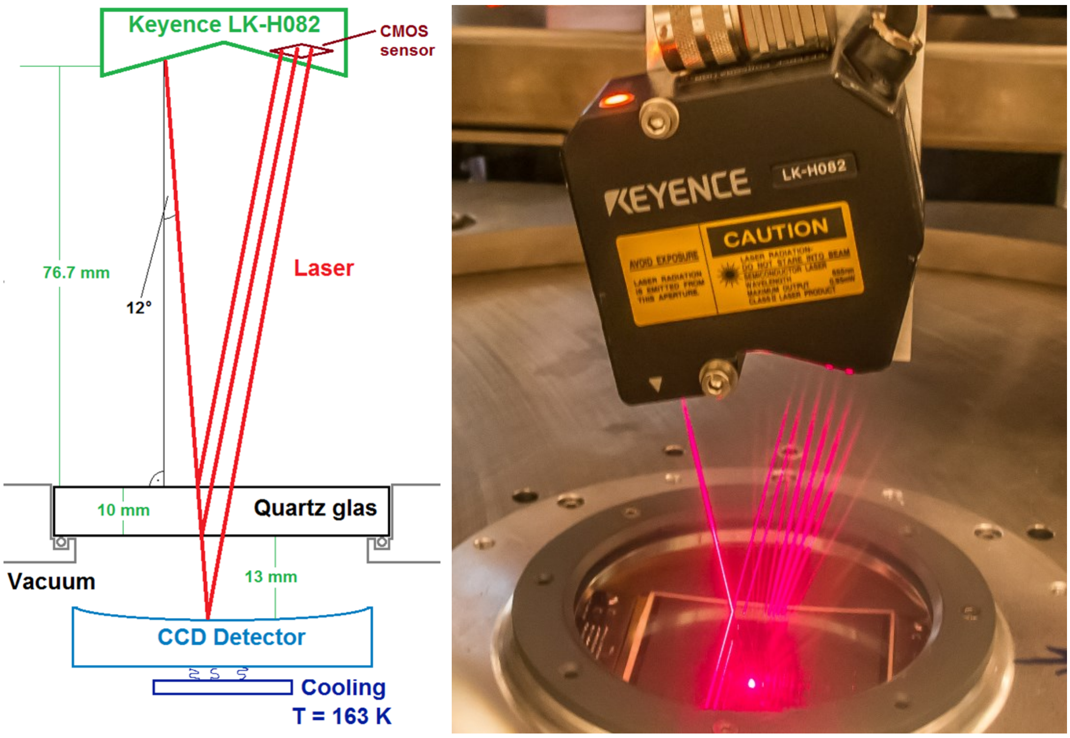

Figure 2 Exact distance measurement of cold detector surface in vacuum through a coated fused silica window. The detector below the window inside an evacuated vessel is antireflection coated and has therefore only a reflectivity of 1…3% at a temperature of 163K. The laser displacement sensor can handle these conditions with an automated brightness adaptation.

4. MACHINE TO OBTAIN AUTOMATED 3D-SCAN WITH TRIANGULATION SENSOR

The used laser triangulation sensor needs a stable mount and a device, which performs an automated 3D-scan on the astronomical detector. Therefore it was mounted on a precise X-Y-Z translation stage. The X and Y-axis are motor driven, enabling a motorized scan of the area underneath. With a manual driven linear translator on the Z-axis the limited measurable range of the triangulation sensor of -17.6… + 14.5 mm is increased by ±25 mm. The support structure for the linear translator is a rectangular frame allowing a flexible use of the machine. For large devices it is possible to mount the whole machine on top of an astronomical camera or instrument. For single detectors the detector cryostat is mounted on a rigid plate below the machine, which is then used like a stand. Two Zebotronics 2-phase Stepper motors (SM 56.1.18J3) drive the two Nadella “KR3306C + 400LP0-1300” 330mm linear modules (axes) in an open loop. The stepper motors are controlled via a PC by the National instruments (NI) “PCI-7332 low cost 2 axis stepper only controller” via the NI “MID-7602 integrated amplifier for two stepper motors”. The PCI-7332 can be easily operated with LabView 2010, if the LabView NI-Motion package is installed.

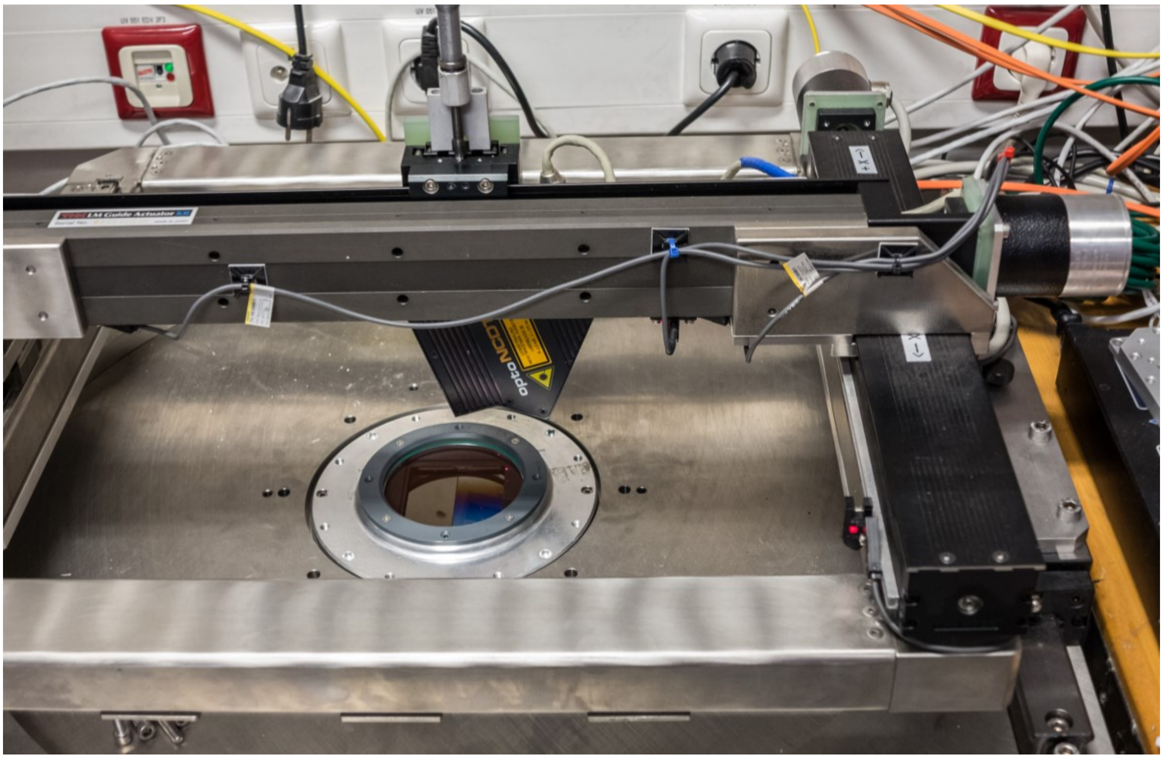

Figure 3 Measurement machine with linear precision X-Y-Z translation stages. The laser sensor is moved on a stable steel mount and allows therefore exact measurements of the topography of astronomical detectors.

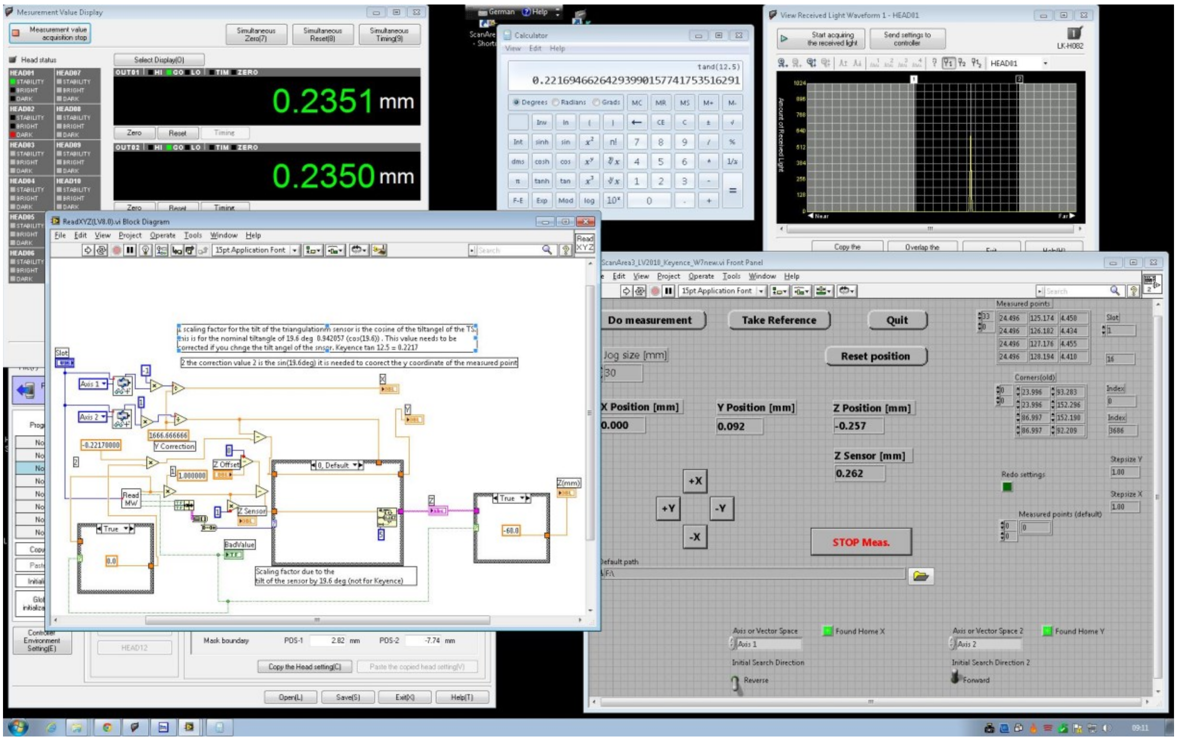

Figure 4: LabView master program to scan detector surface, read laser sensor and document results

After the start of the machine the laser sensor is checked with the Keyence software LK-Navigator and manually placed into its working position with a manual Spindler & Hoyer 50mm linear table TLD65-50 with the Keyence software LK-Navigator. This operates the sensor controller hardware Keyence LK-G50001P, which was delivered with LabView drivers.

4.1 Functionality of measurement machine

The laser displacement sensor was delivered with a control software LK-Navigator for positioning and adjustment of laser triangulation sensor with the following options: Selection of reflecting surface, sampling time and frequency and quality check of signal. This has to be adjusted before each new measurement run of the machine.

The in-house programmed LabView 2010 modules give the following functionality:

1. Calibration of home-position in X and Y.

2. Panel for motorized moving in X and Y with real-time PC-screen readout of Z value of the laser-sensor.

3. Moreover the LabView master program can move the motors manually and automated in various geometric modes (rectangular, circle and annular space type), read-out unattended sensor and axis values to the PC and perform complete data acquisition of several selectable automated measurement routines.

4. Different automated X and Y 3D-scan program options are available as geometric-scan-modes (e., which then acquire X, Y and Z results of the scan into a file.

4.2 Data evaluation with MATLAB

Example of measurement results:

Date/Time: 19/05/2014 17:52
dx/dy: 1.0000 1.0018
Comments: Curved CCD at -80 centigrade in cryostat
Data (X, Y, Z in mm)

84.4968	114.8379	59.1298
84.4968	115.8606	59.1878
84.4968	116.8838	59.2473
84.4968	117.8896	59.2580
84.4968	118.9241	59.3511
84.4968	119.9303	59.3629
84.4968	120.9477	59.4060
84.4968	121.9571	59.4285
84.4968	122.9865	59.5055
84.4968	124.0004	59.5388
84.4968	125.0105	59.5633
84.4968	126.0306	59.6142
84.4968	127.0467	59.6537
84.4968	128.0614	59.6911
84.4968	129.0726	59.7170
84.4968	130.0823	59.7386
84.4968	131.0827	59.7356

…

Later with MATLAB R2010a software the resulting data are filtered, corrected, compared and 3D-plotted. For the alignment of detector cryostats or astronomical instruments the MATLAB routines also give the needed correction values.

As an example the resulting plot of ESO's recent ESPRESSO flat CCD detector (9kx9k pixel, 10 µm) is given to illustrate the capability of the described machine:

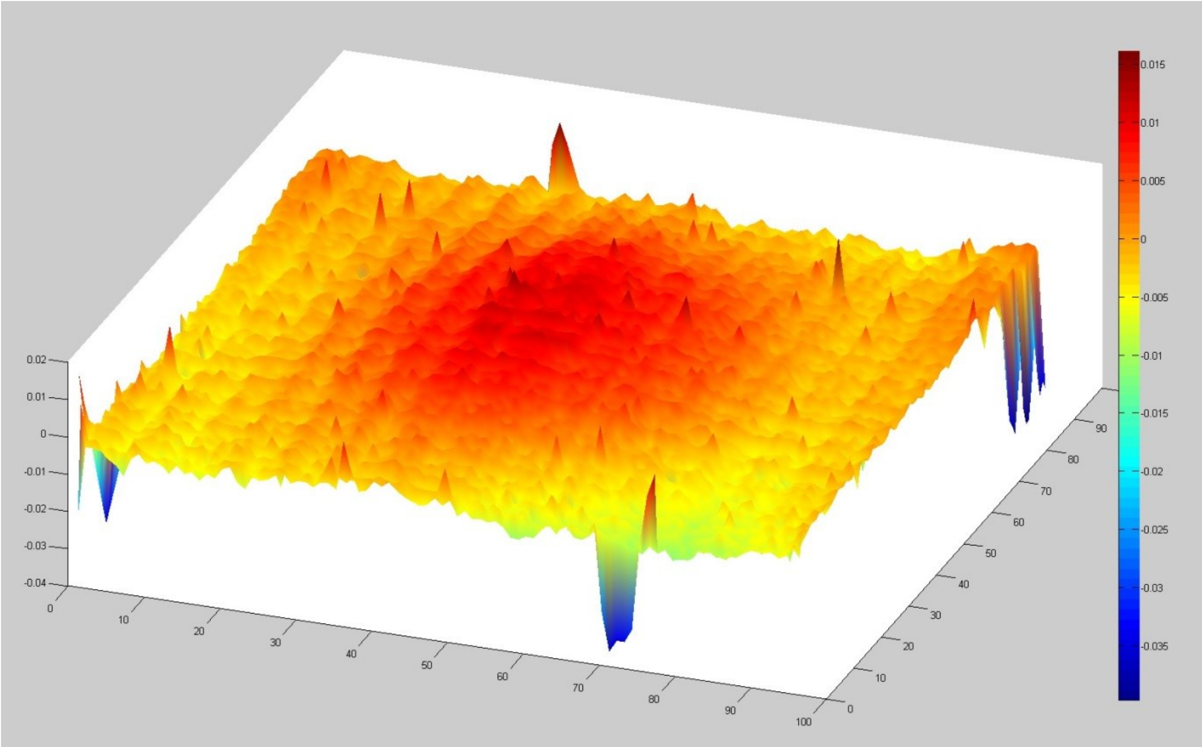

Figure 5 MATLAB-Plot of a cold ESPRESO (flat) detector surface through a cryostat window (all values in mm)

The total cost of this surface measurement machine is low, compared with commercially available and comparable systems.

5. RECENT UPGRADE OF MACHINE WITH A NEW PRECISE AND VERSATILE LASER TRIANGULATION SENSOR

Since the first IDL2000-5 triangulation sensor made by Micro Epsilon from 1999 [2] was not precise enough and could not measure tilted surfaces, the machine was upgraded in 2013 with the Keyence LK-H082 sensor. The new sensor can simultaneously measure several surfaces, which allows an instant measurement of a window reference surface. It also has no problems with warming-up and over-heating of its laser. It is faster, more precise and gives a much larger measurement range at a higher working distance of 76.7mm. Therefore it allows to “look” deeper into cryogenic vessels, where the detectors are mounted and cooled. The precision in X and Y is approx. 70 micron due to the laser spot diameter. The theoretical maximum distance measurement precision is 0.1 micron. With the very dark low reflective detector surfaces a precision of at least 0.5 micron in distance Z could be reached, which is more than sufficient for the characterization of optical detector surfaces. Even surfaces with very dark anti-reflective coatings and with a reflectivity of less than 1% can be measured without re-calibration, because the laser displacement sensor has an automatic built-in amplification calibration. On the real time display of the LK-Navigator the state of the sensor can be checked. If many reflective surfaces are involved, the distance range can be limited and pre-defined in order to filter out the surface of interest. This software also offers many options of sampling time and measurement frequency. The large measurement range of -17.6 +14.5 mm makes it now possible to characterize tilted surfaces and 3D curved detectors.

Advantages of the new laser triangulation sensor:

- ❑ Simultaneous measurement of several surfaces possible, automated with LabView;
- ❑ Tilted surfaces up to 5° are measurable;
- ❑ Large measurement range of -17.6 +14.5 mm
- ❑ No over-heating during long use, which needed re-calibration

5.1 Micro Epsilon Triangulation sensor compared with Keyence LK-H082 sensor

	Micro Epsilon ILD2000-5(SPL)	Keyence LK-H082
Mounting mode	Specular reflection only after modification	Specular reflection
Reference distance	58 mm	76.7 mm
Measurement range	±2.5 mm	-17.6 +14.5 mm
Spot diameter (at ref. distance)	95 µm	70 µm
Linearity	±0.03 %	±0.02 %
Resolution: theoretical / dark CCD	0.5 µm / 2 µm	0.1 µm / 0.5 µm
Sampling cycle	100 µs	2.5-1000 µs (adjustable)
Temperature fluctuation	± 0.1 µm / K	± 0.07 µm / K
Environment resistance: Ambient light Ambient Temperature	 max. 30000 lux 0 - 40°C	 max. 10000 lux 0 - 50°C
Weight	500 g	280 g

Table 1 New Keyence laser triangulation sensor compared with its precursor

5.2 Scheme of new sensor

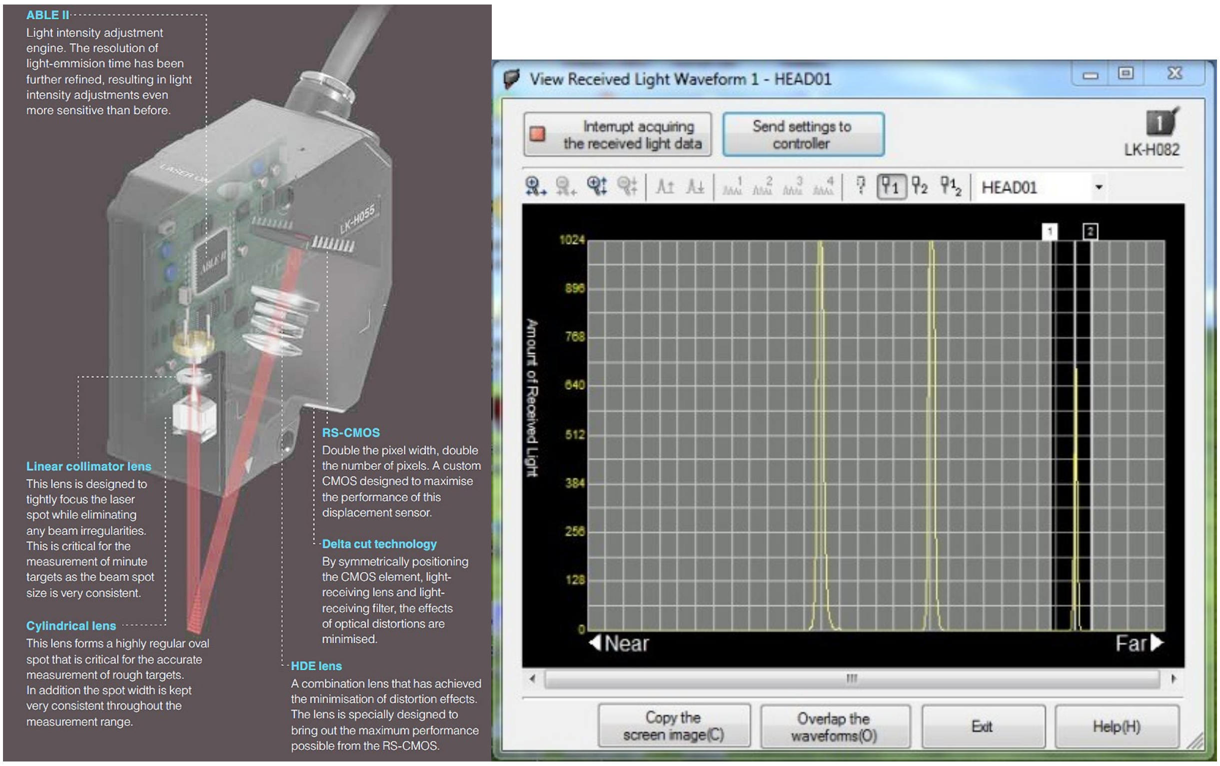

Figure 6 Functional principle of Keyence LK-082 (left) and three simultaneous reflections (top window, bottom window and CCD surface) seen at real time readout of the LK-Navigator software (right)

6. ALIGNMENT OF LARGE DETECTOR MOSAICS

ESO's surface measurement machine can topographically measure single detectors or arrays (mosaics) of detectors up to a size of 340 x 340 mm.

It was successfully used for the ESO WFOV-array at the ESO La Silla observatory, which consists of 9 CCD detectors and the ESO OmegaCAM mosaic camera (VST, Paranal) which consists of 36 CCDs: The final alignment result of the OmegaCAM CCD mosaic shows only a maximum deviation of ±18 micron from the ideal plane for the complete detector array of 260 x 260 mm [4].

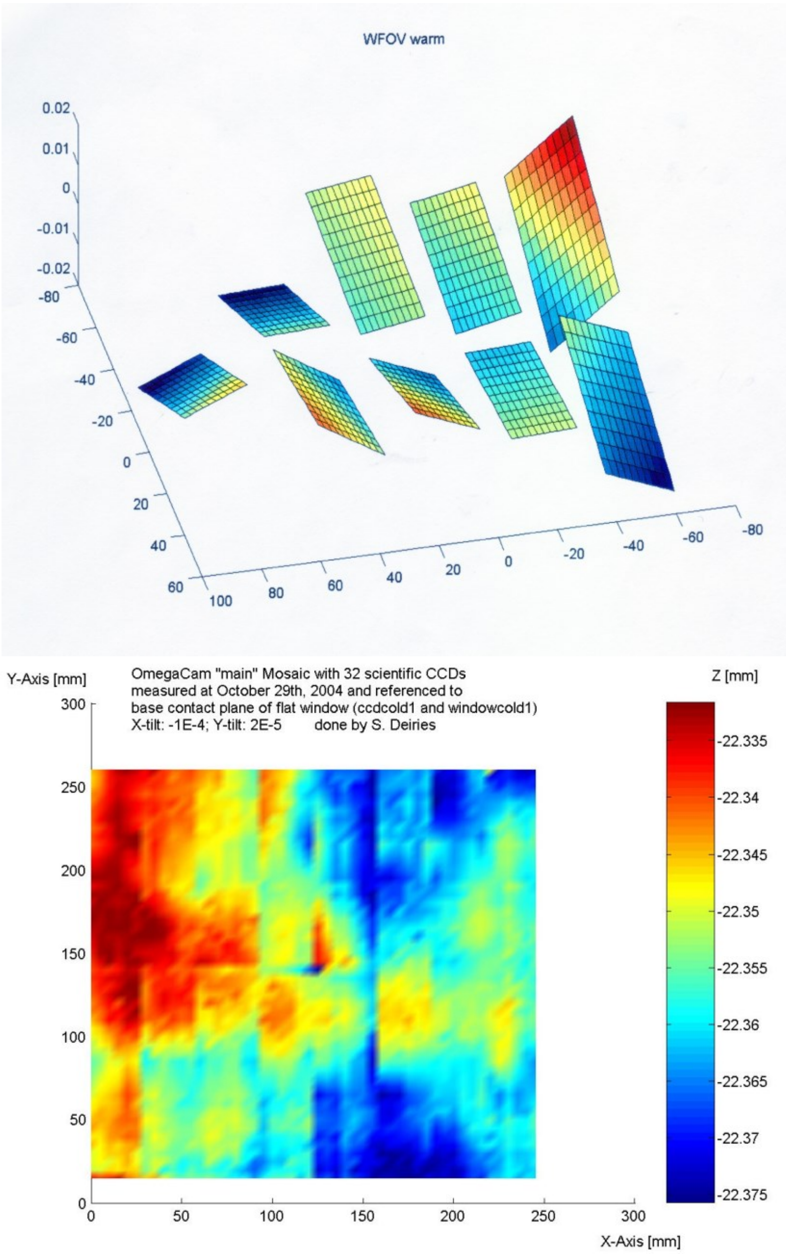

Figure 7 Plot of single CCDs of WFOV mosaic (top) and complete OMEGACAM mosaic after alignment (bottom)

7. MEASUREMENTS OF 3D CURVED CCDS

Working 3D Curved CCDs [1] are a new addition to the world of detectors. Complicated instrument optics can be simplified significantly and improved in image quality with curved CCDs [5]. For the optical design the curved CCD has to have a defined curvature radius. ESO developed in an R&D project [6] together with ITL [7] 3D curved CCDs with a curvature radius in the range of 500 mm. The manufacturing of these CCDs is difficult, but after some failures two CCDs were received and tested at ESO. The surface shape is very critical, especially its homogenous curvature radius over the whole CCD.

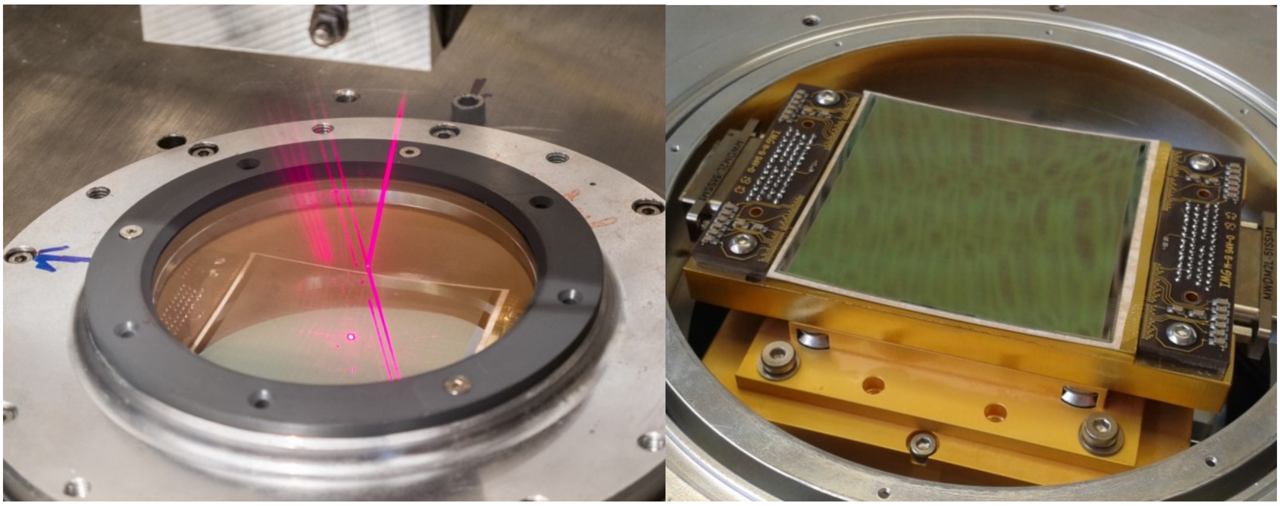

Figure 8 Curved CCD with a size of 60 x 60 mm and a curvature radius of approx. 500 mm

7.1 Radius measurements of 3D Curved CCDs

The spherical fitted radius of curved CCD S/N 10292 was measured with R = 576.85 mm at +20°C. The here used method of spherical radius best fit with MATLAB is the modified “Sphere Fit (least squared)” routine from Alan Jennings [3].

This compares quite well with the three results from ITL measured with a completely different method, which are: 573.79mm, 572.55mm and 567.13mm for three regions of the CCD.

Curved CCDs should not break if cooled down to cryogenic temperatures (-80°C…-120°C) and should keep their shape during cooling, or at least have a defined change in shape. This was also verified with ESO’s topographic surface measurement machine. It was also a proof, that micro movements of the detector inside of the cryogenic chamber can be measured.

7.2 Radius variation of 3D Curved CCDs at different temperatures

The spherical fitted radius of curved CCD S/N 10292 depending on its temperature gives the following results:

at +20°C: r=576.85 mm,
at -80°C: r=576.17 mm and
at -100°C r=575.78 mm.

This means, if getting colder, the curved CCD is bended to a shorter radius. Figure 9 shows the difference of this curved CCD between warm state (+20°C) and cold state (-100°C).

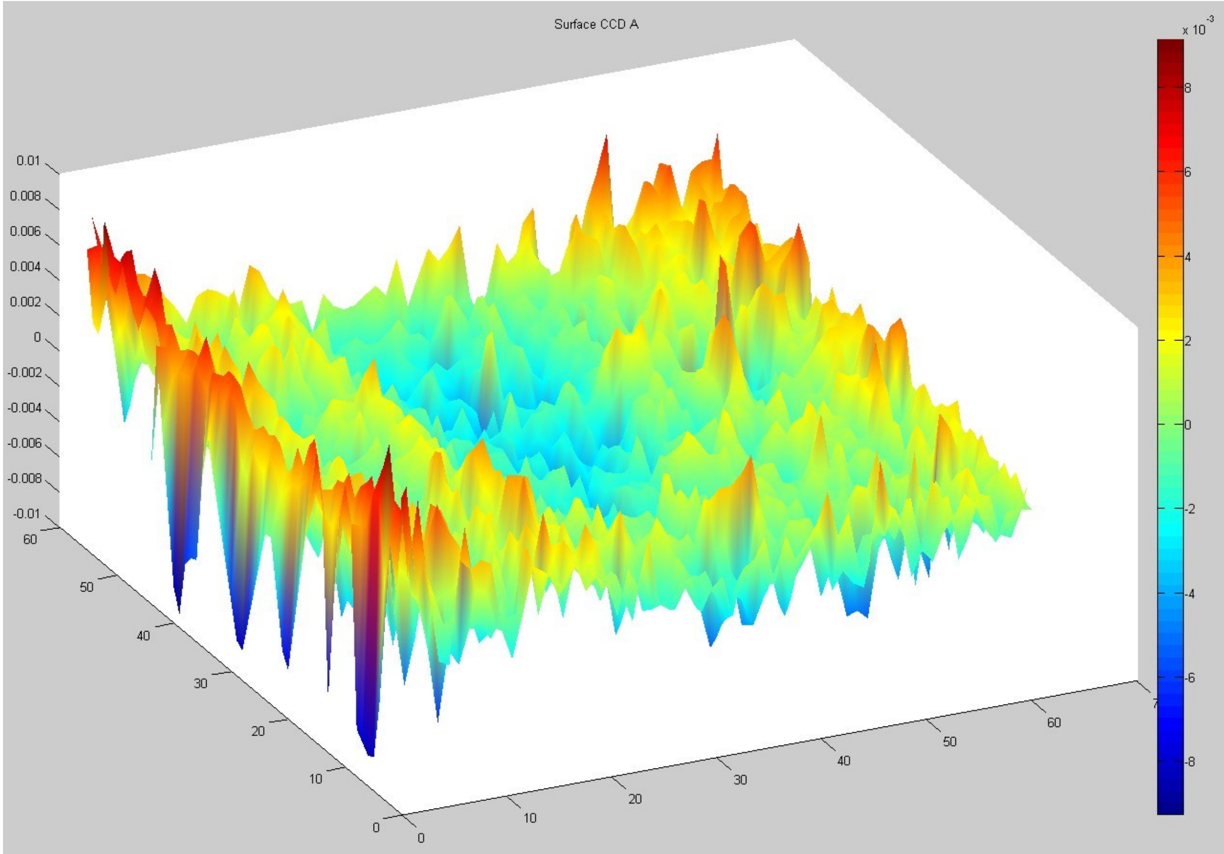

Figure 9 Thermal bending of Curved CCD: Relative difference between cold and warm CCD is less than ±6 micrometer

8. IMPROVED PRECISION OF MACHINE WITH CALIBRATION, MEDIAN FILTERING AND BIAS SUBTRACTION

Figure 10 Precision gauge blocks (nominal thickness ±0.1 micron) and precision glass plate (high flatness of 0.125 micron) for calibration

The laser triangulation sensor was calibrated with 1.0000 mm precision gauge blocks. An absolute precision of 0.1% was measured. A precision plane glass disk with a tolerance of 0.125 µm was used for bias acquisitions with the machine.

8.1 Median filtering

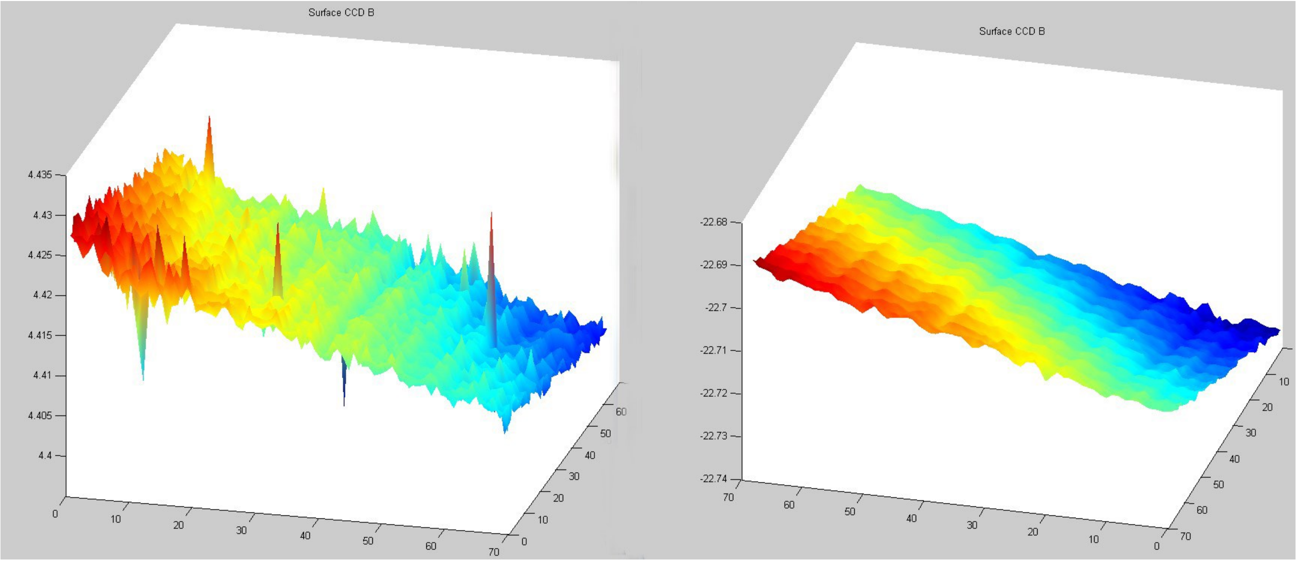

Figure 11 Effect of median-filtering: The left plot shows raw data, the right plot shows the median-filtered version of the measured CCD

Unwanted spikes due to dust reflection and impurities in the surfaces were partially removed by 5 consecutive measurements and taking its median.

More of these spurious features were removed by median filtering with a filter 2x2 or 3x3 “pixel” of the resulting surface grid.

8.2 Bias correction

In order to remove a recurring pattern in all surface measurements, a so-called BIAS frame was taken with a large precision glass plate or disk.

This BIAS, which was derived from 5 measurements shows a regular pattern (of approx. ±2 micron), which seems to result from tolerances of the translation stages and its bearings, possibly also from oscillations during the machine movement.

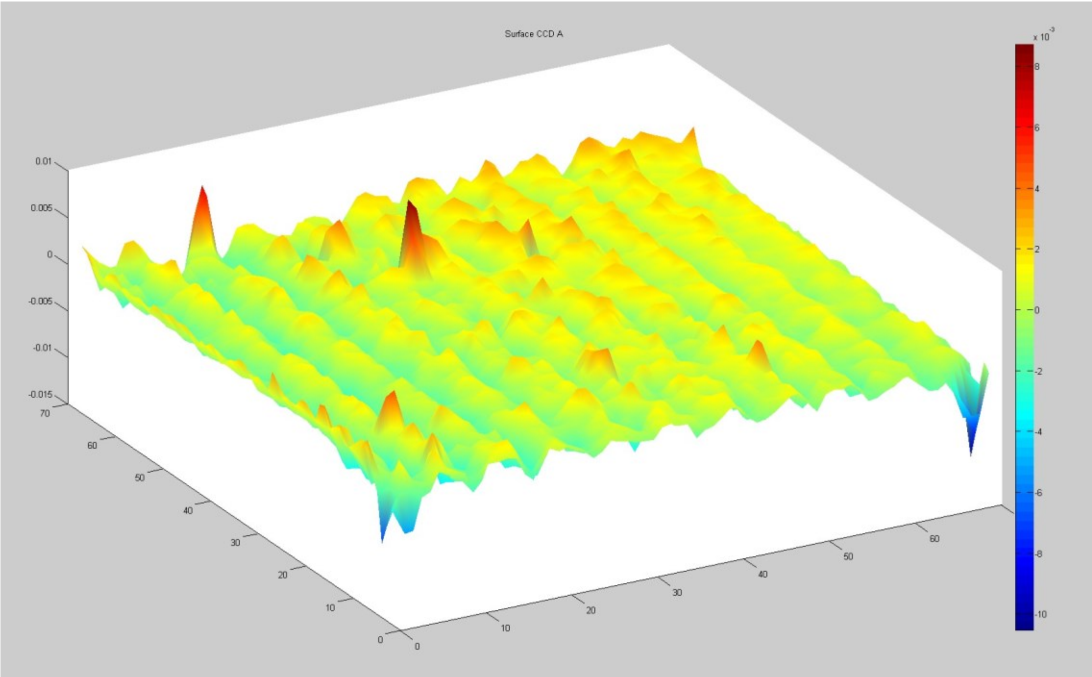

Figure 12 BIAS frame from median of 5 measurements on precision glass plate showing regular pattern from machine

Nevertheless a bias-subtraction of CCD measurements is still not completely successful, because some pattern remains and the measurement could not be flattened. Therefore another approach is foreseen with an automated simultaneous measurement of all 3 surfaces (window surfaces and detector surface). This method should eliminate all "patterns".

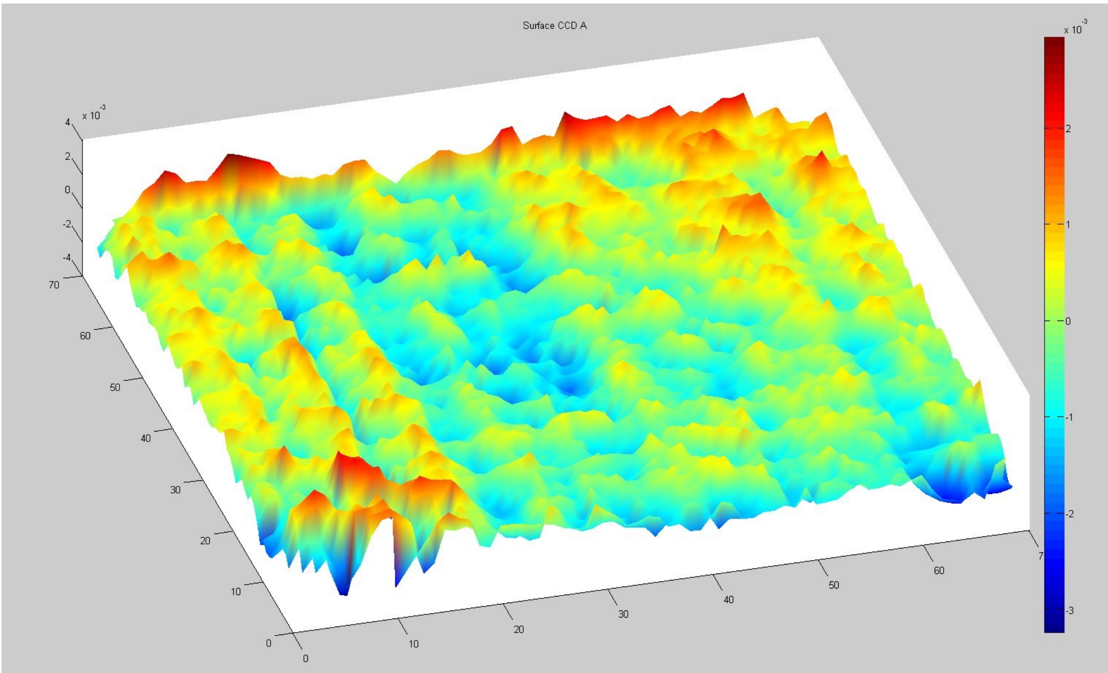

Figure 13 CCD detector measurement with BIAS subtraction: regular pattern could not be removed completely and a pattern of ±1.5 micron is remaining

9. OVERVIEW OF MACHINE AND OUTLOOK

The following components have been used for the precision topographic surface measurement machine for astronomical detectors:

Hardware:

Keyence LK-H082 sensor;
2 x Zebotronics 2-phase Stepper motor (SM 56.1.18J3);
2 x Nadella "KR3306C + 400 LP0-1300" 330 mm linear modules;
Spindler & Hoyer 50 mm manual linear table TLD65-50;
National Instruments "PCI-7332 low cost 2-axis stepper only controller";
National Instruments "MID-7602 amplifier";
Keyence LK-G50001P controller.

Software:

LabView 2010 (with NI-motion package installation);
Keyence software LK-Navigator;
MATLAB R2010a.

It complies with the requirements of mapping and alignment of astronomical detectors inside their cryogenic vessels. Several optical detector systems at ESO were successfully aligned with this device. The machine was built with a fairly low budget of approx. 15k EUR. Compared to commercially available systems– especially interferometers – this is a much cheaper solution. ESO is still in the progress to improve this machine. The goal is to get even better surface precision results of ±0.2 micrometer on astronomical detectors.

REFERENCES

[1] Iwert, O., Ouellette, D., Lesser, M., Delabre, B., "Results and potential of a novel process to produce curved large area scientific imagers", Proceedings of Scientific Detector Workshop 2013, Florence, Italy (2014).
[2] Stroebele, S "A new machine for planarity measurements of CCDs and mosaics of CCDs" Optical Detectors for Astronomy II, 359-364 (2000).
[3] Jannings, A., "Sphere Fit (least squared" (2 July 2013), http://www.mathworks.com/matlabcentral/fileexchange/34129-sphere-fit-least-squared
[4] Iwert, O. et al., "The OmegaCAM 16K x 16K CCD Detector System for the ESO VLT Survey Telescope (VST)", SPIE 6276-11 (2006).
[5] Iwert, O., et al., "Curved Imaging Detectors - New possibilities in Optical System Design", Proceedings Scientific Detector Workshop (2013)
[6] Iwert, O., et al., "Results and potential of a novel process to produce curved large area scientific imagers" , Proceedings Scientific Detector Workshop (2013)
[7] http://www.itl.arizona.edu/