LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

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Surface figure calibration and uncertainty estimate for measurement of ETM04

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1 Introduction

The purpose of this note is to memorialize the method used to calibrate the transmission sphere for measurement of ETM04. ETM04 is a critical element due to it's role in verifying coating uniformity. The uncertainty in this measurement is of order 0.4 nm rms over 300 mm and 0.1 nm rms over 160mm. While the error found in this analysis is sufficient for analysis of ETM04, we expect the uncertainty of the test set to be refined by further calibration.

2 Method

The method used for calibration is a combination of common metrology techniques. The radius of curvature calibration comes from knowledge of the radius of curvature of an existing part, certified by Zygo. The higher spatial frequency knowledge comes from measurement of a very good part in random orientations with respect to the transmission sphere (also called reference sphere.) The random files are averaged to generate a reference data file (RDF) which can be subtracted from the measurement of subsequent optics. Finally, the optic under test is rotated, RDF subtracted, and re-averaged.

2.1 Random averaging

Random averaging was proposed by Hariharan[1] of CSIRO and was used in measurement of the initial LIGO optics. The method is to randomly clock and translate one or more high quality optics in front of the stationary reference surface. The figure of merit for this averaging was duplication of the ASML measurement of ETM03, an optic supplied with certification by ASML(now Zygo) through their subcontract to Tinsley.

3 Reference data file construction

Forty data sets are averaged to construct the reference data file. Sets 1-40 cover rotations of 270 degrees. The average of 1-40 is shown in figure one. A figure of merit for completeness of the RDF was the extent to which any one of the data sets replicated the ASML measurement when the RDF was subtracted. The lowest rms data set examined this way was #35, which gave an rms surface height of 0.536nm rms over a 300mm diameter, compared to the ASML measurement of 0.528. Some of the larger features do not replicate faithfully, possibly due to the incomplete (270 vs 360) "random" angular positions used in the average. The comparison of the ASML (white background) and LIGO (black background) measurements are shown in Figure 2

3.1 Transmission sphere mount problems

After Data set 16 we began to investigate apparent stress on the reference surface. The constraining screws on the lateral stabilizers were loosened, the optic was found to hang top forward in a very unbalanced way. The belly band was moved in an attempt to allow the optic to hang freely without being pulled or pushed by a stabilizer. This was not entirely successful, as the stabilizer at 4:30 is still at the end of it's slot. This issue is

[1] P. Hariharan "Optical flat surfaces: direct interferometric measurements of small-scale irregularities" Opt. Eng. 35(11) 32665-3266 (November 1996) also LIGO-P960052-00

under investigation by Zygo.

Data sets 1-16 were taken before the reference surface was rehung. In order to not lose the work they were treated in the following way.
The difference between avg(1-16) and avg(17-40) was added to each data set 1-16. The 1-16 data sets then took on the familiar look of the 17-40 sets. The difference between these averages is shown in figure 3.

4 Results

ETM04 is measured every 45 degrees in 8 orientations. The final map is the average of all 8 datasets rotated to one orientation (arrow up.) The RDF is subtracted from each data set before averaging. While the error found in this analysis is sufficient for analysis of ETM04, we expect the RDF to be refined by further measurement.

4.1 Uncertainty

The final uncertainty in the measurement of ETM04 is estimated to be of order 0.4nm rms over 300mm and 0.1nm rms over 160mm. This uncertainty is the combination of environmental and RDF errors.

4.1.1 Environmental noise

Environmental errors contribute very little to the final error. Environmental errors can be estimated from subtracting measurements of the same orientation at various times, these are typically of the order 0.1-0.2 nm rms and have a uniform characteristic. This type of noise is shown in Figure 4, which shows the subtraction of two single data sets taken one hour apart. Another metric for long term environmental stability is the subtraction of large averages of data sets at either end of the measurement run. These show a similar character; again the rms is typically 0.1 – 0.2 nm rms. There are rings present in these “difference” data sets that come from varied phasing of reflections within the Zygo system due to slight thermal changes in the room. These rings are the dominant feature in environmental noise and account for 0.01nm rms. This number is estimated by taking the change in rms after the rings are “masked out” of a “difference” data set.

4.1.2 Reference Data File (RDF) error estimation

We check the fidelity of the RDF by rotating any two results to the same orientation and subtracting. The resulting “error” file is a combination of environmental and RDF errors. An example of this error is shown in Figure 5. This image shows the difference between two sets of averages. The first set represents the ETM04 result obtained at 0, 90, 270 and 180. This result is stored, then the average of the sets taken at 45, 135, 225 and 315 is subtracted.

Analyzed this way we find the error is of order 0.4 nm rms over 300mm and 0.1 nm rms over 160mm. An image of the rotated/averaged error file masked to 160mm diameter is shown in Figure 6.

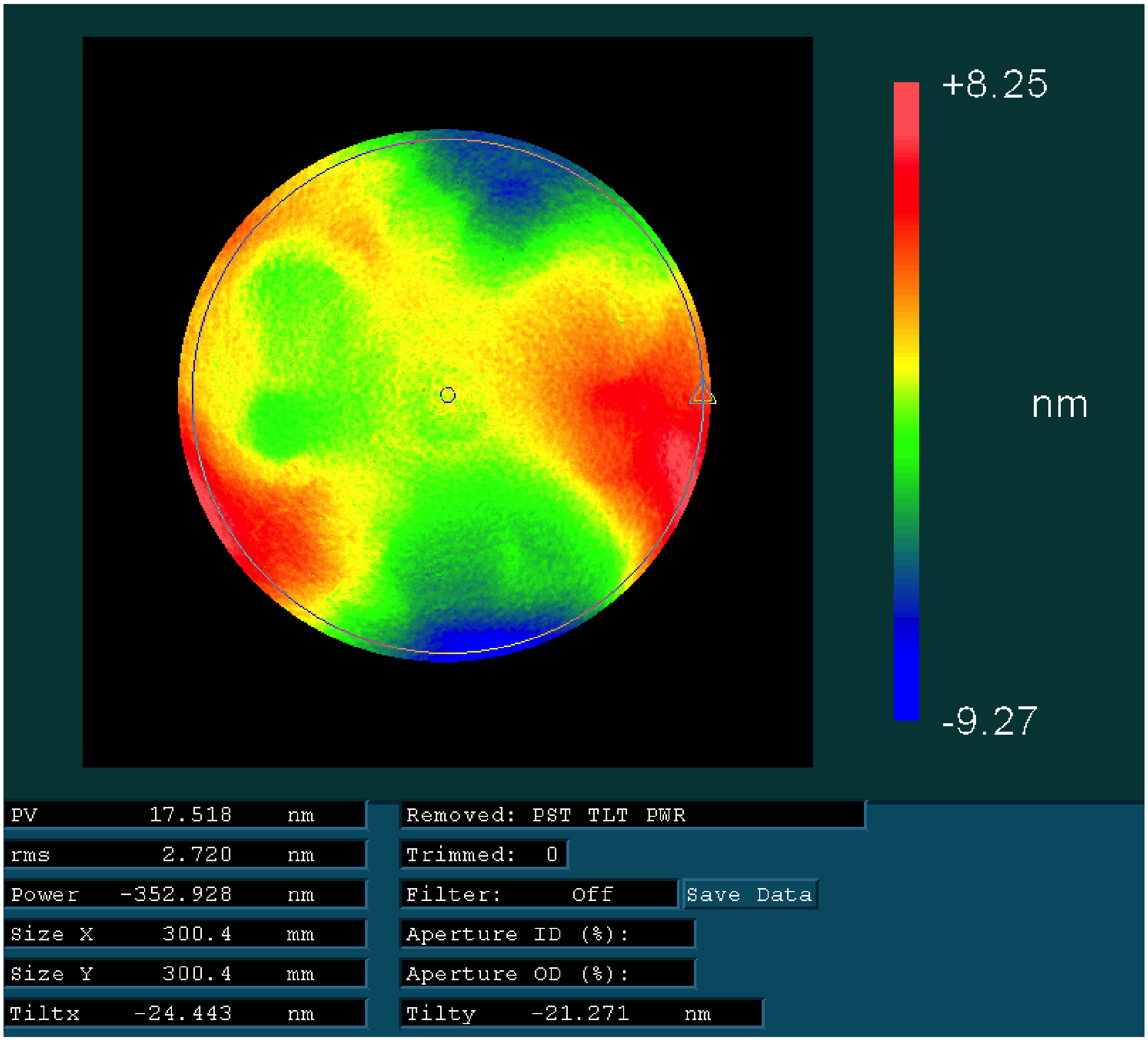

Figure 1: the average of 1-40, with the data sets 1-16 modified before average as described in the section on Transmission sphere mount problems.

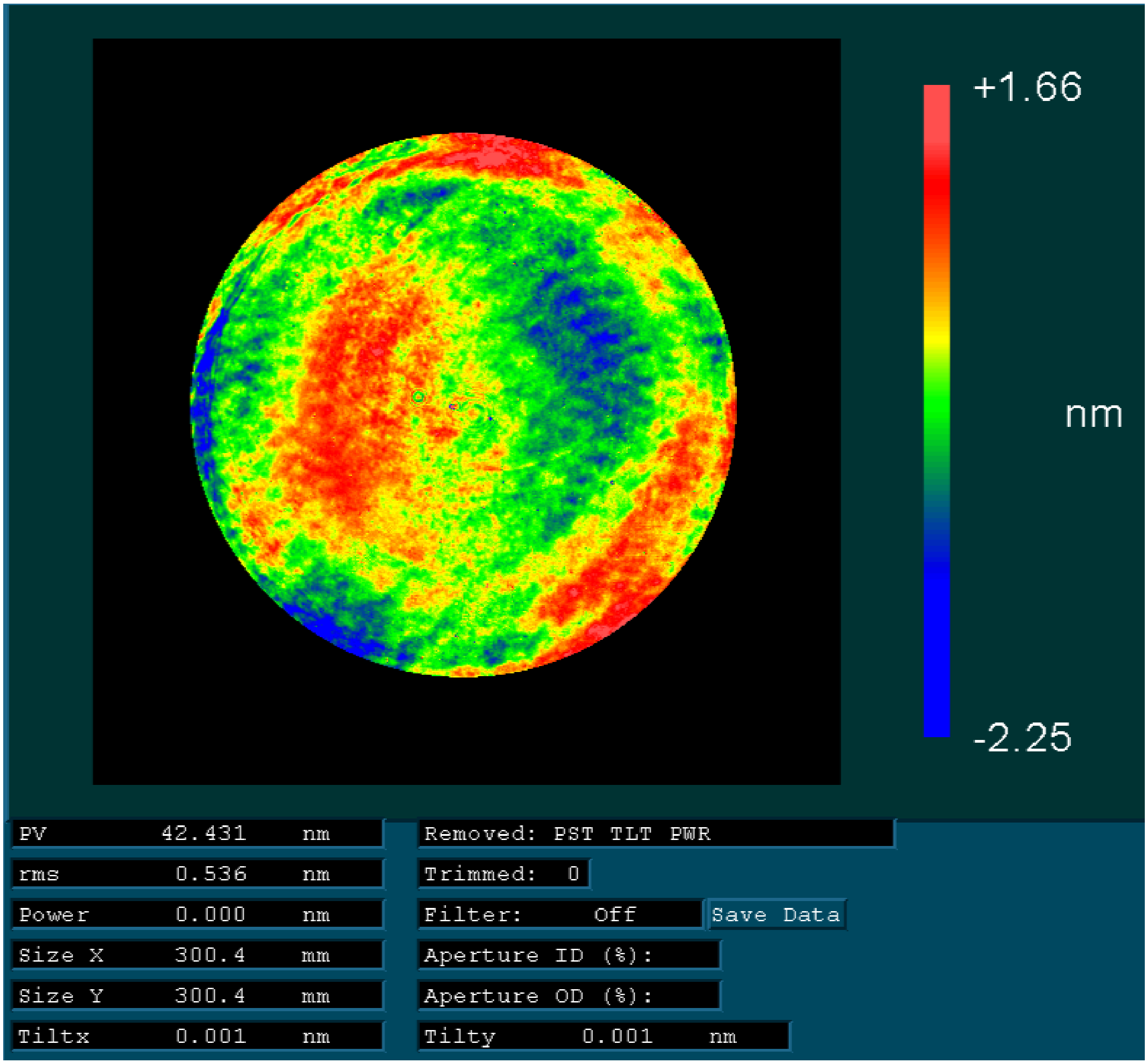

Figure 2a: data set 35 minus the random average 1-40 of ETM03 rms 0.54nm

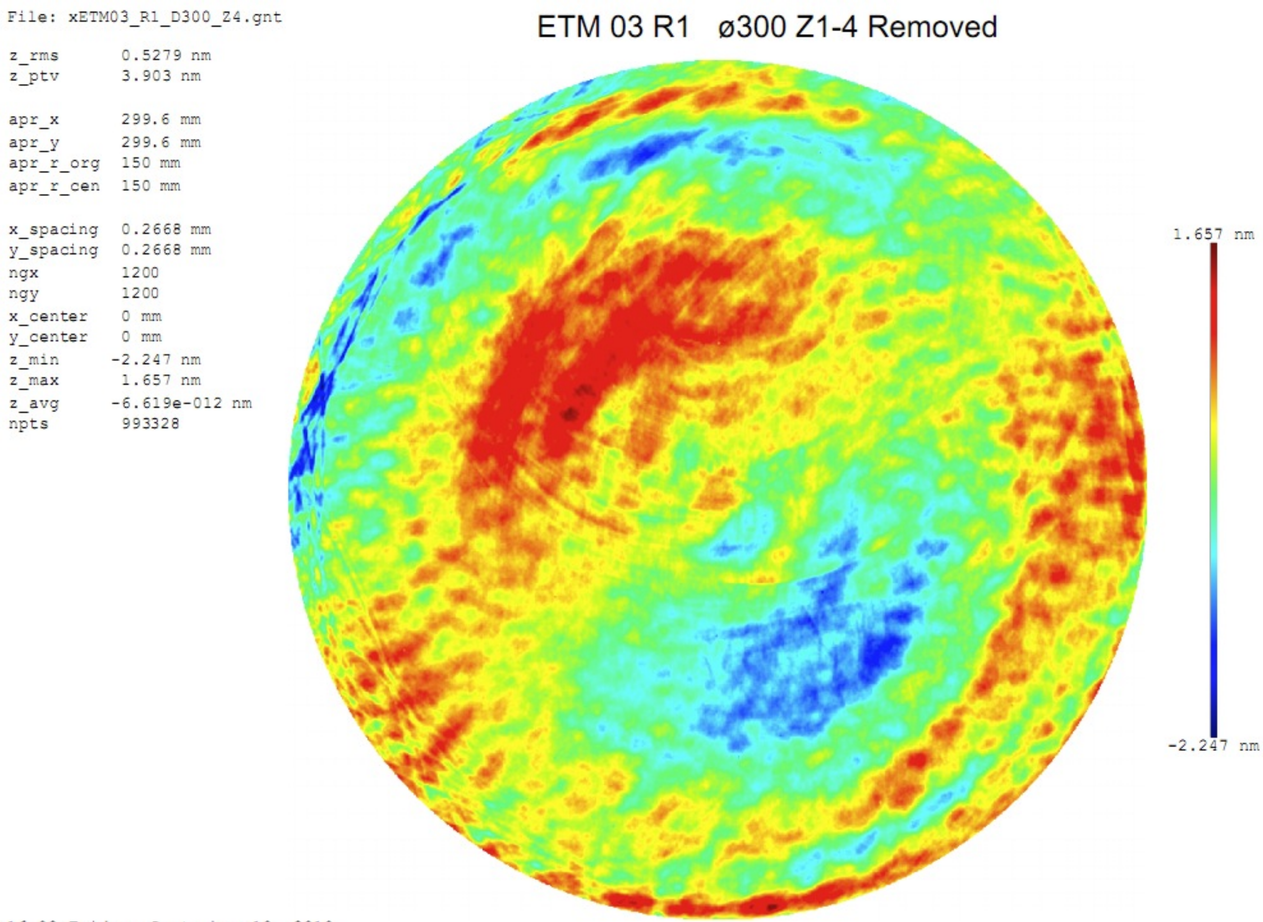

Figure 2b: ASML (now Zygo) measurement of ETM03 over 300mm diameter rms 0.53nm

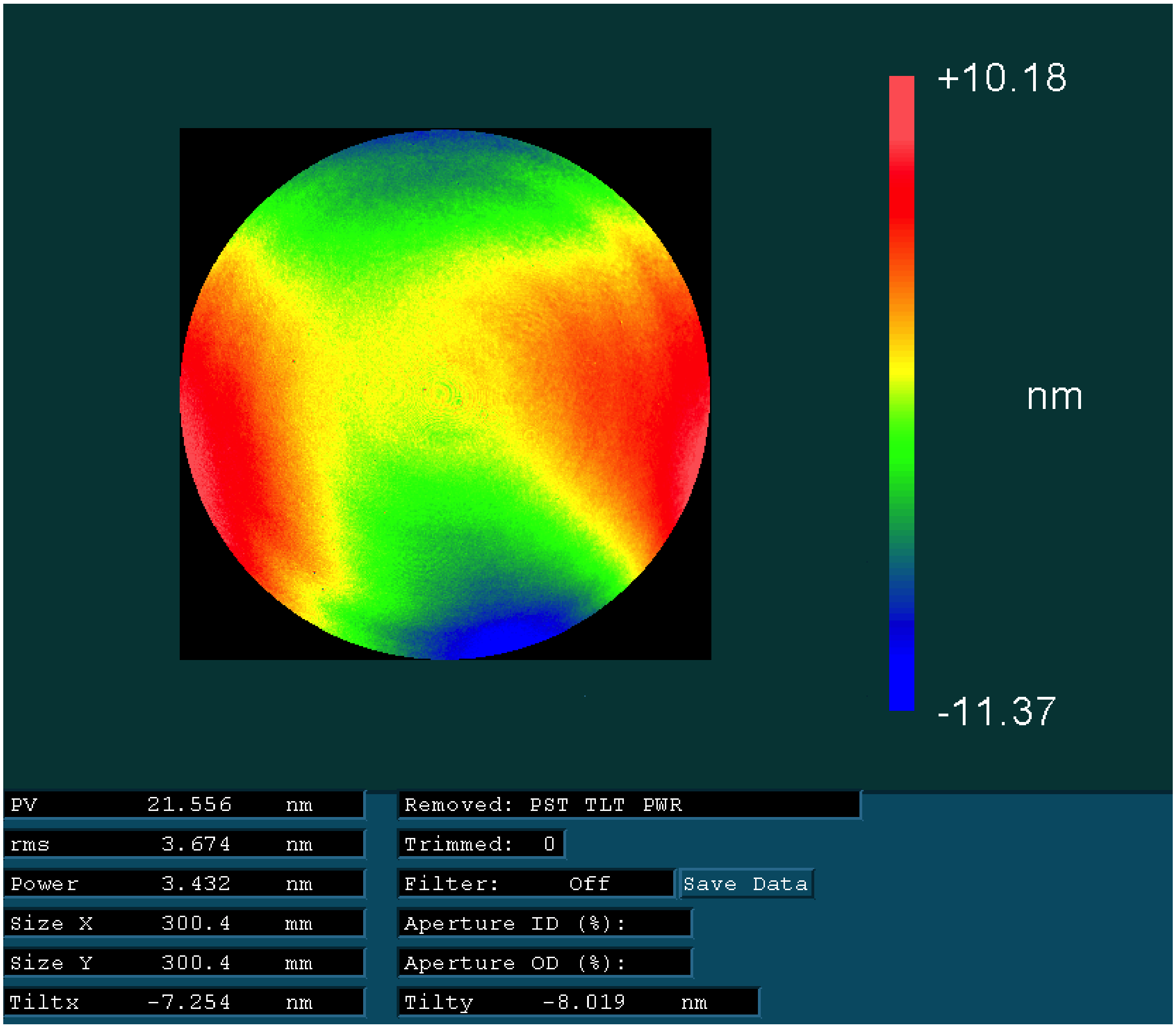

Figure 3: Difference between average(1-16) and (17-40) which presumably represents the difference in stress deformation by the mounting cell.

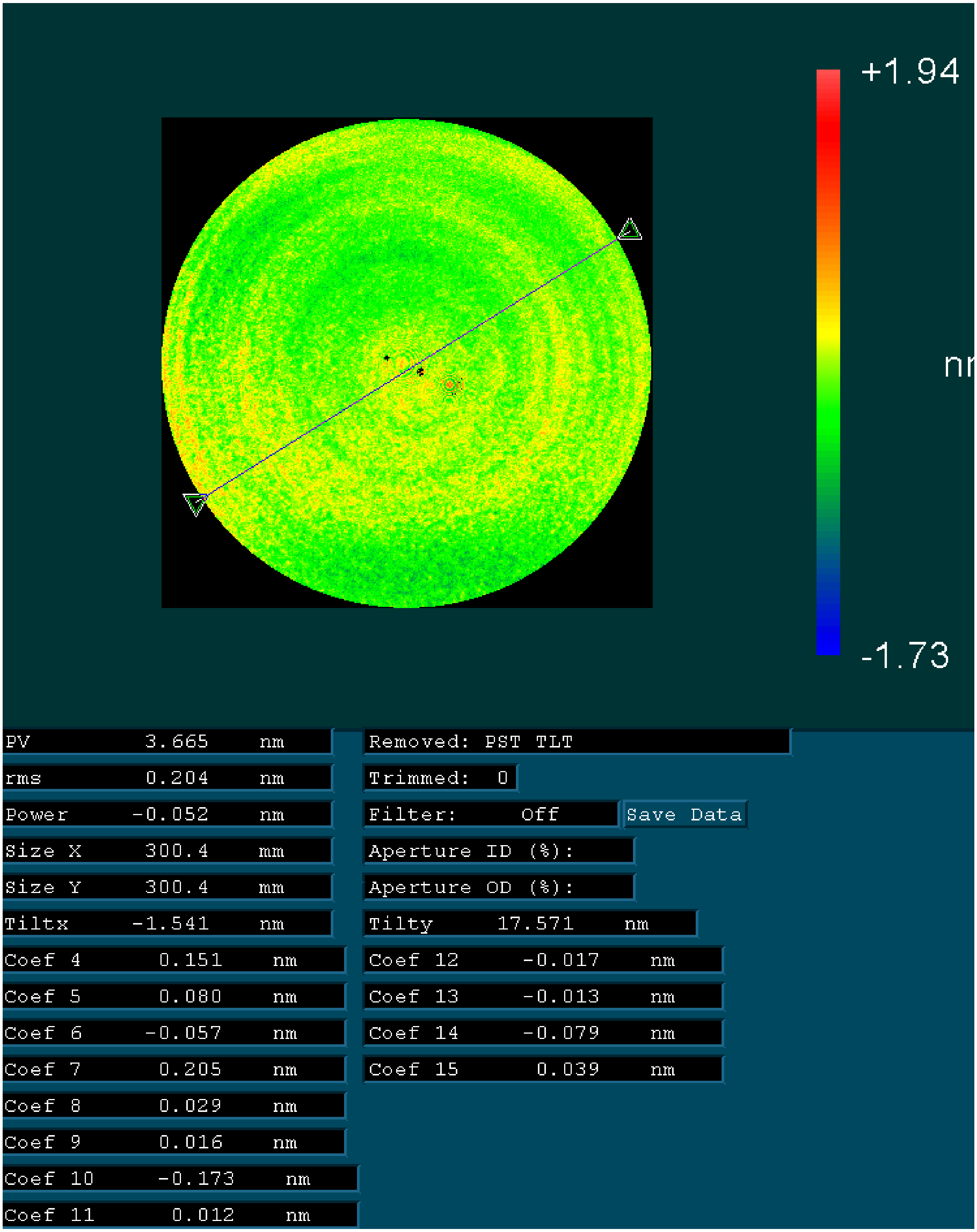

Figure 4: Environmental noise. The subtraction of two single data sets taken one hour apart demonstrates the effect of environmental noise on the uncertainty. Environmental noise is also included in the error file estimation technique.

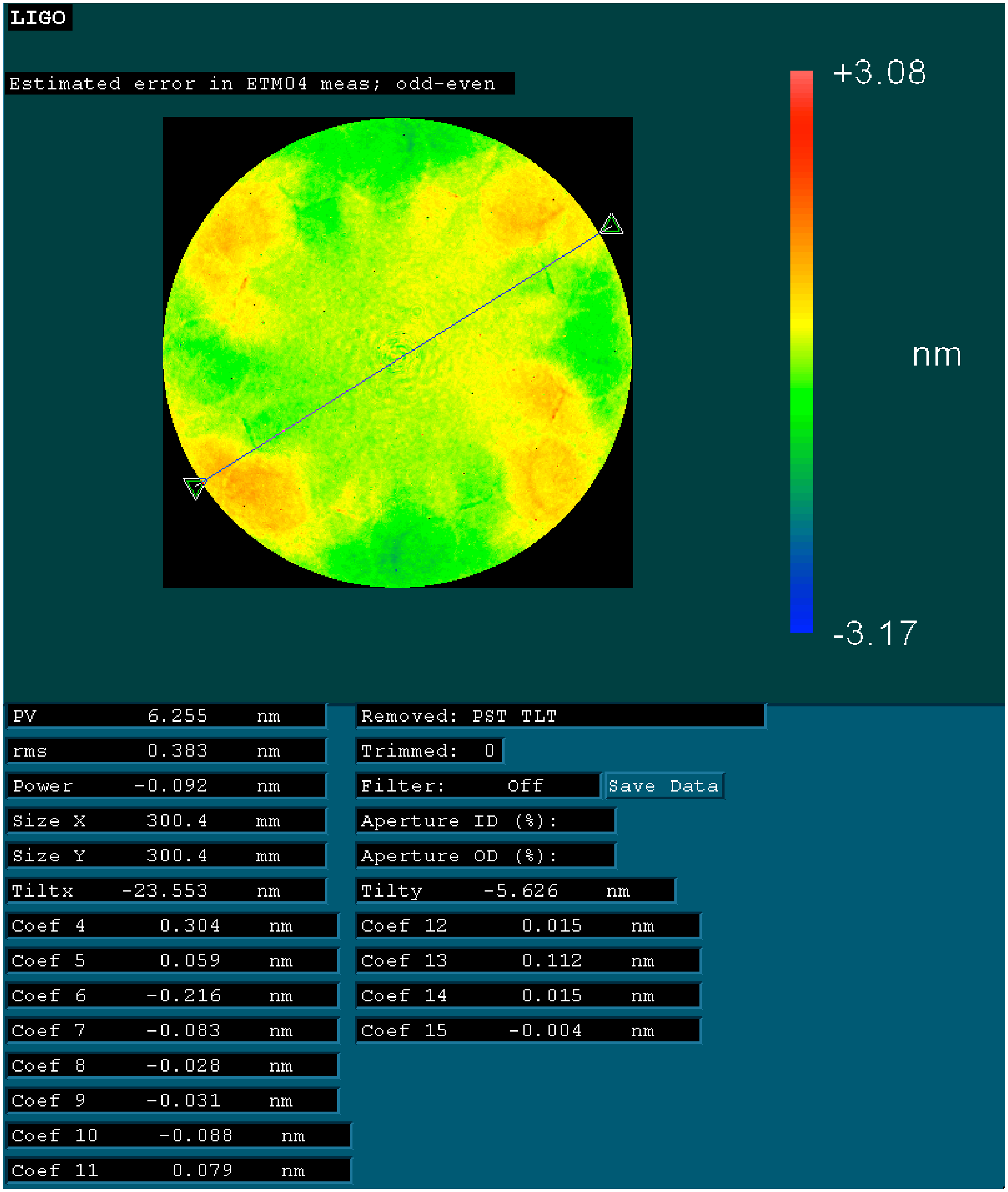

Figure 5: Example of estimated error over a 300mm diameter, the result of subtracting two result files, which were each an average of four orientations. In this case it is the average of the four sets taken at 0, 90, 270 and 180 minus an average of the sets taken at 45, 135, 225 and 315. The result files are rotated to fiducial marks to ensure proper alignment.

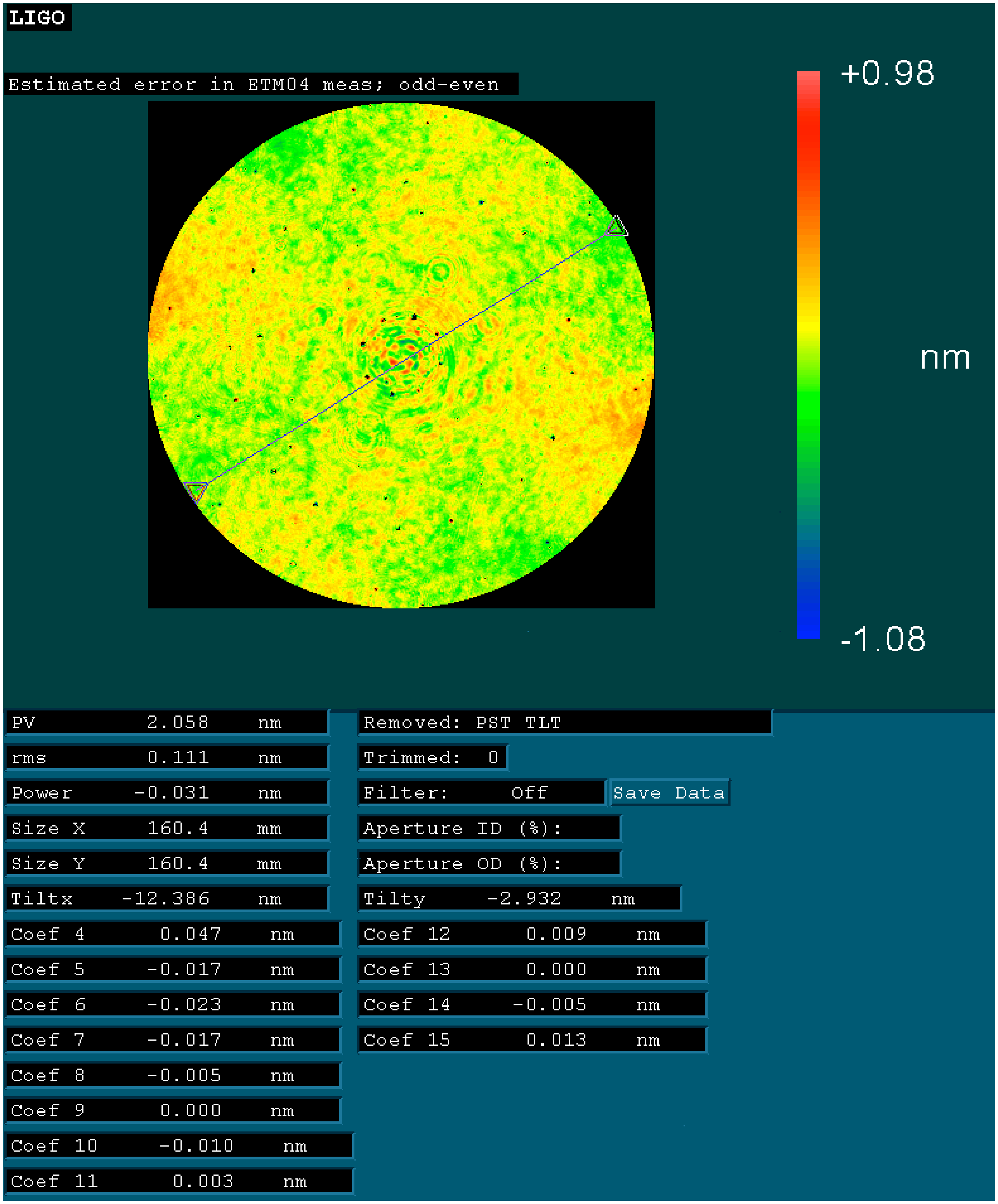

Figure 6: Example of estimated error over a 160mm diameter, the result of subtracting two result files, which were each an average of four orientations. In this case it is the average of the four sets taken at 0, 90, 270 and 180 minus an average of the sets taken at 45, 135, 225 and 315. The result files are rotated to fiducial marks to ensure proper alignment.