SURFACE MAPS FOR BONDED COMPONENTS IN GRAVITATIONAL WAVE DETECTORS

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GRAVITATIONAL WAVE DETECTORS

Gravitational Waves have been detected by large-scale interferometers, which split light to travel down perpendicular arms. Each beam is reflected back from a mirror to recombine with the other, and studying the interference of the recombined light gives information on the difference in path length travelled by each beam[1].

Gravitational Waves create a distortion in space-time as they pass through the beam path, thus allowing their detection by observing fluctuations in the interference as beam paths are distorted.

Detectors need to distinguish the gravitational fluctuations from background noise, primarily:

- Seismic noise through external vibrations, causing instability of mirrors.
- Thermal noise through internal dissipation of the mirror suspensions and friction of their components.

Ensuring bond thickness below ~60nm is an important step in reducing thermal noise levels in Gravitational Wave suspensions. [2]

Several-stage pendulum suspensions are used to limit motional response in the 10-200Hz range (typical seismic frequencies) [2].

Bonded "ears" attach the suspending fibres to the mirrors, avoiding friction from direct contact.

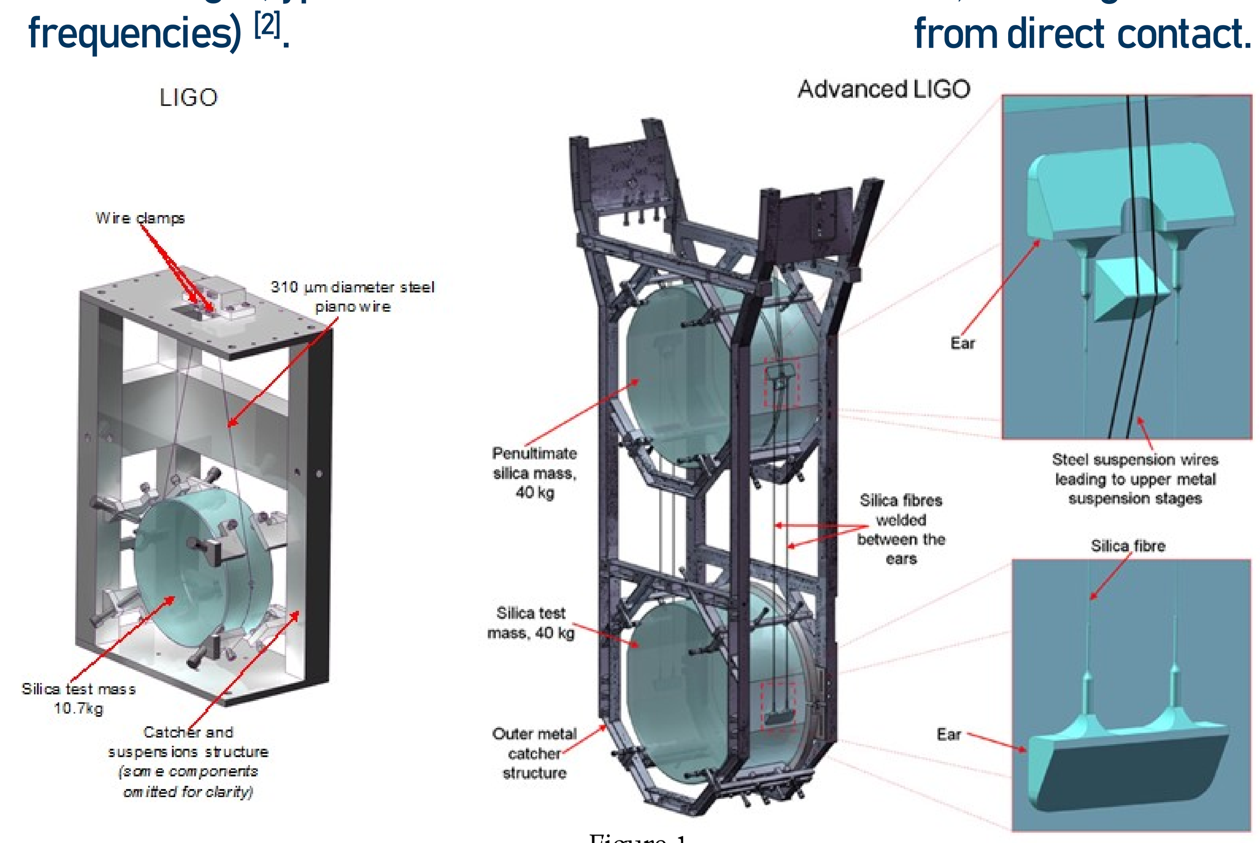

Figure 1
Source: Cumming et al. [2]

The mirrors are suspended to try to isolate them from their surroundings as far as possible, using pendulum systems which limit resonant behaviour to frequencies (10-30Hz) below expected seismic frequencies (10-200Hz). Bonded components then become a dominant source of thermal noise. Overall sensitivity is targeted at $1x10^{-19}$ m $Hz^{-1/2}$ for frequencies near 10Hz [2]. Figure 1 shows suspension designs, including the fused silica "ear" attachments which are bonded to the mirrors to suspend them in updated detector designs.

IMAGING SURFACES: ZYGO INTERFEROMETER

As bonds directly contribute to thermal noise levels, the thinnest possible bonds must be targeted, aiming for thickness no more than 60nm peak-to-valley [2]. It is useful to consider the surfaces of components before bonding, where the flattest surface profiles will give the thinnest bonds.

Components were tested with a *Zygo®* Interferometer, which measures the phase of reflected wavefronts to determine the profile of a component's surface.

A partial transmission plate reflects a *reference* wave and admits a *measurement* wave. By shifting this plate longitudinally, an additional known phase can be introduced and observed upon recombination of the waves. This allows the wavefront from the surface to be accurately mapped and the surface profile to be determined. Figure 2 shows the shifting of the transmission plate (labelled "Reference"), and the series of images captured in a similar interferometer system.

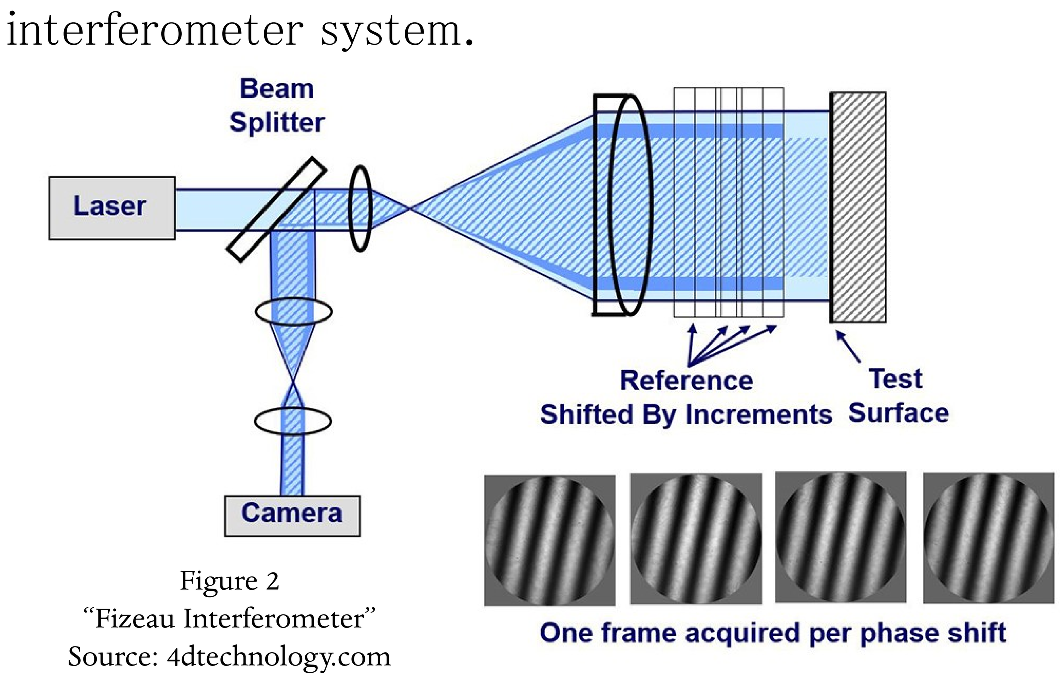

Figure 2
"Fizeau Interferometer"
Source: 4dtechnology.com

PROCESSING ZYGO DATA FILES

A program was implemented using *Python* to process data from Zygo output files, offering a more accessible way to assess surfaces and bonds from any computer, where the Zygo proprietary software may not be available.

Output files of intensity and phase data are obtained from Zygo, read into *Python* and stored as arrays representing 2D maps of a component surface. The program structure is designed to operate mainly using these arrays, with an object created for each file to allow easy access to the data and associated information for each distinct component.

A number of processing steps are carried out for each map object:

- Zygo readings may show tilts from measurement, and these are removed by applying a minimisation of peak-to-valley height, rotating points into the flattest plane.
- Cropping to centre on the valid data or remove discontinuous edge defects.
- Calculating key metrics, peak-to-valley height and root-mean-square height, to provide simple insight into each surface.

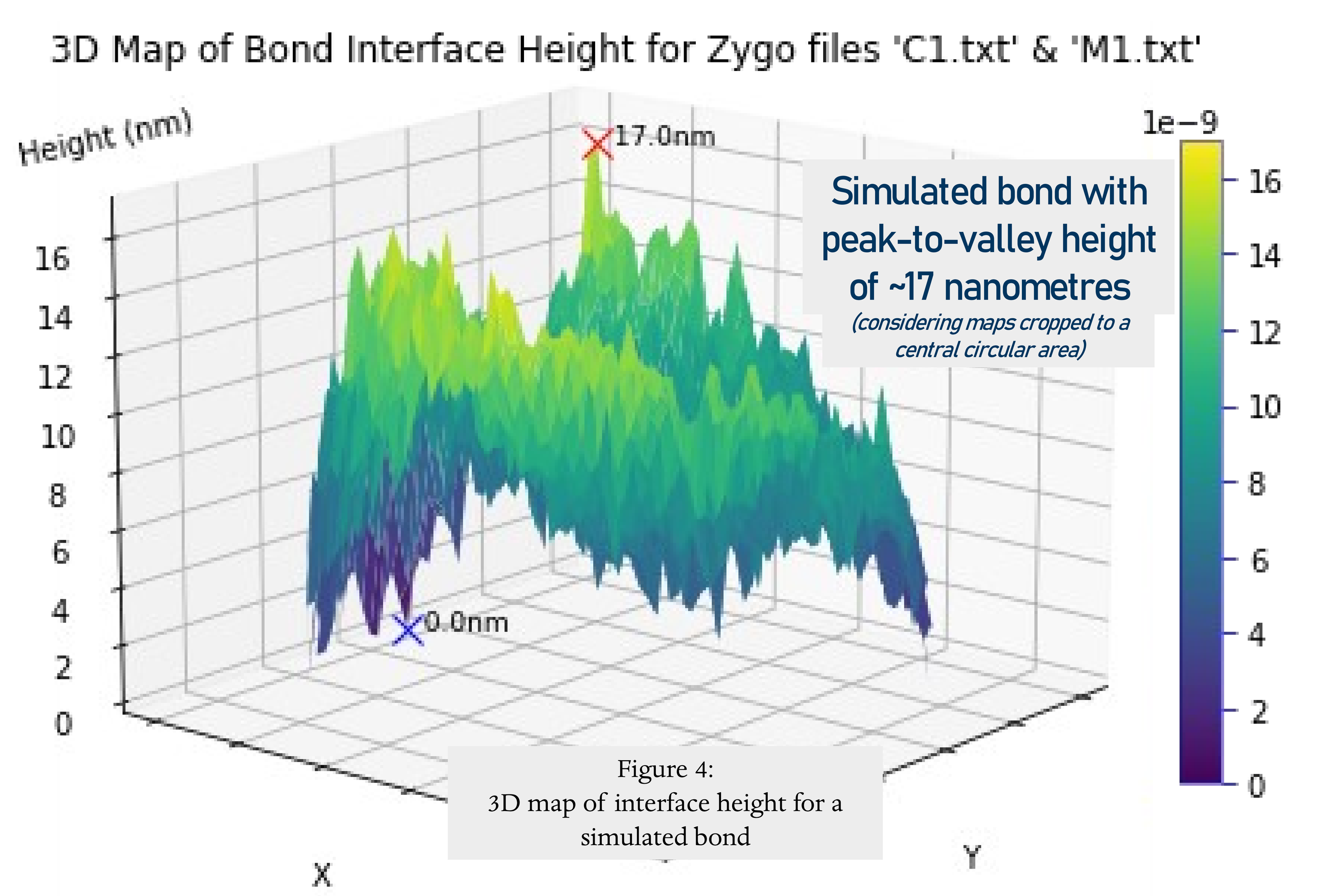

Figure 4:
3D map of interface height for a simulated bond

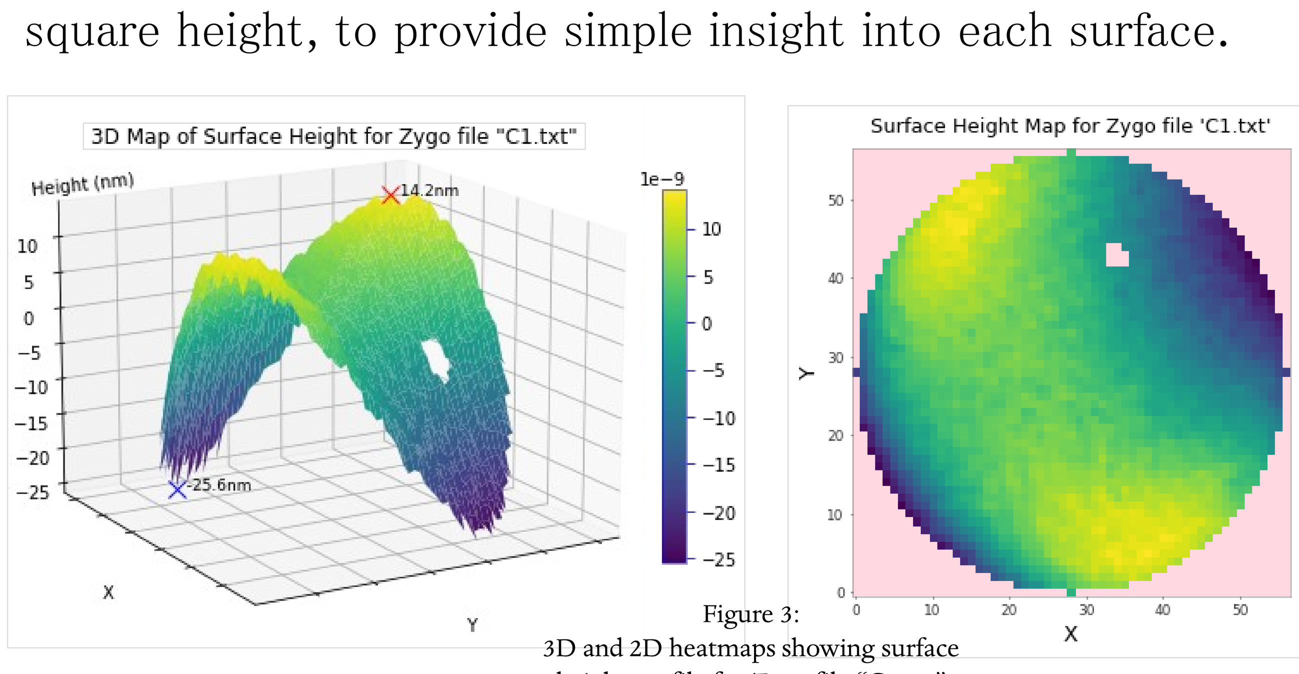

Figure 3:
3D and 2D heatmaps showing surface height profile for Zygo file "C1.txt"

COMPARING BONDS

The program can store multiple surface maps, and combine two maps to simulate their bond. Automated comparisons run between all the possible pairs of stored maps, finding the thinnest bonds between pairs.

A pair of maps are combined to simulate their physical bond interface. The surfaces must be orientated to face each other, thus one map has to be flipped and its values negated - then the sum of the maps gives the differences in heights at each point representing the bond thickness. Further optimisation is applied for the rotation around the z-axis of one map with respect to the other, minimising the peak-to-valley height of the combination.

Bond interface maps are created similarly to the surface maps. Bonds are simulated between pairs of maps and automatically compared for the available combinations. Figure 4 shows the profile of bond height for the optimal bond. Figure 5 shows outputs of the auto-comparison, and visual comparison of bonds.

Figure 5. a) and 5. b): Outputs of auto-comparison of simulated bonds

Bonds are automatically compared and sorted by smallest peak-to-valley/RMS height

5. a)

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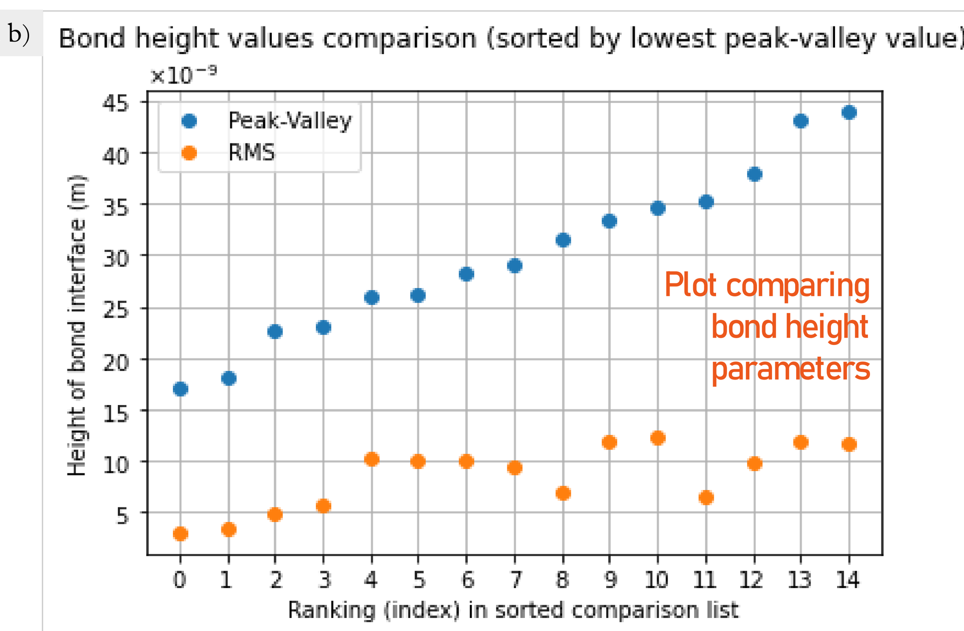
Sample Bonds sorted by lowest peak-to-valley height:

1 -  C1.txt M1.txt
Peak-to-valley Height: 17.0 nm
RMS Height: 3.0 nm

2 -  A1.txt M2.txt
Peak-to-valley Height: 18.0 nm
RMS Height: 3.4 nm
```

Printed output of the flattest bonds (top 2 shown).

5. b)



References:

- [1] B. P. Abbott et al. Phys. Rev. Lett. 116(13):131103–1–131103–12, 2016. http://dx.doi.org/10.1103/PhysRevLett.116.131103
- [2] Cumming, A.V. et al. Classical and Quantum Gravity, vol. 29/no. 3, (2012), pp. 035003. https://doi.org/10.1088/0264-9381/29/3/035003
- [3] MetroPro Reference Guide, Section 12, pgs 12-17 https://www.seas.upenn.edu/~nanosop/documents/MetroProReferenceGuide0347_M.pdf