Appendix A

Attocube positioner characterization

We calibrate and obtain the frequency response of the Attocube nanopositioners model ANPx100 (ANPx100-86-061) and ANPz100 (ANPz100-84-034) referred to as ‘x-Attocube’ and ‘z-Attocube’ respectively in this appendix. The former has a horizontal axis of motion (x) and the latter has a vertical axis of motion (z), see Fig. A.1(a)-(b). The Attocubes can be operated in the continuous piezo fine motion mode or in the step ‘slip-stick’ coarse motion mode. The controller models ANC200 and ANC150 are used for the fine and coarse motion modes respectively, see Fig. A.1(c).

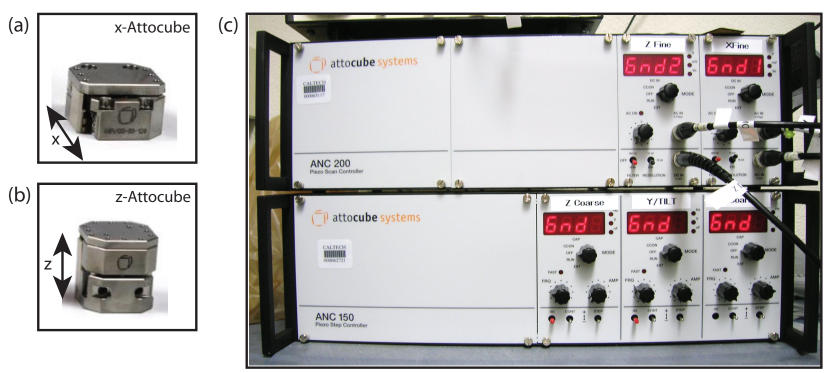

Figure A.1: **(a)** x-Attocube. **(b)** z-Attocube. **(c)** Attocube piezo scan controller ANC200 for fine motion (top) and piezo step controller ANC150 for coarse motion (bottom).

The characterization is carried out by utilizing an 846.4 nm wavelength laser at 193 μW power entering a Michelson interferometer setup on a floated table, see Fig. A.2(a). A small mirror (A) is glued onto an aluminium block, which is screwed onto the Attocube, see Fig. A.2(b)-(c). Four configurations are investigated: x-Attocube (single), x-Attocube (stacked), z-Attocube (single), z-Attocube (stacked). For practical reasons, in the first case, two aluminium blocks (B) and (C) are used (see Fig. A.2), and in the other three cases, only block (B) is used. Stacked configuration refers to mounting a passive "load Attocube" (ANPx100-63-058) in between the driven Attocube to be characterized and the aluminium block. A summary of the loads and their masses are given in Table A.1.

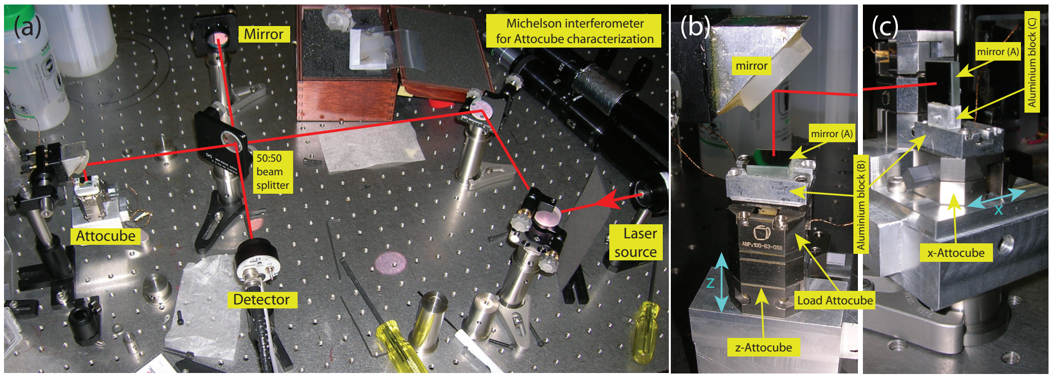

Figure A.2: **(a)** Schematic of setup. **(b)** z-Attocube (stacked) setup. **(c)** x-Attocube (single) setup. Shown in (b) and (c) are: mirror (A), aluminium block (B) and block (C).

Configuration	Item (refer to Fig. A.2)	Mass (g)	Fringe Vis. (%)	Drive Amp. (V_{pp}) @ 0.5 Hz	Drive Amp. (V_{pp}) @ 5 Hz
x-Attocube (single)	Alum. block (B) Alum. block (C) Mirror (A)	6.0 0.8 1.2	95	24	24
x-Attocube (stacked)	Alum. block (B) Mirror (A) Load Attocube	6.0 1.2 24.0	96	24	24
z-Attocube (single)	Alum. block (B) Mirror (A)	6.0 1.2	83	27	30
z-Attocube (stacked)	Alum. block (B) Mirror (A) Load Attocube	6.0 1.2 24.0	89	27	27

Table A.1: Summary of load masses, interferometer fringe visibilities, and triangular wave sweeping amplitudes for Attocube calibration for the four configurations.

For calibration, triangular wave sweeps of frequencies 0.5 Hz and 5 Hz are applied to the Attocube being characterized via the fine-motion controller ANC200. The effective amplitudes[1] of the sweep output to the Attocubes are summarized in Table A.1. Typically, a peak-to-peak sweep scans through about three to five fringes. The sweep signal and detector signal (i.e. the fringes) are recorded and analyzed in a Matlab code, which identifies the peaks in the fringes and computes a calibration

[1]The actual sweep signal voltage is 1/15 of the listed values in Table A.1 as ANC200 has a 15x gain on the DC input.

factor [nm/V] for each pair, based on the mirror displacement associated with a consecutive pair of fringe peaks being equal to one half of the wavelength ($\lambda/2 = 846.4\text{nm}/2 = 423.2\text{nm}$). The triangular wave sweeps are set at two frequencies, 0.5 Hz and 5 Hz, which are recorded over a period of 250 seconds and 25 seconds respectively[2]. For each set of data, a few hundreds of calibration factors (piezo displacement per applied voltage) are computed.

The calibration factor distributions for the x-Attocube (single) case are shown in Fig. A.3; note that as shown in the figure, due to slow drifts in the optics components (e.g. due to air current), the spread is larger for the 0.5 Hz sweep compared to the 5 Hz sweep. The calibration results for all the configurations are summarized in Table A.2. The voltage range for the Attocubes (piezos) is between 0 to 150 V for the fine motion mode. Based on this and using the 5 Hz sweep values, the fine-motion ranges of the Attocubes are calculated and shown in Table A.2. Note that in the coarse-motion mode, the x-Attocube and z-Attocube ranges are 7 mm and 6 mm respectively.

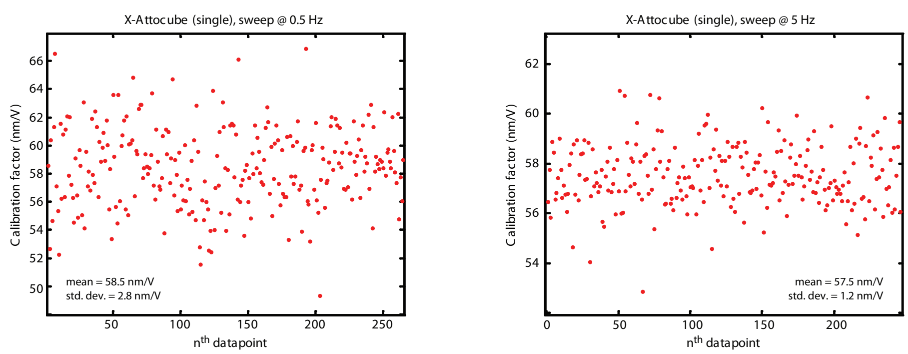

Figure A.3: **Calibration factor** (piezo displacement per applied voltage) distributions for a single x-Attocube for 0.5 Hz and 5 Hz sweep frequencies.

Configuration	Sample size		Calibration factor (mean ± std. dev.)		Range
	@ 0.5 Hz	@ 5 Hz	@ 0.5 Hz	@ 5 Hz	(μm)
x-Attocube (single)	265	246	58.5 ± 2.8 nm/V	57.5 ± 1.2 nm/V	8.63
x-Attocube (stacked)	388	264	83.7 ± 3.8 nm/V	81.8 ± 1.8 nm/V	12.3
z-Attocube (single)	226	249	51.0 ± 2.4 nm/V	51.4 ± 2.2 nm/V	7.71
z-Attocube (stacked)	345	250	49.9 ± 3.1 nm/V	48.1 ± 1.0 nm/V	7.22

Table A.2: Summary of calibration factor results for triangular wave sweeps at 0.5 Hz and 5 Hz. Sample size refers to the number of calibration factors computed. Range is calculated based on 0-150 V voltage range for 5 Hz sweep values.

We note that for the z-Attocube, the calibration factor (displacement per voltage) is larger for the single compared to the stacked configuration (see Table A.2). This is expected as gravitational

[2] In both cases, 30,000 data points are recorded.

force associated with the extra mass directly work against the piezo. On the other hand, the opposite is observed for the x-Attocube, which is not expected. Nonetheless, this is observed throughout all runs and is also observed in the transfer function spectra (see Fig. A.4). A possible cause is the increased inertia of the moving part. Note that here gravitational force acts orthogonal to the axis of motion, potentially introducing some shear forces.

The frequency responses of the Attocubes are obtained by driving the Attocube and recording the transfer function by using a network analyzer (Stanford SR780) in the swept sine mode. The driving amplitudes (see Table A.3) are chosen to be sufficiently small to ensure that the response is well within the peaks of the fringes, so that the response is to a good approximation linear. A summary of the frequency responses for the four configurations is shown in Fig. A.4.

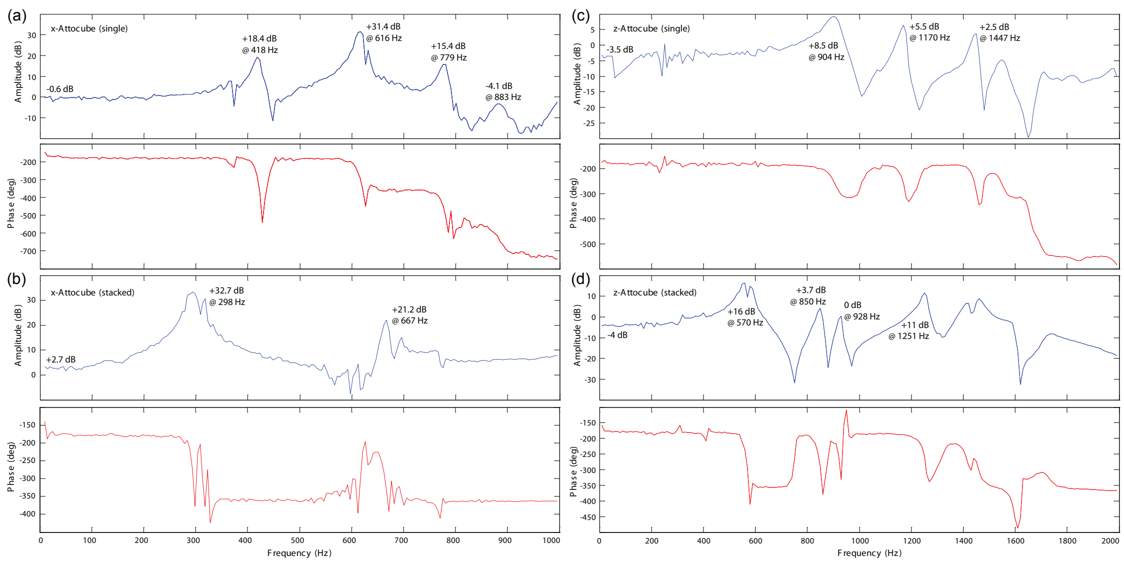

Figure A.4: **Attocube transfer functions** highlighting intrinsic mechanical resonances associated with the four configurations: (a)/(b) Single/stacked x-Attocube; (c)/(d) Single/stacked z-Attocube.

Configuration	Drive Amp. (mV_{pp})	First resonant	
		Frequency (Hz)	Q-factor
x-Attocube (single)	80	418	34.0
x-Attocube (stacked)	80	298	8.1
z-Attocube (single)	400	904	14.4
z-Attocube (stacked)	400	570	11.7

Table A.3: Summary of Attocube intrinsic mechanical resonances.

Finally, Table A.3 summarizes the locations of the first resonants, along with an estimation of the resonant Q-factors computed using $Q \approx f_{\text{res}}/\Delta f$, where f_{res} is the first resonant frequency and Δf

is the corresponding full width half maximum (FWHM)). Note that the first resonant frequency for the z-Attocube is higher than the x-Attocube by about a factor of two. The first resonant frequency is lower for the stacked configuration compared to the single configuration, as expected.