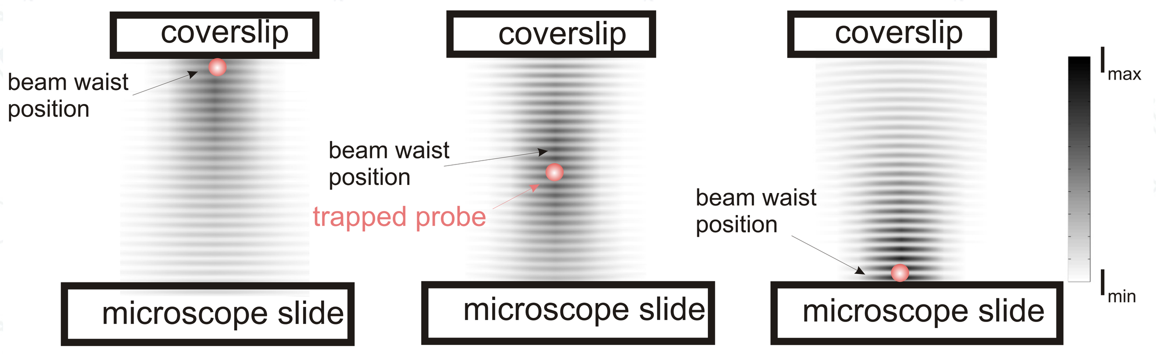
How the size of a particle approaching dielectric interface influences its behavior

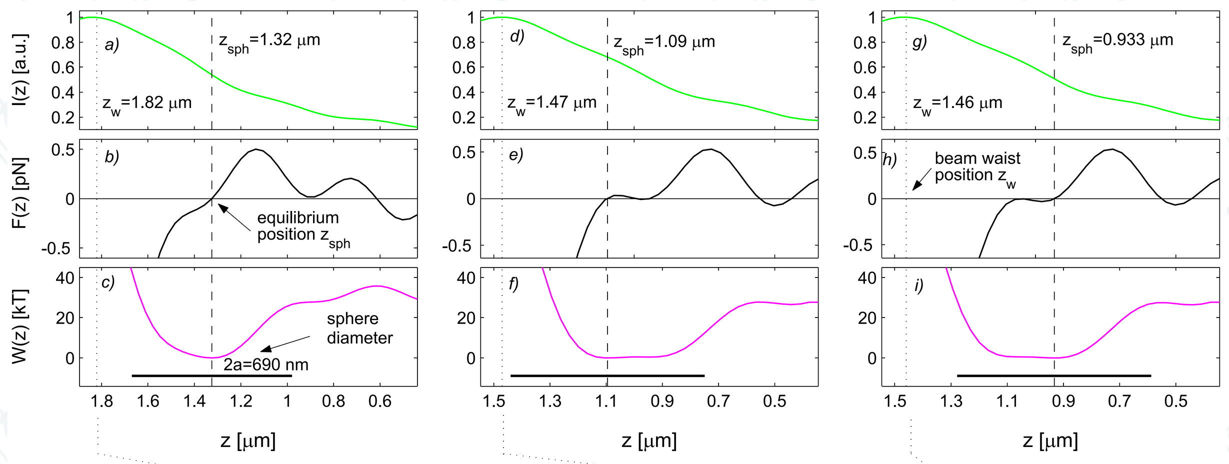
Petr Jákl, Mojmír Šerý, Jan Ježek and Pavel Zemánek
Institute of Scientific Instruments of Academy of Sciences of Czech Republic,
Královopolská 147, 612 64 Brno, Czech republic

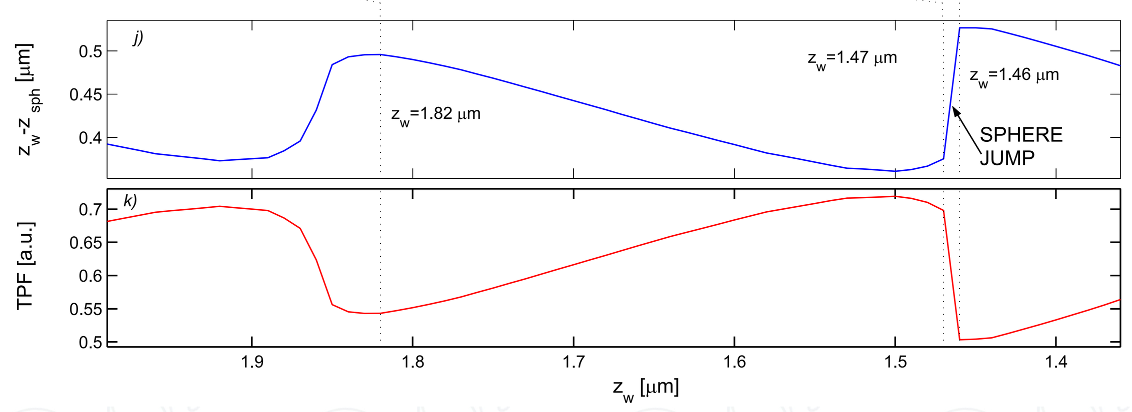
INTRODUCTION

Equilibrium position of particle trapped in common single beam trap (SBT) is slightly beyond the trapping laser beam waist. However, the weak Gaussian standing wave (GSW) component of the resulting field is generated, when the beam is reflected on the bottom slide of the sample chamber. Even the common glass-water interface (reflectivity R=0.4%) generates GSW strong enough to influence the axial position of trapped particle upto the distance several μm from the interface. Particles of different sizes are influenced by the GSW differently.



The incident laser beam waist is in z_w distance from the interface and the equilibrium position of particle confined in the optical trap is z_w-z_{sph} away from the waist. When the waist is moved towards the bottom slide, the particle is influenced by the nodes and antinodes of the GSW and its equilibrium position tends to stay near the weak standing wave traps (SWTs). The trapped particle thus does not move synchronously with the incident beam focus and exhibit jumping behaviour. In the following figure, there is theoretical calculation of on-axis intenzity I(z), axial force acting on the spherical particle F(z) and depth of the potential well W(z) in three positions of the beam waist z_w. The sphere is located in z_{sph}, where is the minimum of potential well. We can see, that in critical position z_w=1.46 μm only 10 nm change of waist position exhibits jump of sphere 157 nm away from the waist. We describe the effect two ways: first, the distance between the waist and the particle is displayed. Second, we assumed fluorescently dyed particles. Since the beam intensity is different at each equilibrium position, the two-photon fluorescence (TPF) that is excited by the beam in the dyed sphere is sensitive detection method of the sphere motion (see bottom of figure).

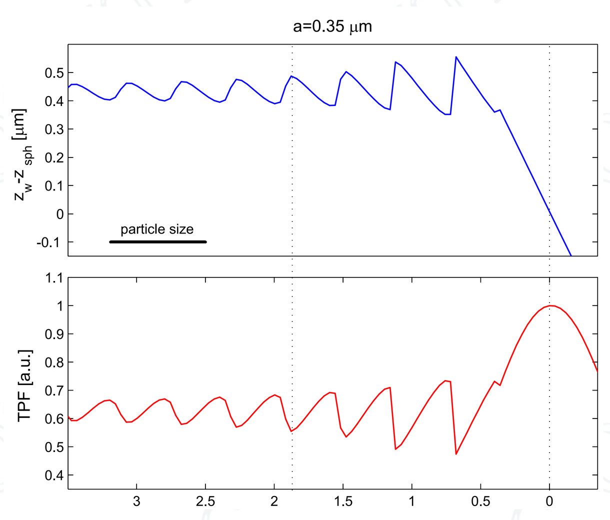


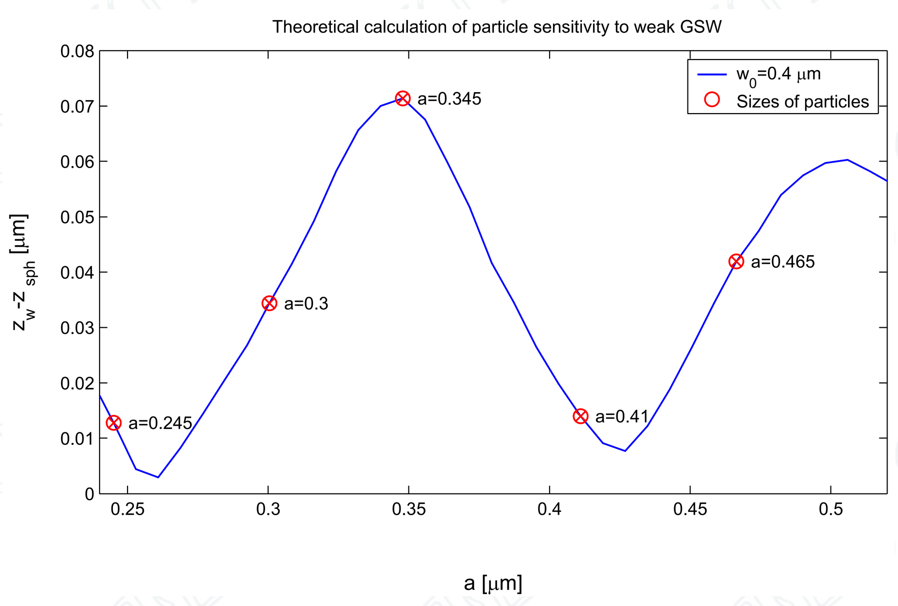


Water-glass reflectivity R=0.4%, laser power P=10mW, beam waist w_0=0.4 μm, refractive indices n_{sph}=1.585, n_{water}=1.332, sphere radius a=345 nm.

THEORETICAL PREDICTION

In the plots on left, there is a comparison between z_w-z_{sph} and TPF signals – the TPF signal is higher near the beam waist, so the minima of TPF correspond to maxima of z_w-z_{sph} (see the dotted line). The zero point of z-axis was set to the first maximum of the TPF signal and TPF was normalized to it. These profiles were calculated for particles of 0.1–0.5 μm radii and we quantified the sensitivity of the particle to the GSW. The quantity z_w-z_{sph} was introduced as average of five subsequent jump lengths starting from the first jump which occurs for z_w<4 μm. The resulting plot (on the right) shows the tendencies of the effect together with chosen particle sizes for experimental work – commercially available sizes close to sensitive, insensitive and medial region of the curve.





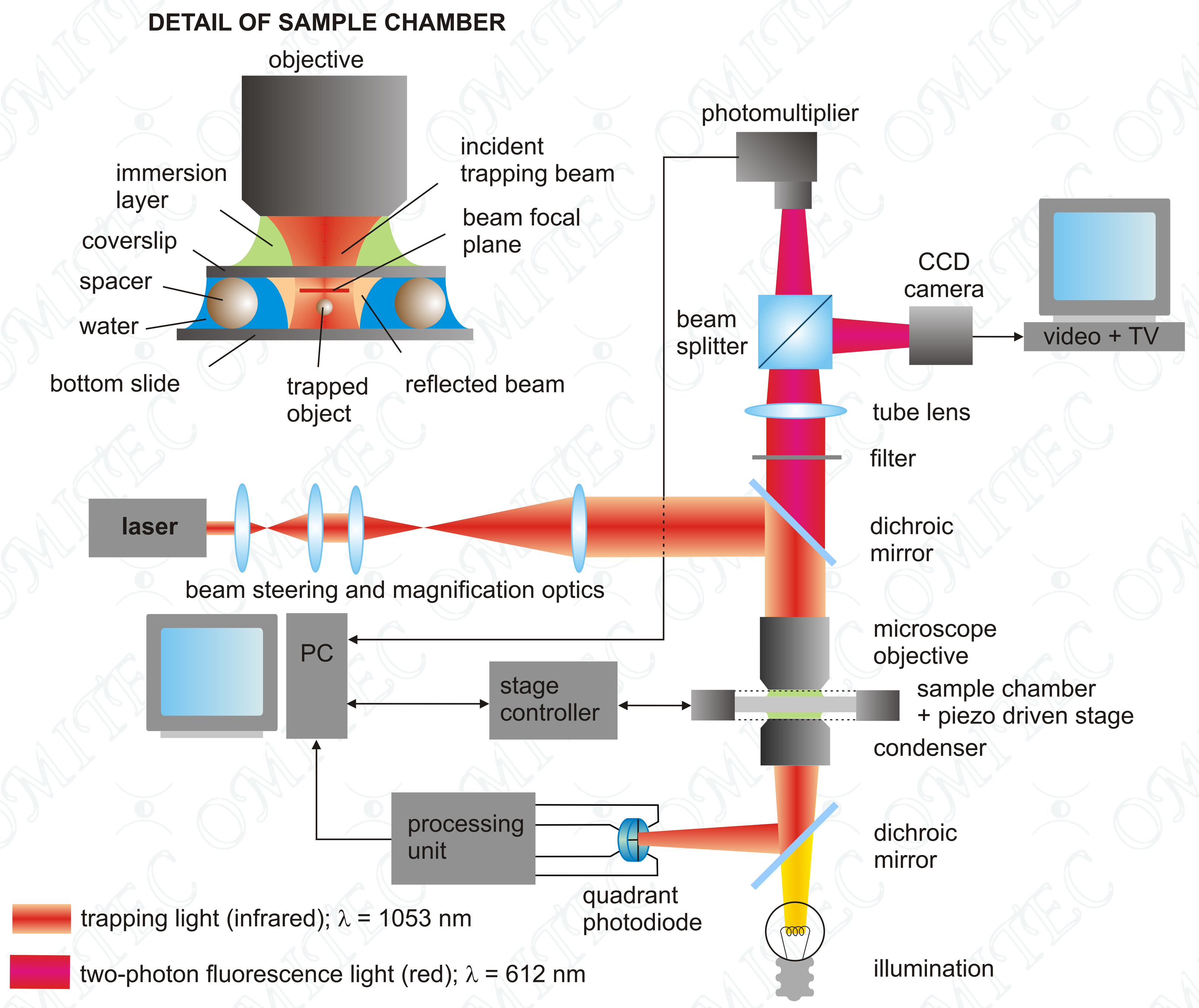
CONCLUSIONS

In this work we demonstrated experimental research on behaviour of optically trapped particles approaching the dielectric interface. It was shown that even common glass bottom slide with reflectivity R=0.4% creates GSW strong enough to deflect particle from its SBT equilibrium position. We measured this behaviour on particles of radii 0.245 μm, 0.3 μm, 0.345 μm, 0.41 μm and 0.465 μm.

The experimentally obtained data were compared to theoretical prediction of the effect. We have prooved that for particle sizes 0.245 μm and 0.41 μm in radius, the unwanted jumps in weak GSW are minimized, whereas when using particle of 0.345 μm radius as SBT probes, the movement exhibits larger jumps when approaching the surface.

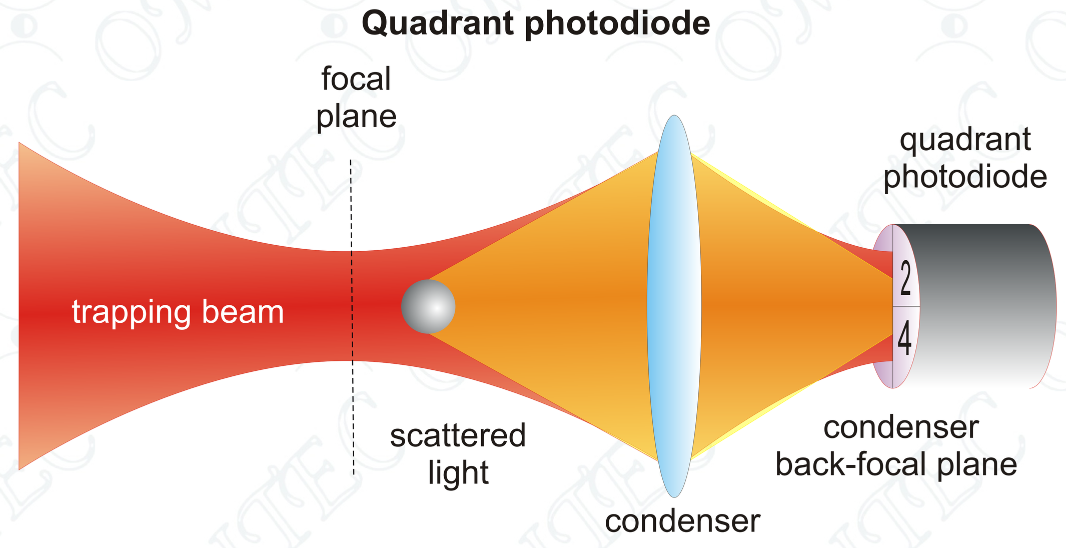
EXPERIMENTAL SETUP

- common glass bottom slide (R=0.4%)
- Nd:YLF laser Spectra Physics T20-W-105C, max output 4W, λ=1053 nm
- photomultiplier tube Hamamatsu R1527
- microscope objective Olympus PH3, 100x, N.A. 1.25 O.I.
- piezo driven stage Physik Instrumente PI517.3C, capacitive sensors, axial range 20 μm, axial repeatibility ±2 nm
- quadrant photodiode EG&G, UV-140BQ-4
- telescope 1: 2.75 mm – 8 mm, telescope 2: 60 mm – 175 mm
- sample spacers – Polysciences, Polybead, diameter 9.14 μm
- fluorescently dyed particles – Duke Scientific, absorbtion 542 nm, emission 612 nm
- particle sizes – radii 0.245 μm, 0.3 μm, 0.345 μm, 0.41 μm and 0.465 μm

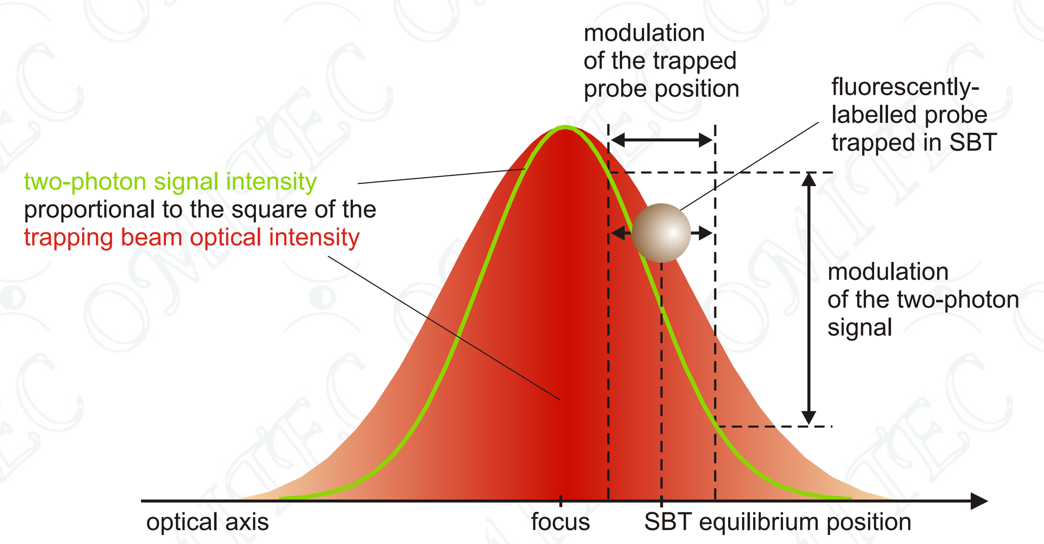


PARTICLE POSITION DETECTION

Quadrant photodiode



Two photon fluorescence



EXPERIMENTAL RESULTS

The z_w-z_{sph} value is directly proportional to signal from quadrant photodiiode (QPD), while TPF is proportional to signal from photomultiplier tube. The measured data were smoothed with discrete Meyer wavelet approximation on level 3. The origin of the z-axis was set to the first maximum of TPF signal and TPF was normalized to value in this point. The QPD calibration was concerned with the range, where the trapped sphere was pushed by the bottom slide from the equilibrium position – the axial movement of the stage directly corresponds with the distance z_w–z_{sph}. So the slope of the edge was used to scale the QPD signal. The QPD signal slowly decreases as the beam waist approaches the sample space, mainly due to the spherical aberration caused by the refractive index mismatch between the coverslip and the water medium. Approximation of the signal in the region of interest was obtained with low-pass filtering and by subtracting the shallow curve from the signal, we got unbent signal oscillating around zero.

To compare the measurement with theoretical predictions, the nearest maximum to z_w=4 μm was found and five subsequent maxima/minima pairs were obtained from the QPD processed signal. Their average value was stored together with particle size.

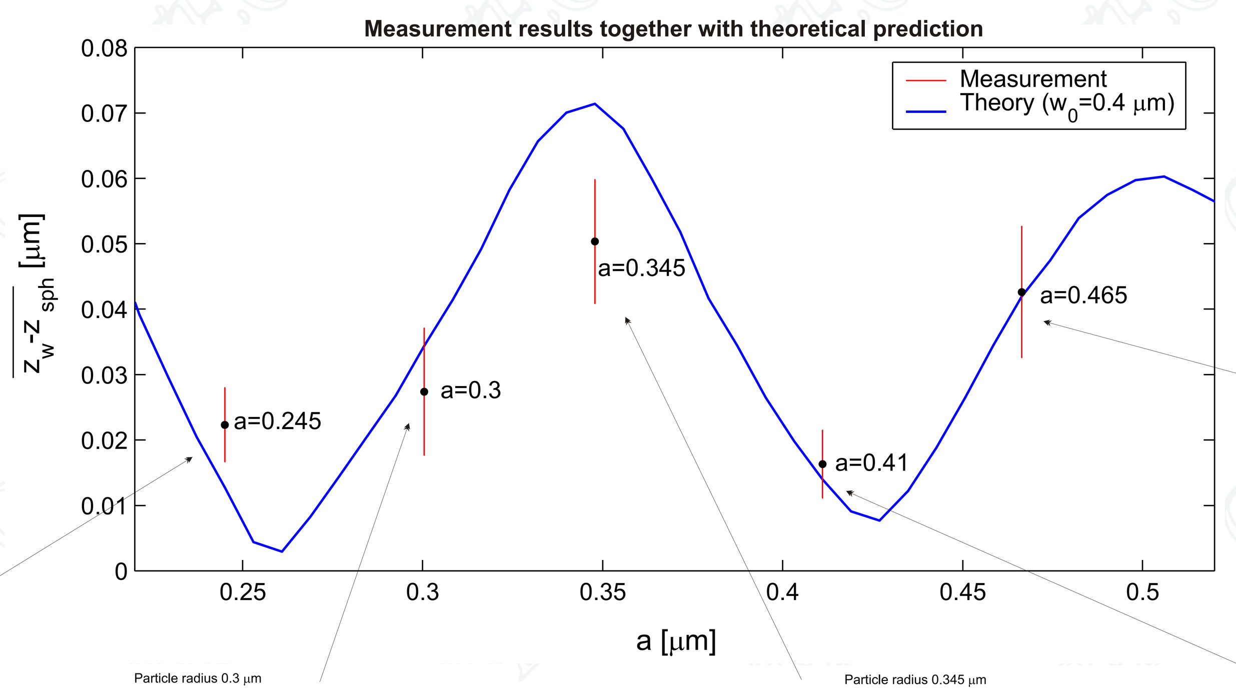
The measurement series are divided into three groups:

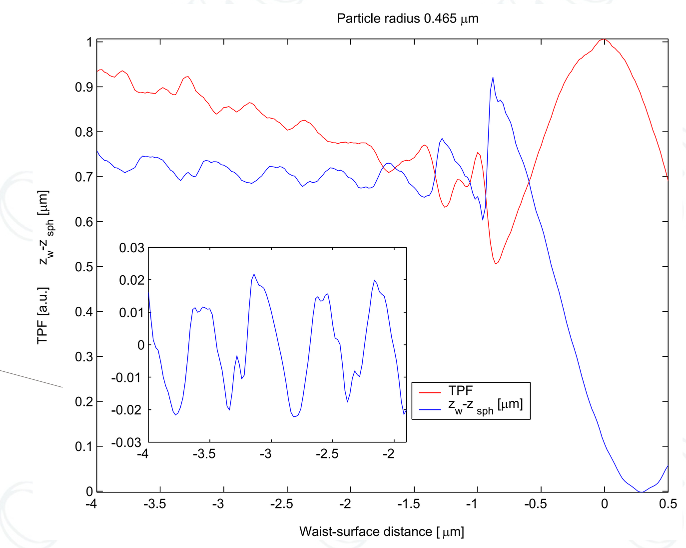
- particles highly sensitive to the GSW – represented by spheres of radius 0.345 μm
- particles medially sensitive to the GSW – spheres of radii 0.3 μm and 0.465 μm
- particles least sensitive to the GSW – spheres of radii 0.245 μm and 0.41 μm

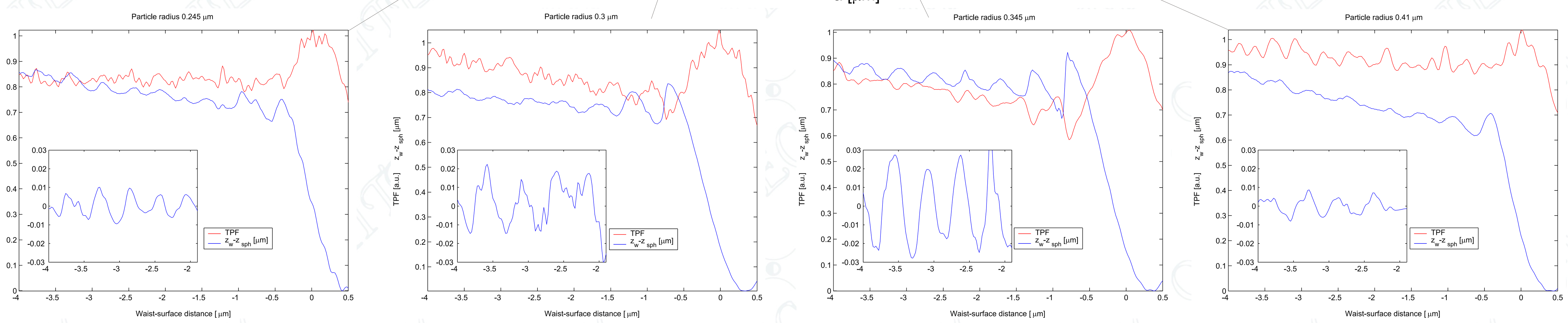
The examples of measurement results can be found in following plots. Each plot consists of QPD (blue) and TPF (red) signals in region of interest, which are already processed and calibrated. Saw-tooth profile of the QPD signal is well-defined and it is shown, that each maximum of z_w-z_{sph} corresponds to minimum of TPF signal. Each plot contains also inset with several peaks following the 4 μm range – signals in insets are already smoothed and unbent. All insets have the same scale, so the difference between modulation depths can be roughly compared with naked eye.

To find out the behaviour of particles of different sizes quantitatively, we acquired large number of z_w-z_{sph} values for each of the particle sizes. Their average values and standard deviations are put in the plot (right figure) together with theoretical sensitivity.

It can be seen, that the behaviour of the particles of radii 0.245 μm, 0.3 μm, 0.41 μm and 0.465 μm are in coincidence with the theoretical prediction. As the laser beam enlarges going through the medium due to spherical aberration, differences between experimental and theoretical results (calculated for w_0=0.4 μm) occur. Another source of deviations is in variation of radii of the spherical particles (coefficient of variation is upto 3% from the mean diameter).







ACKNOWLEDGEMENTS

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