# Precise determination of object position in 1D optical lattice

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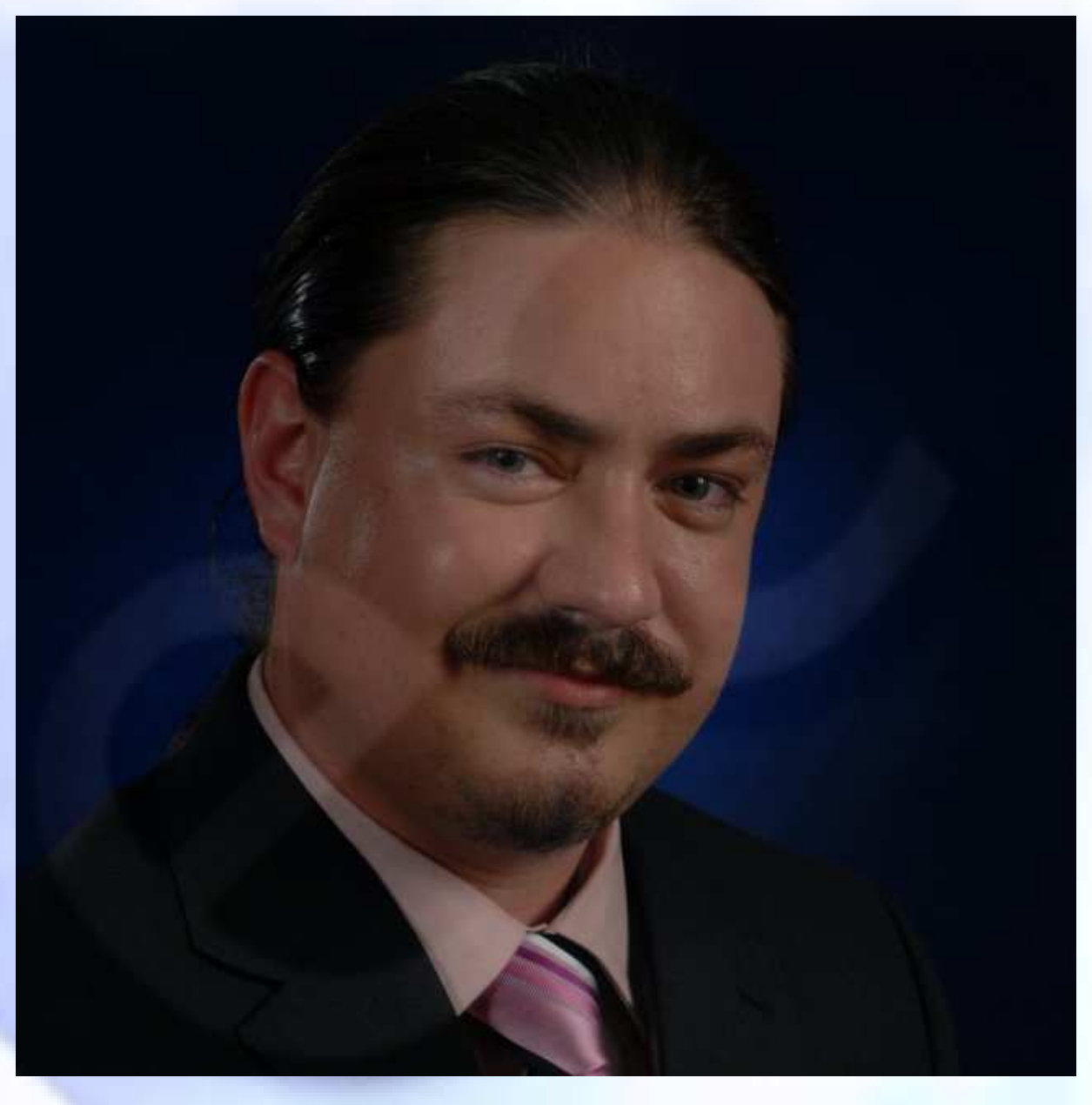

## ABSTRACT

Particle movement with respect to the interference structure of illumination is followed by changes in the light field scattered by the particle. Analyses of these changes together with their calibration provide an excellent way how to determine not only the particle position with respect to the camera but especially with respect to the structure of illuminating field. The algorithm was used in a standing wave optical trap for determination of the trap properties and particle behavior even in standing wave in motion.

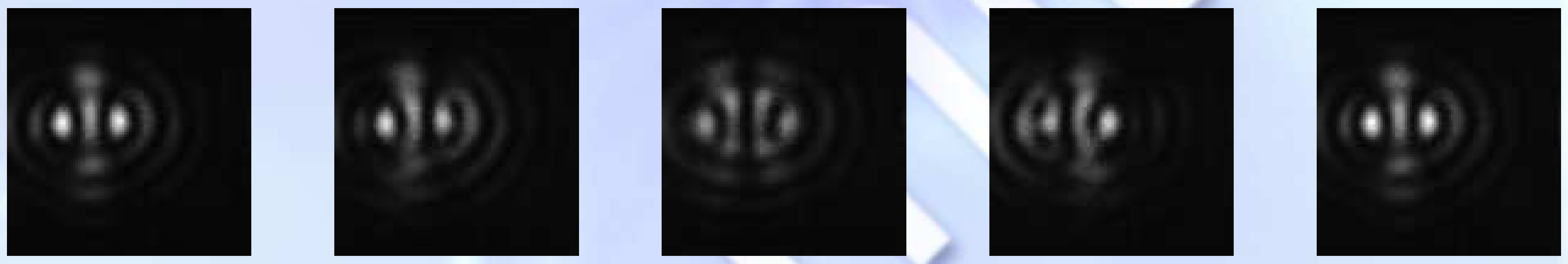

**Figure 1.** Interference patterns of a polystyrene particle 1.070 $\mu$m in diameter illuminated by a standing evanescent wave ($\lambda_{vac} = 532$ nm) taken during fast sweep of the standing wave over the particle by a high-speed CCD camera.

## 1. THE PRINCIPLES

A scatterer stays static in the laboratory system of Cartesian coordinates $x$, $y$, $z$. The particle is illuminated by a standing wave moving in the direction of $z$ axis (since the standing wave is the result of interference of two counter-propagating waves, the motion of the standing wave is controlled by changing the phase of one of these interfering waves). The scattered light is imaged on the plane of CCD.

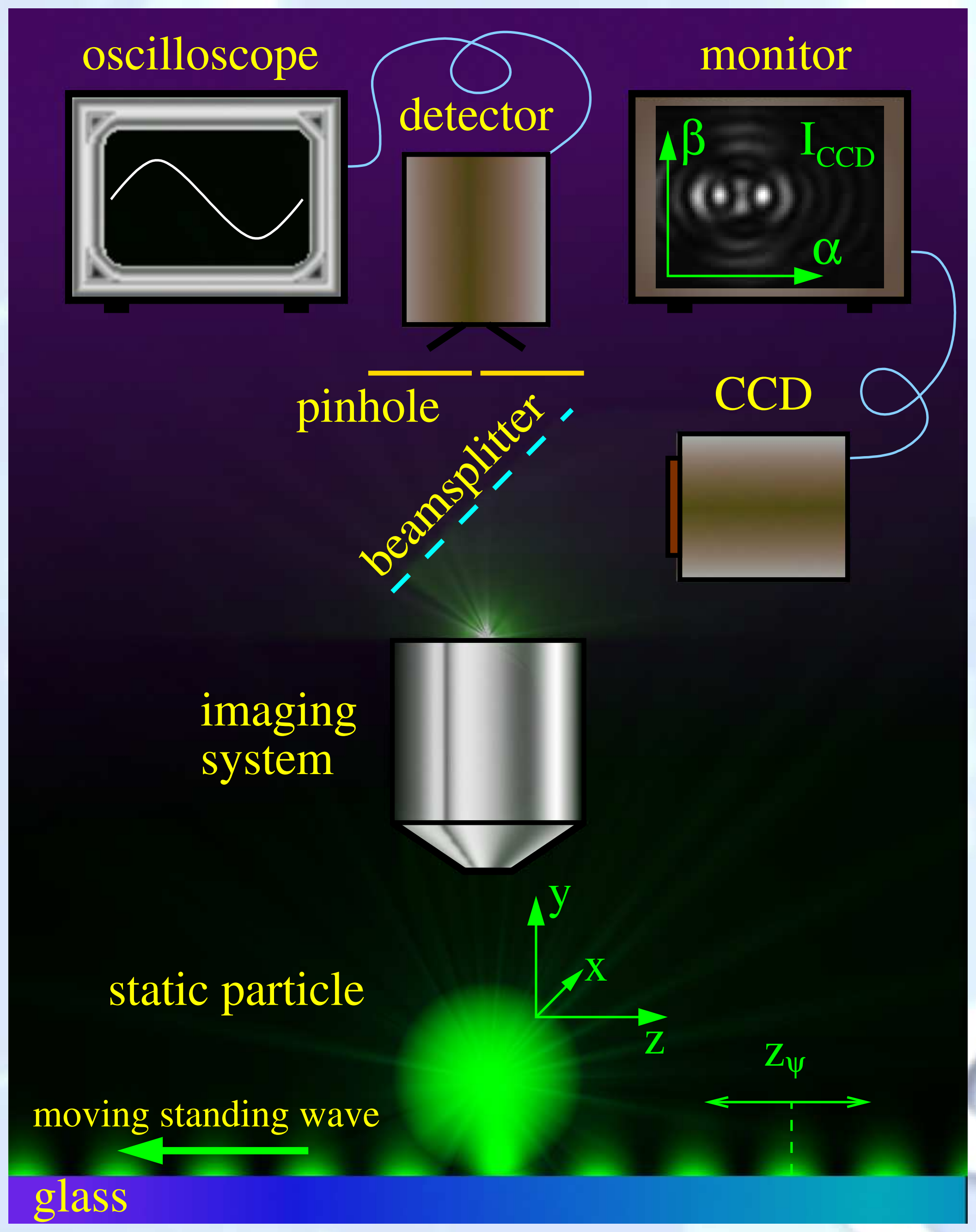

**Figure 2.** Scattering particle illuminated by standing wave.

At each point of CCD $(\alpha, \beta)$ the dependency of light intensity $I_{CCD}$ on the standing wave position $z_\psi$ is described by a cosine function:

$$I_{CCD}(\alpha,\beta) = I_{off}(\alpha,\beta) + I_{amp}(\alpha,\beta) \cdot \cos\left[2kz_\psi + \psi(\alpha,\beta)\right], \qquad (1)$$

where $I_{off}(\alpha,\beta)$, $I_{amp}(\alpha,\beta)$ and $\psi(\alpha,\beta)$ are real functions. Its period is equal to $\pi/k = \lambda/2$ which is the same as the periodicity the of illuminating standing wave. $I_{CCD}$ is defined at each point in the CCD plane by three specific parameters $I_{off}$, $I_{amp}$ and $\psi$.

Any attempt to predict $I_{off}$, $I_{amp}$ and $\psi$ theoretically would require to involve all the parameters of the setup. However this is not necessary since we found the way how to determine them experimentally.

## 2. CALIBRATION OF THE INTERFERENCE PATTERNS

The calibration of the interference patterns is the procedure of determining the parameters $I_{off}(\alpha,\beta)$, $I_{amp}(\alpha,\beta)$ and $\psi(\alpha,\beta)$ at each pixel of CCD camera. Let us have a record of intensity patterns captured while the standing wave illuminating the static particle uniformly moves ($z_\psi = const. \cdot t$). Such record presents Fig. 1. Functions $I_{off}$, $I_{amp}$, and $\psi$ can be obtained by fitting the dependency (1) to the evolution of recorded intensity at each pixel. An example of the result found by this procedure presents Fig. 3.

Now, when $I_{off}$, $I_{amp}$ and $\psi$ are known, we can reconstruct the intensity pattern $I_{CCD}$ for any value of $z_\psi$ using (1).

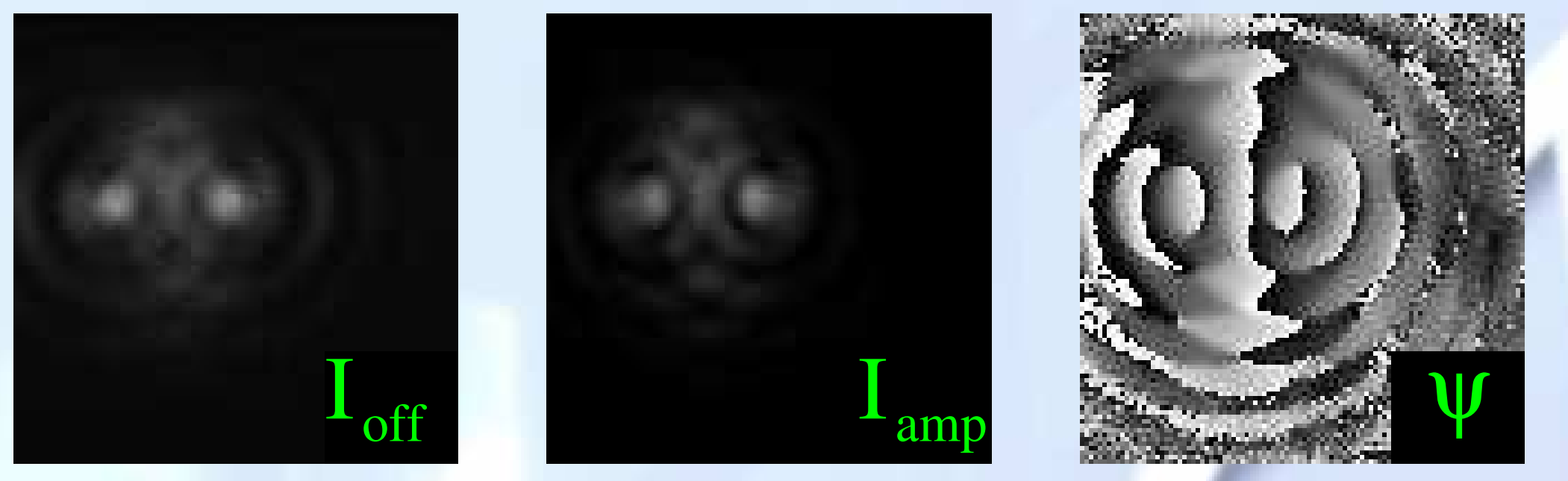

**Figure 3.** Reconstructed functions $I_{off}(\alpha,\beta)$, $I_{amp}(\alpha,\beta)$, and $\psi(\alpha,\beta)$ (black color corresponds to $-\pi$, white corresponds to $\pi$

## 3. PARTICLE TRACKING IN 3D

As the particle moves in static field, the position of the whole intensity pattern of the scattered light copies its motion but at the same time, its shape changes as the particle moves with respect to the standing wave. To determine the particle positions from the CCD record, we have to find for each frame the right shape of the intensity pattern (using (1) and $I_{off}$, $I_{amp}$ and $\psi$ from the callibration procedure) and place it to the right position. The best way how to shift the reconstructed pattern $I_{CCD}(\alpha,\beta)$ to an arbitrary position (using the translational property of the Fourier transform). The output of the optimization process is one value of particle position in the x direction and two values for the z direction ($z$ and $z_\psi$) - see Fig. 4.

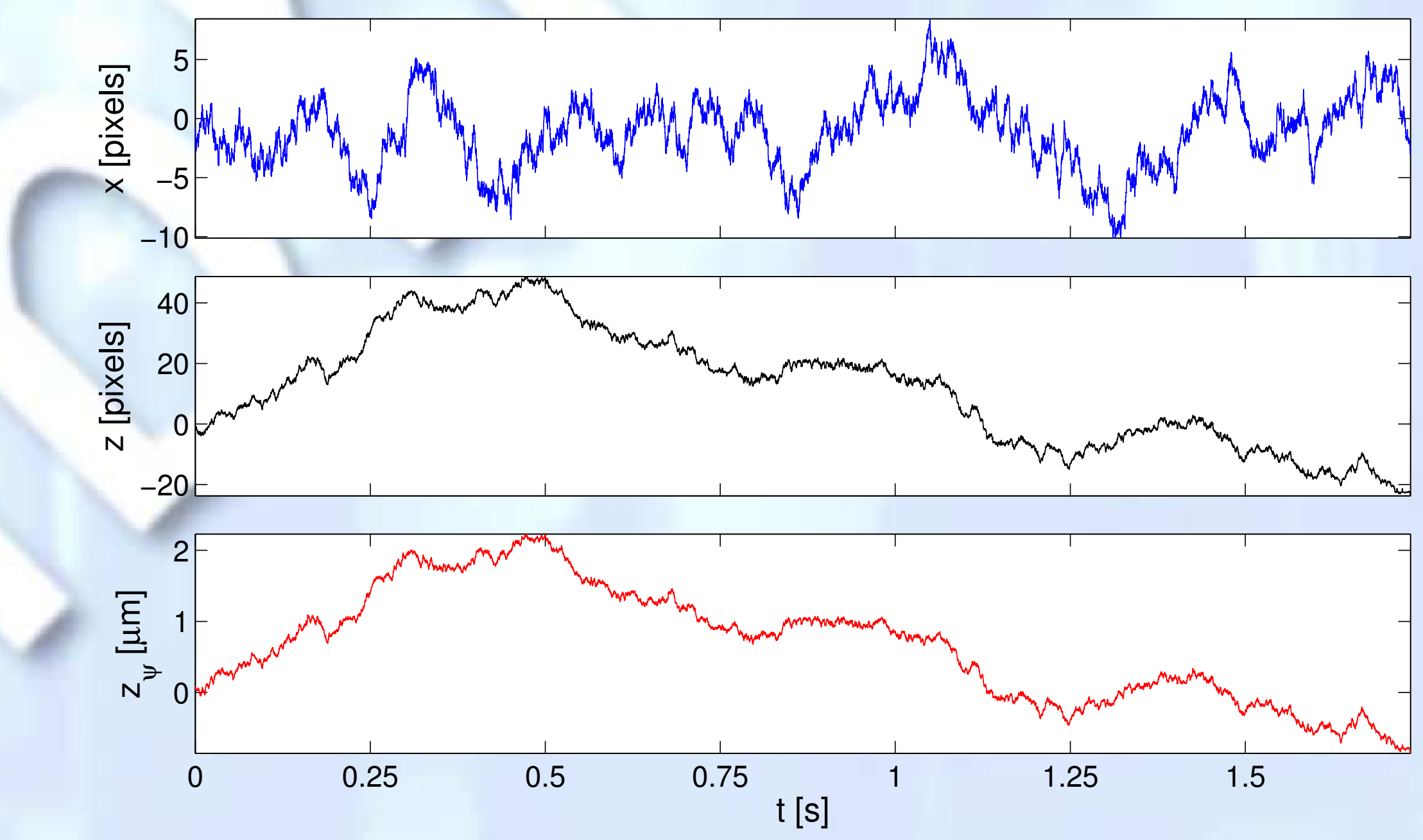

**Figure 4.** Motion of a particle 1.070 $\mu$m in diameter illuminated by a standing evanescent wave ($\lambda_{vac} = 532$ nm).

The $z_\psi$ particle positions obtained from the shape of the intensity pattern are already callibrated from the knowledge of the field periodicity. Therefore this property can be used for calibration of $z$ and $x$ data.

Using evanescent standing wave the record of $y$ positions can be estimated from the total intensity of the CCD interference patterns due to the exponential intensity decay in the y direction. These $y$ values can be callibrated assuming that the velocity distributions of the thermal motion has to be the same for all three axes.

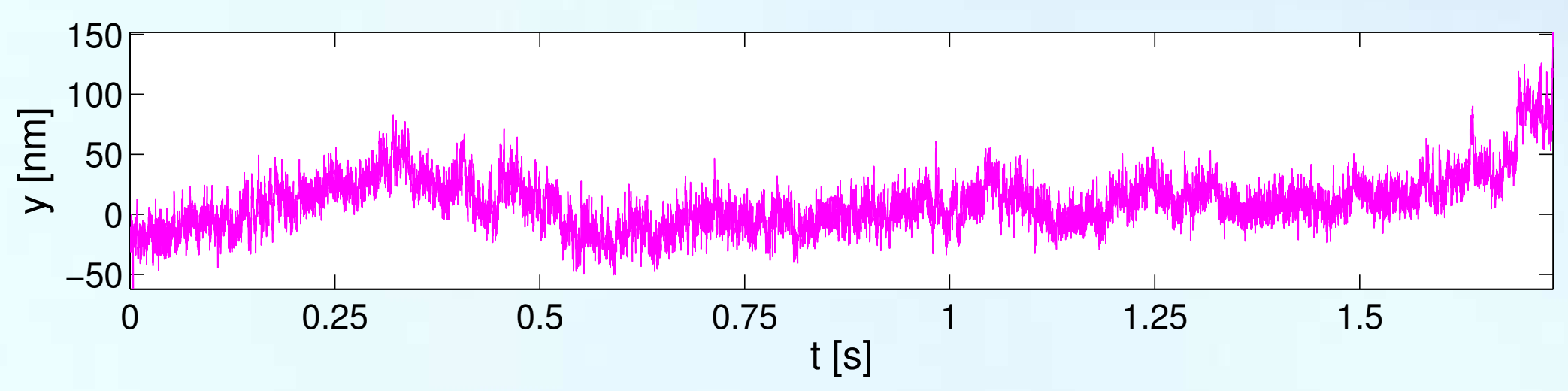

**Figure 5.** The values of particle positions in the $y$ axis computed from the total intensity ratio.

The difference of $z_\psi$ and calibrated $z$ values gives us the information about the movement of the standing wave with respect to the imaging system . This brings the possibility to measure the instability of the systemor to track the particle even in motional standing wave.

## 4. THE APPLICATIONS OF THE METHOD

Precise tracking of particle position enabled us to determine the properties of standing wave optical traps. Figure 6 shows a histogram of particle positions of a particle with 600 nm in diameter.

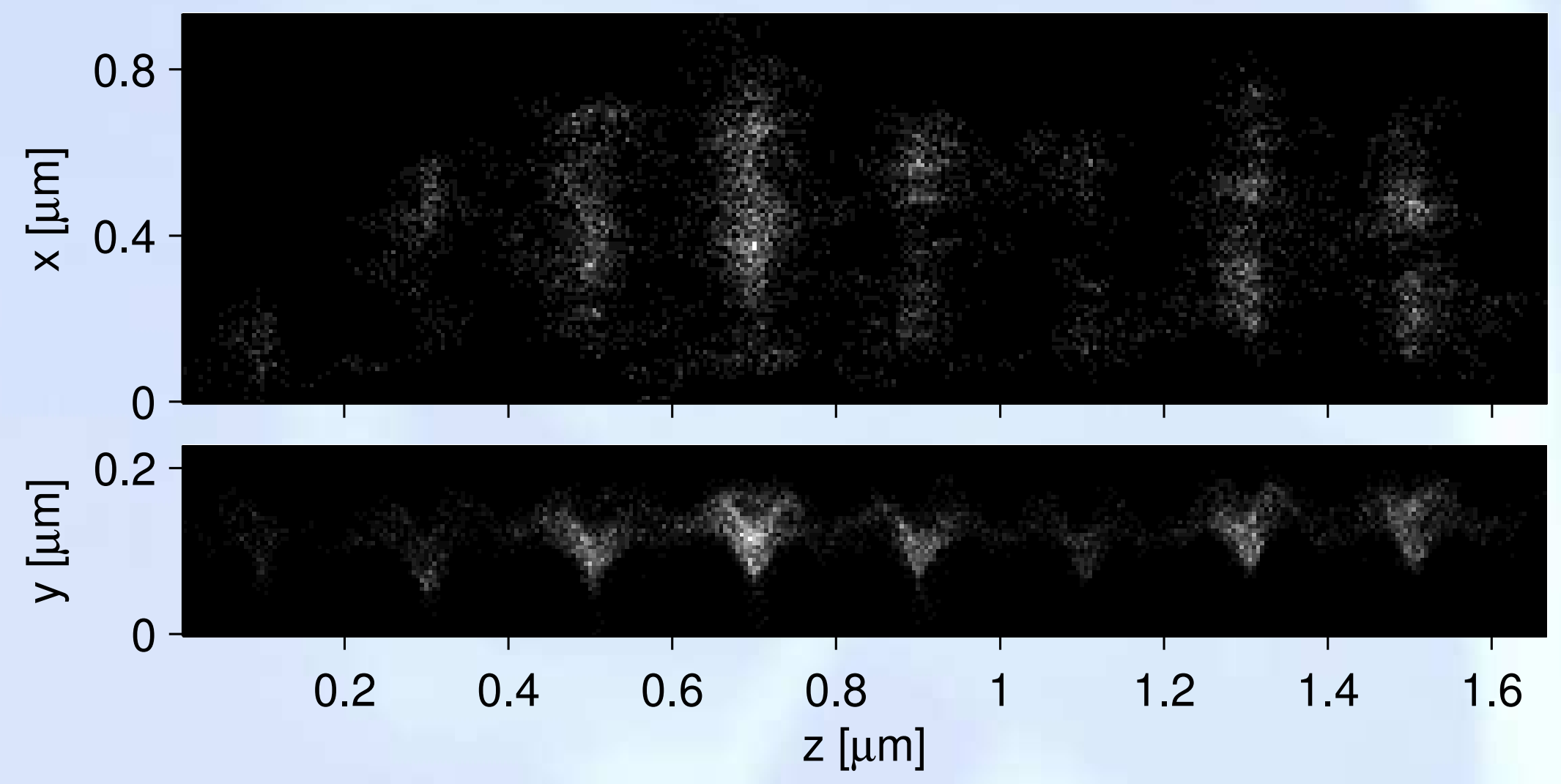

**Figure 6.** Histograms of 600 nm particle positions showing 8 distinct optical traps.

The possibility of particle tracking with respect to the standing wave and at the same time with respect to the laboratory system opens up a prospect to explore in details the particle behavior even in the motional standing wave trap - see Fig. 7.

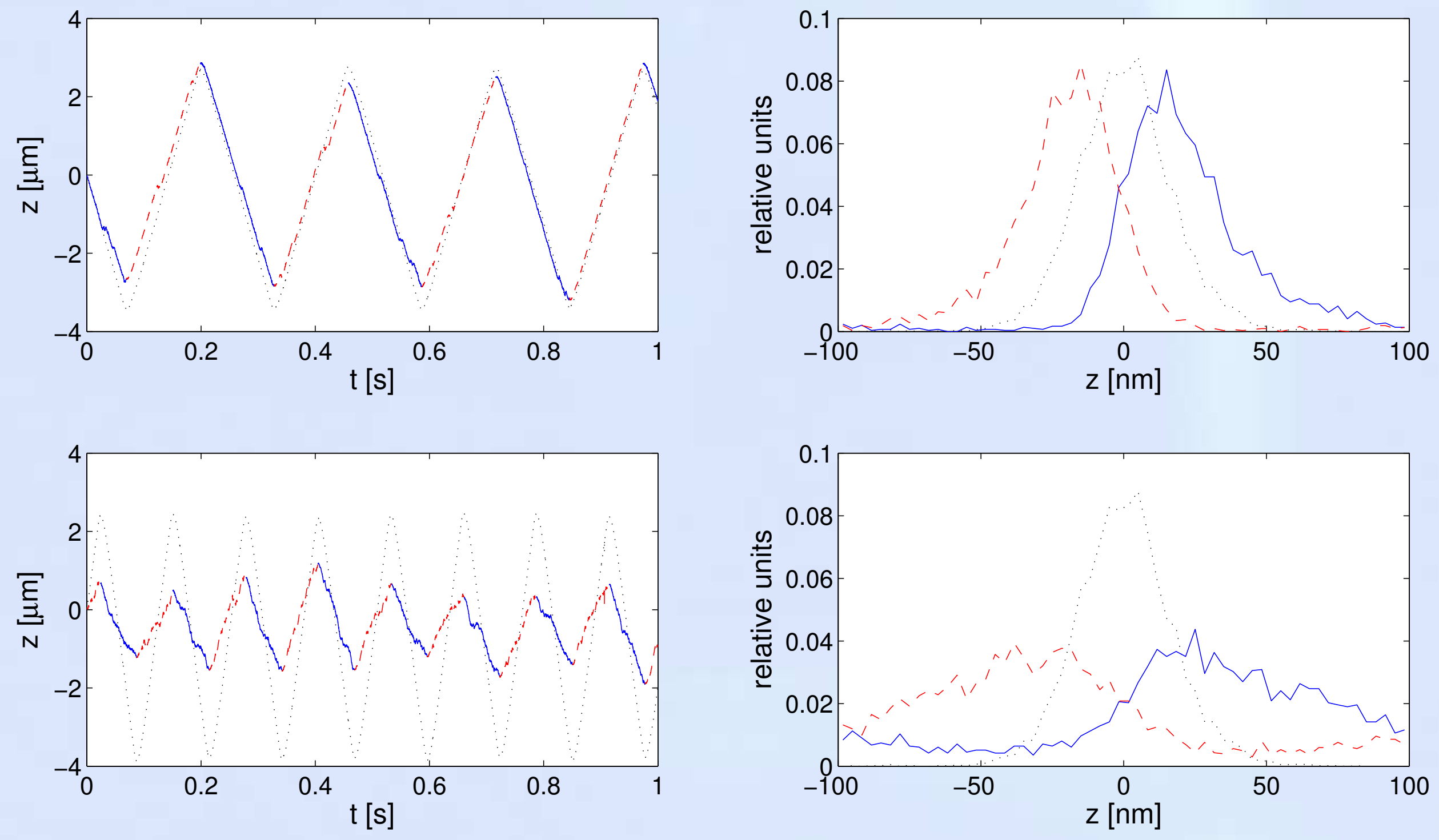

**Figure 7.** A record of the bead position (left plot column) and histograms of bead center position (right) in slowly (47 $\mu$ms$^{-1}$, top raw of plots) and fast (98 $\mu$ms$^{-1}$, bottom) moving evanescent standing wave. LEFT: The dashed and the full segments show position of the bead during movement and the dotted line shows the movement of the standing wave. RIGHT: The histograms of particle position with respect to the standing wave. The dashed and full line histograms correspond to the segments of particle movement from the left column, the dotted line is the histogram for particle in unmovable standing wave.

## 5. CONCLUSIONS

The new method brings a number of unique features:

- The possibility of particle tracking with respect to the illuminating field structure.
- The $x$ anz $z$ positions are obtained with nanometer accuracy even in unstable setups.
- Positions with respect to the standing wave $z_\psi$ are callibrated and can be used to callibrate $z$ and $x$ data.
- Method can be used even if the illuminating (trapping) field moves

## 6. ACKNOWLEDGMENTS

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