Towards optical magnetometry beyond the shot noise limit

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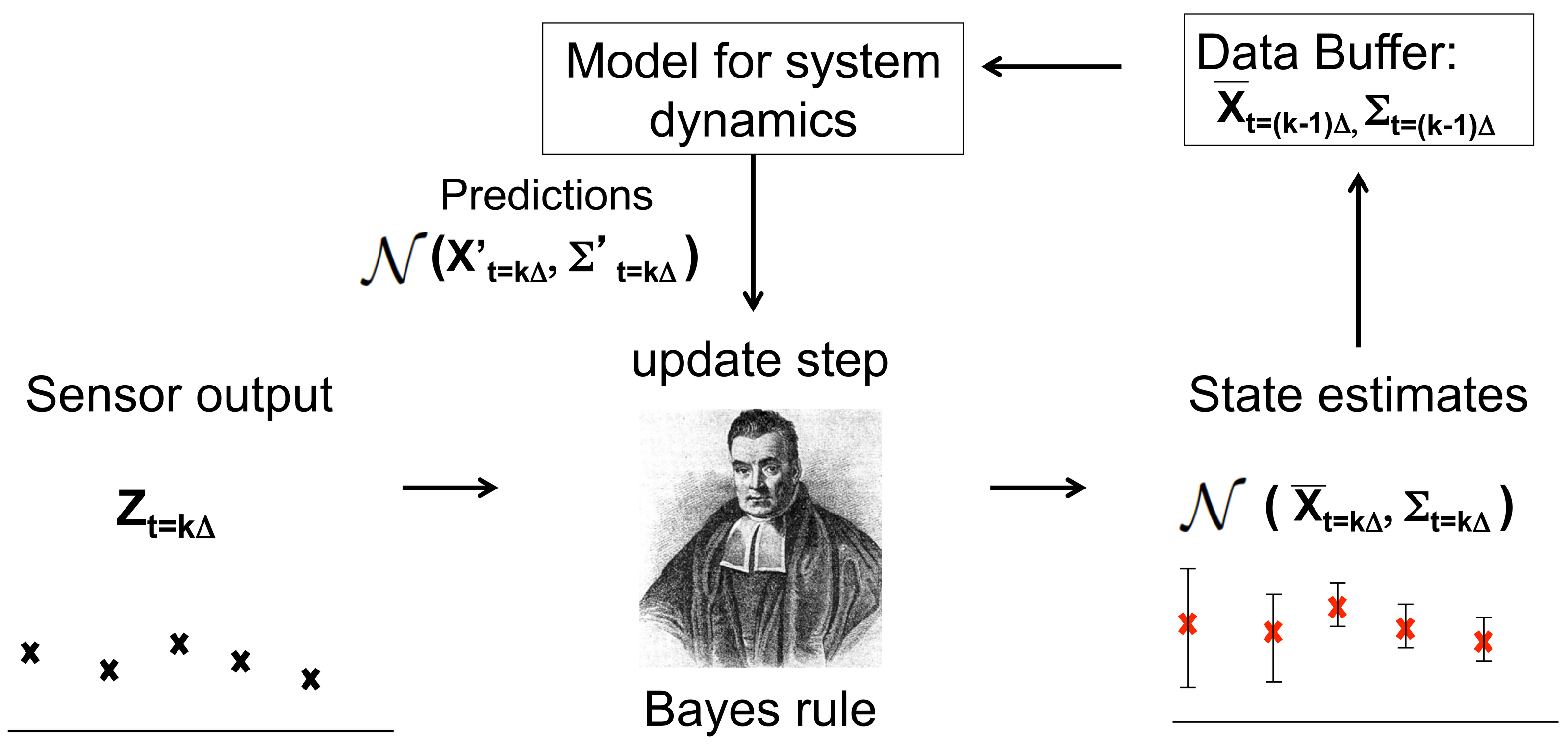
MOTIVATION

Optical magnetometers are fundamentally limited by spin projection noise, optical shot noise, and measurement back action. To study ways to surpass the limits imposed by these noise sources we are developing Bayesian inference techniques for spin state estimation. Here we present our recent work involving Kalman filtering for the task of waveform estimation [1].

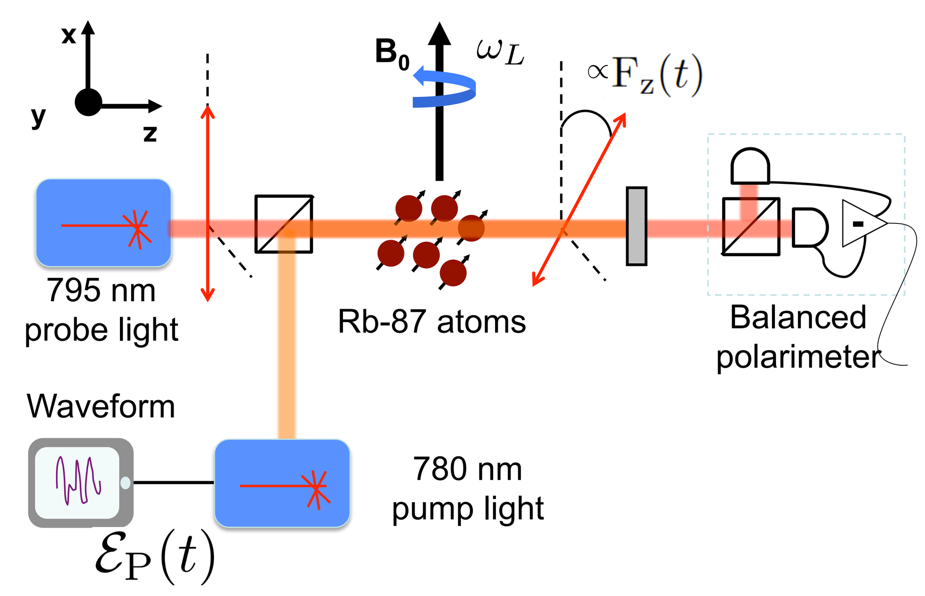
TRACKING SPINS WITH KALMAN FILTER

The Kalman filter (KF), pioneered by Rudolf E. Kalman [2], relies on an iterative Bayesian estimation approach involving all available information to the observer (including measurements, and statistical model for system dynamics and sensor outputs), to yield state estimates for the system of interest. For linear Gaussian systems KF estimates are guaranteed to be optimal.



$$P(A|B)=\frac{P(B|A)P(A)}{P(B)}$$

ATOMIC SENSOR MODEL



A waveform, carried by an optical field, is mapped onto the collective spin orientation of an ensemble of *N* ground state alkali atoms:

$$\mathbf{J}=\sum_{i=1}^{N}\mathbf{f}^{(i)}$$

We model the stochastic motion of the precessing spin ensemble as an Ornstein-Uhlenbeck process:

$$\mathrm{d}J_y(t)=\left(\omega_L J_z(t)-\frac{1}{T_2}J_y(t)\right)\mathrm{d}t+\mathrm{d}W_y(t)\;;\quad \mathrm{d}J_z(t)=-\left(\omega_L J_y(t)-\frac{1}{T_2}J_z(t)\right)\mathrm{d}t+\mathrm{d}W_z(t)$$

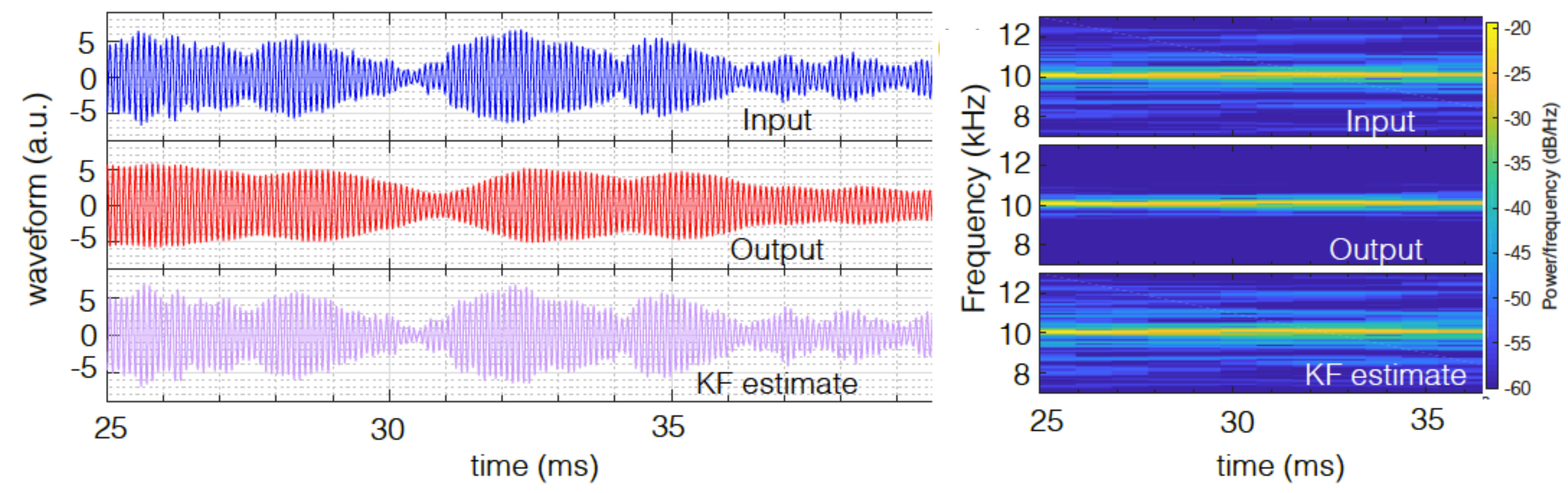
The spins are read out via optical Faraday rotation (FR) of an off-resonance light beam, whose rotation angle is detected with a balanced polarimeter that is inherently noisy due to optical shot-noise:

$$\Theta_{det}(t)=\Theta_{\mathrm{FR}}(t)+\Theta_{psn}(t)$$

Sensor calibration is performed via spin noise spectroscopy [3,4].

TRACKING WAVEFORMS

To validate the filter we apply waveforms with dynamics known to the observer. This approach enables us to compare the KF estimates against the true value of the signal. In this way we verify the accuracy of the statistical model underlying the KF.



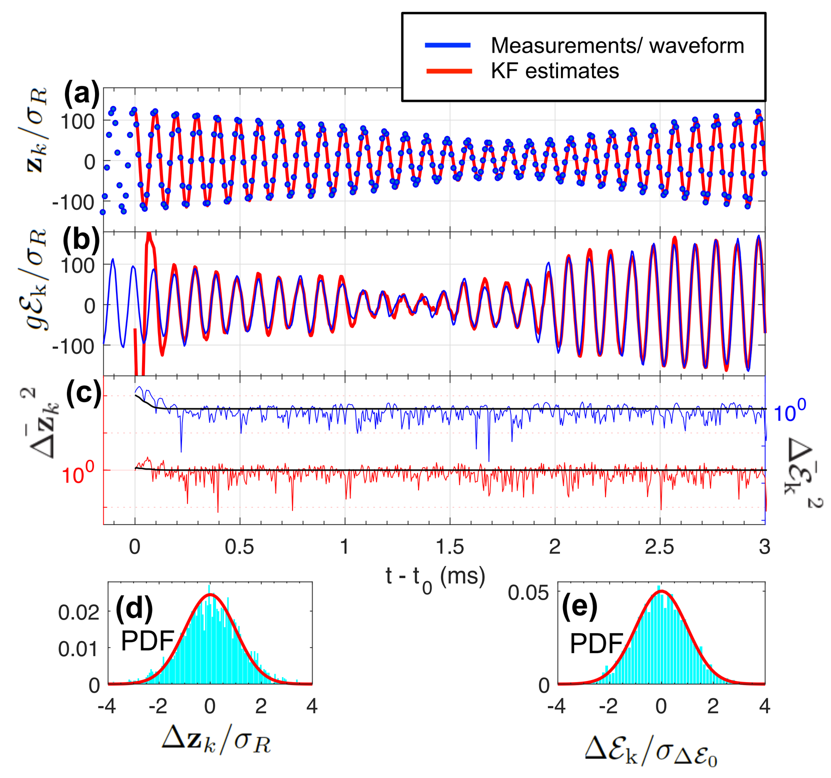
Left: a representative applied waveform (input) along with the corresponding measured angle (output) and the recovered waveform (KF estimate).
Right: spectrograms of input, output and KF estimate showing that rapidly-varying features of the input are suppressed in the output yet are recovered in the KF estimate.

(a) Recorded sensor output and KF estimates.

(b) Applied waveform, corresponding to the realization of an Ornstein-Uhlenbeck process, and KF estimates.

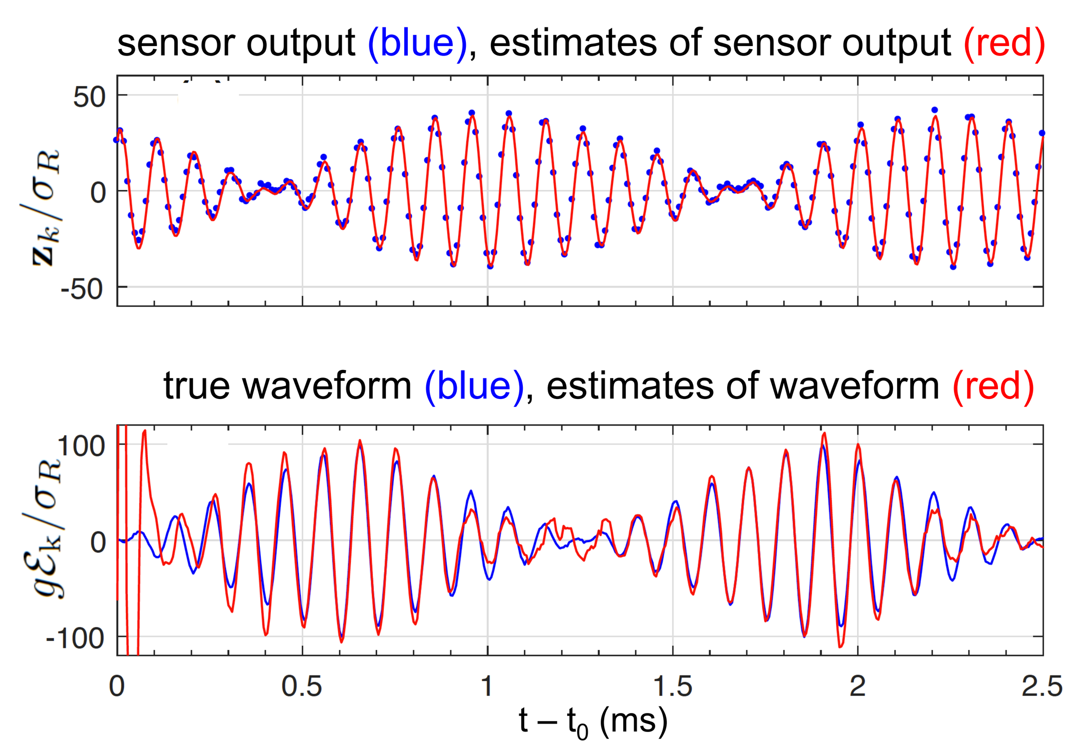
(c) Estimation errors and KF precision.

Probability density functions for innovations (d) and waveform estimation errors (e).



TRACKING UNKNOWN WAVEFORMS

Using our KF we have also explored the regime where the waveform dynamics is only partially known prior to the measurement. We approximate the evolution of the waveform adapting polynomial models [5].



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