

# Trigger-Synchronous Frequency Counting with Time Tagger

## Phase evaluation at sync events for low-noise Kibble balance readout

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In the dynamic phase of a Kibble balance, induced voltage  $U(t)$  and coil velocity  $v(t)$  must be evaluated at the same instants in time to preserve their correlation and obtain a low-noise  $U/v$  ratio. Standard fixed-grid phase estimation is not ideal in this case, because phase values then need to be mapped to the trigger times used by the rest of the experiment. To solve this, Swabian Instruments developed a new custom measurement class, *SyncFrequencyCounter*, that evaluates interferometric phase directly at the external synchronization events. This removes the interpolation step and improves time alignment between phase-derived velocity and voltage acquisition.

### EXPERIMENTAL SETUP

In the BIPM Kibble balance, coil motion is measured with heterodyne Michelson interferometers. The diagram of the experimental setup is shown in Fig.1. The interferometer beat signals are converted to digital signals using low-phase-noise squaring electronics and recorded with the *Time Tagger Ultra*. Synchronization trigger pulses generated by the experiment control (FPGA) are distributed to all instruments, including the digital voltmeters and the Time Tagger; one Time Tagger input records these triggers so that interferometric phase (and derived velocity) can be evaluated at the same trigger instants. A stable 10 MHz reference is supplied as the Time Tagger clock input to ensure long term stability.

### MEASUREMENTS AND RESULTS

To extract coil motion from the heterodyne interferometer signals, the Time Tagger emulates a software-defined reciprocal counter, here operated as an  $\Omega$ -type frequency counter, estimating instantaneous frequency and phase of the MHz beat signals from the recorded signal edges. Other counter modes, such as  $\Lambda$  and  $\Pi$ , are also possible. With the standard *FrequencyCounter* measurement class [1], phase values are produced on a fixed time grid, so when values are needed exactly at the external synchronization triggers,

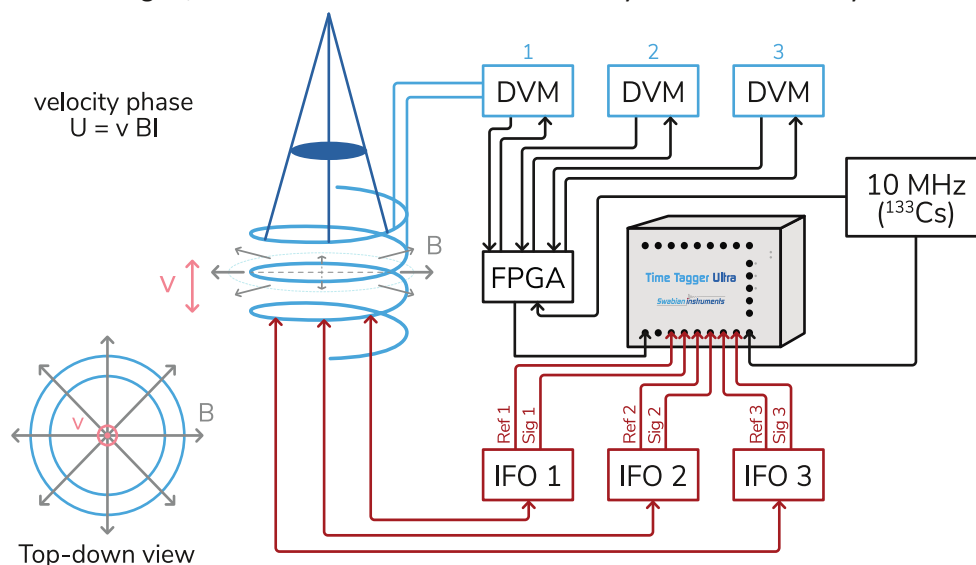


Fig. 1: Experimental setup for trigger-synchronized interferometric phase readout in the BIPM Kibble balance using the Time Tagger. FO: interferometer output; DVM: digital voltmeter.

The contribution of the BIPM to this application note neither represents nor implies an endorsement by the BIPM of the product.

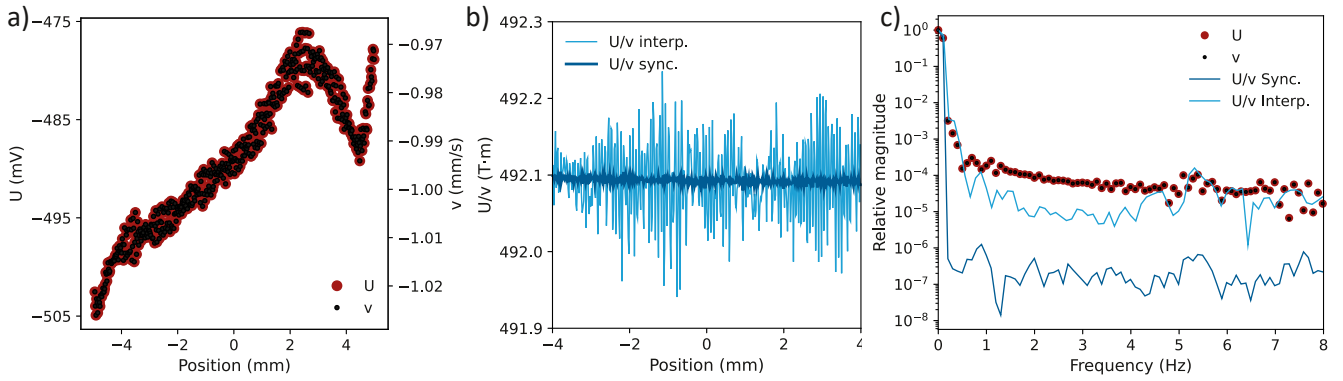


Fig. 2: (a) Induced voltage  $U$  and interferometric velocity  $v$  versus position, evaluated at the same trigger instants. (b) Ratio  $U/v$  versus position using trigger-synchronous phase evaluation and a fixed-grid (interpolated) approach. (c) Relative FFT magnitudes of  $U$ ,  $v$ , and the two  $U/v$  estimates, showing a lower noise floor for the synchronized ratio.

they must be mapped to those trigger instants, typically by interpolation.

For this Kibble-balance application, a custom Python measurement, SyncFrequencyCounter [2], evaluates phase directly at the recorded synchronization events on a separate input channel. This removes the interpolation step, outputs only the required samples, and keeps the interferometric velocity (see equation below) naturally time-aligned with the voltage acquisition used to compute  $U/v$ . The velocity is estimated as:

$$v\left(\frac{t_2 - t_1}{2}\right) = \frac{\phi_{\text{mov}}(t_2) - \phi_{\text{mov}}(t_1)}{t_2 - t_1}$$

where  $\phi_{\text{mov}} = (\phi_{\text{out}_1} - \phi_{\text{out}_2})/2$ , with  $\phi_{\text{out}_{1,2}}$  the phases of the two interferometer outputs. As shown in Fig. 2a,  $U$  and  $v$  individually exhibit significant fluctuations, but their correlation is preserved so that the  $U/v$  remains comparatively stable (Fig. 2b). This is quantified in the frequency domain: the Fourier spectrum of  $U/v$  exhibits a markedly reduced noise floor (Fig. 2c), by two to three orders of magnitude compared to the spectra of  $U$  and  $v$  alone. For reference, when phase is first computed on a fixed time grid and then mapped to the trigger instants via interpolation, the resulting ratio spectrum shows a higher noise floor, consistent with imperfect preservation of the  $U$ - $v$  timing correlation.

## CONCLUSION

Using the Time Tagger as a software-defined  $\Omega$ -type frequency counter enables precise phase and frequency estimation from heterodyne interferometer signals. In this work, a custom trigger-synchronous measurement evaluates phase directly at the experiment's synchronization events, preserving the  $U$ - $v$  timing correlation and yielding a lower-noise  $U/v$  ratio than a fixed-grid phase-evaluation approach requiring interpolation.

## REFERENCES

[1] <https://www.swabianinstruments.com/static/documentation/TimeTagger/api/index.html>

[2] <https://github.com/swabianinstruments/Time-Tagger-Custom-Measurements/tree/main/python/SyncFrequencyCounter>