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# Interferometric fibre link between Braunschweig and Garching for chronometric levelling

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## Introduction

According to general relativity the speed of time depends on the local gravity potential. At the Earth's surface, the comparison of clocks with a height difference of 1 m shows a relative frequency shift of $1\times10^{-16}$. With uncertainties of optical clocks approaching $10^{-18}$ [1, 2], comparing the frequencies of two clocks enables a height difference resolution at the cm level. This chronometric levelling [3, 4] is a new, complementary tool for geodesy allowing direct, fast measurements over continental distances. For long-distance frequency comparisons, interferometric fibre links (IFL) are currently the only technique providing the required accuracy.

## IFL Setup

Mechanical perturbations and temperature fluctuations [5] induce phase noise to an optical carrier transferred over an optical fibre, limiting the long-distance frequency transfer uncertainty to about $10^{-13}$ [6, 7]. To achieve lower uncertainties IFLs are employed: the ultra-stable optical carrier is transmitted over the fibre and part of the light is back-reflected from the remote end to the input end. This bidirectional operation allows forming a giant interferometer for measuring and compensation of the phase noise [8].

In preparation of a chronometric levelling [6, 9] experiment comparing the stationary optical clocks of the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig and PTB's transportable Strontium clock [10] placed at the Max Planck Institute of Quantum Optics (MPQ) in Garching, we have established a new 940 km long IFL between the two locations. To monitor the performance of the frequency transfer, the signal is transferred back from MPQ to PTB on a second fibre, providing a frequency transfer over a total of 1880 km and enabling an out-of-loop characterization. To enable chronometric levelling experiments at the level of 10 cm height resolution, we aim a fractional frequency uncertainty of the frequency transfer of $< 1\times10^{-18}$ for averaging times of $\sim$40 ks.

The attenuation of the link adds up to $\sim$200 dB. Due to the bidirectional operation, we installed four special fourfold bidirectional fibre Brillouin amplifier modules to address these losses. They were developed in-house, provide a gain >40 dB per fibre and direction, generate amplitude-stable signals and are placed every $\sim$200 km.

## Results

We find night-time instabilities of $\Lambda_{1s}$ data samples [7] expressed as overlapped Allan deviation starting at $1.5\times10^{-15}$ and averaging down with averaging time $\tau$ as $(\tau/\mathrm{s})^{-1}$. We reach a fractional frequency transfer instability of $1\times10^{-18}$ after 2000 s of averaging time, with zero-compatible offsets of few $10^{-19}$, supporting chronometric levelling below the cm-level.

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