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Design and manufacture of a reference interferometer for long-range distance metrology

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Abstract
To realize SI-traceable length measurements in air over distances of up to 5 km with a relative uncertainty significantly better than 1 part-per-million (10^{-6}) we develop an outdoor-capable heterodyne interferometer. Beam guidance in two levels enables a compact design. We use a closed frame design to ensure high mechanical stability, and low thermal expansion materials to avoid mechanical drifts. An optimised fixation of the optical components and flexure hinges ensures long-term stability of the optical set-up. Besides stability, another challenge addressed is the fact that the system requires alignment capabilities to better than 0.5 arcseconds.

Geodetic length instrumentation, closed-frame design, thermal and long-term stability, manual positioning system, precision assembly

1. Introduction and requirements

Long range measurements in air play an important role in surveying and geodesy. High-accuracy measurements are necessary to detect changes at critical sites like nuclear waste repositories or dams. Geodetic length instrumentation like GNSS based systems must be verified against terrestrial references to ensure traceability to the SI definition of the metre. For this, the relative uncertainty of the reference lengths should be significantly better than 1 ppm. The accuracy of any optical measurement technique over such a range, however, suffers from the inevitable inhomogeneity of the air index of refraction. In this contribution, we describe the resulting challenges for the design and manufacture of a novel optical standard for measurements up to this range.

The main goal of the newly developed instrument is to measure a length of up to 5 km with a measurement uncertainty of 1 mm (k=2; 95% coverage probability), while for a shorter distance of 1 km the uncertainty of the measurement should be around 100 µm. Based on our previous work [1, 2], we intend to realize the optical length measurement by absolute distance interferometry using intrinsic dispersive refractivity compensation. As optical source, we use two Nd:YAG lasers with a stabilized frequency difference. The two-colour measurement is realized by the fundamental 1064 nm and the frequency doubled 532 nm beams. They are superposed before the interferometer head in two polarization maintaining photonic crystal fibers [3], one delivering the local oscillator and the other the signal beam. We use a classic heterodyne interferometer design to measure the interferential optical phases (see Fig. 1). All optical elements need to be achromatic for both wavelengths. The targeted extreme long range requires a large aperture to reduce diffractive expansion of the optical beams. For robust outdoor operability, we decided to work with an achromatic lens telescope with an exit aperture of 123 mm. The spacings between the three optical lenses is highly critical. The mechanical design of the mount must allow an adjustment of the distance of the two telescope achromates of 540 mm to micrometer level. Small mechanical drifts of the various mounts are inevitable. A mirror can be driven in and out of the beam path between range measurements to enable a reference "0" measurement during operation. Its positioning is better reproducible than 10 µm.

The system will be operated outside in a temperature range of 5 °C to 35 °C, also under adverse conditions. For long range measurements extended integration times are necessary to reduce the impact of turbulence. Therefore, the design must ensure structural, in particular thermal stability even over several tens of minutes on micrometer level. Low-strain mounting of the optical components of the interferometer with very uniform force vectors to ensure long-term stability is also important for mechanical robustness against shock or vibrations during transport and setup. In addition, the system centre of gravity shall coincide with the origin of the three mechanical axes: torques due to the inevitably high load mass at the fragile geodetic mounting point must be avoided. Finally, targeting and beam alignment must ensure that the emitted laser light hits a retroreflector with a circular aperture of only 127 mm. This leads to an alignment precision of less than 0.5 arcseconds in both, the horizontal, and the vertical axes. Finally, the instrument weight should allow two persons mounting it on geodetic pillars.

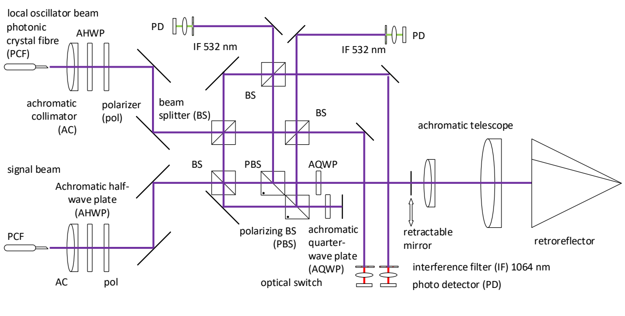

Figure 1. Functional scheme of the heterodyne two-colour absolute distance interferometer.

2. Design and manufacture

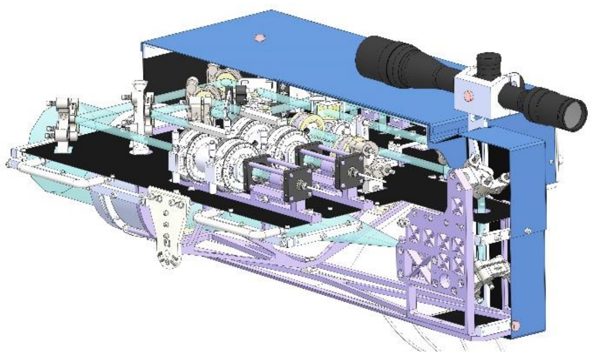

Figure 2. Partial section of the "interferometer head" (laser-light path in green).

For a better handling during transport and installation, the system was divided into two units: the interferometer head (Fig. 2), which accommodates all parts of the optical set-up, and the base with the alignment setup (Fig. 3). In addition, an adjustment structure for initial calibration in the laboratory is used. A corresponding self-centering interface between the two units was developed. One side of the interface has three pairs of dowel pins acting as V-prisms, while the other side consists out of three spheres. They are aligned on the same reference diameter in a 120° angle. Mounting both sides together with a central screw leads to a very well defined and kinematically determined bearing with high reproducibility in the alignment of the optical and the mechanical axes. In addition, the initial assembly of the frame and the interface will be monitored by a coordinate measuring machine. We aim at a small tolerance of the horizontal mechanical axis to the beam axis for both supports of less than ± 30 µm through these measures. The beam guidance inside the interferometer head is realised on two levels. This allows a compact form, a rigid design, and a limitation of the torque on the baseline pillars. Many optical mounts have been developed specifically as well to ensure very uniform and low-stress restraint of beam splitters and waveplates. At the same time, the fixtures must be insensitive to possible impacts during transportation and setup to assure long-term stability of the system. We therefore developed flexure hinges which allow for coarse and fine adjustments in a single device. The angles between optical components and the holding fixtures were optimised to avoid etalon effects in the interferometer. The functional optical components are mounted in a stiff closed-frame design to ensure high mechanical stability. This also helps reducing the temperature influence on the measuring system. Thermal drift is also minimized by using a material (FeNi36) with a low coefficient of thermal expansion (CTE, $\alpha \approx 1.2 \cdot 10^{-6}$ K^{-1}) for all critical parts. Furthermore, the enclosure is thermally as well as mechanically isolated from the optical set-up to eliminate the influence of the surroundings during the measurement. A sighting telescope is mounted on top of the interferometer head to locate the reflector in the first instance.

The base and alignment unit depicted in Fig. 3 must provide a rigid connection between the reference point and the interferometer head. At the same time, one has to be able to move the interferometer head, so that the laser light hits the reflector. The alignment of the system is acquired by a three-stage manual positioning system. In a first step, the instrument is coarsely aligned by hand. This position is fixed by a clamping mechanism. The second stage consists of a small linear table which moves a micrometer gauge. After fixation of the second stage, a fine-tuning gauge connected to a lever finally enables the instrument to be aligned very precisely with the target reflector. This layout is used for both axes. The bearing used in the vertical axis is an adjusted O bearing arrangement. To save space and weight we implemented thin section bearings wherever possible. For the connection between the given geodetic reference points and the base part, we use the standard tripod interface following the ISO 12858-3 standard. Again, the whole design needs to be very stiff, but still compact and lightweight. We use cutouts at regions of low stress and different material combinations where possible. The horizontal axis has a fixed bearing on one side of the interferometer head and a floating bearing on the other side to prevent stress induced bending. The interferometer reference point needs to remain in the plumb line on the pillar reference point. To avoid lateral displacements, we use CTE alloy for the horizontal parts. But vertical displacements below 1 mm are negligible for the long distance measurement. Therefore, thermal expansion is not critical in this direction and the lighter aluminum can be used for the vertical mounting structures. Although numerous cutouts in all parts help to reduce weight, a total system weight of almost 45 kg turned out inevitable.

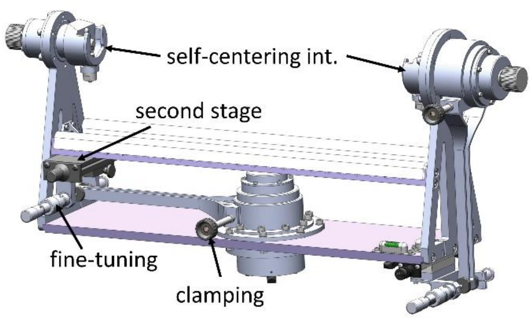

Figure 3. The base setup with the alignment unit. The three-stage positioning system is marked for the vertical axis only. Invar parts are depicted in violet.

3. Conclusion and outlook

At the time of writing this article, manufacturing of the single parts is being conducted and first assemblies are completed. The interferometer head shall be finished in the first quarter, the base and alignment unit in the second quarter of 2021. Setup, adjustments and initial laboratory verification tests are planned immediately after. The full measuring system will then be studied and validated at PTB's long range calibration baseline and the Nummela standard baseline in Finland. In the course of the European "GeoMetre" project, the system will be deployed to novel European reference baselines constructed in Poland and to several European geodetic reference networks at geodetic co-location sites. Later, it is intended to serve as German reference standard for long distance measurements.

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