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A compact and versatile laser-interferometric displacement sensor for space applications

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Abstract

We present a high accuracy, high dynamic range interferometric displacement sensor for space applications. The readout scheme, based on laser frequency modulation, allows for a compact sensor design that enables sub-micron displacement measurements over a baseline of centimetres to metres. The technology will be applied within the SeRANIS mission, to be launched in 2026, where it will serve as a sensor to monitor and control the dynamics of a novel low thermal expansion structure. The sensor is designed to withstand the harsh LEO environment and is furthermore able to operate within a wide temperature range of more than ± 50°C around a nominal value of about 20°C, a novelty for interferometric sensors of this kind. In this presentation we will introduce the basic concept of the sensor, present its capabilities and highlight its wide range of applications.

Keywords: Laser interferometer, motion sensor, displacement sensor

1. Introduction

The high potential of interferometry in space for high-precision measurements has been shown by two missions: LISA Pathfinder and GRACE-FO. LISA Pathfinder (2015-2017) was a technology demonstrator mission for the space-based gravitational wave observatory Laser Interferometer Space Antenna (LISA) [1, 2, 3]. It defines the state of the art in ultra-high precision sensing of the motion of freely floating test masses in space. The US/German GRACE-FO mission (2018-present) for the first time demonstrates the advantages of an inter-satellite interferometric laser link with the goal of monitoring the gravitational field of the Earth [4, 5].

Both these missions demonstrate the feasibility of high precision interferometric sensing in space. However, the optical setups are complex and heavy. In fact, the overall mission designs were completely (LISA Pathfinder) or at least partially (GRACE-FO) tailored to the requirements of the laser interferometer.

To broaden the application of space-based interferometry, DLR brings the space-proven, high precision laser interferometric sensing technique by drastically simplifying the required experimental setups and, thus, making the sensor systems more robust and economic.

2. Interferometric displacement sensing

The concept of laser interferometric displacement sensing is well illustrated by a simple Michelson Interferometer (MI). In a homodyne laser interferometer with a Michelson layout, a single laser beam is split into two paths: a reference and a measurement path. The beams are reflected in each arm by a mirror. The measurement path mirror is attached to the test mass to be sensed. At the beam splitter (BS) the light recombines and interferes. The change of the interference pattern is directly related to the phase shift of the light which is caused by displacement of the test mass mirror. A photodiode (PD) transforms the interference induced intensity fluctuations to an electrical signal (see fig. 1).

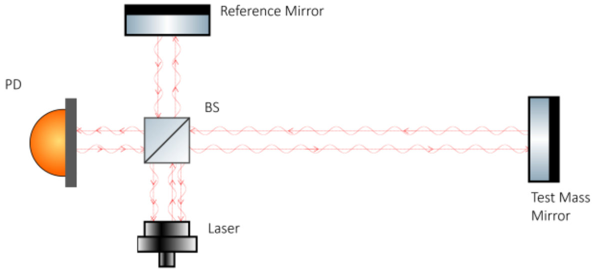

Fig. 1: *Schematic of a simple MI*

While this setup offers a compact and robust experimental architecture, the measurable range of motion for the test mass mirror is limited to a fraction of the laser's wavelength, which is, in the case of the oftentimes used Nd:YAG lasers, 1064 nm.

If a larger dynamic range is required, typically heterodyne interferometry is applied, e.g. in the case of GRACE-FO. However, this requires a more complex experimental setup.

The technique of Laser Frequency Modulation Interferometry (LFMI), employed in the here presented system, offers an auspicious alternative to this dilemma. In LFMI, the simple experimental setup of a homodyne laser interferometer can be used over a much larger (in principle: unlimited) dynamic range [6, 7]. Key to this technique is modulating the frequency of the used laser and employing a sophisticated readout algorithm. The complexity of the measurement is thereby shifted from the experimental to the digital readout domain. Recent advancements in the availability of powerful microcontrollers and field-programmable gate arrays (FPGAs) make this a viable approach.

3. First Application: The Laser Interferometer for Thermal Expansion measurements – LITE

We have developed a compact interferometric setup that applies the technique of LFMI to track thermally induced deformations of a new type of meta-material on-board of the SeRANIS satellite mission, which will be launched in 2026 [8].

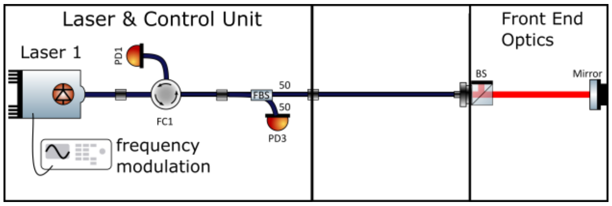

Fig. 2: *Conceptual design of the LITE system. The modulated laser light goes through a faraday circulator (FC) which sends the backwards directed light to the sensing PD (PD1). A fiber-beam-splitter (FBS) sends 50% of the light to a monitor PD (PD3) and 50% to the FEO.*

The LITE instrument can conceptually be split into two parts: passive and very robust optical front-end optics (FEO) and a laser and control unit (LCU), which contains all the required active opto-electronics and fiber-optic components. The front-end optics are connected to the laser box via optical fibers (see fig. 2).

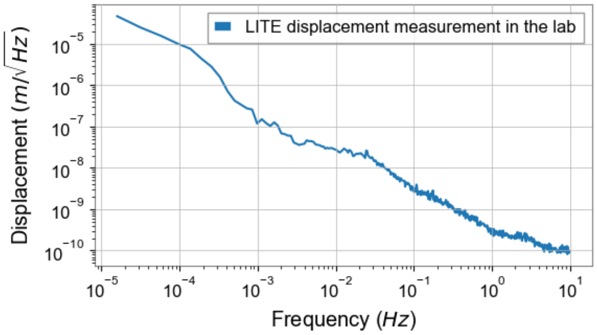

Fig 3: *LITE noise measurement. The 17h measurement is conducted in air in a regular lab environment.*

This implementation allows for the application of the measurement in very demanding environments, while keeping the sensitive, active components in a segregated and more protected area. Preliminary noise measurements give an upper limit of the LITE's sensitivity, shown in fig. 3. At 1 mHz the system measured a displacement of about 0.12 µm/√Hz, in this frequency band the measurement is highly likely dominated by environmental noise in the lab, such as thermal fluctuations.

4. Other fields of application

The robust and versatile LITE instrument can be applied in many different scenarios. Both, local measurements and those over large baseline separations are possible with only minor instrument reconfigurations. This would for example enable high-precision monitoring of structures, optical telescopes, unfolding or scaffolding mechanisms and many more.

Overall system weight	< 2.5 kg
FEO weight	< 0.3 kg
FEO envelope	< 5 cm x 5 cm x 5 cm
LCU envelope	< 23 cm x 7 cm x 33 cm

Tab 1: *LITE key properties. Some of these properties are subject to the intended environment.*

5. Current Status: Flight qualification

The LITE instrument is being developed using a New Space approach to streamline development time and minimise costs. Qualification testing is reduced to thermal vacuum and shock and vibration testing. In addition, extensive simulations of the overall system characteristics are carried out to ensure the intended functionality of the LITE instrument.

As interferometers are typically highly sensitive to angular misalignment, it is a challenge for such devices to withstand high thermal and mechanical vibration loads. The LITE passed both the vibration and thermal vacuum tests carried out in preparation for participation in the SeRANIS mission. The structure was tested in three directions under loads of up to 20 g in a frequency range from 5 Hz to 150 Hz with sinusoidal excitation, and under a load of 18.5 g_{rms} from 20 Hz to 2000 Hz with random vibration. Successful interferometric measurements were conducted in a thermal vacuum chamber during four 12-hour temperature cycles between -30°C and 90°C. The remaining qualification tests will be performed shortly.

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