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ABSOLUTE DISTANCE METROLOGY FOR LONG DISTANCES WITH DUAL FREQUENCY SWEEPING INTERFEROMETRY

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Abstract − Coherent absolute distance interferometry is one of the most interesting techniques for length metrology. In frequency sweeping interferometry (FSI), measurements are made without ambiguity, by using a synthetic wavelengths resulting from a frequency sweep. Accuracy is mainly dependent on the capability to measure the synthetic wavelength, using a Fabry-Perot interferometer (FP) to count resonances as frequency sweeps, and therefore the number of detected synthetic fringes. For large ranges, the number of fringes dominates performance, leading to a linear decrease of the accuracy with range. By increasing the size of the interferometer reference arm, and measuring both the distance and the reference arm independently, it is possible to maintain small distance high accuracy measurements, even for much larger range.

In the context of the ESA-PROBA3 mission (coronagraph and demonstration of metrology for free-flying formation), we implemented a FSI sensor composed of a mode-hop free frequency sweep external cavity diode laser, a high finesse FP (to measure accurately the frequency sweep range) and a dual measurement system to enable the measurements at 150 m with an accuracy at the tens of micrometer level.

In this paper we describe the implementation of the prototype and present the first results obtained for a long range measurement.

Keywords, absolute distance measurement, interferometry, tunable lasers

1. INTRODUCTION

Absolute distance metrology is needed for a wide gamut of applications with different ranges and resolutions. Space missions requiring independent satellites working cooperatively demand several levels of metrology to keep the formation coherent and to enable guidance and navigation of the complete formation [1].

Coherent interferometric absolute distance metrology is one of the most interesting techniques for length metrology. Without movement, measurements are made without ambiguity, using either one or several synthetic wavelengths resulting from the beating of two or more wavelengths (multiple wavelength interferometry [2]) or, in the case of Frequency Sweeping Interferometry [3-5] (FSI), from a continuous frequency sweep.

FSI based sensors are relatively simple devices that fulfil an important role in dimensional metrology. Their parameterisation flexibility allows various configurations, which is a key issue for space applications.

The generation of synthetic wavelength in FSI is based on sweeping the laser frequency within a given sweep range. The technique is not new [6], but it was not effectively exploited until the development of tunable lasers and the emergence of External Cavity Diode Lasers (ECDL). The measurement is performed while frequency sweeps, detection electronics counts synthetic wavelength maxima (temporal "synthetic fringes") without ambiguity. FSI does not require stabilized laser sources and relies only on a tunable laser and a frequency sweep range measurement subsystem based, in our case, on a Fabry-Pérot interferometer (FP).

In FSI, the measurement uncertainty increases with the distance, as consequence of the propagation of the uncertainty of the synthetic wavelength measurement (directly related to the FP performance) [5]. For large ranges this increase in uncertainty is one of the major drawbacks of the technique. To overcome this problem, the measurement process for longer ranges can be reduced to the close range case, by limiting the OPD in the interferometer. This can be achieved by increasing the reference arm with a long reference fibre and introducing the concept of the dual FSI mode, where an ancillary interferometer is used to measure (calibrate) continuously the fibre length. This approach was already presented and the expected performances were simulated based on the results of the single mode FSI prototype [7].

2. FSI FUNDAMENTALS

FSI is based on a tunable laser and a frequency sweep range measurement subsystem based on a FP. The synthetic wavelength (Λ) is inversely proportional to the frequency sweep range (Δν) and is given by:

$$\Lambda = \frac{c}{\Delta\nu} \quad (1)$$

where c is the speed of light. The sweep range measurement is obtained by multiplying the FP free spectral range (FSR) by the number of resonances detected while the laser frequency sweeps. In this case, the frequency sweep range is given by:

$$\Delta\nu = r \cdot FSR \quad (2)$$

where r is the number of detected free spectral ranges detected (number of resonances minus one).

From (1) and (2) we obtain:

$$\Lambda = \frac{c}{r \cdot FSR} \quad (3)$$

FSI measures the absolute value of the OPD between the two arms of a Michelson interferometer (Fig. 1). While the frequency sweeps, detection electronics count the number of fringe cycles including the remainder fractional part (fringe phase), from the beginning to the end of the sweep without ambiguity. The measured length L (half OPD) is given by:

$$L = \frac{N}{2} \cdot \frac{\Lambda}{n} = \frac{N}{2} \cdot \frac{c}{r \cdot FSR \cdot n} \quad (4)$$

where N is the number of synthetic fringes and n the refractive index of the propagation medium.

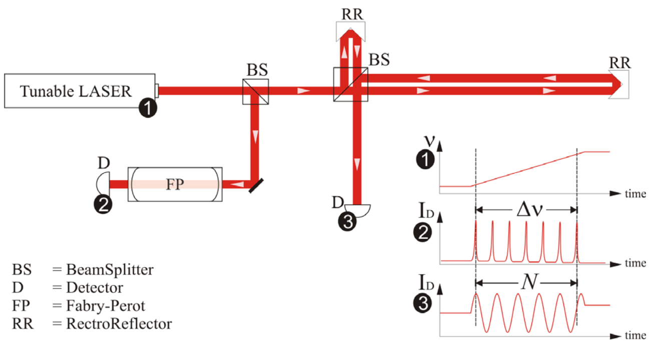

Fig. 1. FSI setup. While the laser sweeps the frequency, the interferometer detector acquires the fringes and a FP measures the sweep range by counting the resonances of the cavity.

2.1. FSI Performances

Sensor performance does not depend on the stability of the absolute value of the frequency but on the uncertainty in the frequency sweep range: therefore there is no need to calibrate the system for absolute frequencies.

The final uncertainty of the system has two major contributors:

- the uncertainty in the measured number (N) of synthetic fringes (the synthetic fringe interpolation uncertainty);
- the uncertainty in the synthetic wavelength value , depending on:
  - uncertainties in the FSR value and
  - determination of the number (r) of detected FSR.

The uncertainty component in N is influenced only by the fringe phase uncertainty because the integer number of fringes can be considered to be measured exactly. This uncertainty only on the synthetic wavelength, and is therefore the dominant component for small distances.

The two following components, in r and in FSR, determine the uncertainty in the sweep range measurement, and are related to the FP performances.

The value of δr is dependent on FP finesse and on the capability of the signal processing to localize resonance maxima. In order to locate resonance maxima in time unambiguously, the maxima of the signal generated by the FP should be clearly discriminated. The higher the finesse, the easier it is to locate accurately each resonance maxima in time and, therefore, reduce derived sensor errors.

The value of δFSR is determined by the FP calibration and stability. The stability depends on length and optical variations induced by temperature and misalignments. For high resolution (low δFSR), thermal stabilization and low-thermal expansion materials like Zerodur may be required.

In contrast to the uncertainty in the synthetic fringe interpolation, the uncertainty components related to the sweep range measurement increase as range increases. These components become dominant for large distances.

The component related to the uncertainty in the refractive index n also scales with the measured distance but in space this factor in null, for test purposes and using standard laboratory environmental control, it can be easily considered negligible.

3. PROTOTYPE IMPLEMENTATION

The prototype was designed to enable measurements for distances around 150 m, in view of the European Space Agency (ESA) PROBA3 mission (coronagraph and demonstration of metrology for free-flying formation). This setup is the follow up of an earlier prototype (single mode FSI) implemented to measure distances up to 10 m [5].

3.1. Dual mode prototype design and implementation

The requirements for the PROBA3 mission absolute distance sensor, imply the measurement at a 10 Hz rate with an uncertainty smaller than 64 µm at 2σ, for a distance up to 150 m.

For such OPD, in a traditional FSI implementation (single interferometer mode), the uncertainty is dominated by the two uncertainty components related to the sweep range measurement. In order to achieve the required uncertainty one would have to increase the FP stability (thermal and mechanical) and improve the calibration and resonance detection characteristics (i.e. using Pound-Drever-Hall technique to lock the laser into FP resonances). As a consequence, the expected impact on sensor complexity would be critical for the implementation of the FSI technique in view of a space application.

The approach we have already proposed [7] and demonstrate in this paper, use two interferometers in a dual FSI scheme. Adding a long reference fibre in the reference arm, the measured OPD is reduced to the real distance minus half fibre optical path length. Using an additional interferometer, the fibre is calibrated with the same accuracy but with lower requirements. This assumes that the fibre length s constant and therefore the calibration will be the result of averaging for a certain time frame (uncertainty reduced by a factor of √N).

For the dual FSI prototype, an air spaced confocal etalon was selected and manufactured under precise specifications. This FP has a FSR of 1.5 GHz, corresponding to a 50 mm spacer made in Zerodur. The cavity is thermally controlled in order to maintain the FSR stability.

The tunable laser is a fiber pigtailed ECDL capable of a mode-hop-free sweep range of 70 GHz (TBL-7000 from NewFocus in a Littman-Metcalf mounting at 1064 nm).

The dual FSI sensor comprises three subunits:

- Laser & Detection – contains the ECDL and the detectors for the two interferometers and the FP.
- FSI Head – FP and FSI interferometers beam splitter.
- Optical Head – forming the interferometer arms.

The three units are connected with FC/APC polarization maintaining fibres.

Fig. 2. shows a picture of the Dual mode FSI sensor breadboard where is possible to identify the FSI Head, the Optical Head, the Laser & Detection unit and the long reference fibre housing.

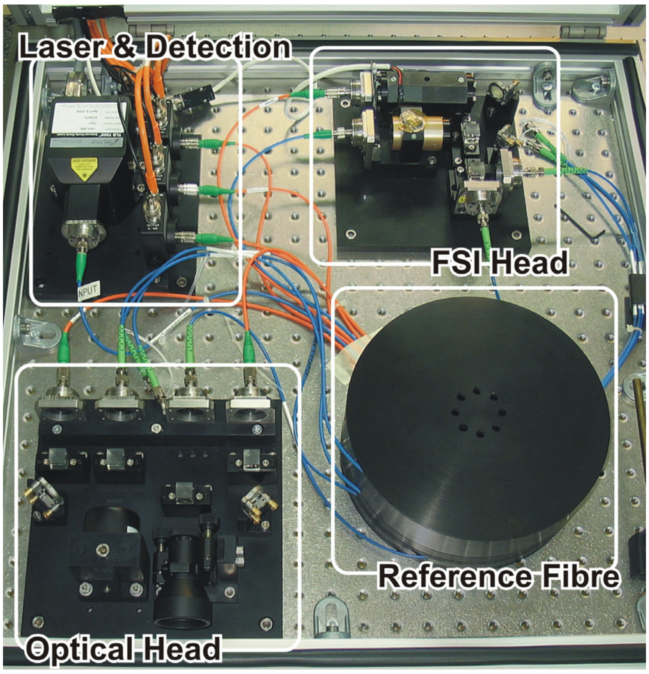

Fig. 2. Dual mode FSI sensor breadboard.

In the Laser & Detection unit, all components are fibre coupled, allowing to position them independently of the other two units. The fibres selected are polarisation maintaining (PM) with FC/APC connectors (low return loss) that will prevent the back reflections to the laser. As the ECDLaser behaviour is highly sensitive to feedback, the FSI Head also includes a Faraday Isolator to prevent any residual back reflection into the laser (the need for this isolator will be determined during the next system tests). The housing of the reference fibre ensures mechanical stability and increases (by inertia) the short term thermal stability.

The measurement interferometer detects the OPD between the OPL of twice the distance in measurement (due to the round trip) and the OPL added by the reference fibre, as it is shown in Fig. 3. (top) - OPL of F_{REF} minus the OPL of F_{MEAS}. The position of the reference retro-reflector (RR_{REF}) determines the location of the point from where the absolute measurement is referenced. The reference interferometer, shown in Fig. 3. (bottom), will measure exactly the OPL added by the reference fibre.

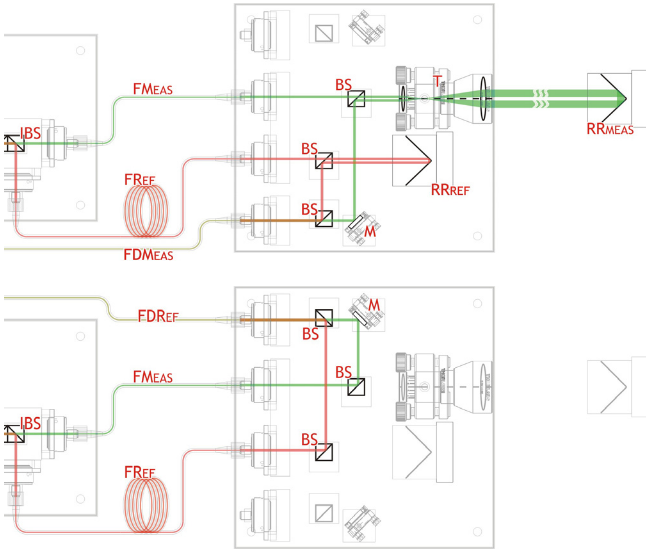

Fig. 3. The dual FSI measurement (top) and reference (bottom) Interferometer.

Fig. 4. presents an example of the acquired signals for the case of a small OPD of 1 m (top) and for the long reference fibre (middle). On the bottom of Fig.4. one can see the common FP resonances.

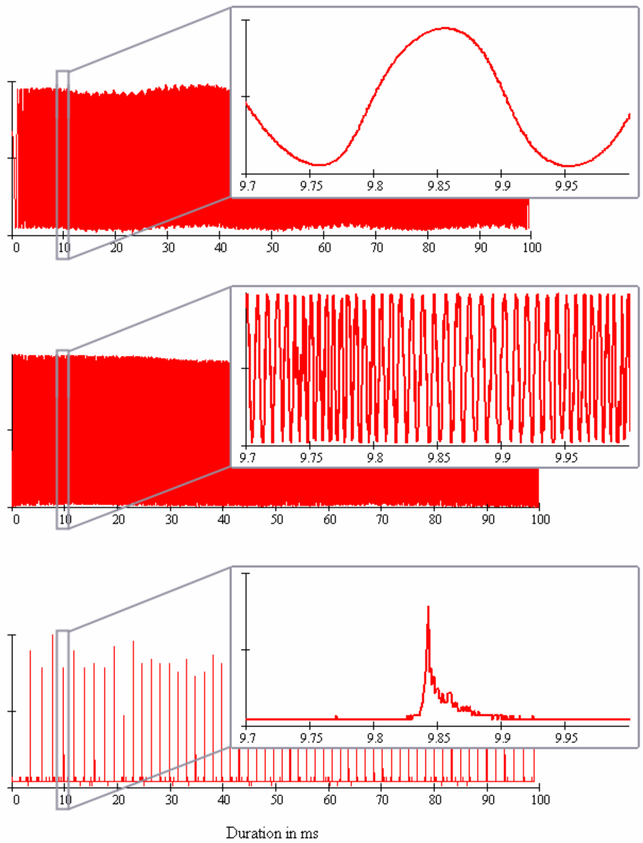

Fig. 4 Typical FSI interferometer and FP signals for a small OPD of 1 m (top) and for the long reference fibre (middle) - 71 m of fused silica, corresponding to an OPL of approximately 100 m – and the resonances common to both (bottom).

3.4. Dual mode performance results

In order to evaluate sensor performance, a set of measurement tests were performed. In this dual FSI approach, the final uncertainty is the sum of three components:

- uncertainty in the measurement of the small OPD (twice the absolute distance minus Reference Fibre length);
- calibration uncertainty of the Reference Fibre OPL;
- change in fibre OPL due to thermal variation.

Besides the measurement dispersion, there are other uncertainty components that can influence the final measurement accuracy. The resolution in the fringe phase and resonance position measurements is currently much smaller than the measurement dispersion, and thus its contribution is not significant. The uncertainty in the calibration of the FP FSR is the most important one for large distance measurements in a single FSI configuration but, in the dual approach, it is possible to achieve a very small contribution considering the value of the dispersion component. We will focus this issue later on this text.

To determine the uncertainty in the measurement of the small OPD, a small reference fibre of 1 m (equal to the measurement fibre) was used, in order to mimic in an optical table the equivalent condition of a larger measurement distance with a large reference fibre. Measurements were made up to 10 m., using a frequency sweep range around 70 GHz, corresponding to a synthetic wavelength of approximately 4 millimetres. Fig. 5 shows the results of the sensor performances for the measurement of the small OPD component, where each point corresponds to the 2σ dispersion (95% confidence interval) for 300 measurements.

As shown in the same figure, this contribution is lower than 10 µm for the first meters, reaching 30 µm for a 10 m absolute distance. It must be noted that the 10 m distance is currently being implemented using a fibre as propagation path (which is more sensitive to thermal variations than air).

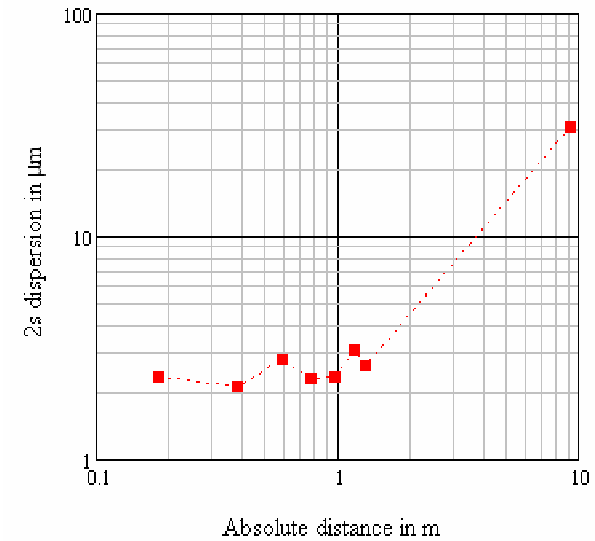

Fig. 5. Uncertainty in the measurement of the small OPD (in µm)

To evaluate the component related with the calibration of the Reference Fibre, we used a 71 m fused silica fibre, corresponding to an OPL of approximately 103 m. 2500 sequential measurements were performed, each with a duration of 100 ms.

For this measurement set, we had to reduce the frequency sweep range down to 40 GHz, about half of the laser capability, in order to reduce the number of detected fringes. This limitation is mainly due to the maximum sampling frequency allowed by the signal acquisition board (5×10^6 samples per second) since several points per fringe are needed to enable a correct fringe processing, covering also a correct sampling rate that copes with any fringe period change due to the frequency instabilities of the laser.

In order to remove outliers caused by the effect of laser instabilities (specially evident for large ranges), every value that lied outside the 3σ of the previous 10 measurement was discarded. Fig.6 shows the histograms of the measurement with and without outliers. As it can be seen, although with this procedure implied discarding approximately 40% of the measurements, the considered measurements show the expected normal distribution.

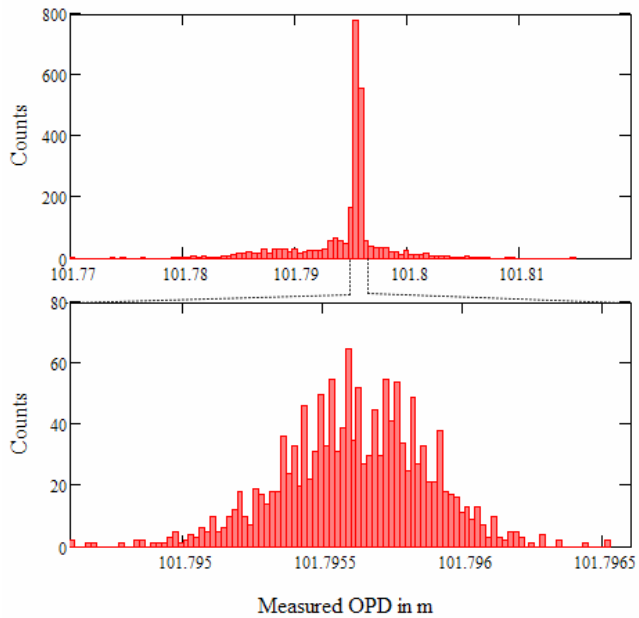

Fig. 6. Histograms of the long reference fibre measurement with (top) and without the outliers (bottom).

After the removing outliers, the measurement dispersion at 2σ was 520 µm for a mean value of 101 795 618 µm, considering a total of 1500 measurement.

The final uncertainty in the fibre OPL will be a function of the number of measurements that contribute to the calculated average length. The longer the calibration duration, the higher will be the decrease (by √N) in the uncertainty value resulting from the measurement dispersion. However, as the OPL of the fibre changes with temperature, the calibration period is limited by the thermal stability of the fibre. In order to apply the averaging processing, the change caused by temperature must be, at least, one order of magnitude lower than the measurement dispersion.

Fig. 7. Shows the decrease in the uncertainty resulting from the process of averaging the measurements (the outliers were not considered).

The length change in fibre OPL due to thermal variation not only limits the calibration duration but also affect directly the final measurement uncertainty. During the measurements, the temperature in the optical table was monitored to evaluate the thermal stability. During the 250 s (2500 measurements of 100ms) the temperature was 21.734±0.007 ºC, leading to an OPL variation in the reference fibre of ±6 µm (considering the thermo-optic coefficient of fused silica of 9×10^{-6} $ºC^{-1}$), which is 2 orders of magnitude smaller than the dispersion (at 2σ).

It must be noted that this is an overestimation as the temperature variation inside the fibre core is expectedly smaller due to thermal inertia introduced by the fibre outer jacket and the fibre housing. It is thus acceptable to consider a calibration time of 250 s, leading to a contribution to the overall uncertainty smaller than 10 µm (Fig. 7). In fact, if necessary, the calibration duration can even be larger: as an example, while air conditioning of our lab was off (to avoid vibration) the variation was smaller than ±0.014 ºC. An active thermal control in the fibre housing would make this contribution negligible.

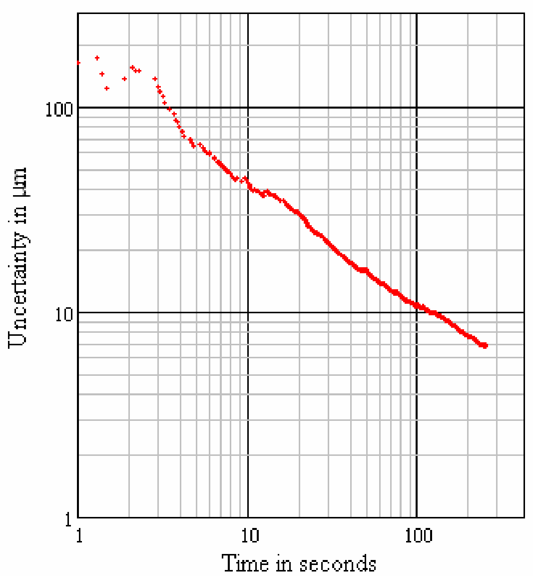

Fig. 7. Decrease in the uncertainty resulting from the process of averaging the measurements of the OPL of the long reference fibre.

As already mentioned, it is acceptable to consider a calibration period of 240 s. Thus, the final overall uncertainty will be the sum of the uncertainty in the measurement of the small OPD with half of the contribution of the long reference fibre calibration (to the absolute distance will be added half the reference fibre OPD). Fig.8. shows the uncertainty for the current dual FSI configuration, using a 71 m fused silica reference fibre, which allows a measurement range from 50 m to 60 m with accuracy smaller than 40 µm.

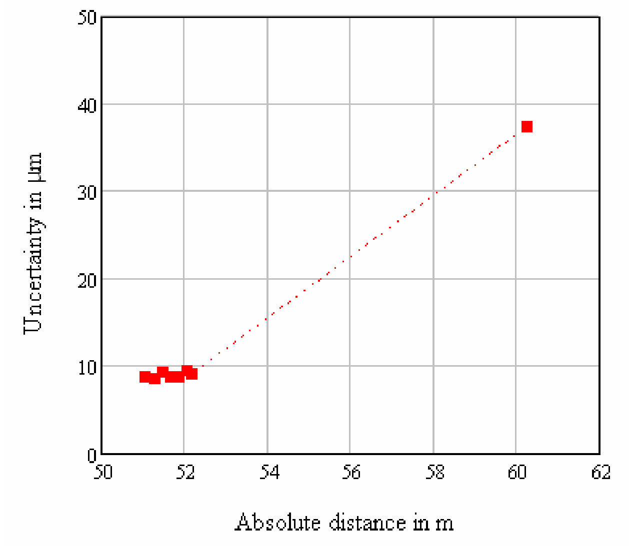

Fig. 8. Overall uncertainty for a 71 m fused silica reference fibre, considering a 4 minute calibration time.

The extension to the final 150 m, implies only the use of a longer reference fibre (200 m of fused silica). Although the length will triple, it will be possible to maintain the same level of accuracy, complying with the required uncertainty below the 62 µm; if one of the following conditions are met:

- increase the acquisition sampling rate in order to use the full frequency sweep range capability of the laser (currently only half);
- increase the calibration period using, and if necessary, implement active thermal control in the fibre housing;

Comparing with the single FSI approach, the long distance measurement using the same uncertainty parameters would lead to an uncertainty of, at least, two orders of magnitude worst than the current dual FSI performance.

4. CONCLUSIONS

This work shows that it is possible to achieve high accuracy at large distances using a dual FSI sensor approach, maintaining the reduced complexity inherent to FSI technique, which is a mandatory condition for space applications.

The first tests demonstrated already that the requirements that drive the design can be easily achievable. They also showed that there are still several path to improve performance, especially in what concerns the reference fibre calibration. The thermal active control of the fibre housing is an issue to be considered in future developments (note that only is needed relative stability).

The next steps will include the implementation of a controlled delay line to enable a better characterisation of the sensor at large distances, and the improvement of the signal processing algorithms, taking into account all the new features that the long reference fibre measurement introduced.

Frequency sweeping interferometry, and in particular the dual sensor concept using a long reference fibre, is can therefore be considered as an proven method for absolute distance metrology of large distances, especially when complexity and robustness are critical drivers, as is the for space metrology applications.

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