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THE ILIADE PROJECT: TELEMETRY WITH NANOMETER PRECISION FOR FORMATION FLIGHT WITH FEMTOSECOND LASER

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Abstract. We discuss high accuracy long distance measurement systems for formation flight space projects. We show how the use of femtosecond lasers may help for more precise performances, possibly leading to a resolution on the nanometer scale.

1 Introduction

Two or more spacecrafts can be in a formation flight configuration if one can monitor the acceleration of each spacecraft or if one can measure the distance between them. The signals delivered by accelerometers or distance measurement systems can then be used in feedback loops as error signals, using thrusters to correct from deviations. If the signal of on board accelerometers is kept to zero, then the spacecraft can be ensured to follow geodetics. Moreover, with a system to measure the distance between the spacecrafts, one can garantee a zero relative speed.

A constant distance between spacecrafts is necessary in projects like DARWIN (ESA 2005) or XEUS (ESA 2005). DARWIN is long base interferometric hyper-telescope, with a base of a few 100 meters. XEUS is an X-ray telescope, where the focusing lens is at a distance of 30 m from the focus sensor. The combination of an inertial system and a distance measurement system is necessary in fundamental physics space projects where one searches deviations from flat space-time, for example LISA (ESA 2000), Pioneer Explorer (Dittus et al. 2005), as well as in geodesy experiments (ESA 2005). LISA is a 5 million km arm interferometer aiming at the detection of gravitational waves. Pioneer Explorer is a spacecraft aiming at assessing the long range acceleration anomaly in the solar gravitational field discovered by the two Pioneer spacecraft (Anderson 2002).

Current systems for length metrology are using RF technology whose accuracy is limited to about 10 microns at best by speckle noise due to the uneven surface on which the diverging radio wave is reflecting. This performance is not sufficient for the above mentioned missions.

In this paper we discuss some properties of distance measurement systems. The length, L, is usually derived from a frequency measurement, ν, with the speed of light, c: $L = c/\nu$. Usually the relative length precision requirements are defined in a given frequency band, and translate into equal requirements on the reference clock relative precision.

We first compare measurement systems that use continuous wave lasers against ones using femtosecond lasers. We show that a fs laser can eliminate some noise sources, such as the common cyclic error.

2 Continuous wave laser versus femtosecond laser

The principle of a length measurement system with a continuous wave laser is to use at least two different frequencies, simultaneously or successively.

The measurement is often performed using a laser beam as a carrier of an RF wavelength, defined by an RF clock. This keeps some useful properties of light, for example the small beam divergence. This principle is illustrated in fig. 1: the laser is amplitude modulated, split into two parts, and one part is sent to a reflector on a remote spacecraft. The relative phase of local and returned beams is measured on a mixer. A first measurement

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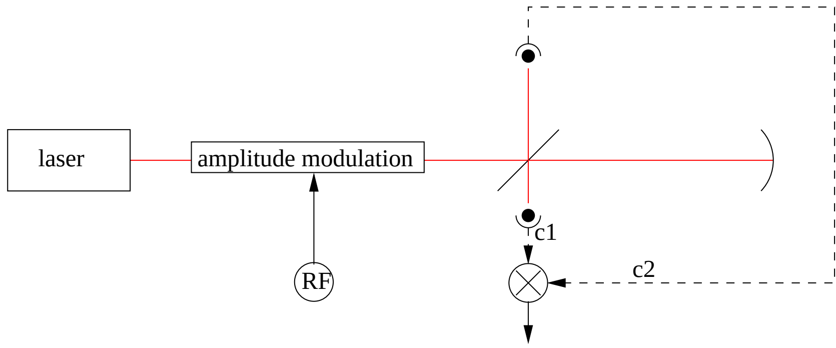

Fig. 1. Principle of length measurement with a CW laser.

ϕ_1 of the phase is done for a modulating frequency f_1, and a second one of ϕ_2 for a modulating frequency f_2. Then the length is reconstructed with

$$L = \frac{c(\phi_1 - \phi_2)}{4\pi(f_2 - f_1)} \quad . \tag{2.1}$$

In this kind of experiment, the main error is often the cyclic error, corresponding to non linearities on reading the phase ϕ in the interval $0 - 2\pi$. Another one would be the variation of the delay between cables c1 and c2.

The precision of the phase measurement can be improved by having a laser modulated in a such way that it delivers femto-second scale pulses. Ye (2004) proposes an experiment where the phase comparison is performed optically rather than electrically, thus improving the possible resolution, see fig. 2. The laser source, beam splitter and reference arm mirror are on-board of a spacecraft, while the measurement arm consists of the beam splitter and a remote mirror. A first rough measurement with a mm precision is achieved with the measurement

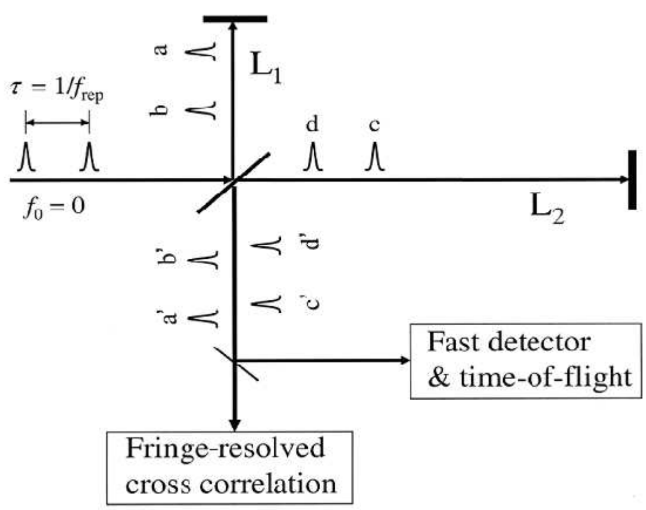

Fig. 2. Proposal by J. Ye for length measurement with a fs laser.

of the delay between pulses a' and c' (fig. 2). The correlation of two pulses gives a micrometer precision; then the phase difference in equation 2.1 is always a multiple of 2π, eliminating the cyclic phase error.

Provided that all pulses have the same shape, a fringe resolved cross-correlation is made possible. This implies a control of the stability of the optical phase, in addition to the stability of the repetition frequency $f_{\rm rep}$. As illustrated in fig. 3, in the frequency domain, the optical frequency of any of the comb teeth is a multiple of the repetition frequency.

Therefore one has to choose two of the three following stabilization techniques:

- a) lock of one tooth of the comb on an optical clock (Fabry-Perot cavity or an atomic transition);

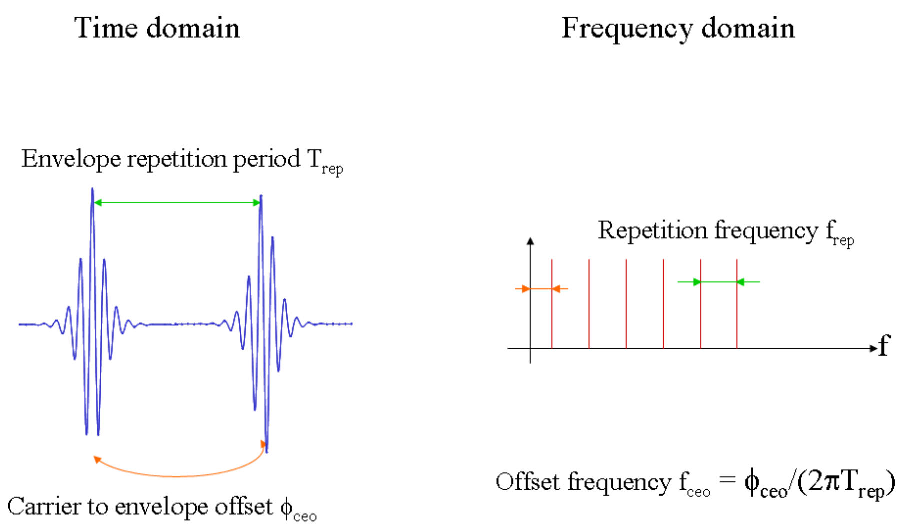

Fig. 3. Two parameters are necessary to describe the mode-locked emission of a femtosecond laser: repetition frequency and carrier-to-envelope offset frequency.

- b) lock of the repetition rate on a RF clock (quartz oscillator or atomic clock);
- c) lock of the carrier-to-envelope phase offset to zero.

One should avoid choosing a) and b) simulaneously, as the two clock references will have different long term drifts. The clock technology is chosen given the requirements for the relative precision and the requirements on the timescale for the measurement.

A usual way to measure the carrier to envelope offset frequency is the so-called "f-2f" technique, illustrated on fig 4 (Udem 2002).

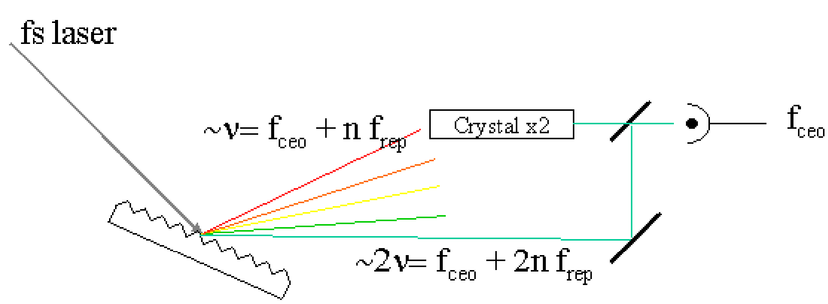

Fig. 4. Measurement of the carrier-to-envelope offset frequency

The use of fs laser for length metrology in air has been in use for several years in the Japanese Institute of Metrology (Minoshima 2000; Minoshima 2003), leading to accuracies at one micrometer. The experiment in vacuum may help to improve the noise budget, but this has to our knowledge not yet been experimentally demonstrated. A two color laser system, using both synthetic wavelength and interferometry will possibly demonstrate the nanometer accuracy (Dubovitsky 2003, 2005)

3 The "Iliade" project

At the Observatoire de la Côte d'Azur we are designing a setup on the 10 m scale that will combine three levels of measurement accuracy. One, two or three accuracy levels could be used, without considerable changes of the setup, depending on the mission requirements. The first level includes a time of flight measurement, with a sub-mm accuracy. It levers the ambiguity of the following levels that are measuring phases. The second level, with a sub-micrometer resolution, uses the repetition rate wavelength as a synthetic wavelength. This fills the gap to level three. The third level is using an interferometric phase measurement, with a nanometer resolution ($\lambda/1000$).

The goals of the project are:

- to check the stability of time of flight measurement, in order to allow the junction with the second level;
- to check the frequency noise spectrum of the laser sources in order to allow the third level;
- to realize a stabilized high repetition rate laser source;
- to validate the chronometry/interferometry combination, and evaluate the performances of the experiment.

We hope to demonstrate experimentally an accuracy on the nanometer scale, and show that this result can be extended to the 100 m scale of the space-based applications.

References

Anderson, J.D. et al. 2002, Phys. Rev. D 65, 082004.

Dittus, H. et al. 2005, arXiv:gr-qc/0506139

Dubovitsky, S. et al. 2005, Lasers and Electro-optics, CLEO/Pacific Rim, IEEE, 946

European Space Agency 2005, SCI-A/2005/301/DARWIN/DMS/LdA

European Space Agency 2005, SCI-A/2005/139/DL

European Space Agency 2000, ESTEC/RD7-5070-Lisa-Final-Report.pdf

European Space Agency 2005, ESTEC/RD6-5070-Exec-Summary.pdf

Minoshima, K., Matsumoto, H., 2000, Appl. Opt. 39, 5512

Minoshima, K. et al. 2003, Ultrafast Phenomena XIII, Vol. 71

Lay, O.P. et al. 2003, Opt. Let. 28, 890

Udem, Th. et al. 2002, Nature 416, 233

Ye, J. 2004, Opt. Let. 29, 1153