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A COMPACT OPTICAL 5 DEGREES OF FREEDOM ATTITUDE SENSOR FOR SPACE APPLICATIONS

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INTRODUCTION

A typical issue of modern space missions is the measurement of the relative attitude (orientation and position in space) of one part of the satellite with respect to the reference frame (main body) of the satellite or the relative attitude of two parts of the same satellite or even two or more satellites flying in formation. To name but a few applications of attitude transfer systems (ATS): distributed sensing elements like interferometric systems [1], co-aligned instruments [2], instruments with remote detectors (such as large or deployable instruments [3]) or multiple spacecraft (formation flying). Another typical example of remote detector is a magnetometer that has to be located far away from the influence of the satellite electronics but whose relative attitude with respect to the satellite has to be monitored and/or controlled.
Here we describe the experimental results achieved with a prototype of a new compact optical sensor, capable of measuring 3 linear coordinates and 2 rotations (pitch and yaw, but it is extendable also to roll), based on a multi-wavelengths laser system and compact spatial qualified position sensing devices. The manufactured prototype has demonstrated to be able to provide sub-arcsecond and micrometers sensitivity in all directions.

EXPERIMENTAL

At INRIM, in collaboration with Thales Alenia Space, we have developed a compact and lightweight sensor designed to be used on synthetic aperture radar (SAR) satellites where the absolute distance and the orientation between the two antennas must be accurately known. The sensor is formed by an active head and a passive target placed in the remote site to be controlled. The set-up is presented in Fig. 1 whereas the picture of the active head is presented in Fig. 2. The active head is based on three independent laser measurement systems for the 2D lateral translations, pitch and jaw (2D angular translation) and the longitudinal translation. The lasers have different wavelengths allowing separation and recombination of the measurement paths. The longitudinal distance sensor is based on a synthetic wavelength interferometer (SWI), capable of measuring the absolute distance between an active optical head and the passive target with an uncertainty of few micrometers. The passive target consists of a dichroic mirror coupled to a corner cube retroreflector. Accuracy of few micrometers and sub-arcsecond resolution have been achieved at distances up to 10 m. The measurement bandwidth exceeds 100 Hz. We will see in the following sections some details of the different metrologies.

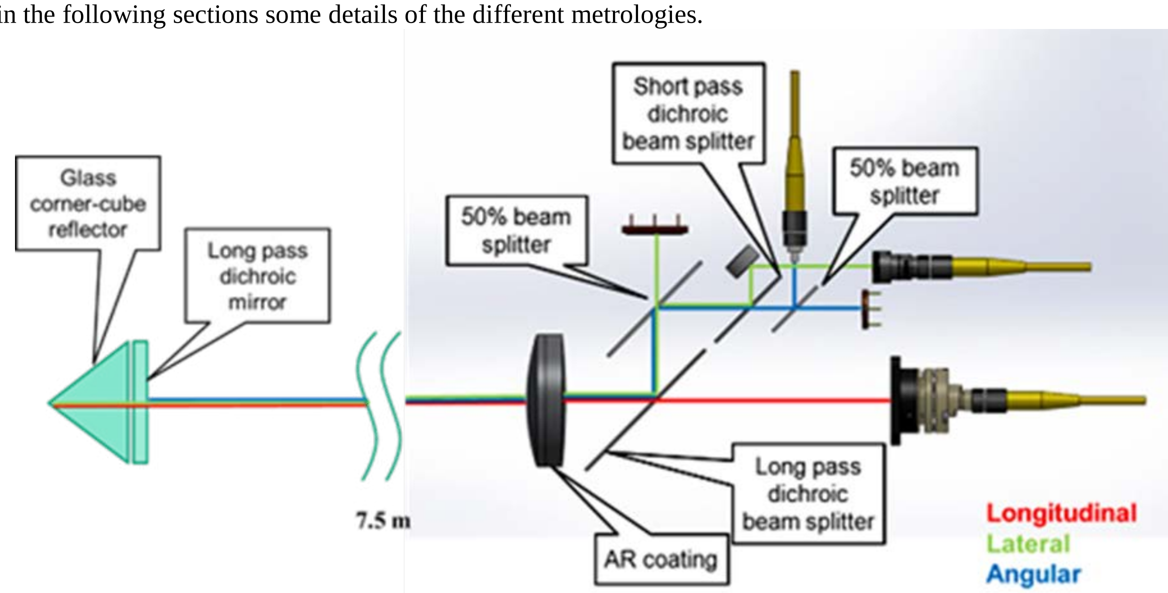

Fig. 1. Optical scheme of the attitude sensor. It is formed by the optical head (right) and the passive target (left). The three laser paths are represented in red, green and blue respectively for the 1542, 850 and 780 nm wavelengths

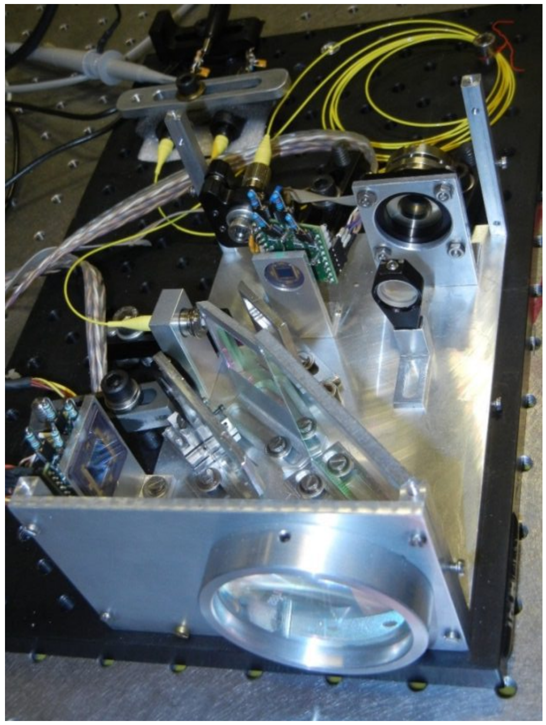

Fig. 2. Picture of the COATS prototype (box opened)

A.2D angular metrology

The angular metrology is based on a 780 nm laser source which is collimated by the main output lens and sent to the passive target (in Fig. 1 the laser path is in blue). Here it is reflected by the dichroic mirror behaving as a flat mirror at 780 nm. The reflected beam will enter the lens of COATS with an angle 2α with respect to the main optical axis where α is the rotation of the passive target to be measured. The laser is eventually focussed on a position sensitive detector (PSD) placed in the focal plane of the lens. The position of the focussed spot on the detector surface is proportional to the tilt angle in two orthogonal directions.

B. 2D lateral metrology

The lateral metrology is based on a 850 nm laser which is collimated by the lens at the output of the fiber in combination with the output lens of COATS (in Fig. 1 the laser path is in green). The result is a collimated laser beam with few millimetres diameter. The beam passes through the dichroic mirror of the passive target and hits the corner cube reflector. The latter induces a displacement of the reflected beam equal to 2x where x is the distance of the corner cube vertex from the main optical axis. The beam is eventually sent to a position sensitive detector placed in a position between the main lens and the focal plane of the lens. The position of the spot on the detector surface is proportional to the lateral displacement in two orthogonal directions.

C. Longitudinal metrology

The set-up of the longitudinal metrology is presented in Figure 3 where two extended cavity diode lasers (ECDL) at 1542 nm are directly coupled to polarization maintaining (PM) fibers. The lasers have a narrow linewidth of some kilohertz allowing long coherence length for long range distance measurement. The lasing frequency of the two lasers (ν1 and ν2) can be tuned continuously without mode jumps by means of the laser temperature control with a frequency difference ranging from zero to about 40 GHz. A fast modulation input is used to lock with a PLL the laser frequency difference (synthetic frequency), $\Delta\nu = \nu2 - \nu1$, to a frequency synthesizer referenced to the local realization of the SI second. In this way the distance measurement is traceable to the SI metre. The superposition of the two radiations is sent to two AOMs, driven by two different frequencies f2 and f1 in order to implement the superheterodyne detection: the displacement information is contained in the phase of the synthetic frequency $\Delta\nu$ that is too high to be conditioned and acquired by the electronics; the super-heterodyne detection scheme consists in down-converting the synthetic frequency to the lower frequency $f2 - f1$, at the kilohertz level, maintaining the same phase information at the synthetic frequency. The launched beam is expanded to a diameter of about 2 cm, by means of a telescope, corresponding to a Rayleigh distance of about 400 m. After having travelled a distance *L* the beam is reflected by a corner cube and passing through the same optical components is re-coupled into the fiber and sent to the PIN detector through a circulator. On the detector the radiation is superposed with the radiations with frequency $\nu1 + f1$ and $\nu2 + f2$ coming from the two AOMs. An optical switch has been added to have a local zero in the relative distance measurement.

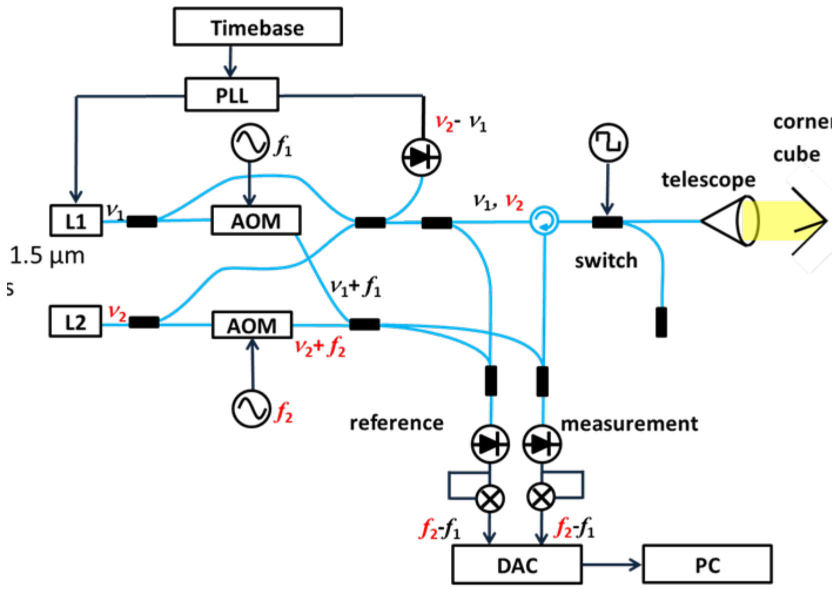

Fig. 3. Set-up for the longitudinal metrology. The synthetic wave is generated by mixing two extended cavity lasers in the PM fibers. A superheterodyne detection system is used to measure the phase of the synthetic wave at the fixed frequency of 120 kHz.

We present in Fig 4 the power spectral density (PSD) of the distance fluctuations for different distances of the retroreflector corner cube (CC). The noise limit is measured by sending directly the radiation to the detector, short-circuiting the circulator and the launching in air. The other PSDs are measured for different positions of the corner cube. It is possible to see that the noise in distance measurements is limited by the air turbulence, beam wandering and by vibration of the set-up that causes amplitude fluctuation.

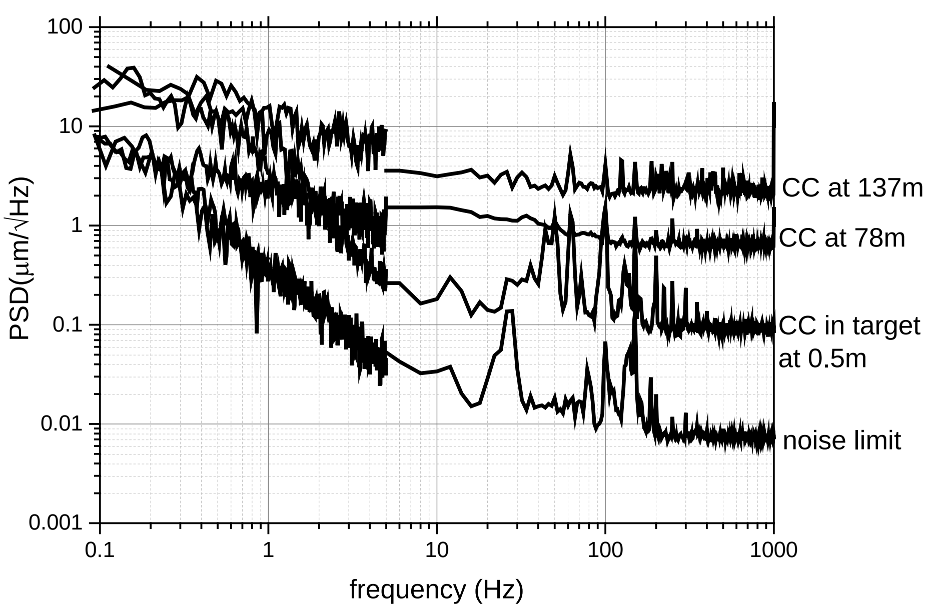

Fig. 4. Power spectral density of the longitudinal distance fluctuation for different positions pf the retroreflector. The noise limit is obtained by short-circuiting the circulator and the launching in air.

To demonstrate the applicability of the longitudinal distance scheme also in other situations, beyond the 5 degrees of freedom attitude sensor, we positioned the corner cube at a distance of about 500 m in an underground corridor and we measured the distance fluctuation, presented in Fig 5. The drift is due to the change of the temperature of air: over a distance of 500 m a change of 100 µm is due to a change of 0.2 °C. The fast fluctuations are due to turbulence caused the passage of personnel close the laser beam.

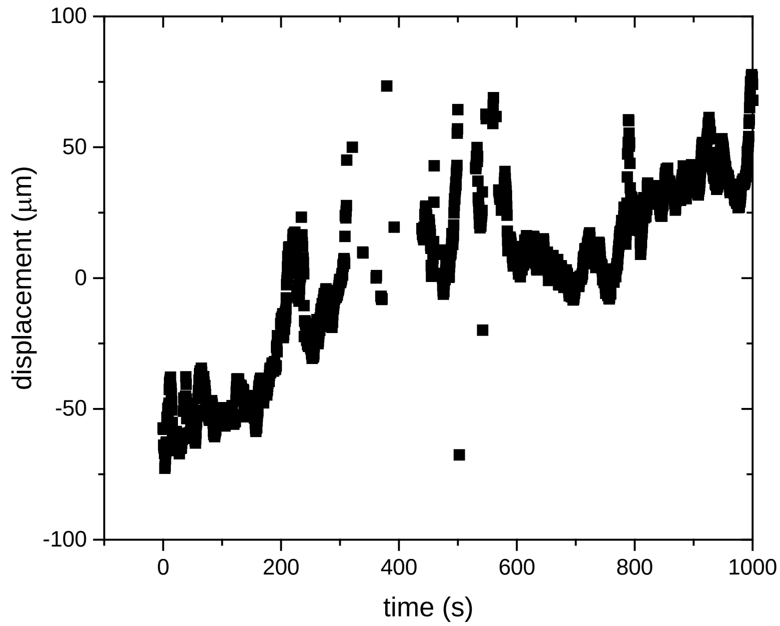

Fig. **5**. Time series of the distance fluctuation measured over a total path of 500m in underground corridor. The distance drift is caused by the drift in air temperature. The fast fluctuations are caused by turbulence in air.

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