7.1.3 Optical Bench

Each Optical Bench (OB) consists of a 350x200x40 mm baseplate made of ULE™ and of the optical elements (mounted on this baseplate) which form part of the interferometer for the detection of the gravitational waves and constitutes the reference resonant cavity for the stabilisation of the laser frequency.

The central part of the OB hosts the Inertial Sensor head containing the proof mass, which defines the reference point for the measurement of the distance variation between the S/C by means of the laser interferometers.

The photodiodes for the detection of the signals produced by the interferometer, the resonant cavity, the beat of the two local lasers, the laser amplitude variation, and the CCD for the initial acquisition of the incoming laser beam are also accommodated on the OB.

The general requirements applicable to the OB are:

- maximisation of the dimensional stability of the optical assembly and minimisation of the thermal power dissipated on the OB so that:
  - the stability frequency of the laser locked to the reference cavity is maximised (Pre-phase A target $\delta\nu \leq 30$ Hz/√Hz in the frequency range from 10^{-3} Hz to 10^{-1} Hz [1];
  - the differential variation of the optical path length (OPL) between the local and in the incoming laser beams and between the two local laser beams do not exceed 5 pm/√Hz in the frequency range from 10^{-3} Hz to 10^{-1} Hz [1];
- maximisation of the power transmitted to the other satellites and minimisation of the wavefront error (WFE) of the outgoing beam (overall allocation = 53 nm rms) and of the incoming beam (overall allocation = 106 nm rms);
- minimisation of the straylight level on:
  - the photodiode for the detection of the interferometer signal, in order not to spoil the heterodyne efficiency;
  - the CCD for the initial acquisition of the incoming laser beam, to allow, if possible, the execution of this operation without blocking the local laser beam (and thus its transmission to the other S/C's).

More specific requirements applicable to the single elements of the OB are provided and discussed in the following sections, together with the detailed description of the OB layout, optical design, mechanical design and budgets.

7.1.3.1 Optical Bench layout

The final layout of the OB is shown in Figure 7.1-14.

The linearly polarised light generated by the active laser source is routed via a polarisation maintaining mono-mode optical fiber (fiber 1) to the OB, where a motorised positioner allows to adjust its in-line and lateral displacements. The fiber is suitably rotated about its axis, so that the outgoing beam is nominally linearly polarised in a plane perpendicular to the OB (S polarisation). After being collimated to a size that matches the 60x magnification of the telescope, the beam arrives the at the polarising beamsplitter ps1, which deviates 99.5% of the power outside the bench, towards the telescope, where it arrives with circular polarisation. The remaining portion (0.5%) leaks through the ps1 and is squeezed by the beam compressor bc1 to match the active area of the quadrant photodiode qp1, the sensor that detects the beat signal between the local beam and the incoming beam from the remote S/C. The latter is collected by the telescope and sent on the OB where it is partially deviated (5%) by the beamsplitter s2 towards the CCD utilised for the initial detection of the remote beam (the polarising beamplitter in front of this sensor reduces partially the - unpolarised - star light and scattered straylight). The remaining part bounces off the proof mass and is routed by ps1 towards qp1, where it overlaps the local laser beam. The polarisation of the outgoing and incoming laser beam on the OB and their selective routing through the polarising beamsplitters is shown in Figure 7.1-15.

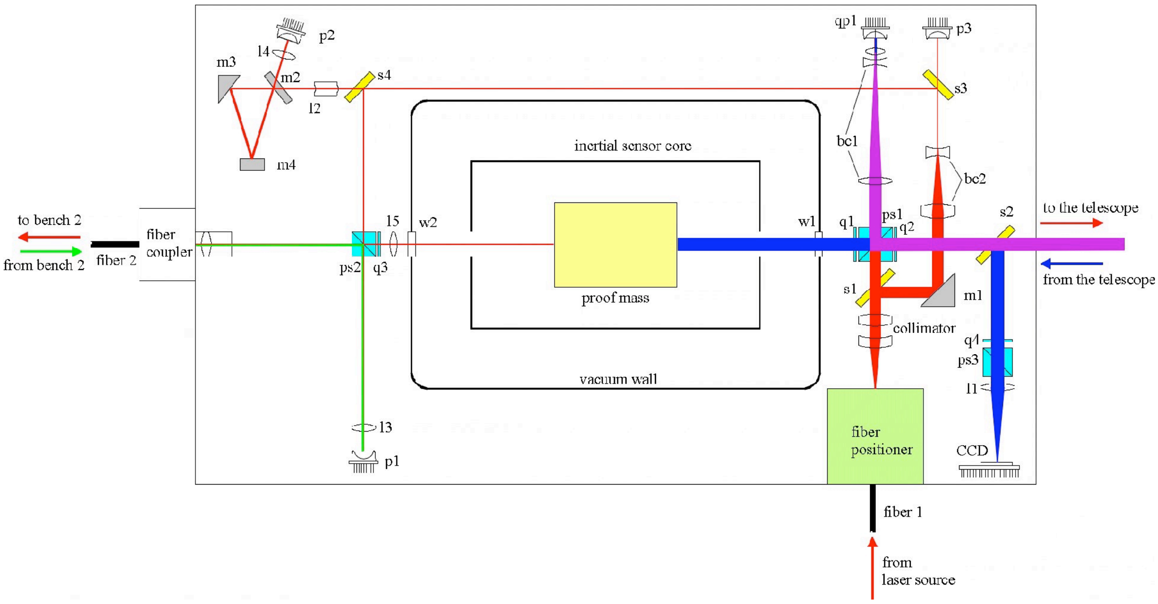

Figure 7.1-14 - Optical Bench layout

Between the collimator and ps1, a small portion of power (0.25%) is separated from the main beam by the beamsplitter s1 (the beamsplitter s2 is not utilised for this purpose to avoid possible backreflections on the CCD from the following optics), is passed through the beam compressor bc2 and is separated in two parts by the beamspitter s3. The beam crossing s3 is intercepted by the photodiode p3 that provides the signal for the stabilisation of the laser power. The beam reflected by s3 towards the rear part of the OB is in turn divided in two parts by the beamsplitter s4. One part is focused in the reference optical cavity constituted by the three mirrors m2, m3, m4, and then reaches the photodiode p2 that provides the signal for the stabilisation of the laser frequency. The other part is mostly reflected (99%) towards the back of the proof mass by the polarising beamsplitter ps2, while the remaining 1% leaks through this element and goes to the photodiode p1. The beam reflected off the back of the proof mass is focused, with polarisation P, in the optical fiber (fiber 2) that brings it to the second OB of the S/C, where it comes out with polarisation S thanks to a 90° twist of the fiber. In turn, the beam of the local laser that feeds the OB 2 comes through fiber 2 on OB 1 and is deflected almost completely by ps2 on the photodiode p1 that detects the beat signal of the two local lasers. This signal is utilised for phase locking the two lasers and to detect the motion of the proof masse relative to the OB (to be removed from the interferometric signal between the local and the remote laser).

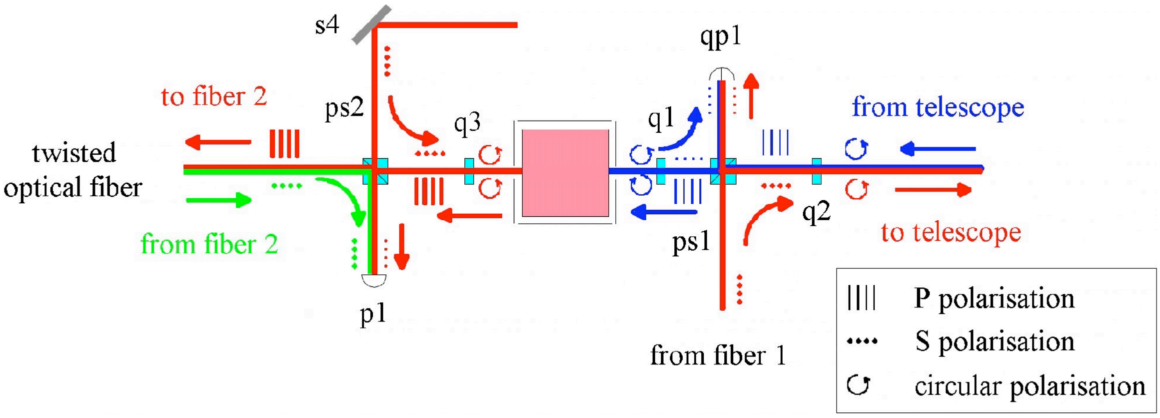

Figure 7.1-15 - Polarisation of the laser beams on the optical bench

The principal characteristics of the optical elements of the OB are summarised in Table 7.1-3. More details about the lenses are provided in section 7.1.3.2. The reflectivity of the beamsplitters s1, s3, s4 ps2 has been chosen so to:

- provide a minimum power of 1 mW to the photodiode p3, as required for the laser amplitude stabilisation;
- provide a minimum power of 0.5 mW to the reference cavity as required for the laser frequency stabilisation;
- limit to a maximum of 100 μW the power bounced off the back of the proof mass [1];
- provide a sufficient power to the photodiode p1;
- minimise the power subtracted to the main beam.

Table 7.1-3 - Main features of the optical elements of the Optical Bench

Element	Main features
Lenses	Material: Fused Silica (n = 1.4496, dn/dT = $9.6\cdot10^{-6}$ K^{-1}, CTE = $5.2\cdot10^{-7}$ K^{-1}, absorptance = $5\cdot10^{-4}$ m^{-1})
Beamsplitter (s1, s2, s3, s4)	Material: Fused Silica Thickness: 3 mm Reflectivity: 0.25% (s1), 5% (s2), 40% (s3), 15% (s4)
Polarising beamsplitter (ps1, ps2, ps3)	Material: Fused Silica Thickness: 15 mm (ps1), 10 mm (ps2), 10 mm (ps3) Reflection & Transmission efficiency: R_S = 99.5% T_P = 95% (ps1), R_S = 99% T_P = 90% (ps2), R_S = 99.5% T_P = 90% (ps3)

Quarter waveplate (q1, q2, q3, q4)	Material: Crystal Quartz (n_o = 1.5341, n_e = 1.5428, dn/dT = $5 \cdot 10^{-6}$ K^{-1}, CTE = $13.2 \cdot 10^{-6}$ K^{-1}) Thickness: 1 mm Retardation tolerance: λ/100 (±1.8°)
Mirror (m1, m2, m3, m4)	Material: Fused Silica (m2), ULE™ (m1, m3, m4) Thickness: 3 mm (m2), 4 mm (m4), 15 mm side length (m1), 10 mm side length (m3) Reflectivity: 99.96% (m1), 99.995% (m2), 99.792% (m3), 99.792% (m4)
Window (*) (w1, w2)	Material: Fused Silica Thickness: 3 mm (sufficient to withstand a 1 bar pressure difference)
Optical fibers (fiber 1, 2)	Core material: Fused Silica Mode field diameter: 8.6 μm Numerical Aperture: 0.12 Length: ~1 m Attenuation 3 dB/km Polarisation extinction ratio: 35 dB (for 1° misalignment about the fiber axis) Minimum bend radius: 12.5 mm

(*) The windows are mounted on the walls of the vacuum vessel of the Inertial Sensor

7.1.3.2 Optical Design

The design of all the OB lenses has been performed using the Code V ray tracing software.

Collimator

The collimator is a two-lens system designed according to the following requirements:

- produce, in combination with the 60× telescope, a transmitted laser beam with a waist close to the telescope primary mirror having a radius ***r* = 133.8 mm** (= 0.446×telescope diameter), so to maximise the transmitted power [1];
- minimisation of the WFE of the outgoing beam.

The laser beam transmission path is shown in Figure 7.1-16. At the telescope output, the WFE caused by the optical aberrations of collimator + telescope is **λ/330 rms** (computed considering the gaussian distribution of the energy in the beam). The WFE and the tilt of the outgoing beam can be adjusted by small longitudinal (δ_L) and transversal (δ_T) translations of the fiber tip by means of the fiber positioner:

δ_L = +10 μm   WFE = λ/100 rms , δ_T = ±10 μm   tilt = ±6 μrad (linear behaviour)