Abstract

Optical fibre links for frequency dissemination are a key tool for Time and Frequency metrology and for the future redefinition of the SI second. They are based on the transmission of an ultrastable laser, whose frequency is referenced to an atomic clock at the National Metrology Institute (NMI) where it is generated, along standard telecom fibres. The fibre length variations due to temperature, acoustic and seismic noise deteriorate the stability of the signal by introducing phase noise on the optical carrier and thus need to be compensated for. Various techniques have been proposed to this task; at the highest performances, the frequency of an optical carrier can be delivered through thousands of kilometers with uncertainty at the 10^{-19} level, i.e. 5 orders of magnitude better than satellite techniques. This enables to disseminate atomic clocks of new generation at their intrinsic level of uncertainty. A fibre-based network of NMIs has been developed in Europe and is continuously growing, for the remote comparison of atomic clocks and frequency standards validation. More recently, fibre-based transfer of optical frequencies started to be exploited for other scientific purposes. In Italy a fibre link of almost 2000 km has been developed, connecting the Istituto Nazionale di Ricerca Metrologica (INRIM), the Italian NMI, to the National Institute for Astrophysics (INAF) and the Space Geodesy Center (CGS) of the Italian Space Agency (ASI) for experiments of Very Long Baseline Interferometry (VLBI) for geodesy and radio astronomy, the European Laboratory of Non linear Spectroscopy (LENS) and the National Institute of Optics (INO) for experiments of high precision spectroscopy on cold atoms and molecules. A connection to the French border has also been developed, in view of a connection to the European fibre network.

The first part is focused on the technical implementation and characterization of the Italian link, connecting the INAF radio telescopes, in central Italy, to CGS in southern Italy, for a total length of 1204 km. In order to simultaneously provide multiple laboratories of the country with an ultrastable signal and to cope with the attenuation across the whole network, a cascaded link has been developed. The full network has been divided in five spans, each provided with an ultrastable laser, phase-locked to the incoming light, and independent noise cancellation electronics.
A further technical aspect addressed in this thesis is the implementation of the optical two-way noise cancellation scheme. It is an alternative to the Doppler scheme for remote comparisons of frequency standards, which is more immune to optical attenuation and build-up of phase noise. In this thesis I describe for the first time the results we obtained with such technique in a real field, with independent setups for data processing, and address the most critical aspects. I show that this technique allows remote clocks comparisons at the 10^{-19} level of uncertainty.
Finally, I report on the phase noise characterization of submarine fibres, performed on two 200 km fibre links connecting Malta to Sicily. This measurement campaign has been performed in collaboration with the University of Malta and the National

Physical Laboratory (NPL). We found that the phase noise on submarine fibres is orders of magnitude lower than on terrestrial fibres of the same length, which is interesting in view of future transcontinental comparisons of atomic clocks.

The second section of the thesis is dedicated to some applications of the fibre-based dissemination of frequency standards. The first is in radio astronomy, in particular, in Very Long Baseline Interferometry (VLBI). This technique is based on the simultaneous observation of an object in the sky with many telescopes on the Earth: by correlating the data of each telescope, the resolution is improved by orders of magnitude with respect to a single antenna observation. One of the limiting factors is the frequency instability of the local frequency reference. If two telescopes share the same reference, its uncertainty contribution becomes negligible in the final correlation. In this thesis I describe the implementation and characterization of a fibre link that disseminates a common frequency reference to two radio telescopes managed by INAF and ASI as well as the results of the preliminary tests in preparation to the first common-clock experiment.
Another application of optical fibre links is in relativistic geodesy. I describe a proof-of-principle experiment of chronometric levelling, jointly performed by INRIM, NPL and the Physikalische-Technische Bundesastalt (PTB). An optical clock has been transported to the Laboratoire Soutterain de Modane (LSM) at the French border, 1000 m higher than Torino, and compared to the INRM primary frequency standard through a 150 km fibre link. By measuring the relativistic redshift between the two clocks, the difference of the gravity potential between the two locations is retrieved and compared with the results of traditional gravimetry techniques. This thesis reports the realization of the fibre link, its characterization and the results of the chronometric levelling experiment.
The last application exploits optical fibre as sensors of seismic noise. This thesis describes the first demonstration of earthquakes detection using optical fibres and coherent interferometry techniques, performed in collaboration with NPL, the British Geological Survey and the University of Malta. We predict the possibility of detecting earthquakes with ultra long-haul transoceanic fibres installed for telecom purposes. This would enable to reveal small seismic events generated on the bottom of the oceans which remain currently undetected due to the high costs of operation of seismic sensors in a submarine environment.