Università degli Studi di Salerno

Dipartimento di Matematica
Scienze Matematiche, Fisiche ed Informatiche
XI Ciclo - Nuova Serie
Curriculum in Fisica dei sistemi complessi e dell'ambiente

Ph.D. Thesis
in

High-sensitivity strain measurements from underground interferometric stations: geodynamic phenomena at Gran Sasso and first records from Canfranc

Candidate
Verdiana Botta

Supervisor	Coordinator
Prof. Luca Crescentini	**Prof. Patrizia Longobardi**

Academic Year 2011-2012

Abstract

Earth's surface and interior continuously deform as a result of geological and geophysical processes. To study these phenomena and to understand better the rheological properties of the Earth, measurements of Earth's deformation become of fundamental importance, providing a critical link between Earth's structure and dynamics, also in order to optimize the response to natural hazards and identify potential risk areas.

The study of crustal deformation is a complex but very important research topic that encompasses several scientific disciplines, including differential geometry, theory of elasticity, geodynamics and physics in general.

The use of different kind of geodetic data to study geodynamic phenomena became increasingly important, playing a key role in the knowledge of their temporal and magnitude variations at many different spatial and time scales. These measurements provide significant constraints on the changes in Earth's lithosphere and processes that cause them, like for example movements of magma, changes in strain before, during, and after earthquakes, motion of ice sheets.

Yet even today, large portions of the Earth are infrequently monitored, or not at all.

Deformation can be measured in several ways, as relative movement of points on the Earth's surface, through measurements of strain and tilt, or by GPS (Global Positioning System), VLBI (Very Long Base Interferometry) and SLR (Satellite Laser Ranging) measurements. Among the different types of instruments, the laser strainmeters (or interferometers), measuring the displacement between two points away from a few meters to over a kilometer, are characterized by very high accuracy and long-term stability, necessary to investigate processes of crustal deformation. The analysis of interferometric data allows to study both local and global geodynamic phenomena in a broad band of frequencies.

This thesis introduces results related to some analysis of data recorded by two laser interferometers installed at Gran Sasso (Italy) Underground Laboratories and describes the installation of two new laser interferometers in the Canfranc (Spain) Underground Laboratory, at the end of August 2011, with the analysis of their first sequences.

In the first chapter some general concepts about strain, crustal deformation and their measurements are introduced. The study of the deformation on the Earth's surface improved in the last fifty years, changing from mostly descriptive and qualitative to more quantitative. The state and magnitude of the stress in the Earth's lithosphere, and thus of the deformation, play an important role on various geophysical problems, such as the plate mechanisms, energy budget of the Earth, earthquake mechanism and crustal movements.

In Chapter 2 there is a description of the Earth's tidal deformation. The body tides, due to a direct effect of gravitational attraction from the Sun, Moon and other objects, can be modeled very accurately. In addition, there is a part of deformation, known as ocean loading, arising from the mass fluctuations of the oceans. These last is also rather well understood, but the modeling of its effects still needs to be improved. This phenomenon is very significant for the interferometric strain sequences because they are clearly dominated by the semidiurnal and diurnal strain tides.

Chapter 3 describes the laser interferometry and, in particular, the operating principle of the Gran Sasso (Italy) laser interferometers, which provide very high-sensitivity strain data, by comparing the optical length of a longer measurement arm (about 90 meters in length) and a shorter fixed reference arm (about 20 cm in length). Although the interferometers measure strain directly, the presence of cavities, topography, and local inhomogeneities of the crust can modify the strain measurement considerably. Also environmental and anthropic effects appear as anomalous or noise signals in a broad frequency range, which includes for example the Earth tides. It is necessary to take some or all these possible effects into account, depending on the phenomenon studied.

In Chapter 4 data produced by Gran Sasso interferometers, first alone and then together with those produced by a third laser interferometer installed in Baksan (Russia) Underground Laboratory, are used to estimate the Free Core Nutation (FCN) parameters. Even if tidal signal-to-noise ratio for strain is usually lower than for gravity, the analysis of strain data is promising, because relative perturbations in strain tides are about 10 times larger than in gravity tides. The inversion of realistic synthetic tidal parameters (obtained from observed amplitude and phase of eight diurnal tidal components) shows that the resolving power of strain tides is comparable to that of gravity tides if tidal parameters are inverted minimizing the $\mathcal{L}^2$ misfit (as usually done). Both resolving powers improve if data are inverted minimizing the $\mathcal{L}^1$ misfit, and this improvement is particularly notable for gravity tides. The inversions of strain records have been performed after correcting measured strain for local distortion of the regional strain field and ocean loading. For estimating the FCR parameters, eight diurnal tidal constituents (Q_1, O_1, P_1, K_1, Ψ_1, Φ_1, J_1 and OO_1) have been used, by comparing measurements (corrected for ocean loading) and model predictions (corrected for the local strain distortion), minimizing the $\mathcal{L}^1$ misfit. The analysis of the only Gran Sasso strain data provides a value for the FCN period (about 429 sidereal days) robust and comparable to those from gravity tides, obtained from the joint inversion of data from several stations. The agreement between observations and predictions looks better than in any previous work that makes use of strain tides. The joint analysis of Gran Sasso and Baksan strain data confirms, but does not improve, these results recently obtained. In both cases the quality factor is not well constrained because of the large uncertainty on the Ψ_1 phase; however the results are consistent with recently published values (≈ 20000).

In Chapter 5 the new mode of faulting, discovered in the last decades and referred to as slow slip earthquakes, is examined. Many aspects of slow slip remain unexplained. Here an attempt to describe the characteristics of the rupture propagation through the analysis of strain records from three different slow events related to the 1978 Izu-Oshima (Japan) earthquake, the 1999 Durmid Hill (California) slow event and the 2003 Tokachi-oki (Japan) earthquake. The signals recorded during these slow events exhibit the same peculiarities observed in the strain sequences recorded at Gran Sasso during the 6 April 2009 L'Aquila earthquake, first direct measurement of the diffusive character of the rupture propagation. By using two different propagation mechanisms along 1D straight paths, namely constant propagation velocity and diffusive processes, predicted strain history at both interferometers is fully consistent with diffusive slip propagation, but inconsistent with constant velocity propagation. Not all slow earthquakes analysed are consistent with only one of the two models tested. Two of the four slow events (L'Aquila and Izu-Oshima F3 fault) are only consistent with diffusive slip propagation. Constant velocity propagation gives much worst fit to data, being unable to fit the shape of minimum observed on signals recorded by BA interferometer and SHI borehole strainmeter for L'Aquila and Izu-Oshima slow earthquakes, respectively. For both slow events, the seismic moment density decreases about linearly with distance along the path, like the steady-state solution of 1D diffusive processes. In the other cases (Durmid Hill, Tokachi-oki and Izu-Oshima F4 fault) it is not possible to discriminate the type of propagation. Observations are consistent with both types of slip propagation but for them the shape of seismic moment seems somewhat unrealistic, being a bell-shaped distribution peaked on the nodal line. These results suggest the necessity to deepen the source features, not well constrained in some cases. Moreover, also the assumption of 1D very thin path might be a source of uncertainty.

In the last chapter the installation, occured in August 2011, of two new laser interferometers is described and their first records analysed. These instruments, operating since November 2011, are installed in the Canfranc (Spain) Underground Laboratory (LSC). The LSC is located at depth in one of the most seismically active areas in Western Europe, at the Pyrenean chain that marks the boundary between the European plate and the Iberian microplate. The first tests on strain data recorded by these interferometers evidence the capability of producing clear records of low-frequency signals, for example relating to seismic waves, Earth free oscillations, and possible local aseismic stress release. A preliminary tidal analysis shows a good agreement between observed and predicted tides in the diurnal tidal band, suggesting that, if any, local strain distortion effects are small. In the semidiurnal tidal band, discrepancies between observed and predicted tides are noticeable; this might be a consequence of inadequate Earth and/or ocean models. These results deserve further investigation; in particular it would be interesting to deepen the local distortion effect in the different frequency bands and estimate the ocean loading in more detail, especially in the Bay of Biscay which could be the main source of the discrepancies observed in the semidiurnal tidal band.