Magnetic Diagnostics Algorithms for LISA Pathfinder: System Identification and Data Analysis

Abstract and Main results

LISA (Laser Interferometer Space Antenna) is a joint mission of ESA and NASA, which aims to be the first space-borne gravitational wave observatory. In the present days, some of its characteristics are being redefined due to budget constraints. Nevertheless the LISA concept is still alive. The LISA concept consists in a constellation of three spacecraft at the vertexes of an equilateral triangle of side 5 million kilometers. The constellation will orbit around the Sun trailing the Earth by some 20 degrees. Each of the spacecraft harbors two proof masses, carefully protected against external disturbances such as solar radiation pressure and charged particles, which ensures they are in nominal free-fall in the interplanetary gravitational field. Gravitational waves will show as differential accelerations between pairs of proof masses, and the main aim of LISA is to measure such acceleration using laser interferometry. The technologies required for the LISA mission are many and challenging. This, coupled with the fact that some flight hardware cannot be tested on ground, led ESA to define a technology demonstrator to test in flight the required critical technologies. This precursor mission is called LISA Pathfinder (LPF). The payload of LISA Pathfinder is the LISA Technology Package (LTP), and will be the highest sensitivity geodesic explorer flown to date. The LISA Technology Package is designed to measure relative accelerations between two test masses in nominal free fall placed in a single spacecraft, since one LISA arm is squeezed from 5 million kilometer to 35 cm. Its success will prove the maturity of the necessary technologies for LISA such as the Optical Metrology System and the Drag Free concept. The differential acceleration reading will be perturbed by identified disturbances, such as thermal fluctuations or magnetic effects. These disturbances are monitored by the Diagnostics Subsystem. The Magnetic Diagnostics System is one of its modules and is a critical subsystem, since magnetic noise is apportioned to 40% of the total noise budget. In this respect, to estimate the magnetic noise contribution, the Magnetic Diagnostics Subsystem will have two main tasks: (1) estimate the magnetic properties of the test masses, i.e., their remanent magnetic moment and susceptibility, and (2) infer the magnetic field and its gradient at the location of the test masses. To this end, the Magnetic Diagnostics Subsystem includes two coils which generate controlled magnetic fields at the locations of the test masses. These magnetic fields will excite the dynamical response of both test masses. In this thesis we state that by adequate processing of the kinematic excursions delivered by the interferometer, the magnetic characteristics of the test masses can be estimated within 1% accuracy level [1, 2, 8, 10]. Additionally, the Magnetic Diagnostic Subsystem includes a set of four tri-axial fluxgate magnetometers. However, the magnetic field and its gradient need to be measured at the positions of the test masses and the readouts of the magnetometers do not provide a direct measurement of the magnetic field at these positions. Thus, an interpolation method must be implemented to calculate them. This is a difficult problem, mostly because the magnetometers are too distant from the locations of the test masses (more than 20 cm away) and because there are not sufficient magnetic channels to go beyond a classical linear interpolation method, which yields extremely poor interpolation results. Consequently, in this thesis we present and validate an alternative interpolation method based on neural networks. We put forward its robustness and accuracy in several mission scenarios and we stress the importance of an extensive magnetic testing campaign. Under these assumptions, we deliver magnetic field and gradient estimates with 10% accuracy [3, 4, 9, 11]. Finally, the estimate of the magnetic noise contribution to the total acceleration between the two LPF's test masses is determined with an accuracy of 15%. This result represents an enhancement of the estimation quality in one order of magnitude with respect to former studies and this will have a direct impact in the quality of the readings in LISA Pathfinder and in future LISA-like missions.

Most remarkable achievements and impacts

(1) **The design of the Optimum magnetic design experiment to estimate the magnetic properties of the LISA Pathfinder test masses.** The author has designed the experiment procedure that will have to take place in flight and has built the data analysis software architecture/pipeline to process all telemetered data coming from such experiments. It has defined a statistical method to find the optimum frequency and optimum amplitude of the magnetic excitation of the coils to achieve optimum performance of the experiment taking into account the control architecture of the satellite and its dynamical characteristics. This work will allow the LPF science team to perform optimum magnetic experiments during mission operations and analyse its results. Future investigations will have to consider plausible non-homogeneities in the magnetic properties test masses, or high frequency excitations for both coils [1, 2, 8, 10].

(2) **Neural Network Interpolation algorithm for magnetic field and magnetic field gradient estimation.** It was the author merit to find that a two order of magnitude improvement in the interpolation results can be reached by suitable use of neural network algorithms. He elaborated a clear methodology for the use of this tool in the present satellite configuration. Remarkably, this methodology includes the estimation of magnetic field gradients, too, an undreamed of possibility with the LTP's rather limited magnetic measurement system. Future investigations will focus on the performance of such methods for other LISA-like missions and on other statistical modeling tools such as Bayesian methods or other clustering techniques [3, 4, 9, 11].

(3) **LPF simulator.** The author has contributed in the building of the integral LISA Pathfinder simulator, including its payload and spacecraft. He has become the leading contributor in the implementation of the state space model, which offers much more efficient capabilities in terms of precision, dynamics resolution, and MIMO representation. Also, he has coded the magnetic diagnostics module inside such simulator. Future work will focus on the improvement of speed and accuracies of the some of the modules included in the simulator [5, 6, 7].

Most relevant publications as a result of this thesis work

[1] M. Diaz-Aguiló, A. Lobo, E. García–Berro. *Inflight magnetic characterization of the test masses onboard LISA Pathfinder.* **Physical Review D** (**2012). Accepted.**

[2] M. Diaz-Aguiló, I. Mateos, J. Ramos-Castro, A. Lobo, E. García–Berro. *Design of the magnetic diagnostics unit onboard LISA Pathfinder.* **Aerospace Science and Technology** (**2011). Accepted.**

[3] M. Diaz-Aguilo, A. Lobo, E. García–Berro. *Neural network interpolation of the magnetic field for the LISA Pathfinder Diagnostics Subsystem*. **Experimental Astronomy, 30 Issue 1, 1-21 (2011).**

[4] M. Diaz-Aguiló, E. Garcia-Berro, J.A. Lobo. *Theory and modelling of the magnetic field measurement in LISA PathFinder*. **Classical Quantum Gravity 27 035005 (2010).**

[5] F. Antonucci et al. *LISA Pathfinder Data Analysis.* **Classical Quantum Gravity, 28, Issue 9, 094006 (2011).**

[6] F. Antonucci et al. *LISA Pathfinder mission and status.* **Classical Quantum Gravity, 28, Issue 9, 094001 (2011).**

[7] M. Hewitson, M. Diaz-Aguiló, A. Grynagier, *A linear MIMO model of LPF implemened in LTPDA S2-AEI-TN-3069*. **ESA report (2010).**

[8] M. Diaz-Aguiló, E. García-Berro, J.A. Lobo, *Algorithm specification for the Magnetic Diagnostics onboard LPF. S2-IEC-TN-3071.* **ESA report (2009).**

[9] M. Diaz-Aguiló, E. García-Berro, J.A. Lobo, *Neural Network algorithms for magnetic diagnostics in the LTP. S2-IEC-TN-3052.* **ESA report (2009).**

[10] M. Diaz-Aguiló, E. García-Berro, J.A. Lobo, *Magnetic experiments on board the LTP. S2-IEC-TN-3044-magnetic-EMP-v1.0.* **ESA report (2010).**

[11] Diaz-Aguiló, E. García-Berro, J.A. Lobo, *LTP Magnetic Field Interpolation. S2-IEC-OTH-3026.* **ESA report (2009).**