Development and testing of the gravitational wave antenna MiniGRAIL in its full-featured configuration

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Introduction

The weakness of gravitational interaction makes the detection of gravitational waves one of the most challenging tasks for experimental physics. While they were predicted by Einstein's Theory of General Relativity almost a century ago, they are still not measured directly, despite the dramatic improvement of the detectors sensitivity. So far, only indirect evidence of existence of gravitational waves was made by an observation of the binary pulsar $PSR1913 + 16$ made by Hulse and Taylor [1, 2]. The slowing down of the revolution period of the pulsar occurs at the exact rate predicted by general relativity for the emission of gravitational wave.

But a weak interaction with matter is what makes them so interesting for astrophysicists. Hardly absorbed by matter it allows physicists to look at events, which are not observable by electromagnetic waves detectors.
The history of gravitational wave detectors counts more than 45 years of development. Joseph Weber built the first antenna in 1965 [3] It was a 1.5 ton Aluminium bar, suspended in vacuum at room temperature. It had a resonant frequency of $1.6\,kHz$. In 1968 he built a second detector to do coincidence measurements. By using piezoelectric transducers he was able to reach a strain sensitivity $\frac{\Delta h}{h}$ in the order of 10^{-16}. Although he reported [4] measuring a coincidence signal between two detectors, the amplitude of the signal was way above the expected level for the gravitational waves and was not confirmed by the results of other groups. The current generation of detectors is approximately six orders of magnitude more sensitive, but is still not able to report a detection of a gravitational wave signal.

All currently existing gravitational wave detectors are based on two principles:

The first type are interferometric detectors: LIGO, consisting of two interferometers - LIGO Hanford and LIGO Livingston (USA)[5], VIRGO at Cascina (Italy)[6], GEO600 at Hannover (Germany)[7] and TAMA300 in Japan[8].

Another type is the resonant detector: bar detectors: AURIGA in Legnaro (Italy)[9], NAUTILUS at Frascati (Italy) and two spherical detectors: Mario Schenberg in Brasil [10] and MiniGRAIL [11] in Leiden.
This work only focuses on the latter type of detectors, and MiniGRAIL in particular. All resonant detectors are designed in a similar way. The sensitive part is the cylindrical or spherical mass with high mechanical quality factor(in the order of 10^6). It is mechanically well decoupled from the environment noise sources (seismic, acoustic, electric, etc). The intrinsic thermal noise of the detector mass is reduced by oper-

ation at cryogenic temperatures. A gravitational wave passing through a detector excites the quadrupole resonant modes of the resonant mass. To detect this motion, a secondary, much lighter, mechanical oscillator(transducer) is attached. Its resonance frequency is tuned to the one of the sensitive mode of the main resonator. This transducer is electrically coupled to the external readout circuit.

A spherical gravitational wave detector has many distinguishable features. Some of them it shares with the bar antennas (price, compactness, maintenance cost, resonance detection principle), but some are really unique: unlike the bar detectors, the sphere is equally sensitive for a gravitational wave coming from any direction. It is also capable of determining the polarization of the incident gravitational wave. One would have to construct 5 equivalent bars to obtain the same amount of information. The sphere also has a larger cross section than a bar for equal operating frequency. An overview of the properties of spherical gravitational wave detectors can be found in [12].

However, there are some practical problems in operating spherical detectors. An omnidirectional operation requires using multiple transducers, which affects the reliability of the detector. The calibration and data analysis of the spherical antenna is also more complicated. To solve this problem Johnson and Merkowitz proposed a configuration called a truncated icosahedral gravitational wave antenna (TIGA)[13]. The six transducers are placed on the 6 pentagonal faces of truncated icosahedron. High symmetry allowed developing a simple algorithm of reconstructing the gravitational signal, using fixed combinations of transducer outputs.

This thesis is focused on building the full acquisition system and preparation of MiniGRAIL for a first scientific run, with a full 6 transducer configuration at millikelvin temperatures.

The first chapter of this thesis gives a general introduction into gravitational waves and the principles of gravitational wave detection. An overview is focused on the properties of spherical resonant detectors and on the MiniGRAIL setup in particular.

Chapter 2 is focused on the development of MiniGRAIL acquisition system, Chapter 3 describes improvements in the setup that were made based on the results of preceding cool downs. In chapter 4 the results of the first calibration run of MiniGRAIL are presented. An application of a sensitive 2-stage SQUID amplifier, developed for MiniGRAIL, in magnetic resonance force microscopy (MRFM) experiment is described in chapter 5.