

立教大学学術推進特別重点資金(立教SFR)
個人研究
2020年度研究成果報告書

研究代表者	所属部局・職	氏名
	Faculty of Science, Department of Physics Assistant Professor B	Simon Zeidler 印
研究課題	Novel Methods to Measure the Gravity Constant with the Aid of Laser-Interferometers	
研究期間	2020年度	
研究経費 (1円単位)	(支出金額) 930,000円 / (採択金額) 930,000円	

研究の概要 (200~300字で記入、図・グラフは使用しないこと。)

Gravity is in physics one of four universal forces. But, although we know the other three forces (strong interaction, weak interaction, electromagnetic force) very well, gravity is measured to a much less precision. This causes problems as more sensitive our instruments become and as more we strive to know about our universe. In particular, we know that the other three forces converge to a shared strength at very small scales but we cannot say anything about gravity as we have no measured data at the same scales.

The proposed research aims to fill this gap. I want to measure differences in the gravity proposed by the standard Newtonian law and the one which actually rules at small scales. There are two key aspects in this research:

- I want to overcome difficulties that previous studies had with environmental influences (air-flow, electrostatics, etc.) by using almost only optical techniques like laser-interferometer in a laboratory. An important study in this regards is already ongoing in Prof. Murata's laboratory of the department of physics at Rikkyo University.
- A combination of Prof. Murata's experiment with the most precise measurement facility for gravity-related phenomena in Japan, KAGRA. It is a large-scale laser-interferometer (two 3km long laser-arms) in the Gifu prefecture and it aims for the search of gravitational waves, which are microscopic ripples in the gravity field.

キーワード (研究内容をよく表しているものを3項目以内で記入。)

[Gravity] [Interferometer] [Optics]

研究成果の概要 (図・グラフ等は使用しないこと。)

The main outcome of the project during the funding period is threefold. First, a pilot-study has been pursued in order to calculate the expected outcome of a laser-based microgravity measurement in a laboratory. Second, a laser-system and an interferometer have been built with the aid of the SFR-funds which was one of the key-aspects to achieve. Finally, connections between the NewtonV experiment from Prof. Murata and KAGRA have been established successfully and a student from Prof. Murata's lab has been already working together with the gravitational-wave group at NAOJ (National Astronomical Observatory of Japan) on KAGRA related research.

- **Pilot Study to Estimate the Expected Outcome of the Proposed Experiment**

In this study a conservative approach has been used to estimate the impact of a gravity field on an electromagnetic wave (having a constant polarization). I assumed two light-fields, one passing through a gravity potential (probe beam) and the other one being in a field-free space (reference beam), then both light-fields will have different phases even though traveling the same distance. This is because in general relativity, the frequency f of electromagnetic waves is decreasing when moving away from (time independent) gravity fields and is increasing when moving towards them. The change in frequency is assumed to follow the equation:

$$f = f_0 \cdot (1 - \varphi_G/c^2),$$

with f_0 being the undisturbed frequency, φ_G the gravity potential and c the speed of light in vacuum.

Obviously, the change of phase depends on the strength of the gravity field and for how long the probe beam travels through it. A laser-beam having a wavelength in the visible wavelengths range and facing the gravity of a 10 kg circular plate in a constant distance of 1mm (the beam travels perpendicular to the plate's normal axis) for about 1m, will show a phase difference of $\sim 10^{-16}$ with respect to the reference beam. That corresponds to a wavelength shift of roughly 10^{-23} m between probe beam and reference beam.

That is very small number, however nowadays the techniques to measure such extreme values are quite advanced. Gravitational wave detectors like LIGO in the USA and KAGRA in Japan can measure already shifts of the order of 10^{-24} m at variation frequencies of ~ 100 Hz. Nevertheless, for a realistic approach towards a direct measurement of G at small distances in a laboratory, more groundwork needs to be done.

- **Setup of Laser-System and Interferometer**

The SFR fund for this project has been mainly used to buy the necessary items for the setup of a laser-system and basic optical elements for an interferometer using that laser.

The laser being used in this system is a He/Ne laser at 635nm wavelength (Thorlabs LDM635) with a maximum power throughput of 5mW. I analyzed the divergence of the beam over a length of 1m using a beam-profiler which has been also purchased with the funding. The laser is strongly elliptical and shows multiple modes in horizontal direction besides the Gaussian mode which is nevertheless the dominant one. Therefore, a mode-cleaning is being build up right now based on the pinhole-technique where a lens focuses the beam on a pinhole of a specific diameter. Since lensing corresponds to a Fourier-transformation of the beam-shape, higher order modes will become side-lobes of the Gaussian shape which unperturbed from the transformation. The pinhole, thus, just cuts out these higher order modes and a cleaned beam remains. With this technique a more sensitive interferometer can be build.

Nevertheless, an interferometer could be build already with this laser source in a basic Michelson design and its sensitivity could be estimated to be the ground-motion level of the laboratory which is an expected outcome since no suspensions have been used for the optical setup to this point. Measuring the ground-motion was therefore also a necessity in the setup to set the threshold for the sensitivity. This was performed by using a 731A/P31 piezo-accelerometer from Wilcoxon©. At this point it is worth mentioning that the general noise-level of the laboratory is relatively low in the low-frequency range as even oceanic waves on the Japanese coastline could be detected by the ground-motion measurements.

- **Connections Facilitated between NewtonV, NAOJ, and KAGRA**

With the aid of Prof. Murata from Rikkyo and Prof. Tomaru from NAOJ, connections have been established between Rikkyo and KAGRA. In fact, we have planned a field trip to KAGRA in order to use the location of the predecessor to KAGRA, CLIO, for running NewtonV in a much more quiet environment. Since the geological structure of the surrounding mountains makes it an ideal place for high-sensitive measurements, we hoped for a decreasing ground-noise level in the NewtonV experiment. However, the situation regarding COVID-19 has made it impossible for us to do any business-trips this year. Thus, we have postponed these field-trips. We are optimistic that we can pursue our plans within the next fiscal year, given the state of emergency is lifted.

研究成果の概要 (つづき)

Beside these plans, a student of Murata's laboratory went together with me to NAOJ and inspected the measurement devices used there to characterize optics for KAGRA. These devices are unique in the sense that they perform high-sensitive absorption and birefringence measurements for very large optical substrates within the same setup. With the responsible person for these devices at NAOJ (Dr. Matteo Leonardi), we discussed the next measurement-run on Sapphire substrates where new growing-techniques of Sapphire crystals provided by several companies from Japan and abroad are planned to be tested with respect to absorption and homogeneity (birefringence). This is a state-of-the-art research topic as KAGRA is the only large-scale laser-interferometer which uses Sapphire substrates for its main mirrors.

※この(様式2)に記入の、成果の公表を見合わせる必要がある場合は、その理由及び差控え期間等を記入した調書(A4縦型横書き1枚・自由様式)を添付すること。

研究発表 (研究によって得られた研究経過・成果を発表した①～④について、該当するものを記入してください。該当するものが多い

場合は主要なものを抜粋してください。)

- ①雑誌論文 (著者名、論文標題、雑誌名、巻号、発行年、ページ)
- ②図書 (著者名、出版社、書名、発行年、総ページ数)
- ③シンポジウム・公開講演会等の開催 (会名、開催日、開催場所)
- ④その他 (学会発表、研究報告書の印刷等)

① not applicable

② not applicable

③ not applicable

④ For the next KAGRA f2f meeting (scheduled for August 2021 in Toyama, Japan), I am preparing a poster in which I am presenting this project. That was being planned already in 2020, but due to the COVID19 pandemic, all f2f meetings in 2020 have become online-only meetings and usual poster presentations were not possible.