IV International Workshop on Gravitomagnetism and Large-Scale Rotation Measurement

Wednesday, 14 June 2023 - Friday, 16 June 2023

Book of Abstracts

Contents

Welcome / 2

Welcome

Large Laser Gyroscope / 4

Ginger

Author: Angela Dora Vittoria Di Virgilio[1]

[1] *Istituto Nazionale di Fisica Nucleare*

GINGER (Gyroscopes In GEnereal Relativity -> Gyroscopes IN GEophysics and Relativity ?), array of ring laser gyroscopes (RLG), is entered the construction phase. The three-years plan is to install and to make operative 2 RLGs inside the underground Gran Sasso laboratory. One of the two will be oriented at the maximum Sagnac signal in order to evaluate the orientation, with respect to the instant angular rotation axis, of the second RLG, with vertical area vector. The apparatus, its plan, and its final target will be described.

General Relativity / 13

ACES: Testing general relativity with cold-atom clocks in space

Author: Luigi Cacciapuoti[1]

[1] *European Space Agency*

Atomic Clock Ensemble in Space (ACES) is developing a cold-atom clock and high-performance links to test general relativity from the International Space Station. With a fractional frequency instability and inaccuracy of 1x10^{-16}, the ACES clock signal will establishing a worldwide network to compare clocks in space and on ground. ACES will provide an absolute measurement of Einstein's gravitational redshift, it will search for time variations of fundamental constants, contribute to test topological dark matter models, and perform Standard Model Extension tests. The network of ground clocks participating to the ACES mission will additionally be used to compare clocks over different continents and measure geopotential differences at the clock locations.

The flight model of the ACES payload is close to completion. System tests have already confirmed the performance of the clock signal distributed by ACES. The microwave time and frequency link is currently under test. The single-photon avalanche detector of the ACES optical link has been tested successfully.

The ACES mission concept, its scientific objectives, and the recent test results will be presented together with the major milestones that will lead us to the ACES launch

Geophysical applications / 16

Underground Geophysics at the INFN Laboratori Nazionali del Gran Sasso

Corresponding Author: gaetano.deluca@ingv.it

At the beginning of 2023 the STRIC project started under the PNRR (EU funding).
This proposal includes a part linked to the purchase of instrumentation for underground geophysics in the INFN LNGS.
In particular, it is foreseen:
- the financing, together with the INFN, of the GINGER experiment (ring laser with an opening of about 5 meters);
- installation of a superconducting gravimeter to be kept in continuous recording;
- broad-band seismic sensors both for the underground seismic array (together with the 21 short-period sensors) and for the seismic station of the INGV national network (GIGS)
- increased and improved monitoring of the chemical-physical parameters of the groundwater around the LNGS (above all hydraulic pressures).

Space Applications / 23

The LARES and LARES 2 satellites for tests of gravitational physics and frame-dragging

Author: Ignazio Ciufolini[1]

[1] *Agenzia Spaziale Italiana*

Corresponding Author: ignazio.ciufolini@unisalento.it

The two missions of the Italian Space Agency (ASI), LARES and LARES 2 have the main objectives to test the general theory of relativity (GR) and to measure with high accuracy the phenomenon of frame dragging. Frame-dragging is an intriguing phenomenon of GR which implies that a current of mass-energy, such as the rotation of a body, generates spacetime curvature. LARES has already tested frame-dragging with an accuracy of a few parts in one hundred and verified other aspects of GR and of alternative gravitational theories, such as the weak equivalence principle. LARES 2 will test and verify frame-dragging and GR with greatly improved accuracy. The accuracy of such a measurement is dependent on the accurate knowledge of the Earth gravitational field, on the data of the other laser-ranged satellites LAGEOS and LAGEOS 2, on the particular design of the satellites and on the orbital injection accuracy. Concerning this last aspect, both launches of LARES in 2012, with the VEGA launcher, and LARES 2 in 2022, with the empowered version VEGA C, were extremely accurate. Both launchers were developed by ESA-ASI-Avio. In particular LARES 2 was released into the orbit with an injection accuracy which was better than what we expected by about an order of magnitude. Therefore, we estimate to get a measurement of frame-dragging with a relative accuracy which, in a number of years, will reach a few parts in one thousand or even 10-3. To reach such a level of accuracy every perturbation needs to be known, measured or estimated with extremely high accuracy. The presentation will discuss the principles of these space experiments and some design details of the missions.

Conclusions / 24

Round Table: Highlights and Future Perspectives

Conclusions / 25

Students Awards and Closing Remarks

Poster Session / 30

6C seismic observations in China

Authors: Chang Chen[1]; Yun Wang[2]; Chun Yang[2]; Wei Li[2]

[1] *China University of Geoscience,Beijing*

[2] *China University of Geosciences, Beijing*

Corresponding Authors: wangyun@mail.gyig.ac.cn, chch6108@163.com

A complete six-component (6C) seismic wave field includes three translational components and three rotational components. Traditional seismic observation and research only focus on the translational motions, but exploration of rotational seismology has a long history (Aki and Richards,2002; Lee et al.,2009). With the development of rotational seismometers, especially the high-precision optical rotational seismometers, further investigation on the rotational motions have raised gradually. Rotational seismology could be applied in strong-motion, broadband seismology, earthquake engineering and many other fields (Igel et al.,2005; Schmelzbach et al.,2018).

In recent years, we have carried out several 6C seismic observations in many regions of China, including earthquake observations in Quanzhou and Lijiang, test of rotational seismometers and deep underground observation in Huainan and engineering seismic experiments in Tangshan.

The additional wave field brought by rotational components help to estimate phase velocity of shallow media (Wassermann et al.,2016). In September 2020, we executed a shallow seismic experiment in Tangshan, China. The test field locates in an abandoned coal area, backfilled with building trash and surround by traffic lines. In this experiment, four types of seismometers were installed to record 6C seismic records, including eentec R-2 molecular-electronic rotational seismometer and FOSN-II fiber-optic rotational seismometer. The seismic signals was excited by a conventional hammer and a 3-directional controlled vibration. Results show that the fundamental Rayleigh wave dispersion curve calculated by single-station 6C observation is consistent with the dispersion curves extracted with array of geophones.

High precision rotational observation depends on stations with low ambient noise. The use of deep underground space for geophysical observation has great advantages. A typical example is the ring laser gyroscope GINGERino located within LNGS (Laboratori Nazionali del Gran Sasso, the underground INFN laboratory) in central Italy (Simonelli et al.,2016; Belfi et al.,2017). Using the underground tunnel space of the discontinued Huainan Panyi-East Coal Mine (848 meters underground) in China, we have deployed several multi-physics joint observations since 2020 (Wang et al.,2023). The 6C seismic observation has used a variety of broadband seismometers and fiber-optic rotational seismometers (Chen et al.,2022). Results indicate that the fiber-optic rotational seismometers could record the teleseismic rotational signals with an epicentral distance of about 1000 km, and the rotational components is helpful to estimate the back azimuth of earthquake and the phase velocity of surface wave.

In the future, more 6C seismic observations will be applied to deep underground observation, construction engineering, marine seismic experiment, site effect and other research in China.

Reference

Aki K and Richards P G. (2002) Quantitative Seismology.
Belfi, J., Beverini, N., Bosi, F., Carelli, G., Cuccato, D., De Luca, G., Virgilio, A., Gebauer, A., Maccioni, E., Ortolan, A., Porzio, A., Saccorotti, G., Simonelli, A. and Terreni, G. (2017) Deep underground rotation measurements: GINGERino ring laser gyroscope in Gran Sasso. Review of Scientific Instruments, 88(3), 034502.
Chen, C., Wang, Y., Guo, G., Cao, Y., Li, S., Zhang, D., Jian, Y. and Wang, C. (2022) Deep underground observation comparison of rotational seismometers. Chinese Journal of Geophysics (in Chinese), 65(12): 4569-4582
Igel, H. , Schreiber, U. , Flaws, A. , Schuberth, B. , & Cochard, A. . (2005). Rotational motions induced by the m8.1 tokachi-oki earthquake, september 25, 2003. Geophysical Research Letters, 32(8).
Lee, W., Igel, H. and Trifunac, M. D. (2009) Recent advances in rotational seismology. Seismological Research Letters, 80(3), 479-490.
Schmelzbach, C., Donner, S., Igel, H., Sollberger, D., Taufiqurrahman, T., Bernauer, F., et al. (2018).

Advances in 6C seismology: Applications of combined translational and rotational motion measurements in global and exploration seismology. GEOPHYSICS, 83(3), WC53–WC69.
Simonelli, A., Belfi, J., Beverini, N., Carelli, G., Di Virgilio, A., Maccioni, E., Luca, D. and Saccorotti, G. (2016). First deep underground observation of rotational signals from an earthquake at teleseismic distance using a large ring laser gyroscope. arXiv preprint arXiv:1601.05960.
Wang, Y., Yang, Y., Sun, H. et al. Observation and research of deep underground multi-physical fields—Huainan −848 m deep experiment. Sci. China Earth Sci. 66, 54–70 (2023).
Wassermann, J., Wietek, A., Hadziioannou, C., & Igel, H. (2016). Toward a Single-Station Approach for Microzonation: Using Vertical Rotation Rate to Estimate Love-Wave Dispersion Curves and Direction Finding. Bulletin of the Seismological Society of America, 106(3), 1316–1330.

Space Applications / 31

Astrodynamical Missions, Gravitomagnetism and Reference Frames

Author: Wei-Tou Ni[1]

[1] *National Tsing Hua University, Taiwan*

Corresponding Author: wei-tou.ni@wipm.ac.cn

Frame dragging is a crucial aspect of relativistic gravity and a manifestation of gravitomagnetism. After Lense-Thirring papers, over 100 years of theoretical investigation and experimental endeavor have established the precision in the astrodynamical measurement up to 1 % level by Gravity Probe B and LAGEOS-LARES mission. Planned/Proposed astrodynamical missions will measure and separate the
gravitomagnetic effects from their other goals. This will further improve the precision of measuring gravitomagnetic effects experimentally. Ongoing large-scale rotation experiments on earth and underground are reaching the sensitivity of measuring
gravitomagnetic effect. These developments will lead to establishing an ultra-precise reference frame based on Earth and the solar system. It will be useful for fundamental astronomy and space navigation.

Large Laser Gyroscope / 32

Large scale space interferometry to measure galactic gravitomagnetism

Authors: Angelo Tartaglia[1]; Massimo Bassan[2]

[1] *Politecnico di Torino*

[2] *Istituto Nazionale di Fisica Nucleare*

The proposal that will be presented is to use space based interferometers, designed for gravitational waves detection, as sensors for the gravitomagnetic field of the Milky Way. The technique would be based on the asymmetric propagation of light along the closed contour of the interferometer originated by the various components of the proper rotation of the device and by the chirality of the space time due to the angular momentum of our galaxy. A size with sides in the order of one million kilometres or more should allow the detection of both components of the angular momentum: the visible and the dark one (if it is there).

The principle idea is discussed and the various practical problems and ways out are mentioned, using LISA as an example. The expected signal could be modulated thanks to the annual oscillation of the plane of the interferometer with respect to the galactic plane and to the spin axis of the Sun.

General Relativity / 33

Gravitomagnetic field and gravitational waves

Author: Matteo Luca Ruggiero[1]

Co-author: Antonello Ortolan [2]

[1] *Università degli Studi di Torino*

[2] *Istituto Nazionale di Fisica Nucleare*

Corresponding Author: matteoluca.ruggiero@unito.it

We discuss here the possibility to detect high frequency gravitational waves by exploiting gravitomagnetic effects. In the laboratory frame, using the construction of the Fermi frame, the field of a gravitational wave can be described in terms of gravito-electromagnetic fields that are transverse to the propagation direction and orthogonal to each other. In particular, the gravito-magnetic field acts on spinning particles and under suitable conditions, a gravito-magnetic resonance may appear: this phenomenon can be used to design a new type of gravitational wave detectors, based on collective spin excitations, e.g. spin waves in magnetized materials.

Geophysical applications / 34

Earth's Rock and Roll: Rotational Motions in Seismology

Corresponding Author: igel@geophysik.uni-muenchen.de

The unwanted noise of ring lasers (whenever seismic wave fields perturb their measurements of Earth's rotation rate) has led to a new field: rotational seismology. The additional ground motion components (i.e. rotation around three orthogonal axes) had been widely ignored, as they are very difficult to measure. Yet, when combined with collocated standard seismometers (three components of displacement) a wealth of information can be recovered from the wavefield. We will report on these new developments with applications in seismic tomography, earthquake physics, planetary seismology, engineering, and other fields.

General Relativity / 35

Lorentz Violation and Sagnac Gyroscopes

Corresponding Author: jtasson@carleton.edu

This presentation will review the implications of Lorentz Violation for Sagnac gyroscopes using the framework of the Standard-Model Extension.

Large Laser Gyroscope / 36

High Resolution Inertial Earth Sensing with Large Sagnac Interferometers

Author: Ulrich Schreiber[1]

Co-authors: Jan Kodet [1]; Thomas Klügel [2]

[1] *Technical University of Munich*

[2] *Federal Agency of Cartography and Geodesy*

Corresponding Author: ulrich.schreiber@tum.de

Ring lasers are now resolving the rate of rotation of the Earth with 8 significant digits. Technically they constitute a Sagnac interferometer, where a traveling wave resonator, circumscribing an arbitrary contour, defines the optical frequency of two counter-propagating resonant laser beams. Subtle non-reciprocal effects on the laser beam however, cause a variable bias, which reduces the long-term stability. Over the last two years, we have improved the performance of the G ring laser to the point, that we obtain long-term stable conditions over more than a year. Advances in the modeling of the non-linear behavior of the laser excitation process as well as some small but significant improvements in the operation of the laser gyroscope are taking us now right to the doorstep, where the periodic part of the Length of Day variation of the Earth rotation can be recovered. This talk outlines the current state of the art of inertial rotation sensing in the geosciences. Furthermore, we discuss the next steps for a further enhanced sensor stability. At this point in time there is no apparent fundamental limit of this technique in sight.

Poster Session / 37

GINGER analysis pipelines

Authors: Angela Dora Vittoria Di Virgilio[1]; Simone Castellano[1]

[1] *Istituto Nazionale di Fisica Nucleare*

Corresponding Author: simone.castellano@pi.infn.it

Gingerino, prototype for the GINGER experiment, is a ring laser gyroscope that measures the Earth angular velocity, exploiting the Sagnac effect.
Such a measurement, other than for geophysical purposes, is for fundamental physics measurements, if performed with precision and accuracy better than one part over 10^9.
GINGER is a multipurpose experiment, and a few pipelines are developed for its data analysis.
A geophysics dedicated pipeline is meant to be fast, with suitable filters and data decimation; the high sensitivity analysis is developed in more directions: correcting laser non-linearities, by expansion in series of the "raw"signal (linearization) and linear regression methods; utilizing a double Sagnac signal, which allows to improve of a factor 2 the signal-to-noise ratio, and monitoring the double signal as a feedback on data.
Such methods are described, and current results on Gingerino data.

Poster Session / 38

Comparison between GNSS and the Gingerino.

Author: Giuseppe Di Somma[1]

[1] *Istituto Nazionale di Fisica Nucleare*

Corresponding Author: giuseppe.disomma@pi.infn.it

The detection of local deformations is a hot topic in geodesy. In our analysis we compare the signal from Gingerino with the ones from the GNSS stations, homogeneously selected around the position of Gingerino. Then we derived the rotational component of the area circumscribed by the GNSS stations and compared it with the Gingerino signal.
We used two different methods. In the first one, using Gingerino position as the pole, the rotational

component of each individual station is derived and then the rotation vector associated to the area circumscribed by the stations is obtained by performing a weighted average. In the second method, we calculate the z-component of the curl of the area circumscribed by the constellation of stations at Gingerino position.
The coherences between the signals from the two different methods and the Gingerino signal show similar structures that even exceed 60% coherence over the 6-15 days period.
This is the first time a comparison between these instruments has been performed and the promising results encourage to extend the analysis over longer periods.

Space Applications / 39

What could be learned from ring laser gyroscope about the Earth's rotation?

Author: Christian Bizouard[1]

[1] *Observatoire de Paris*

Corresponding Author: christian.bizouard@obspm.fr

The modern astrogeodetic techniques allow to determine the Earth's rotation around its center of mass with unprecedented accuracy. The orientation of the International Earth reference frame with respect to the geocentric International Celestial Reference Frame is obtained to within 0.1 mas, which corresponds to an equatorial arc of 3 mm. However, the striking harvest of results obtained by the astrogeodetic techniques seems to have reached a threshold. There has been no real progress since the 2010's: the nutation terms below 14 days are still not perfectly recovered, the intra-daily and subdaily fluctuations of the polar motion motion and UT1 are not followed regularly. In this respect, the observations brought by the ring laser gyroscope (RLG) could allow a better recovery of these frequency bands, as well as the sub-hourly band, which cannot be explored by the mean of astrogeodesy.

Poster Session / 40

Multi-axis quantum gyroscope with multi loop atomic Sagnac interferometry

Author: Matthias Gersemann[1]

Co-authors: Ann Sabu [1]; Ashwin Rajagopalan [1]; Christian Schubert [2]; Dennis Schlippert [1]; Ernst Rasel [1]; Mouine Abidi [1]; Philipp Barbey [1]; Sven Abend [1]; Yueyang Zou [1]

[1] *Leibniz Universität - Institut für Quantenoptik, Welfengarten 1, 30167 Hannover, Germany*

[2] *Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Institut für Satellitengeodäsie und Inertialsensorik, Germany*

Corresponding Author: gersemann@iqo.uni-hannover.de

Inertial sensors based on matter-wave interference show great potential for navigation, geodesy, or fundamental physics. As known from the Sagnac effect, their sensitivity to rotations increases with the space-time area enclosed by the interferometer. In the case of light interferometers, the latter can be enlarged by forming multiple (fibre) loops. However, the equivalent for matter-wave interferometers remains an experimental challenge. This contribution presents a concept for a multi-loop atom interferometer with a scalable area formed by multiple light pulses. It exploits ultra-cold atomic ensembles, produced with atom-chip technology, combined with symmetric beam splitting and a relaunch mechanism. Due to its scalability, it offers the perspective to achieve high sensitivities to rotations in compact volumes. In addition, it can be extended by adding a second orthogonal beam

splitting axis, which enables the detection of multiple rotational components. Following this conceptualization, the experimental design of a multi-axis quantum gyroscope with multi-loop capability based on the previously mentioned ideas is presented.

We acknowledge financial support from the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy - EXC-2123 QuantumFrontiers - 390837967 and through the CRC 1227 (DQ-mat), as well as support from DLR with funds provided by the BMWi under grant no. DLR 50NA2106 (QGyro+).

Space Applications / 41

Verification of the gravitational interaction in the field of the Earth with the LARASE and SaToR-G experiments

Author: David Lucchesi[1]

[1] *Istituto Nazionale di Fisica Nucleare*

Corresponding Author: david.lucchesi@roma2.infn.it

The previous experiment LARASE (LAser RAnged Satellite Experiment, 2013-2019) and the current experiment SaToR-G (Satellite Test of Relativistic Gravity, 2020-2024) – both funded by the National Scientific Committee 2 (CSN2) of the National Institute for Nuclear Physics (INFN) – have so far allowed to obtain a series of significant results in the study of the gravitational interaction in the so-called weak-field and slow-motion (WFSM) limit of General Relativity (GR) in its linearized form. In the WFSM limit of the theory, Einstein's equations reduce to a form quite similar to those of electromagnetism, with a gravitoelectric field produced by masses, analogous to the electric field produced by charges, and a gravitomagnetic field produced by mass currents, analogous to the magnetic field produced by electric currents.
These two fields are at the origin of two non-classical precessions of the orbit of an artificial satellite. The first precession is due to the mass of the Earth, and it is known as Schwarzschild's or Einstein' s precession of the orbit. This is a spin-independent secular precession. The second precession is due to the angular momentum (or spin) of the Earth, and it is known as the Einstein-Thirring-Lense secular precession of the orbit. The latter is a spin-orbit effect, also known as frame-dragging, as Einstein called it. This precession is related with intrinsic gravitomagnetism.
The LARASE and SaToR-G experiments focused on measuring these precessions using the geodetic satellites LAGEOS (NASA, 1976), LAGEOS II (ASI/NASA, 1990) and LARES (ASI, 2012) as test masses. These are passive satellites equipped with corner cube retroreflectors tracked by means of the powerful Satellite Laser Ranging technique. The main goal was to verify the motion of each test mass along a geodesic of spacetime by means of a very precise determination of their orbits. The challenge is represented by a reliable modeling of the main gravitational and non-gravitational perturbations (NGPs) acting on the considered satellites.
Indeed, both types of perturbations can have a negative impact in relativistic measurements. Mismodeling of gravitational perturbations, especially of the even zonal harmonic coefficients, can completely mask the tiny relativistic precessions due to GR because of their much larger classical precession of the orbit. Conversely, NGPs are very complicated to model and have a periodic impact in the orbital elements, with very long period perturbations superimposed on the relativistic precessions making their measurement extremely complicated.
The results achieved by the two experiments will be presented in the measurement of the main relativistic precessions in the orbits of the three satellites together with the consequent limits obtainable from these measurements for several theories of gravitation alternative to GR. These constraints may concern both metric theories of gravitation, such as scalar-tensor theories, and non-metric theories of gravitation, such as torsional theories. Finally, the prospects for future measurements of the gravitational interaction in the Earth field with laser-ranged satellites will be presented.

Poster Session / 42

Fundamental Physics with the Galileo Constellation: the Galileo for Science Project

Author: Feliciana Sapio[1]

Co-authors: David Lucchesi [1]; Massimo Visco [1]; Carlo Lefevre [2]; Marco Cinelli [2]; Alessandro Di Marco [2]; Emiliano Fiorenza [2]; Pasqualino Loffredo [2]; Marco Lucente [3]; Carmelo Magnafico [4]; Roberto Peron ; Francesco Santoli [2]; Natalia Gatto [2]; Francesco Vespe [5]

[1] *Istituto Nazionale di Fisica Nucleare*

[2] *IAPS-INAF*

[3] *INAF/IAPS*

[4] *Istituto Nazionale di Astrofisica*

[5] *Italian Space Agency*

Corresponding Author: fel.sapio@studenti.unina.it

The Galileo for Science Project (G4S_2.0) is an Italian Project funded by the Italian Space Agency (ASI) that aims to provide Fundamental Physics measurements with the Galileo-FOC constellation. These concern both the analysis of atomic-clocks data and that of satellite orbits. A new accurate analysis of the satellites onboard atomic-clocks can lead to two significant results: i) measuring the gravitational redshift and, consequently, making a local position invariance (LPI) test, and ii) searching for possible Dark Matter Domain-Wall of Galactic origin. Conversely, precise orbit determination (POD) of satellites allows the relativistic precessions of satellite orbits to be measured at a much higher altitude than previous measurements with passive geodetic satellites.
In particular, the two satellites GSAT-0201 and GSAT-0202 on elliptical orbits will be exploited for the measurement of the gravitational redshift, as the on-board atomic clocks frequency is periodic-modulated with respect to on-ground clocks. Whereas for the Dark Matter constraints, the entire Galileo constellation will be considered: the goal is to search for interactions with possible Dark Matter candidates, such as Domain Wall, that would cross the entire constellation. If this happens, on-board clocks would have to change their frequency relative to a reference clock on Earth.
Finally, measuring the relativistic precessions will allow to study possible deviations from General Relativity and to compare its prediction with those of other theories of gravitation.

To pursue the goals of G4S_2.0, a fundamental key point in our analysis is obtaining the satellite's position, as a product of the POD. As a consequence, modeling, as better as possible, the complex effects of the Non-Gravitational Perturbations (NGPs) is essential, such as the direct solar radiation pressure. Many of our efforts go in this direction. The state of the art will be presented, both as regards the measurements of Fundamental Physics and the development of new models for NGPs.

General Relativity / 49

Fundamental physics with table-top experiments: A particle theory perspective

From atom interferometry to NMR, table-top experiments have been pushing the frontier of precision for decades. In this talk, I will present a particle theory perspective on how these advances can be used to look for well-motivated beyond the standard model particles and phenomena.

Rotation Sensors / 50

GINGERINO sensitivity and quantum noise

Corresponding Author: alberto.porzio@na.infn.it

Absolute angular rotation rate measurements with sensitivity better than prad/sec would be beneficial for fundamental science investigations. On this regard, large frame Earth based ring laser gyroscopes are top instrumentation as far as bandwidth, long term operation and sensitivity are concerned.
GINGERINO, the active ring laser prototype of the GINGER collaboration, has shown an unprecedented sensitivity close to 2×10^{-15} rad/sec for $\sim 2 \times 10^5$ s of integration time. This sensitivity is more than a factor 10 better than the shot–noise as defined by actually accounted theoretical prediction for ring lasers.
The usually adopted theoretical model relies on the strong hypothesis that the two counter propagating beams are completely independent so that their field variables are uncorrelated. In this context, the shot-noise for a ring laser is the sum of the shot-noise accounted for the two single beams.
In this contribution we will present the experimental determination of the GINGERINO noise limit in its present configuration and discuss possible novel approach for elaborating an amended theoretical model that account for the interaction of the two beams at a quantum level.

Poster Session / 51

Modeling and analysis of Distributed Acoustic Sensing (DAS) data in microseismic monitoring applications.

Author: Davide Pecci[1]

Co-authors: Eusebio Stucchi [2]; Giacomo Rapagnani [2]; Juan Porras [2]; Michele De Solda [2]; Renato Iannelli [1]; Francesco Grigoli [2]

[1] *Dipartimento di Ingegneria dell'Energia, dei Sistemi, del Territorio e delle Costruzioni. Università di Pisa*

[2] *Dipartimento di Scienze della Terra*

Corresponding Author: g.rapagnani@studenti.unipi.it

DAS technology is particularly suitable for microseismic monitoring application in geothermal environments. This instrumentation can resist to high temperatures (up to about 100℃ or more) higher than the operational temperature of standard acquisition instruments (e.g., geophones), allowing the fiber to be located very close to the reservoir. For this reason, DAS is particularly useful for induced seismicity monitoring of Enhanced Geothermal System (EGS). Being of recent development, this acquisition technology still lacks appropriate modeling and analysis tools able to handle such a large amount of data without losing efficiency. Furthermore, open-access DAS datasets are still a rarity, if compared to other geophysical datasets (e.g., seismological data). Therefore, we aim to generate an open-access synthetic (but realistic) DAS dataset that may help the geophysical community to develop "ad hoc"data analysis methods suitable for this kind of data. In the presented work we make use of the spectral element modeling software 'Salvus', developed by Mondaic, which also allows the simulation of DAS data. In particular, it outputs a strain measurement between all points defined as receivers in the simulation. Using the repositories of DAS data collected at the geothermal test site Frontier Observatory for Research in Geothermal Energy (FORGE) located in Utah (USA), we tried to simulate realistic DAS acquisition conditions of seismic events related to low-magnitude natural seismic activity from the nearby Mineral Mountains and microseismic events related to hydraulic stimulation operations for the generation of an EGS.
In order to obtain realistic synthetic data, we first analyze the spectral properties of real noise waveforms by using the Power Spectral Density (PSD) Analysis. Starting from observed PSDs we model the synthetic noise waveforms using a stochastic approach. Then we add it to the synthetic event traces and compare them with the observed ones. We finally test a semblance-based event detector on a 1-hour continuous waveforms of synthetic data to evaluate the performance of the detector in different operational conditions (e.g., different noise levels and inter-event times).

Poster Session / 52

ROMY: On the operation and monitoring of a heterolithic large ring laser array

Author: Andreas Brotzer[1]

Co-authors: Heiner Igel [1]; Karl Ulrich Schreiber [2]; Felix Bernauer [1]; Jan Kodet [3]; Joachim Wassermann [1]

[1] *Ludwig Maximilians University Munich*

[2] *Technical University Munich, Geodetic Observatory Wettzell, Germany*

[3] *Technical University Munich, Geodetic Observatory Wettzel*

Corresponding Author: brotzer@geophysik.uni-muenchen.de

The large ring laser array ROMY (ROtational Motions in seismologY) consists of four Sagnac interferometer, each representing an individual, high-sensitive rotation rate sensor, joined as a tetrahedral, heterolithic structure, due to its triangular rings of 12 meter side length. This size and the heterolithic construction introduces new challenges in the operation and monitoring of a large ring laser. Currently high performing ring lasers, such as G-ring, are individual, monolithic large ring lasers, that are less affected by mechanical instability, however, suffer from orientation changes that contribute to the variation in Sagnac frequency. Exploiting the full potential of a large ring laser array, such as ROMY, would enable to observe rotational ground motions close to the rotational low noise model for all three components of rotation.

We discuss required steps towards a stable and enhanced performance of the heterolithic ring laser array ROMY, especially for seismology and present implemented tilt and environmental monitoring (temperature, humidity, pressure) as well as the influence of the signal processing chain on the obtained signals.

Geophysical applications / 53

Large-band tiltmeters for Newtonian Noise studies in Virgo and ET detectors

Author: Luciano Errico[1]

Co-authors: Annalisa Allocca [2]; Enrico Calloni [1]

[1] *Istituto Nazionale di Fisica Nucleare*

[2] *Universita' di Pisa - INFN Pisa*

In the field of gravitational waves detectors, seismic activity is a source of noise that can affect the sensitivity of the apparatus in many different ways. The most direct way consists in the shaking of the test masses induced by seismic activity; nonetheless, test masses can also be moved by a time-dependent gravity gradient generated by seismic activity (the so called Newtonian Noise). Direct seismic noise at low frequency is well monitored in all gravitational wave detectors and it is heavily suppressed by using actively-controlled multi-pendulum stages. Gravity gradient noise is not limiting the sensitivity of the second generation of GW detectors, but it could be a limiting noise for the next generation (like the Einstein Telescope) and thus it is useful to develop high-precision tiltmeters in order to monitor seismic activity, reconstruct the gravity gradient in time and subtract this noise passively or actively. Up to now, INFN Napoli group is producing large frequency band tiltmeters to both study Newtonian Noise and provide an extra sensor for seismic monitoring at low frequency. The first of this new tiltmeters has been recently installed in Virgo and it will acquire data during the whole Virgo scientific run O4.

General Relativity / 54

Testing Theories of Gravity by GINGER Experiment

Author: Salvatore Capozziello[1]

[1] *Università degli Studi di Napoli Federico II*

Many efforts are devoted to probe theories of gravity by Earth and space-based experiments at ultraviolet and infrared scales. In this debate, we propose straightforward tests by the GINGER experiment, which, being Earth based, requires little modeling of external perturbations, allowing a thorough analysis of the systematics, crucial for experiments where sensitivity breakthrough is required. Specifically, we show that it is possible to constrain parameters of gravity theories, like scalar-tensor or Horava-Lifshitz gravity, by considering their post-Newtonian limits matched with experimental data. In particular, we use the Lense-Thirring measurements provided by GINGER to find out
relations among the parameters of theories.

General Relativity / 55

Seismic Isolation of Advanced Virgo+

Corresponding Author: valerio.boschi@pi.infn.it

Since the first detection of gravitational waves in 2015, Advanced Virgo and Advanced LIGO interferometers have been able to detect almost 100 sources, starting the multi-messenger astronomy era. We will provide an overview of Advanced Virgo+ detector, concentrating on the seismic isolation system of its main optical components, the so-called superattenuator. We will discuss its mechanics and control strategies together with the perspectives and challenges for the future.

Poster Session / 56

Influence of the cavity impedance in a passive resonant laser gyroscope

Author: Yuhong Zhong[1]

Co-authors: Haobo Zhang [1]; Kui Liu [2]; Xiaohua Feng [1]; Yuxuan Chen [1]; Jinpei Yao [1]; Yawen Liu [1]; Zehuang Lu [1]; Jie Zhang [1]

[1] *Huazhong University of Science and Technology*

[2] *Sun Yat-sen University*

Corresponding Author: d202280060@hust.edu.cn

The optical ring cavity is the core component of a laser gyroscope. A higher finesse and narrower linewidth cavity are required. However, the property of cavity impedance matching is another key parameter for a passive resonant gyroscope (PRG). For a free-space PRG, the laser is injected into the cavity and the laser frequency is locked to the cavity resonance by using the Pound-Drever-Hall (PDH) method. The discriminant slope in the PDH scheme plays an important role in reaching a better locking performance and hence a higher sensitivity of the gyroscope. We find the cavity finesse and the cavity impedance matching factor affect the discriminant slope differently. The balance of high finesse and low impedance matching factor can be optimized through the relationship of the discriminant slope with respect to the mirror parameters. Moreover, the lower impedance matching factor allows a higher intra-cavity laser power, which can increase the ultimate sensitivity of the gyroscope.

Poster Session / 57

Polarization-selective locking scheme in a passive resonant gyroscope

Author: Haobo Zhang[1]

Co-authors: Kui Liu [2]; Xiahua Feng [1]; Yuxuan Chen [1]; Yuhong Zhong [1]; Jinpei Yao [1]; Yawen Liu [1]; Jie Zhang [1]; Zehuang Lu [1]

[1] *Huazhong University of Science and Technology*

[2] *Sun Yat-sen University*

Corresponding Author: haobo_zhang@hust.edu.cn

Passive resonant gyroscope (PRG) is a type of rotation detector based on Sagnac effect, which has shown application potentials in inertial navigation, geophysics, and fundamental physics. Laser-frequency-locking techniques are essential in PRGs to keep the external injection laser resonant with the passive ring cavity. Here we realize a locking scheme based on the polarization property of the ring cavity, which does not require phase modulations on the laser source, avoiding the residual amplitude modulation noise introduced by electro-optic modulator as in the traditional Pound-Drever-Hall locking method. The phase shifts of the two orthogonal polarization eigen-modes used for locking are analyzed, and the influences of polarization elements on locking performance are also evaluated. Ultimately, we implement the polarization-selective locking scheme on a $30\ \mathrm{cm}\times 30\ \mathrm{cm}$ sized PRG, achieving a rotation sensitivity of $1.0\times 10^{-7}\ \mathrm{rad/s}/\sqrt{\mathrm{Hz}}$.

Large Laser Gyroscope / 58

Research progress on large-scale passive laser gyroscopes operated at 532 nm

Author: Yuxuan Chen[1]

Co-authors: Kui Liu [2]; Xiaohua Feng [1]; Haobo Zhang [1]; Yuhong Zhong [1]; Jinpei Yao [1]; Yawen Liu [1]; Zehuang Lu [1]; Jie Zhang [1]

[1] *Huazhong University of Science and Technology*

[2] *Sun Yat-sen University*

Corresponding Author: yuxuanchen@hust.edu.cn

Large-scale laser gyroscopes are precise devices for angular velocity measurement based on Sagnac effect, and their performance is positively related to the scale factor. To obtain a higher rotational resolution, we develop a large-scale-factor green laser gyro with a size of 8-meter by 8-meter in Wuhan, China, operated at a wavelength of 532 nm. The expected Sagnac frequency is 556.7 Hz. The cavity Q-factor is inferred to be 2.8×10^{12} via an estimated mirror loss of 34 ppm each. At the same time, its twin, the 10-meter by 10-meter green-light-gyro, is also being prepared at Sun Yat-sen University in Zhuhai, China. This talk will focus on the scheme design and noise evaluation of these two setups.

Large Laser Gyroscope / 59

Long- term operation of a large-scale passive laser gyroscope

Author: Kui Liu[1]

Co-authors: Yuxuan Chen [2]; Haobo Zhang [2]; Yuhong Zhong [3]; Jinpei Yao [2]; Yawen Liu [2]; Jie Zhang [2]; Zehuang Lu [2]; Xiahua Feng [2]

[1] *Sun Yat-sen University*

[2] *Huazhong University of Science and Technology*

[3] *Huazhong University Of Science And Technology*

Large-scale laser gyroscopes with sufficiently high sensitivity are inertial sensors with the capability to measure the rotational components of various geophysical motions. However, the specific application require that the instrument can be run continuously. The cavity perimeter fluctuations and laser frequency noise become challenges in larger-scale passive resonant gyroscopes (PRGs). In this talk, we introduce a three-wave differential locking scheme for a 3 m by 3 m large-scale PRG, resulting in an in-situ measurement of the cavity perimeter with nanometer resolution. Furthermore, the laser frequency noise is effectively suppressed with an additional gain of 30 dB by a double-stage locking system, based on the three-wave differential locking scheme. Finally, the rotation rate resolution of our 3 m×3 m gyroscope improves to 1.1×10^{-9} rad/s over 200 s and operated for 5 months without interruption. Several teleseismic events with a Love wave content larger than 10^{-9} rad/s have been routinely recorded during the long-term run. The simplicity, robustness, and effectiveness of the locking scheme are important to the long-term operation of large-scale PRGs aiming for applications in the geosciences.

Poster Session / 60

Hollow Core Photonic Crystal Fibers in High-Precision Sensing Applications

Author: Alessandro Porcelli[1]

Co-authors: Andrea Camposeo [2]; Antonio Alvaro Ranha Neves [3]; Dario Pisignano [4]; Donatella Ciampini [5]; Ennio Arimondo [4]; Peter Seigo Kincaid [6]

[1] *Dipartimento di Fisica "E. Fermi" - University of Pisa*

[2] *NEST, Istituto Nanoscienze-CNR*

[3] *Universidade Federal do ABC*

[4] *University of Pisa*

[5] *Dipartimento di Fisica "E. Fermi" - University of Pisa, INFN*

[6] *Scuola Superiore Sant'anna*

Corresponding Author: alessandroporcelli91@gmail.com

Hollow Core Photonic Crystal Fibers (HC-PCFs) are a novel type of optical fibers, featuring several physical characteristic making them suitable for the development of high precision, next generation optical and optomechanical sensors. The hollow core and single-material structure allow for high power delivery and strongly increase the stability of interferometric fiber optic gyroscopes (IFOGs) by reducing non-reciprocal noise due to temperature fluctuations and electromagnetic radiation. We report on the characterization of optical guiding properties of HC-PCFs as well as their application as high-resolution temperature sensors through optical trapping and guidance of dielectric probes in the hollow core.

Rotation Sensors / 61

Rotation sensors based on atom interferometry

Author: Christian Schubert[1]

Co-authors: Arne Wacker [1]; Christian Deppner [1]; Marcel Eichelmann [1]; Sandra Gerlach [1]; Waldemar Herr [1]; M Gersemann [2]; S Abend [2]; E.M. Rasel [2]

[1] *Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Satellitengeodäsie und Inertialsensorik*

[2] *Leibniz Unversität Hannover, Institut für Quantenoptik*

Corresponding Author: christian.schubert@dlr.de

In analogy to light interferometers, atom interferometers are sensitive to rotations if they enclose an area. Due to the different energy scales of the interfering particles, atom interferometers can potentially reach competitive sensitivities to large laser gyroscopes while maintaining a comparably compact and transportable sensor size [1]. In this contribution, we will introduce the principle of atom interferometry, discuss the current status of rotation sensors based on atoms in free fall as well as relevant developments, and show a concept for a multi-loop atomic Sagnac interferometer with an anticipated sensitivity of 20 prad/s at 1 s [1].

[1] C. Schubert, S. Abend, M. Gersemann, M. Gebbe, D. Schlippert, P. Berg, E. M. Rasel , Sci. Rep. 11, 16121 (2021).

Geophysical applications / 63

Multi-geophysical observations in HDUL, China

Author: Yun Wang[1]

Co-authors: Chang Chen [1]; Wei Li [1]; Yi Zhang [1]

[1] *China University of Geosciences, Beijing, 100083*

Compared with the surface, deep underground laboratories are characterized with ‘super-quiet’ and ‘ultra-clean’environment, which could be a perfect experimental platform for long-term and high-precision geophysical observation and relevant research (Gaffet et al.,2003; Rosat et al.,2016; Simonelli et al.,2016; Bruno & Fulgione, 2019; Wang et al.,2022). Since 1950s, many underground laboratories have been established using cavities in mountain or mining tunnels (Lesko, 2008, 2015; Acernese et al., 2010). We rehabilitate a discarded coal mine, where the mining tunnels reach deep to -848m below sea level, and are buiding Huainan Deep Underground Laboratory (HDUL); and simultaneously execute nearly two-year of joint geophysical observations (Wang et al.,2023), including radioactivity survey, gravity, geomagnetic, magnetotelluric and seismic observations.
It is verified that the levels of ambient noise, vibration and electromagnetic interference at HDUL is obviously prior to the surface environment. It can be inferred that HDUL not only benefit for ultra-lower background cosmic observation and research, depurative magnetic and electric observations, quiet gravity and seismic observations, it will provide helps to clean and correct the polluted data observed at the surface and provide ideal platform to metrological research (Chen et al.,2022; Chen et al.,2023; Sun et al.,2022). As many research have supported that the underground Lab is specially suitable to perform space physics, atmospheric physics, astronomics, cosmology, solid geophysics etc, multi-disciplinary observation and studies, our low-temperature SQUID magnetic observation in HUDL presents fT magnetic background, which promise the probability to explore the origin of intrinsic magnetic field of the earth and possible correlation between the Schumann’ resonance and the brain magnetic field.

References
Acernese F, De Rosa R, De Salvo R, et al. 2010. Long term seismic noise acquisition and analysis in the Homestake mine with tunable monolithic sensors. Journal of Physics: Conference Series, 228: 012036, doi: 10.1088/1742-6596/228/1/012036.
Bruno, G., & Fulgione, W. (2019). Flux measurement of fast neutrons in the Gran Sasso underground laboratory. The European Physical Journal C, 79(9), 747. https://doi.org/10.1140/epjc/s10052-019-7247-9
Chen, C., Wang, Y. (2023). Deep Underground Earthquake Observation: Translations, Rotations and Applications. 84th EAGE annual.

Chen, C., Wang, Y., Guo, G., Cao, Y., Li, S., Zhang, D., et al. (2022). Deep underground observation comparison of rotational seismometers. Chinese Journal of Geophysics (in Chinese), 65(12), 4569–4582. https://doi.org/10.6038/cjg2022Q0318
Gaffet, S., Guglielmi, Y., Virieux, J., Waysand, G., Chwala, A., Stolz, R., et al. (2003). Simultaneous seismic and magnetic measurements in the Low-Noise Underground Laboratory (LSBB) of Rustrel, France, during the 2001 January 26 Indian earthquake. Geophysical Journal International, 155(3), 981–990. https://doi.org/10.1111/j.1365-246X.2003.02095.x
Lesko K T. 2008. The deep underground science and engineering laboratory at Homestake. Journal of Physics: Conference Series, 136: 022022, doi: 10.1088/1742-6596/136/2/022022.
Lesko K T. 2015. North American deep underground laboratories: Soudan Underground Laboratory, SNOLab, and the Sanford Underground Research Facility. AIP Conference Proceedings, 1672(1): 020001, doi: 10.1063/1.4927978.
Rosat, S., Hinderer, J., Boy, J.-P., Littel, F., Boyer, D., Bernard, J.-D., et al. (2016). First analyses of the iOSG-type superconducting gravimeter at the low noise underground laboratory (LSBB URL) of Rustrel, France. E3S Web of Conferences, 12, 06003. https://doi.org/10.1051/e3sconf/20161206003
Simonelli, A, Belfi Jacopo, Beverini Nicolò, Carelli Giorgio, Di Virgilio Angela, Maccioni Enrico, et al. (2016). First deep underground observation of rotational signals from an earthquake at teleseismic distance using a large ring laser gyroscope. Annals of Geophysics, 59, 1. https://doi.org/10.4401/ag-6970
Sun, H., Chen, X., Wei, Z., Zhang, M., Zhang, G., et al. (2022). A preliminary study on the ultra-wide band ambient noise of the deep underground based on observations of the seismometer and gravimeter. Chinese Journal of Geophysics (in Chinese), 65(12): 4543-4554, https://doi.org/10.6038/cjg2022Q0559
Wang, Y., Jian, Y., He, Y., Miao, Q., Teng, J., Wang, Z., et al. (2022). Underground laboratories and deep underground geophysical observations. Chinese Journal of Geophysics (in Chinese), 65(12): 4527-4542, https://doi.org/10.6038/cjg2022Q0404
Wang, Y., Yang, Y., Sun, H., Xie, C., Zhang, Q., Cui, X., et al. (2023). Observation and research of deep underground multi-physical fields—Huainan −848 m deep experiment. Science China Earth Sciences, 66(1), 54–70. https://doi.org/10.1007/s11430-022-9998-2

Rotation Sensors / 64

Doppler Gyroscopes: Frequency vs Phase Estimation

Author: John Howell[1]

Co-authors: Einav Grynszpan [2]; Merav Khan [2]; Stefania Residori [3]; Umberto Bortolozzo [3]; Ziv Cohen [2]

[1] *Institute of Quantum Studies Chapman University; Racah Institute of Physics, Hebrew University of Jerusalem*

[2] *Racah Institute of Physics, Hebrew University of Jerusalem*

[3] *Hoasys, Nice, France*

The burgeoning field of quantum metrology seeks to find “quantum advantages”over existing classical measurement schemes. Owing to its importance in gyroscopes and gravitational wave detection as well as its fundamental nature in all branches of interferometry, phase estimation beyond the standard quantum limit has been the prototypical example. Pragmatically, due to loss, quantum phase estimation techniques have, so far, only offered a few percent improvement over the standard quantum limit in the few-photon regime or a few dB improvement in the high power regime. However, what if phase estimation for a class of experiments is suboptimal? Depending on the measurement apparatus, phase estimation may have different fundamental limits than frequency estimation. I will discuss a new type of gyroscope that relies on an ultra-steep, frequency-dependent gain measurement rather than performing phase estimation in a passive gyroscope. Withthis technique we can achieve orders of magnitude improvement below the phase-estimation standard quantum limit of a single-loop Sagnac interferometer of the same size. I will discuss important insights into a long-debated open question about the role of Doppler shifts in the Sagnac effect.

Geophysical applications / 65

6C recordings from Stromboli volcano

Author: Thomas Braun[1]

Co-authors: Felix Bernauer [2]; Frederic Guattari [3]; Heiner Igel [4]; Joachim Wassermann [2]; Sabrina Keil [4]

[1] *Istituto Nazionale di Geofisica e Vulcanologia*

[2] *Ludwig Maximilians University Munich*

[3] *iXblue*

[4] *Department of Earth and Environmental Science, Ludwig-Maximilians-University Munich*

Near field recordings and thus finite source inversions of volcano-induced events often suffer from unaccounted effects of local tilt, saturation of classical instrumentation, unknown shallow velocity structure and doubtful orientation of the instruments. In addition, if the station number is limited the results of moment tensor inversions are very often not well constrained. Recent advances in hardware development made it possible to install several very broadband, high sensitive rotational motion sensor, based on fiber optical gyroscope technology, in very close distance of an activate volcano, i.e., on Stromboli volcano in 2016, 2018 and 2022, respectively. Using this new instrument together with classical instrumentation (i.e., translational seismometer, infrasound and tilt meter) we were able to record more than four weeks of permanent strombolian activity at Stromboli during these two experiments. The resulting six axis measurements reveal clear rotations around all three coordinate axis. We are furthermore able to demonstrate how this six axes measurements can help to improve the location procedure due to the property of a fiber optic gyro to act as a physical wave polarizer. We also demonstrate the application of a single site shallow velocity estimation using volcanic background noise only, which will further improve the reliability of the source mechanism estimate. As a concluding step we will demonstrate how the use of sparse 6C measurement might be able to reduce the ambiguity of moment tensor inversions of volcano related signals.

Geophysical applications / 66

Gravimetry in the Italian area: future developments and perspectives

Author: Filippo Greco[1]

Co-authors: Federica Riguzzi [2]; Giovanna Berrino [3]

[1] *INGV-OE*

[2] *INGV-ONT*

[3] *INGV-OV*

In Italy, gravimetry is largely carried out since ’80 to study and monitoring active volcanoes of central-southern and insular Italy, but was not extensively applied in seismic areas, except in Central Italy, where gravity measurements have been performed since 2018, aimed to study the dynamics of the main tectonic processes, also including absolute stations already present and measured in the area for different purposes. Here we present the state-of-the-art of the gravimetry in Italy and the developments and perspectives. Specifically, in order to lay the foundations for a multidisciplinary approach to natural risk assessment, a large-scale gravity network in Italy, which in the most advanced development will consist of about 10 sites, homogeneously distributed throughout the country, is under realization. The network will allow for determining the temporal variations of the long-term and long-wavelength gravity field in seismic and volcanic areas. The sites will be equipped with absolute or relative gravimeters in continuous or pseudo-continuous recording (e.g. 1 measurement every week). For this purpose, superconducting gravimeters and atomic and ballistic absolute gravimeters will be used, the only instruments capable of providing a highly precise and stable signal even in the long term. This network, will supplements the newly established National Reference Gravimetric Network (G0) and the National Gravimetric Service in the planning stage

Welcome / 68

Partecipant Registration

cancellate / 69

Precision rotation measurements with atom interferometry

Author: Runbing Li[1]

[1] *Wuhan Institute of Physics and Mathematics*

Atomic interferometry was developed based on the matter wave characteristics of atoms. Due to their shorter wavelength, the atom sensors have demonstrated their advantage on the scale factor for more precision rotation measurements. Meanwhile, the particle-like characteristics of the atoms make them more sensitive to environment noise, such as vibration noise, magnetic field and light field fluctuations, which limits the improvement of phase sensitivity. In this talk, I will review the research progress of atom-interferometer gyroscope and discuss the feasibility of developing different high-precision atom-interferometer gyroscopes for different application fields.

Rotation Sensors / 70

Self-calibrated atom interferometry for absolute rotation measurement

Author: Zhanwei Yao[1]

[1] *Wuhan Institute of Physics and Mathematics*

In this talk, I will discuss our recent progress in the absolute rotation measurement with an atom interferometer gyroscope. The high-precision gyroscope was developed by precisely aligning the orientation of three pairs of Raman beams thus to construct a large-area interference loop area. The scale factor of the atom-interferometer gyroscope is calibrated by precisely measuring the atomic velocity. In our experiments, the stability of atomic velocity was measured, and the dominant errors were evaluated. By modulating the atomic velocity, we demonstrate a self-calibrated method to extract the absolute phase shift caused by an arbitrary rotation in a large dynamic range.

General Relativity / 71

The ZAIGA Project

Author: Mingsheng Zhan[1]

[1] *Wuhan Institute of Physics and Mathematics Chinese Academy of Sciences*

ZAIGA is an acronym for Zhaoshan long-baseline Atom Interferometer Gravitation Antenna. ZAIGA project concept was proposed in 2019. The first phase of the project was funded recently. It will be a platform to test gravity theory with large scale atomic interferometers, atomic gyros and atomic optical clocks. In this talk I will tell the progress in design and building of the project.

Space Applications / 72

The role of the GGOS network in the definition of high precision geodynamic parameters

Authors: Cinzia Luceri[1]; Giuseppe Bianco[2]

[1] *e-GEOS S.p.A*

[2] *Agenzia Spaziale Italiana*

The Space Geodesy Centre of the Italian Space Agency is one of the the few core stations of the GGOS (Global Geodetic Oberving System) ground network. A "core station"hosts all the three main space geodetic techniques, namely Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI) and Global Navigation Satellite Systems (GNSS), precisely co-located in a common area.
The GGOS mission is the maintenance and the improvement of the International Terrestrial Reference Frame (ITRF) and its connection with the International Celestial Reference Frame (ICRF): each observing technique has its strengths and weaknesses with respect to the so-called three pillars of geodesy, namely geokinematics, earth gravity field and earth rotation.
Satellite Laser Ranging is particularly efficient in measuring the low-order coefficients of the geopotential and the instantaneous position of the Earth Center of Mass, which is the origin of the Terrestrial Reference Frame.

Poster Session / 74

Light Interferometer for Measurement of the Gravitational Behavior of Antimatter

Author: Giuseppe Vinelli[1]

Co-authors: Fabrizio Castelli [1]; Gabriele Rosi [1]; Guglielmo Maria Tino [1]; Leonardo Salvi [1]; Marco Giulio Giammarchi [1]; Massimiliano Rome' [1]; Michele Guido Sacerdoti [2]; Rafael Ferragut [3]; Valerio Toso [1]

[1] *Istituto Nazionale di Fisica Nucleare*

[2] *L-NESS and Department of Physics, Politecnico di Milano*

[3] *Politecnico di Milano*

Corresponding Author: giuseppe.vinelli@unifi.it

The QUPLAS (QUantum interferometry and gravitation with Positrons and LASers) experiment aims to test fundamental physical laws with antimatter by measuring the Positronium (Ps) fall in the Earth's gravitational field. Such measurement would represent a test of the Einstein Equivalence Principle and the CPT symmetry and is further motivated by the lack of information on antimatter behavior in the gravitational field.
The setup and techniques of the experiment involve three phases of production, preparation, and interference of the positronium beam. I will discuss the design, simulation and optimization of the Single Photon Large Momentum Transfer (LMT) Mach-Zehnder interferometer [1] composed by 23 laser pulses and used in the final stage of the experiment to reveal the influence of the Earth's gravitational field through the relationship that binds the phase shift of the wave function of Ps to the gravitational acceleration: $\Delta\phi = k_{eff}\ gT^2$. By simulating the interferometer, it was possible to estimate its efficiency, contrast and signal acquisition times as well as determining fundamental operating parameters such as the size, shape and power of the laser pulses and the divergence requirements on the positronium beam. These results will be shown in the exhibition.

[1] G. Vinelli et al., arXiv:2303.11798 [physics.atom-ph].

Welcome / 75

Introductory remarks

Corresponding Author: angela.divirgilio@pi.infn.it