A network of heterodyne laser interferometers for monitoring and control of large ring-lasers

Alberto Donazzan[1,2], Giampiero Naletto[1,2,3], Maria G. Pelizzo[2,3], Davide Cuccato[1,2],
Alessandro Beghi[1,2], Antonello Ortolan[4], Jacopo Belfi[5], Filippo Bosi[5], Andrea Simonelli[5,11],
Nicolò Beverini[6], Giorgio Carelli[6], Enrico Maccioni[6], Rosa Santagata[7], Alberto Porzio[8,10],
Angelo Tartaglia[9], and Angela Di Virgilio[5]

[1]Department of Information Engineering, Università di Padova, 35131 Padova, Italy
[2]INFN – Sezione di Padova, 35131 Padova, Italy
[3]CNR-IFN – Sezione di Padova, 35131 Padova, Italy
[4]INFN – Laboratori Nazionali di Legnaro, 35020 Legnaro (PD), Italy
[5]INFN – Sezione di Pisa, 56127 Pisa, Italy
[6]Department of Physics, Università di Pisa, 56127 Pisa, Italy
[7]Laboratoire de Physique des Lasers CNRS, Université Paris 13, 93430 Villetaneuse, France
[8]CNR-SPIN, 80126 Napoli, Italy
[9]Department of Applied Science and Technology, Politecnico di Torino, 10129 Torino, Italy
[10]INFN – Sezione di Napoli, 80126 Napoli, Italy
[11]Ludwig-Maximilians-Universität München, 80333 München, Germany

ABSTRACT

The sensitivity achieved by large ring-laser gyroscopes will make it possible to detect faint relativistic effects related to the rotation of the Earth's mass. This task requires a strict control of the ring cavity geometry (shape and orientation), which can be performed by a novel network of portable heterodyne interferometers, capable of measuring the absolute distance betweeen two retro-reflectors with a nominal accuracy better than 1nm. First steps have been taken towards the realization of this device and a starting prototype of distance gauge is under development and test.

Keywords: interferometry, metrology, heterodyne, ring-laser, gyroscopes, phase measurement

1. INTRODUCTION

The Lens-Thirring (LT) effect, also know as "inertial frame dragging", is a gravitational effect predicted by General Relativity which manifests as a continuous change in orientation of a spinning gyroscope moving around a massive rotating body.[1] The frame dragging produced by the Earth's rotating mass, although being very weak, has been detected so far through satellite based techniques down to 5 % accuracy.[2] Both the dedicated space mission Gravity Probe B (GP-B) and the data collected from laser ranged satellites, that is LAGEOS (LAser GEOdynamics Satellite), LAGEOS II and LARES (Laser Relativity Satellite), confirmed the LT effect with an increasing level of confidence.[3, 4]

We highlight the fact that, however impressive, all these results derived from several years of satellite orbits integration and complex data analysis, which permitted to get rid of the many present systematics and random errors and to provide a reliable value for the relativistic LT term.

A different approach to the detection of the Earth induced frame dragging consists of using large size ring-laser gyroscopes for accurately monitoring the Earth rotation rate. This quantity, collected in a ground-based laboratory and thus with respect to a dragged reference frame, will be compared to the Earth's rotation estimate

---

Further author information: (Send correspondence to A.D.)
A.D.: E-mail: alberto.donazzan@pd.infn.it, Telephone: +39 049 981 7490

provided by IERS (International Earth Rotation and Reference Systems Service), which is referenced to the fixed stars frame. The desired LT effect, together with other relativistic terms, can be obtained from the difference between these two quantities. The order of magnitude of the relativistic terms depends on the latitude, but is always below 1 part per billion of the Earth's rotation rate.[5] This means a required accuracy better than $10^{-14}\,rad/s$ for the angular rotation measurement.

Currently large ring-lasers are reaching increasingly higher sensitivities, already allowing for outstanding geophysical and geodetic measurements.[6] General Relativity tests and, more broadly, Fundamental Physics applications are just one step forward in the detection capabilities of these devices. Nevertheless such targets require several improvements, both in science and technology related to these instruments.

A Ring-laser gyroscope consists of a closed polygonal cavity where two oppositely traveling optical waves resonate. In an inertial frame each beam follows a path of the same length, but, if the system is rotated, a round-trip time difference occurs between the clockwise rotating and the counter-clockwise rotating beam, as they experience a longer and a shorter path respectively. This translates into a frequency difference of the two beams and an optical beat can be extracted from the cavity. Such a beat carries the information about the rotation rate of the reference frame. This physical phenomenon is known as "Sagnac effect" and the Sagnac frequency f_s (i.e. the frequency of the beat signal between the two beams) reads

$$f_s = \underbrace{\frac{4A}{\lambda p}}_{scale\ factor} \mathbf{n} \cdot \mathbf{\Omega} \tag{1}$$

where A and p are the area enclosed by the cavity and its perimeter respectively, λ is the wavelength of the laser beam, $\mathbf{n}$ is the vector normal to the plane where the ring-laser cavity lies and $\mathbf{\Omega}$ is the rotation rate vector. Thus Ω and f_s are linearly dependent through the parameter $(4A)/(\lambda p)$, which is known as "scale factor". This factor is purely geometrical and must be well known and kept constant to the same level of accuracy required for the angular rotation measure,[5] i.e. better than 1 part in 10^{10}.

2. THE GINGER PROJECT

GINGER (Gyroscopes IN GEneral Relativity) is an experiment proposal for the first time on ground measurement of the Earth induced LT effect.[7–10] More specifically, GINGER will consist of an array of at least three mutually orthogonal square ring-lasers (6-10 m in side), arranged, for instance, in a cubic or octahedral configuration, as shown in Figure 1a and Figure 1b. The tri-axial design will provide a complete estimation of the laboratory frame angular velocity. GINGER will be located in a deep underground site, possibly the INFN - National Laboratories of Gran Sasso, which is now housing a site characterization prototype called GINGERino.[11]

As previous experience on rigid ring-lasers has already demonstrated, ring-lasers with a monolithic design, that is which rely on passive stabilization means, do not allow to achieve the extremely high accuracy required for General Relativity tests, even in the most performing condition obtained with the "G" ring-laser in Wettzell.[6] In order to face this issue, GINGER will show an actively controlled heterolithic structure, whose geometry will be monitored and conveniently stabilized within the previously mentioned strictly binding specifications. A real-time gauge of the ring-lasers' geometrical frame is therefore necessary.

Until now two solution approaches have been implemented: ring-laser perimeter measurement based on the analysis of its cavity modes;[12] (square) ring-laser diagonals measurement through Pound-Drever-Hall interrogation of the Fabry-Perot cavities formed by each couple of opposite mirrors.[13] Unfortunately, the information gathered from the inside of a ring-laser cavity is not sufficient to properly constrain the instrument's geometry. This is due to all data collected by means of the two above approaches are strictly dependent on the ring-laser dynamics, such as backscattering and cavity non linearities. Therefore a third approach, based on an external metrology system, could reveal to be the only feasible solution to this open issue.

A possible realization of this alternative is represented by the "External Metrology Truss"[14,15] conceived by NASA's Jet Propulsion Laboratory (JPL) for the Space Interferometric Mission.[16] This device had to provide multiple length measurements, down to 10 pm precision, of the distances between several couples of retro-reflective
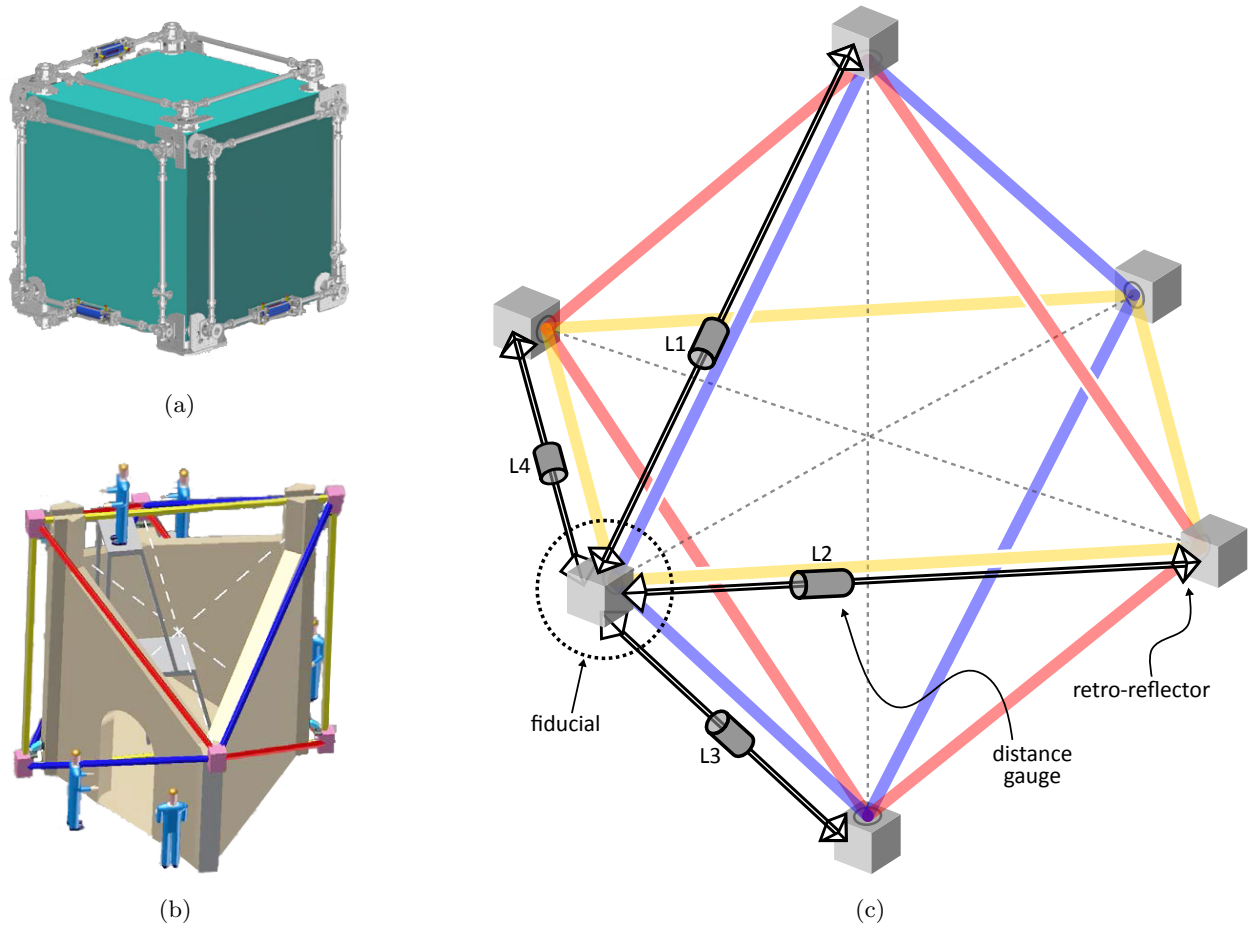
Figure 1: Simplified layout of the GINGER ring-laser array: (a) cube configuration; (b) octahedral configuration; (c) external metrology truss matched with GINGER in the ochtahedral configuration (for a clearer appearance only one complete vertex is showed).

fiducials located at specific locations on the spacecraft. The spacecraft geometry determination was mandatory for a reliable knowledge of the baseline length of a stellar interferometer aimed to planet finding. The monitoring truss was made up of a network of heterodyne laser interferometers. A common light source was provided by a fiber coupled $1319\,nm$ Nd:YAG continuous wave (cw) laser. Source light was split in half and each part sent to an acousto-optic modulator (AOM), where a frequency offset was introduced between the halves: heterodyne lights were created in this way and, after proper splitting, sent to every interferometer via polarization maintaining optical fibers (PMOF). Each interferometer (a single distance gauge) layed on a compact and portable Zerodur® base, where all the optics were firmly fixed. Single distance measurements were obtained by detecting the phase shift between two heterodyne beatings: the reference beating, generated by direct recombination of the source lights, and the measurement beating, generated by recombination between the source light and the measurement beam, which had travelled along a racetrack between two fiducials.

Together with this main displacement detection system, there existed some other subsystems working to provide additional features: a double laser source and an acousto-optical switch, devoted to two-colors interferometry for the determination of the absolute distance between the fiducials[14] with a better than $10\,\mu m$ accuracy; a pointing dithering system which protected against misalignments of the interferometer with respect to the axis ideally connecting the fiducials.[17] For a detailed description of the distance gauge refer to Ames et al.[18]

3. MONITORING GINGER'S GEOMETRY

Basically, the idea is to adapt the above concept to the case of GINGER. Moreover, this external metrology system will send its data to a feedback control loop, whose actuators will be multi-axial piezo-positioning stages carrying each ring-laser mirror.

If we consider an octahedral shape as the GINGER final configuration, every fiducial (one for each vertex) could be ideally composed by a single bulk substrate featuring both the ring-laser super-mirror, which is shared by 3 ring-lasers, and 4 corner retro-reflectors, one for each edge leaving from the given vertex. Thus the external metrology truss will be ideally set up by placing 12 compact distance gauges along the corresponding edges of the octahedron (Figure 1c). A dedicated vacuum system will be necessary to guarantee independent measurements from any ring-laser dynamics. Extremely accurate manifacturing of the fiducials will be essential as well, together with their geometrical characterization.

Furthermore, depending on the number of available interferometers and the type of physically craftable fiducials (either simple one-direction backreflectors, or multidirectional ones), an array of cross measurements can be realized to over-constraint the "rigidity" of the ring-laser array. Then, thanks to a detailed mathematical model of its geometry and a multivariable control scheme, it will be possible to drive the actuators to properly move the mirrors and actively control all the relevant dimensions of the cavities. In such a way, it will be possible to keep GINGER's geometry locked within the required accuracy, independently of any environmental disturbances.

The first step towards the realization of this device is the construction of its fundamental element, i.e. the compact heterodyne laser interferometer.

4. DESIGN OF THE DISTANCE GAUGE

The first working example of a distance gauge for GINGER will be a simplified prototype: its preliminary design will let us evaluate parts behavior, alignment issues and links between single components and overall system performances. The prototype will lie on a vibration isolated optical table and work in a standard air environment, certainly without claim to reach the final desired precision. The goal for this first step is to keep track of fiducials relative displacements with errors smaller than $100\,nm$.

The prototype's optical design mostly follows what was conceived for SIM, at least with respect to its basic working principle and the means of splitting between reference and measurement beams. The source light comes from a cw Nd:YAG DPSS laser featuring a $> 1\,kHz$ linewidth (over $100\,ms$) and analog frequency tunability; its $1064\,nm$ beam is fiber coupled right after exiting the device by means of a mirrors couple and an aspheric lens and then routed to a $50:50$ fiber splitter through single mode PMOF (Figure 2). Each half is then sent to a in-fiber AOM which shifts its optical frequency by respectively $150\,MHz$ and $150\,MHz + \Delta f$, where Δf can be tuned in the range from $0\,Hz$ to about $10\,MHz$. Finally, both beams travel through refractive fiber collimators and are ready to proceed across the free-space section of the distance gauge. The source beams exiting from the collimators show a cross section diameter of $8\,mm$ ($1/e^2$ width), which can be possibly adjusted using a couple of lenses arranged in keplerian telescope configuration.

The simplified optical schematic of a single interferometer is showed in Figure 3. The setup is similar to that of a standard Mach-Zehnder interferometer and actually this is the optical path that the reference beams (central part of each source beam) follow before recombinating and giving birth to a reference light beating. The measurement beam is picked out by means of a double sided mirror drilled at its center. This mirror spatially splits one of the source beams in two parts: the inner part, propagating straight through the hole along the Mach-Zehnder path, and the outer part, with a ring shaped section, hitting the mirror and travelling along a racetrack. In fact, this beam measures the distance between the fiducials by making a loop: the beam goes to the first fiducial (on the left of Figure 3) and hits it off-center; the reflected beam is offset and goes past the gauge to hit the second fiducial on the right; then the beam reflected by is offset again and lines up again with the double-sided mirror; finally the beam hits the back side of the drilled mirror and proceeds down to the
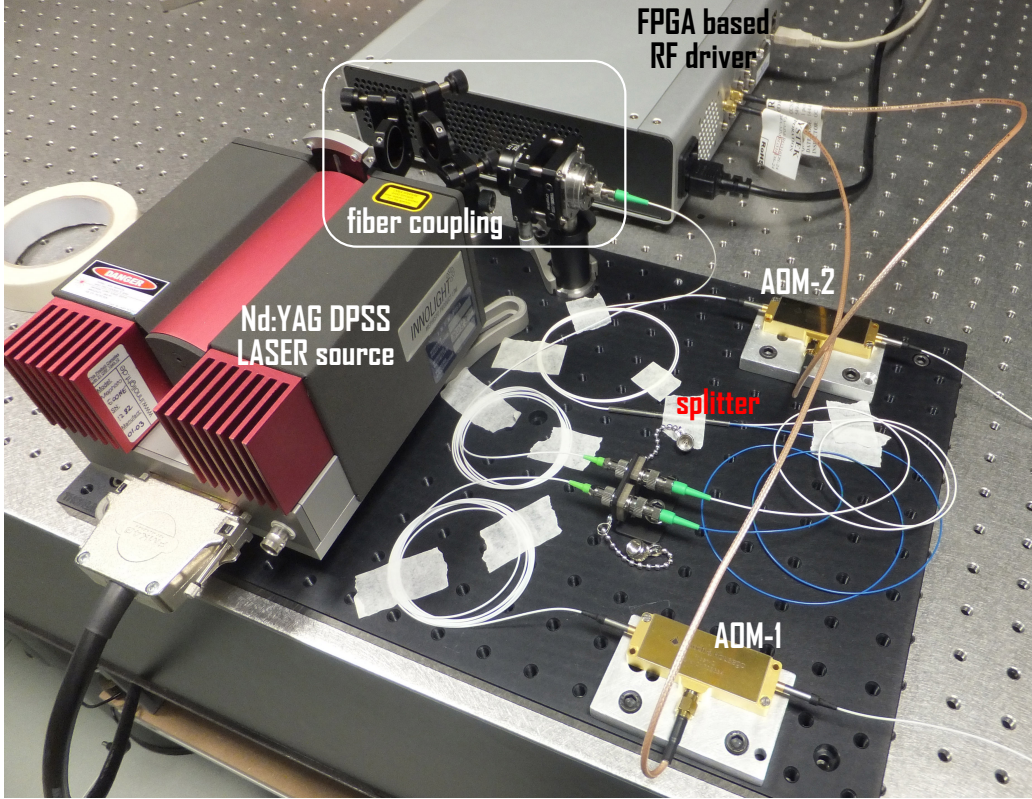
Figure 2: Heterodyne source unit on its optical breadboard.

beam-combiner. With respect to its reference counterpart, the beam travelling along the racetrack gathers a phase delay ϕ directly proportional to the relative displacement l between the fiducials:

$$\phi = \frac{2\pi}{\lambda} \cdot 2l$$

where λ is the optical wavelength of the laser source. A measurement light beating is therefore generated by the recombination between the outer parts of the source beams.

Providing two optical beats at the interferometer output guarantees best rejection to external noise, due to the fact that such noise affects both the reference and the measurement beams in the same way.[19] Both beams are effectively travelling along the same path and they uniquely differ in the presence of the racetrack, which is followed only by the measurement beam. Then any possible phase delay between the output signals exclusively generates along that section of the interferometer. We recall that the reference and measurement lights are spatially separated, reducing the risk of signals intermixing if compared to polarized light solutions.[18] The whole system, being polarization independent, cannot, in principle, be affected by optics refractive index variations, which are highly dependent on environmental conditions.

A second drilled mirror deflects the measurement beating on a detector different from the reference one. Both of these detectors are transimpedance amplified photodiodes with switchable gain and their generated voltage signals are sent to an oscilloscope on which first rough phase measurements will be performed.

4.1 The racetrack

As previously mentioned, the spatial separation between measurement and reference beams is provided by a drilled double mirror, operating at 45° angle of incidence. Its 45° tilted hole lets the reference beam walk through and reach the recombination beam-splitter (beam-combiner) immediately after. Instead, the annular
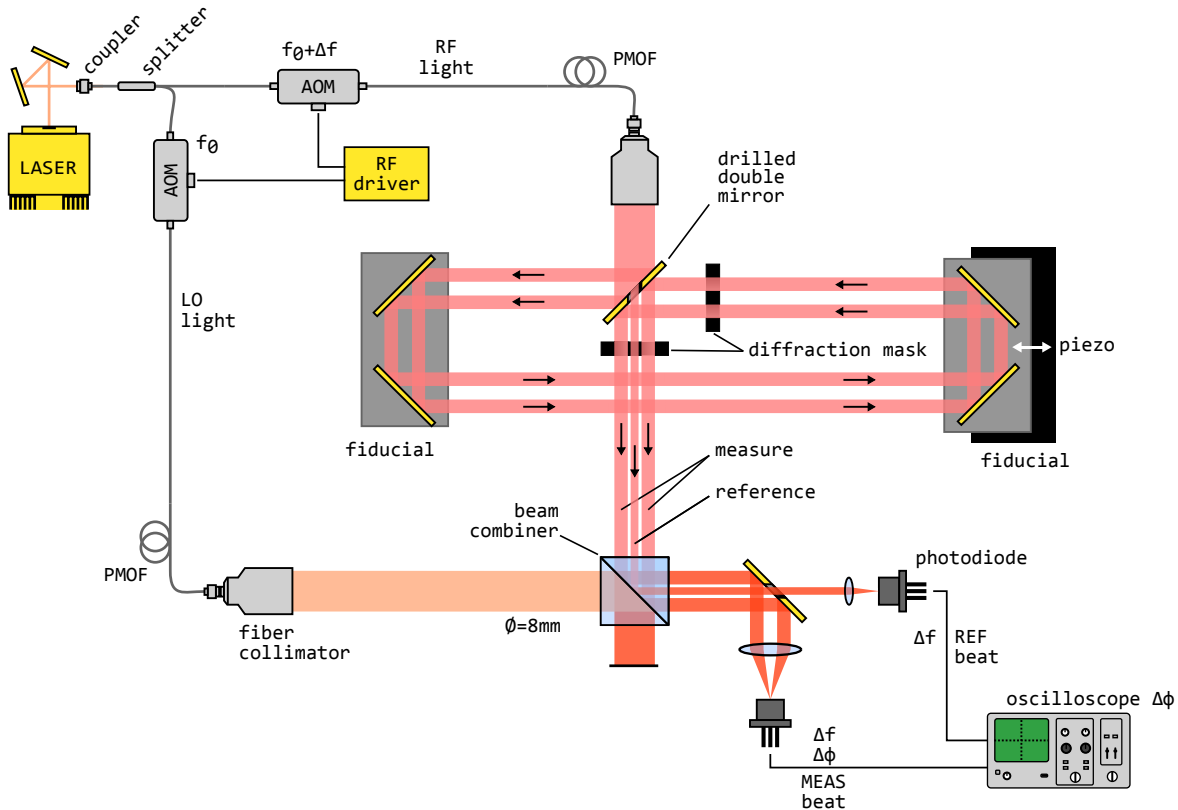
Figure 3: Layout of the distance gauge.

part of the beam is sent along the racetrack, made up by the drilled mirror itself and 4 auxialiary gold mirrors. These additional gold mirrors are set up in two prealigned fixed pairs, as to form two 2D retroreflectors; one of them will be placed on a nano-positioning translational stage in order to carry out performance tests of the prototype. The drilled mirror and its mounts were 3D modeled, showing non trivial footprint issues due to the 45° incidence angle and the necessity to keep a wide enough clear aperture on both sides of the mirror. A 2" diameter is chosen in order to avoid beam shading by mounts. The central hole is $4\,mm$ in diameter, which ensures almost even splitting of the optical power between reference and measurement beams.

According to some early evidence from the alignment procedures, diffraction from the mirror circular aperture severely spoils both the reference and the measurement beams, which do not maintain their circular and ring-like cross sections respectively. We plan to place properly shaped masks along the $4\,m$ test distance for a better spatial isolation of the beams, given that a mixing of them badly compromises the distance measurements.

5. CONCLUSION AND FUTURE DEVELOPMENTS

The open issue of monitoring the geometry of a large ring-laser array is under investigation. Detecting the Earth induced Lense-Thirring effect with such an instrument offers several challenges in terms of dimensional stability of several meters wide mechanical structures. Inspired by a space-borne application, we studied and developed a new metrological technique for this ground-based experiment. Experimental work is now focusing on the implementation of the optical design of a proof-of-concept heterodyne displacement gauge: assembly and alignment of the interferometer are underway and we will be able to start signal acqusition and data taking very soon.

Several key issues are to be investigated as well: single gauge mechanical design, oriented towards compactness and reproducibility; design, manifacturing and characterization of multidirectional fiducials; geometry modeling and control scheme design for the stabilization of the full system. Facing and overcoming all these challenges

will be of key importance towards the construction of heterolithic large frame detectors for General Relativity tests.

REFERENCES

[1] Mashhoon, B., Hehl, F. W., and Theiss, D. S., "On the gravitational effects of rotating masses: The thirring-lense papers," *General Relativity and Gravitation* **16**(8), 711–750 (1984).

[2] Ciufolini, I., Paolozzi, A., Pavlis, E. C., Koenig, R., Ries, J., Gurzadyan, V., Matzner, R., Penrose, R., Sindoni, G., Paris, C., Khachatryan, H., and Mirzoyan, S., "A test of general relativity using the LARES and LAGEOS satellites and a GRACE Earth gravity model. Measurement of Earth's dragging of inertial frames," *European Physical Journal C* **76**, 120 (Mar. 2016).

[3] Ciufolini, I. and Pavlis, E. C., "A confirmation of the general relativistic prediction of the lense-thirring effect," *Nature* **431**, 958–960 (Oct. 2004).

[4] Everitt, C. W. F., DeBra, D. B., Parkinson, B. W., Turneaure, J. P., Conklin, J. W., Heifetz, M. I., Keiser, G. M., Silbergleit, A. S., Holmes, T., Kolodziejczak, J., Al-Meshari, M., Mester, J. C., Muhlfelder, B., Solomonik, V. G., Stahl, K., Worden, P. W., Bencze, W., Buchman, S., Clarke, B., Al-Jadaan, A., Al-Jibreen, H., Li, J., Lipa, J. A., Lockhart, J. M., Al-Suwaidan, B., Taber, M., and Wang, S., "Gravity probe b: Final results of a space experiment to test general relativity," *Physical Review Letters* **106**, 221101 (May 2011).

[5] Bosi, F., Cella, G., Di Virgilio, A., Ortolan, A., Porzio, A., Solimeno, S., Cerdonio, M., Zendri, J. P., Allegrini, M., Belfi, J., Beverini, N., Bouhadef, B., Carelli, G., Ferrante, I., Maccioni, E., Passaquieti, R., Stefani, F., Ruggiero, M. L., Tartaglia, A., Schreiber, K. U., Gebauer, A., and Wells, J.-P. R., "Measuring gravitomagnetic effects by a multi-ring laser gyroscope," *Physical Review D* **84**, 122002(23) (2011).

[6] Schreiber, K. U. and Wells, J. P. R., "Invited review article: Large ring lasers for rotation sensing," *Review of Scientific Instruments* **84**, 041101– (2013).

[7] Di Virgilio, A., Schreiber, K. U., Gebauer, A., Wells, J.-P. R., Tartaglia, A., Belfi, J., Beverini, N., and Ortolan, A., "A laser gyroscope system to detect the gravito-magnetic effect on earth," *International Journal of Modern Physics D* **19**(14), 2331–2343 (2010).

[8] Allegrini, A., Belfi, J., Beverini, N., Bosi, F., Bouhadef, B., Carelli, G., Cella, G., Cerdonio, M., Di Virgilio, A. D., Gebauer, A., Maccioni, E., Ortolan, A., Porzio, A., Ruggiero, M. L., Schreiber, U. K., Solimeno, S., Stefani, F., Tartaglia, A., Zendri, J.-P., and Wells, J.-P. R., "A laser gyroscope system to detect the gravito-magnetic effect on earth," *Journal of Physics: Conference Series* **375**(6), 062005 (2012).

[9] Di Virgilio, A., Allegrini, M., Beghi, A., Belfi, J., Beverini, N., Bosi, F., Bouhadef, B., Calamai, M., Carelli, G., Cuccato, D., Maccioni, M., Ortolan, A., Passeggio, G., Porzio, A., Ruggiero, M. L., Santagata, R., and Tartaglia, A., "A ring lasers array for fundamental physics," *Comptes Rendus Physique* **15**(10), 866–874 (2014).

[10] Ortolan, A., Belfi, J., Bosi, F., Di Virgilio, A., Beverini, N., Carelli, G., Maccioni, E., Santagata, R., Simonelli, A., Beghi, A., Cuccato, D., Donazzan, A., and Naletto, G., "The ginger project and status of the gingerino prototype at lngs," in [*Proceedings, 14th International Conference on Topics in Astroparticle and Underground Physics (TAUP 2015)*], *J. Phys. Conf. Ser.* **718**(7), 072003 (2016).

[11] Belfi, J., Bosi, F., Di Virgilio, A., Beverini, N., Carelli, G., Giacomelli, U., Maccioni, E., Simonelli, A., Beghi, A., Cuccato, D., Donazzan, A., Naletto, G., Ortolan, A., Pelizzo, M. G., Porzio, A., Altucci, C., Velotta, R., and Tartaglia, A., "Very high sensitivity laser gyroscopes for general relativity tests in a ground laboratory," in [*2016 European Frequency and Time Forum (EFTF)*], 1–4 (April 2016).

[12] Belfi, J., Beverini, N., Bosi, F., Carelli, G., Di Virgilio, A., Maccioni, E., Ortolan, A., and Stefani, F., "A 1.82 m2 ring laser gyroscope for nano-rotational motion sensing," *Applied Physics B* **106**(2), 271–281 (2012).

[13] Belfi, J., Beverini, N., Calamai, M., Carelli, G., Maccioni, E., Di Virgilio, A., Santagata, R., Porzio, A., Cuccato, D., Ortolan, A., and Solimeno, S., "Absolute control of the scale factor in gp2 laser gyroscope: Toward a ground based detector of the lense-thirring effect," in [*European Frequency and Time Forum & IEEE International Frequency Control Symposium (EFTF/IFC), 2013 Joint*], 795–798 (2013).

[14] Halverson, P. G., Kuhnert, A., Logan, J., Regehr, M., Shaklan, S., Spero, R., Zhao, F., and Chang, T., "Progress towards picometer accuracy laser metrology for the space interferometry mission," in [*Proceedings of ICSO 2000, 4th International Conference on Space Optics*], 417–428, NASA JPL (2000).

[15] Halverson, P. G., Alvarez-Salazar, O., Azizi, A., Dekens, F., Nemati, B., and Zhao, F., "Progress towards picometer accuracy laser metrology for the space interferometry mission - update for icso 2004," in [*Proceedings of ICSO 2004, 5th International Conference on Space Optics*], 515–522, NASA JPL (2004).

[16] Nemati, B., "Sim planetquest: Status and recent progress," in [*Proceedings of SPIE: Advances in Stellar Interferometry*], **6268**, NASA JPL (2006).

[17] Logan, J. E., Halverson, P. G., Regehr, M. W., and Spero, R. E., "Automatic alignment of a displacement-measuring heterodyne interferometer," *Applied Optics* **41**, 4314–4317 (2002).

[18] Ames, L. B., Barrett, B., Bell, R., Dries, L., Dutta, K., Halverson, P. G., Holmes, B., Kvamme, E. T., Leary, D. F., Perkins, P., Scott, M., Van Eck, T. E., and Zhao, F., "Sim external metrology beam launcher (qp) development," in [*Proceedings of SPIE: Interferometry in Space*], **4852**, 347–354, NASA JPL (2003).

[19] Hirano, M., "Optical heterodyne measurement method," in [*Handbook of Optical Metrology*], Yoshizawa, T., ed., CRC Press (2009).