Roadmap for gravitational wave detection in space
– a preliminary study†

GAO Wei1,2, XU Peng1,3, BIAN Xing1,2, CAO Zhoujian1,4, CHANG Zijing5, DONG Peng1,3, GONG Xuefei1, HUANG Shuanglin6, JU Peng7, LUO Ziren8, QIANG Li’e7, TANG Wenlin9, WAN Xiaoyun10, WANG Yue5, XU Shengnian1, ZANG Yunlong1,2, ZHANG Haipeng6 & LAU Yun-Kau1,3,5*

1Institute of Applied Mathematics, Academy of Mathematics and Systems Science, Chinese Academy of Sciences, Beijing 100190, China;
2University of Chinese Academy of Sciences, Beijing 100049, China;
3Morningside Center of Mathematics, Chinese Academy of Sciences, Beijing 100190, China;
4State Key Laboratory of Scientific and Engineering Computing, Academy of Mathematics and Systems Science, Chinese Academy of Sciences, Beijing 100190, China;
5Department of Mathematics, Henan University, Kaifeng, Henan 475001, China;
6Department of Mathematics, Capital Normal University, Beijing 100089, China;
7Department of Geophysics, College of the Geology Engineering and Geomatics, Chang’an University, Xi’an 710054, China;
8Max-Planck-Institut für Gravitationsphysik (Albert Einstein Institut), D-30167 Hannover, Germany;
9Aerospace Flight Dynamics Laboratory, Beijing Aerospace Control Center, Beijing 100094, China;
10Qian Xuesen Laboratory of Launch Vehicle Technology, Beijing 100094, China;

Received August 13, 2014; accepted September 1, 2014; published online September 29, 2014

PACS number(s): 67.85.Lm, 03.75.Ss, 05.30.Fk

Citation: GAO W. et al. Roadmap for gravitational wave detection in space – a preliminary study. Sci China-Phys Mech Astron, 2015, 58: 014201, doi: 10.1007/s11433-014-5609-8

Gravitational wave detection in space, relativistic experiment, satellite gravity, grace follow-on, gravitomagnetism, post-Newtonian approximation.

1 Introduction

In 2008, under the auspices of the National Microgravity laboratory of the Institute of Mechanics, Chinese Academy of Sciences (CAS), an (unofficial) gravitational physics consortium comprising a number of institutes and universities both within and outside the CAS was established. The primary objective of the consortium is to coordinate and promote research in the detection of gravitational wave in space in China. A roadmap was soon worked out in order to build up the expertise and required technologies step by step for future prospective Chinese mission. As a first step of the roadmap, a geodesy mission to monitor the temporal variation of the Earth gravity field using low-low satellite to satellite tracking by means of laser interferometry will be developed. This will enable us to acquire the key technologies at a lower level of precision and at the same time assemble a core team for further development. As a geodesy mission will only test laser interferometry in space and is less stringent in requirement in inertial sensor related technologies, a LISA Pathfinder (LPF) type mission is also required at some stage to test the inertial sensor and the related dragfree technologies to the level of precision required by gravitational wave detection. As the two proof masses in a LPF type mission may be regarded naturally as a one dimensional gravity gradiometer, in recent years, some work has also been ongoing to explore possible additional scientific benefits of a LPF type mission, apart from testing the key technologies in space.
Supported by the Xiandao (pioneer explorer) program of the National Space Science Center of the CAS, the general relativity group of the Morningside Center of Mathematics and Institute of Applied Maths, CAS have been undertaking the task of doing preliminary study on the prospective missions outlined in the roadmap. The purpose of the present article is to present an overview of the work we have been doing in this area.

The outline of the present article is described as follows. In the next section, we will outline a feasible design and its primary science driver for a mission to detect gravitational waves in space. This is then followed in Section 3 by a sketch of a geodesy mission study we have been doing. In Section 4, we will discuss the precision measurement of the Earth's gravitomagnetic field as possible additional science for a LISA Pathfinder type mission. Sone brief remarks will be made in Section 5 to conclude this paper.

2 Gravitational wave detection in space

Concurrent to the mission study in satellite gravity beginning in 2009 which will be described in next section, a preliminary study was also made on the scientific potential of a spaceborne gravitational detector whose most sensitivity frequency band centers around 0.01 or 0.1 Hz. The main theme of the study was to look at possible gravitational wave sources around 0.01Hz which was not entirely well understood at then. With ALIA adopted as a representative mission concept around the 0.01Hz band, further analysis revealed that there is a rich source of intermediate mass black hole binaries at high redshift and the detection would shed light on the black hole-galaxy coevolution during the structural formation process of the Universe.

During 2011-2013, a subsequent, more indepth study was made. This time technological constraints were taken into account and we strived to obtain a balance between merits in science and viability in technologies. With this guideline in mind, after examining a few mission options, a mission concept with the following baseline design parameters is favoured as a blueprint for more in depth study in the near future.

| L (m) | D (M) | P (W) | $S_{\text{pos}}$ ($\text{pm} \sqrt{\text{Hz}}$) | $S_{\text{acc}}$ ($\text{m s}^{-2} \sqrt{\text{Hz}}$) |
|-------|-------|-------|-------------------|-------------------|
| $3 \times 10^7$ | 0.45-0.6 | 2 | 5-8 | $3 \times 10^{-13}$ (> 0.1mHz) |

Table 1 Baseline design parameters.

Moreover, the mission design is also capable of probing
IMRI (intermediate mass ratio inspiral) in dense star clusters in the local Universe. Presented in Table 2 is some event rate calculations for IMRIs in local Universe. The results are given in Table 2. It should be remarked that estimate is model dependent and subject to many uncertainties and we should not attach too much importance to the precise numbers. Instead, it illustrates the advantage of shifting slightly the most sensitive region of the measurement band to a few hundredth Hz. As far as IMRIs are concerned, the event rate goes up as the cubic of the improvement in sensitivity.

| Mission option | Upper level of confusion | Lower level of confusion |
|----------------|--------------------------|-------------------------|
| 5pm (D=0.6m)   | ~ 90                     | ~ 130                   |
| 8pm (D=0.45m)  | ~ 26                     | ~ 32                    |

Table 2 Expected globular cluster harbored IMBH-BH final inspirals and mergers detectable for year-long observation, scaled in unit of $10^{-15}$ $\nu_0$ $10^{10} M_{\odot}$.

The result of the study suggests that, by choosing the arm-length of the interferometer to be three million kilometers and shifting the sensitivity floor to around one-hundredth Hz, together with a very moderate improvement on the position noise budget, there are certain mission options capable of exploring light seed, intermediate mass black hole binaries at high redshift that are not readily accessible to eLISA/LISA, and yet the technological requirements seem to within reach in the next few decades for China.

### 3 Low-low satellite to satellite tracking using laser interferometry

In 2009, commissioned by the National Space Science Center, Chinese Academy of Sciences, a comprehensive study was undertaken in order to understand various aspects of a future low-low satellite to satellite tracking mission with microwave ranging replaced by laser interferometry.

During the feasibility study, different groups undertaking different tasks within the mission study suggested possible mission designs for future satellite gravity missions. Due to the limitation imposed by aliasing generated by the atmosphere and ocean currents, perhaps in a way not too surprising, subject to minor variations, all groups came up with very similar mission design (see for instance Zheng), compare also with that of the NGGM mission (Gruber, Anselmi) whose mission design parameters are given in the following table.

| Mission duration | Orbit    | Accelerometer (mHz to 3Hz) | Laser (mHz to 3Hz) | Satellite altitude | Inter satellite range |
|------------------|----------|---------------------------|-------------------|--------------------|----------------------|
| 1 10-year        | Polar    | $10^{-10}$ ms$^{-2}$ Hz$^{-1/2}$ | $10 \sim 30$ nmHz$^{-1/2}$ | 300km              | 50 ~ 200km           |
| 2 10-year        | Polar    | $10^{-9}$ ms$^{-2}$ Hz$^{-1/2}$ | $10 \sim 30$ nmHz$^{-1/2}$ | 420 ~ 450km        | 50 ~ 200km           |

Table 3 Baseline design parameters for two representative mission options.

The critical difference between the two mission designs is the attitude of the orbit. For option 1 in Table 3, thruster (dragfree) technology is required to maintain the orbit at such a low attitude.

By means of the semi-analytic method (Sneeuw), the capability of static gravity field recovery of the mission designs is illustrated in Fig 4–Fig 5.

---

**Figure 4** Static gravity field recovery in terms of spherical harmonic degree variance for different altitudes (range: 100km, laser metrology: 10nm/√Hz).

**Figure 5** Static gravity field recovery in terms of spherical harmonic degree variance for different laser accuracy (altitude: 300km, range: 100km).

For the capability to track temporal variation of the Earth gravity field, using the GLDAS model and taking into account of AOD aliasing, the hydrological signal recovery is
displayed in the following figures for the two mission design considered.

**Figure 6** GLDAS anomaly for October, 2009, up to degree and order 90. Units of ugal gravity anomaly.

**Figure 7** Recovered GLDAS anomaly for October, 2009, up to harmonic degree 90. (Altitude at 300km with 400km Gauss filter).

**Figure 8** Recovered GLDAS anomaly for October, 2009, up to harmonic degree 90. (Altitude at 450km with 400km Gauss filter).

Work is still ongoing to understand the various aspects of the mission concepts (see for instance Gaowei, Xupeng).

4 Precision measurement of gravitomagnetic field in terms of gradiometry

Apart from detection of gravitational waves, another outstanding problem in experimental relativity is the detection of gravitomagnetic field [17] [18] of a rotating body which may be regarded as a test of general relativity at the planetary scale. As the GM field is part of the spacetime curvature, it will contribute to the tidal forces acting on a family of nearby free falling particles. It is natural to contemplate to detect its presence through the measurement of the tidal force gradient generated by the GM field [19] [20]. As the two free falling test masses (TMs) in the LISA Pathfinder type mission naturally constitute a one dimensional gravity gradiometer, apart from testing the technologies for gravitational wave detection, we also try to look at whether such mission is also capable of measuring GM field around a planet.

**Figure 9** Two TMs are housed in the along track direction following a nearly circular orbit. The spacecraft may be viewed as a gyroscope rolling about the transverse direction $e_3$.

Consider an ideal case in which the Earth is modelled as a uniform rotating spherical body. Let $(t, x_i), i = 1, 2, 3$ be the Earth centered coordinates and $e_{a1}, a = 1, 2, 3$ be the Earth pointing orthonormal three frame attached to the center of mass of the spacecraft. Units in which $c = G = 1$ will be adopted.

Given an Earth pointing, drag-free spacecraft orbiting the Earth in a nearly circular orbit (radius $a \approx 1000km$) with constant inclination $i$. Two TMs are housed in the along track direction separated by a distance $d \approx 50cm$. (see Fig.9). Let $\delta^i$ be the relative displacement of the two TMs. In a time scale short compared with the Lense-Thirring precession of the orbital plane and subject to $\delta^i \ll d$, at the 1PN level, the geodesic deviation (Jacobi) equation describing the relative displacement $\delta^i$ may be simplified to become (see [21] for details)

\[
\ddot{\delta}^1(t) = -2\omega \dot{\delta}^2(t) + \frac{6J\omega d \cos i}{a^3},
\]

\[
\ddot{\delta}^2(t) = 2\omega \dot{\delta}^1(t) + 3\omega^2 \delta^3(t) - \frac{9d J t \omega^2 \cos i}{a^3},
\]

\[
\ddot{\delta}^3(t) = -\omega^2 \dot{\delta}^3(t) + \frac{3d J t \omega \sin i \cos(\omega t)}{a^3}.
\]

At the Newtonian level, we recover the well known Clohessy Wiltshire [22] (Hill) equation from (1).
matches the frequency $\omega$ harmonic motion. Up to a constant, the frequency of the force Lorentz type force acting on the TMs and results in a forced The presence of a gravitomagnetic field serves to generate a resembles that of a simple harmonic oscillator (see Fig.10).

For a circular orbit, take one TM as reference, the motion of the second TM in the transverse direction is equivalent to that of a forced harmonic oscillator with natural frequency which matches that of the orbital frequency.

In the direction transverse to the orbit plane, at the Newtonian level, it is known that the relative motion of the two TMs resembles that of a simple harmonic oscillator (see Fig.10). The presence of a gravitomagnetic field serves to generate a Lorentz type force acting on the TMs and results in a forced harmonic motion. Up to a constant, the frequency of the force matches the frequency $\omega = \sqrt{\frac{M}{c^2}}$ determined by the central gravitational potential and this gives rise to a resonant forced harmonic oscillation. Further numerical simulations indicate that the resonant oscillation prevails for more general elliptic orbits and with Earth gravity field multiples taken into account. The amplitude of the oscillation will not grow unbounded when nonlinearity of the Lense-Thirring precession of the orbit plane takes effect, but this will occur in a time scale much longer than the mission lifetime of around one year. By integrating the PN generalization of the CW equations in (1), we further find that the growing oscillation amplitude of the TMs in the transversal direction is given by (see Fig.11)

$$s_{GM}(t) = \frac{3GdJ \sin i \sin(\omega t)}{2c^2 a^2} t,$$  \hspace{1cm} (2)

For medium orbit experiment, the signal has frequency about $0.1mHz$ and its magnitude will reach a few nanometers within $1 \sim 2$ days.

To understand the physical picture underlying the signal readout given in (2), we note that gravitomagnetic field, apart from generating a Lense-Thirring precession of the orbital plane, also generates a precession of the orthonormal frame $e_{(a)}$ \cite{23}. In particular, the results in the precession of the plane perpendicular to $e_{(3)}$ that contains the TMs. As a result, the relative displacement of the two TMs is actually generated by the differential precession between the orbital plane and the plane perpendicular to $e_{(3)}$ (see Fig. 22). If we regard $e_{(a)}$ as a gyroscope resembling that in the GPB experiment \cite{24} and the orbit itself is also a gigantic gyroscope, then we may see that a very distinctive feature of the proposed measurement scheme is that, unlike GPB or LAGEOS/LARES \cite{25, 26} which measures precession with respect to an globally defined inertial reference, it measures the differential precession of the two gyroscopes.

With the theoretical foundation of the measurement scheme worked out above, there remains many key issues to be resolved or understood in order to implement the measurement scheme in a physically realistic situation (see for instance \cite{28}). The study is still ongoing and we hope to report further progress in the near future.

5 Concluding Remarks

An overview is given on the work we have been doing in the past few years in relation to detection of gravitational wave in space. Needless to say there is no end to such study. It is envisaged that more in depth study will be undertaken in the next few years to contribute to the development of gravitational wave detection in China.

Acknowledgements

The work presented here was supported by the National Space Science Center, Chinese Academy of Sciences (project number XDA04070400 and XDA04077700). Prof. Wenrui Hus effort to promote gravitational wave detection in space in China motivated our study in the first place. We are also grateful to Prof. Shuangnan Zhang for his support throughout the course of our work. Professors Shing-Tung Yau and Lo Yang have been very supportive and the Morningside Center in China motivated our study in the first place. We are also grateful to Prof. Shuangnan Zhang for his support throughout the course of our work. Professors Shing-Tung Yau and Lo Yang have been very supportive and the Morningside Center in China motivated our study in the first place. We are also grateful to Prof. Shuangnan Zhang for his support throughout the course of our work. Professors Shing-Tung Yau and Lo Yang have been very supportive and the Morningside Center in China motivated our study in the first place. We are also grateful to Prof. Shuangnan Zhang for his support throughout the course of our work. Professors Shing-Tung Yau and Lo Yang have been very supportive and the Morningside Center in China motivated our study in the first place. We are also grateful to Prof. Shuangnan Zhang for his support throughout the course of our work. Professors Shing-Tung Yau and Lo Yang have been very supportive and the Morningside Center in China motivated our study in the first place. We are also grateful to Prof. Shuangnan Zhang for his support throughout the course of our work. Professors Shing-Tung Yau and Lo Yang have been very supportive and the Morningside Center in China motivated our study in the first place. We are also grateful to Prof. Shuangnan Zhang for his support throughout the course of our work. Professors Shing-Tung Yau and Lo Yang have been very supportive and the Morningside Center in China motivated our study in the first place. We are also grateful to Prof. Shuangnan Zhang for his support throughout the course of our work. Professors Shing-Tung Yau and Lo Yang have been very supportive and the Morningside Center in China motivated our study in the first place. We are also grateful to Prof. Shuangnan Zhang for his support throughout the course of our work. Professors Shing-Tung Yau and Lo Yang have been very supportive and the Morningside Center in China motivated our study in the first place. We are also grateful to Prof. Shuangnan Zhang for his support throughout the course of our work. Professors Shing-Tung Yau and Lo Yang have been very supportive and the Morningside Center in China motivated our study in the first place. We are also grateful to Prof. Shuangnan Zhang for his support throughout the course of our work. Professors Shing-Tung Yau and Lo Yang have been very supportive and the Morningside Center in China motivated our study in the first place. We are also grateful to Prof. Shuangnan Zhang for his support throughout the course of our work. Professors Shing-Tung Yau and Lo Yang have been very supportive and the Morningside Center in China motivated our study in the first place. We are also grateful to Prof. Shuangnan Zhang for his support throughout the course of our work. Professors Shing-Tung Yau and Lo Yang have been very supportive and the Morningside Center in China motivated our study in the first place. We are also grateful to Prof. Shuangnan Zhang for his support throughout the course of our work. Professors Shing-Tung Yau and Lo Yang have been very supportive and the Morningside Center in China motivated our study in the first place. We are also grateful to Prof. Shuangnan Zhang for his support throughout the course of our work. Professors Shing-Tung Yau and Lo Yang have been very supportive and the Morningside Center in China motivated our study in the first place. We are also grateful to Prof. Shuangnan Zhang for his support throughout the course of our work. Professors Shing-Tung Yau and Lo Yang have been very supportive and the Morningside Center in China motivated our study in the first place. We are also grateful to Prof. Shuangnan Zhang for his support throughout the course of our work. Professors Shing-Tung Yau and Lo Yang have been very supportive and the Morningside Center in China motivated our study in the first place. We are also grateful to Prof. Shuangnan Zhang for his support throughout the course of our work. Professors Shing-Tung Yau and Lo Yang have been very supportive and the Morningside Center in China motivated our study in the first place. We are also grateful to Prof. Shuangnan Zhang for his support throughout the course of our work. Professors Shing-Tung Yau and Lo Yang have been very supportive and the Morningside Center in China motivated our study in the first place. We are also grateful to Prof. Shuangnan Zhang for his support throughout the course of our work. Professors Shing-Tung Yau and Lo Yang have been very supportive and the Morningside Center in China motivated our study in the first place. We are also grateful to Prof. Shuangnan Zhang for his support throughout the course of our work. Professors Shing-Tung Yau and Lo Yang have been very supportive and the Morningside Center in China motivated our study in the first place. We are also grateful to Prof. Shuangnan Zhang for his support throughout the course of our work. Professors Shing-Tung Yau and Lo Yang have been very supportive and the Morningside Center in China motivated our study in the first place. We are also grateful to Prof. Shuangnan Zhang for his support throughout the course of our work. Professors Shing-Tung Yau and Lo Yang have been very supportive and the Morningside Center in China motivated our study in the first place. We are also grateful to Prof. Shuangnan Zhang for his support throughout the course of our work. Professors Shing-Tung Yau and Lo Yang have been very supportive and the Morningside Center in China motivated our study in the first place. We are also grateful to Prof. Shuangnan Zhang for his support throughout the course of our work. Professors Shing-Tung Yau and Lo Yang have been very supportive and the Morningside Center in China motivated our study in the first place. We are also grateful to Prof. Shuangnan Zhang for his support throughout the course of our work. Professors Shing-Tung Yau and Lo Yang have been very supportive and the Morningside Center in China motivated our study in the first place. We are also grateful to Prof. Shuangnan Zhang for his support throughout the course of our work. Professors Shing-Tung Yau and Lo Yang have been very supportive and the Morningside Center in China motivated our study in the first place. We are also grateful to Prof. Shuangnan Zhang for his support throughout the course of our work. Professors Shing-Tung Yau and Lo Yang have been very supportive and the Morningside Center in China motivated our study in the first place. We are also grateful to Prof. Shuangnan Zhang for his support throughout the course of our work. Professors Shing-Tung Yau and Lo Yang have been very supportive and the Morningside Center in China motivated our study in the first place. We are also grateful to Prof. Shuangnan Zhang for his support throughout the course of our work. Professors Shing-Tung Yau and Lo Yang have been very supportive and the Morningside Center in China motivated our study in the first place. We are also grateful to Prof. Shuangnan Zhang for his support throughout the course of our work. Professors Shing-Tung Yau and Lo Yang have been very supportive and the Morningside Center in China moti

1 Bender P L. Additional astrophysical objectives for LISA follow-on missions. Class Quantum Grav, 2004, 21: S1203
2 Bender P L and Begelman M C. Trends in Space Science and Cosmic Vision 2020. ESA SP-588 (Noordwijk:ESA Publications Division) pp 3-8, 2005
3 Gong X, et al. A scientific case study of the ALIA mission. Class Quantum Grav, 2011, 27: 084010
4 Gong X, et al. Descope of the ALIA mission. To appear in Journal of Physics: Conference Series, 2014.
5 Lau Y K, et al. Feasibility study of gravitational wave detection in space. Report submitted to the National Space Science Center, Chinese Academy of Sciences for the project XDA04070400, 2014
6 Bender P L and Hils D. Confusion noise level due to galactic and extragalactic binaries. Class Quantum Grav, 1997, 14: 1439
7 Farmer A J and Phinney E S. The gravitational wave background from cosmological compact binaries. Mon Not R Astron Soc, 2003, 346: 1197
8 Sesana A, Volonteri M and Haardt F. The imprint of massive black hole formation models on the LISA data stream. Mon. Not. R. Astro. Soc., 2007, 377: 1711
9 Arun K G, et al. Massive Black Hole Binary Inspirals: Results from the LISA Parameter Estimation Taskforce. Class. Quantum Grav., 2009, 26: 094027
10 NGO – Revealing a hidden Universe: opening a new chapter of discovery£Assessment Study Report” ESA/SRE(2011)19 December 2011
11 A. Anselmi, et al. Assessment of a Next Generation Mission for Monitoring the Variations of Earth's Gravity. Final Report, Document SD-RP-AI-0668, Thales Alenia Space, 22 (2010).
12 Gruber Th., et al. Earth System Mass transport mission: Concept for a Next Generation Gravity Field Mission, Final Report, NGGM-D (2014).
13 Sneeuw, N. J. A Semi-Analytical Approach to Gravity Field Analysis from Satellite Observations. Bayerische Akademie d. Wissenschaften, Munich (2000).
14 Zheng Wei, et al. Accurate and rapid error estimation on global gravitational field from current GRACE and future GRACE Follow-On missions, Chinese Physics B, 18(08): 3597–3604 (2009).
15 Wei Gao, et al. Possible application of future satellite gravity mission to earthquake study in China, a scientific case study of the Wenchuan earthquake. To appear in GRACE Fellow-On in China, A Program of Space Advance Gravitiy Measurement.
16 Peng Xu et al. A preliminary study of level 1A data processing of a low-low satellite to satellite tracking mission, accepted to be published in Journal of Geodesy and Geodynamics.
17 Thorne K S, Gravitomagnetism, jets in quasars, and the Stanford Gyroscope Experiment, in Near Zero: New Frontiers of Physics edited by Fairbank J D and et al., 1988, pp. 573-586.
18 Ciufolini I and Wheeler J A, Gravitation and Inertia. 1995, Princeton University Press.
19 Braginskii V B and Polnarev A G, Relativistic spin-quadrupole gravitational effect, ZhETF Pis ma Redaktsiju, 1980, 31, 444.
20 Mashhoon B, Paik H J and Will C M, Detection of the gravitomagnetic field using an orbiting superconducting gravity gradiometer. Theoretical principles, Phys. Rev. D, 1989, 39, 2825.
21 Peng Xu et al, Precision measurement of planetary gravitomagnetic field in general relativity with laser interferometry in space (I) ! Theoretical foundations. preprint
22 Clohessy W H and Wiltshire R S, Terminal Guidance System for Satellite Rendezvous. Journal of the Aerospace Sciences, 1960, 27, 653.
23 Schiff L I, Motion of a Gyroscope According to Einstein’s Theory of Gravitation. Proceedings of the National Academy of Science, 1960, 46, 871-882.
24 Everitt C W F et al, Gravity Probe B: Final Results of a Space Experiment to Test General Relativity, Phys. Rev. Lett., 2011, 106, 221101.
25 Ciufolini I, A Comprehensive Introduction to the LAGEOS Gravitomagnetic Experiment: From the Importance of the Gravitomagnetic Field in Physics to Preliminary Error Analysis and Error Budget, International Journal of Modern Physics A, 1989, 4, 3083.
26 Ciufolini I and Pavlis E C, A confirmation of the general relativistic prediction of the Lense-Thirring effect, Nature, 2004, 431, E958.
27 Ciufolini I et al, Testing General Relativity and gravitational physics using the LARES satellite, European Physical Journal Plus, 2012, 127, 133.
28 Peng Xu et al, Precision measurement of planetary gravitomagnetic field in general relativity with laser interferometry in space (II) ! Signal to Noise Ratio Analysis. preprint