LISA Pathfinder最初の結果

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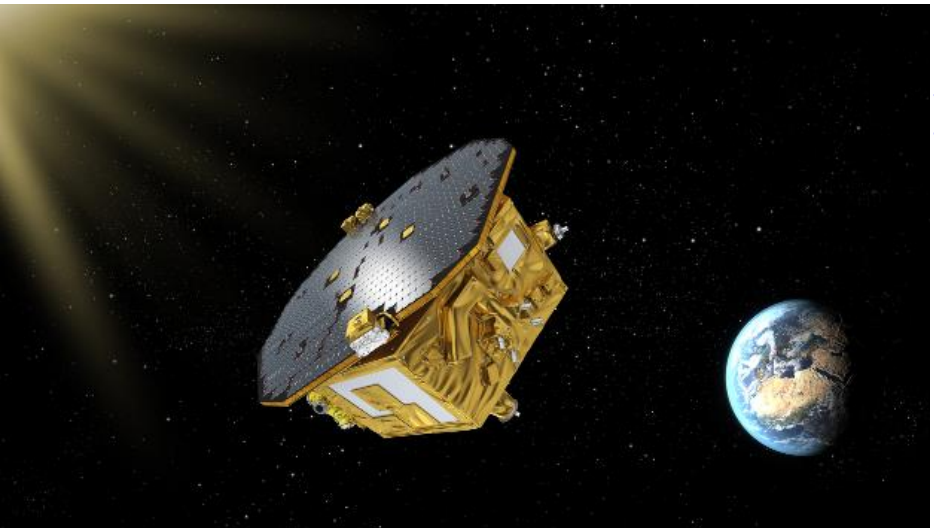
LISA Pathfinder

- 宇宙重力波望遠鏡LISAの技術実証機
  LISA: Laser Interferometer Space Antenna
- 2015年12月3日 打ち上げ成功
- 2016年1月22日 L1に到達
- 2016年2月22日 ドラッグフリー達成
- 2016年3月1日 science mission開始
- 2016年6月7日 最初の結果公開

http://spaceflight101.com/lisa-pathfinder/photos-vega-lights-up-the-night-over-the-amazon-launching-lisa-pathfinder/



http://sci.esa.int/lisa-pathfinder/56910-lisa-pathfinder-in-space/

esa

European Space Agency

公開された論文

- M. Armano+, PRL 116, 231101 (2016)
  Sub-Femto-g Free Fall for Space-Based Gravitational Wave Observatories: LISA Pathfinder Results
- 加速度雑音と
  変位雑音を評価
  →LISAが可能

Selected for a Viewpoint in *Physics*
PRL **116,** 231101 (2016) PHYSICAL REVIEW LETTERS week ending 10 JUNE 2016

Sub-Femto-*g* Free Fall for Space-Based Gravitational Wave Observatories: LISA Pathfinder Results

M. Armano,[1] H. Audley,[2] G. Auger,[3] J. T. Baird,[4] M. Bassan,[5] P. Binetruy,[3] M. Born,[2] D. Bortoluzzi,[6] N. Brandt,[7] M. Caleno,[8] L. Carbone,[9] A. Cavalleri,[10] A. Cesarini,[9,†] G. Ciani,[9,†] G. Congedo,[9,‡] A. M. Cruise,[11] K. Danzmann,[2] M. de Deus Silva,[1] R. De Rosa,[12] M. Diaz-Aguiló,[13] L. Di Fiore,[14] I. Diepholz,[2] G. Dixon,[11] R. Dolesi,[9] N. Dunbar,[15] L. Ferraioli,[16] V. Ferroni,[9] W. Fichter,[17] E. D. Fitzsimons,[18] R. Flatscher,[7] M. Freschi,[1] A. F. García Marín,[2,§] C. García Marirrodriga,[8] R. Gerndt,[7] L. Gesa,[13] F. Gibert,[9] D. Giardini,[16] R. Giusteri,[9] F. Guzmán,[2,‖] A. Grado,[19] C. Grimani,[20] A. Grynagier,[17,¶] J. Grzymisch,[8] I. Harrison,[21] G. Heinzel,[2] M. Hewitson,[2] D. Hollington,[4] D. Hoyland,[11] M. Hueller,[9] H. Inchauspé,[3] O. Jennrich,[8] P. Jetzer,[22] U. Johann,[7] B. Johlander,[8] N. Karnesis,[2] B. Kaune,[2] N. Korsakova,[2] C. J. Killow,[23] J. A. Lobo,[13,*] I. Lloro,[13] L. Liu,[9] J. P. López-Zaragoza,[13] R. Maarschalkerweerd,[21] D. Mance,[16] V. Martín,[13] L. Martin-Polo,[1] J. Martino,[3] F. Martin-Porqueras,[1] S. Madden,[8] I. Mateos,[13] P. W. McNamara,[8] J. Mendes,[21] L. Mendes,[1] A. Monsky,[2,§] D. Nicolodi,[9,**] M. Nofrarias,[13] S. Paczkowski,[2] M. Perreur-Lloyd,[23] A. Petiteau,[3] P. Pivato,[9] E. Plagnol,[3] P. Prat,[3] U. Ragnit,[8] B. Raïs,[3] J. Ramos-Castro,[24] J. Reiche,[2] D. I. Robertson,[23] H. Rozemeijer,[8] F. Rivas,[13] G. Russano,[9] J. Sanjuán,[13,††] P. Sarra,[25] A. Schleicher,[7] D. Shaul,[4] J. Slutsky,[26] C. F. Sopuerta,[13] R. Stanga,[27] F. Steier,[2,§] T. Sumner,[4] D. Texier,[1] J. I. Thorpe,[26] C. Trenkel,[15] M. Tröbs,[2] H. B. Tu,[9,‡‡] D. Vetrugno,[9] S. Vitale,[9] V. Wand,[2,§§] G. Wanner,[2] H. Ward,[23] C. Warren,[15] P. J. Wass,[4] D. Wealthy,[15] W. J. Weber,[9] L. Wissel,[2] A. Wittchen,[2] A. Zambotti,[6] C. Zanoni,[6] T. Ziegler,[7] and P. Zweifel[16]

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Sub-Femto-*g* Free Fall for Space-Based Gravitational Wave Observatories: LISA Pathfinder Results

M. Armano *et al.*
Phys. Rev. Lett. **116**, 231101 – Published 7 June 2016

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Physics See Viewpoint: Paving the Way to Space-Based Gravitational-Wave Detectors

More

得られた雑音スペクトル

- (5.2±0.1) fm s^{-2}/rtHz　　(34.8±0.3) fm/rtHz

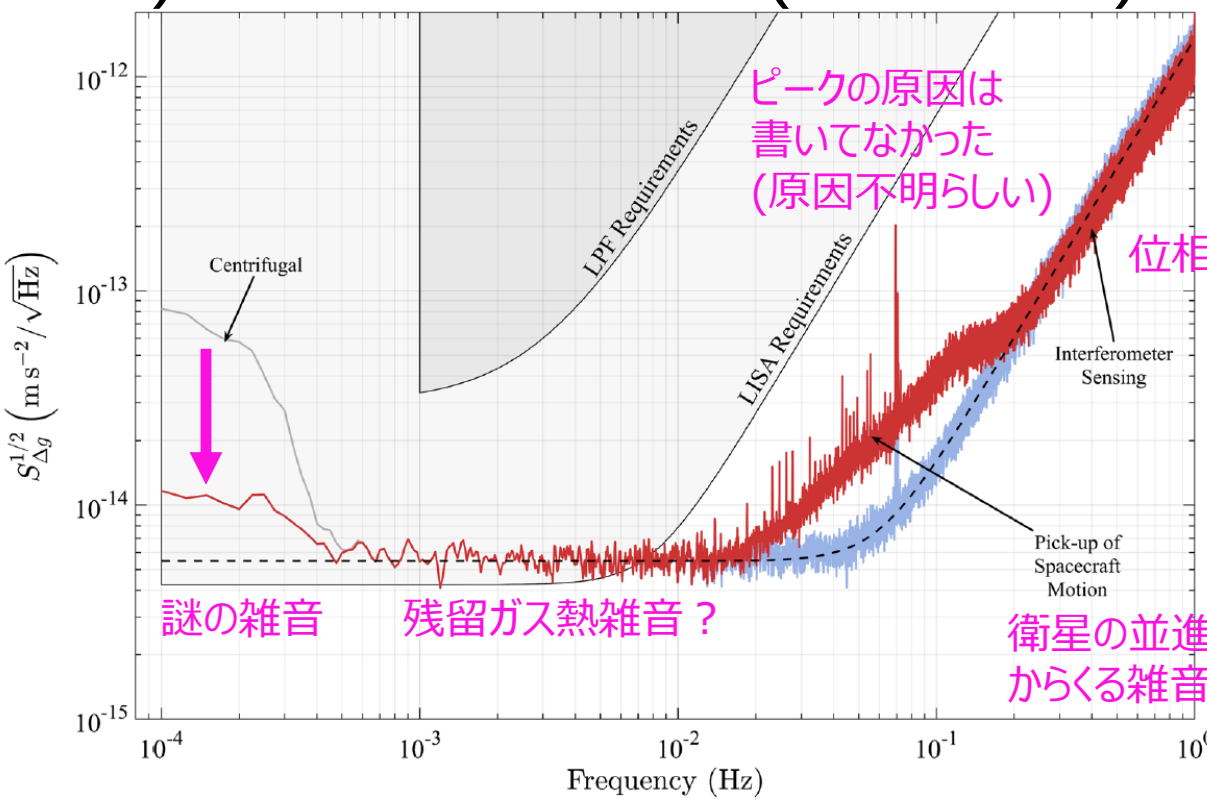


FIG. 1. Gray: ASD of Δg, $S_{\Delta g}^{1/2}(f)$, measured for 6.5 days starting 127 days after launch. The ASD is the result of averaging 26 periodograms of 40 000 s each, which results in a relative error (1σ) of 10% in $S_{\Delta g}^{1/2}$. The effective spectral resolution, set by the spectral window, is $\Delta f \simeq \pm 50\ \mu$Hz. The absolute calibration of the measurement is better than 5%. Red: ASD of the same time series after correction for the centrifugal force (visible at the lowest frequencies). Light blue: ASD after correction for the pickup of spacecraft motion by the interferometer (IFO), visible in the 20–200 mHz range. Dashed smooth black line: $S_{\Delta g}(f) = S_0 + S_{\mathrm{IFO}}(2\pi f)^4$ with $S_0^{1/2} = (5.57 \pm 0.04)\ \mathrm{fm\,s^{-2}/\sqrt{Hz}}$ and $S_{\mathrm{IFO}}^{1/2} = (34.8 \pm 0.3)\ \mathrm{fm/\sqrt{Hz}}$. Note that the level of S_0 has decreased further in subsequent measurements, as quoted in the abstract and shown in Fig. 3. Shaded areas: LISA and LISA Pathfinder requirements for Δg. The LISA single test-mass acceleration requirement [2] has been multiplied by $\sqrt{2}$ to be presented here as a differential acceleration.

残留ガス熱雑音か？

- 9.5 μPaのH_20で説明可能
  (H_2なら3倍)
- 加速度雑音レベルは1/tで
  次第に減少
- 2月始めに宇宙に開放して
  真空引きを始めたばかり

- 温度変調してdF/dΔTを測定
  することにより < 22 μPa
  であることは別途測定した

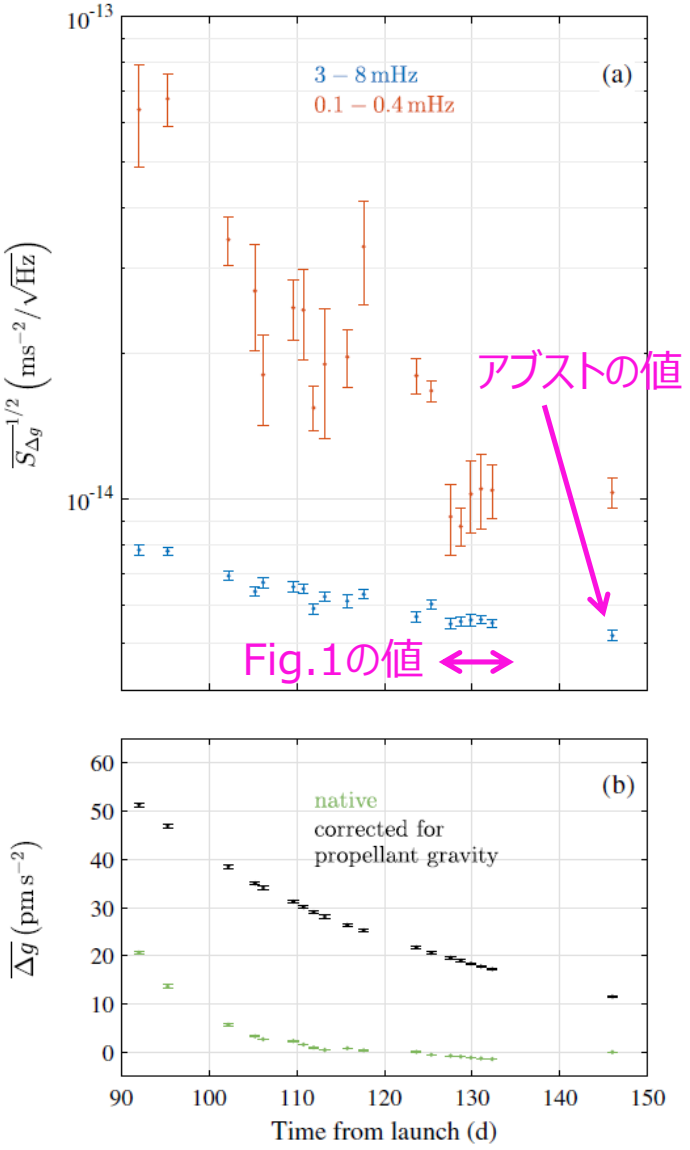


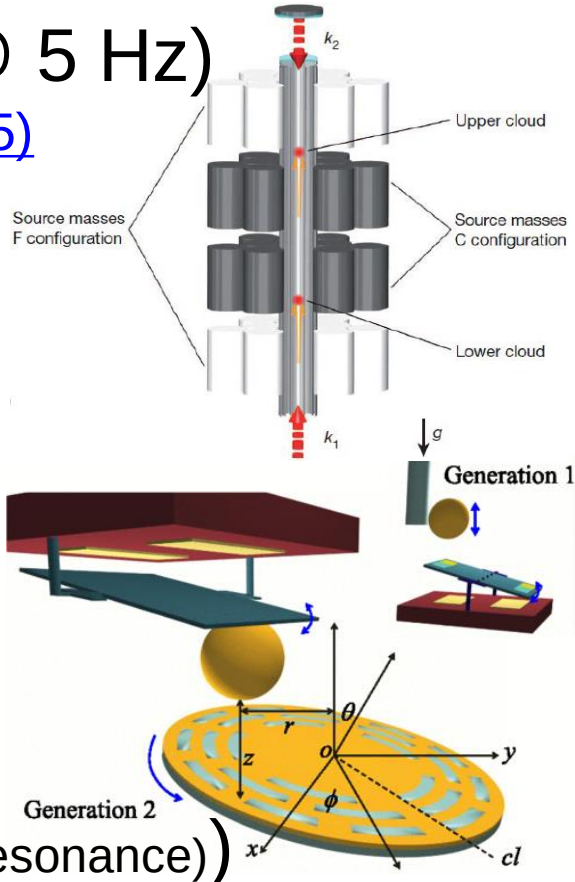
FIG. 3. (a) Square root of the averaged power spectral density of Δg in the 3–8 mHz and 0.1–0.4 mHz frequency

0.5 mHz以下の謎の雑音

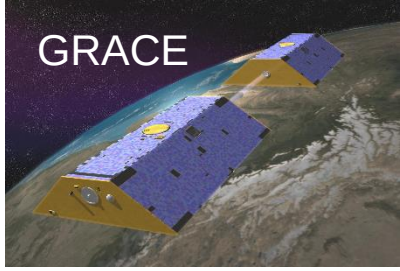
- アクチュエータ雑音→×
  DC的な相対加速度は予想よりも小さかった(し次第に減少している)のでforce authority(制御ゲイン？)を下げたため、当初の想定よりも効いていない
- 帯電変動 → たぶん違う(~3 fm s^{-2}/rtHz @ 0.1 mHz)
  今後わざと帯電させて測定する予定
- 熱勾配雑音 → <~1 fm s^{-2}/rtHz @ 0.1 mHz
  50 μK/rtHz @ 0.1 mHz (サーミスタ)
- 古典輻射圧雑音 → ~2 fm s^{-2}/rtHz
  0.4 μW/rtHz
- 磁場雑音 → <~3 fm s^{-2}/rtHz @ 0.1 mHz
  100 nT/rtHz @ 0.1 mHz (磁場センサ)
- 時間とともに減少しているのも謎(推進薬の減少と関係？)

どのくらいすごいの？

- 重力波検出器として
  h ~ 9.3e-14 /rtHz @ 0.1 Hz
  (腕長: 376 mm)
  (cf. Phase-II TOBA: 1e-10 /rtHz @ 5 Hz)
  A. Shoda PhD thesis (University of Tokyo, 2015)
- 万有引力定数Gの測定
  0.54e-15*g /rtHz @ 0.7-20 mHz
  (c.f 原子干渉計: 3e-9*g @ 1sec)
  G. Rosi+, Nature 510, 518 (2014)
- 重力逆二乗則の検証
  10 fN/rtHz @ 0.7-20 mHz
  (TM: 1.928 kg)
  (cf. MTO: 6 fN/rtHz @ 307 Hz (on resonance))
  Y.-J. Chen+, PRL 116, 221102 (2016)



その他衛星との比較

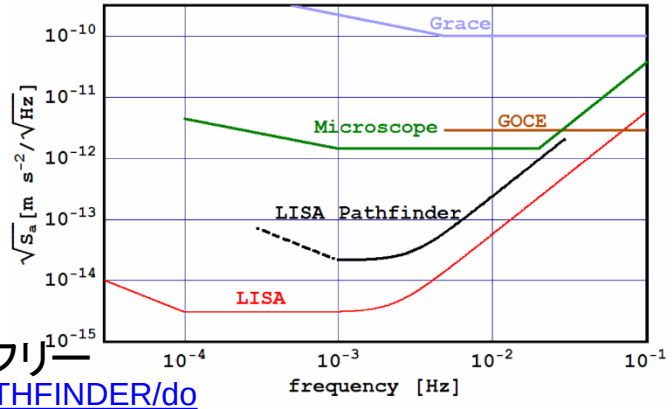


https://en.wikipedia.org/wiki/Gravity_Recovery_and_Climate_Experiment

- 加速度雑音
  - LPF: 5.2e-15 m s^{-2}/rtHz @ 0.7-20 mHz (1.928 kg)
  - GRACE: 1e-10 m s^{-2}/rtHz @ 1 mHz (< 100 g)
  - GOCE: 3e-12 m s^{-2}/rtHz @ 1 mHz (320 g)
  - Pre-DECIGO要求値: 3e-18 m s^{-2}/rtHz (30 kg)
- 変位雑音
  - LPF: 3.48e-14 m/rtHz @ 0.1 Hz
  - Pre-DECIGO要求値: 2e-18 m/rtHz @ 0.1 Hz

http://www.esa.int/Our_Activities/Observing_the_Earth/GOCE/Introducing_GOCE

LPFは地球から1.5e6 km離れた
ラグランジュ点L1でのリサージュ軌道
GRACE, GOCEは地球周回軌道で
高度350 km, 250 km
Pre-DECIGOは未定(地球周回？)
LPF, GOCE, Pre-DECIGOはドラッグフリー



http://www.rssd.esa.int/SP/LISAPATHFINDER/docs/LPF_Science_Case.pdf

Figure 5: Comparison of required performances of various missions for relative geodesic deviation of test-mass pairs. For LISA Pathfinder the mission requirements are reported as the solid line. The dashed tail is a design goal. Actual projected performance is discussed later.

較正とか

- 不確かさは5 %以下らしい
- 較正ラインで地上試験との一致を2σで確認
- レーザー強度を変調させ、輻射圧で独立に較正して20 %の精度で一致を確認

- 論文中、eLISAの名前は一度も出ていない
- GW150914のことは一切触れられてない
- LPF単体での科学的成果についても触れられてない

Vitale, however, points out that it is important for researchers to stay focused on the mission's immediate goal. "*Our main objective is to demonstrate freefall*," he says, "*and we don't want to be distracted from that.*"

http://www.nature.com/news/freefall-space-cubes-are-test-for-gravitational-wave-spotter-1.18806

測定方法

- ヘテロダイン干渉計 (35 mW @ 1064 nm)
- 衛星に対するTM1の動きがなくなるようにμNスラスタで衛星をドラッグフリー制御
- TM1に対するTM2動きがなくなるようにTM2の動きを静電アクチュエータで制御
- 4つの干渉計
  reference, frequency, X1, X12

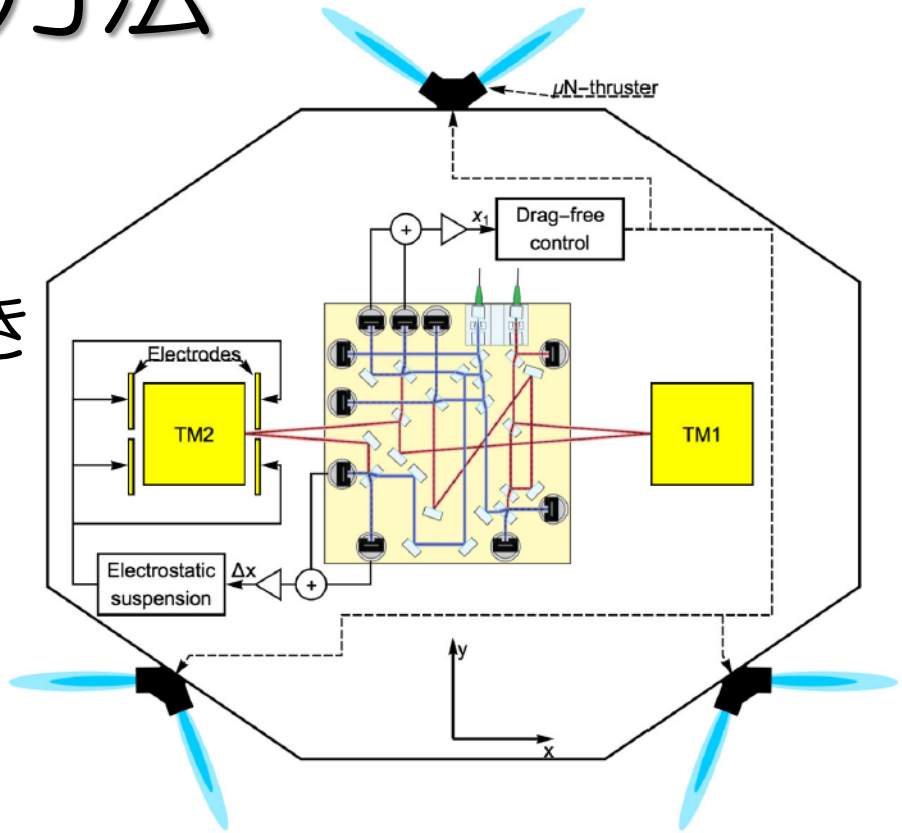
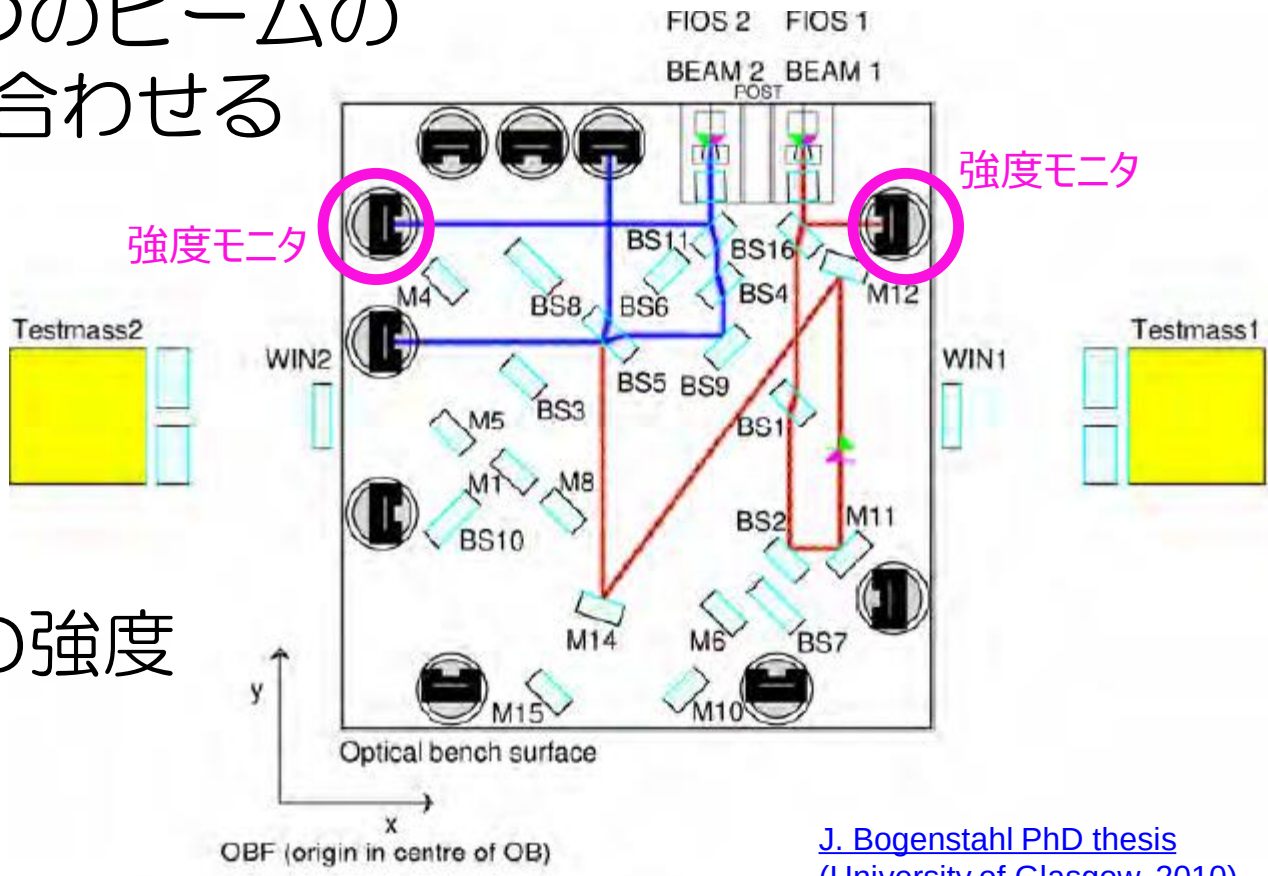


FIG. 2. A schematic of LPF. The figure shows TM1, TM2, and the optical bench beam paths for measuring Δx and x_1. The measurement of Δx drives the electrostatic suspension of TM2, which applies the necessary electrostatic forces by means of the electrodes represented by the four gold plates facing TM2. All other electrodes surrounding the TMs are not shown. The measurement of x_1 drives the drag-free control loop that uses the micronewton thrusters to exert forces on the spacecraft. The figure depicts the x and y axes we use in this Letter, while z is normal to the figure.

参照干渉計

- 2つのビームの相対位相を測定
  ファイバで導入される位相差など
  制御して2つのビームの
  相対位相を合わせる



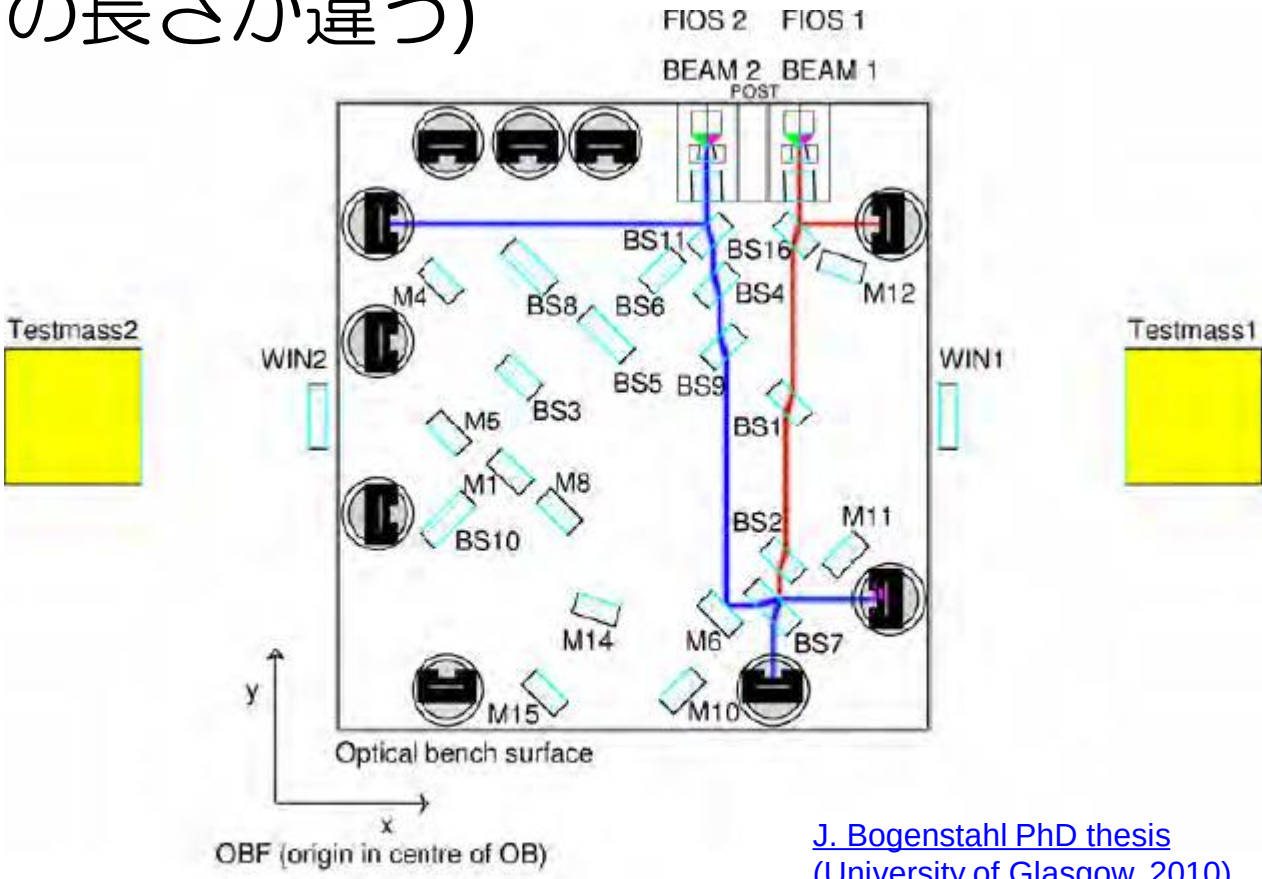
- 2つのビームの強度
  モニタもある

J. Bogenstahl PhD thesis
(University of Glasgow, 2010)

Figure 4.8: OptoCAD simulation of the reference interferometer.

周波数干渉計

- 2つのパスの光路長を非対称(~38.4 cm)にして周波数安定化
  (ファイバーの長さが違う)



J. Bogenstahl PhD thesis (University of Glasgow, 2010)

Figure 4.9: OptoCAD simulation of the frequency interferometer.

X1干渉計

- Optical Benchに対するTM1の動きを測定
- 光検出器はQPDなので変位と角度揺れの3自由度

G. Heinzel+, CQG 20, S153 (2003)

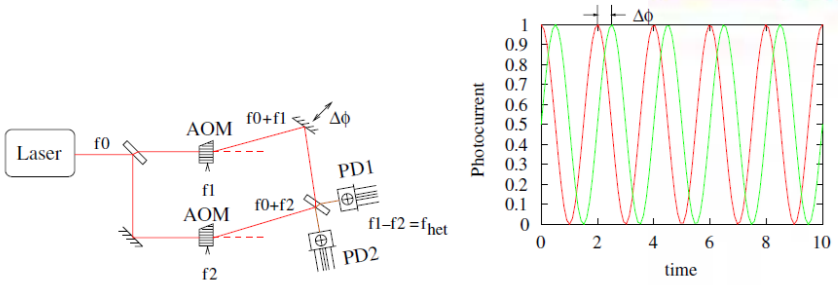
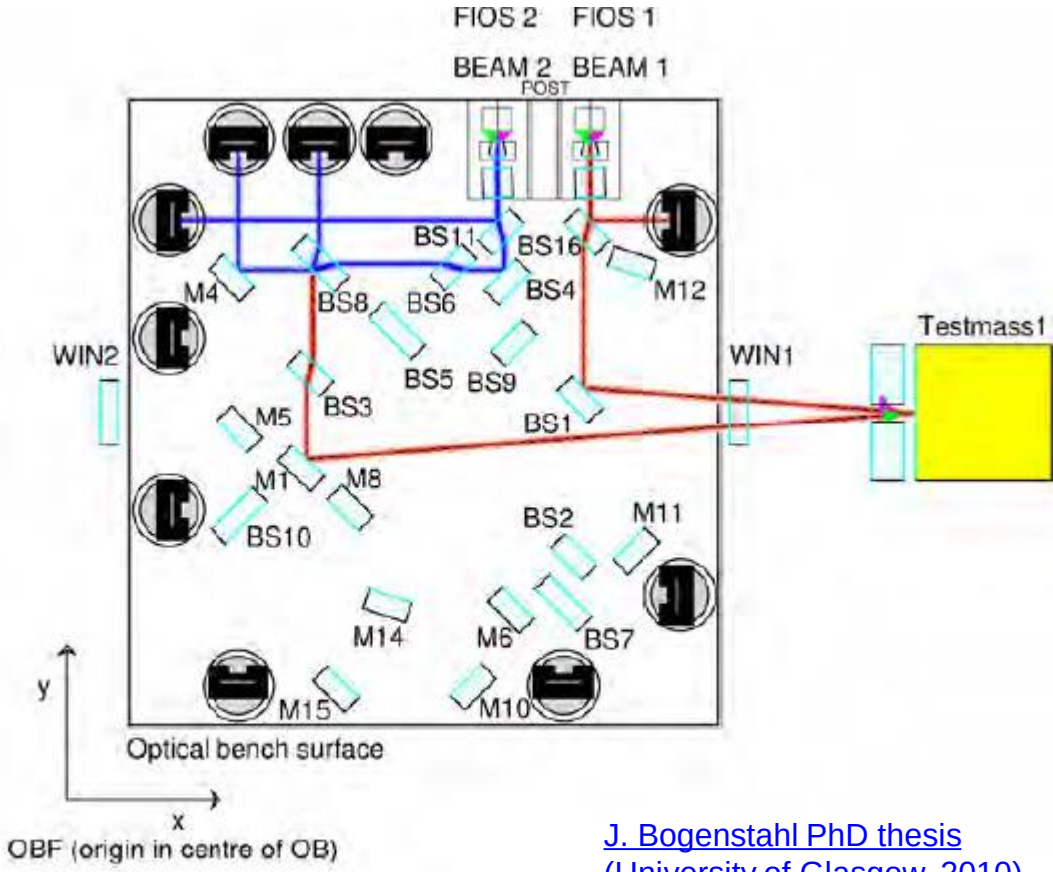


Figure 3. Heterodyne Mach–Zehnder interferometer: schematic (left) and typical photodiode signal (right).

component at the heterodyne frequency f_{het}. The time dependence of the heterodyne signal is given by

$$\cos\left(2\pi f_{het}\, t - \frac{2\pi l}{\lambda}\right) = \cos(2\pi f_{het}\, t - \varphi),$$



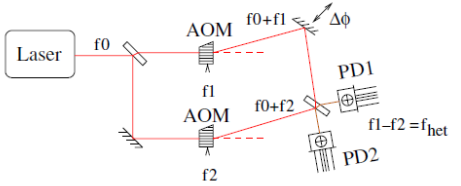
J. Bogenstahl PhD thesis (University of Glasgow, 2010)

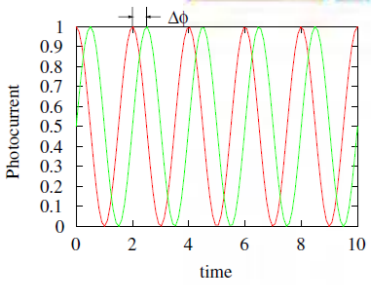
Figure 4.10: OptoCAD simulation of the X1 interferometer.

X12干渉計

- TM1とTM2の間隔(376 mm)の変動を測定
- 相対変位と相対角度揺れの3自由度

G. Heinzel+, CQG 20, S153 (2003)





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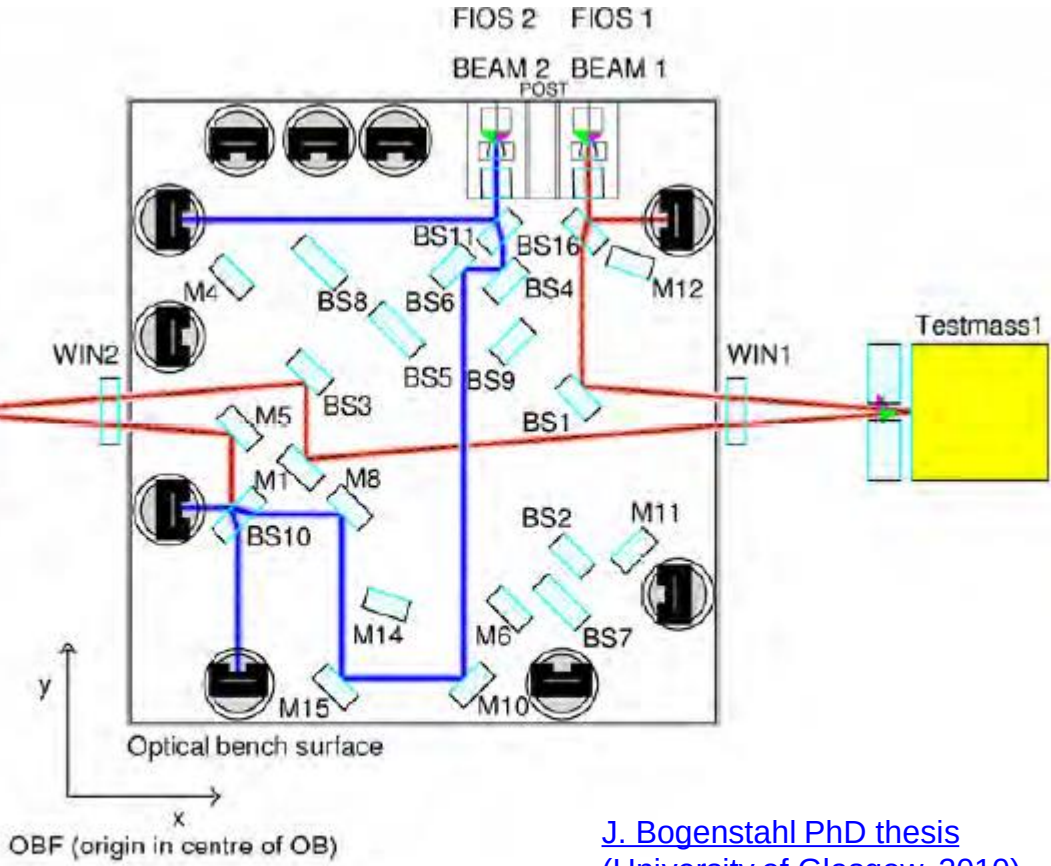


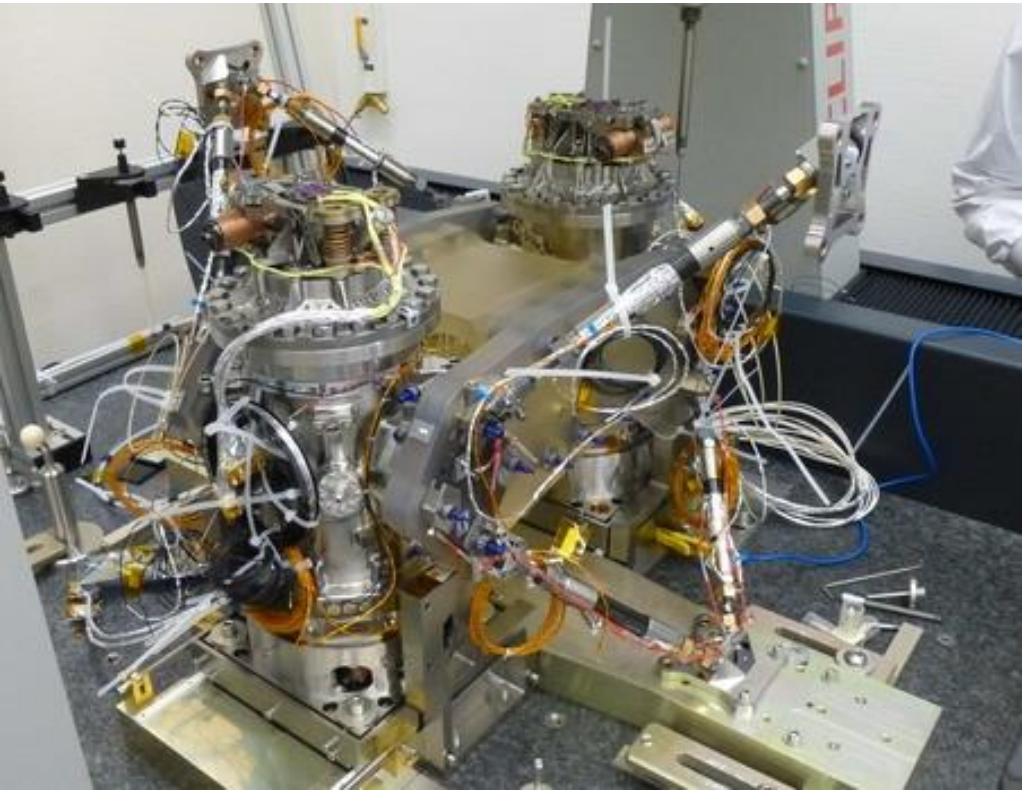
J. Bogenstahl PhD thesis (University of Glasgow, 2010)

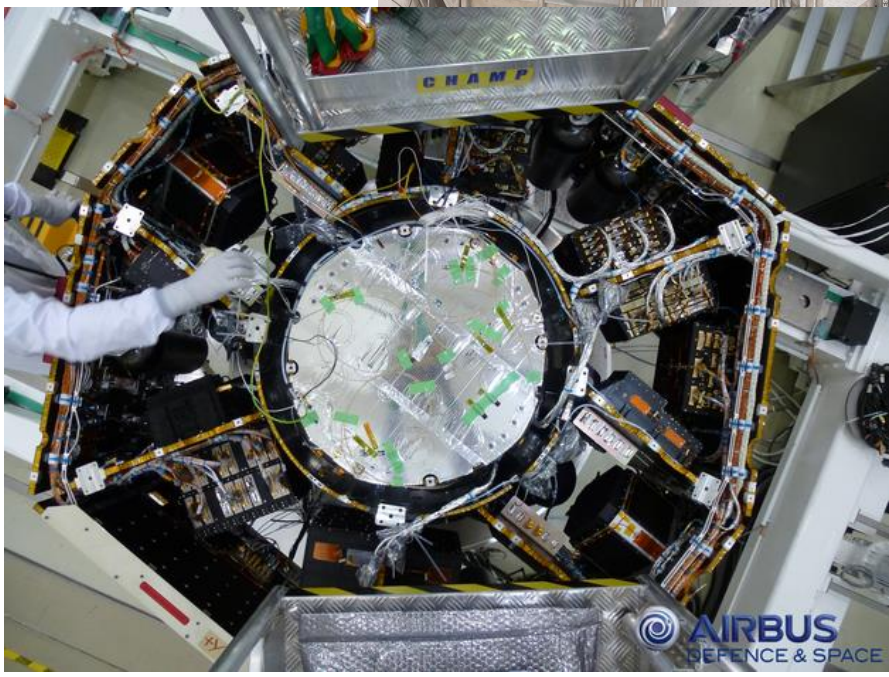
Figure 4.11: OptoCAD simulation of the X1-X2 interferometer.

LPFの中身

- LTP: LISA Technology Package が中心部品

http://sci.esa.int/lisa-pathfinder/56864-lisa-pathfinder-being-integrated-to-the-vega-launchers-payload-adaptor/



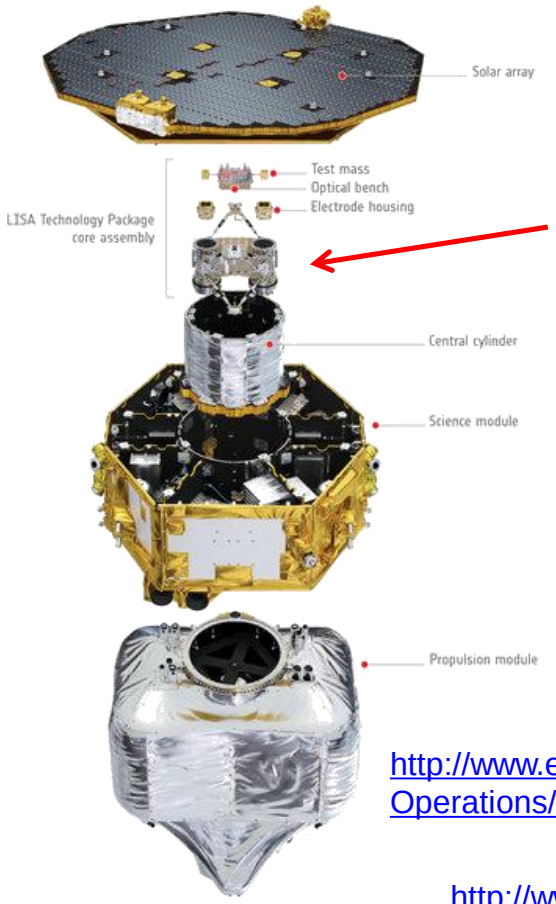


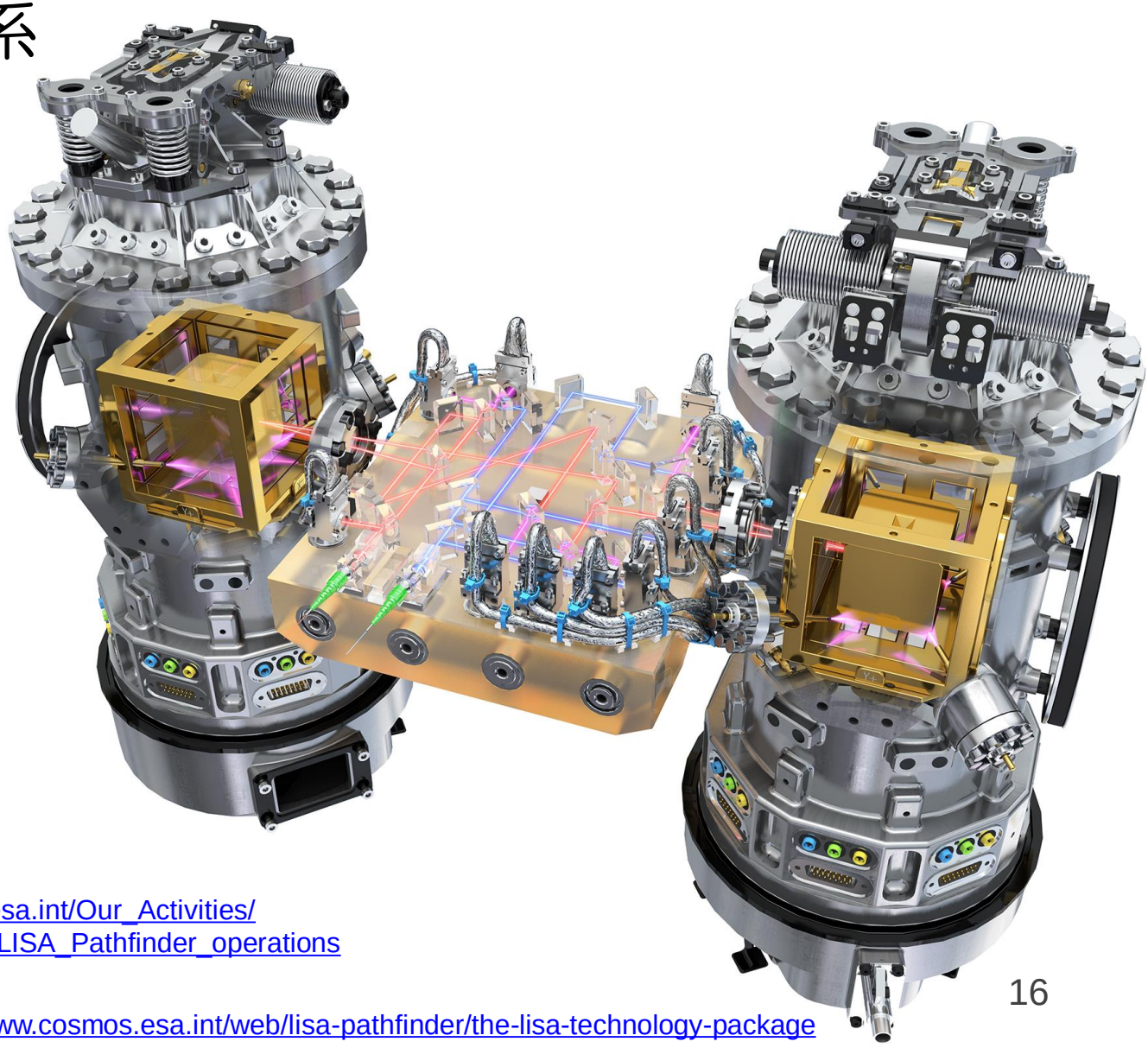
http://sci.esa.int/lisa-pathfinder/55634-ltp-core-assembly-of-the-lisa-technology-package/

http://sci.esa.int/lisa-pathfinder/56025-lisa-technology-package-core-assembly-integration/

LISA Technology Package

- 慣性センサ系と光計測系



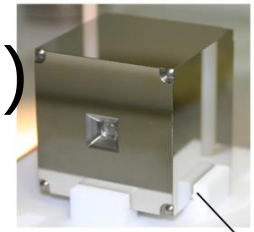


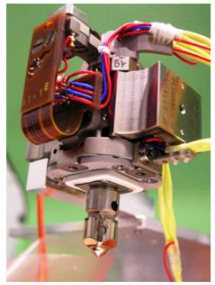
http://www.esa.int/Our_Activities/Operations/LISA_Pathfinder_operations

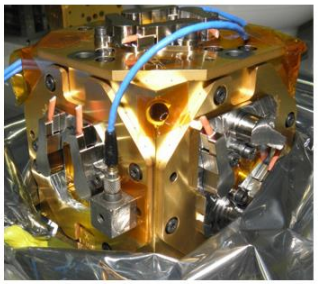
http://www.cosmos.esa.int/web/lisa-pathfinder/the-lisa-technology-package

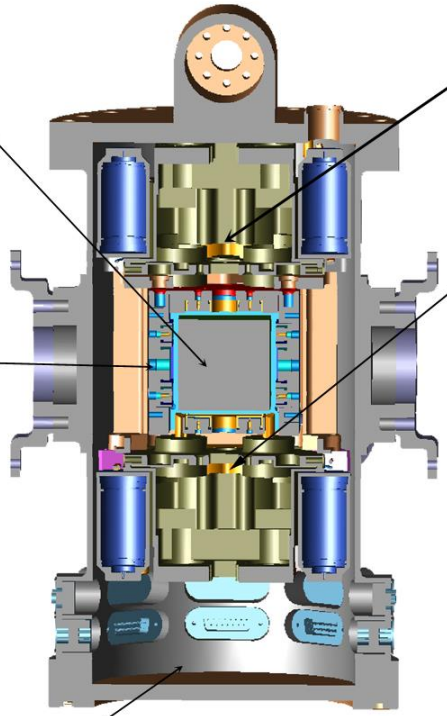
慣性センサ系

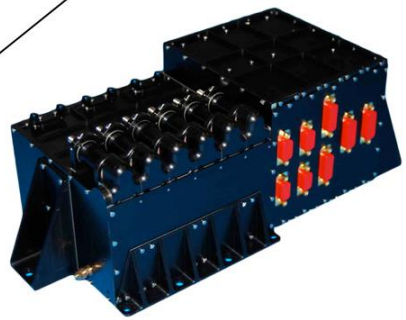
- TM(Au-Pt合金)と極板のついたハウジング
  静電センサ/アクチュエータ
  静電場遮蔽
  TM-極板間隔:
  2.9-4 mm
- クランプ・リリース機構 (打ち上げが長年延期された要因)
- UV帯電除去(TMとハウジング両方)


Test Mass

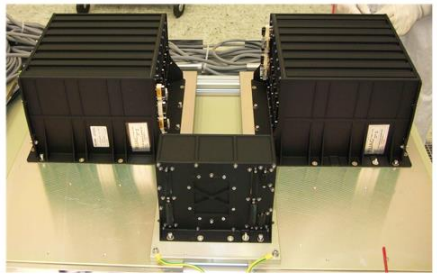

Grabbing, Position and Release Mechanism


Electrode Housing




UV Light Unit

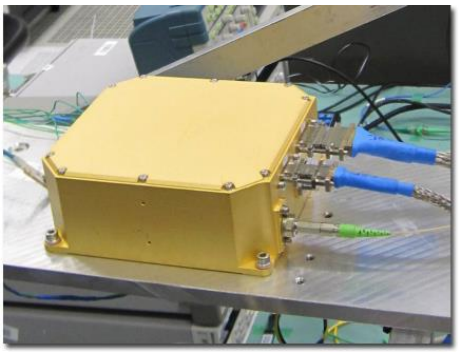

Vacuum Chamber


Front End Electronics

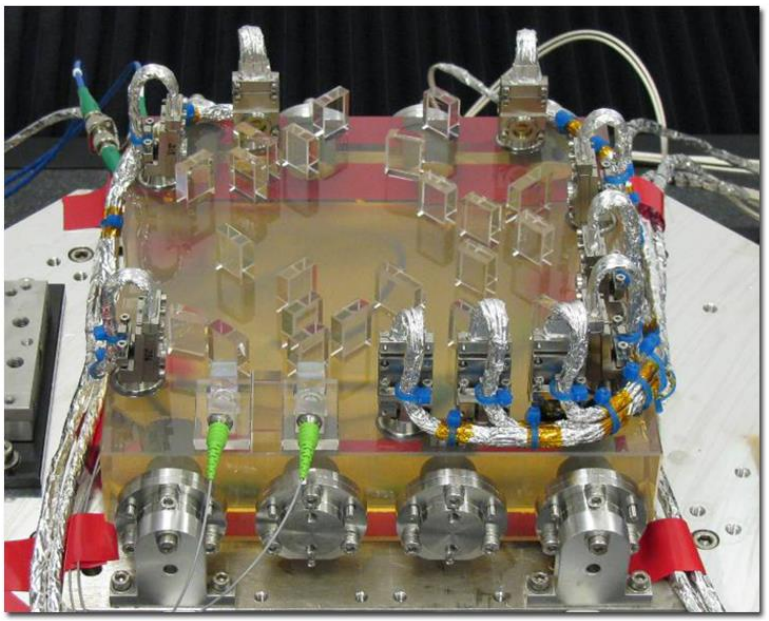
http://www.cosmos.esa.int/web/lisa-pathfinder/inertial-sensor

光計測系

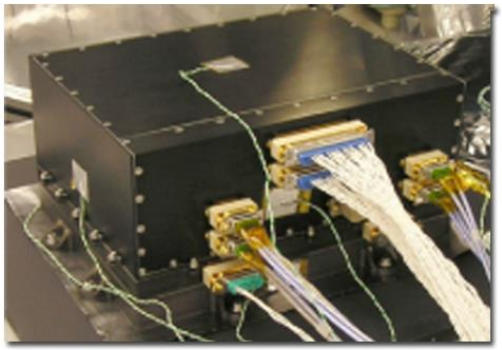
- 35 mW NPROレーザー、強度/位相変調系(AOMで強度安定化(?)/周波数安定化)、Optical Bench、ビート周波数の位相測定器(0.2 urad/rtHz & レンジ >100 μm なのでヘテロダイン干渉計)



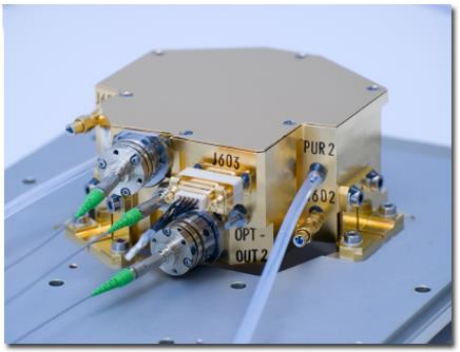
Reference Laser Unit (Tesat)



Optical Bench Interferometer (University of Glasgow)



Phasemeter (University of Birmingham)



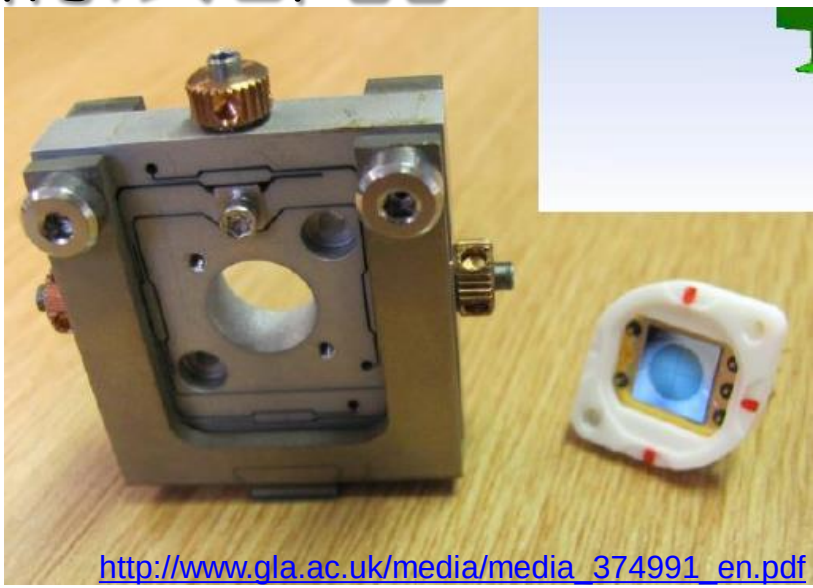
Laser Modulator (APC/RUAG)

Data Management Unit (IEEC/NTE)

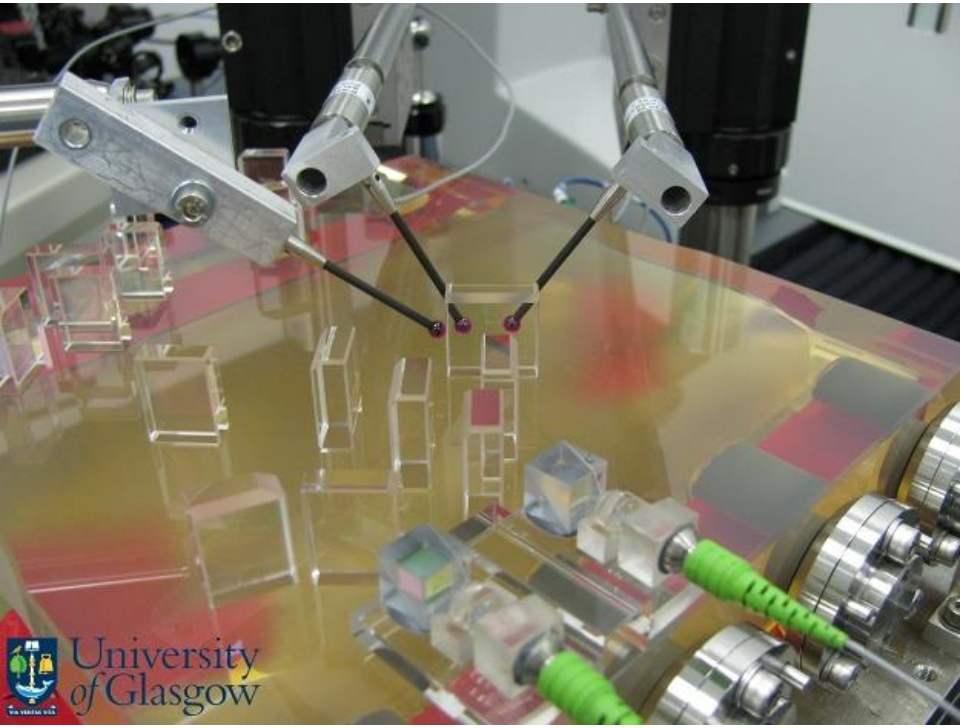
http://www.cosmos.esa.int/web/lisa-pathfinder/optical-metrology-subsystem

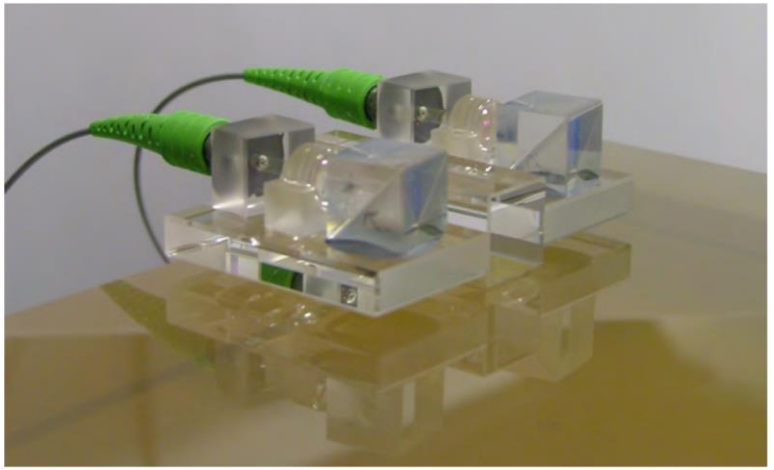
Optical Bench構成部品

- 光検出器はQPD(InGaAS)でアラインメントもモニタ



http://www.gla.ac.uk/media/media_374991_en.pdf





J. Bogenstahl PhD thesis (University of Glasgow, 2010)

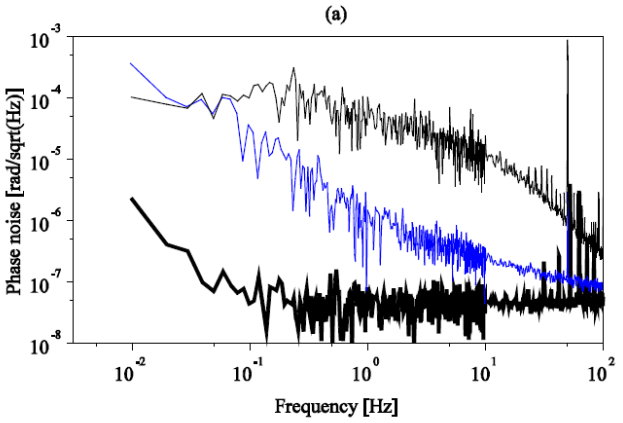
Figure 5.1: Photograph of the fibre injector qualification model pair bonded onto the post on the prototype LTP optical bench.

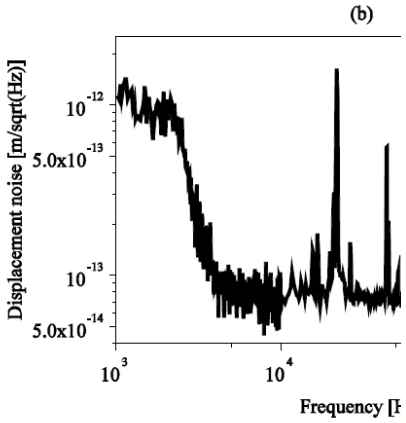
http://sci.esa.int/lisa-pathfinder/51919-constructing-the-lisa-pathfinder-flight-optical-bench/

穀山さんphasemeterとの比較

- LPF phasemeter: 0.2 urad/rtHz @ 0.1 Hz
  (ヘテロダイン信号は1 kHz)
- 穀山さんphasemeter: 0.05 urad/rtHz @ 0.1 Hz
  (使った信号は80 kHz)

W. Kokuyama+, arXiv:1602.03701
Simple digital phase-measuring algorithm for low-noise heterodyne interferometry





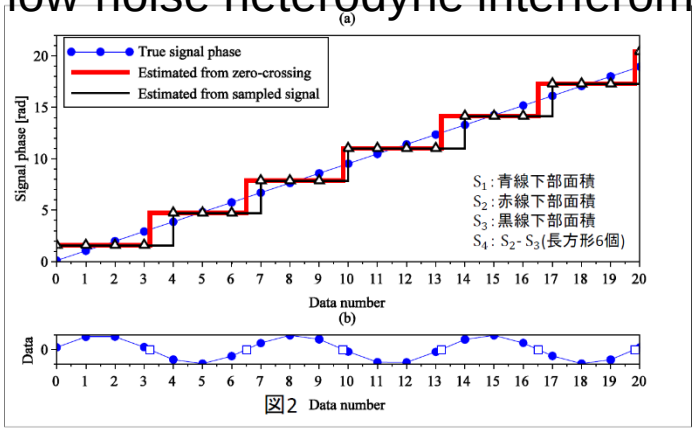


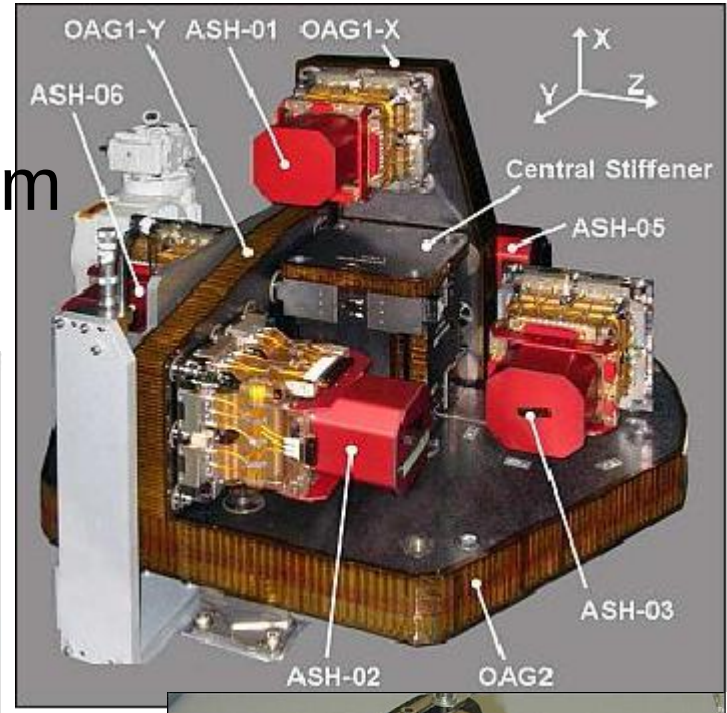
図2

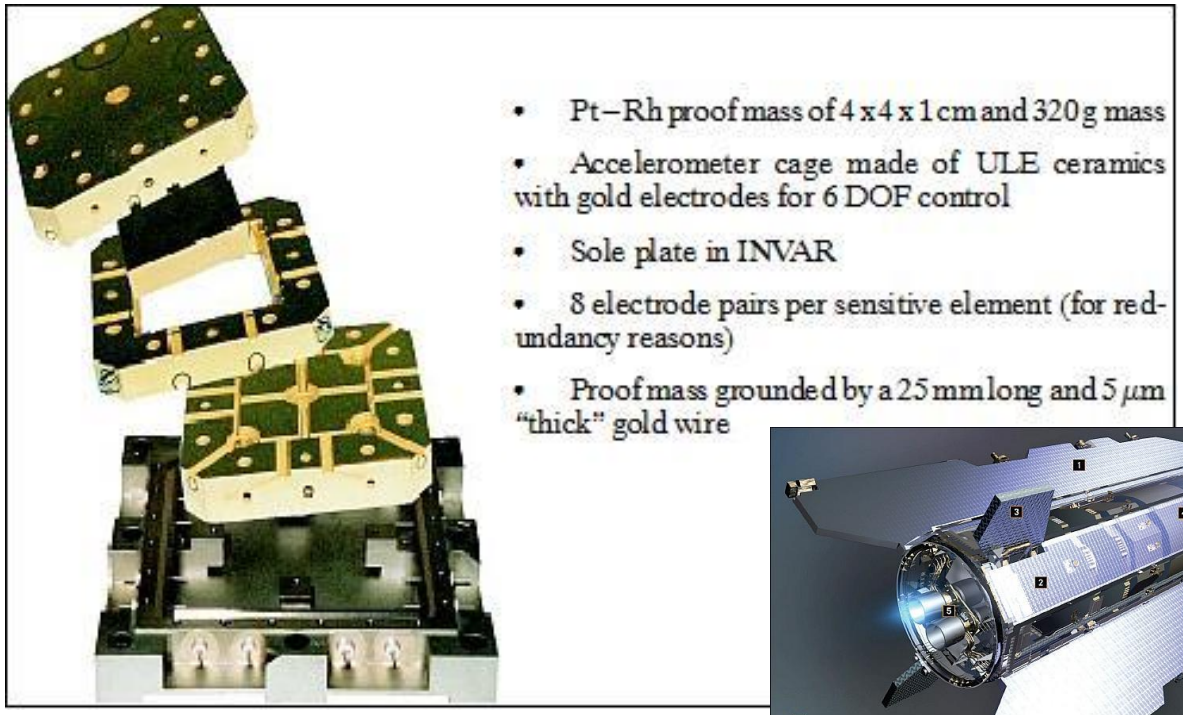
図2(b)が入力信号を示す。図2(a)の青丸は、その瞬時位相 $\phi(i)$ をプロットしたものである。このとき、(1)式の和演算は、図2 (a)青丸の下部の面積 S_1 を求めることに相当する。

Fig. 4. (a) Results for the test with electronics. The thick line shows the result for the proposed algorithm. The thin black line shows the noise level with the lock-in amplifier and a 30 m delay line. The thin blue line shows for the result with the lock-in amplifier and an artificial phase delay implemented with a low-pass filter. (b) Results for the test with laser Doppler vibrometer.

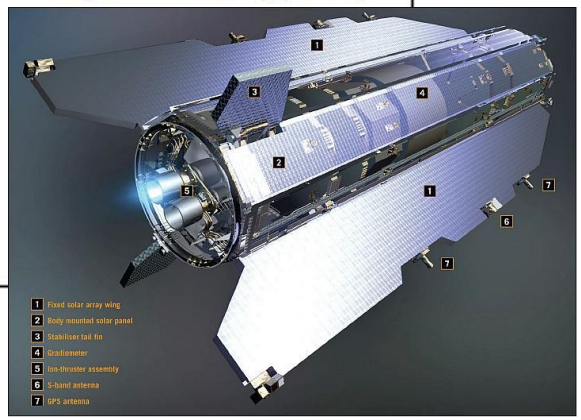
GOCEの加速度計

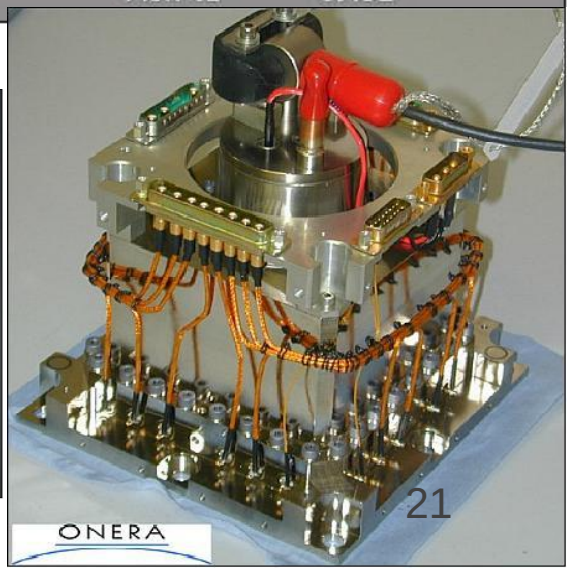
- 3軸にペアの加速度計
- 320 gのTMと極板の間隔0.3 mm
- Au細線で帯電除去





- Pt–Rh proof mass of 4 x 4 x 1 cm and 320 g mass
- Accelerometer cage made of ULE ceramics with gold electrodes for 6 DOF control
- Sole plate in INVAR
- 8 electrode pairs per sensitive element (for redundancy reasons)
- Proof mass grounded by a 25 mm long and 5 μm "thick" gold wire





https://directory.eoportal.org/web/eoportal/satellite-missions/g/goce

PRLの次のページの論文

- A. Sesana, PRL 116, 231102 (2016)
  Prospects for Multiband Gravitational-Wave Astronomy after GW150914
- eLISAを使えばaLIGOで受かるBHBを先に検出可能

PRL 116, 231102 (2016) PHYSICAL REVIEW LETTERS week ending 10 JUNE 2016

Prospects for Multiband Gravitational-Wave Astronomy after GW150914

Alberto Sesana
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(Received 21 February 2016; revised manuscript received 8 April 2016; published 8 June 2016)

The black hole binary (BHB) coalescence rates inferred from the Advanced LIGO detection of GW150914 imply an unexpectedly loud gravitational-wave (GW) sky at millihertz frequencies accessible to the Evolved Laser Interferometer Space Antenna (eLISA), with several outstanding consequences. First, up to thousands of BHBs will be individually resolvable by eLISA; second, millions of nonresolvable BHBs will build a confusion noise detectable with a signal-to-noise ratio of a few to hundreds; third—and perhaps most importantly—up to hundreds of BHBs individually resolvable by eLISA will coalesce in the Advanced LIGO band within 10 y. eLISA observations will tell Advanced LIGO and all electromagnetic probes weeks in advance when and where these BHB coalescences will occur, with uncertainties of <10 s and <1 deg^2. This will allow the prepointing of telescopes to realize coincident GW and multiwavelength electromagnetic observations of BHB mergers. Time coincidence is critical, because a prompt emission associated to a BHB merger will likely have a duration comparable to the dynamical time scale of the systems and is possible only with low-frequency GW alerts.

複数帯域での観測

- eLISAで検出してから10年以内にaLIGOで検出
- eLISAの設計を再考すべき
- 規模縮小はこのような科学的成果を失う
  3本目の腕
  最低2e6 km

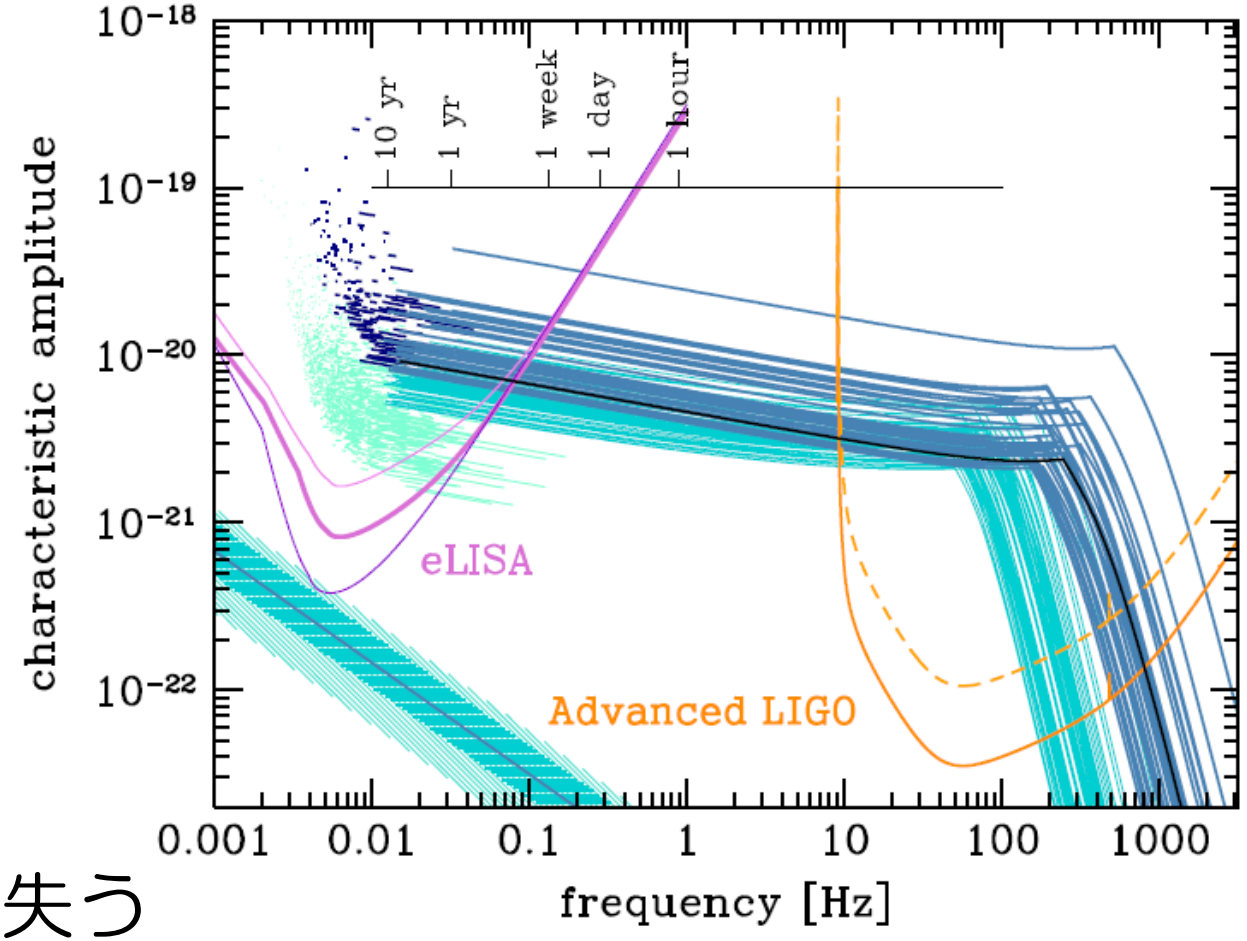
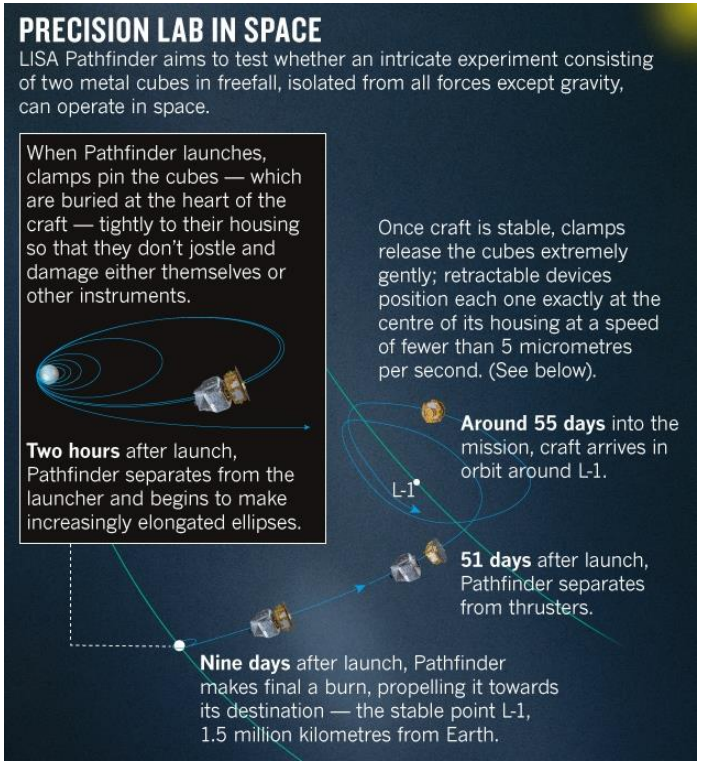
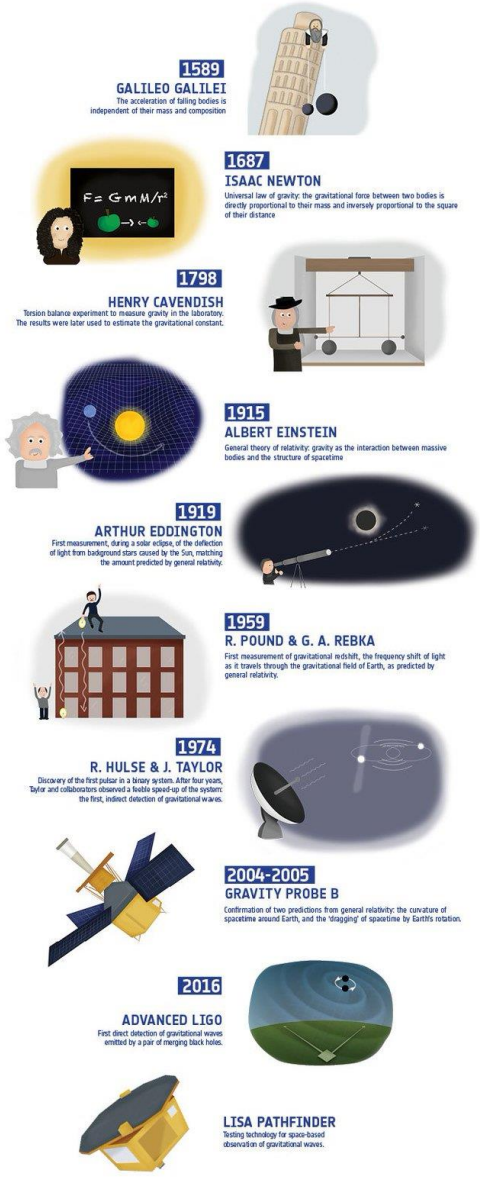


FIG. 1. The multiband GW astronomy concept. The violet lines are the total sensitivity curves (assuming two Michelson) of three eLISA configurations; from top to bottom, N2A1, N2A2, and N2A5 (from Ref. [11]). The orange lines are the current (dashed) and design (solid) Advanced LIGO sensitivity curves. The lines

まとめ

- 極めて順調
- かっこいい





http://www.nature.com/news/freefall-space-cubes-are-test-for-gravitational-wave-spotter-1.18806

- 1998年に最初の提案、
  2000年に採択、
  当初は2006年打ち上げ
  予定だった

http://sci.esa.int/lisa-pathfinder/57374-investigating-gravity-a-timeline-of-great-physics-experiments-updated/