Space-Based Quantum Sensors and Engineering

ISSUE: What are the development challenges and the future applications of space-based quantum sensors for space science and space engineering?

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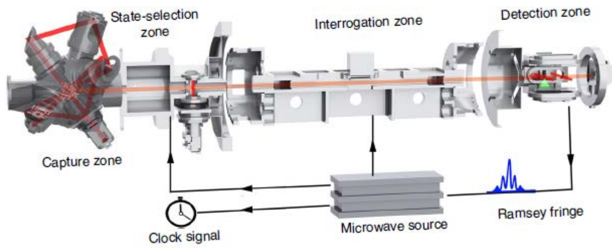
10/15/2020

Quantum PNT-related space demonstrations

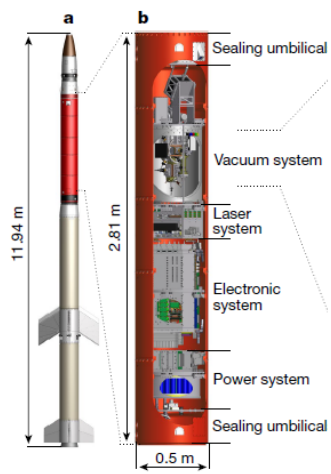


ARTICLE

DOI: 10.1038/s41467-018-05219-z OPEN

In-orbit operation of an atomic clock based on laser-cooled ^{87}Rb atoms

Liang Liu[1], De-Sheng Lü[1], Wei-Biao Chen[2], Tang Li[1], Qiu-Zhi Qu[1], Bin Wang[1], Lin Li[1], Wei Ren[1], Zuo-Ren Dong[2], Jian-Bo Zhao[1], Wen-Bing Xia[2], Xin Zhao[1], Jing-Wei Ji[1], Mei-Feng Ye[1], Yan-Guang Sun[2], Yuan-Yuan Yao[1], Dan Song[1], Zhao-Gang Liang[1], Shan-Jiang Hu[2], Dun-He Yu[2], Xia Hou[2], Wei Shi[2], Hua-Guo Zang[2], Jing-Feng Xiang[1], Xiang-Kai Peng[1] & Yu-Zhu Wang[1]

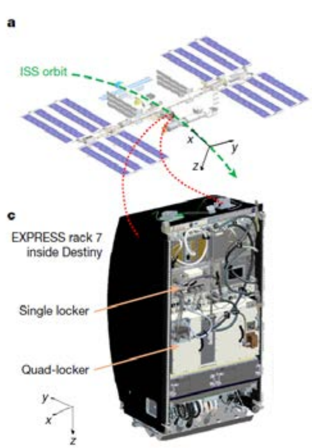


LETTER

https://doi.org/10.1038/s41586-018-0605-1

Space-borne Bose–Einstein condensation for precision interferometry

Dennis Becker[1,16], Maike D. Lachmann[1,16], Stephan T. Seidel[1,15,16], Holger Ahlers[1], Aline N. Dinkelaker[2], Jens Grosse[3,4], Ortwin Hellmig[5], Hauke Müntinga[3], Vladimir Schkolnik[2], Thijs Wendrich[1], André Wenzlawski[6], Benjamin Weps[7], Robin Corgier[1,8], Tobias Franz[7], Naceur Gaaloul[1], Waldemar Herr[1], Daniel Lüdtke[7], Manuel Popp[1], Sirine Amri[8], Hannes Duncker[5], Maik Erbe[9], Anja Kohfeldt[9], André Kubelka-Lange[3], Claus Braxmaier[3,4], Eric Charron[8], Wolfgang Ertmer[1], Markus Krutzik[2], Claus Lämmerzahl[3], Achim Peters[2], Wolfgang P. Schleich[10,11,12,13], Klaus Sengstock[5], Reinhold Walser[14], Andreas Wicht[9], Patrick Windpassinger[6] & Ernst M. Rasel[1*]



Article

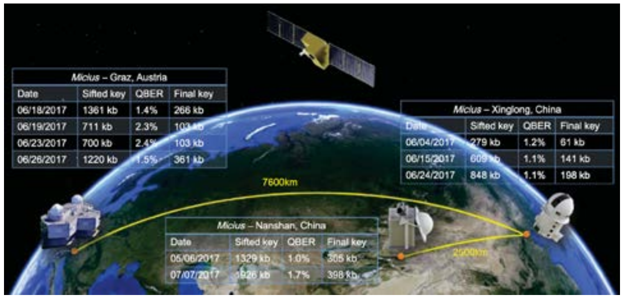
Observation of Bose–Einstein condensates in an Earth-orbiting research lab

https://doi.org/10.1038/s41586-020-2346-1

Received: 30 October 2019

David C. Aveline[1,2], Jason R. Williams[1,2], Ethan R. Elliott[1,2], Chelsea Dutenhoffer[1], James R. Kellogg[1], James M. Kohel[1], Norman E. Lay[1], Kamal Oudrhiri[1], Robert F. Shotwell[1], Nan Yu[1] & Robert J. Thompson[1]

Quantum communications and networks space demonstrations



PHYSICAL REVIEW LETTERS **120**, 030501 (2018)

Editors' Suggestion | Featured in Physics

Satellite-Relayed Intercontinental Quantum Network

Sheng-Kai Liao,[1,2] Wen-Qi Cai,[1,2] Johannes Handsteiner,[3,4] Bo Liu,[4,5] Juan Yin,[1,2] Liang Zhang,[2,6] Dominik Rauch,[3,4] Matthias Fink,[4] Ji-Gang Ren,[1,2] Wei-Yue Liu,[1,2] Yang Li,[1,2] Qi Shen,[1,2] Yuan Cao,[1,2] Feng-Zhi Li,[1,2] Jian-Feng Wang,[7] Yong-Mei Huang,[8] Lei Deng,[9] Tao Xi,[10] Lu Ma,[11] Tai Hu,[12] Li Li,[1,2] Nai-Le Liu,[1,2] Franz Koidl,[13] Peiyuan Wang,[13] Yu-Ao Chen,[1,2] Xiang-Bin Wang,[2] Michael Steindorfer,[13] Georg Kirchner,[13] Chao-Yang Lu,[1,2] Rong Shu,[2,6] Rupert Ursin,[3,4] Thomas Scheidl,[3,4] Cheng-Zhi Peng,[1,2] Jian-Yu Wang,[2,6] Anton Zeilinger,[3,4] and Jian-Wei Pan[1,2]

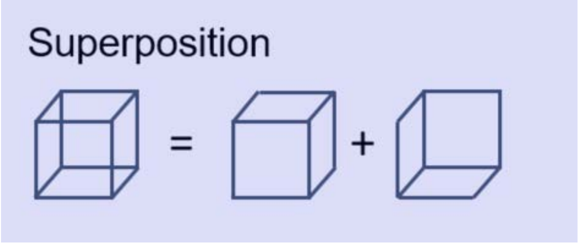
LETTER

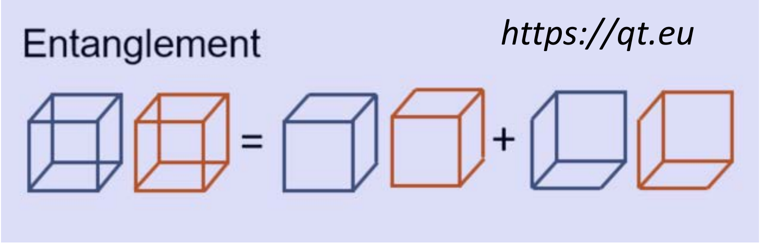
doi:10.1038/nature23675

Ground-to-satellite quantum teleportation

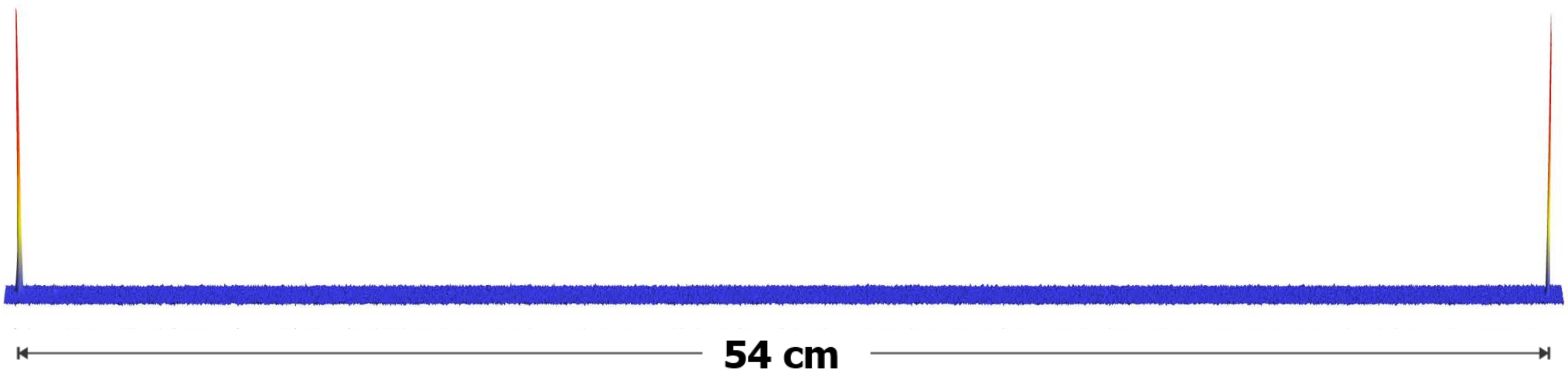
Ji-Gang Ren[1,2], Ping Xu[1,2], Hai-Lin Yong[1,2], Liang Zhang[2,3], Sheng-Kai Liao[1,2], Juan Yin[1,2], Wei-Yue Liu[1,2], Wen-Qi Cai[1,2], Meng Yang[1,2], Li Li[1,2], Kui-Xing Yang[1,2], Xuan Han[1,2], Yong-Qiang Yao[4], Ji Li[5], Hai-Yan Wu[5], Song Wan[6], Lei Liu[6], Ding-Quan Liu[3], Yao-Wu Kuang[3], Zhi-Ping He[3], Peng Shang[1,2], Cheng Guo[1,2], Ru-Hua Zheng[7], Kai Tian[8], Zhen-Cai Zhu[6], Nai-Le Liu[1,2], Chao-Yang Lu[1,2], Rong Shu[2,3], Yu-Ao Chen[1,2], Cheng-Zhi Peng[1,2], Jian-Yu Wang[2,3] & Jian-Wei Pan[1,2]

The quantum principles of distributed entanglement and superposition enable measurements which are (potentially!) superior to existing approaches.



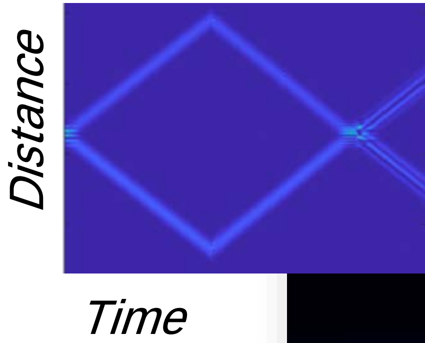


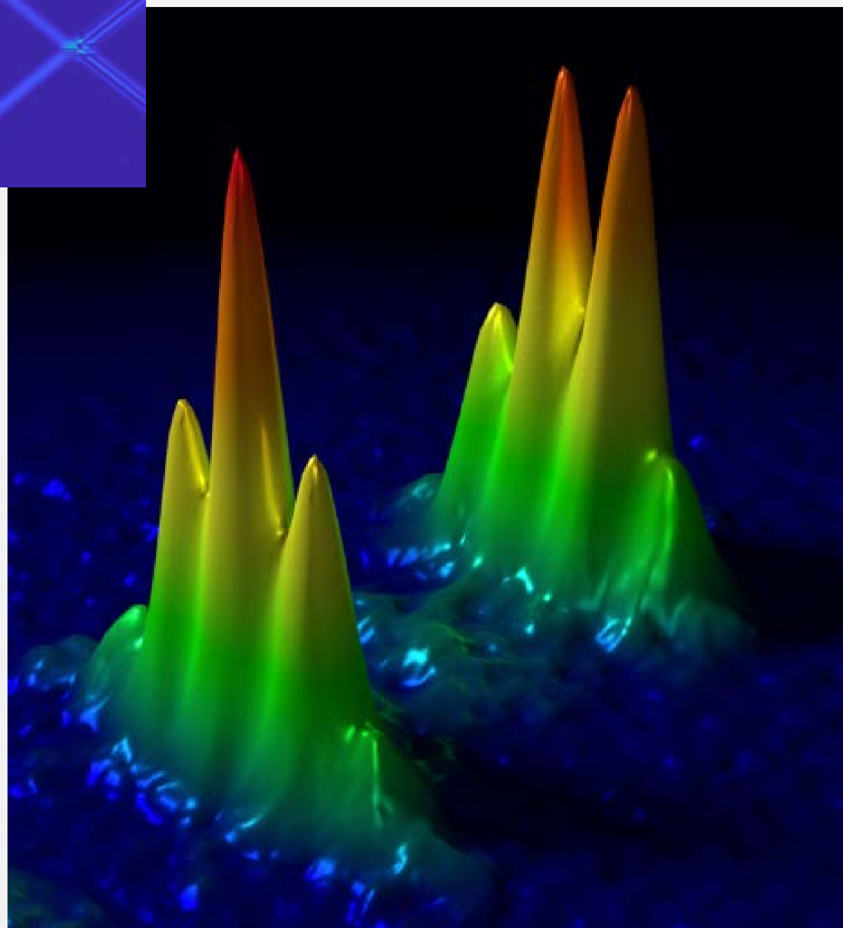
Atomic wavepacket superposition

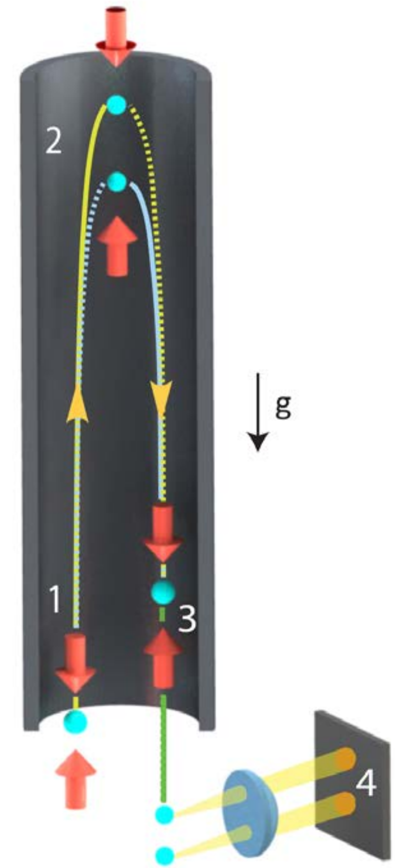


Kovachy, et al., Nature (2015).

Atomic wavepacket interference







Superposed atomic wavepackets interfere

Asenbaum, PRL (2017).

Phase shifts

Term	Phase Shift	
1	$k_{\text{eff}}\, g\, T^2$	Gravity
2	$2\mathbf{k}_{\text{eff}} \cdot (\boldsymbol{\Omega} \times \mathbf{v})\, T^2$	Coriolis
3	$k_{\text{eff}} v_z \delta T$	Timing asymmetry
4	$\frac{\hbar k_{\text{eff}}^2}{2m} T_{zz} T^3$	Curvature, quantum (tidal)
5	$k_{\text{eff}} T_{zi} \left(x_i + v_i T\right) T^2$	Gravity gradient
6	$\frac{1}{2} k_{\text{eff}} \alpha \left(v_x^2 + v_y^2\right) T^2$	Wavefront

8e9 rad

T_{ij}, gravity gradient

v_i, velocity; x_i, initial position

g, acceleration due to gravity

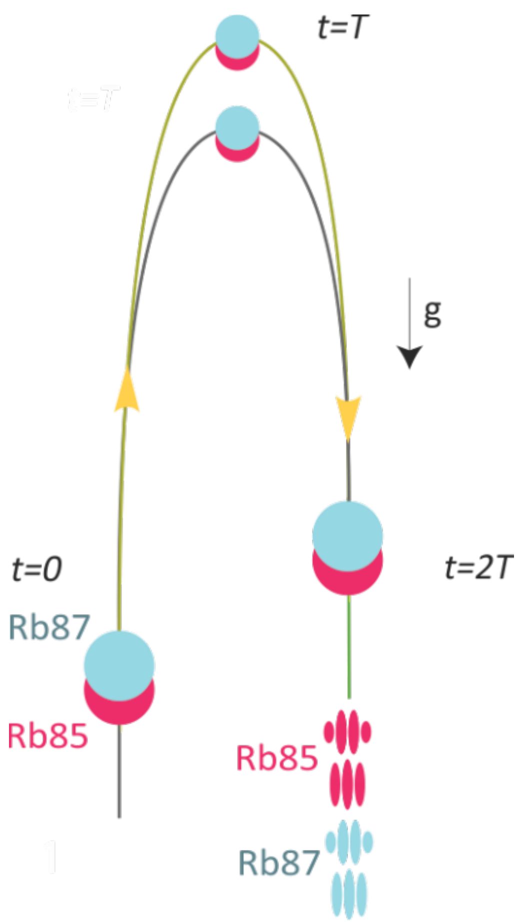
T, interrogation time

k_{eff}, effective propagation vector

Large phase shifts imply dramatic sensitivity to inertial forces

C. Overstreet, P. Asenbaum, and M. A. Kasevich, *Physically Significant Phase Shifts in Matter-Wave Interferometry*, arXiv:2008.05609 (2020).

Equivalence Principle



Atom-Interferometric Test of the Equivalence Principle at the 10^{-12} Level

Peter Asenbaum,* Chris Overstreet,* Minjeong Kim, Joseph Curti, and Mark A. Kasevich†

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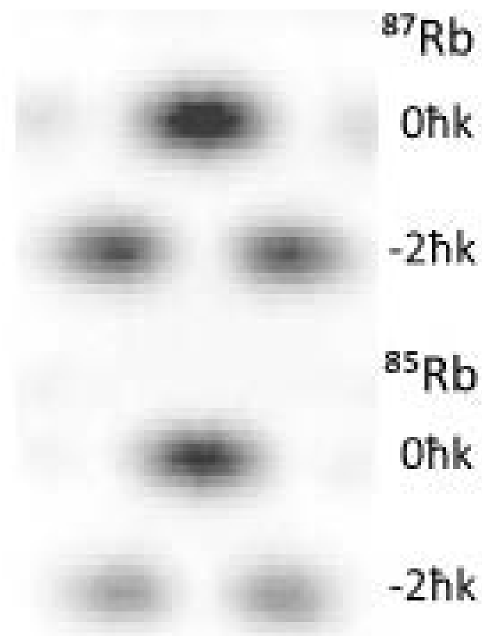
(Received 26 June 2020; accepted 5 October 2020)



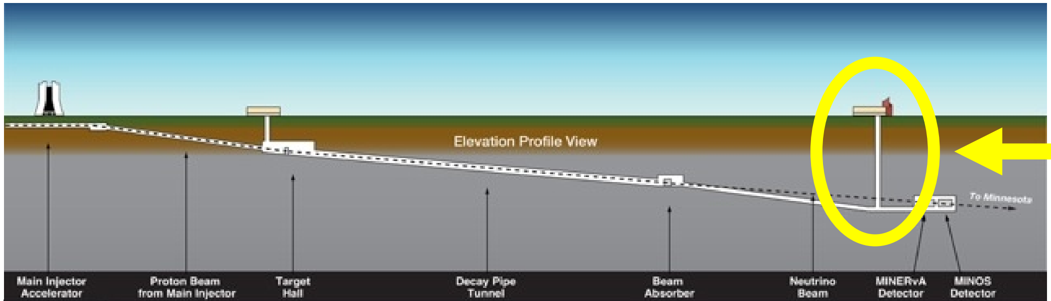
Current: 4e-12 $\delta g/g$

Future ground precision: < 1e-13 $\delta g/g$

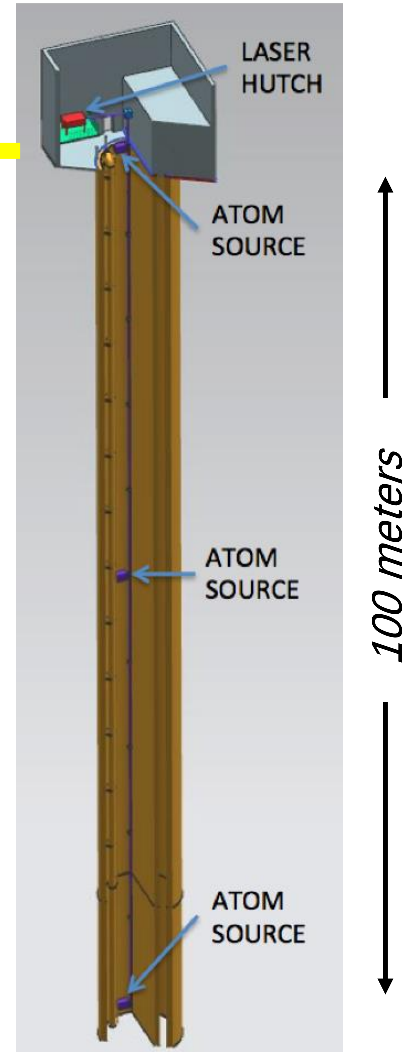
Space: < 1e-14 $\delta g/g$

P. Asenbaum, C. Overstreet, M. Kim, J. Curti, and M. A. Kasevich, *Atom-Interferometric Test of the Equivalence Principle at the 1e-12 Level*, arXiv:2005.11624 (2020).

MAGIS-100: Dark matter detector at Fermilab



Neutrino Beam Line for MINERvA and MINOS Experiments



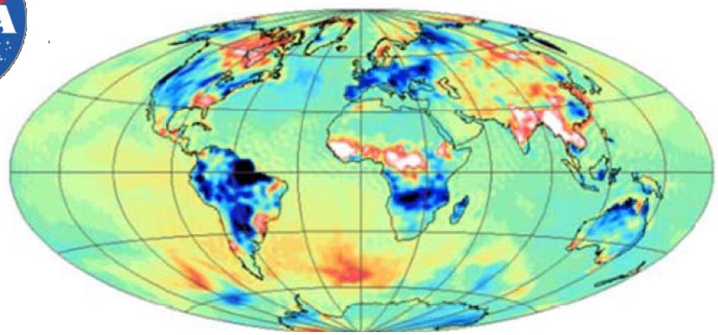
SCIENTIFIC AMERICAN CELEBRATING 175 YEARS

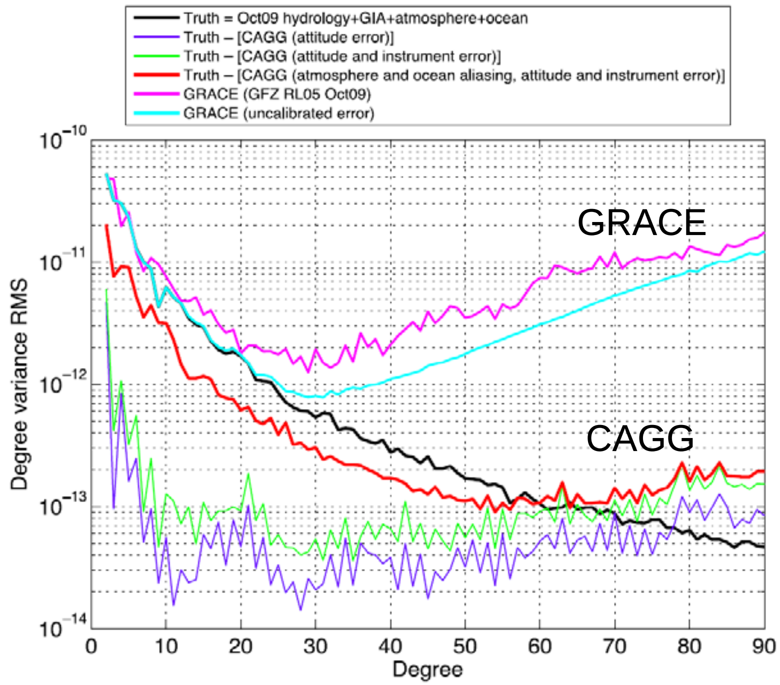
New Instrument Will Stretch Atoms into Giant Waves

Room-sized "atom waves" could help probe the quantum realm

By Charlie Wood | Scientific American February 2020 Issue

Satellite geodesy





Analysis from S. Luthke, GSFC

Simulation of hydrology map from space-borne atom interferometer gravity gradiometer.

~ 1 cm equivalent water height resolution.

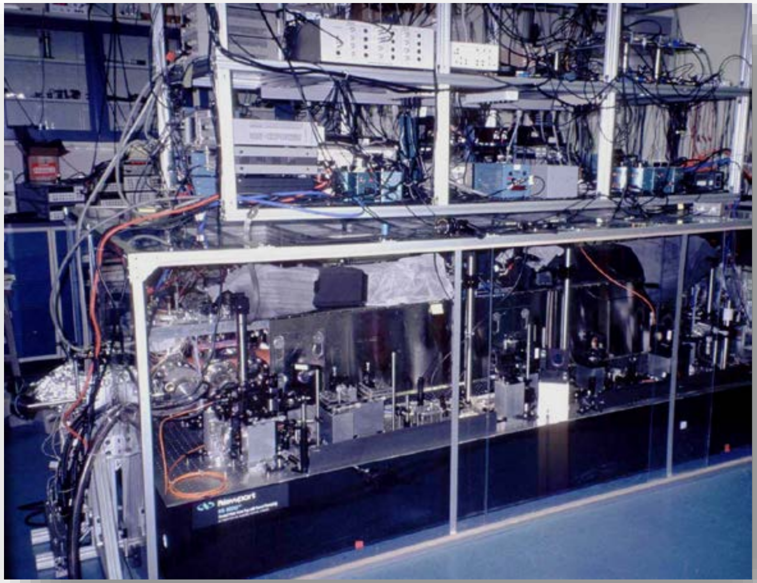
Instrument:

- 4 m baseline
- single-axis
- rotation compensation
- <1e-4 E design resolution

Development of prototype funded by NASA (POC B. Saif); Instrument built by AOSense, Inc.

Gyroscopes / Atom interferometer

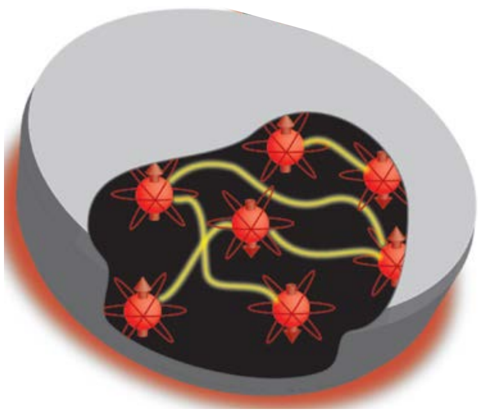
(2017-present) Navigation grade+ gyro, AOSense, Inc. Thermal atomic beam.



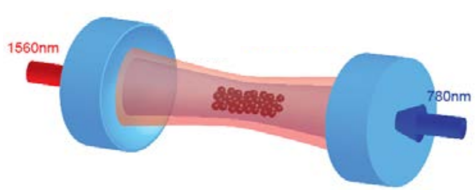
(1997) First laboratory demonstration of precision atom interferometric gyroscope. (2002) 2e-6 deg/hr$^{1/2}$. MK, Stanford. Thermal atomic beam.

Entangled state sensors

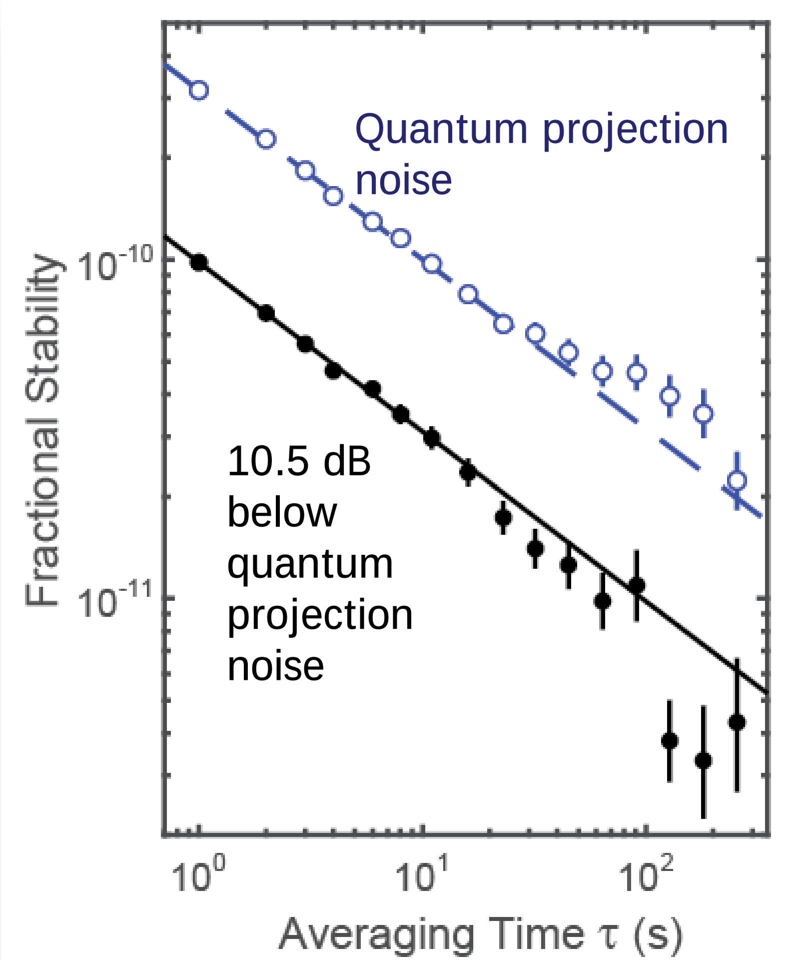
Entangled states will lead to 10x noise improvement in sensors (magnetometers, gyroscopes, clocks) in coming decade.



Atom-cavity interactions are used to create entangled many-atom quantum states.



Entangled-state atomic clock.



O. Hosten, et al., Nature (2016).

R&D questions

What are optimal quantum states for given measurement classes?

How can these states be efficiently prepared?

How are these states detected?

What are the technical and fundamental limits?
- (unknown) classical/quantum boundaries?

What physical systems will benefit?
- clocks?
- inertial sensors?
- magnetometer?
- optomechanical?

Our team