ON THE POTENTIAL OF STE-QUEST CLOCKS FOR RELATIVISTIC GEODESY

By Ruxandra Bondarescu (ITP-Zurich)

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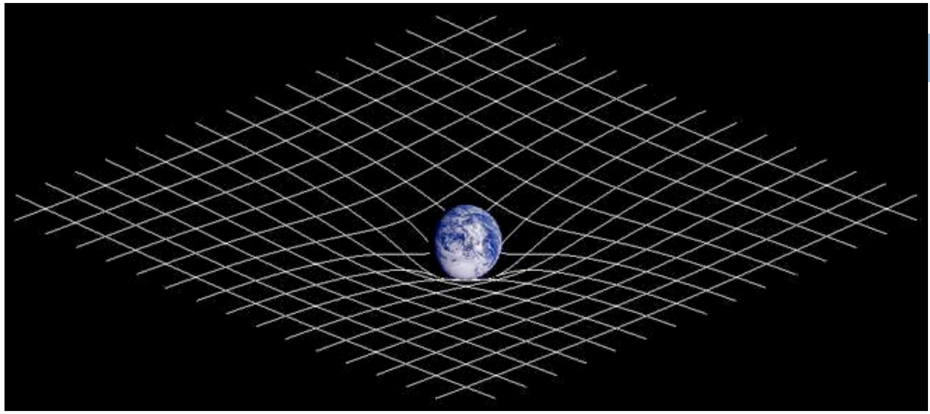
Partly based on Bondarescu *et al*. Geophys. J. Int. 2012, vol 191, pages 78-82, arXiv: 1209.2889.

STE QUEST clocks

- Atomic clock technology progressing at an amazing rate
  - Improvement in stability & accuracy of about an order of magnitude a decade
  - 2012 Nobel Prize: Serge Haroche & David Wineland for particle control in the quantum world
    - For observing individual quantum systems without destroying them
  - 920 km optical fiber link with accuracy ~ 4 x 10^{-19} (Predehl et al., Science 2012)
  - BUT still no accurate, stable and portable clocks, which is part of the promise of STE-QUEST
  - PTB – Paris first clock comparison to measure geoid planned with ($\Delta f/f = 10^{-18}$)!!
- STE QUEST clock will be portable enough to be flown in space
  - What can we can be achieved on Earth with a portable atomic clock of high stability and accuracy?
  - What can be achieved in space with such clocks?

Direct Application of General Relativity



Space tells matter how to move.
Matter tells space how to curve.
(Miner, Thorne and Wheeler)

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

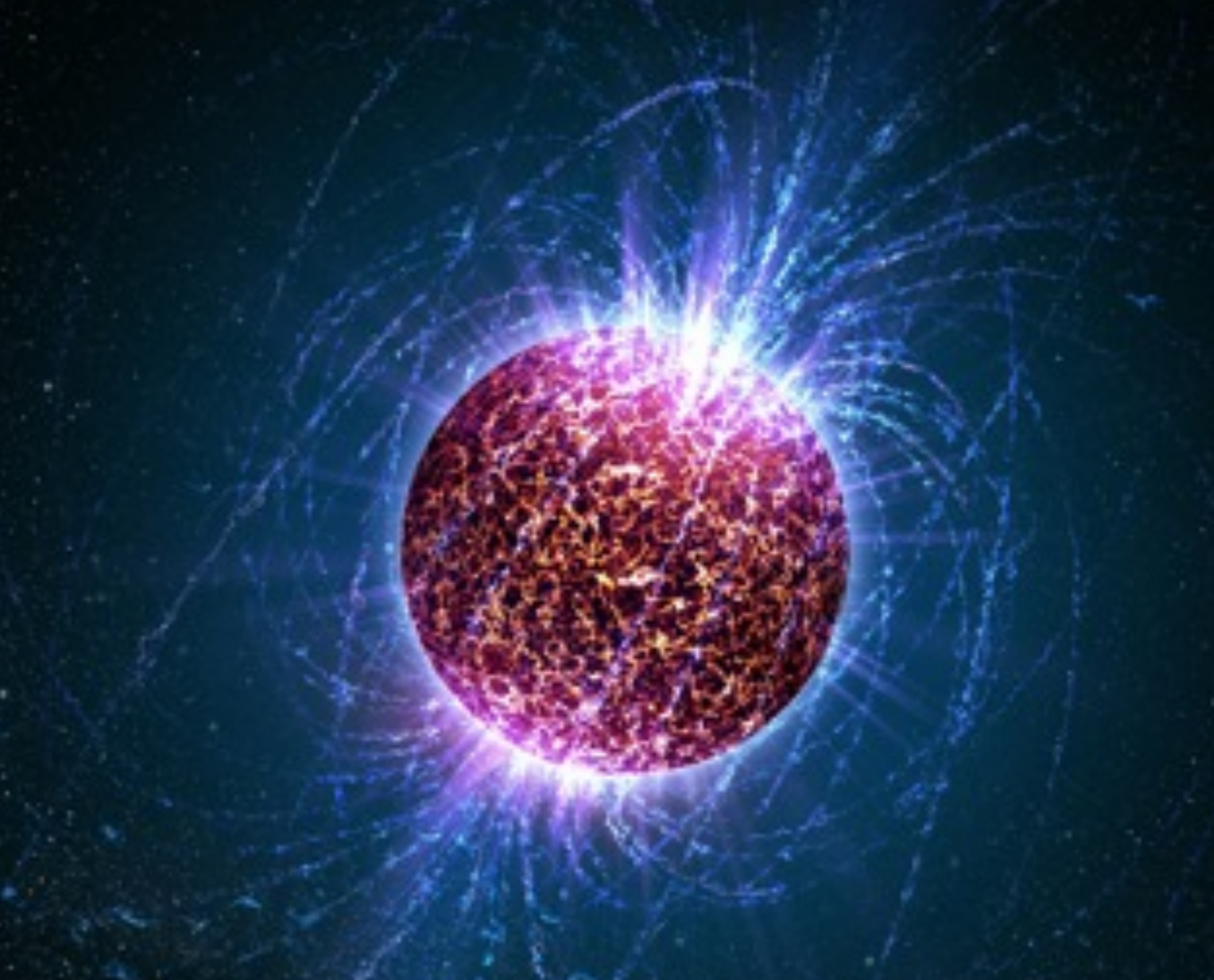
Space-time curvature = Matter content (Einstein's equations)

- **Time does not flow everywhere at the same speed. The closer an observer is to something heavy, the slower her clock ticks!**

Time near a black hole …

On a black hole horizon time stops altogether.
An observer infinitely close to the horizon will not age at all!

Time near a neutron star ..



On a neutron star clocks tick at about half their rate on Earth…

Image Credit: PSU

On Earth …

Ticks faster

Small differences in the speed of time are crucial to every day life!

Wine stays in the open bottle because the time at the bottom is slower than at the top.

- **the difference in time flow between two clocks placed at 33 cm one above the other has been measured!**

  (Chou et al, 2010)

Ticks slower

Current Clocks in Laboratories

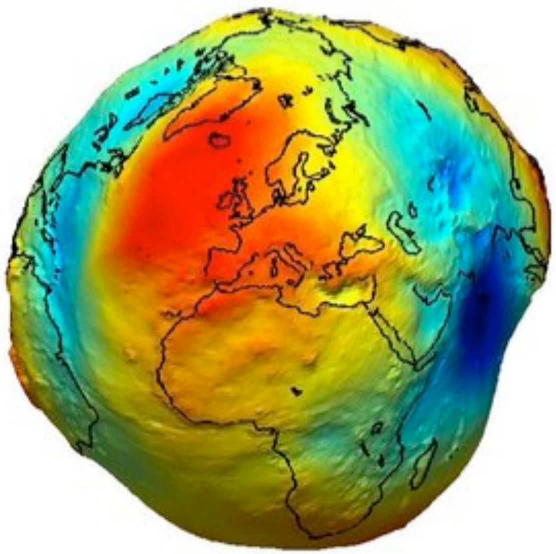
- optical lattice clock: Yb+
  - Stability 5 x $10^{-16}/\sqrt{\tau}$ in 1 sec
  - Measurement uncertainty ~ 10^{-17}
  - $\Delta f/f = 10^{-17}$ corresponds to 10 cm in geoid height

- single ion clocks: Al +
  - Relative stability ~ 3 x $10^{-15}/\sqrt{\tau}$ in 1 sec
  - Measurement uncertainty ~ 7 x 10^{-18}

Surveying Earth's Interior with Clocks

- **A clock over a heavy rock will tick slower than one placed on top of a large empty underground cave.**
  - **A portable atomic clock will slow down as it passes over the rock and speed up as it passes over the cave.**
- **Portable atomic clocks are sensitive to local, small scale sub-structure** (<< 100 km)
- **detectable or not? It depends on**
  - **Precision and stability of the clock measurements**
  - **size & shape of the anomaly, on the density contrast with the surrounding material, and on the distance to the observer.**
- Clocks can measure changes in the gravitational potential on the local scale due to mineral and petroleum deposits, structure of tectonic plates, ground water reservoirs and even buildings…
- The geoid accounts for the effects of all subsurface density variations.

Local Measurements of the Geoid



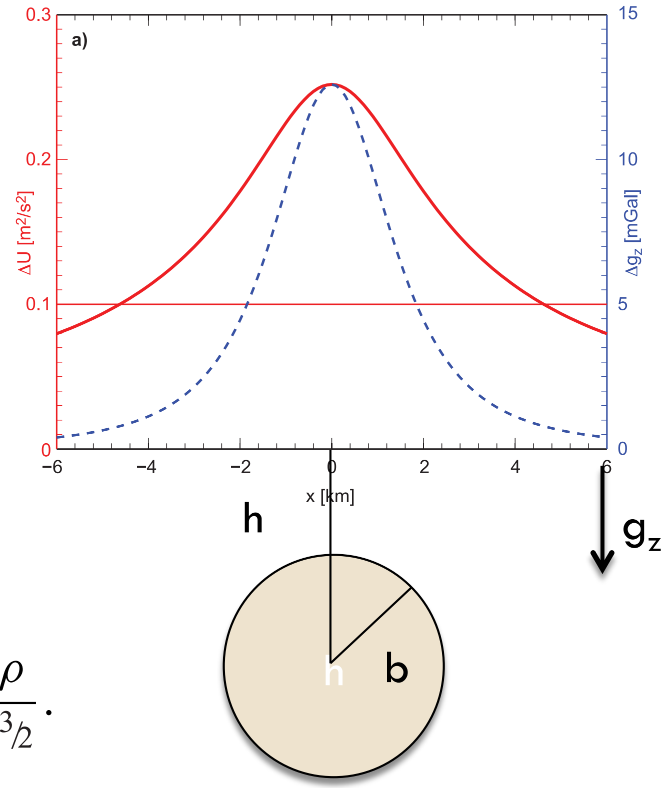
- **Clocks provide the most direct method to determine the geoid locally** (Bjerhammar, 1986)
  - Geoid is the surface of constant gravitational potential that extends the mean sea level. A ball on the geoid will just sit there. It will not roll up or down. To measure: one clock at mean sea level and another one anywhere on the continent.
  - **Tick rate of clocks is constant of the geoid after corrections e.g., from tides, etc.**
  - **Clocks measure geopotential differences at the location of the clock**
  - ALL current methods that determine the geoid measure derivatives of the potential – vectors or tensors that need to be integrated. The integration is typically ill defined.
  - Geoid known to 30-50 cm (locally from gravimeters + leveling)
  - GOCE & GRACE – satellite measurements of geoid (poor spatial resolution: 100 km; geoid height ~ 1 – 2 cm)
  - On the ground: PTB – Paris first clock comparison to measure geoid planned at $\Delta f/f = 10^{-18}$!!!
- Complementary to measurements from gravimeters and accelerometers
  - independent measurements with very different characteristics

Simple example: Buried Sphere

Unkowns

- Depth to the center of the buried sphere
- Radius of the sphere
- Density contrast

Reduce the degeneracy of the inverse problem by combining gravimetric & atomic clock measurements



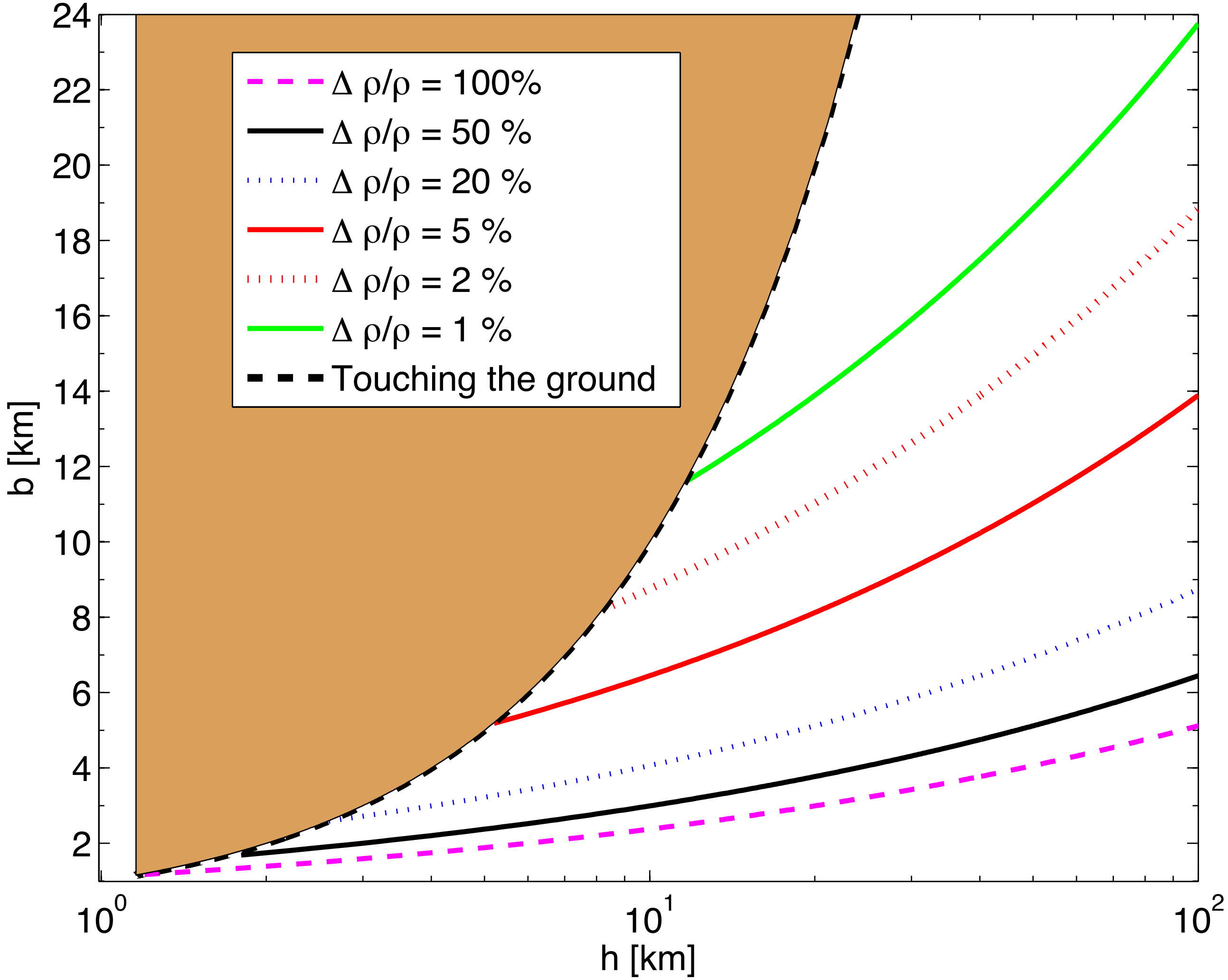
$$\frac{\Delta U}{\Delta g_z} = h + \frac{x^2}{h} \approx h \text{ for } x \ll h.$$

$$\Delta g_z(x) = \frac{4\pi G h b^3 \Delta\rho}{3\,(x^2 + h^2)^{3/2}}.$$

$$\Delta f/f \approx \Delta U/c^2$$

$$\Delta U(x) = \frac{4\pi G b^3 \Delta\rho}{3\,(x^2 + h^2)^{1/2}}$$

Radius of sphere vs. depth



$\Delta U_{max} = 1\ m^2/s^2$

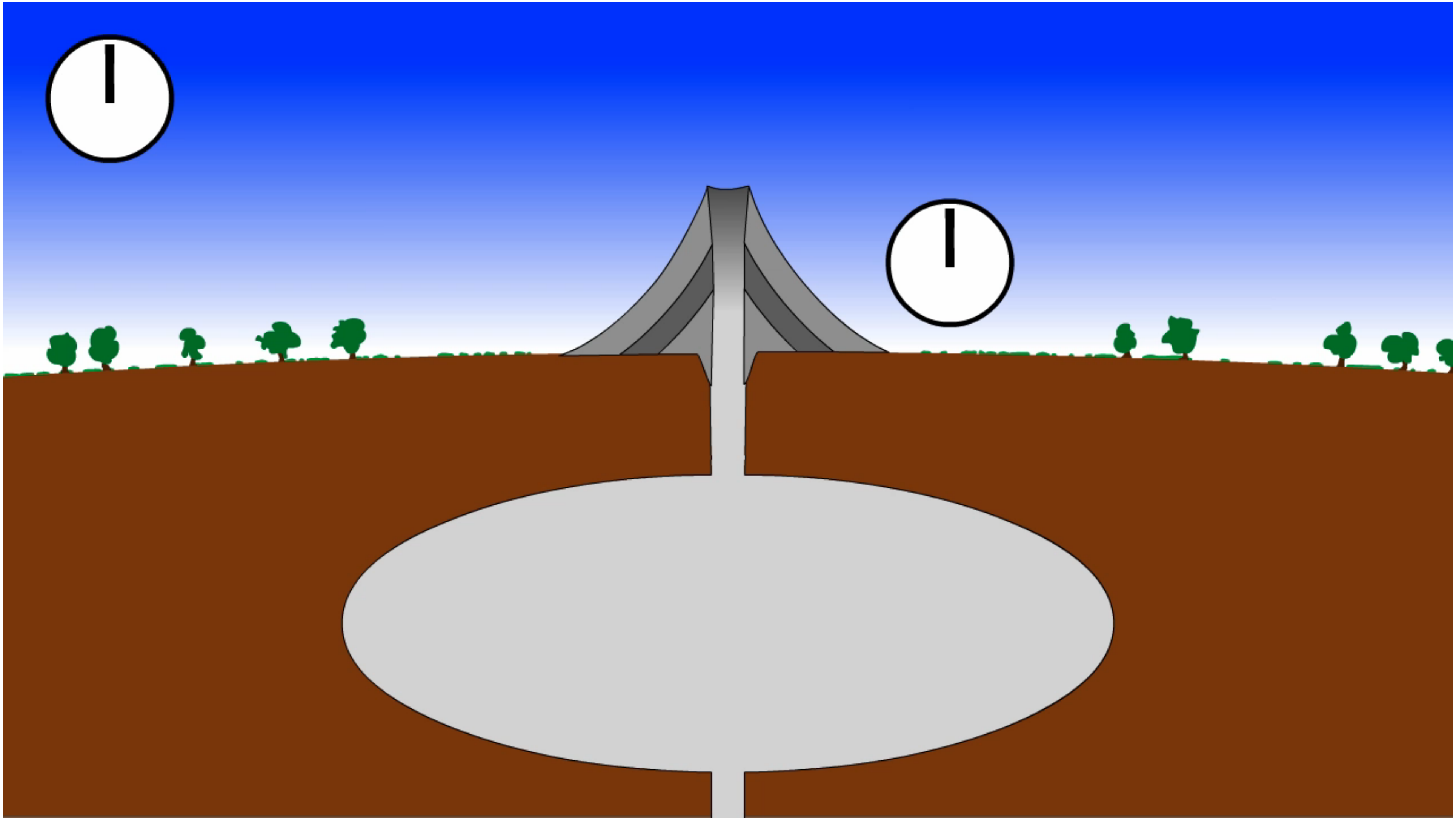
$\Delta f/f = 10^{-17}$

$$b = \left(\frac{3h \Delta U_{\max}}{4\pi G \Delta\rho} \right)^{1/3}$$

Volcanoes

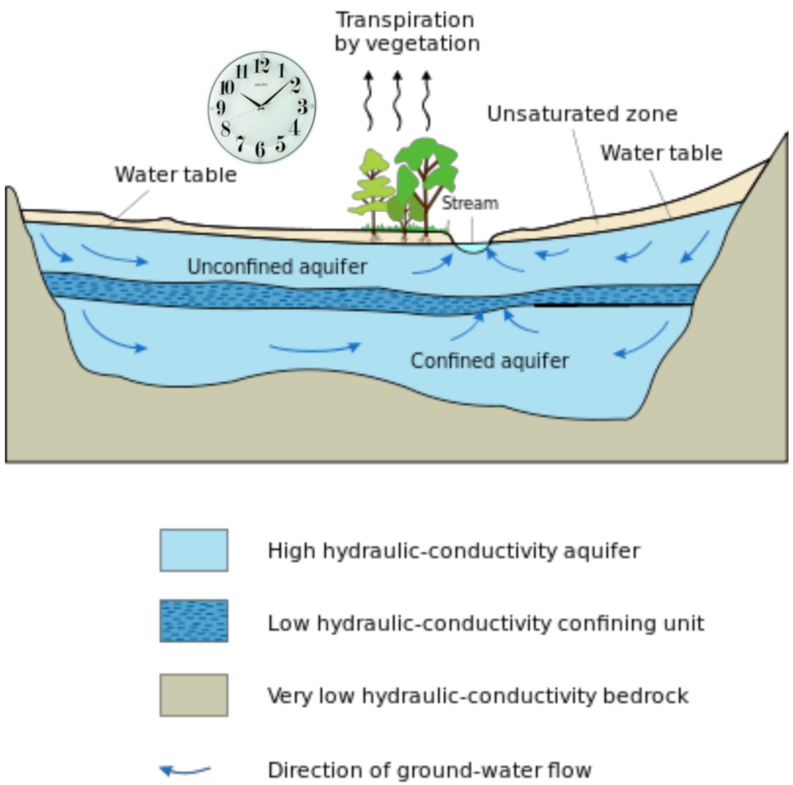
- Clocks can measure changes inside the volcano BEFORE the ground moves!
  - How large in the magma chamber? Is it partially filled? Is it empty?
  - Dikes are closer to the surface
- Combine with existent measures
  - For Etna, e.g., slow ground movement: a few millimeters per year via GPS
  - Takes > 10 years to measure
- Combine with gravity measurements?

Movie by Thomas Glauninger (IT University of Zurich)

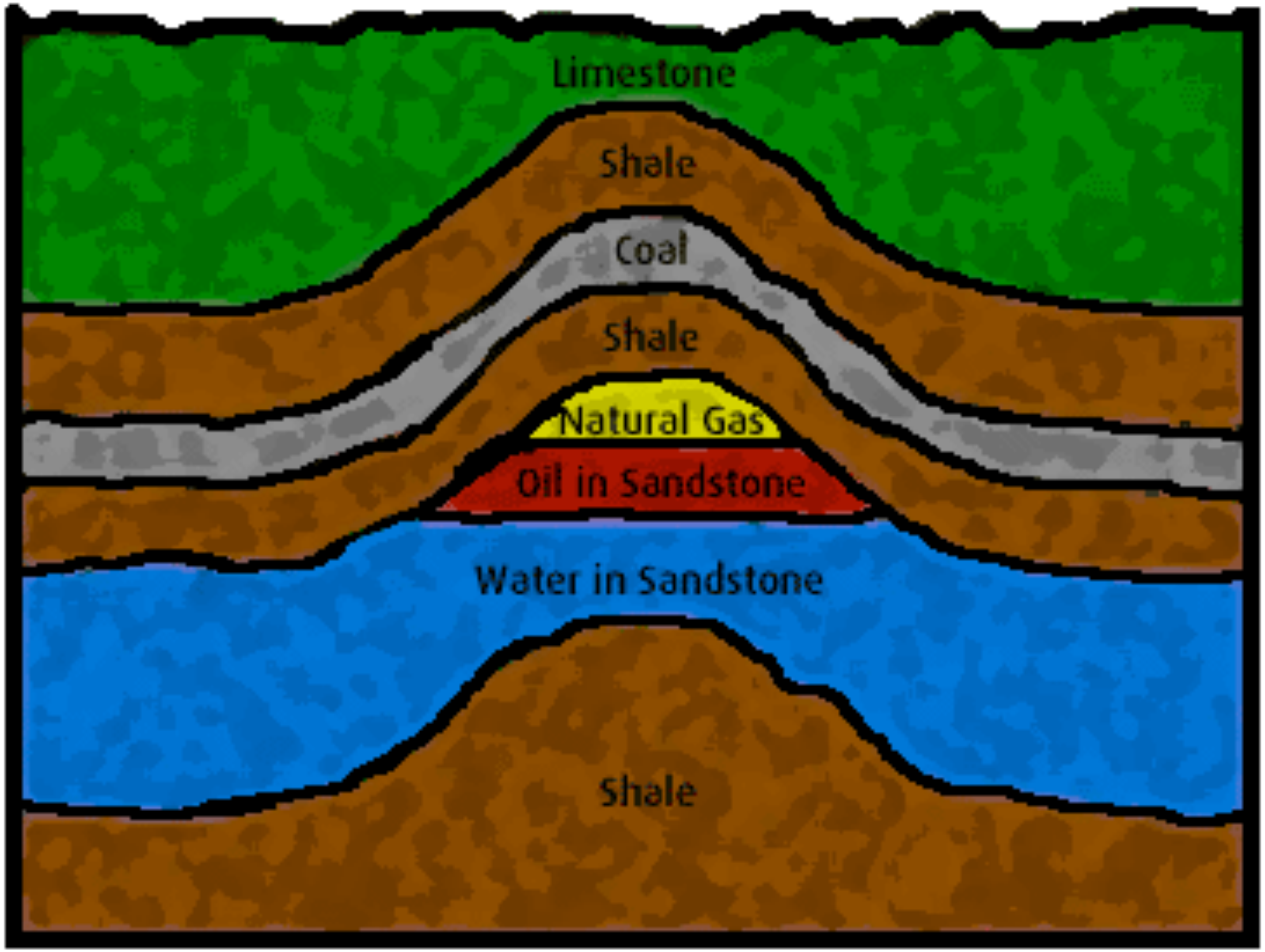


Water, Oil and Minerals

- **Detectable with clocks?** Depends on the size of the deposit/water reservoir and on the density contrast
- Oil has roughly the same density as water
  - Lower density contrast because of the porosity of the surrounding material: 1% - 2%
- Some minerals are mixed in with other materials => small density contrast

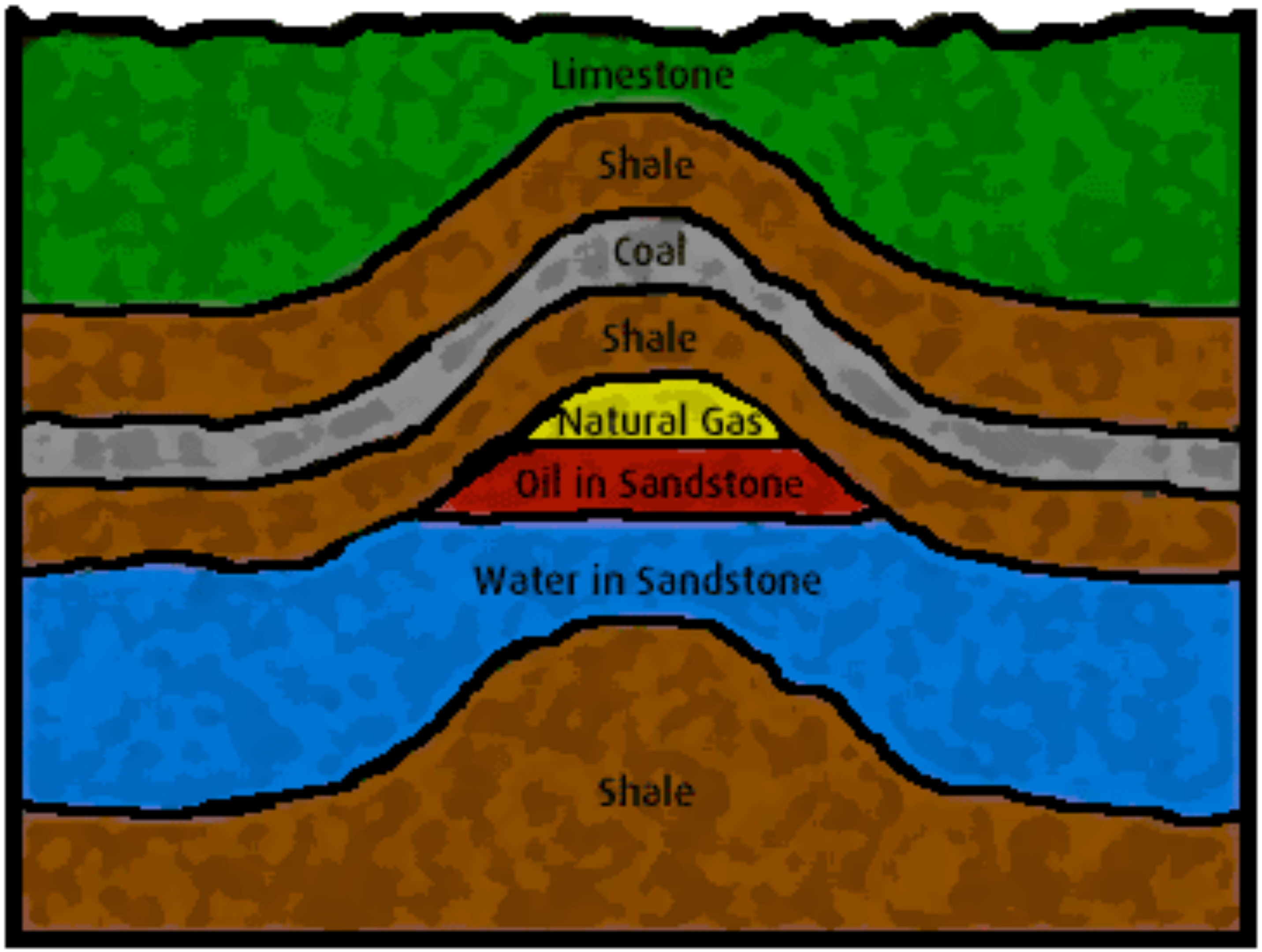


Reference clock



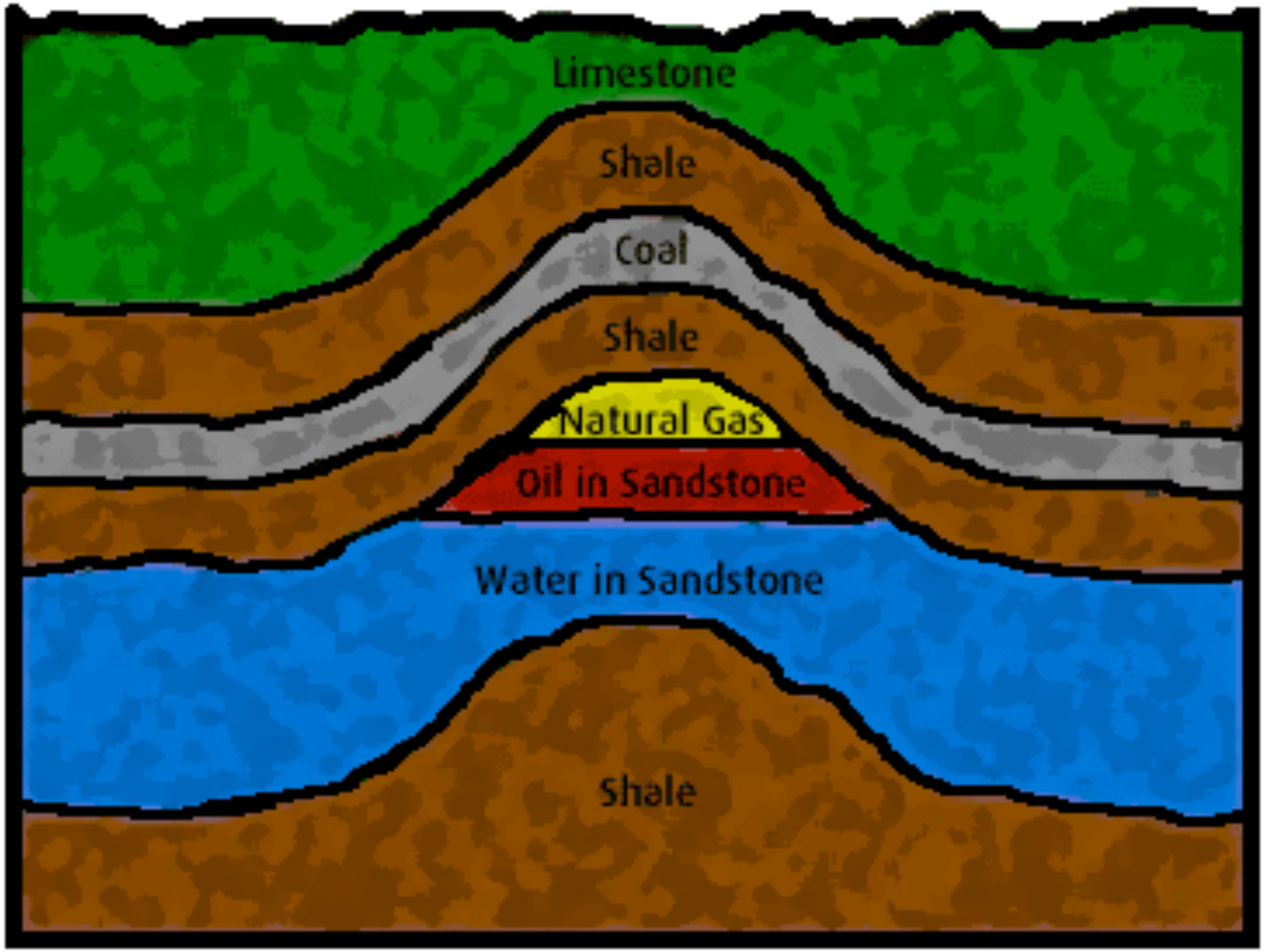
Portable clock
Tick rate is faster
Over oil/gas deposit

Reference clock



Portable clock
Tick rate goes back up

Reference clock



Atomic Clocks in Space

- Can clocks be part of future GRACE/GOCE missions? When are they accurate enough? What would a clock provide?
  - A very stable frequency reference.
    - Reduce oscillator noise?
    - Improve tracking of space crafts?
  - Multiple space-craft setup of future GRACE
    - 4 clocks: second derivative of the gravitational potential?
      - Could be important for geoid measurements
  - Accelerometers have a drift noise ~ 1/f that limits their low frequency performance.
    - Clocks are better at resolving low multipoles perhaps without so much averaging
  - LISA Pathfinder technology could be our precedent for exporting GR testing technology to relativistic geodesy/geophysics
- Atomic clocks have been steadily improving since the 1950s. No end in sight yet! Important to use their full potential!

Conclusions

- Atomic clocks provide the most direct local geoid measurements
  - They measure potential differences at the location of the clock
  - Add detail to satellite maps
  - Calibrate satellites?
- The measurements are non-instantaneous – there are corrections that have to be considered, e.g., from tidal effects
- Provides an independent measurement from gravimeters, accelerometers with independent sources of errors
- Can be combined with local gravimetric & InSAR/GPS & other measurements to reduce the degeneracy of the inverse problem
  - Different scaling, different systematics, *etc.*
  - Gravimeters are more accurate. However, they measure the gradient of the potential, which is a vector. Its integral is poorly defined since its direction is not known accurately.

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Atomic clocks get a grip on gravity

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MEASURING Earth's hidden structures could soon be as simple as looking at

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Prospecting for Oil or Gold? Check the Time

POSTED BY: DOUGLAS MCCORMICK / WED, NOVEMBER 14, 2012

Clocks low in the gravity well run slower than those higher up. That's just a relativistic fact of life—one that we take advantage of every time we use the Global Positioning System. (I remember how cool I thought it was when I first learned that clocks in orbiting GPS satellites have to be programmed to correct for relativistic time dilation.) Within the past year, experimentalists comparing the speeds of widely separated atomic clocks (connected via fiber optic cable) have shown that current chronometers, with uncertainties around 10^{-16}, are sensitive enough to detect the change in time's flow that accompanies a shift of a meter or less in relative elevation.

The geoid is the Earth-swaddling surface of equal gravitational potential that more or less coincides with global mean sea level. Or, from the chronometric viewpoint, the surface on which all clocks tick at the same rate. The geoid isn't smooth. As we have known for years (and continue to prove with increasing detail), the geoid undulates. Its rise and fall betray details of objects and events far below the surface.

Writing in Geophysical Journal International (the paper is also available on arXiv.org), a team of researchers from Switzerland, the United States, and Romania shows that clocks accurate to within 10^{-18} could map the geoid to within about a centimeter and show the sizes and locations of mass variations far below the surface. Since the accuracy of standard reference clocks has increased at a steady order-of-magnitude-per-decade since the 1950s—and since newly built optical atomic clocks and proposed designs for highly charged ion and nuclear clocks promise to increase that rate substantially—it is clearly time prepare for an age in which we can map the crust and mantle by watching time slip by.

Imagine a bubble of magma 20 percent denser than the surrounding rock. University of Zurich physicist Ruxandra

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Atomic Clocks To Measure Earth's Geoid From The Ground

Satellites give a rough picture of the Earth's geoid. Now physicists say atomic clock technology is ready to give a better picture from the ground

3 comments

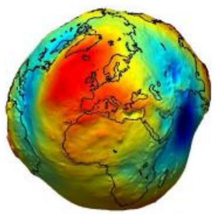
THE PHYSICS ARXIV BLOG
Monday, September 17, 2012

rchers say atomic clocks now good enough to measure E... http://phys.org/news/2012-10-atomic-clocks-good-earth-geoid

- Quantum Physics

Researchers say atomic clocks now good enough to measure Earth's geoid

October 1, 2012 by Bob Yirka



Enlarge

Credit: ESA

(Phys.org)—Researchers from the University of Zurich say that atomic clock technology has sufficiently progressed to the point that it should now be feasible to use them to measure the Earth's geoid, thereby producing more accurate geophysical estimates of oil and mineral deposits, as well as water reservoirs. The team, led by Ruxandra Bondarescu write in their paper published in *Geophysical Journal International*, that atomic clock accuracy now approaches a frequency ratio inaccuracy of 10^{-18} which they say should provide an accuracy in measuring a equipotential surface area equivalent to just one centimeter.

КОМПЬЮЛЕНТА

НАУКА И ТЕХНИКА

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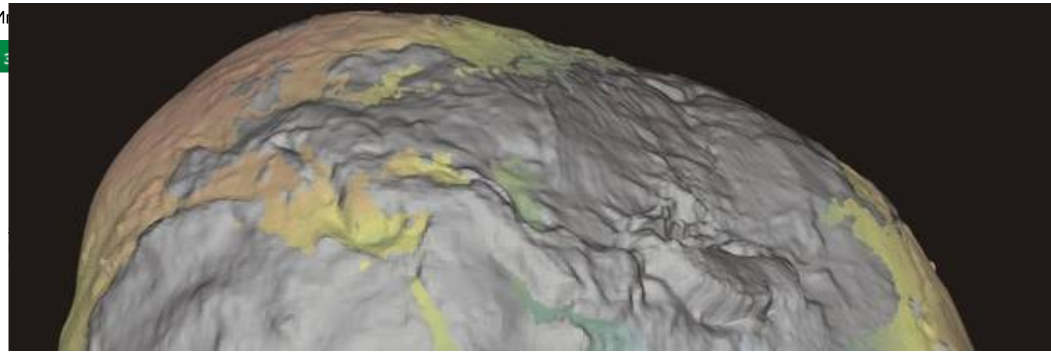
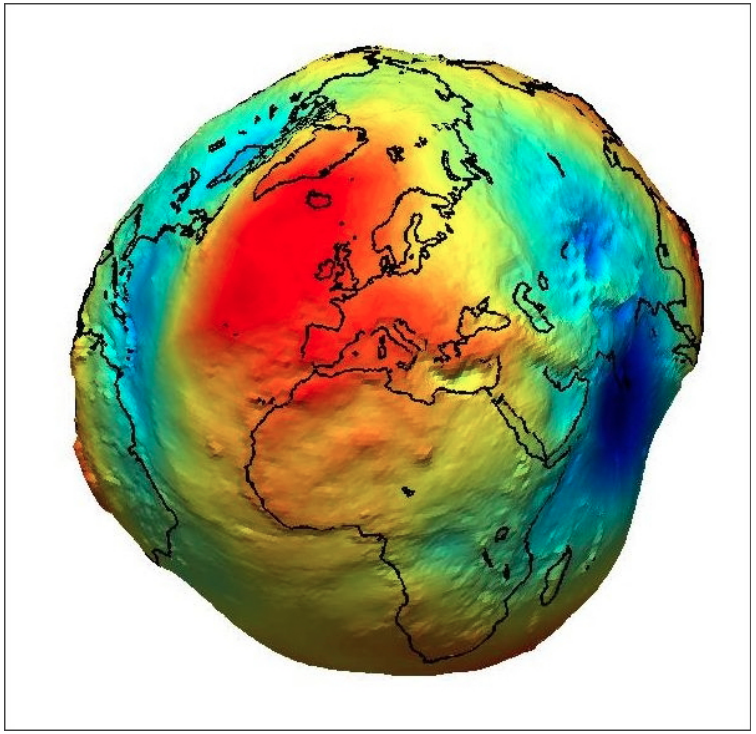


Предложен новый метод определения формы Земли

01 октября 2012 года, 19:04 | Текст: Александр Березин | Послушать эту новость

Земля — геоид (а масло — масляное, но об этом в другой раз). При помощи спутников мы можем относительно точно измерить глубину его впадин и высоту выступов. Собственно говоря, эта работа уже ведётся. И она весьма интересна практически, ведь в тех точках геоида, где гравитация сильнее, чем обусловливает его форма, близко к поверхности находятся залежи необычно тяжёлых или очень лёгких веществ.

Но чтобы всё корректно посчитать при помощи спутников, их измерительные инструменты нуждаются в частой калибровке. А обработка данных требует колоссальных вычислительных мощностей.



То, что гравитационное поле Земли неоднородно, известно давно, но вот использовать такую неоднородность для поиска полезных ископаемых ещё не удавалось. (Здесь и ниже иллюстрации Ruxandra Bondarescu et al.)

Группа исследователей из Цюрихского университета (Швейцария) во главе с Руксандрой Бондареску предложила более простой и, кажется, весьма точный метод определения формы геоида и даже гравитационных аномалий при помощи всего одного типа инструментов. Правда, в помощь инструменту придётся придать теорию относительности.

In Reichweite: Genaue Vermessung des Geoids vom Erdboden

Zürich (Schweiz) – Die wahre physikalische Form der Erde – das sogenannte Geoid – lässt sich grob durch die U[...] tellitenbahnen bestimmen. Eine sehr viel genauere Vermessung des Geoids mithilfe von At[...] den sei in greifbarer Nähe, so ein internationales Forschertea[...] l Jo[...] Eine detaillierte Kenntnis des Geoids ist für die Geophysiker von großer Bedeutung, da si[...] ckschlüsse auf Dichteanomalien im Inneren der Erde erlaubt.

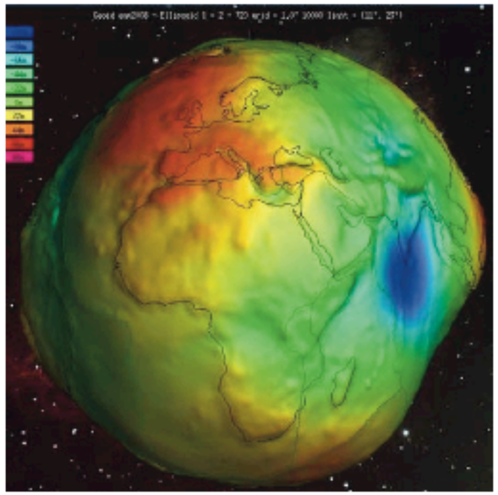
Le 4 octobre 2012 à 14h29

Par Laurent Sacco, Futura-Sciences

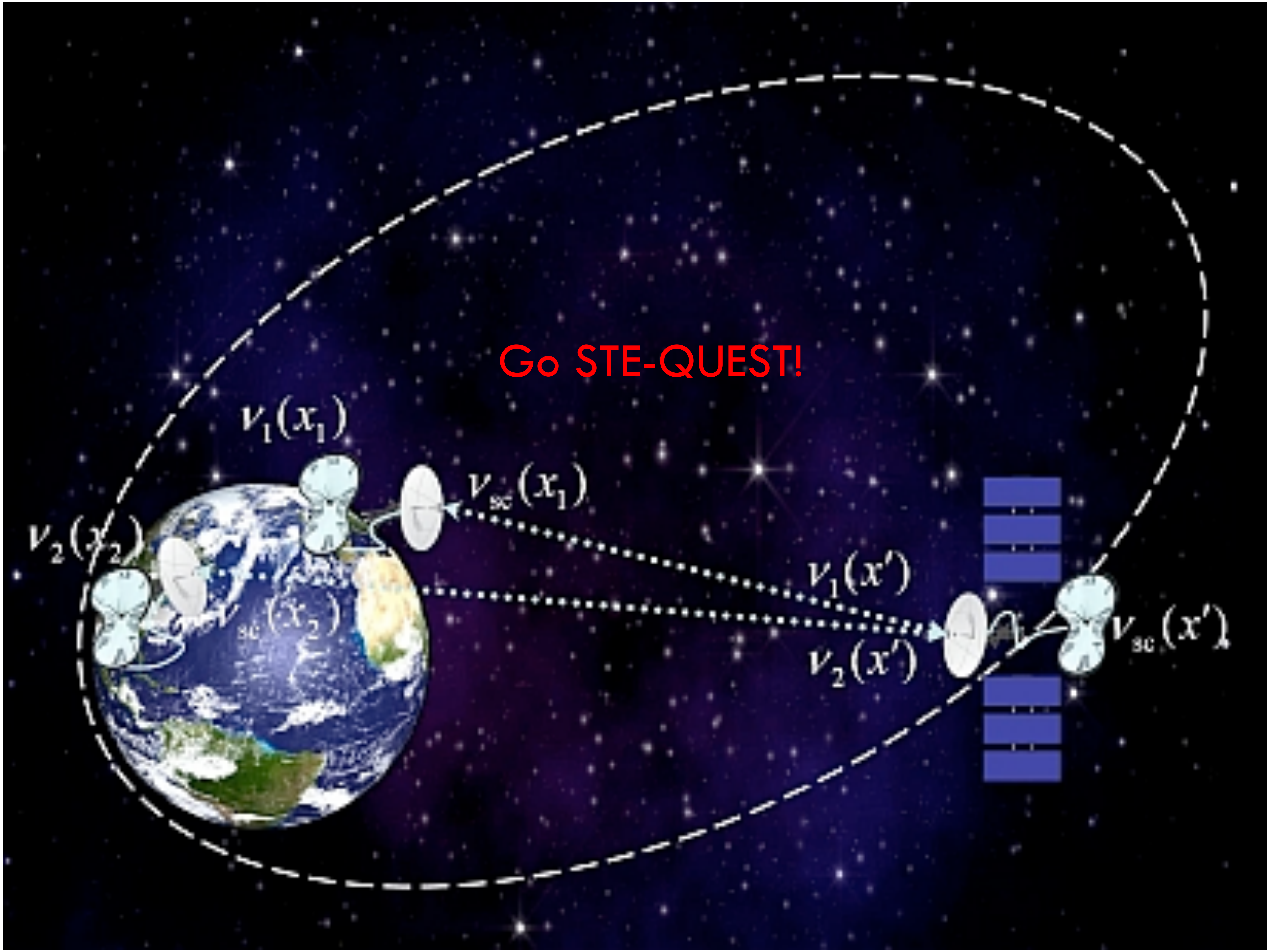
On peut découvrir du pétrole grâce à la relativité générale

La connaissance précise de l'intensité du champ de gravitation de la Terre est utilisée depuis longtemps pour chercher du pétrole ou des minerais. Le ralentissement du temps provoquée par ce champ, prédit par la relativité générale d'Einstein, devrait bientôt permettre de le mesurer à l'aide d'horloges atomiques et d'atteindre une résolution spatiale meilleure que celle que l'on obtient avec des satellites.

La précision des horloges atomiques n'a cessé de progresser depuis les travaux de pionniers comme Norman Ramsey. Elles sont si sensibles que l'on peut désormais mesurer l'effet de ralentissement de l'écoulement de temps, découlant des équations de la relativité générale, avec deux horloges séparées par une altitude de seulement 30 cm. Il existe d'ailleurs des projets d'horloges atomiques pour tester précisément la théorie d'Einstein, afin de montrer l'existence d'effets relevant d'une nou-



Sur cette image de la Terre, où le relief a bien sûr été fortement exagéré,


Go STE-QUEST!
$\nu_1(x_1)$
$\nu_{sc}(x_1)$
$\nu_2(x_2)$
$\nu_{sc}(x_2)$
$\nu_1(x')$
$\nu_2(x')$
$\nu_{sc}(x')$

Underground water level changes