Einstein on the ISS

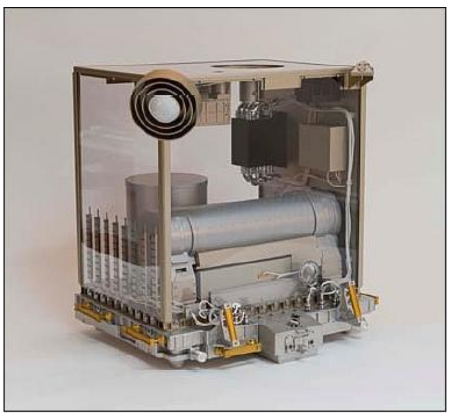
ACES (Atomic Clock Ensemble in Space) is an ESA mission in fundamental physics research and to increase satellite navigation accuracy based on a new generation of clocks operated in the microgravity environment of the International Space Station (ISS).

Clock comparisons using the ACES experiment, currently scheduled to be launched and installed on the international station Columbus external platform facility in early 2017, linked through state of the art microwave capabilities to the ground will allow to measure differences in the Earth gravitational field corresponding to altitude differences of the order of 10 cm.

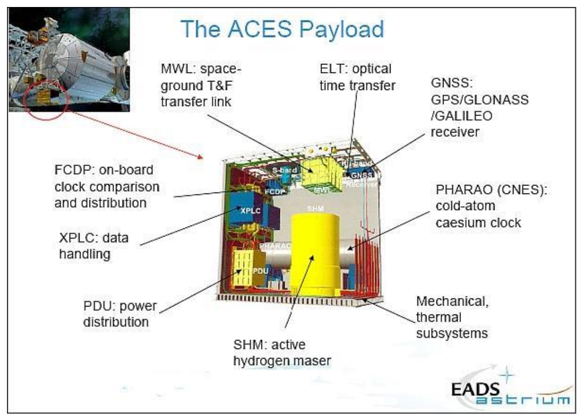
This will open the door to relativistic geodesy. Since time distribution and experiments of quantum mechanics must take relativistic effects into account, one can envisage that if future Global Navigation Satellite System (GNSS) constellations will be equipped with clocks accurate enough to allow measuring Earth's gravitational field with a similar accuracy, a breakthrough in geodesy can be achieved, and a possible new range of services and space applications can be expected.

Understanding the local and global structure of space-time is one of the main challenges of fundamental physics. Progress in this domain can provide insights to "new physics", resulting in the unification of the laws of nature — in particular of general- and quantum field theory.

Thus the ISS is becoming a laboratory for new experiments and new technologies, allowing precision measurements allowing unprecedented accuracies to explore the structure of space-time itself. [2]



Front: PHARAO, ELT



Back: SHM (Hydrogen Maser),

Figure 1: Illustration of the ACES payload design (image credit: ESA, EADS Astrium);.[1]

Fundamental Physics tests		
Measurement of the gravitational red shift	Absolute measurement of the gravitational red-shift at an uncertainty level < $50 \cdot 10^{-6}$ after 300 s and < $2 \cdot 10^{-6}$ after 10 days of integration time	Space-to-ground clock comparison at the 10^{-16} level, will yield a factor 35 improvement on previous measurements (GPA experiment).
Search for time drifts of fundamental constants	Time variations of the fine structure constant α at a precision level of $\alpha^{-1} d\alpha/dt < 1 \times 10^{-17}$ year^{-1} down to 3×10^{-18} year^{-1} in case of a mission duration of 3 years	Optical clocks progress will allow clock-to-clock comparisons below the 10^{-17} level. Crossed comparisons of clocks based on different atomic elements will impose strong constraints on the time drifts of α, m_e/Λ_{QCD}, and m_u/Λ_{QCD}
Search for violations of special relativity	Search for anisotropies of the speed of light at the level $\delta c / c < 10^{-10}$	ACES results will improve present limits on the RMS parameter α based on fast ions spectroscopy and GPS satellites by one and two orders of magnitudes, respectively.

Table 1: Overview of ACES mission objectives (Ref eoportal/ ISS-Aces/Pharao) [1]

Timely Arrival of Pharao Space Clock [3]

ESA has welcomed the arrival of Pharao, an important part of ESA's atomic clock experiment that will be attached to the ISS Columbus external platform in 2017.

Delivered by France's CNES space agency, Pharao is accurate to a second in 300 million years, which will allow scientists to test fundamental theories proposed by Albert Einstein with a precision that is impossible in laboratories on Earth.

To achieve its accurate timekeeping, the Pharao space clock uses lasers to cool caesium atoms down to –273°C, close to absolute zero ("cold clock").

Figure 2: Delivery of Pharao to ESA (25 July 2014)

Internet of clocks

Accurate timekeeping is vital for pinpointing our location, secure banking and fundamental science, but it is not easy to compare data from the many atomic clocks on Earth. ACES is more than just one clock in space. Pharao will be accompanied by the Space Hydrogen Maser, which uses a different technique to keep track of time. This clock uses hydrogen atoms as a frequency reference and offers better stability but for a shorter time.
By coupling the two clocks, ACES will provide the scientists with a unique, highly stable time reference in space. The project will link together atomic clocks in Europe, USA, Japan and Australia with their space counterparts via microwave and optical links to create an 'internet of clocks' and to deliver precise timekeeping. Connecting all these clocks is a significant part of ACES, with France's Cadmos User Support and Operations Centre (USOC, Toulouse) taking responsibility for operating the instruments on the Station.

Using the Station's robotic arm, the 375 kg payload will be installed on a platform outside Europe's Columbus space laboratory by an ESA Astronaut.

The main interconnections of the ACES experiment within the overall ISS ground segment are shown in Figure 3 (left hand side). ACES ground operations functions include the monitoring and control of the

ACES payload and of the Micro Wave Link (MWL) and Optical Link (SLR) ground terminals as well as the generation, archiving and distribution of the data products based on the measurements performed in space and on ground.

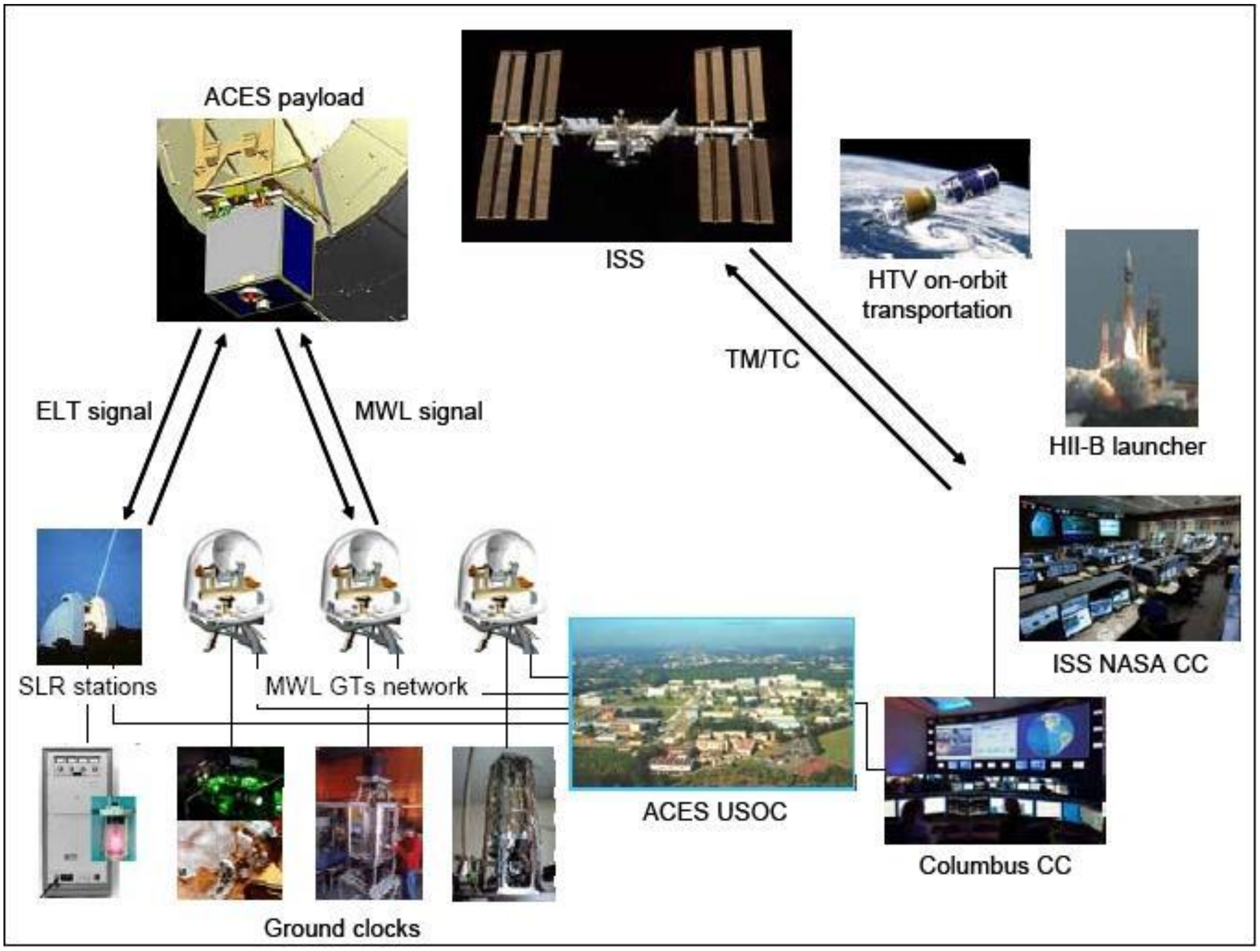


Figure 3: Main Functions of the ISS Ground Segment and ACES Experiment Data Flow [1]
SLR: Optical time transfer, MWL: Microwave links for time and frequency transfer.

ACES, due to a much more precise synchronization of terrestrial atomic clocks may offer a new opportunity to realize that the interpretation of Einstein's relativity theory still is not yet as clear as his wonderful equations:

Time Synchronization and Einstein's Relativisitic Time

In order to illustrate the significance of the ACES experiment, assuming the results would turn out be as accurate or even better, SpaceOps asked of the opinion of Peter Ostermann – Independent Research, Munich (peos@independent-research.org), and author of a most recent book (in German) and paper (English) on the influence and interpretation of Einstein's theories on the Cosmological Concordance Model - CCM (see also Journal Book Reviews – Qutr#4, 2014):

If the ACES results would turn out as expected could there be an influence on Einstein's General Relativity / Special Relativity Theories (GRT/SRT) as well?

Ostermann: I have no doubt that the Experiment results will turn out as predicted. In addition to the significant accuracy improvements of the GPS navigation system capabilities, the ACES fundamental physics experiment results might effectively enhance the synchronization of terrestrial atomic clocks by an order of magnitude, thus allowing revisiting Einstein's concept of proper length and time definitions.

It is a proven fact that already GPS has confirmed Einstein's equations as applied to the onboard atomic clocks. This confirmation will be increased by ACES to unprecedented accuracies by Galileo and future GNSS projects. But it does not at all confirm any need to ascribe physical properties to space and time itself. Instead it is completely sufficient to apply Einstein's equations to physical objects like in particular to the prototype meter and atomic clocks.

A fundamental problem of the interpretation of relativity theory is that using atomic clocks for synchronization the light time for a signal going from east to west around the rotating earth – using a sufficient number of ideal deflection mirrors within vacuum ducts and neglecting technical problems of such a procedure – would be different from a signal going the same way from west to east. Today's definition of the meter reads: *The meter is the length of the path travelled by light in vacuum during a time interval of 1/299792458 of a second.* Therefore, if taken literally, this definition would mean a different circumference (up to ± 60 m) of the Earth in both cases, which clearly is impossible. The irritating consequence is that then there is a difference in the speed of light depending on position and direction in rotating systems (up to approx. ± 460 m/s in case of the Earth) if clocks are used which are globally synchronized correctly. Today this synchronization is effectively done using orbiting spacecraft in the baryonic 'quasi-inertial' system of the Earth. The chance to *internally* carry out such synchronization has been considered impossible for many decades. When strictly adhering to an uncritical acceptance of a 'constant speed of light' it seemed excluded, while only the physical quantity c (e.g., in $E = mc^2$) is a true natural constant.
Nevertheless an internal global synchronization should be possible statistically also by using optical waveguide connections between a network of terrestrial atomic clocks. The conditions for such a procedure is discussed in *"Die Einweg-Lichtgeschwindigkeit auf der rotierenden Erde und die Definition des Meters",* arXiv:gr-qc/0208056.

The first decisive historical statement on this problem was made by Theodor Kaluza in his treatment of Ehrenfest's rotating disk paradox. His solution has been seemingly ignored for a long time. Already in 1910 he introduced for the first time (on one page and three and a half lines in the journal: "*Zur Relativitätstheorie*; Phys. Zeitschr. 11") the non-Euclidean geometry into relativity theory – about two years before Einstein's and Grossmann's 1913 *"Entwurf einer verallgemeinerten Relativitätstheorie und einer Theorie der Gravitation"*. According to Kaluza, Einstein's synchronization method of using 'middle in time reflection' westward or eastward around the equator would yield a time-lag (*"Schlußfehler"*) of about $2 \cdot 10^{-7}$ s, which has been confirmed by the famous experiments of Sagnac, Michelson & Gale as well as by Hafele & Keating, though only indirectly so far. This is commonly known but not yet consequently implemented into the interpretation of relativity theory.

Taking also differences in altitude into account, at first the rates of all corresponding terrestrial atomic clocks have to be adjusted (by a correction factor X_i) from proper times τ_i to that of global system time t_{global} by technical procedures, i.e. by appropriate digital tuning. In addition, Kaluza's 'time lag' δ_i has to be distributed proportionately over the corresponding line of latitude b (the longitude is denoted φ here).

$$t_{\text{global}} \equiv \tau_i \cdot X_i + \delta_i$$

where

$$\delta_i = \frac{R_b^2\,\omega_{\text{E}}}{c^2}(\Delta\varphi)_i$$

$$R_b = r_{\text{E}} \cos b$$

On the rotating Earth, in clear contrast to a usual Einstein-synchronization, this procedure will arrive internally with the baryonic inertial system's coordinate time as externally represented by GPS time so far.

The failure of any internal synchronization according to Einstein's "middle in time reflection" in rotating systems proves that his Special Relativity Theory (SRT) concept of proper length and proper time can only strictly apply in local inertial frames of e.g., a rotating disk – and thus due to Einstein's equivalence principle in local inertial frames of real gravitational fields. In particular, this means in local inertial frames of the Universe only.

Substantially, the results provided by Kaluza caused Einstein to finally write: „In der allgemeinen Relativitätstheorie können Raum- und Zeitgrößen nicht so definiert werden, dass räumliche Koordinatendifferenzen unmittelbar mit dem Einheitsmaßstab, zeitliche mit einer Normaluhr gemessen werden könnten.“ *(In general relativity, space and time can not be defined in such quantities that spatial coordinate differences could be measured directly with the standard scale unit nor with a standard clock).* – *Die Grundlage der allgemeinen Relativitätstheorie*; Ann. d. Phys. 49 (1916), S. 769

This conclusion, however, seriously questions – not to say may contradict – a hypothetical *universal* expansion as naïvely understood today by the Concordance Model. So ACES, due to a much more precise synchronization of terrestrial atomic clocks may offer a new opportunity to realize that the interpretation of Einstein's relativity theory still is not yet as clear as his wonderful equations.

To avoid any problem of different statements concerning the equatorial circumference of the Earth, an unambiguous definition of the SI length unit should read: "The meter is the length of the path travelled bi-directionally by light in vacuum (the same way there and back) during a time interval of 2 x 1/299792458 of a second."

References

[1] eoPortal https://directory.eoportal.org/web/eoportal/satellite-missions/i/iss-aces-pharao
[2] http://www.navipedia.net/index.php/Fundamental_Physics
[3] http://www.esa.int/Our_Activities/Human_Spaceflight/Research/Timely_arrival_of_Pharao_space_clock

Related links

- Pharao at CNES
  http://www.cnes.fr/web/CNES-en/4488-pharao.php
- Where is the International Space Station?
  http://www.esa.int/Our_Activities/Human_Spaceflight/International_Space_Station/Where_is_the_International_Space_Station
- European space laboratory Columbus
  http://www.esa.int/Our_Activities/Human_Spaceflight/Columbus
- Experiment archive
  http://eea.spaceflight.esa.int/

- http://www.esa.int/Our_Activities/Space_Engineering_Technology/Challenging_Einstein_on_the_ISS_ACES_takes_a_step_ahead
- Albert Einstein Documentary on History Channel (https://www.youtube.com/watch?v=NyK5SG9rwWI)

Joachim J. Kehr Editor SpaceOps News, Journal of Space Operations