ACES Science

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ACES Science objectives review

Benefits-Cost Analysis Panel study, January-April 2021

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ACES Science Review

esa

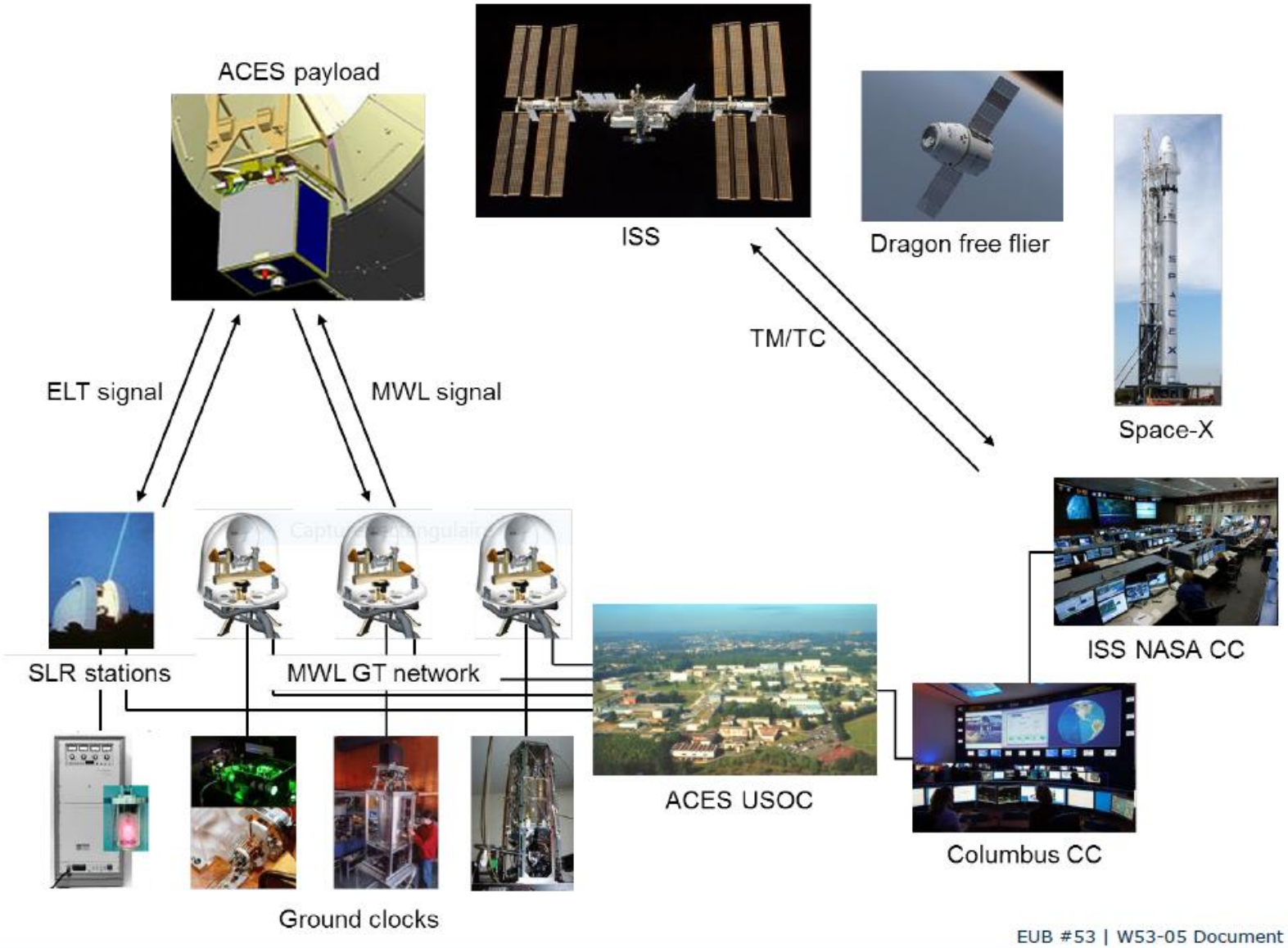
- Scientific review panel appointed in February 2021 to re-assess the ACES scientific relevance in light of the recent advances in clock-based research
- The panel thoroughly examined:
  - Scientific relevance
  - Technology maturity
  - Degraded mission scenarios
  - Strategic importance
  - International cooperation

√ The scientific objective has preserved its validity and interest

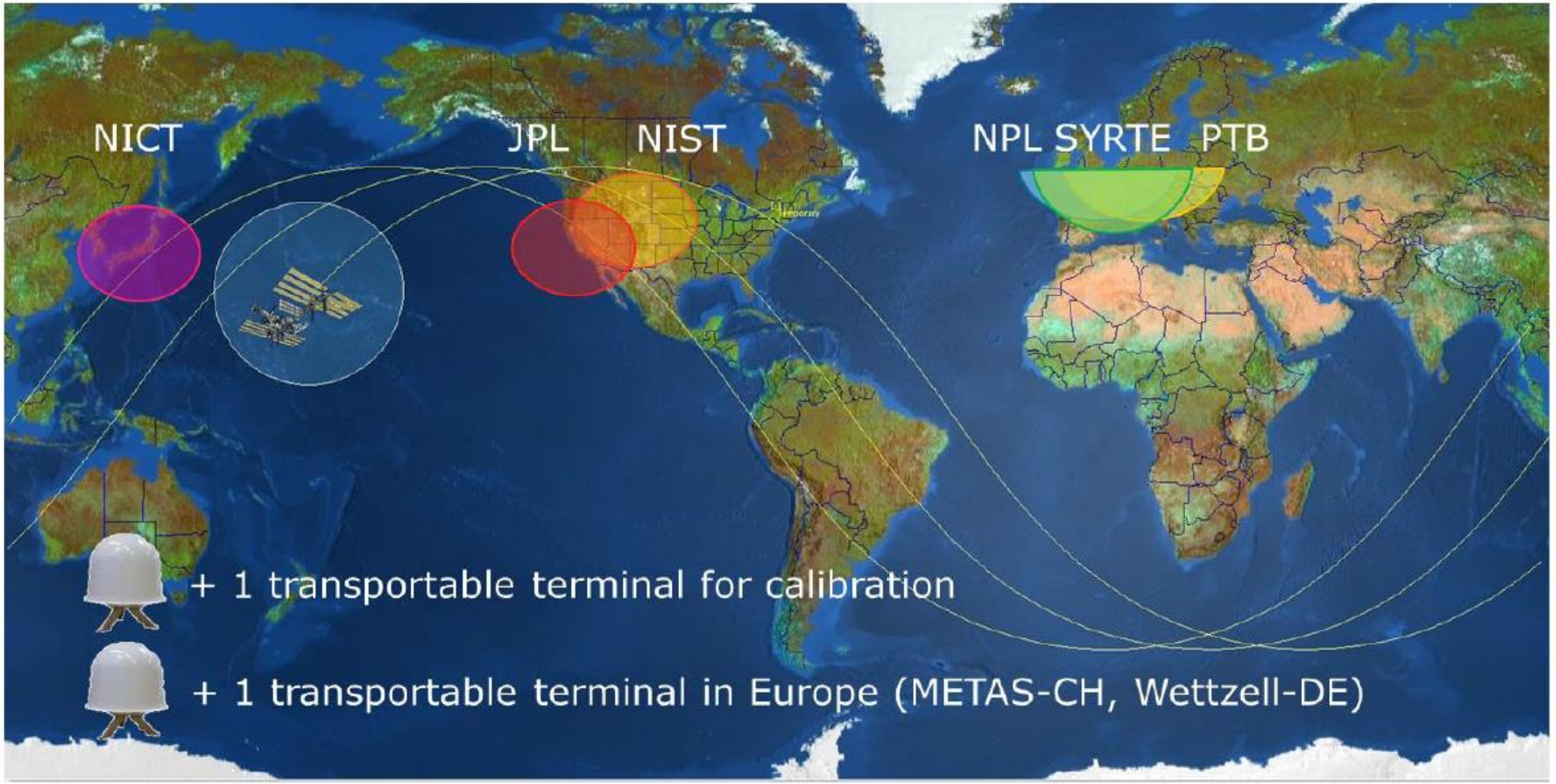
X The scientific objective has been surpassed by recent results

New New scientific investigation

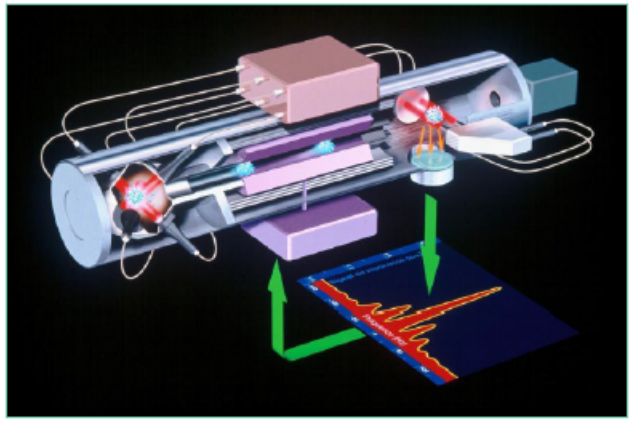
ACES Mission Concept

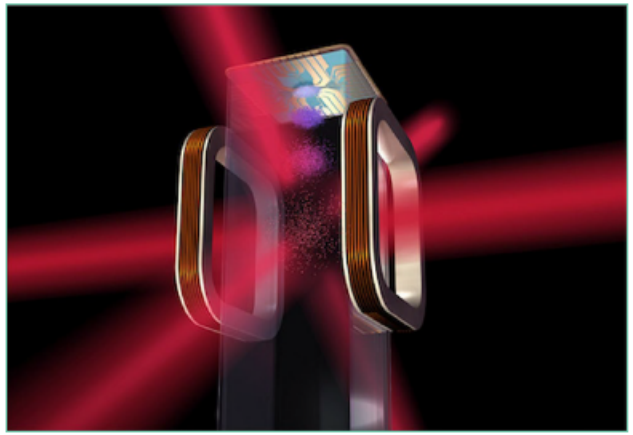


ACES MWL network



Cold Atoms in Space





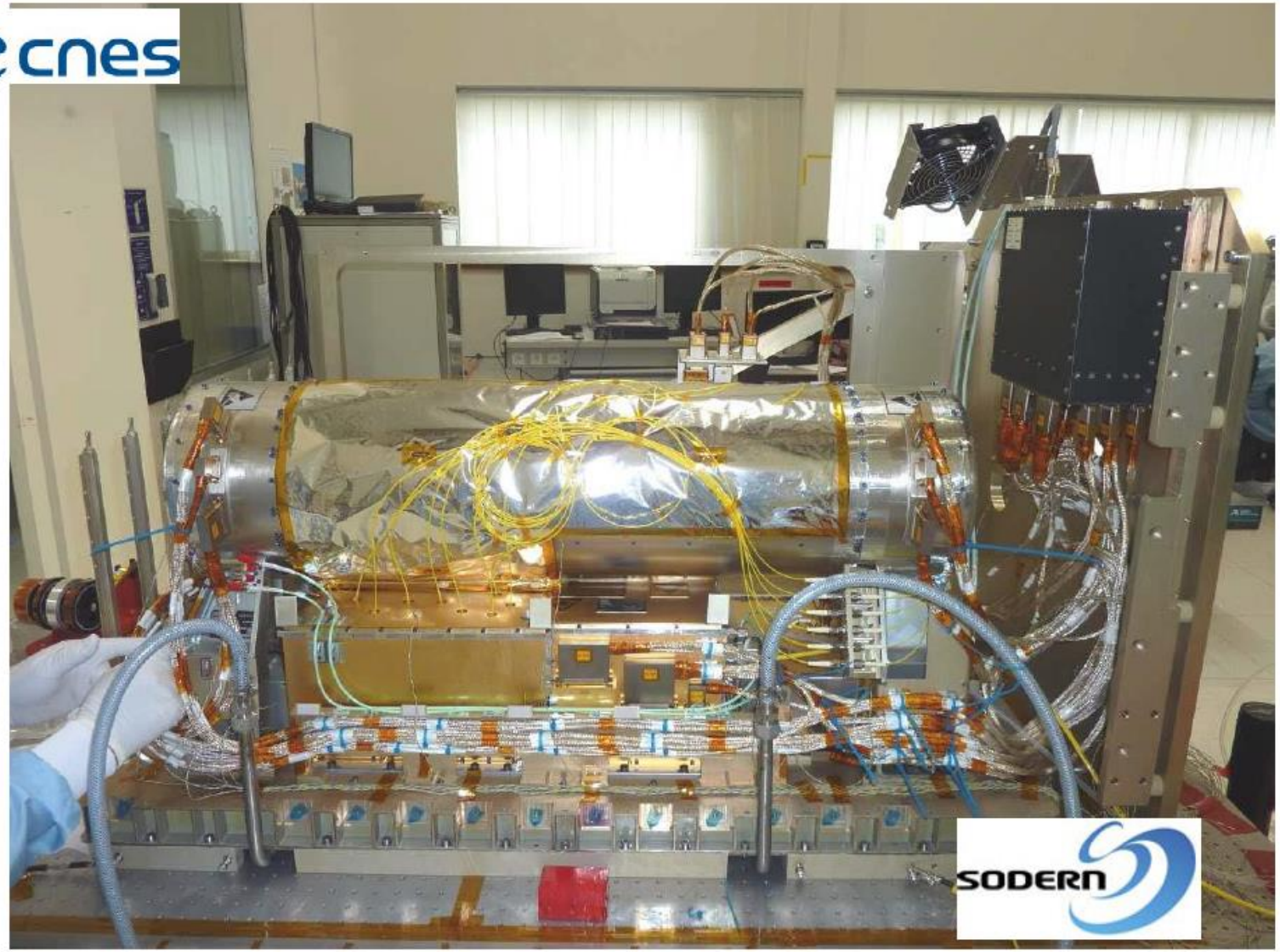
Credits: NASA/JPL

- PHARAO is primary frequency standard using laser cooled Cs atoms
- PHARAO operation requires tuning of the cold atom sample parameters under weightlessness conditions: atoms number, temperature, launch speed, preparation/interrogation/detection
- To that purpose, a series of experiments will be performed with the objective of optimizing the clock operation (stability and accuracy)
- The DLR sounding rocket experiment (2018) and the NASA Cold Atom Lab (2020) have performed several experiments using laser cooled and magnetically trapped atoms (BEC)
- The Chinese experiment CACES (2018) has measured Ramsey fringes with cold Rb atoms on orbit
- They are important milestones towards the use of cold atoms in space, however…

ACES remains the only mission using laser cooled atoms for high precision time and frequency measurements in space

PHARAO FM

Cold atom cesium clock designed for microgravity operation



Flight model tested and delivered to ESA in July 2014

Clocks Validation in Space

	ACES Mission Objectives	ACES performances		Scientific background and recent results
	Test of a new generation of space clocks			
√	***Cold atoms in microgravity***	Study of cold atom physics in microgravity		Key to develop atomic sensors for high-precision measurements in space. The NASA CAL experiment on-board the ISS has performed the first studies, but ACES remains the only mission using them for metrological applications.
√	***Validation of the cold atom clock PHARAO***	Freq. stability	$1 \cdot 10^{-13}$ @ 1 s	PHARAO is the most stable and accurate clock ever developed for space. Optical clocks on the ground have reached the $1 \cdot 10^{-18}$ stability and accuracy level thus enriching the ACES science output via ground-to-ground clock comparisons.
			$3 \cdot 10^{-16}$ @ 1d	
			$1 \cdot 10^{-16}$ @ 10d	
		Freq. accuracy	$1\text{-}2 \cdot 10^{-16}$	
√	***Validation of the active H-maser SHM***	Freq. stability	$4.1 \cdot 10^{-15}$ @ 100 s	Galileo PHM stability is about a factor 10 worse than SHM. Active H-masers for space with comparable performance are available at Vremya (RU). ACES is therefore placing European industry (SpT) at the forefront of active H-masers for space.
			$2.1 \cdot 10^{-15}$ @ 10^3 s	
			$1.5 \cdot 10^{-15}$ @ 10^4 s	
		Freq. accuracy	Not applicable	

Time and Frequency Links Validation in Space

ACES Mission Objectives	ACES performances					Scientific background and recent results
Test of a new generation of time and frequency links for space						
√ ***Validation of MWL and ELT***	Space-to-ground time transfer stability					MWL and ELT noise floor is significantly better than specified. Such performance enable space-to-ground comparisons to better than $1 \cdot 10^{-17}$ @ 1 d. Ground-to-ground time transfer stability reaches $1 \cdot 10^{-17}$ after 1 d in common view (CV) and 3-4 d in intercontinental non-CV comparisons. MWL remains the state-of-the-art for free-space microwave T&F transfer. ELT has similar performance on the long term. Coherent optical links (through fiber and free space) have demonstrated stabilities at the $1 \cdot 10^{-19}$ in less than an hour. Fiber links will provide additional methods for the characterization of MWL and ELT.
	τ	MWL		ELT		
	300 s	0.3 ps		4 ps		
	1 d	7 ps		4 ps		
	10 d	23 ps		7 ps		
√ ***Comparison of ground clocks***	Ground-to-ground time transfer stability					
	τ	MWL		ELT		
		CV	nCV	CV	nCV	
	300 s	1 ps	-	6 ps	-	
	2700 s	-	2 ps	-	6 ps	

See talk by A. Amy-Klein
And by Y. Prochazka for ELT

Fundamental Physics Tests

	ACES Mission Objectives	ACES performances	Scientific background and recent results
		Fundamental physics tests	
√	***Measurement of the gravitational red shift***	Absolute measurement of the gravitational red-shift at a precision < $50 \cdot 10^{-6}$ after 300 s and < $2 \cdot 10^{-6}$ after 10 days of integration time.	ACES will yield an improvement of a factor 70 over the GPA experiment and a factor 10 to 20 over recent tests involving Galileo 5 and 6 satellites. P. Delva et al. PRL '18
√	***Search for time drifts of fundamental constants***	Time variations of the fine structure constant α at a precision level of $\alpha^{-1} \cdot d\alpha / dt < 1 \cdot 10^{-17}$ yr $^{-1}$ down to $3 \cdot 10^{-18}$ yr $^{-1}$ in case of a mission duration of 3 years.	The drift of the fine structure constant has been constrained to $1 \cdot 10^{-18}$ yr $^{-1}$ in the $^{171}Yb^{+}$ experiment at PTB. ACES will perform comparisons of clocks based on different atomic elements on a worldwide scale thus constraining the time variations of all three fundamental physical constants (α, m_e/Λ_{QCD} and m_q/Λ_{QCD}).
X	***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 GPS satellites by one order magnitude. Best limits today are reaching $\delta c / c < 2.6 \cdot 10^{-11}$, a factor 4 better than the ACES results.

Tokyo skytree expt
Best test near the Earth surface at $9\ 10^{-5}$
See talk by M.Takamoto

Talk by C. Lisdat

related Talk by T. Mehlstaubler

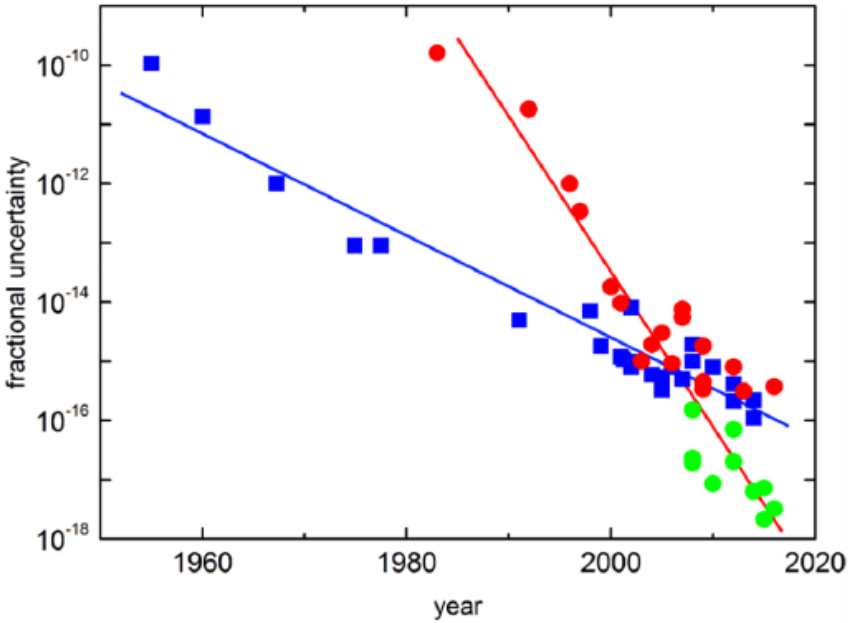
Fundamental Physics Tests

(New)

ACES Mission Objectives	ACES performances	Scientific background and recent results
Fundamental physics tests		
Dark matter search with atomic clocks	Establish bounds on topological dark matter models based on the comparisons of clocks in the ACES network. See talk by A. Derevianko	The ACES network can ensure comparisons of atomic clocks based on different atomic transitions down to $1 \cdot 10^{-17}$. Limits on variations for each of the three fundamental constants can be established thus testing different terms in the model Lagrangian and imposing limits on the three energy scales Λ_α, Λ_e, and Λ_q. Clock comparisons can be performed continuously on 20 d intervals thanks to the ACES MWL thus extending the analysis on the interval T between encounters by one order of magnitude.

Future Redefinition of the Second – New Application

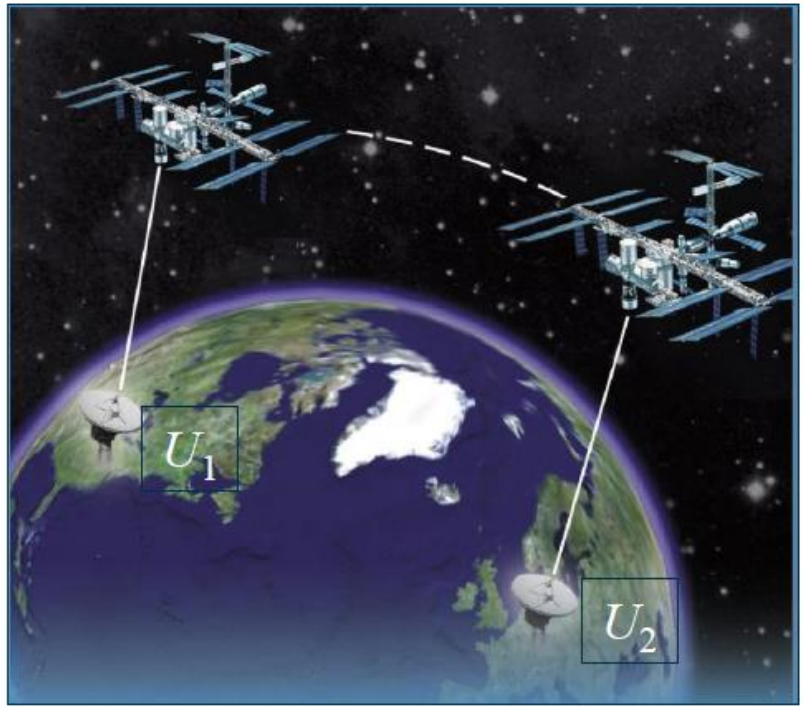
- Optical clocks have reached an accuracy two orders of magnitude better than the best Cs microwave clocks today used to realize the base unit *second* in the SI
- This asks for a new definition of the SI second based on an optical transition
- ACES, with its capability of comparing optical clocks on ground across four continents, will be essential to test a new infrastructure for the operational realization of the *optical* SI second

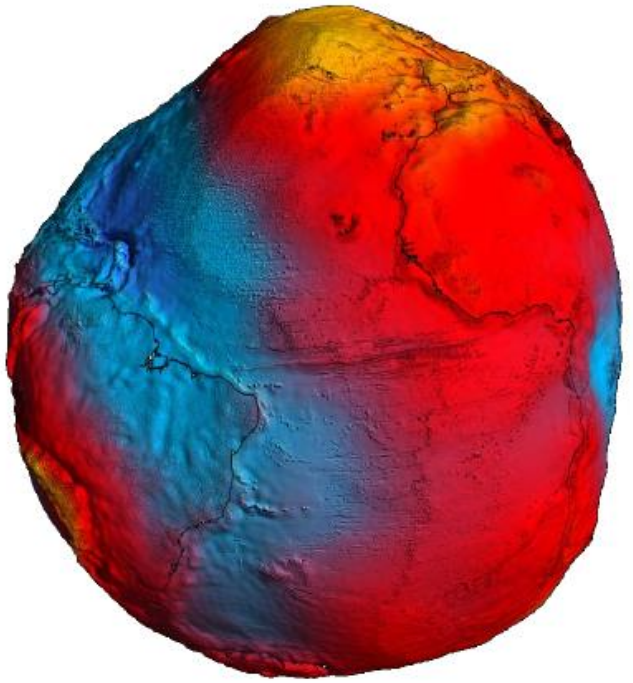


Metrologia 55, 188 (2018)

ACES with its advanced microwave technology (MWL) is a necessary demonstrator that the new definition can be put into action immediately; ELT will then be a precursor for the dissemination of an optical timescale

Relativistic Geodesy





- Relativistic geodesy: mapping of the Earth gravitational potential based on the precision measurement of the red-shift between clocks at two different locations
- ACES will perform intercontinental comparisons of optical clocks at the 10^{-17} level after 4 days of integration time, measuring the local height of the geoid at the 10 cm level

The global coverage offered by ACES will complement the results of the CHAMP, GRACE, and GOCE missions

Conclusion

- Since 1997, ACES has successfully passed numerous scientific reviews with outstanding evaluations
- This group has re-evaluated the ACES science objectives in view of the recent mission context and taking into account the fast progress in optical clocks and fiber links
- Science objectives:
  - Test of the red shift with PHARAO clock remains an outstanding objective.
  - Special relativity test has become obsolete,
  - … but new and improved science objectives have emerged:
    - The search for dark matter with the ACES worldwide network of clocks
    - Connecting optical clocks over 4 continents, ACES will bring its share to the redefinition of the SI second
    - Geodesy with optical clocks connected to the ACES network is a breakthrough
  - Secondary objectives remain important as well
- The scientific importance of ACES both for space-based research and its strategic role in the worldwide context for international cooperation, knowhow development at European industry, and technology development, is confirmed to be outstanding