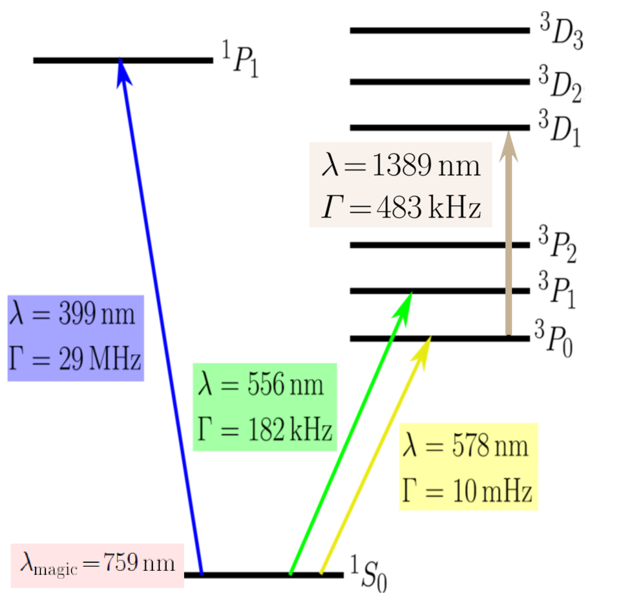
Metrological Characterization Of The Yb Lattice Clock At INRIM

Benjamin Rauf[1,2]; Marco Pizzocaro[1]; Pierre Thoumany[1]; Gianmaria Milani[1,2]; Michele Gozzelino[1]; Filippo Bregolin[1]; Giovanni Antonio Costanzo[1,2]; Cecilia Clivati[1]; Filippo Levi[1] and Davide Calonico[1]

[1]Istituto Nazionale di Ricerca Metrologica (INRIM), Physical Metrology Division, Str. delle Cacce 91, 10135 Torino, Italy

[2]Politecnico di Torino, Dipartimento di Elettronica e Telecomunicazioni, C.so duca degli Abruzzi 24, 10125 Torino, Italy,

INTRODUCTION



The spin- and total-angular-momentum forbidden $^1S_0 \rightarrow {}^3P_0$ transition in ^{171}Yb has been recognized by the BIPM as a secondary time standard. At our laboratories in INRIM an optical lattice clock based on Yb is **fully operational** and currently being characterized. We present **preliminary results of the absolute frequency measurement** utilizing our IT-CsF2 atomic fountain clock and a first estimate of the Yb uncertainty budget.

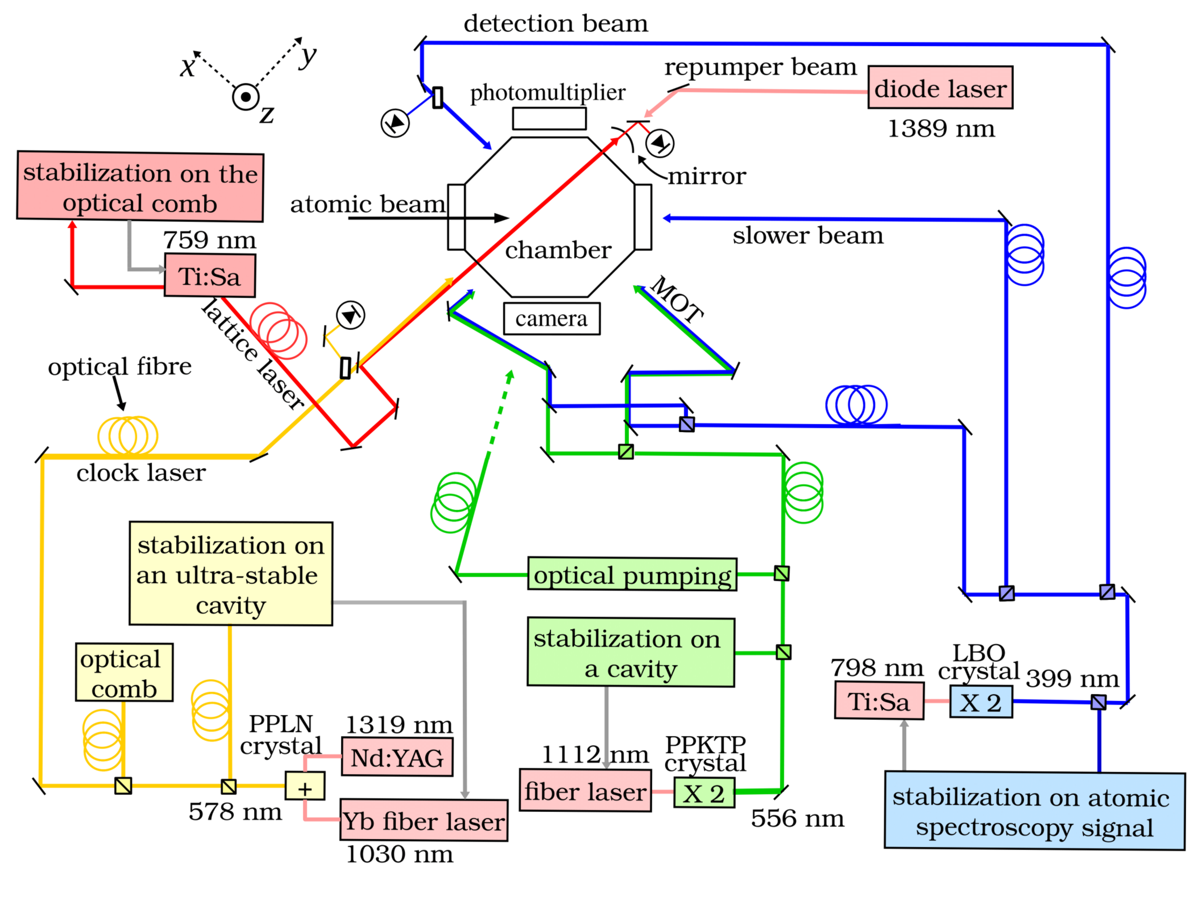
EXPERIMENTAL SETUP

The atoms are cooled and trapped in a two-stage Magneto-Optical-Trap (MOT), with the **first stage** operating (for 50 ms) at the broad $^1S_0 \rightarrow {}^1P_1$ 399 nm line and the **2nd stage**, which lasts 60 ms, on the narrow $^1S_0 \rightarrow {}^3P_1$ 556 nm transition. The atoms are subsequently transferred to the optical lattice (retro-reflected beam, waist 45 µm), which is working at the **magic wavelength** (759 nm). The clock laser has a waist of 200 µm and is superimposed with the lattice.

Inside the 1D horizontal lattice the atoms are **spin-polarized** and afterwards probed on the **clock transition** $^1S_0 \rightarrow {}^3P_0$ (578 nm) by a laser stabilized to an ultra-stable cavity. A **repumper** laser working on the $^3P_0 \rightarrow {}^3D_1$ line transfers the atoms back into the ground state.

The clock-laser is stabilized via the Pound-Drever-Hall method to a 10 cm **ultra-stable cavity** made of Corning ULE, with fused-silica mirrors and ULE rings.

Pizzocaro et al., IEEE UFFC 59, 426-431 (2012)



Blue Laser 798 nm → 399 nm

2nd harmonic generation of a Ti:Sa laser via LBO (LiB_3O_5) crystal in enhancement cavity (Hänsch–Couillaud locking), Output ca. 0.5 W from 1 W input, Frequency locked to atomic resonance via transverse spectroscopy on an auxiliary atomic beam

Pizzocaro et al., Appl. Opt. 53, 33883392 (2014)

Green laser 1112 nm → 556 nm

2nd harm. generation of amplified fiber laser using PPKTP (periodically poled $KTiOPO_4$) crystal in single-pass, Typical Output: 10 mW, Frequency locked to stable cavity.

Lattice laser 759 nm

Ti:Sa laser, Typ. power on atoms: 1.0 W, Frequency locked to magic wavelength via frequency comb.

Yellow laser 1030 nm + 1319 nm → 578 nm

Sum frequency generation of Nd:YAG and fiber-laser with PPLN (period. poled $LiNbO_3$) waveguide, Typ. Output = 7.2 mW, Freq. locked to ultra-stable cavity.

Repumper laser 1389 nm

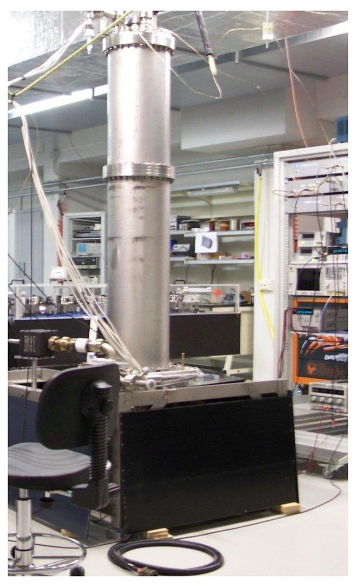
Distributed Feedback (DFB) Laser, Typical power on atoms: 10 mW, No frequency stabilization needed

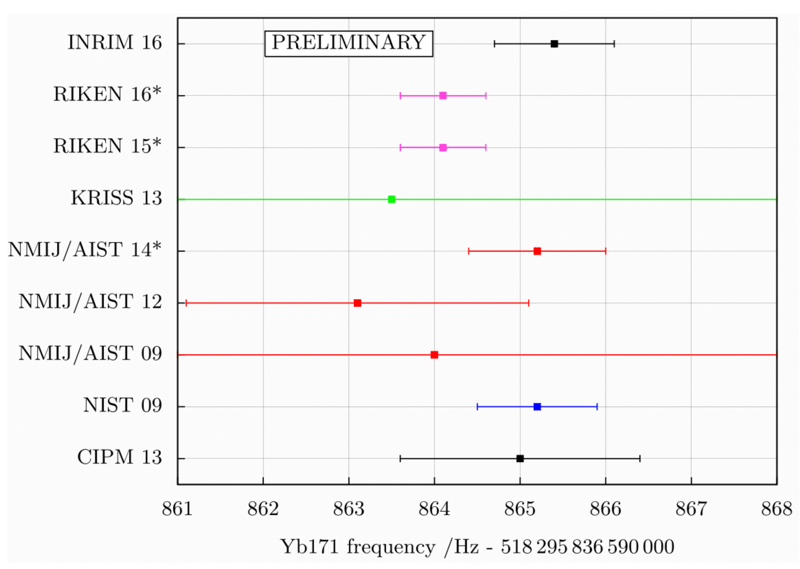
The atoms are emitted in a collimated beam by an effusion oven at 400°C. The slower beam, which is working **without** magnetic coils for **Zeeman-slowing**, is facing them through a hot window. The atoms are trapped inside the custom aluminum chamber, designed for wide optical access with indium-sealed viewports. 10 thermistors are distributed all over the chamber for blackbody-shift evaluation and it is being kept at ultra-high vacuum (pressure < 10^{-9} mbar). The MOT coils are outside of the vacuum chamber, aligned in the vertical direction.

ABSOLUTE FREQUENCY MEASUREMENT

We started a measurement campaign for determination of the absolute frequency of the Yb clock-transition with respect to the INRIM **cryogenic fountain IT-CsF2**. The first measurements agree with the recommended value from CIPM-2013 at the present level of uncertainty, which is 1.3×10^{-15}

Levi et al., Metrologia 51, 270 (2014)





PRELIMINARY ACCURACY BUDGET

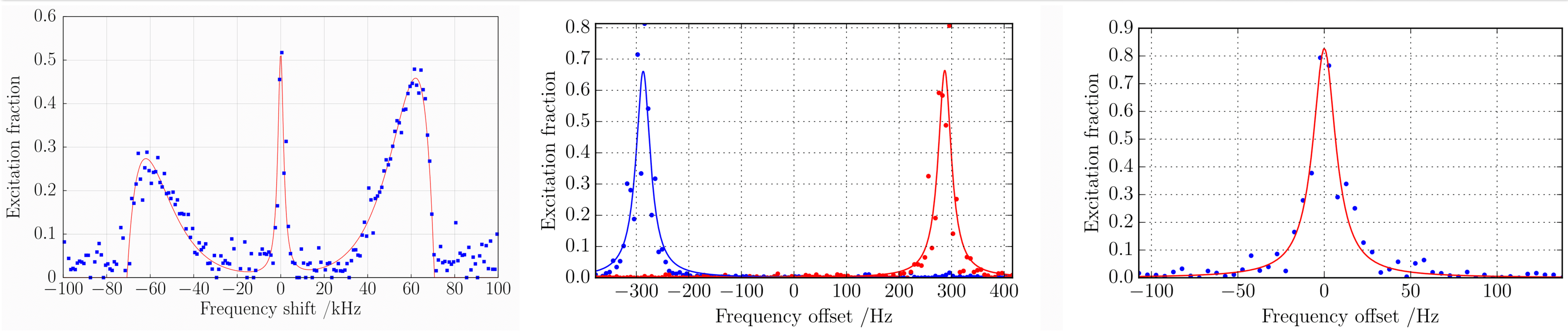
Effect	Shift /Hz	Unc. /Hz
Quadratic Zeeman shift	-0.14	0.02
Lattice Polarizability	-0.16	0.06
Hyperpolarizability	0.06	0.02
Blackbody shift	-3.2	0.3
Collisional shift	0.01	0.09
Probe light shift	0.0027	0.0012
Gravitational red shift	13.474	0.002
Total	10.1	0.3 ($6 \cdot 10^{-16}$)

A number of effects have already been evaluated. These are given in the table above with the resulting shifts and uncertainties. The evaluation of those effects not listed is under way.

The first order **lattice light shift** and the **density shift** have been determined by **interleaving measurements** of high/low lattice power or density.

The **magic wavelength** has been determined to be 394798228(10) MHz with a linear lattice light shift coefficient $b = -0{,}0225(3)\ {}^{Hz}/_{Ghz \cdot Er}$.

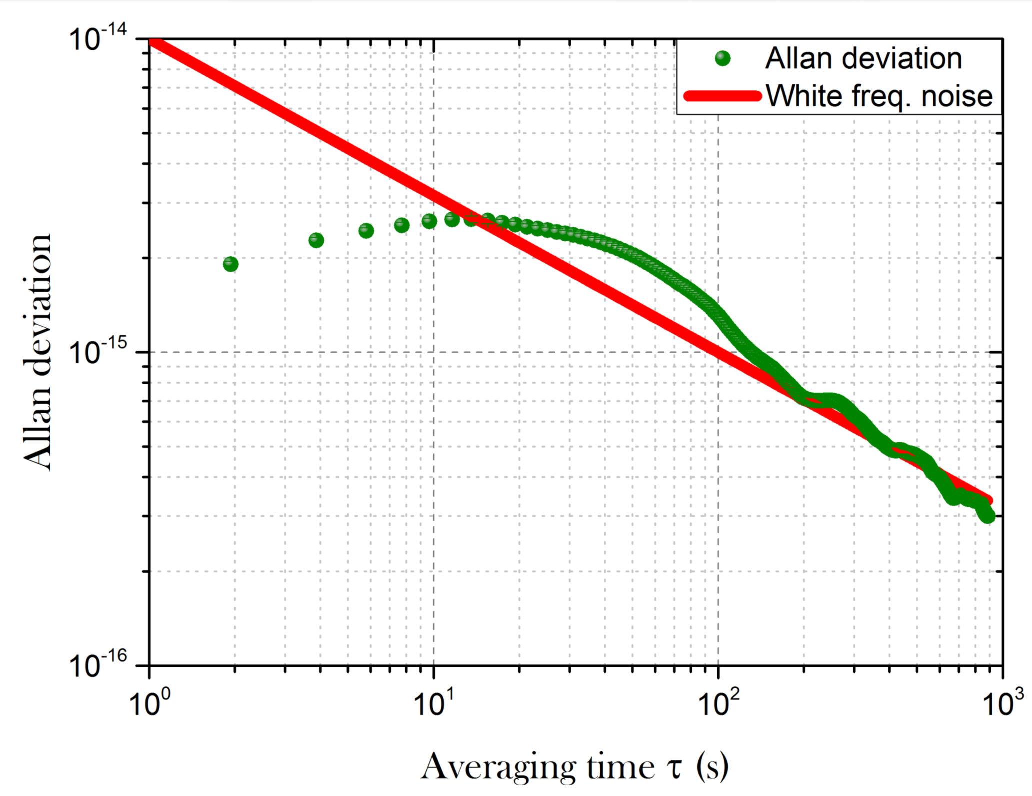
SPECTROSCOPIC RESULTS



Left: Sideband spectroscopy with a Rabi pulse of 100 ms and optical probe power of 100 µW. From the sidebands shapes we deduce a lattice depth of **300 Er**. **Center:** spin-polarized spectroscopy signals with an external magnetic field of B = 0,25 mT. If atoms are pumped to the $^1S_0$, $m_F = -1/2$ state (blue points) the excitation fraction of the left line is maximized, while no atoms are excited on the right one. With pumping to the $^1S_0$, $m_F = +1/2$ state (red points) the opposite behavior is obtained. Pumping efficiency reaches **98%**. **Right:** zoomed-in spin-polarized spectroscopy signal showing a linewidth of **16,0 ± 0,5 Hz**.

One clock cycle consists out of 150 ms of cooling and trapping followed by another 100 ms of clock-transition spectroscopy and detection. After capture in the blue MOT roughly 50% of the atoms are transferred to the green MOT. We capture about $2 \cdot 10^3$ atoms in the lattice. The atoms are then spin-polarized with **98% efficiency** to one of the two hyperfine ground states and subsequently loaded into the lattice. The atomic temperature inside the lattice is **4.5 µK** and the lifetime reaches 2.7 s.

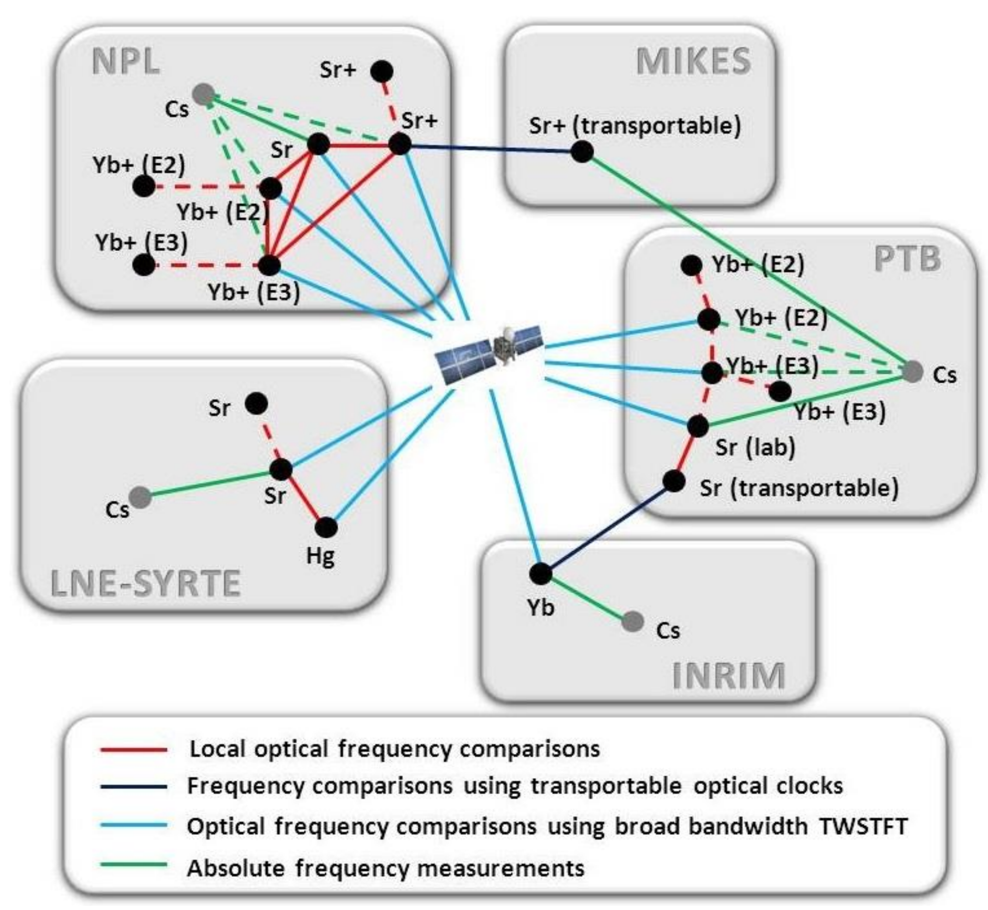
STABILITY



On top is an **Allan-plot** of the stability of two **interleaved** and independent locks on the clock transition, which is the self-referenced clock stability. The stability is ca. $1 \cdot 10^{-14}/\sqrt{\tau}$.

LOCAL AND REMOTE COMPARISONS / FUTURE PROSPECTS

Our clock takes part in the MRP project International Timescales with Optical Clocks (**ITOC**). It is the **only neutral Yb** optical lattice clock in the planned ensemble of measurements and it will shortly be **compared** to the transportable **Strontium clock** developed at **PTB**. Further remote and local comparisons (with the transportable **Yb lattice clock** from **Düsseldorf** developed under SOC-2) are planned. Moreover our clock will also be used for **reference signal distribution** via the national fiber link to Florence, Bologna and Medicina, which has been installed as a part of the AQUASIM (Advanced Quantum Simulation and Metrology) project.



The black-body-radiation **(BBR) shift** is estimated by a simple model of the vacuum chamber and the known polarizability of Yb. This model divides the system into 3 parts: The aluminum chamber, the atomic oven tip (400°C) and the hot window (230°C). Their BBR field as seen by the atoms is calculated by taking not only the irradiation in direct line of sight, but including reflections on the inside of the stainless-steel junctions, leading to an **effective total angle** under which the electromagnetic field is seen by the atoms. The uncertainty is **now limited** by the unknown effective solid angle underlying the hot window. We have therefore recently exchanged it for a cold mirror inside the vacuum, allowing us to **constrain the relative uncertainty** to the 10^{-17} region in the future. All other shifts and uncertainties were calculated by applying sensitivities from literature.

Sherman et al., PRL 108, 153002 (2012)
Lemke et al., PRL 103, 063001 (2009)
Nemitz et al., arXiv:1601.04582 (2016)

CONTACT

b.rauf@inrim.it
http://www.inrim.it
http://rime.inrim.it/labafs

ACKNOWLEDGEMENTS

EMRP European Metrology Research Programme ▸ Programme of EURAMET
The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

Ministero
Istruzione
Università
Ricerca

The authors acknowledge funding from the EMRP Project SIB55-ITOC, MIUR Project PRIN2012 AQUASIM and ITN Marie Curie Project FACT. The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.