Istituto Nazionale di Ricerca Metrologica (INRIM)

Report to the 20th Meeting of the CCTF

INRIM’s Time and Frequency Activities.

September 2015

Summary

Introduction

This report is not intended as a comprehensive presentation of all the activities of the INRIM's Time and Frequency group, but only to highlight some of the most relevant accomplishments and changes with respect to the past.

After a recent reorganization of INRIM's scientific structure all time and frequency activities are now part of a single Program of the Physical Metrology Division.

The Time and Frequency Program is operating his ensemble of clocks and frequency standards according to the following scheme.

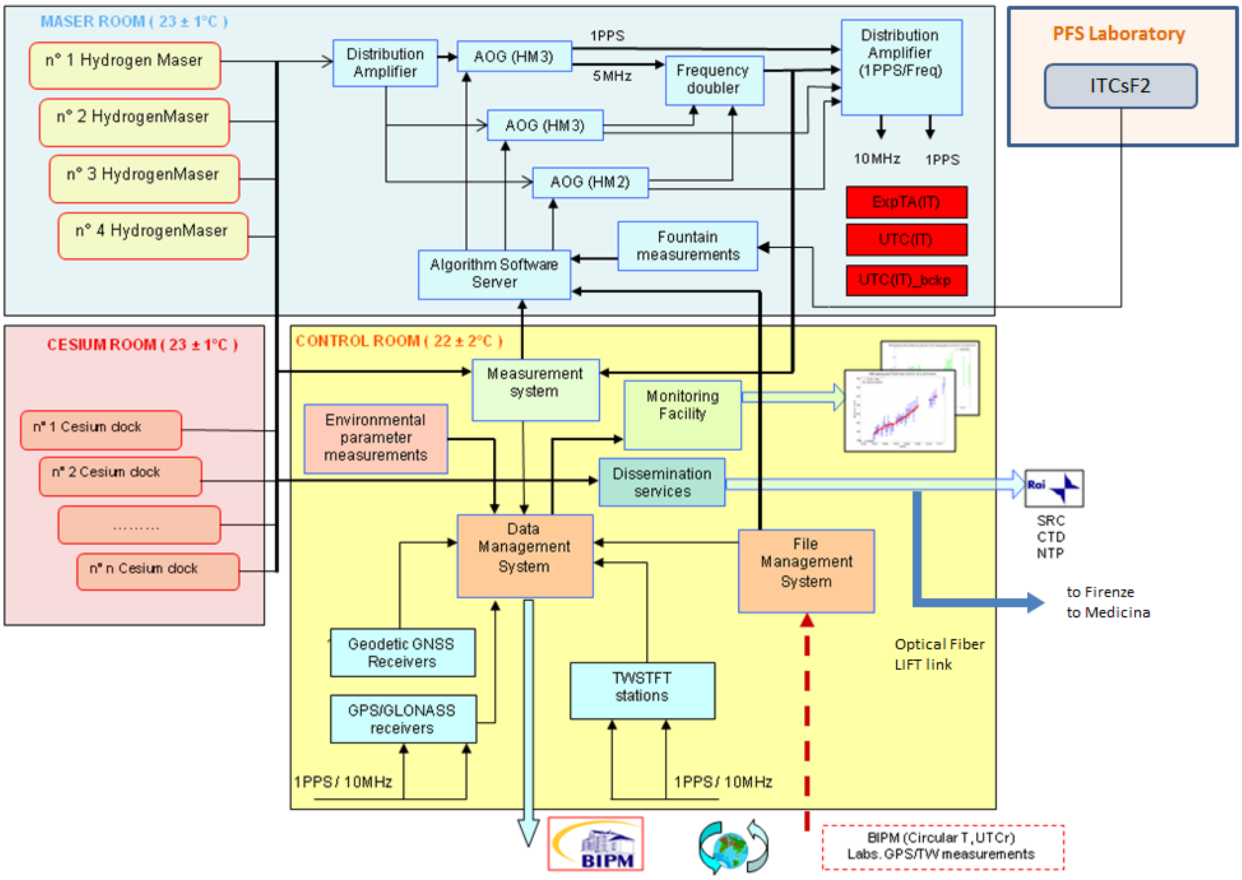

Figure 1: UTC(IT) generation and distribution

The most recent improvements are the development of a new steering algorithm that include UTCr and ITCsF2, the experimental use of the optical fiber link to distribute high accuracy frequency reference signals to some Italian scientific users, and the realization of an Yb optical lattice clock.

Primary frequency standard

In the past years INRIM has completed the accuracy evaluation of its new cryogenic Cs fountain primary frequency standards ITCsF2, and has routinely operated it to calibrate UTC(IT) master clock as well as TAI.

The accuracy budget of ITCsF2, as is extensively discussed in [10], is summarized in the following table (report to BIPM april 2015):

Summary of ITCsF2 accuracy evaluation

Physical effect	Bias (10^{-16})	Uncert. (10^{-16})
Zeeman effect	1087.7	0.8
Blackbody radiation	-1.45	0.12
Gravitational redshift	260.4	0.1
Microwave leakage	-1.2	1.4
DCP	-	0.2
2nd order cavity pulling	-	0.3
Background gas	-	0.5
Total Type B**		**1.7**
Atomic density (typical LD)*	-3.9	1.4
Total	**1341.6**	**2.2**

Table 1. ITCsF2 uncertainty budget during the period 57124-57139.

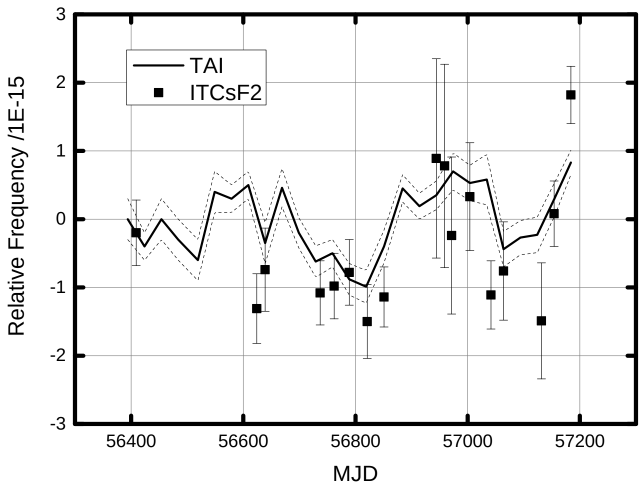

Figure 2: ITCsF2 vs TAI as reported in the BIPM circular T for the period 2013-2015.

Since last CCTF meeting ITCsF2 provided 17 official TAI calibrations for a total measurement time of 330 days. During 2012 and 2013 IT CsF2 was also compared to NISTF1 and NISTF2. The result of this comparisons was used to perform a new accurate direct measurement of the blackbody radiation shift [13], exploiting the difference in temperature between NISTF1 and the two cryogenic fountains. The result of this new evaluation of the blackbody coefficient for Cs is in good agreement with both theoretical estimations and a previous indirect measurement.

$$\beta = -(1.719 \pm 0.016) \times 10^{-14}.$$

UTC(IT) generation

The generation of UTC(IT) time scale is currently carried out by means of an ensemble of 10 commercial atomic oscillators, namely six Cesium beam tubes (Symmetricom High Performance HP-5071A) and four Active Hydrogen Masers (#2 Symmetricom MHM-2010, #1 Kvartz CH1-75A and #1 T4Science iMaser3000, the latter installed in year 2014). More in details, the physical realization of UTC(IT) is based on a 5 MHz signal provided by an Active Hydrogen Maser considered as Master Clock (MC) to be sent to a phase micro stepper (namely AOG), that automatically compensates that signal for its frequency offset and drift versus UTC. The compensation parameters are computed starting from the monthly BIPM evaluation of UTC(IT), as well as from its "rapid" version (yielded weekly), together with the use of the results of Time Laboratory's internal measurements systems. The frequency offset correction is manually applied to the AOG, while the frequency drift correction is automatically applied every hour, through a dedicated PC.

In the following Figure, the behavior of UTC(IT) time scale is presented for the 2013-2015 period, in terms of time and relative frequency offsets with respect to UTC.

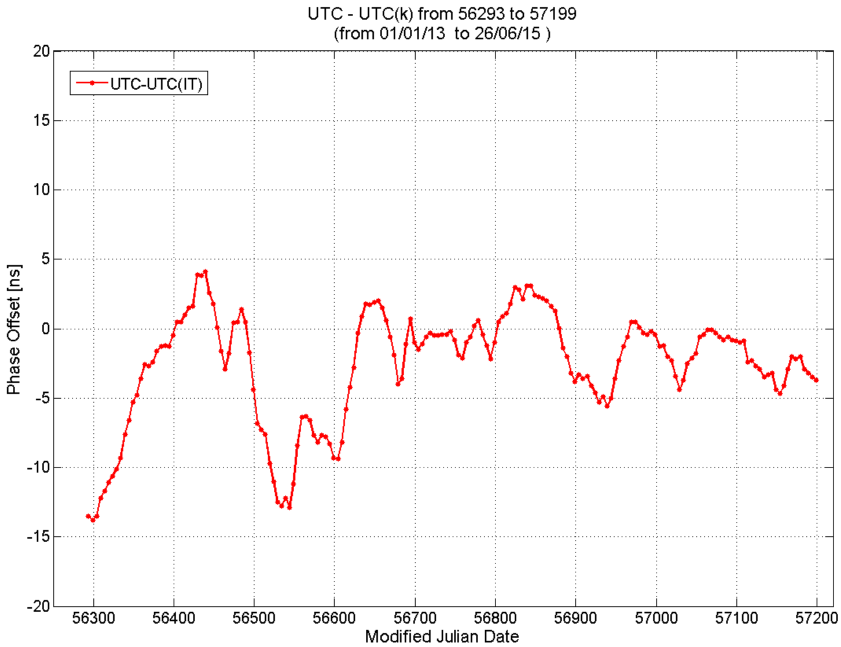

Figure 3: UTC(IT) vs UTC time offset, as per BIPM Circular T estimates, for the 2013-2015 period.

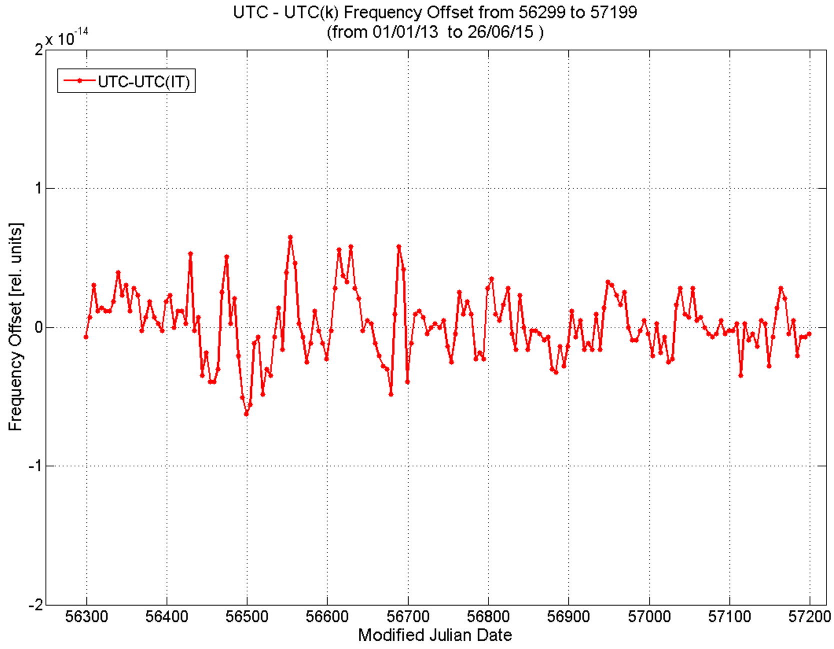

Figure 4 UTC vs UTC(IT) relative frequency offset, as per BIPM Circular T estimates, for the 2013-2015 period.

In the following figure, the behavior of UTC(IT) vs UTC is represented in comparison with a selection of major physical realization of UTC around the world (NICT, NIST, NPL, OP, PTB, ROA, USNO), expressed again in terms of time offsets for the same period (2013-2015).

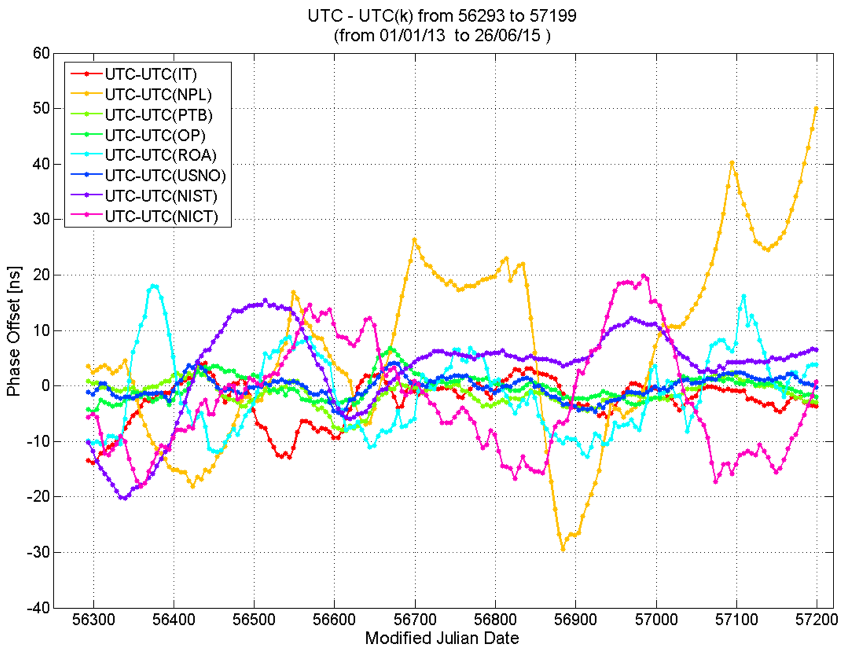

Figure 5 UTC vs UTC(IT) in comparison with a selection of international physical realizations of UTC, for the 2013-2015 period

As stated above, the current UTC(IT) generation system is not totally autonomous and, hence, in case of a failure of either the MC or the AOG, a human intervention is required to replace the main chain with the backup one. In this sense, a new system for the generation of UTC(IT) time scale has been conceived and is under realization, aimed at granting for improved robustness and reliability, as well for better performances. From an HW point of view, different solutions are under evaluation. The first one – already started in its experimental version - is being composed by up to four parallel Maser+AOG chains, all based on a dedicated workstation aimed at implementing steering and functional paradigms devoted at operating and controlling the whole system, granting for up to four parallel and cross-locked time scales. The time scale better behaving, will be chosen as the "master" one and considered operative and distributed to all the INRIM Time Laboratory and external users, by means of a dedicated "switching matrix", allowing to commute (automatically and manually) among the different chains, with phase and frequency continuity. Beside this new possible HW approach, a new scheme for the computation of the frequency corrections to be applied has been envisaged, as per the following functional scheme:

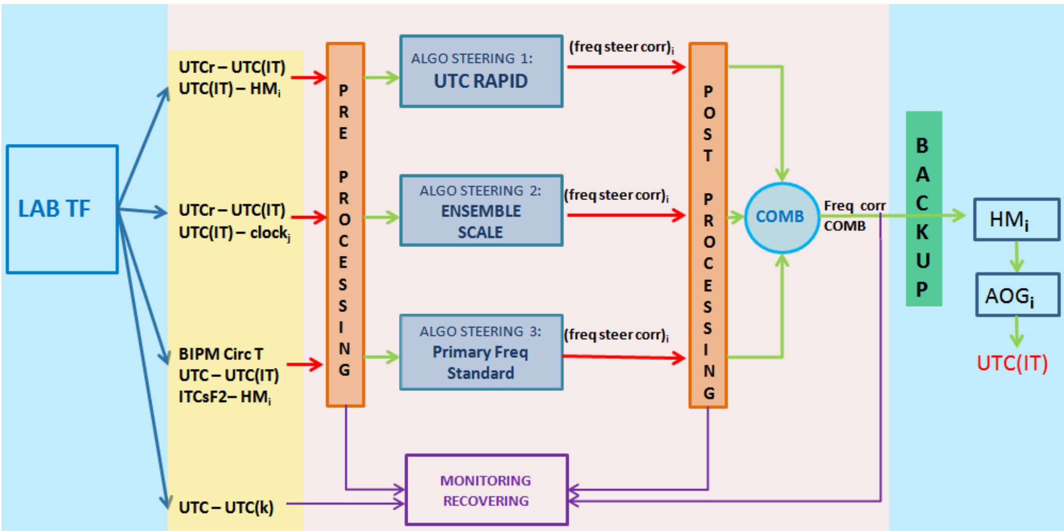

Figure 6: Scheme of the new UTC(IT) steering algorithms

The frequency steering will be evaluated by three parallel independent steering chains. The first one is based on BIPM rapid UTC data, the second one on an ensemble time scale using all the INRIM commercial Cesium beam tubes and Active Hydrogen Masers, while the third one makes use of the measures of INRIM Cesium fountain ITCsF2. The ITCsF2 also contributes to the TAI realization by the BIPM.

All input measurement data will be automatically provided. The first step in the analysis will be a pre-processing stage aimed at detecting and filtering possible anomalies on the measurements. Then, the steering parameters of the same Maser will be evaluated in parallel by the 3 chains.

Finally, the outputs consistency will be checked by the post-processing block and then a combiner will determine the frequency correction to be provided to the AOGs, to steer the frequency of the Hydrogen Masers and, hence, to generate the future time scale UTC(IT).

Currently, the evaluation based on UTC rapid and on the ITCsF2 primary frequency standard are automatically operated and an experimental time scale based only on the ITCsF2 steering is generated in parallel to the official one, to acquire confidence in the developed system, while In the next months the third steering algorithm - based on the clock ensemble - will be put in place for experimentation.

The generation of UTC(IT) time scale is supported by different time and frequency transfer equipment based on geostationary and GNSS satellite systems, namely #2 TWSTFT stations, #3 GNSS Timing receivers and #7 GNSS dual frequency geodetic receivers for timing applications.

More in details, the UTC(IT) time scale is compared every two hours with remote time scales generated at ten European and two U.S. laboratories, by the TWSTFT method. The two TWSTFT earth stations installed at INRIM are designated as IT01 and IT02. IT02 station is used to officially contribute to TAI/UTC as calculated and published by the BIPM in the Circular T; this station is also used to compare UTC(IT) to the Galileo system Time generated at the two Precise Time Facility (PTF) in the frame of the Galileo project. The second station, IT01, is currently used in the frame of ITOC project for comparisons of optical clocks using improved broadband two-way satellite time and frequency transfer (other NMIs involved in the ITOC broadband measurements are NPL, OP and PTB). It is planned to cross-calibrate IT01 against IT02, to use IT01 as hot-redundant back-up station of the operational IT02 station. In parallel, most of the #10 INRIM GNSS (geodetic) receivers for timing applications are operated at INRIM "RadioNavigation Laboratory" (RNL), a Laboratory that is strongly complementary with respect to the INRIM Time Laboratory one, being it devoted at hosting the GNSS receiver aimed at remotely comparing atomic clocks and time scales, through geodetic devices and algorithms. This Laboratory is currently equipped with a permanent IGS/EUREF station (called IENG) connected to UTC(IT) and a GESS (Galileo Experimental Sensor Station, namely GIEN) connected to a free running active hydrogen maser employed in the GSTB-V2, Giove Mission and TVF projects for the development of Galileo. Other six GNSS (GPS+GLONASS+GALILEO+BEIDOU) geodetic receivers for timing applications, connected to atomic clocks/time scales, are operated aimed at supporting a wide range of international cooperation among NMIs and Geodetic Institution for the development of new geodetic systems/methods for the remote comparison of atomic clocks and time scales, using the current GPS, but also the new ones, especially Galileo (in this sense, a dedicated project in cooperation with ESA and the Royal Observatory of Belgium - ROB - is active and aimed at evaluating the time transfer capabilities of the new E5 Galileo signal).

Optical frequency standards

During the last years INRIM has continued to develop a clock based on the $^1S_0 \leftrightarrow {}^3P_0$ clock transition (≈579 nm) in ^{171}Yb atoms confined in optical lattices. Important technological developments were done in the realization of reliable laser sources and in the realization of the physical structure of the Yb clock [11,24].
Yb atoms are loaded in a lattice laser tuned at the magic wavelength according to the operation scheme depicted in the following figure.

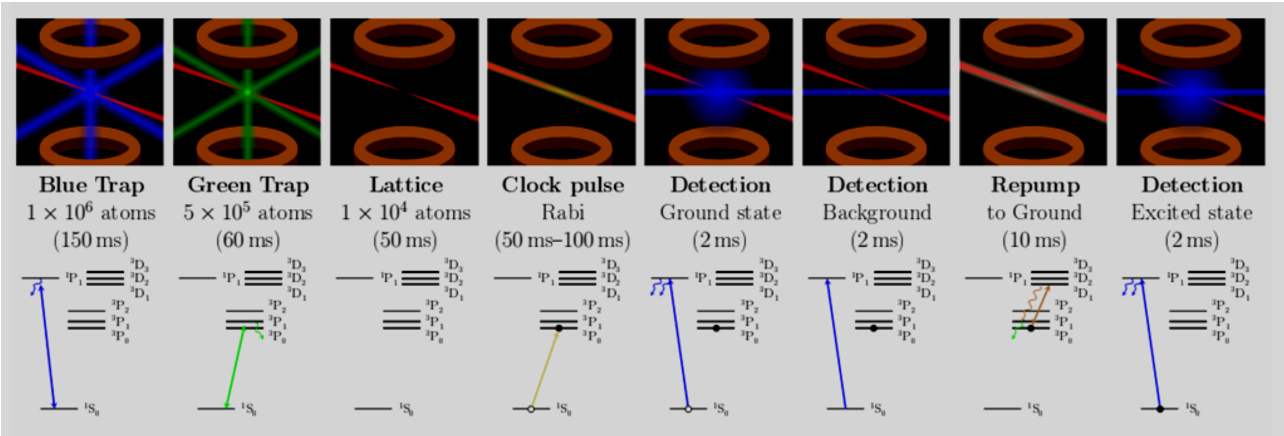

Figure 7: Yb clock cycle and atomic levels

Some 10000 atoms are currently loaded in the lattice laser at the end of the cooling cycle; the life time of the trap is measured to be around 1 s. Spectroscopic analysis of the trapped atoms started recently showing a narrow spectral line (25 Hz) and a satisfactory S/N ratio. Accuracy and stability of the optical clock are currently under complete evaluation. The preliminary accuracy was assessed to be 6e-15 (relative frequency), mainly limited by the blackbody radiation temperature knowledge.
The absolute frequency measurement of the clock transition with respect to the cryogenic fountain ITCsF2 using a fiber femtosecond laser frequency comb is in progress.

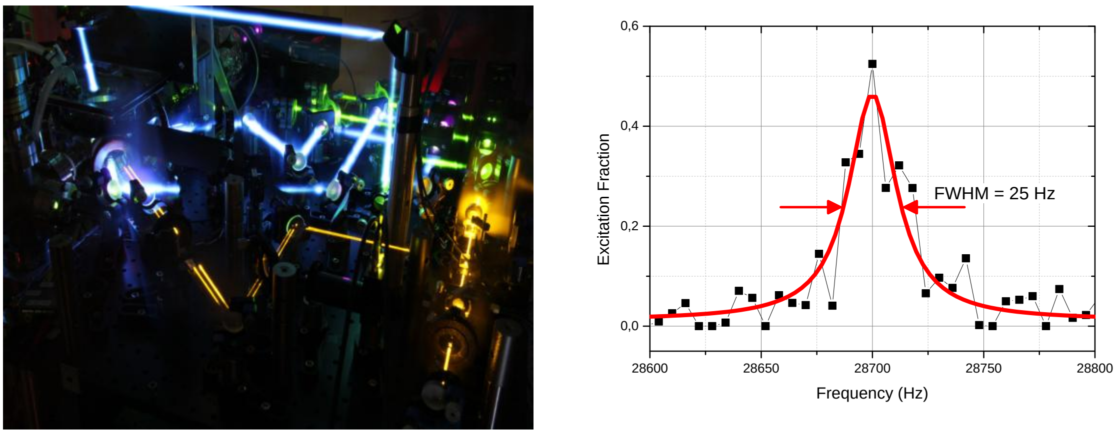

Figure 8: Yb clock: picture of the experiment and spectroscopic line of the $^1S_0$-$^3P_0$ transition, with 25 HzFull Width at Half Maximum.

Optical fiber link

INRIM's Time and Frequency program has developed the first lags of an Italian optical fiber link infrastructure to disseminate time and frequency signals to highly qualified scientific and industrial users.

Two main tracks were developed and are now fully operative: the first one (150 km in CWDM architecture) connects INRIM to LSM (Laboratorie Souterranee de Modane) a French laboratory located in the Frejus tunnel at the French-Italian border. The second one (650 km in dark fiber and DWDM architecture) connects INRIM to the INAF radio-telescope in Medicina (near Bologna) and the scientific campus of Firenze University where is located the LENS (European Laboratory for Nonlinear Spectroscopy) and where important atomic and molecular spectroscopic experiments are operated.

The following extensions of the optical link are currently being pursued: Firenze-Fucino-Matera (1000 km) and Modane-Paris (800 km).

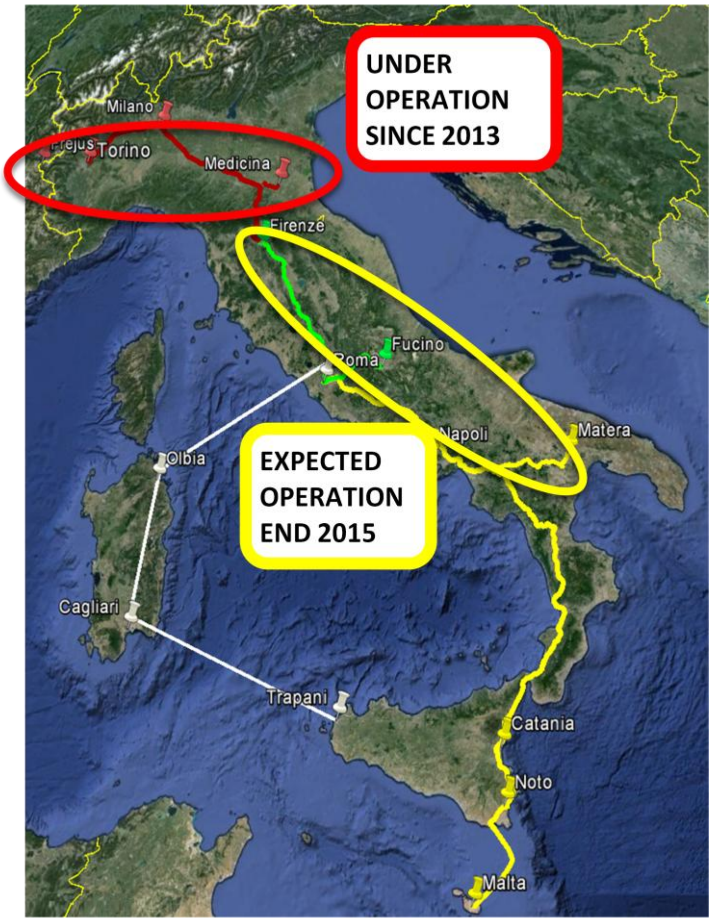

Figure 9: Italian optical fiber link.
The connections Torino-Modane and Torino-Bologna-Firenze are fully operative;
the link toward Roma, Napoli,Fucino and Matera is currently under development.

Research activities were aimed to study different operational schemes of the optical fiber link that can improve the stability of the frequency comparison and reduce the noise figure of the link itself. In particular two distinct techniques were theoretically and experimentally studied: the two way link and the post-process delay-change. [6,12].

Studies were also performed on the use of different type of bidirectional optical amplifiers (Raman and Brillouin) conducting field experiments and tests on real links. In particular was proved the possibility to use Raman amplification in a link, in DWDM architecture, with the simultaneous presence of internet data traffic.

The link INRIM-LSM is realized within the frame of EMRP-ITOC project, and will provide the frequency comparison means between a transportable Sr clock and the resident INRIM Yb clock. The experiments goal is to perform a test of relativistic geodesy, where the clock sensitivity to the gravitational field is used to test general relativity predictions. On the longer run, this link is also aimed to connect INRIM to Paris and to the larger fiber network being developed in Europe.

The link connecting INRIM to INAF aims to provide absolute frequency reference to VLBI antenna that will result in improved measurement accuracy, and when optical clock will be available, also a much lower noise local oscillator opening to radio-astronomy new observation windows. At LENS, instead, a number of high accuracy atomic and molecular experiments are performed that will have important benefits from having high accuracy frequency reference available.

Presently the frequency of an ultrastable laser, frequency locked to UTC(IT), is currently disseminated via fiber link to LENS and INAF, where it is used as accurate frequency reference.

The southern extension of the link will connect the Galileo Time Facility located in Fucino, providing to Galileo Time a direct comparison with UTC(IT) and a primary frequency standards. The link will then reach Matera where is located the ASI's Geodetic Center.

INRIM has demonstrated to be able to disseminate frequency signals with accuracy in the 1E-19 range over 1300 km [9].

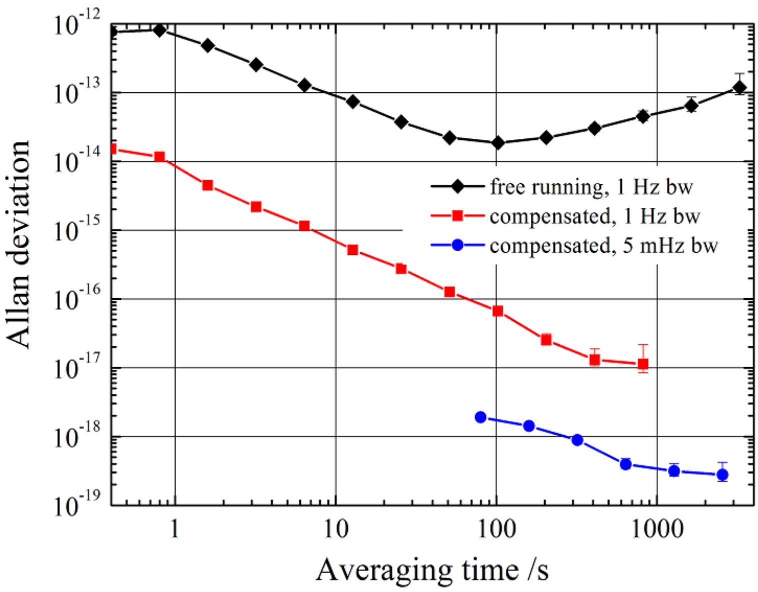

Figure 10 – Accuracy of the INRIM-LENS link.

Time dissemination

The current dissemination services operated at INRIM, are based mainly on the RAI Radio Televisione Italiana (Italian public broadcaster) Radio and TV signals and the NTP (Network Time Protocol) system.

Concerning the first method, new SRC (Segnali RAI Codificato) generators for time dissemination via RAI Radio/TV channels have been realized, aimed at replacing the current old operative systems. Beside the generators, a new SRC monitoring system has been designed and put in operation, allowing to monitor all the generation, transmission and reception steps related to this system. Thy system is used by RAI itself to synchronize part of their internal systems, as well as to provide to the country wide area synchronization capabilities at millisecond level.

Concerning NTP, a new redundant HW platform has been completed, granting for better reliability of this system, to be considered notably important for time dissemination in Italy. At present, in fact, the request average of the three INRIM NTP servers, is stated at a level of about 3750 requests per second, with a positive trend during last years. INRIM, with this system, allows for wide area synchronization capabilities at millisecond level, as well as for calibration activities on this domain towards important customers, like "Autostrade per l'Italia" (Italian biggest motorway company), adopting the NTP as the synchronization mean for its speed control system called "Tutor" (average speed measurements on defined and critical motorway strands). For the future, it's envisaged to carry out studies and activities aimed at improving this time dissemination system, adopting important added value features, like certification.

INRIM contribution to Galileo GNSS

INRIM is deeply committed in the development of the European Global Navigation Satellite System Galileo in collaboration with other NMIs and industrial companies. In the last 15 years, INRIM was involved in about 30 European projects.

The activities are mainly following two main streams, as described below

1. Participation to the definition, realization, and validation of the Galileo timing system

INRIM has been responsible of the validation of the Galileo space clocks for the first experimental satellite GIOVE A and B, and for the first 4 In Orbit Validation satellites. Currently INRIM contributes to the characterization of the onboard clock of the Galileo constellation now based on 8 satellites and on the validation of the UTC and GGTO dissemination carried out by the Galileo signal, in collaboration with ORB.

INRIM has developed, tested, and operated a Time Validation Facility for the In Orbit Validation phase (2010-2014) validating the behaviour of all the system clocks, the Galileo System time scale and also acting as provisional Time Service Provider, providing to the Galileo Control Centre the necessary correction to maintain the Galileo time in agreement with UTC. This was accomplished with the collaboration of EU NMIs, namely NPL, OP, PTB, and ROA. INRIM is currently collaborating to the subsequent Full Operational Capability phase lead by a Spanish company GMV

2. Development and test of timing services based on the Galileo signals

INRIM has started additionally activities developing and testing time services based on the Galileo signals. In the frame of an ESA contract, the capability of time transfer of the Galileo signals, particularly based on the new Galileo transmission frequency and modulation, is tested in collaboration with ORB.

Recently INRIM got the coordination of one of the largest project funded by the European Commission in the frame of Horizon 2020, with 13 partners (2015-16). The projects named DEMETRA aims to demonstrate the feasibility of delivering EGNSS improved timing services to end users by utilising an operational demonstrator and conducting tests with representative pilot applications and real users.

The partners are from 8 European member states, including 5 metrological research institution (ORB, VTT, NPL, UFE and INRIM). The project will evaluate new or improved time services to fill the gaps of the identified user needs relative to the currently available services. These will include: high accuracy calibrated time transfer to a monitored and certified remote time stamping.

The proposed services could become the basis for European timing standards, facilitating the independence from GPS for the synchronisation of critical European infrastructures and fostering the dissemination through Europe of common standardized time services, based on EGNSS.

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