REPORT TO THE 19th SESSION OF CCTF Sept 13-14, 2012
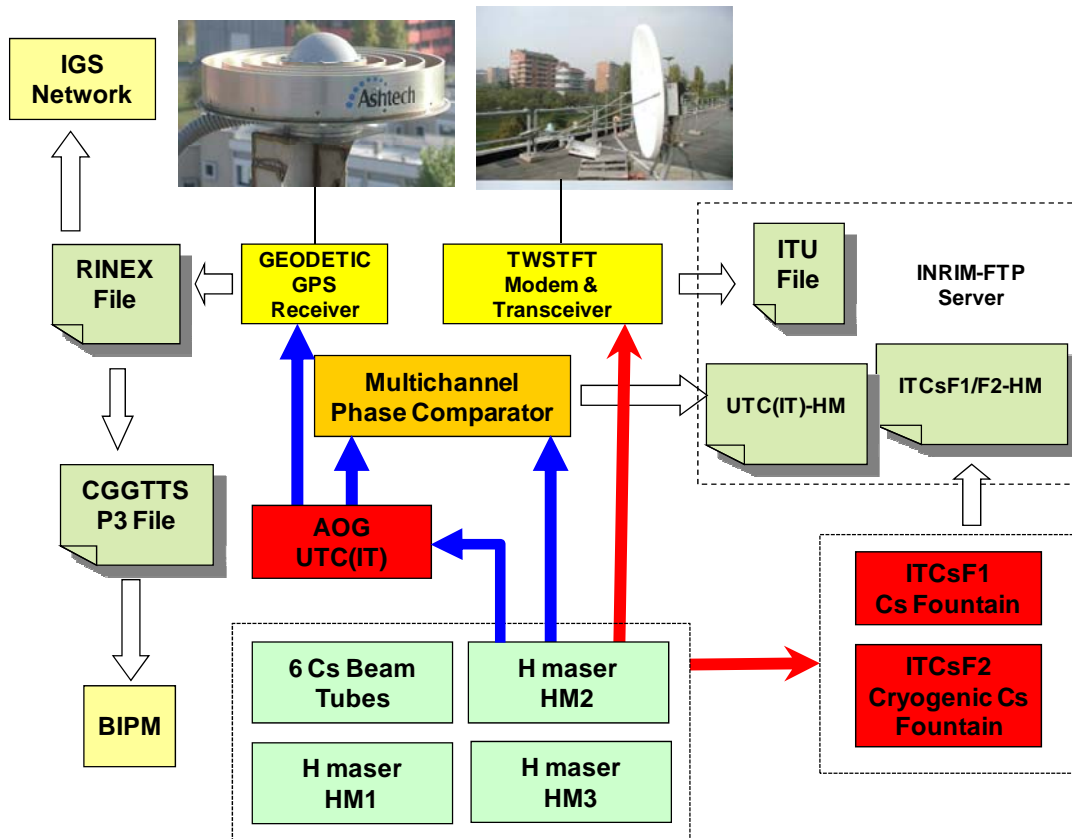## ISTITUTO NAZIONALE DI RICERCA METROLOGICA I.N.RI.M

Introduction

Since 2004, INRIM has operated the metrological system depicted in Figure 1, based on three different kind of atomic frequency standard, and all the transfer techniques recognized by the community to be the most accurate and reliable nowadays.

Figure 1. Block diagram of the time and frequency transfer facilities at INRIM

As shown in the picture, INRIM disposes of two primary atomic frequency standard, the laser cooled Cs fountains ITCsF1 and the cryogenic ITCsF2 and has an ensemble of commercial atomic clocks composed of six Cs beams and three hydrogen maser: HM1, HM2, and HM3.

Since June 2006 UTC(IT) has been generated using a hydrogen maser as a reference.

INRIM participates to the IGS and to the Two Way Satellite Time and Frequency Transfer networks; the GPS Carrier Phase receiver linked to the IGS is referenced to UTC(IT), while the TWSTFT transceiver is driven directly by a hydrogen maser.

INRIM Cs fountain ITCsF1

The Cs fountain primary frequency standard IT-CsF1 has provided 7 frequency evaluations of the TAI unit since last CCTF meeting, as shown in the following figure. Uncertainty of different runs spanned from to 1.3 to 0.9 x 10^{-15} (total uncertainty including link to TAI).
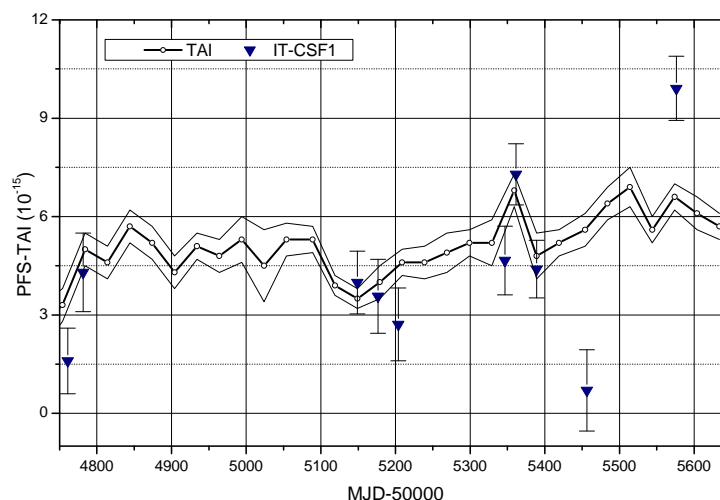

Figure 2. IT-CsF1 TAI frequency evaluations as reported in the BIPM circular T for the period 2008-20012.

Frequency accuracy in the same period spanned between 5 and 8·10^{-16}. Typical accuracy evaluation is reported in Table 1.

Effect	Bias (x10^{-15})	Uncertainty (x10^{-15})
2nd order Zeeman Effect	45.6	0.2
Blackbody Radiation	-28.5	0.3
Gravitational Redshift	26.1	0.01
Atomic Density	-3.0	0.3
Microwave effects	0	0.5
Total	+43.2	0.7

Table 1. Summary of corrected and uncorrected shift and uncertainty budget for IT-CsF1

In late 2011 we decided to upgrade few components of IT Cs F1, particularly we have inserted new platinum thermistor to replace thermocouple temperature readings, and we improved few components of the master laser servo system. To perform this maintenance we had to stop F1 operation for several months. We are planning to return to a full operative system in the next few months.

INRIM Cs Cryogenic fountain ITCsF2

In the last few years INRIM developed a second Cs fountain. This work is carried on together with the Time and Frequency Division of NIST.

The most innovative concept in the new fountain is the operation in cryogenic regime at liquid Nitrogen temperature, feature that will allow a better control of the Blackbody radiation shift and result in a better accuracy in the realization of the second.

The Ramsey interaction region is constantly kept at cryogenic temperature and the total shift is reduced by two order of magnitude with respect to room temperature. The overall uncertainty related to the Blackbody is also strongly reduced.

We have preliminarily characterized the fountain accuracy and we have run two remote frequency comparison with NIST fountains, showing a good frequency agreement.

The preliminary accuracy budget of IT CsF2 is the following:

Effect	Bias (x10^{-15})	Uncertainty (x10^{-15})
Zeeman Effect	112.7	0.2
Blackbody Radiation	-0.15	0.05
Gravitational Redshift	26.12	0.01
Atomic Density	-0.5	0.4
Microwave effects	0	0.4
Total	138.17	0.6

Table 2. Summary of corrected and uncorrected shift and preliminary

uncertainty budget for IT-CsF2.

Frequency comparisons carried out against NIST fountain NIST F1 gave the following results:

MJD 55979.45 - 55991.57: y(ITCsF2-NIST-F1) =   1.1x10-15   ±2.1 x10-15
MJD 56082.55 - 56101.55: y(ITCsF2-NIST-F1) =   -0.7 x10-15   ±1.1 x10-15

Figure 3: The cryogenic fountain IT-CsF2

INRIM laser cooled lattice Yb clock

INRIM has continued its research activity toward the realization of an optical lattice Yb clock. Yb atoms were trapped and cooled in a double stage MOT, using firstly the 399 nm laser resonant on the $^1S_0 \rightarrow {}^1P_1$ transition, and then the 556 nm laser, resonant on the intercombination line $^1S_0 \rightarrow {}^3P_1$.

Some 10^5 atoms were trapped in the blue MOT and transferred in the green MOT with an efficiency of approximately 50%.

The ultrastable clock laser at 578 nm, resonant on the $^1S_0 \rightarrow {}^3P_0$ forbidden transition was already realized and fully characterized. This wavelength is obtained by frequency sum on a non-linear waveguide crystal, of two laser respectively at 1319 nm and 1030 nm. A total power of 12 mW is achieved in the yellow. Two independent ultrastable lasers were realized by locking the yellow light to two independent high finesse cavities hold in temperature stabilized, acoustically and seismically shielded environment. Standard Pound-Drewer-Hall stabilization technique is implemented to lock the free-running laser to the ultrastable cavities. A final linewidth approaching 1 Hz is achieved. A laser stability of 2×10^{-15} between 0.3 and 100 s was measured experimentally (drift removed).

The realization of the lattice trap is scheduled for late 2012 and the completion of the clock is expected in 2013.

INRIM is partner of the SOC2 project (Development of high-performance transportable and breadboard optical clocks and advanced subsystems), founded by the European Community, aiming to realize transportable optical clocks based on Yb and Sr, involving 16 scientific partners (NMIs, Universities and Industries).
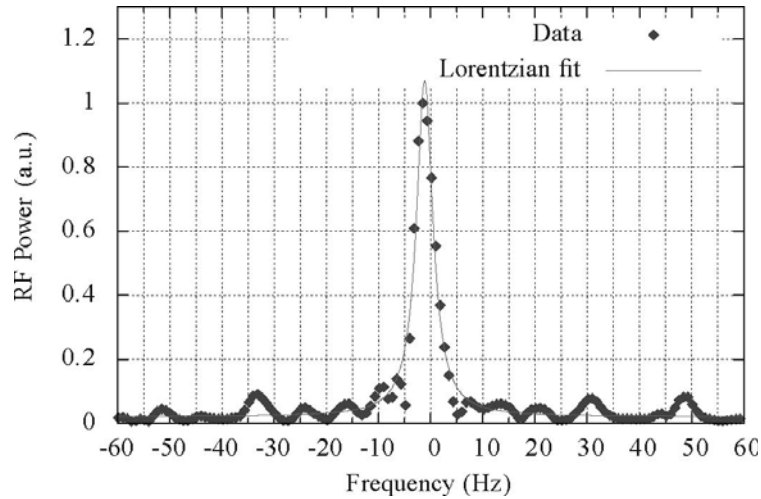
Figure 4: Beat note between two stabilized lasers at 578 nm.

INRIM Pulsed Optically Pumped Cell clocks

In the framework of cell clocks development, in collaboration with Universitè Neuchatel, funded by ESA, a laboratory prototype of pulsed optically pumped (POP) rubidium frequency standard has been implemented. In particular, the pulsed optical pumping process is performed by a DFB diode laser on a cell containing buffer gas, separated in time by a Ramsey interaction scheme defined by a double microwave pulse. The clock transition is detected through the optical absorption signal observed via a low noise photo diode. The POP operation is based on the idea to separate in time pumping, interrogation and detection phases so that the clock transition is excited in absence of any laser radiation. This technique allows to strongly reduce the light shift, which mainly impairs the medium term stability of vapour cell clocks; also we have the possibility to set the pumping and detection light power at respective optimum level, improving simultaneously the pumping efficiency and the detection S/N.

The short-term stability of the prototype is 1.7×10^{-13} at 1 s, a value limited by the residual laser AM noise and by the Dick effect. A frequency drift of 6×10^{-15}/day is observed

This stability is the best ever reported by a vapour cell rubidium frequency standard and makes the POP frequency standard extremely attractive in those fields where are required features as good short and medium term frequency stabilities, reliability low mass volume and consumption.
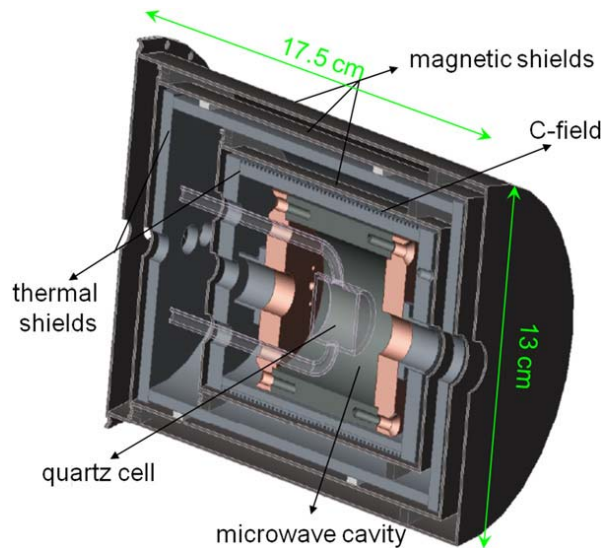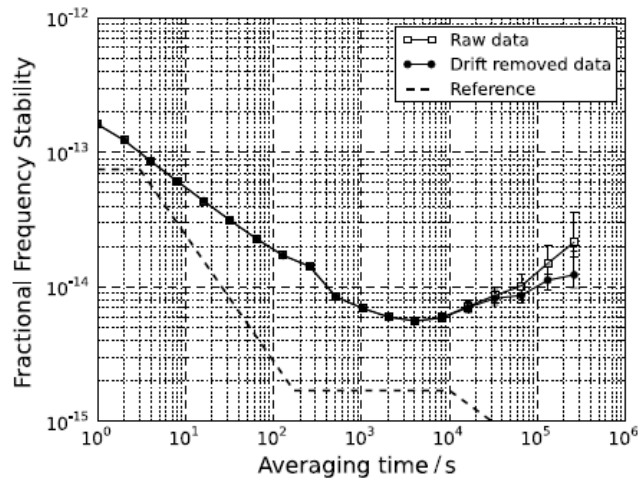
Figure 5: Physical set-up of the POP clock

Figure 6: Frequency stability of the POP clock

INRIM Optical fiber link

In the last few years INRIM started working on the realization of an optical fiber link, connecting Torino with Firenze, where the European Laboratory for Nonlinear Spectroscopy is located, and where a Sr optical clock experiment is carried on. Also we are working to realize a second link connecting Torino with Laboratoire Souterrain de Modane (LSM), aiming to realize a cross border link between Italy and France along the Frejus tunnel.

The Torino Firenze link constitute also the back-bone of a wider Italian fiber network, that will connect Milano and Bologna, where important scientific facilities are present (Politecnico and IFN-CNR in Milano, and Osservatorio Radioastronimico di Medicina near Bologna).

INRIM is partner of the project NEAT-FT (Accurate time/frequency comparison and dissemination through optical telecommunication networks) founded by the European Metrological Research Program (EMRP), aimed to develop a continental fiber network for time and frequency metrology, that involves nine European NMI.

Laboratory experiment produced quite good results showing the possibility of frequency comparison in the 10^{-19} range. Preliminary results were carried on with 100 km fiber spools in the lab, while in a

second phase a real loop of 47 km running under the city of Torino was rent and used as a test bed. This urban loop showed similar stability results. Currently we are working to prepare the bidirectional amplifiers that will be installed along the 650 km link between Torino and Florence.
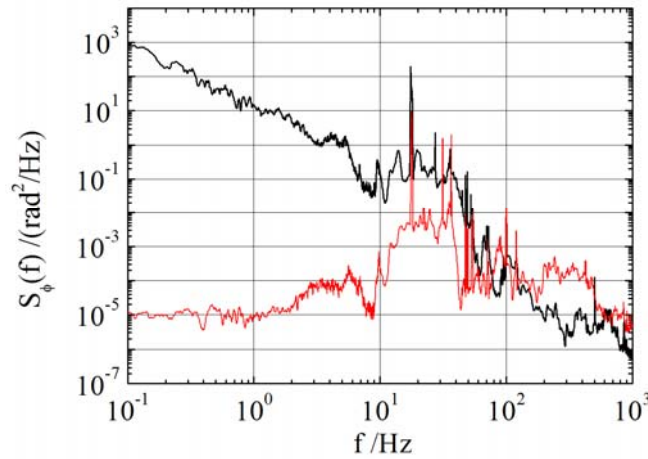

Figure 7: Comparison of detected laser phase noise using a free-running and compensated link.
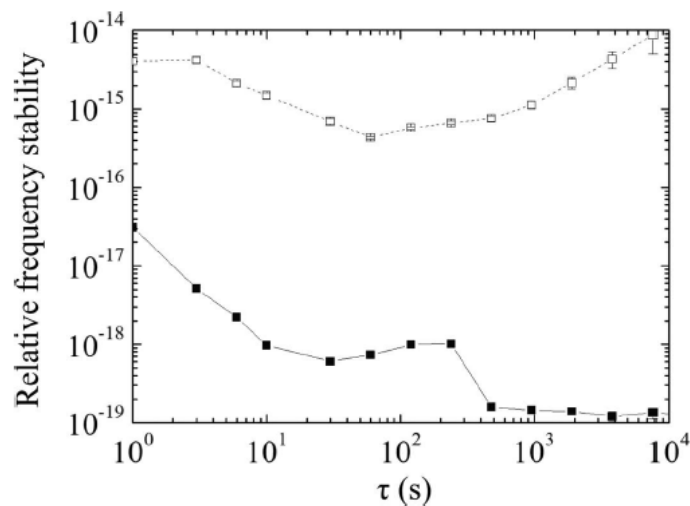

Figure 8: Relative stability of the free-running □ and compensated link ■, acquired with a Λ-type frequency counter.

Generation of the National Time Scale UTC(IT) and synchronization tools

The Italian Time Scale UTC(IT) is based on six commercial atomic cesium beam clocks and three active hydrogen masers, the same devices contributing also to TAI. Starting from July 2006, UTC(IT) has been physically generated by an active hydrogen maser plus an Auxiliary Output Generator (AOG) to compensate for the frequency drift and offset of the maser. A block diagram of the UTC(IT) generation chain is shown in Figure 9.
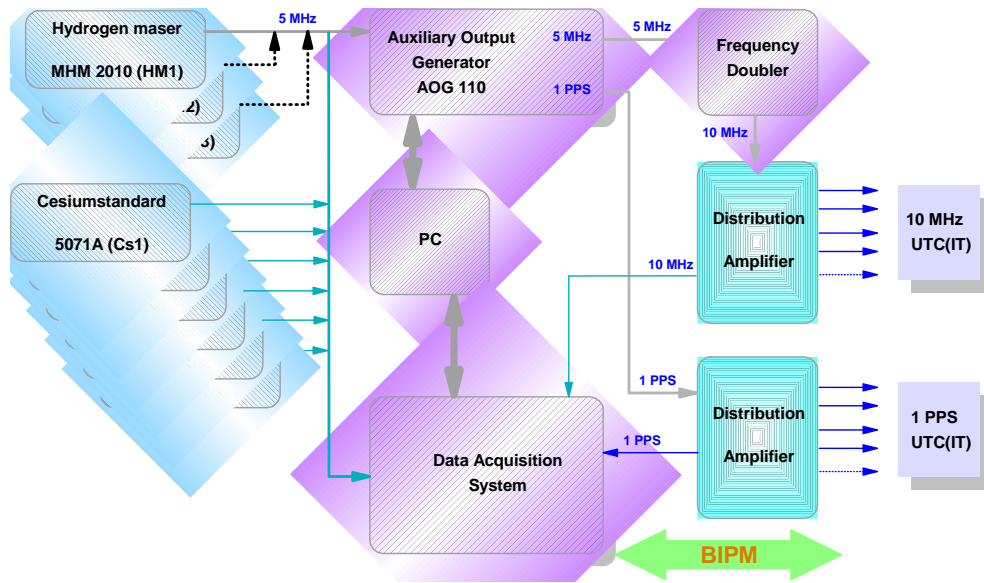
Figure 9. UTC(IT) time scale generation chain

For the future it is planned to introduce a modified scheme, based on a redundant generation of the time scale, as depicted in Fig. 10.
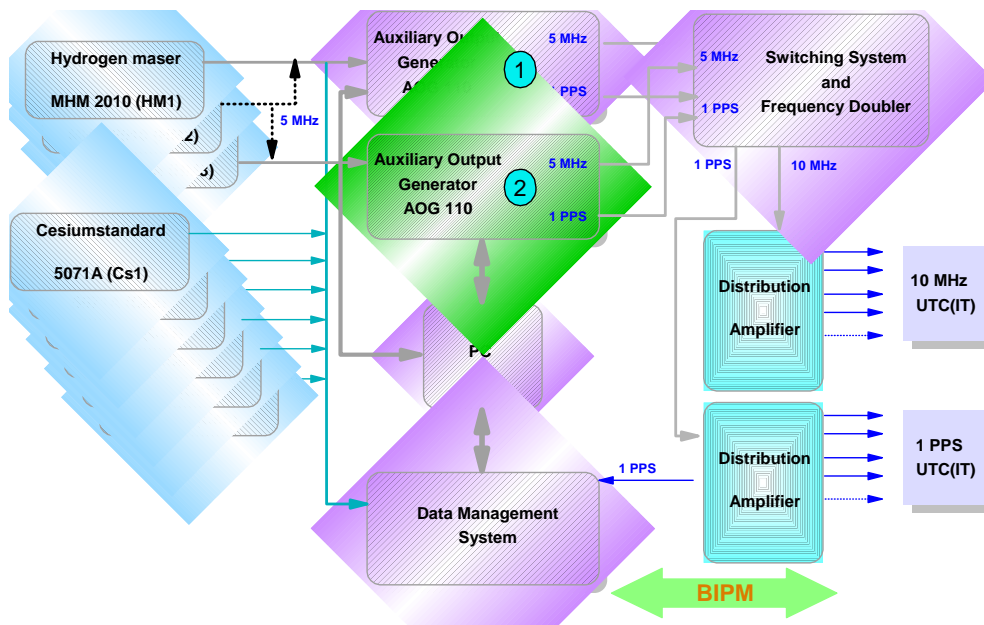

Figure 10. Modified UTC(IT) time scale generation chain

The behaviour of UTC(IT) versus UTC from 2009 to 2012, as obtained from BIPM Circular T, is reported in Figure 11.
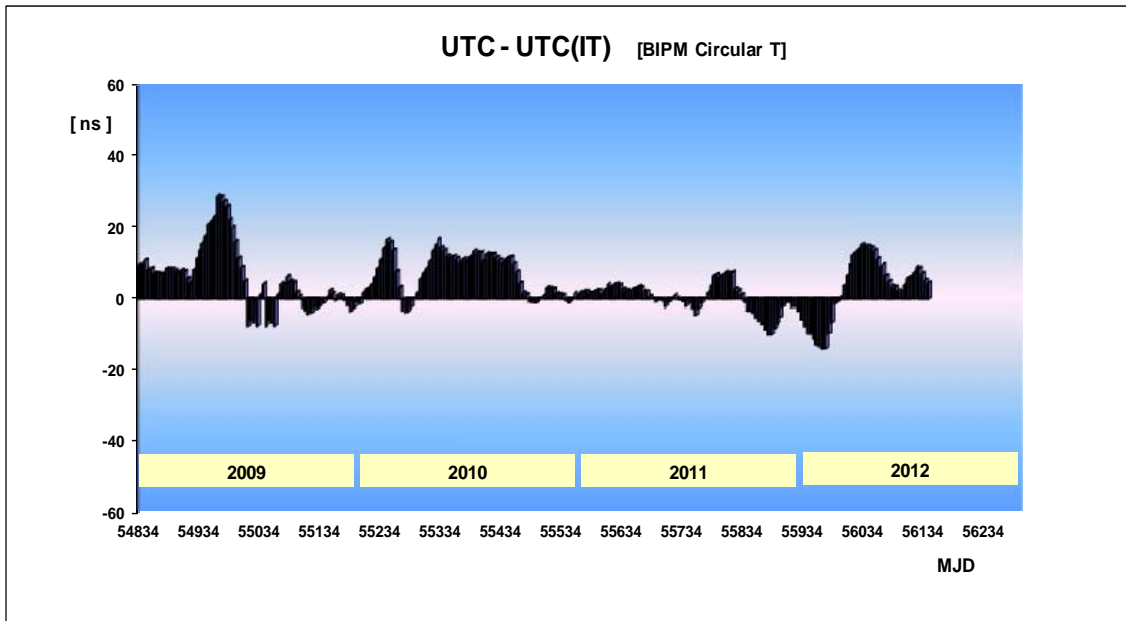
Figure 11. UTC(IT) vs. UTC (January 2009 – July 2012) via BIPM Circulars T

The mean time deviations averaged over one year (7 months for 2012) and the standard deviations on the single (5 days) differences are:

January 2009 – December 2009	6 ns	($1\sigma = 9$ ns)
January 2010 – December 2010	7 ns	($1\sigma = 6$ ns)
January 2011 – December 2011	0 ns	($1\sigma = 4$ ns)
January 2012 – July 2012	3 ns	($1\sigma = 9$ ns)

While the corresponding frequency standard deviations over 5 days are:

January 2009 – December 2009	$\sigma = 0,5 \cdot 10^{-14}$
January 2010 – December 2010	$\sigma = 0,5 \cdot 10^{-14}$
January 2011 – December 2011	$\sigma = 0,3 \cdot 10^{-14}$
January 2012 – July 2012	$\sigma = 0,5 \cdot 10^{-14}$

The maximum time deviation of UTC(IT) versus UTC, in the same period, has been maintained within -14 ns and +29 ns, with a mean value of 4 ns and a standard deviation of 8 ns (1 σ).

Starting from January 2012, INRIM is participating with its reference clocks to UTCr, the experimental "rapid" UTC computed by BIPM, together with about 40 other National Laboratories.

In addition to the customary Time and Frequency Transfer equipment, INRIM is also operating two GPS+GLONASS (Javad Legacy and Septentrio PolaRx 3TR) and two GPS only (Ashtech ZXII-3T and Septentrio PolaRx2) dual frequency geodetic receivers used for the remote comparison of atomic clocks and time scales.

Ashtech ZXII-3T receiver is traceable to UTC(IT) by means of its Reference Frequency (20 MHz) and 1PPS signals and is used as IGS/EUREF/RTIGS sensor station, internationally indicated as "ieng". Measurements performed by this receiver are stored in 30 s sampling rate RINEX files and periodically sent to the IGS/EUREF Local/Regional/Global data centres to be

processed. The same measurements results are sent (1Hz rate) to a data server at Natural Resources Canada (NRCan) in the frame of the Real Time IGS Pilot Project, with the aim to provide clock estimates with a reduced latency time: "near-real time" products (2 h) and "real-real time" products (5 m).

RINEX files generated by the Ashtech ZXII-3T receiver are processed at INRIM by means of a TAI P3 algorithm and the results are regularly sent to BIPM for its All-In-View computations. Thanks to the fruitful collaboration established since 2004 with the Geodetic Survey Division (GSD) of NRCan, some studies have been carried out to evaluate the time and frequency transfer capabilities of Precise Point Positioning (PPP) algorithm. PPP is able to yield clock estimates with frequency stability lower than that provided by other time and frequency techniques, such as TWSTFT over continental and Intercontinental baselines.

PPP is currently showing good performances for frequency transfer, especially in terms of stability and important studies are carried out internationally in order to improve also the accuracy characteristics of the geodetic tools. In this frame fruitful calibration exercises are carried out jointly with ROA and PTB for the development and assessment of a new calibration technique "link based". The PPP algorithm, in the NRCan version is used by the BIPM for the computation of its TAI links and INRIM contributes with its IENG station. The other geodetic receivers are used for internal evaluation and studies, especially for the first prototype of Galileo Receiver hosted at the INRIM premises. This receiver was the reference station in the frame of the GIOVE Mission (Galileo In Orbit Validation Experiment), the experimental phase carried out by the European Space Agency and other continental Industries and Institutes, for the development of the European Global Navigation Satellite System Galileo.

INRIM has important collaboration with other NMI and European Industries for the development of new techniques for the remote comparison of atomic clocks and time scales. Among these, it's worth to recall the cooperation with a Spanish Aerospace company called GMV for the development of a new tool based on a GNSS network receivers algorithm, to be easily used at Time and Frequency Laboratory for the monitoring of its devices in order to promptly react in case of problems and anomalies.

INRIM has collaborated, with support of ROA, to the calibration of the CERN and Gran Sasso physics laboratories for the measurement of the neutrino speed.

INRIM regularly participates in the TWSTFT synchronization network with its Ku-band VSAT station IT02. The INRIM time scale is compared with remote time scales of 11 European and 2 USA laboratories following an agreed schedule with 12 measurement sessions per day. Operation of the TWSTFT measurements is completely automated by software.

The INRIM-PTB TWSTFT link is the primary link used to transfer INRIM clocks and primary frequency standard ITCsF1 to TAI. It has been calibrated three times in the past (2003, 2005, 2008) using a transportable TWSTFT station provided by the Johanneum Research of Graz, achieving calibration uncertainties between 1 and 1.2 ns (1σ). In Figure 12 is shown the transportable TWSTFT station used in these calibrations. In February 2008, the satellite used for the TWSTFT link was changed from IS707 (307 °E) to IS3R (317 °E).

The old station IT01 is still maintained and used as a backup or for experiments. It was used in the common clock experiment which allowed to preserve the link calibration when the satellite provider changed the satellite.
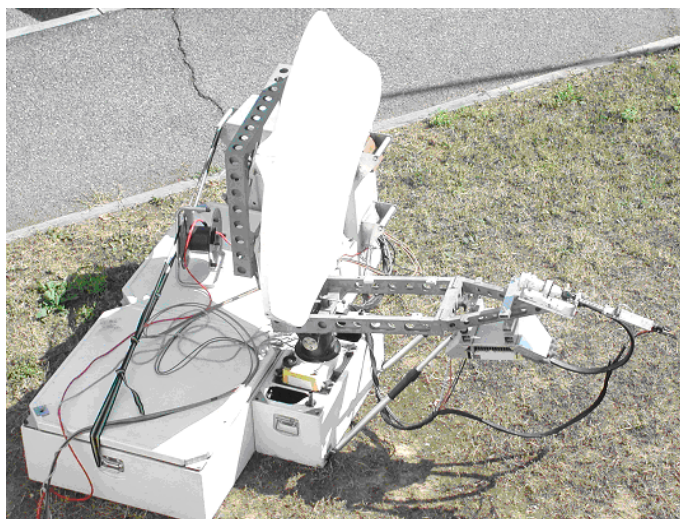
Figure 12. Transportable TWSTFT station

The real time dissemination services of Italian legal time have been continued on the RAI national broadcasting transmissions (AM and FM) and on the telephone lines (CTD – Telephone time code), together with the NTP Internet time service (ntp1.inrim.it, ntp2.inrim.it).

The Time and Frequency Laboratory, besides providing the traceability to the national time and frequency standard of remote oscillators and clocks by means of different synchronization techniques (mostly GPS), also supplied to the Italian Accreditation Body for calibration (SIT) the reference standards for the inter-laboratory comparisons.

In the frame of the MRA, 16 INRIM Calibration Measurement Capabilities, for frequency and time interval, were approved and published since 2005 in the KCDB (Key Comparisons Data Base) of BIPM.

INRIM contribution to the Galileo system

In the last 10 years the INRIM *time scale and algorithm group* has been deeply involved in the development of the European satellite navigation system, named Galileo. Galileo is a project of the European Union and the European Space Agency. In the last years the main achievement is the set up of the *Galileo Time Validation Facility* (TVF) financed by the European Space Agency for supporting the *In Orbit Validation* phase of the project with the first 4 satellites in space and the complete ground structure in operation foreseen for early 2013.

The *Time Validation Facility* is a resource placed in INRIM and able to fulfil two main aims:

A. Check the behaviour of all the space and ground Galileo clocks with respects to the ground reference time scale
B. Provide to the *Galileo Control Center*, the necessary validation of the Galileo reference time scale and a daily correction to maintain Galileo System Time within 50 ns with respect to the international time UTC. This task is accomplished with the collaboration of 4 EU national metrological laboratories: NPL, PTB, ROA, and SYRTE.

Fig 13: the Galileo Time Validation Facility in INRIM

After design and development, since autumn 2011 a preliminary version of the *Galileo Time Validation Facility* is in operation and has supported the validation of the clocks of the first two Galileo satellites launched in October 2011. In 2012 the TVF started the interface to the Galileo Ground Control Centre to connect the Galileo Time to the UTC international time scale. The *In orbit Validation* of the Galileo system with the support of the TGVF is planned for 2013.

References

F.Levi et al., Cryogenic Fountain Development at NIST and INRIM: Preliminary Characterization, IEEE Transactions on UFFC Vol 57 n 3, pg: 600-605 (2010)

M. Pizzocaro et al., Realization of an Ultrastable 578-nm Laser for an Yb Lattice Clock, IEEE Transactions on UFFC, Vol 59, 3, pg 426-431 (2012).

Micalizio, S., Calosso, C. E., Godone, A., Levi F., Metrological characterization of the pulsed Rb clock with optical detection, Metrologia,
 Vol. 49, 4 pg 425-436, (2012)

Micalizio, S., et al., Pulsed Optically Pumped Rubidium Clock With High Frequency-Stability Performance IEEE Transactions on UFFC Vol: 59, 3 pg: 457-462, (2012)

C. Clivati et al., Planar-Waveguide External Cavity Laser Stabilization for an Optical Link With 10(-19) Frequency Stability IEEE Transactions on UFFC, 58 12, p 2582-2587 (2011).