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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.

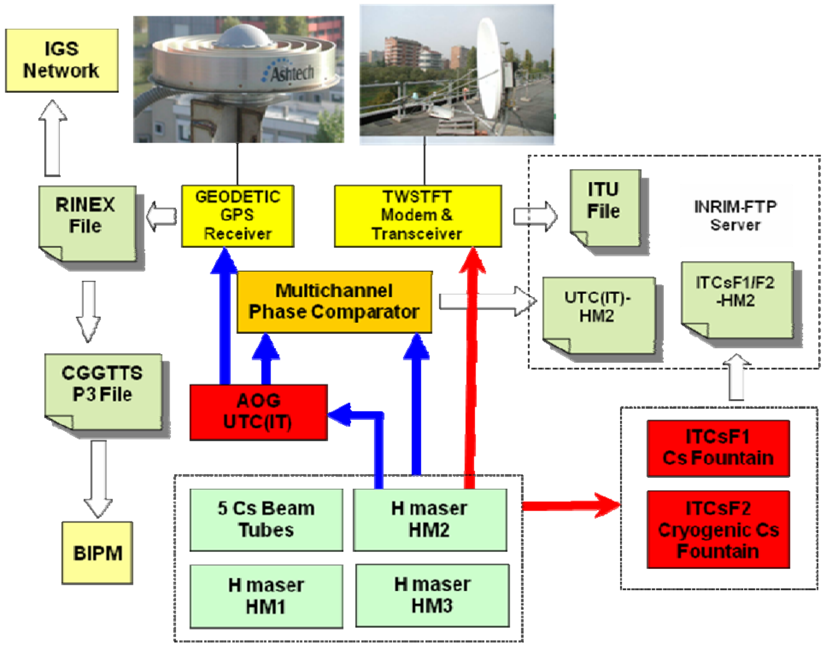

Figure 1. Block diagram of the time and frequency transfer facilities at INRIM

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 five Cs beams and three Hydrogen maser, HM1, HM2, and HM3.

Since June 23rd 2006 UTC(IT) has been generated from the HM2 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 the HM2.

INRIM laser cooled Cs fountain ITCsF1

The Cs fountain primary frequency standard IT-CsF1 has provided 10 frequency evaluations of the TAI unit in the 2006-2008 period, as shown in Figure 2. Uncertainty of each run spanned from to 1.0 to $1.8{\cdot}10^{-15}$ (total uncertainty including link to TAI).

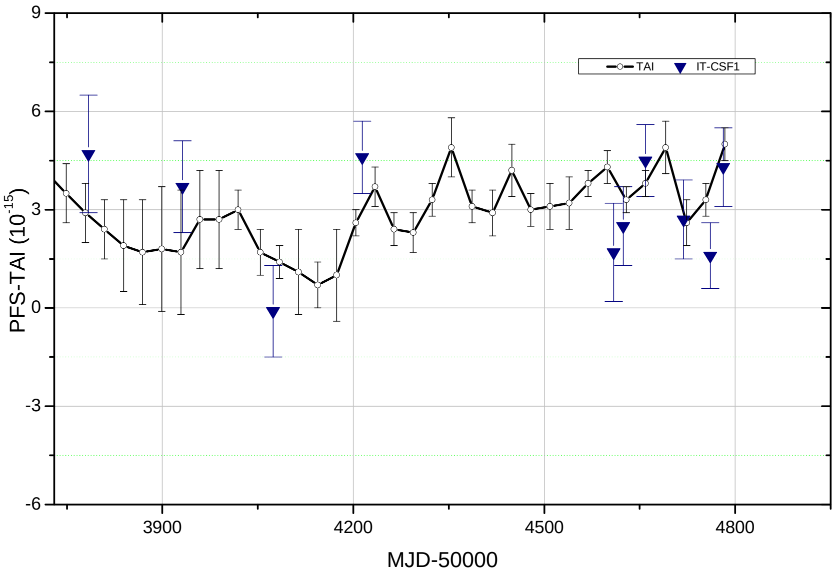

Figure 2. IT-CsF1 TAI frequency evaluations as reported in the BIPM circular T for the period 2006-2008. Triangles: IT-CsF1 frequency. Open circles + line: TAI frequency.

Frequency accuracy in the same period spanned between 5 and $8{\cdot}10^{-16}$. Typical accuracy evaluation for a 2008 run is reported in Table 1

Effect	Shift (10^{-15})	Uncertainty (10^{-15})
2nd order Zeeman Shift	+45.6	0.2
Blackbody Radiation Shift	-28.5	0.3
Gravitational Red Shift	+26.1	0.1
Microwave Leakage Shift	--	0.5
Collisional Shift (Systematic)	-3.0 (*)	0.3
Other shifts	--	0.1
Total	**+43.2**	**0.7**

Table 1. Summary of corrected and uncorrected shift and uncertainty budget for IT-CsF1, period MJD 53774-53794

In the last few years the operation of IT-CsF1 has been improved, with new hardware, a revision of the evaluation procedure and the adoption of new techniques for the data analysis.

Replacement of the master laser for cooling and detection helped to reduce the dead time during an evaluation run. During 2008, average dead time was 15% for a typical 20 days evaluation run.

Blackbody Radiation shift has been re-evaluated and the related uncertainty is now ($3 \cdot 10^{-16}$) larger than before.

The microwave leakage is carefully checked before and after each run. The evaluation is achieved using differential measurements, operating alternately the fountain at standard ($\pi/2$ pulse) and high ($(2n-1)\pi/2$ pulse with n up to 4) microwave power. Using a model which describes the microwave shift with respect to the pulse strength [1], the frequency shift due to the leakage has been evaluated and it is, on average, less than $3 \cdot 10^{-16}$. This uncertainty is expected to be further reduced in the near future when a new low-noise synthesizer, which has been already installed on IT-CsF2, will be used for IT-CsF1.

The frequency shift due to the cold collisions is evaluated using differential measurements, operating alternately the fountain at low and high density regimes and extrapolating the frequency to the zero-density condition. When the IT-CsF1 fountain operates in standard conditions, (MOT capture followed by Doppler molasses expansion) the cold collision shift is linearly dependent by the density with a negative coefficient. This coefficient, which is used to extrapolate the frequency to the zero-density condition, is usually evaluated with an uncertainty which is comparable with its value. Then, there is a non-negligible probability that a measurement of the coefficient could have a positive value, which is actually consinstent with the theory prediction. A new data analysis procedure, which uses the Bayes inference to take into account the information provided by the theory together with the measurement outcome has been developed [2], and a reduction of the uncertainty related to the frequency extrapolation to zero-density has been demonstrated [3].

The uncertainty due to the fountain dead time has been evaluated using a recent model reported in [4]

INRIM laser cooled 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 to 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. In Figure 3 the temperature of the Ramsey interaction region during one week of operation is reported.

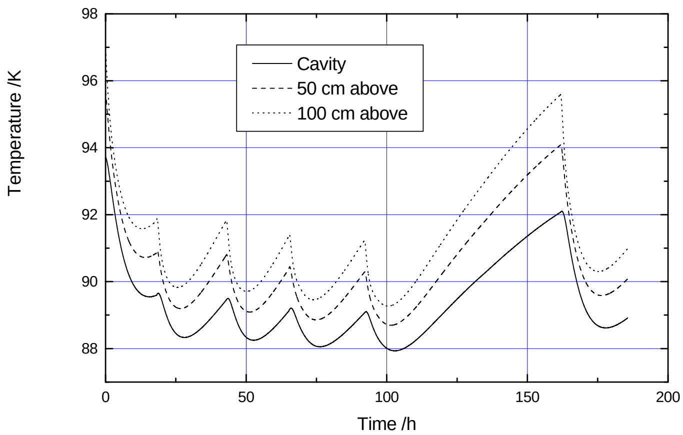

Figure 3. Time record of F2 interaction region temperatures

Up to now we have characterized the most important frequency biases and we haven't observed unexpected behaviour. More measurements are however required to accomplish a full accuracy evaluation. In Figure 4 a plot of the Ramsey fringes of F2 is reported.

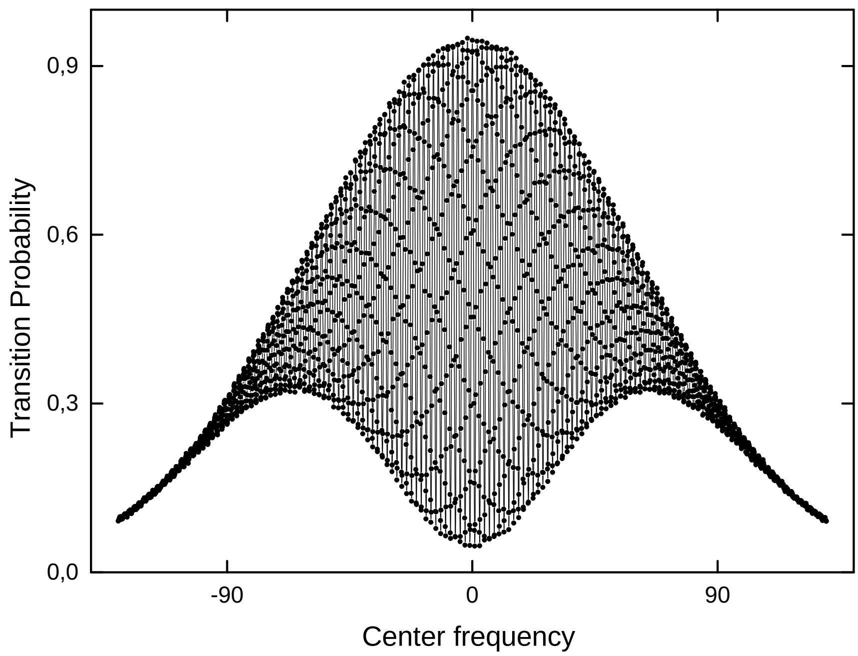

Figure 4. Ramsey fringe pattern is shown for a toss height of 1m. The corresponding Ramsey time is 550 ms yielding a linewidth of 0.9 Hz.

A preliminary accuracy evaluation of the standard is started and we hope to report the first data to BIPM by the end of the year [5].

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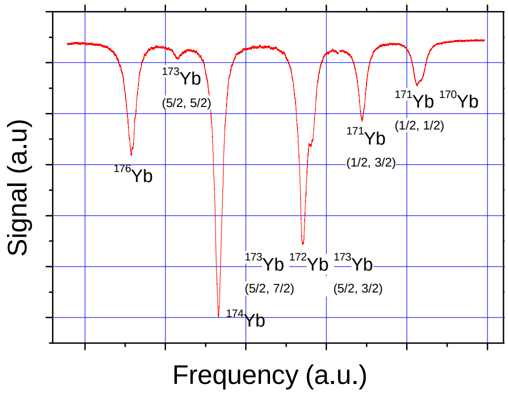
INRIM laser cooled lattice Yb clock

INRIM has started a research activity toward the realization of an optical lattice Yb clock. The blue (399 nm) and green (556 nm) sources required to trap and cool the atoms have been realized, and the blue MOT was observed.

Work is in progress toward the realization of green MOT and the successive loading of the atoms into the optical lattice. In parallel we are proceedings toward the realization of a narrow linewidth laser to observe the clock transition.



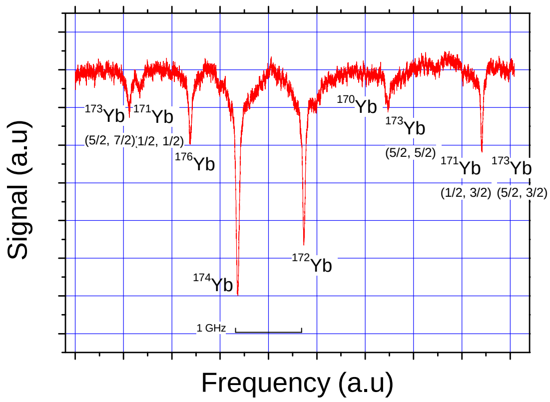


Figure 5. Yb beam spectroscopy on the $^1S_0$-$^1P_1$ and $^1S_0$ $^3P_1$ transitions

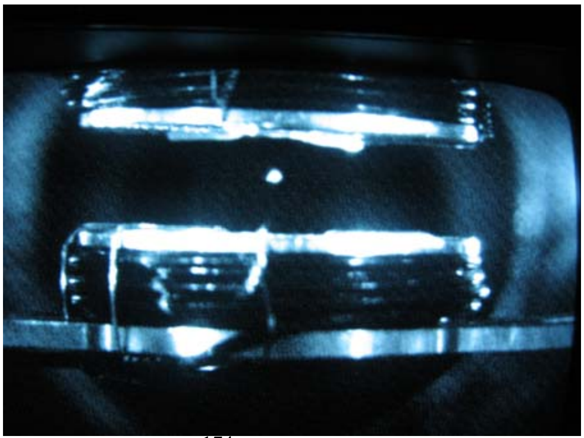


Figure 6. Picture of ^{174}Yb atoms loaded in a blue MOT

INRIM Cell clocks

In the framework of cell clocks development, 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 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 microwave signal observed via a high Q microwave cavity at the end of the second microwave pulse. The POP operation is based on the idea to separate in time pumping, interrogation and detection phases so that the clock transition is observed without any applied laser. This technique avoids then the noise conversion from the laser to the clock signal, also the light shift, which mainly impairs the medium term stability of vapor cell clocks, is greatly reduced.

The short-term stability of the prototype expressed as Allan deviation has been measured and it is 1.2×10^{-12} at 1 s, a value limited by the Dick effect (7×10^{-13}) and by the thermal noise. A frequency drift of 6×10^{-14}/day experimentally correlated to the environmental parameters has been removed to the raw data. In the medium and long term no flicker floor has been observed until 100000 s reaching the value of 3×10^{-15}, and highlighting the absence of any noise contribution coming from either the laser or the electronics.

This stability is among the best ever reported by a vapor cell rubidium frequency standard and makes the POP frequency standard extremely attractive in those fields where good short and medium term frequency stability, reliability and simple working operation are required, such as space applications.

With the goal of improving these results, in collaboration with LTF-University of Neuchatel, the possibility to detect the clock transition in the optical domain has been considered. The optical detection may lead in effect to some advantages with respect to the microwave detection, such as a lower or negligible cavity pulling, a lower operation temperature (which implies a lower spin exchange contribution) and a higher signal-to-noise ratio.

Moreover, we have experimentally demonstrated a new pumping scheme (applicable to both microwave and optical detection) able to increase the number of atoms making the clock transition. This technique consists of a suitable sequence of laser and microwave pulses that pump most of the ground state atoms in one of the clock levels. The possibility of increasing in this way the clock signal of a factor of three has been demonstrated.

All these features may lead to a better frequency stability performance than that previously reached.

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

The Italian Time Scale UTC(IT) is based on five 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 7.

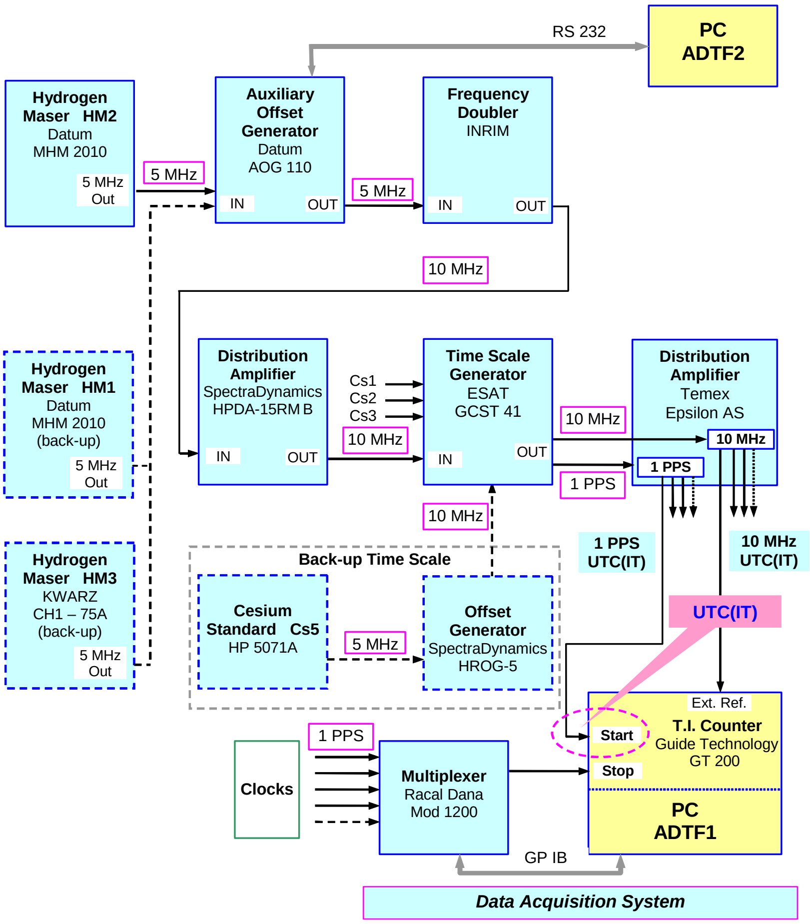


Figure 7. UTC(IT) time scale generation chain

The behaviour of UTC(IT) versus UTC from April 2006 to March 2009, as obtained from BIPM Circulars T, is reported in Figure 8.

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

April 2006 – March 2007	7 ns	(1σ = 18 ns)
April 2007 – March 2008	14 ns	(1σ = 19 ns)

April 2008 – March 2009 19 ns ($1\sigma = 10$ ns)

While the corresponding frequency standard deviations over 5 days are:

April 2006 – March 2007	$\sigma = 1{,}4 \cdot 10^{-14}$
April 2007 – March 2008	$\sigma = 0{,}7 \cdot 10^{-14}$
April 2008 – March 2009	$\sigma = 0{,}6 \cdot 10^{-14}$)

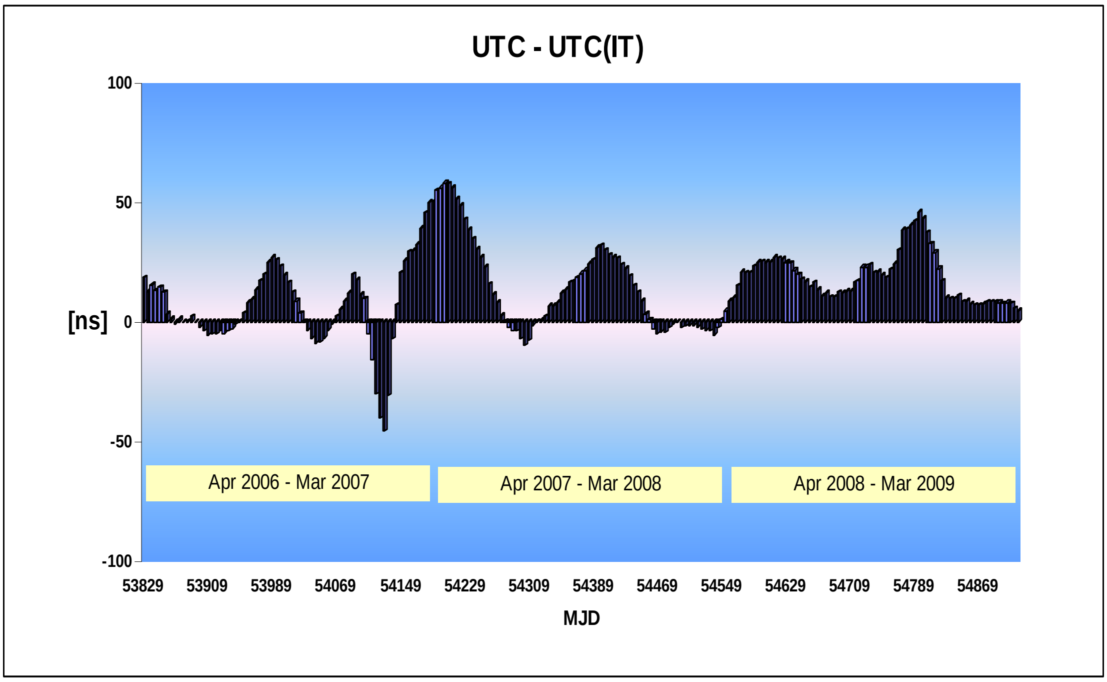


Figure 8. UTC(IT) vs. UTC (April 2006 – March 2009) via BIPM Circulars T

The maximum time deviation of UTC(IT) versus UTC, in the same period, has been maintained within -46 ns and +58 ns, with a mean value of 13 ns and a standard deviation of 17 ns (1 σ).

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 (Two Way Satellite Time and Frequency Transfer) over continental and Intercontinental baselines.

PPP is currently showing good performances for frequency transfer, but not the same for time transfer applications mainly due to the delays introduced by the receiver and the antenna. In September 2007 a differential calibration of INRIM Ashtech ZXII-3T has been performed by means of an absolutely calibrated receiver provided by BIPM, in the frame of its international calibration campaigns, with an associated uncertainty of 5 ns.

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 is 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 is involved in such a project with the metrological characterization of atomic clocks onboard GIOVE A and GIOVE B experimental satellites, and hosts and characterize the reference station connected to an Active Hydrogen Maser and used as the reference station.

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 9 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.

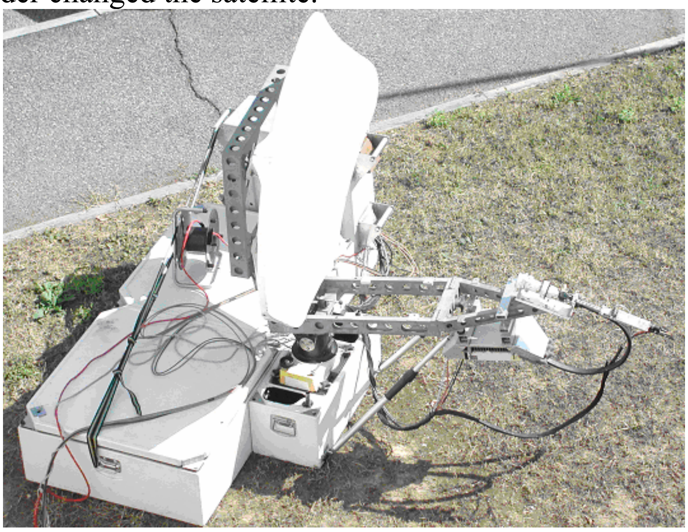


Figure 9. Transportable TWSTFT station

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.

Time scale, algorithm, and 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.

Figure 10 illustrates the importance of clocks, measurement systems, and reference time scales for achieving the best level of accuracy in determining the user position. In addition a time dissemination service is also added maintaining the navigation system reference time closely connected to the international time reference the Universal Time Coordinated.

Since 1999 INRIM has been involved in all the different aspects of timing in Galileo and particularly in these last years four main projects are in progress: the contribution to the GIOVE Mission, to the Precise Time Facility, to the Time Service Provider, and to the ESA Advanced Integrity Algorithms.

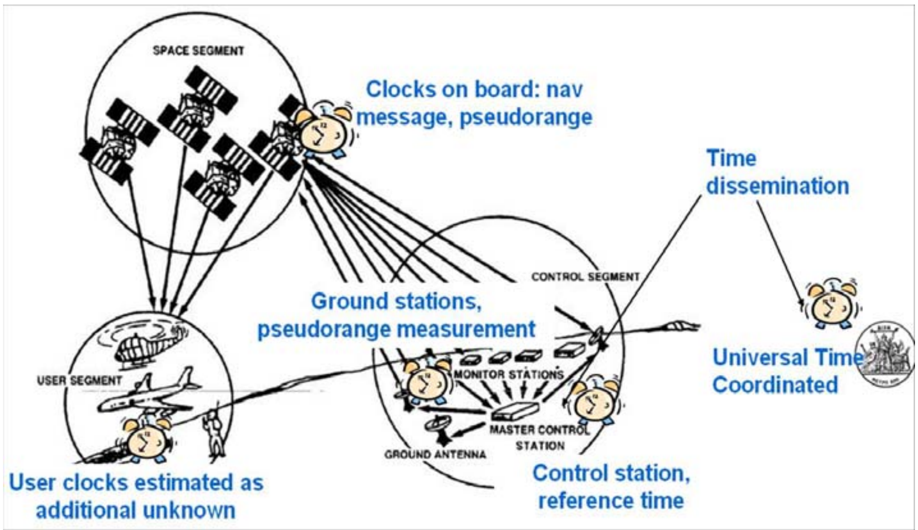


Figure 10. in the space and ground segments of a navigation system as well as in the connection to the metrological community, clocks, time scales, and time measures play a fundamental role

Since 2006 an experimental phase called GIOVE Mission has been launched supported by ESA. INRIM contributes hosting a Galileo prototype receiver connected to a reference clock (Figure 11), and analyzing the data coming from the first experimental Galileo satellites in order to characterize the on board clocks.

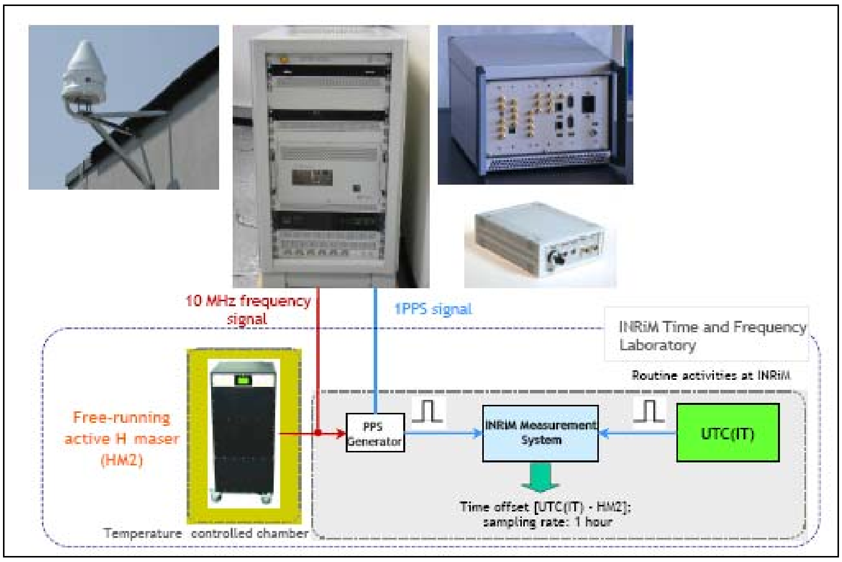


Figure 11. the prototype Galileo receiver hosted at INRIM and connected to the Italian reference time scale

Working on the received satellite signals it has been possible to estimate the noise of the Galileo overall measurement system (Orbit Determination and Time Synchronisation ODTS), which is at the level of the state of the art time transfer systems.

The analysis of the onboard clocks has allowed the understanding of the clock behaviour in space and the development of new statistical tools inspired by the space situation and of interest also for the metrological timekeeping. For example in Figure 12 the Dynamic Allan Deviation extend the classical concept of Allan deviation estimating the noise of a clock as a function of the observation interval, to the case of non stationary behaviour adding a third axis, the epoch, representing the evolution in time of the Allan deviation and hence of the clock instability.

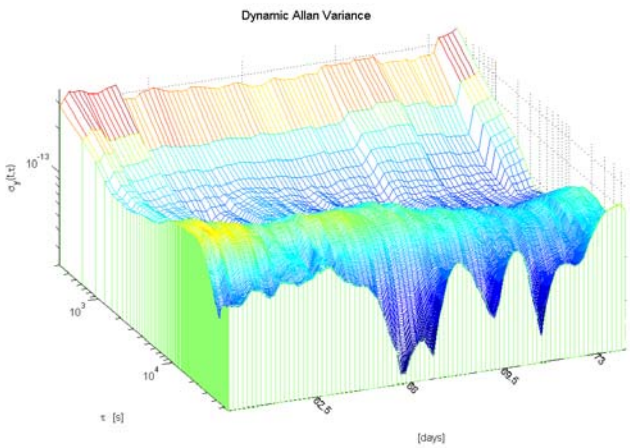


Figure 12. The Dynamic Allan Deviation extend the classical 2 dimensional analysis to a time variant system

In addition INRIM is involved in the development of the final Galileo timing system by designing the time scale algorithm of one of the Galileo ground time laboratories named Precise Timing Facility.

INRIM contributes also to a consortium of different industries and UTC(k) laboratories currently developing the prototype of the Galileo Time Service Provider, supported by the European Union, with the aim to provide to the Galileo system the necessary corrections to maintain the Galileo system time in agreement with the international time reference UTC.

Concerning the development of time scale algorithms, the group is working in collaboration with the BIPM, the Politecnico di Torino, University of Turin and Perugia.

INRIM chairs the WG on TAI and also the Sub-Working Group of the CCTF on "Algorithms" (http://www.bipm.org/en/committees/cc/cctf/working_groups.html) and in this frame the V Symposium on Time Scale Algorithm has been organized in 2008 in collaboration with BIPM, USNO, and ROA.

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