REPORT TO THE 17TH SESSION OF CCTF

ISTITUTO NAZIONALE DI RICERCA METROLOGICA I.N.RI.M

ITALY

Introduction

The Istituto Elettrotecnico Nazionale "G. Ferraris" has now become Istituto Nazionale di Ricerca Metrologica INRIM, jointly with the former Istituto Metrologico "G. Colonnetti".

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

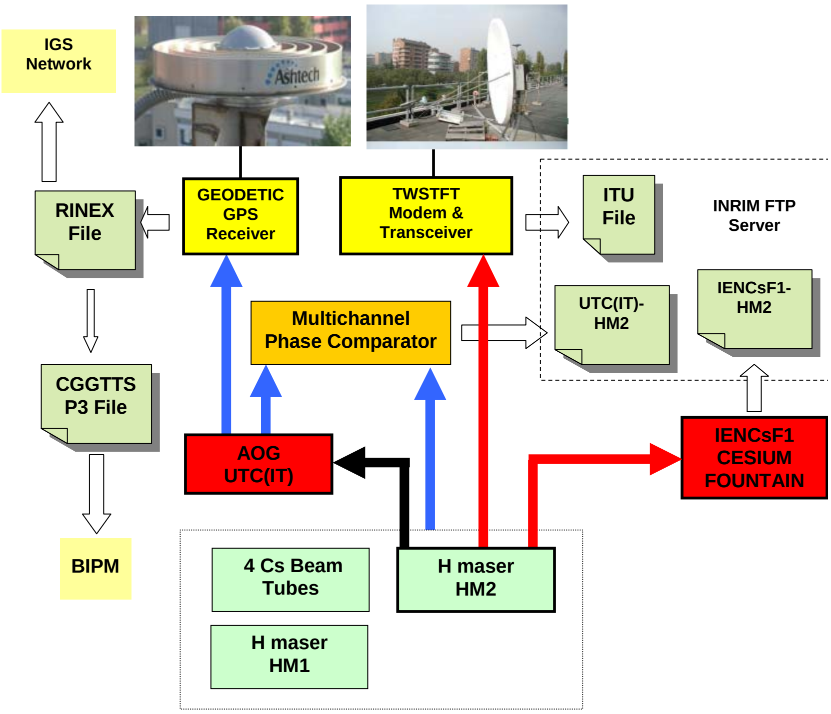

Figure 1. Block diagram of the time scale generation and of the time and frequency transfer facilities at INRIM

As shown in the picture, INRIM disposes of a primary atomic frequency standard, the laser cooled Cs fountain IEN-CsF1 and has an ensemble of commercial atomic clocks composed of five Cs beams and two hydrogen maser, HM1 and HM2.

Until June 23rd 2006 (52909 Modified Julian Date) the Italian time scale UTC(IT) has been generated from one of the Cs beam clocks, while since this date UTC(IT) is generated starting from the hydrogen maser HM2.

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 IENCsF1

The Cs fountain IENCs-F1 has been continuously operated as primary frequency standard and provided up to now ten TAI evaluations, with improved accuracy from 30 to 6 parts in 10^{16} and total uncertainty ranging from 40 to 13 parts in 10^{16} , including the uncertainty contributions from the frequency transfer methods, the statistical flywheel noise and the measurements dead time.

In Figure 2 we report a graph of IEN-CsF1 contributions to TAI, while in Table 1 is shown the present accuracy budget of a typical TAI evaluation run.

Effect	**Shift ($\times 10^{-15}$)**	**Uncertainty ($\times 10^{-15}$)**
Magnetic field	+45.9	0.1
Blackbody Radiation	-29.4	0.1
Gravitational field	+26.4	0.1
Microwave	--	0.4
Atomic density (Systematic)	-2.6 (*)	0.3
Background gas		0.1
Light shift		0.1
Statistics (including zero density extrapolation)	--	0.6
Total	+40.3	0.8

Table1. Summary of corrected and uncorrected shifts and uncertainty budget for IEN-CsF1, period MJD 53774-53794.

(*) Average value.

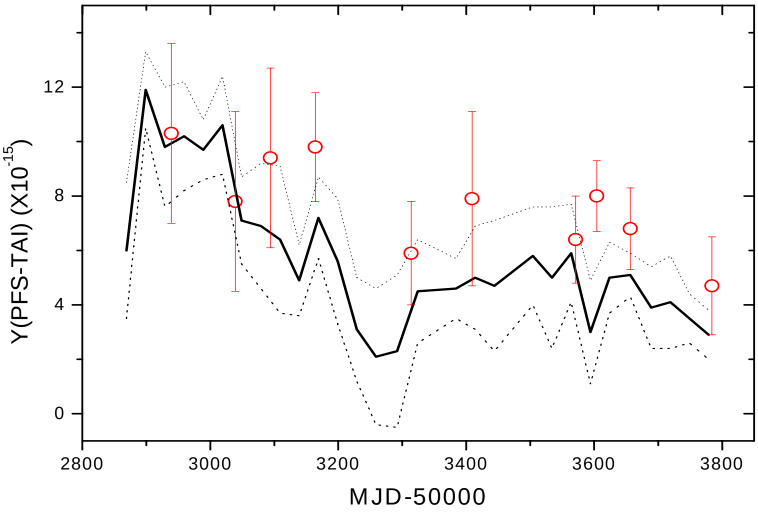

Figure 2. IEN-CsF1 TAI frequency evaluations since 2003 (MJD 52800 = 10/06/2003) reported on BIPM circulars T. Circles: IEN-CsF1 evaluations. Solid line: TAI frequency. Dot lines: upper and lower TAI uncertainty (1σ).

The hydrogen maser HM2 has reached a steady state regime and it now exhibits very good performances. In Figure 3 we show the Allan deviation of the IENCs-F1 fountain when operated with a BVA quartz phase locked on the HM2 maser. In the short term, we observe a frequency instability of 3×10^{-13} $\tau^{-1/2}$, and the white frequency noise still dominates at about 10^{6} second (~4×10^{-16} Allan deviation). We deduce the flicker floor to be $<3\times10^{-16}$ and the random walk noise component $<2\times10^{-19}$ $\tau^{1/2}$.

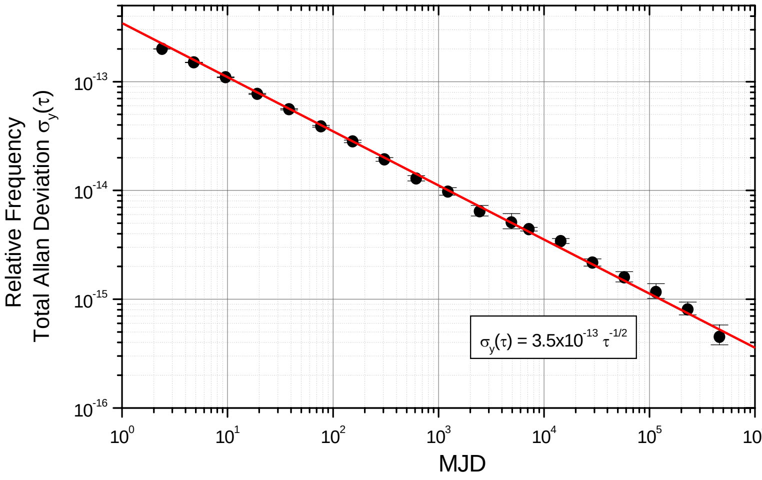

Figure 3. IEN-CsF1 vs IEN-HM2 relative frequency instability

The laboratory has taken a great advantages of the HM2 noise properties, especially while managing the dead time in fountain measurements and while using the maser as transfer oscillator in the remote comparisons.

At the end of 2004 the first multi-fountain synchronized remote comparison has been carried out, comparing IEN-CsF1 with two other Cs fountains at SYRTE and at NPL, using GPS-P3, GPS carrier phase and TWSTFT transfer methods . The comparison involved also PTB and NIST time scales and transfer facilities, as well as BIPM and Bern University respectively for GPS-P3 and GPS Carrier Phase data analysis.

The three fountains resulted to be all in agreement at the 4×10^{-15}, while the comparison offered also the possibility to investigate the ultimate performances of the present satellite transfer methods, and in Figure 4 the related results are reported. It is shown a frequency instability of $\sim1\times10^{-14}\tau^{-1}$ (τ expressed in days) until 5 days (6×10^{-16}). This has suggested a previous over-estimation of the comparison uncertainty contribution from the links (evaluated in $3\times10^{-14}\tau^{-1}$).

In the figure we present the Allan deviation of the double differences $(HM_1 - HM_2)^{TW} - (HM_1 - HM_2)^{GPSCP}$ between the pairs NPL-INRIM, SYRTE-INRIM, NPL-SYRTE, where the index 1,2 refer to the masers in the lab 1 or 2, while the labels TW and GPSCP refer to the Two Way Satellite Time and Frequency Transfer Technique and to the GPS carrier phase method.

The double difference is a reasonable observable as the hydrogen masers noise is strongly rejected allowing the measurement of the transfer method instabilities.

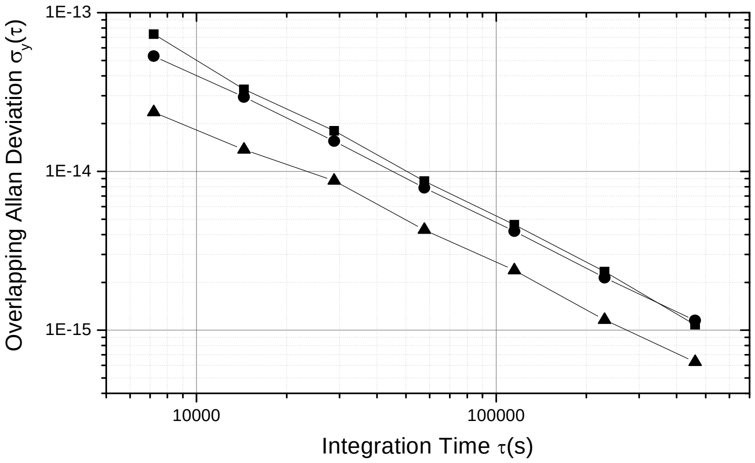

Figure 4. Allan deviations of double frequency differences in remote masers frequency comparison (see text), for the masers pairs NPL-INRIM (Squares), SYRTE-INRIM (Circles), NPL-SYRTE (Triangles), using TWSTFT and GPS-CP techniques.

During 2006, INRIM has re-evaluated the location of its laboratories over the Geoid, to improve the uncertainty of the gravitational red-shift for the atomic clocks and especially for IENCsF1.

IEN-CsF1 is located at (242.52±0.03) m over the Geoid, corresponding to a relative correction of $2.643(1)\cdot10^{-14}$. This orthometric height is obtained by accurate evaluation of the geodetic height of the fountain with respect to the ellipsoid WGS84 and the evaluation of the Geoid undulation with respect to INRIM position. The INRIM geodetic height is available at millimeter level thanks to the participation to the network IGS (International Global Navigation Satellite System Service) since the begin of 2003. By the use of geodetic GPS receivers, this network allows to know the receivers antenna position with respect to the ellipsoid WGS84. The undulation in geodesy identifies the difference between the geodetic height respect to an ellipsoid and the orthometric height referred to the Geoid which by convention has the same gravity potential than over the Ellipsoid surface. The undulation determination at INRIM has been determined with respect to WGS84 ellipsoid, using three different methods. First, the undulation was evaluated from the global geodetic model EGM96 (1 m accuracy), then recently using spirit leveling techniques (orthometric height markers from the Italian Geographical Military Institute, IGM and local geometric leveling from the markers to the clock laboratory, 2 cm accuracy) and third, an evaluation has been carried out using an improved release of the Italian quasi-geoid model ITALGEO99 (4 cm accuracy). All the three undulation value are in agreement and the weighted average has been chosen to evaluate undulation at INRIM.

The orthometric height uncertainty (3 cm) is therefore better than the Geoid reference potential value that presently is limited to 10 m^2s^{-2} equivalent to 10 cm in terms of location and 1×10^{-17} in terms of relative frequency shift. Therefore this is the present uncertainty for the gravitational correction in IENCsF1, as reported in Table 1.

We may point out that a determination of the gravitational correction beyond the 1×10^{-17} accuracy level is a challenge, due to the evaluation and to the stability of the Geoid reference.

During 2005 and 2006 a relevant attention has been paid to the microwave related shift on the fountain, developing theoretical models and implementing specific tests that are now routinely performed while calibrating TAI.

We think that microwave related problems are still a challenge in fountains operation at 10^{-16} level and that these effects have to be continuously monitored they are quite unstable in time.

Another important aspect in absolute frequency measurements using the fountain is the dead time occurring in the run. The uncertainty contribution due to dead time has been evaluated using mathematical models and it deeply involves the local oscillator noise figure. At INRIM, the instability of HM2 allowed a relative uncertainty contribution $<4\times10^{-16}$ even for 40% of dead time in the measurement. This relevant result has increased the reliability of TAI evaluations and has given the possibility to perform some additional tests even during a measurement run without a degradation in the final uncertainty.

Further studies in this domain should be welcomed to obtain more sophisticated and reliable models. This should allow to decrease the dead time uncertainty contribution increasing the performances in absolute frequency measurements, including TAI calibration.

Cell clocks

In the framework of cell clocks development, a laboratory prototype of pulsed optically pumped (POP) rubidium frequency standard has been implemented. The POP operation is based on the idea to separate in time the pumping, the interrogation and the 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 and 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 overlapping Allan and Thêo deviations has been measured and it is shown in Figure 5: we found 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.

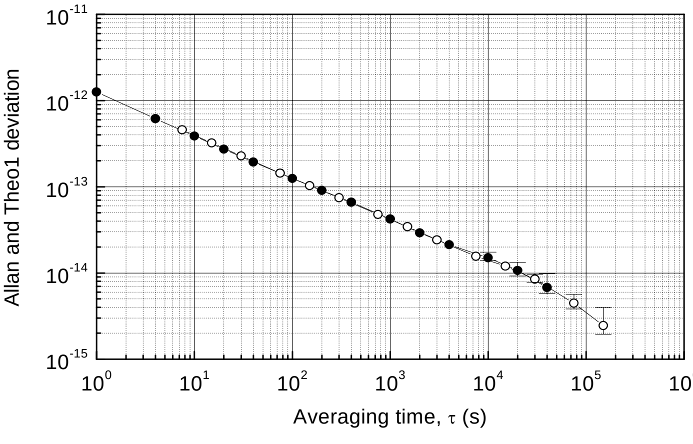

Figure 5. POP clock frequency instability. Black circle: Allan deviation, open circle: Theo deviation.

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.

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

The generation of the National Time Scale UTC(IT), known as UTC(IEN) previous to February 2006, has been realized using five commercial atomic beam clocks and two active hydrogen masers, the same devices contributing also to TAI, and generated by the steered output of a master cesium HP 5071A clock using its internal microstepper. Since November 2005, an external microstepper with higher resolution was used instead of the internal one, and the master cesium clock was installed into a more strictly temperature controlled room (±0,1°C). More frequent evaluation and steering of the frequency offset of the clock has also been applied since November 2005. In Figure 6 is represented a view of the two INRIM temperature controlled rooms and the master cesium clock inside one of them.

Figure 6– Temperature controlled room for INRIM master clock up to June 2006

The time deviations averaged over one year of UTC(IT), versus the international time scale UTC (Circular T), were found of 0,01 μs (1σ = 0,04 μs) in 2004, of 0,03 μs (1σ = 0,06 μs) in 2005 and of 0,01µs (1σ = 0,01 µs) in 2006 and the corresponding average frequencies were equal to 0,1·10^{-14} (1σ = 1,9·10^{-14}), 0,1·10^{-14} (1σ = 1,8·10^{-14}) and 0,1·10^{-14} (1σ = 1,1·10^{-14}) respectively.

In the same period, the maximum time deviation of UTC(IT) versus UTC has been maintained within a minimum of -118 ns and a maximum of +86 ns. After the changes in the configuration of the time scale generation implemented in November 2005 the behaviour of UTC(IT) has been improved. In Figure 8 the time offset of the national time scale UTC(IT) versus UTC from January 2005 to May 2006 is represented: it clearly shows that, starting from November 2005, thanks to the changes introduced in the time scale generation, the maximum time deviation of UTC(IT) vs. UTC has been maintained within narrower limits (±30 ns).

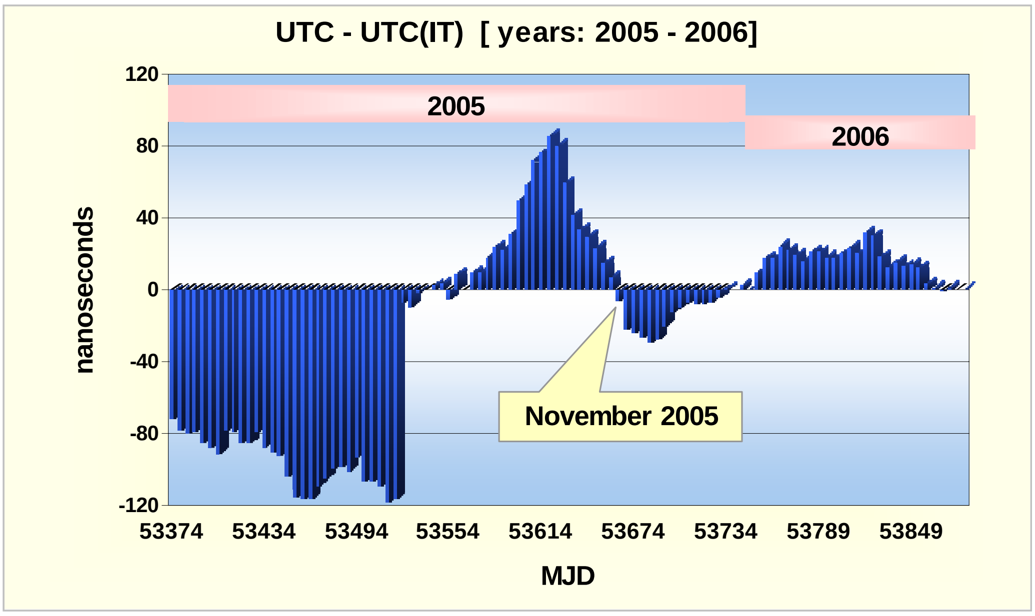

Figure 7– UTC – UTC(IT) plot for the period from January 2005 to May 2006

At the beginning of 2006, some operational tests have been performed aiming to generate UTC(IT) by means of a Datum MHM 2010 active Hydrogen maser, to improve the short and medium term stability of the time scale itself. After preliminary evaluations on an experimental time scale generated with this architecture and compared with some International time scales, the new time scale generation scheme has been implemented in June 2006 and it is operating with an improved short-medium term stability.

INRIM has sent regularly to BIPM the GPS-P3 synchronization data supplied by an “Ashtech Z-XII 3T - Metronome” geodetic GPS receiver, obtained from the output RINEX files, contributing to a TAI computation performed by BIPM using this kind of data. The RINEX files, supplied by the same receiver, using UTC(IT) as reference, have been sent regularly to the GeoDAF data centre of the Italian Space Agency (ASI), to be used by the EUREF Permanent Network

(EPN), and subsequently by the International GPS Service (IGS). In Figure 8 is reported a view of the GPS Laboratory and of a receiving antenna.

Figure 8– INRIM GPS Laboratory with climate chamber and outdoor receiving antenna

INRIM has regularly contributed to the “NRTD - Near Real Time Data” and to the “RRTD - Real Real Time Data ” pilot projects, developed and operated by the IGS Real Time Working Group. With this project, the real time GPS data provided by the receivers is routed to the Natural Resources of Canada (NRCan) server. “Near real-time” (2 hour latency – International network of about 40 stations) and “real real-time” (5 minute latency – North America regional network) estimates of the UTC(IT) time scale versus a VRC (Virtual Reference Clock), are regular products supplied by the IGS Real Time Project.

By means of the same Ashtech Z-XII 3T GPS receiver, in collaboration with the Geodetic Survey Division of NRC, and with the collaboration of nine international timing laboratories, an experimental assessment of the Precise Point Positioning (PPP) technique in time transfer was successfully carried out in 2004–2005. The results obtained indicate the PPP as a promising additional synchronization technique if compared, for instance, to the TWSTFT. PPP, autonomously, provides recovery of IGS combined clock solution at sub nanosecond level, and comparing the results with the two-way technique, the noise level of PPP is potentially lower than TWSTFT over European baselines and probably on transatlantic baselines.

INRIM has been regularly participating in the INTELSAT TWSTFT network, following the full schedule and using, since June 2005, the new TWSTFT station (IEN02) made of an “Anacom Anasat SE ku” transceiver and a “SATRE TWSTFT 079 Dual Receiver Channel” modem (see Figure 9).

Figure 9 – Front view of the SATRE Modem used at INRIM

In November 2005, INRIM took part in a calibration campaign aiming to measure the differential delay both of the new INRIM operative TWSTFT earth station and of the old one (IEN01 used as back-up), versus other five international laboratories: NPL (UK), OP (F), PTB (D), SP (SE) and VSL (NL). This activity, performed under the responsibility of the Johanneum Research - Austria, has been carried out by means of a co-location of the transportable reference station TUG01 and allowed the calibration of the UTC(k) labs links to TAI with uncertainties at level of 1 nanosecond.

In July 2005, INRIM participated in the Euromet comparison TF TI-K1 for time interval calibrations, consisting in the measurement of the delays of some reference cables mounted inside the BEV01 travelling standard supplied by BEV – Austria. This calibration exercise involved 27 European metrological laboratories and is scheduled to end by mid 2006.

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.ien.it, ntp2.ien.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, have been approved and published since 2005 in the KCDB (Key Comparisons Data Base) of BIPM.

Algorithms and mathematical methods in metrology and applications to Galileo GNSS

The Time and Frequency Dept is deeply involved in European research projects in collaboration with different space industries and research institutes devoted to the development of the European Global Satellite Navigation System "Galileo".

In the year 2004/2005 in the frame of the first experimental phase in the Galileo project supported by the European Space Agency named Galileo System Test Bed (GSTB) V1, INRIM in collaboration with Alenia Spazio realized a timing station able to generate in real time for about one year an experimental time scale, the Experimental Galileo System Time (E-GST). In addition, a set of experiments dedicated to the assessment of metrological features of E-GST were carried out showing that the robustness of the algorithm versus anomalies is still the most challenging research activity.

The stability and accuracy performances of the resulting E-GST versus the international TAI/UTC time scales are reported in the Figure 10, showing that the GSTB V1 target have been almost completely achieved, despite a number of difficulties encountered, and that one-year behaviour of E-GST is comparable to that of the best time scales in the world.

GALILEO
GSTB-V1

	Galileo target	GSTB target	GSTB Achieved (9 months on-line)
Accuracy |TAI - E-GST|	<50 ns (95%) over any yearly interval	< 1 µs	71 ns (95%)
Stability @1day |TAI - E-GST| (2 σ)	$< 5.5 \cdot 10^{-14}$	$< 5.5 \cdot 10^{-14}$	$2.9 \cdot 10^{-14}$ extrapolated from BIPM 5 day data
Uncertainty on the prediction |TAI - E-GST|	28 ns (2 σ)	33 ns (2 σ)	40 ns (2 σ)

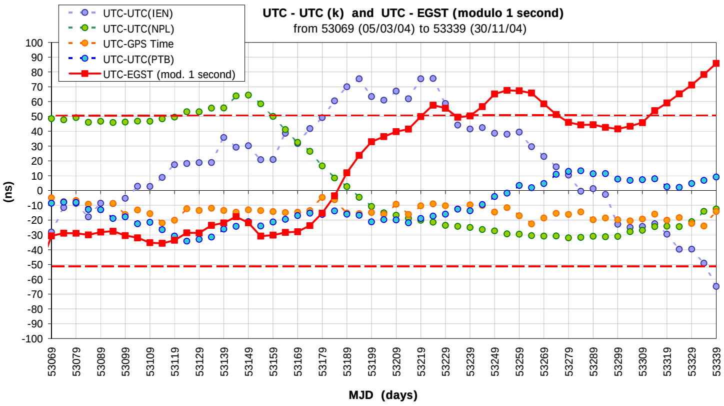

Figure 10 - Stability and accuracy performances reached by the Experimental Galileo System Time

Currently the INRIM staff is involved in three European project related to the development of the Galileo system started in 2005 and continuing till 2008, namely:

1. Galileo System Test Bed (GSTB) V2, supported by ESA, INRIM role is the metrological characterization of the on-board clocks plus the operation and characterisation of one of the first Galileo/GPS geodetic receiver referenced to the INRIM H maser
2. Galileo Phase CDE1, supported by ESA, INRIM contributes to the development of the Galileo time laboratory named Precise Time Facility by designing the Galileo time scale algorithm
3. Galileo Time Service Provider Prototype, supported by the European Union, INRIM contributes as UTC(k) laboratory providing clock and synchronisation data as well as supporting the algorithm design

In collaboration with the *Politecnico di Torino, University of Turin and Perugia*, the development of statistical technique apt to modelize the atomic clock signal and to estimate the clock noise are investigated.

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 is under organisation in collaboration with BIPM, USNO, and ROA and foreseen for March 2008 at the Real Observatorio de la Armada.

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