REPORT TO THE 16TH SESSION OF CCTF

ISTITUTO ELETTROTECNICO NAZIONALE “G.FERRARIS”

ITALY

1 Atomic Frequency Standard

Cesium fountain

The cesium fountain primary frequency standard denominated IEN CsF1 was completed in all its parts and its accuracy was obtained as a results of theoretical calculations and experimental results. In 2003 IEN started reporting the fountain data to BIPM for TAI calibration.
The accuracy of the IEN-CsF1 is 1.6 $x10^{-15}$ as reported in the following table:

Effect	Correction ($x10^{-15}$)	Uncertainty ($x10^{-15}$)
2nd Zeeman Shift	-47.09	0.04
Blackbody Radiation	+30.10	0.07
Atomic Density	+3	1.2
Gravitational Potential	-26.4	0.1
Others Effects	-	< 1
Total	-40.4	1.6

The fountain frequency stability is measured to be $3x10^{-13}\tau^{-1/2}$ versus an Hydrogen Maser, limited on the short term by the local oscillator noise (a high quality BVA quartz oscillator), as reported in figure 1.

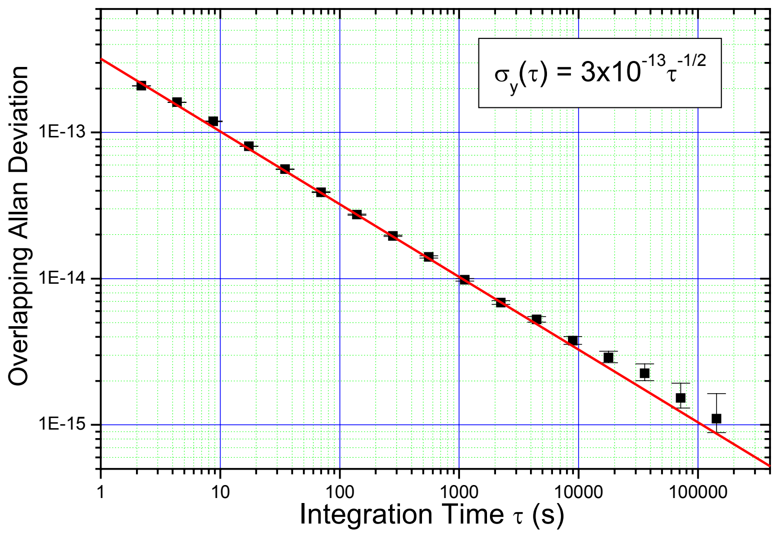

Figure 1 – IEN-CsF1 frequency stability

Theoretical and experimental work towards the measurement of the Blackbody radiation shift in Cs primary frequency standards was carried on.

Unchanged the theoretical model the Blackbody rely on, the new data available in literature on Cs dipole moments and frequencies of the optical transitions give a new value for the black body shift:

$$\frac{\Delta \nu}{\nu_0} = -(1.49 \pm .07) \times 10^{-14} \left(\frac{T}{300}\right)^4 \left[1 + 0.014\left(\frac{T}{300}\right)^2\right]$$

The experimental value obtained changing the radiation temperature in our fountain gives for the leading order coefficient $-(1.43 \pm 0.11) \times 10^{-14}$ in quite good agreement with the theory (figure 2). A more detailed discussion is reported in appendix I.

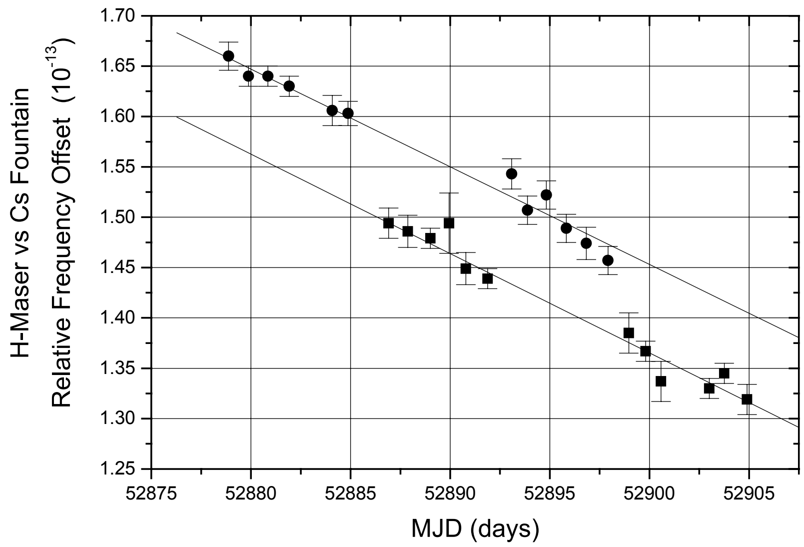

Figure 2 - Relative frequency difference between the fountain and the H-Maser. ● T=328 K, ■ T=358 K, ─linear fit.

Cell clocks

Funded by ESA, in the framework of the development of new technologies for the European navigation system Galileo, a prototype of a CPT maser clock was developed. The idea of the CPT maser starts from the consideration that, with this approach, it is possible to better control several effects that up to now impaired the performances of laser pumped rubidium frequency standards.

The results obtained are encouraging since it appears that most of the noise originating from the laser is reduced below the white and thermal noise level for measurement times up to 5000 s. The dominant noise/drift effect is quite probably due to temperature fluctuations (figure 3).

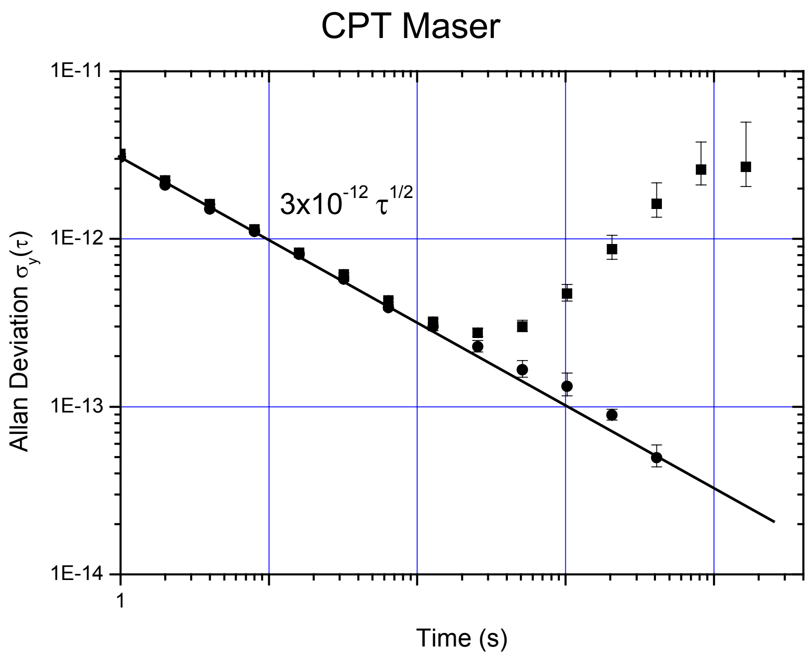

Figure 3 - Measured Allan Standard deviation: (square) full data; (circle) drift removed.

New studies started also on the old idea of the pulsed optically pumped vapor cell frequency standard. Several new features of this frequency standard have been theoretically predicted showing promising results in the development of a high stability frequency standard.
Experimental works on this clock is currently carried on at IEN facilities.

Optical frequency standards

The work on optical frequency standards is just started at IEN. We are directing our work to the development of neutral atoms frequency standards and specifically to alkaline-earth or alkaline-earth like atoms (Ca, Sr, Yb).
A new laboratory is dedicated to these new frequency standards and general purpose instrumentation has been acquired like a tunable Titanium sapphire laser and an optical comb generator.

2 Generation of the national time scale UTC(IEN)

During the years 2001 and 2002, two active hydrogen masers by Sigma-Tau were installed at IEN. A new distribution system for the maser frequencies, based on high stability distribution amplifiers, has been installed, serving the Time and Frequency laboratory, the primary frequency standard laboratory and the atomic spectroscopy laboratory.
Four commercial cesium clocks (HP 5071A high performance type) continuously contributed to the generation of the IEN atomic time scale and to TAI. During 2003 the two hydrogen masers started their contribution to the TAI generation too.
The UTC(IEN) time scale was generated by the steered output of a HP 5071A cesium clock. A high accuracy programmable phase microstepper was purchased with the aim of generating UTC(IEN) as the steered output of an hydrogen maser. Preliminary time scale generated with this equipment is currently under evaluation.

The average time difference of the national time scale UTC(IEN) versus the international time scale UTC, was 0,05 μs (σ = 0,03 μs) in 2001, of 0,02 μs (σ = 0,03 μs) in 2002 and of 0.03μs (σ = 0,03 μs) in 2003 amd the corresponding average frequencies were $0{,}2\cdot10^{-14}$ ($\sigma = 1{,}3\cdot10^{-14}$), $-0{,}1\cdot10^{-14}$ ($\sigma = 1{,}8\cdot10^{-14}$) and $0{,}2\cdot10^{-14}$ ($\sigma = 1{,}5\cdot10^{-14}$) respectively. In the years 2001 to 2003, the maximum time deviation of UTC(IEN) versus UTC has been kept well below 100 ns. In the Figure 4 is reported the time offset of the Italian time scale UTC(IEN) versus UTC during 2003.

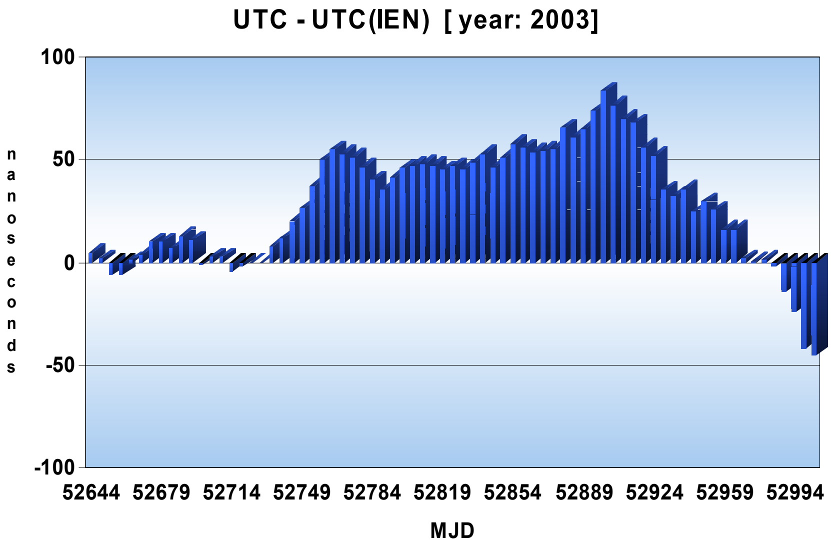

Figure 4. UTC-UTC(IEN) plot during the year 2003

During 2003, IEN sent regularly to BIPM the GPS-P3 synchronization data supplied by an Ashtech ZXII3T Metronome geodetic GPS receiver (driven by the UTC(IEN) frequency) and processed by a dedicated software.
Since December 2003, the hourly and daily RINEX files, supplied by the same receiver, have been regularly sent to the GeoDAF data centre of the Italian Space Agency (ASI - Matera), to be used by the EUREF Permanent Network (EPN), and subsequently by the International GPS Service (IGS).
Another GPS geodetic receiver, namely the Javad Legacy with timing option, has been also operating since July 2003 in the framework of the Galileo System Test Bed V1 (GSTB V1), driven by the H maser generating the time scale (E-GST) for GSTB-V1 experiment. In the Figure 5 a picture the Ashtech and Javad GPS geodetic receives is reported, together with the auxiliary equipments.

Figure 5. The geodetic receiver set-up

The IEN TWSTFT measurement system has been operating since 2001; its operation was completely automated, allowing to perform the intensive measurement schedule agreed 2003.
Starting from 2002 the TWSTFT IEN-PTB link is the primary link for TAI calculation and the link with GPS CV has being kept as backup. For this reason and in the framework of a the GSTB V1 project with ESA, in June 2003 the IEN promoted a high accuracy calibration of this TWSTFT link using a travelling reference station. The calibration was made under a contract with Johanneum Research and the Technische Universitaet Graz, which provided the TWSTFT station and operated it at both IEN and PTB. Calibration accuracy obtained was 1 ns (1σ).

Figure 6. The TUG portable station collocated at IEN during the IEN-PTB link calibration activity

A second TWSTFT station will be ready to operate at IEN during 2004; the TWSTFT signal from TL (Telecommunication Laboratory, Taiwan) was successfully received in January 2004, demonstrating the possibility of a IEN participation to the Europe-Asia TWSTFT link.
Due to the failure of the reference GPS Common View receiver (NBS-31) in 2002, the service was switched to a 3S-Navigation multichannel receiver. A new multichannel receiver (model TTS-2) was purchased in 2003 and at the moment is kept as backup.

The real-time dissemination services of legal time in Italy, on the RAI national broadcasting transmissions (AM and FM) and on the telephone lines have been continued, together with the Network Time Protocol (NTP) service for the clock synchronisation through the Internet network.

The accreditation activity in the frame of the Italian Accreditation Service SIT increased the number of the centres accredited for frequency and/or time interval to a total of 26 by the end of 2003. The traceability to the national time and frequency standard has been provided by means of different synchronization techniques (coded time signals and GPS). The consulting activity to establish the traceability to the national time standard of secondary calibration laboratories has also been continued. Different inter-laboratory comparisons were organized between the IEN and the SIT centres using quartz or rubidium oscillators as travelling standards.
In the frame of the EUROMET Technical Committee for Time and Frequency, IEN has taken part to the Analysis Working Group for the review of the CMCs tables of other European Laboratories; an update of the IEN 2002 CMCs, according to the guidelines of the CCTS working group on the MRA, has also been provided in 2003.
In May 2003, IEN hosted the "Colloquium on UTC time scale", organised by the Special Rapporteur Group of the Working Party 7A of the International Telecommunication Union; the presentation and papers are available in the IEN website (www.ien.it)

3 Algorithms and mathematical methods in metrology and applications to Galileo GNSS

The IEN team 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 particular, IEN is involved in the definition and design of the algorithm of the Galileo System Time, in the design, development, and implementation of an experimental time laboratory for the first phase of the Galileo experimental tests, and in the definition of the role that UTC(k) labs could play inside the Galileo system.

Namely, the project in which IEN is involved are

1) "GALILEOSAT Phase B2 and C0" funded by the European Space Agency, for the design of the Galileo System Time scale

2) "Galileo System Test Bed V1", the first experimental phase of the Galileo system, funded by the European Space Agency, in which the IEN time lab plays the role of experimental Galileo *Precise Timing Station* generating the experimental *Galileo System Time* in collaboration with Alenia Spazio. The aim is an experiment of one year (2004) in which the timing activity planned for the Galileo system are carried out in a real laboratory generating an ensemble time scale based on Cesium clocks and H masers, and steered on TAI with the external collaboration of PTB and NPL.

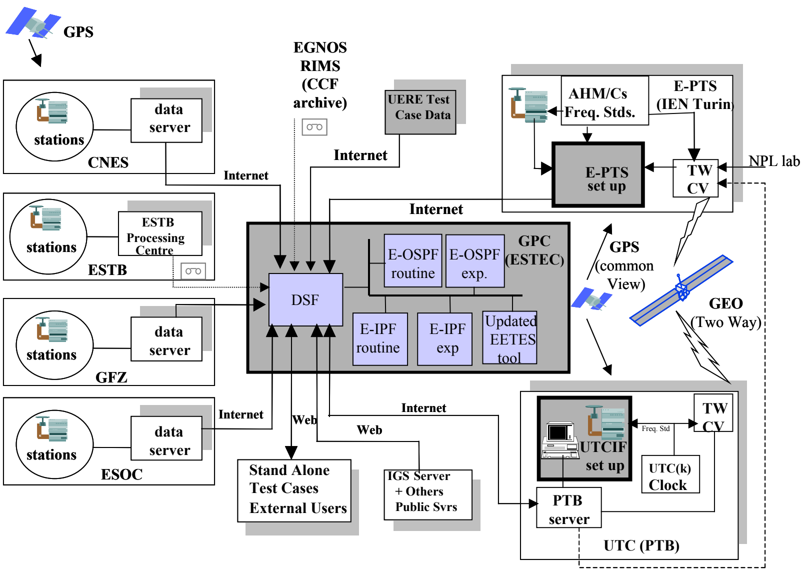

Figure 7. The GSTB V1 core infrastructure (ESA archive)

3) "Galileo Mission Implementation", funded by the VI Framework Program of the EC with the aim of defining the role of the external Time Service Provider, an entity constituted by UTC(k) labs that provides to the Galileo system the information to keep the Galileo System Time in agreement with TAI. The project is coordinated by NPL with the collaboration of IEN and PTB.

In collaboration with the *Politecnico di Milano, University of Turin*, and the *Real Observatorio de la Armada* of San Fernando in Spain, the development of a statistical technique apt to estimate the different sources of noises from the clock comparison measures as well as mathematical modes apt to model the atomic clock are under investigation.
IEN chairs the WG on TAI and also the sub Working group of the CCTF on "Algorithms" (http://www.ien.it/tf/cctf/) and in that frame the IV Symposium on Time Scale Algorithm was organised at the BIPM in March 2002 in collaboration with BIPM and USNO.

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Appendix I

About the Black Body Radiation Shift

The AC stark shift produced by the Black Body Radiation (BBR) is taken into account for Primary frequency standard accuracy since BIPM recommendations of 1996.
The physical law that rules the frequency shift as a function of the environment temperature is very general and derives directly from the Planck and Boltzmann radiation laws:

$$\Delta \nu / \nu_0 = \beta (T/300)^4 \left[1 + \varepsilon (T/300)^2 \right]$$

The above formula at room temperature is a good theoretical approximation up to the 10^{-16} range, the ε term is not discussed here since its contribution is of few units in 10^{-16}.
In the CCTF recommendation of 1996 for the parameter β was given the value:

$\beta = -1.69(4) \times 10^{-14}$

This value origins from the measurements of [Mowat] in agreement with the theoretical calculation of [Feichtner] for the Cs hyperfine differential polarizability, together with the theoretical relation established by [Itano] between the AC stark effect and the BBR shift.
At IEN we have repeated the calculation of Feichtner, using the new physical parameters reported in literature for the Cs dipole moments and the frequencies of the optical transitions involved [Micalizio and references therein].
The result we have obtained is:

$\beta_{IEN-T} = -1.49(7) \times 10^{-14}$

At IEN we have also experimentally tested the above calculation, by changing the radiation temperature of IEN-CsF1 [Levi] following the experimental method firstly reported by [Bauch]. We have obtained the value:

$\beta_{IEN-E} = -1.43(11) \times 10^{-14}$

There is another point that must be highlighted. If we use the most accurate measurement of the DC stark shift in cesium [Simon] to infer the BBR shift coefficient we obtain a value closer to the BIPM recommended one

$\beta = -1.711(3) \times 10^{-14}$

We have not yet found a scientifically proved explanation for this discrepancy; we believe that a possible one can be connected to the presence of an hyperpolarizability term [Pal'chicov] not taken into account in the analysis of the experimental data.

As a first check, the theory developed allowed us also to correctly predict the total polarizability of the ground state as measured in many different experimental works [Amini].

As a second check of our calculation, we have tested that using the old Cs physical parameters we could obtain the old number; being this the case we think that a general discussion should be done on the whole issue of the BBR shift.

We are not claiming that the theory developed is completely correct, since the atomic model we have used can be improved by experts in the field, but surely the old number recommended, and the associated uncertainty, has to be reconsidered in the present framework.

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