TIME AND FREQUENCY ACTIVITIES AT IEN

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Abstract

The Time and Frequency Department of the Istituto Elettrotecnico Nazionale (IEN), as national laboratory for time and frequency metrology in Italy, is charged of the realization and dissemination of the national time and frequency standards and the development of new frequency standards and synchronization techniques.
The present status of these activities and their future developments are reported in the paper.

INTRODUCTION

Time and Frequency Laboratory of IEN has been working in this metrologic field for more than 60 years and is responsible for Italy of the research, realization, and dissemination of the SI unit of time [1]. Since the seventies the realization of the local UTC time scale has been based on a cesium clock ensemble that also contribute to the international time scales TAI and UTC established by BIPM.
The research activity of the Laboratory has traditionally concerned the realization of atomic frequency standards, the frequency synthesis and the noise measurement techniques as well as, the realization of time scales and the study of related algorithms and the experimentation of synchronization systems. Significant changes have occurred in the time and frequency metrological scenario in the last decades, such as the worldwide continuous availability of an accurate time source at 1μs level (GPS), the improved features of commercial cesium standards, the first realization of new generation of primary cesium standards, based on optical molasses, reaching accuracies at the 10^{-15} level, the development of global navigation systems (GNSS), a new foundation of the international metrological organization with the establishment of the regional metrology organizations and the signature of mutual recognition agreement of national measurement standards and calibration certificates.
In what follows, an overview is given of the present and foreseeable activity of the IEN Time and Frequency Laboratory where the effects due to the above avenues are evident.

ATOMIC FREQUENCY STANDARDS

CESIUM ATOMIC FOUNTAIN

In cooperation with NIST (Boulder, Colorado) and the Politecnico di Torino, a cesium atomic fountain project has been started in 1997.
The optical system and the vacuum chambers for cooling and detection have been set up: the optical system consists of two main laser systems, frequency stabilized on cesium D_2 transition. One system consists of a master DBR (Distributed Bragg Reflector) diode laser frequency locked on the $6S_{1/2}$, $F=4 \rightarrow 6P_{3/2}$, $F=5$ transition, and amplified by means of two slave diodes; this system is used to trap, cool, and detect the cesium atoms. The other laser system, consists of a second DBR diode laser, locked on the

$6S_{1/2}$, F=3 $\rightarrow$ $6P_{3/2}$, F=4 transition, and is used as repumping light in the trapping and in the detection regions.
The vacuum system consists of a trapping chamber, two detection regions, one above and one below the trapping zone; we are currently installing the upper part of our fountain, with the microwave cavities, the drift tube and the magnetic shields.
The experiment operation is completely automated through a PC. Three computer boards take care of the main functions: a pattern generator allows a fast and precise timing of the clock sequences, a multi-digitizer allows a real-time analysis of the time of flight (TOF) signals and a GPIB board allows the programming of many instruments.
The fountain has been operated with the following characteristics: number of trapped Cs atoms 10^7; lower temperature achieved ≤ 2 μK, measured with the standard TOF technique. The tossing system, in the moving molasses frame, has been developed and tested.
In Fig. 1 is shown the time of flight signal of atoms launched at increasing velocities as detected in the lower detection region; the progressive loss of signal is mainly due to the thermal expansion of the atomic cloud.

COHERENT POPULATION TRAPPING MASER

The studies performed on the application of three-level systems in the atomic frequency standard field, has shown the possibility to realize a new kind of maser, the Coherent Population Trapping (CPT) maser. Studies considering the use of rubidium or cesium as emitting atoms have shown that such a maser can have a very promising short-term stability.
A good understanding of the physics of this new atomic frequency standard has now been reached, jointly with a clear experimental picture. Works are in progress in order to realize a first operating prototype. The interested reader can found a review paper in these PTTI proceedings [2].

SHORT-TERM FREQUENCY STABILITY MEASUREMENT SYSTEMS

For many years IEN has been involved in the experimental and theoretical investigation of noise processes in oscillators and in frequency multiplication chains. Large efforts were devoted in previous time to the frequency synthesis from microwave up to the near infrared. More recently, IEN has given a contribution in the analysis of the clocks' behavior for the high speed synchronous digital communication networks.
In this frame we have considered the necessity to upgrade our frequency stability measurement capability, with particular attention, on one side (time domain), to the short and medium averaging times (1÷1000) s and, on the other side (frequency domain), for integration times less than one second, towards high performance phase noise measurement systems. In order to improve our time domain frequency stability measurement resolution, we have focused the attention on the well known Dual-Mixer Time-Difference technique. A first prototype working at 10 MHz with a beat note of 1 Hz shows an Allan deviation level of $5{,}6 \cdot 10^{-14} / \tau$, between 1 and 1000 s, and a temperature sensitivity of some picosecond per Celsius [3]. This system gives an appreciable improvement on frequency resolution over the previous IEN system; nevertheless this work is open for improvement.
On the side of phase noise measurement systems, we are working on some different aspects. Three main goals are: the extension of the measurement capabilities up to the microwave region, now limited at the radio frequencies range (5÷300) MHz; the reduction of the noise level of the measurement system; and, last but not least important, the reproducibility/accuracy of the noise measurements.
At present, the work is focused in setting up a measurement system based on the cross-correlation scheme, in such a way to reduce the white phase noise floor. We intend successively to investigate the possibility given by the carrier suppression interferometric technique, proposed recently and independently by the University of Western Australia and the LPMO (Besançon, France).

TIME SCALE GENERATION

The National Time Scale UTC(IEN) is realized with five commercial cesium standards, four of them being Hewlett-Packard 5071A of the High Performance type, and the rate of the master clock selected is steered to UTC using its internal microstepper. The independent local atomic time scale TA(IEN) is also based on the same clock ensemble. The frequency instabilities (ADEV) of these time scales, for the period October 1997 to October 1999, is shown in Fig. 2, computed from the data published in BIPM Circulars T, for observation times from 5 to 150 days; meanwhile Fig. 3 reports the frequency deviations, averaged over 5 days, of UTC(IEN) for the same period computed from the same data source. Over the whole period (MJD 50724 to 51479), the frequency values ranged between $-4{,}2\cdot10^{-14}$ and $6{,}5\cdot10^{-14}$ and the associated standard deviation was $1{,}9\cdot10^{-14}$. The goal of maintaining a synchronization of UTC(IEN) within 100 ns to UTC, as recommended by the CCDS, has been achieved at 1σ level but, as shown in Fig. 4, it has still been exceeded as maximum deviation in the 30% of the cases. This means that a different criterion for the frequency correction, by a timely prediction of its rate towards UTC of the master clock, should be implemented to be completely compliant with the target. The master clock correction values applied for the period considered are reported below and also shown in Fig. 3.

Date	MJD	Master clock correction [ns/d]	Reference in Fig. 3
1 October 1997	50722	+12,58	1
9 January 1998	50822	+14,77	2
29 May 1998	50962	+9,85	3
9 November 1998	51126	+11,5	4
24 May 1999	51322	+10,4	5
8 August 1999	51392	+9,33	6

The future developments foreseen in the time scale realization will follow two directions, improving the reliability in the real-time generation of UTC(IEN) and the stability of TA(IEN), including cesium frequency standards, maintained in other Italian research institutes, in the IEN ensemble time scale. Concerning the first issue, a new time scale generator and switching unit is under development and will be operative in the year 2000. Fig. 5 shows the block diagram of this device that will receive at its inputs the standard frequencies of all the cesiums available, check their amplitude, and perform continuous phase comparisons among the input signals in order to detect any anomaly in the system and avoid discontinuities in the generation of UTC(IEN) in real time. The phase stepper resolution of the new time scale generator will allow the synchronization of UTC(IEN) versus an external reference at 1 ns.

INTERNATIONAL TIME TRANSFER

The IEN time scales are routinely compared to UTC by means of the GPS common-view comparisons performed with two C/A code receivers, namely a single-channel NBS/GPS type and a 18 channel GPS/GLONASS receiver, 3S Navigation GNSS 300T-type, that was put in operation in October 1998.
To compare the GPS common-view results obtained from these receivers, in Fig. 6 we have reported the daily values of their differential delays from October 1998 to November 1999; it can be seen that a 5 ns offset is present due to the fact that no calibration of the 300T delay receiver is yet available. The standard deviation of this data set is 2 ns. Concerning the results obtained from the GLONASS signals using six channels of the 3S receiver, Fig. 7 shows the instability plot (ADEV) versus UTC(IEN) for observation times from 1 to 70 days. The fact that the noise level is higher than what one could expect, as there is no S/A on the GLONASS signals, could be related to the receiver biases for the different

GLONASS frequencies that need to be calibrated. During the period considered, the average number of GPS satellites observed was 27 instead of 11 to 13 GLONASS. Another way of evaluating the behavior of the GLONASS part of this receiver consists in comparing the daily values UTC – GLONASS, given in the Circulars T, with similar data obtained through the UTC(IEN) – GLONASS daily averages corrected for the UTC – UTC(IEN) differences interpolated at 1-day intervals. This results, reported in Fig. 8, show a quite good agreement in the restitution of the time scales differences.
The delay of the NBS/GPS receiver was calibrated four times in the period 1996-1998 by means of the circulation of the BIPM3 C/A single-channel reference receiver [4] showing, as can be seen from the results below, a slight increase with time of its calibration factor, the differential time correction for the link UTC(IEN) – UTC(OP), being: –17 ns (1996), –15 ns (1997), –21 ns (1998/1) and –23 ns (1998/2). As a consequence of these calibrations, on July 2, 1999 (MJD 51362), the delay compensation inside the IEN receivers was increased by 18 ns, as suggested by BIPM. Both IEN receivers have been included in the 1999 GPS/GLONASS calibration campaign performed by means of BIPM-A, R100-30 receiver and it is expected that the results will improve the accuracy of the time comparisons performed on both satellite systems.
The work on the IEN VSAT station devoted to the two-way time transfers (TWSTFT) using INTELSAT 706 communication satellite, operating in the (12–14) GHz band, has been completed with the automation of the transceiver, the MITREX modem functions, and the data collection and management. A considerable amount of time has been devoted to the qualification of the VSAT station according to the European Standards and now it is undergoing the approval from the national INTELSAT Signatory; it is expected to be fully operational and to join the international two-way network at the beginning of 2000. A representation of the IEN two-way equipment is given in Fig. 9. As a first sample of the performance of the IEN synchronization system, in Fig. 10 are reported some results relative to UTC(IEN) – UTC(TUG) (2 minute sessions, no Sagnac corrections applied) obtained during a first run of the measurement program in November 1999 (MJD 51494 to 51508). On the same plot are reported the difference between these time scales obtained by GPS common-view measurement, interpolated for the TWSTFT measurement time. A typical value observed for the standard deviation is 0.8 ns. Between the two datasets there is an offset ranging between 268 to 271 ns due to the fact that no calibration of the IEN station delay is available yet. For this purpose, a satellite simulator will be developed in order to measure at each two-way session the station up-link and down-link delays.
The IEN will also start in 2000 to experiment the GPS carrier phase measurement technique in time scale comparisons through a geodetic receiver related to UTC(IEN).

UTC(IEN) DISSEMINATION

TIME DISSEMINATION SERVICES

UTC(IEN) is available to users in Italy by means of dedicated services performed through the national radio broadcasting company RAI, the telephone network, and Internet. The first two services disseminate a date and time-coded information according to formats published in [1, 5], meanwhile the last one consists in the synchronization of two NTP (Network Time Protocol) primary servers, installed in the IEN buildings, by the telephone time code. This service can be accessed at the following server addresses: "time.ien.it" and "tempo.cstv.to.cnr.it".
The RAI coded time signals are still the most used source of legal time in Italy in the commercial and industrial environment and they also serve to discipline the frequency of quartz oscillators in calibration centers. Nevertheless the use of GPS signals in these fields is becoming more and more widespread also in Italy. The coded time signals available on regular dial-up telephone connections, that follow a format common to 13 European countries, address mostly the PC clocks synchronization and have seen a slow

but constant increase of the daily calls; by the end of 1999 we can register 650 calls with an average duration of 15 seconds.
The implementation of the date and time authentication systems for documents validation and commercial and financial transactions is under development in the most industrialized countries. For these purposes, Certification Authorities (CA) are going to be established in each country to electronically sign documents using a Public Key Infrastructure (PKI) system. A secure and reliable time source is needed by these authorities to guarantee a legal value to these documents; the CA will have in fact a dedicated part in their validation system, called Time Stamping Authority (TSA), to provide a trusted time certification.
In Italy, the governmental body charged of the information exchange in the Public Administration (AIPA) has prescribed in 1999 that the TSA shall be synchronized within 1second to UTC(IEN). In this frame, IEN is developing a new time service that will allow the dissemination of trusted time signals to the TSAs using secure dial-up telephone circuits.
The proposed approach allows any TSA to use different time sources to generate their trusted time information (e.g. GPS receivers, radio broadcasted time signals, telephone coded time signals) in order to have the necessary redundancy, but they will have to call at least daily the IEN certification service to get an authenticated synchronization versus UTC(IEN). This will be done using a secure (PKI) telephone connection, and a certification of the date and time information will be delivered. The certification procedure involves the determination of the round-trip time of the telephone connection. IEN will randomly assess via Internet the compliance of the TSA time stamping asking the signature of a document carrying the reference date and time information. It is eventually foreseen that the Certification Authorities become calibration centers accredited in the field of Time by the Italian Calibration Service (SIT)

TRACEABILITY TO UTC(IEN)

A constant increase of activity has been observed in the field of the remote certification of the reference oscillators of calibration laboratories and scientific institutions (about 30 at present) that are performed with different synchronization techniques, depending on the necessary uncertainty levels.
The extensive use of GPS-disciplined oscillators (GPSDO) by some of these laboratories, and the need to trace their measurements to UTC(IEN) as requested by the ISO 9000 standards and by the ISO 25 Guide, drove the IEN to study this problem [6], through a careful characterization of the accuracy and stability of these devices in the short and long term, both at the IEN laboratory and remotely.
The agreed measurement protocol has been in use during the past two years and the results reported in [7] show that the daily frequency deviation of the GPSDOs can be determined at the level of few parts in 10^{-13} by remote calibration. Some GPSDOs are used as frequency and time references in the calibration centers accredited by SIT and the assessment of their uncertainty level performed in 1998 proved successful.
By the end of 1999 there are 20 of these secondary centers operative and 6 more are expected by the year 2000 because are undergoing the accreditation procedure. The uncertainties levels accredited lay in the range from $2 \cdot 10^{-9}$ to $3 \cdot 10^{-13}$, depending on the traceability chain chosen by the center.
The involvement in this field of the IEN time and frequency laboratory will increase heavily because of the necessity to organize more intercomparisons between the centers and for the evaluation of the new calibration procedures developed. For this purpose, a frequency intercomparison will be repeated in the year 2000 among some of the SIT centers to reassess their calibration capabilities. A device made of a free rubidium oscillator and a GPS multichannel receiver will be used as traveling standard. This will allow to IEN a real-time verification of the frequency of the oscillator in calibration, overcoming the problems encountered in the past experiences due to the poor frequency retrace of the traveling standards.

Another aspect that will have to be carefully looked at regards the standardization of some basic calibration procedure, to be submitted for agreement to the technical committee of the European Accreditation body (EA) in cooperation with other accreditation services and the development of guidance documents for the implementation of the ISO/TAG 4/WG3 Guide in the time and frequency calibrations.

REFERENCE TIME SCALES IN SPACE APPLICATIONS

Some activities related to the evaluation of aims and characteristics of a reference time scale to be used in space applications were performed at IEN in the last years and are currently going on. These activities were stimulated by the European project of a GNSS II. IEN firstly collaborated with DLR (Germany) on a ESA/ESTEC Contract on "Intersatellite ranging and autonomous ephemeris determination for future navigation systems" [8, 9, 10] on the definition of the System Time Scale and on the evaluation of clock prediction uncertainty and its impact on UERE (User Equivalent Range Error).
Currently, the European GNSS project Galileo is in its "definition phase" that will last till Nov. 2000. IEN is involved in the evaluation of a reference time scale and its possible use to disseminate time as one of the most interesting features for the Time and Frequency laboratories. To this aim researches are going on concerning the clock error prediction and the estimation and weighting of the stability of individual clocks.

CONCLUSIONS

The time and frequency activities performed at IEN cover most of the issues coming from the research and users communities. Some of the topics considered above that will be the more significant in the future for the IEN Laboratory include:

- the completion of cesium fountain and the development of adeguate measurement systems for high resolution stability measurements;
- the regular participation in the international Two-Way synchronization network and the experimentation of the GPS carries phase technique;
- the improvement of the realization of UTC(IEN) time scale by including an H-maser in the clock ensemble.

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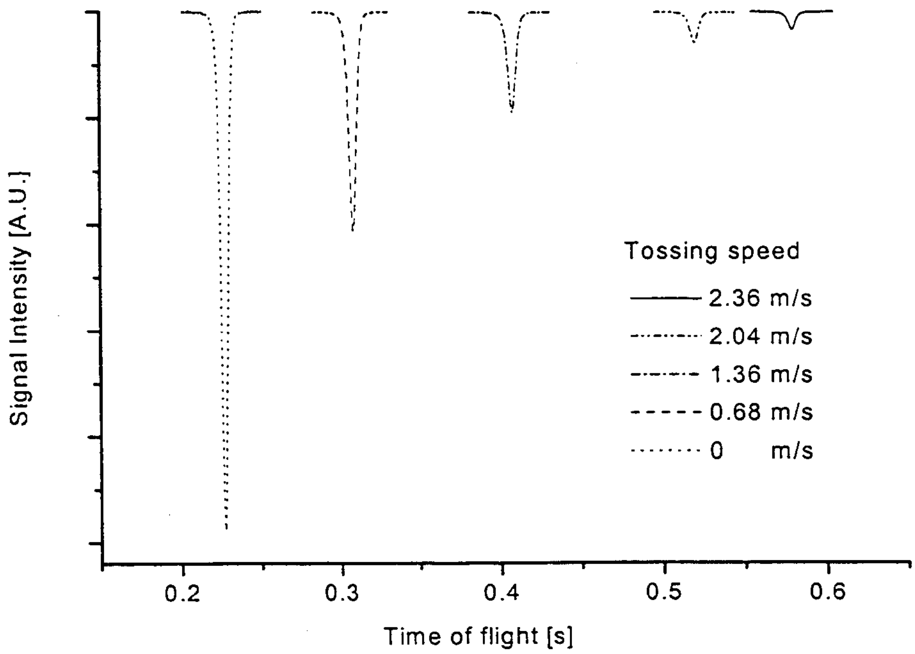

Fig. 1 –Time of flight signal of atoms in the IEN cesium fountain

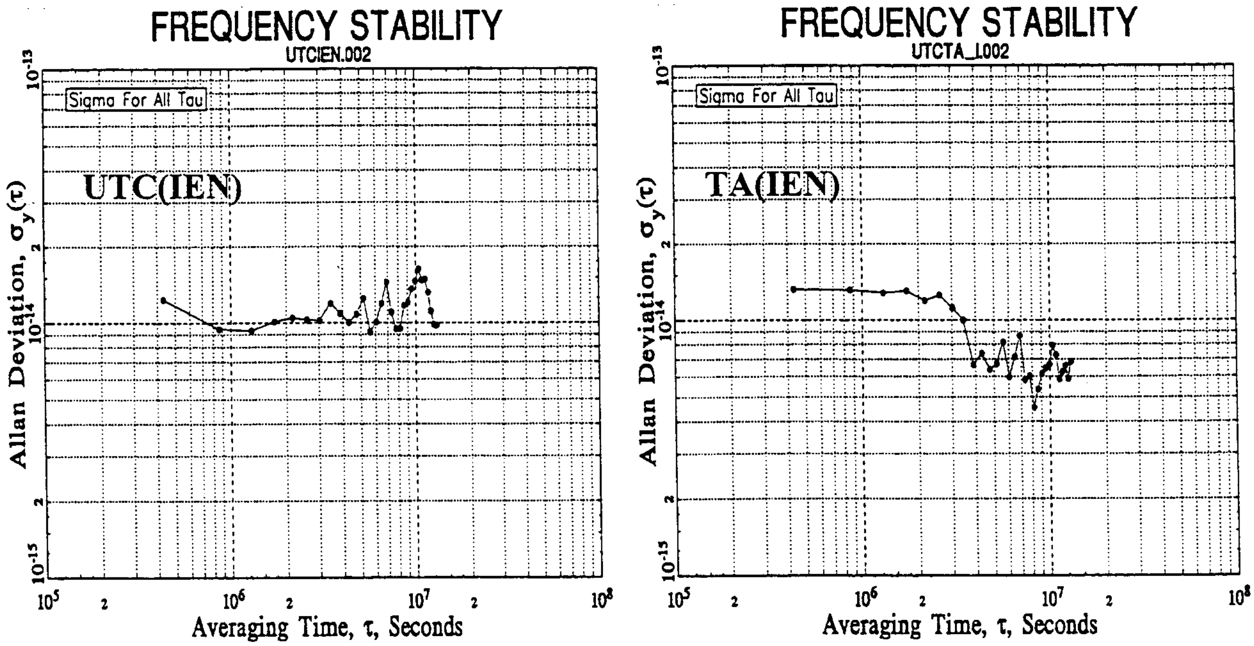

Fig. 2 – Frequency instability of UTC(IEN) and TA(IEN) vs. UTC (October 1997 – October 1999)

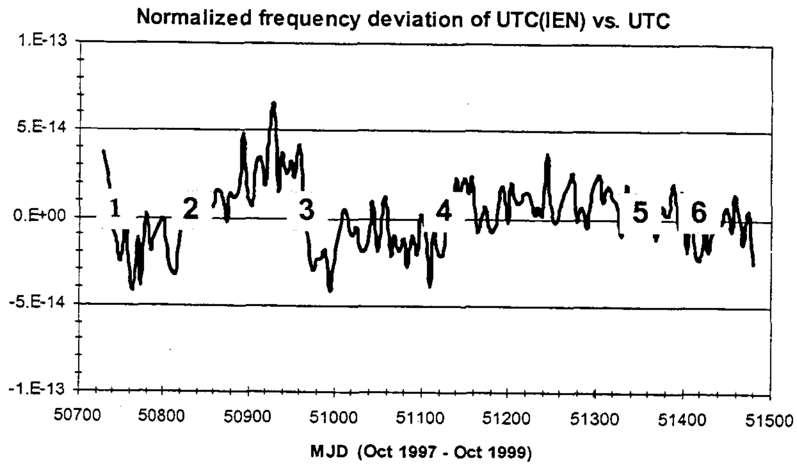

Fig. 3 – Frequency behavior of UTC(IEN) vs. UTC, BIPM Circular T

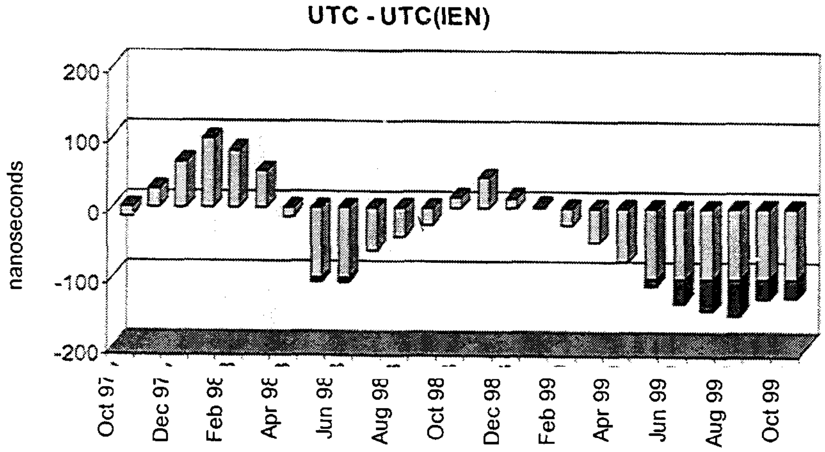

Fig. 4 – UTC(IEN) time scale behavior vs UTC, BIPM Circular T

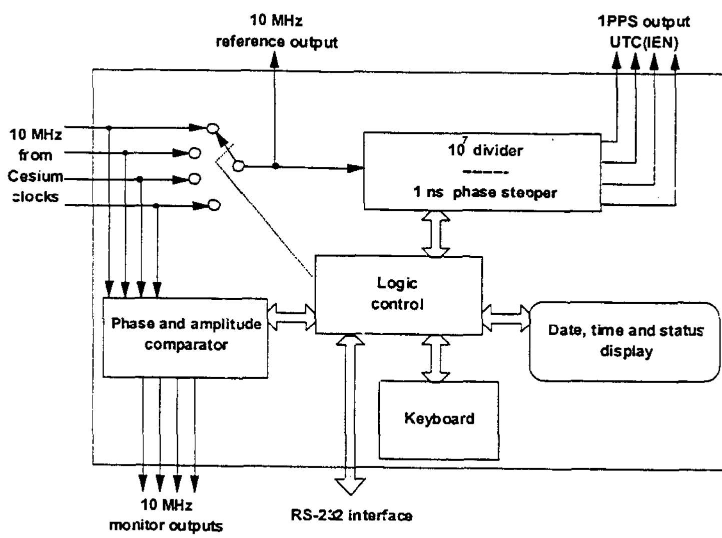

Fig. 5 – Block diagram of the new IEN time scale generator

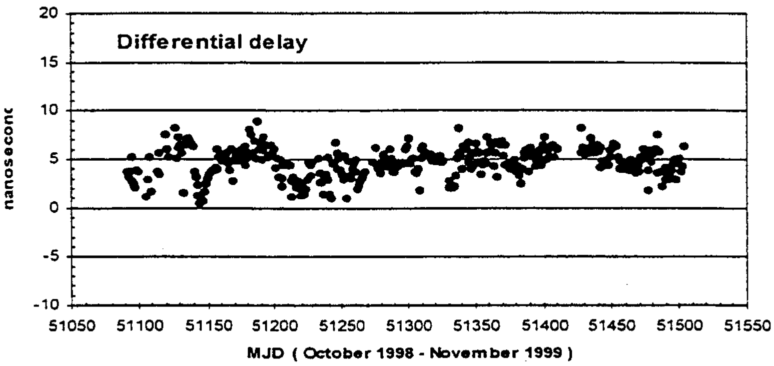

Fig. 6 – Differential delay of the two IEN GPS receivers

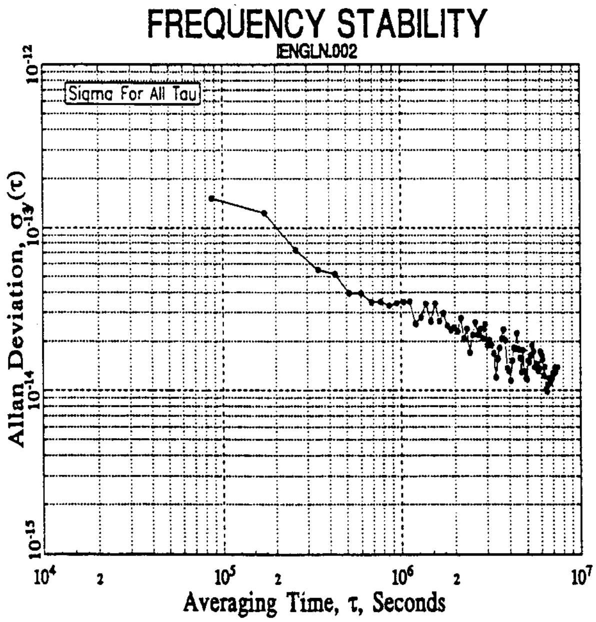

Fig. 7 – Frequency instability of UTC(GLONASS) vs. UTC(IEN)

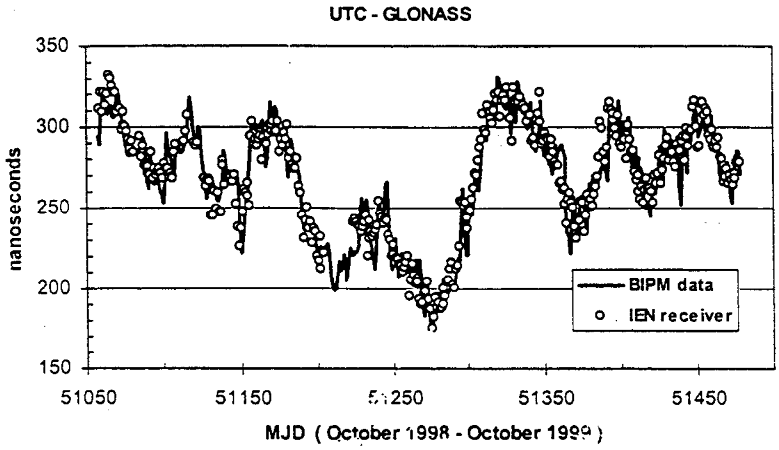

Fig. 8 – Comparison of UTC(GLONASS) vs. UTC via BIPM and IEN

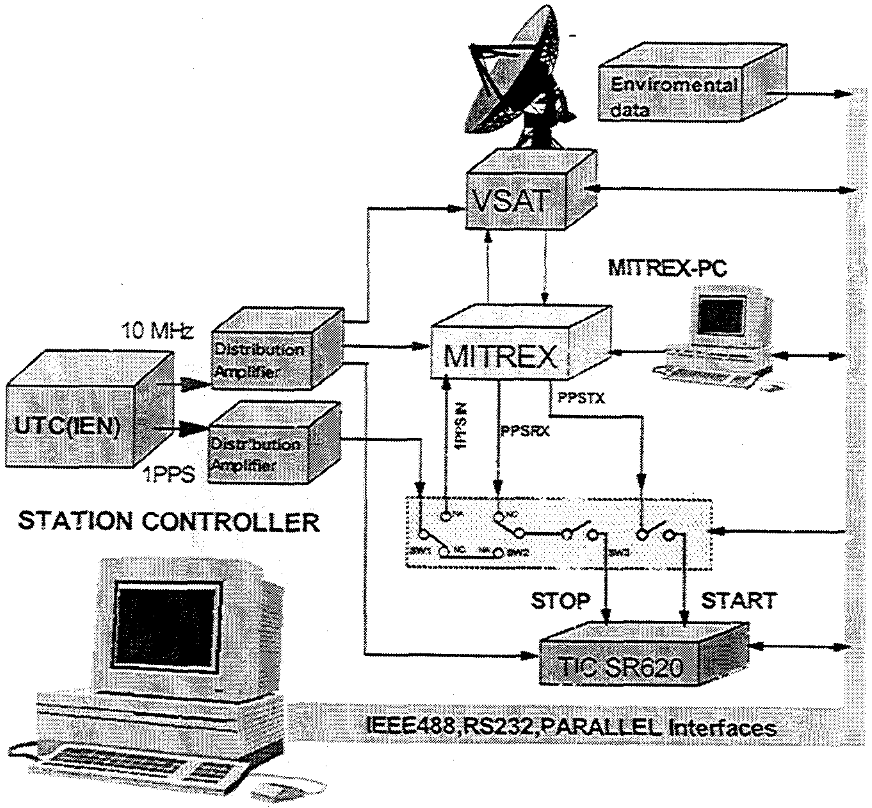

Fig. 9 – Block diagram of the IEN TWSTFT equipment

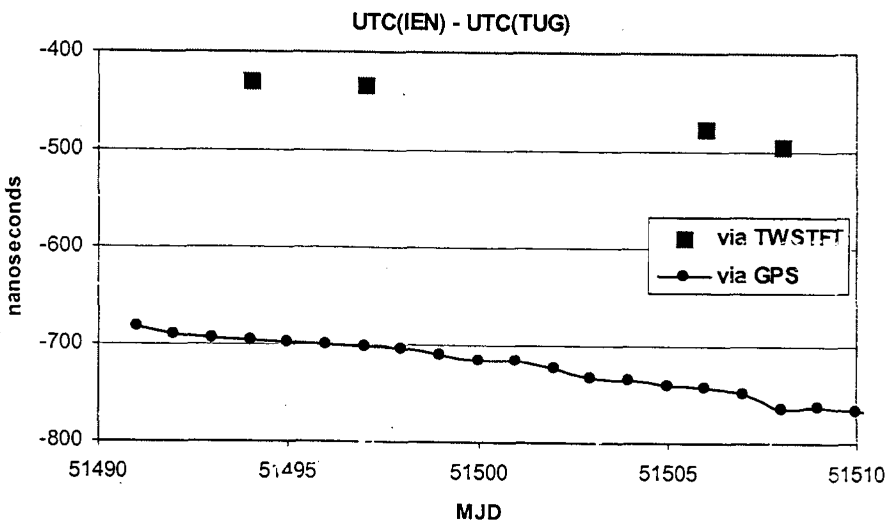

Fig. 10 – UTC(IEN) – UTC(TUG) via TWSTFT and GPS