SHORT-TERM CHARACTERIZATION OF GPS-DISCIPLINED OSCILLATORS AND FIELD TRIAL FOR FREQUENCY OF ITALIAN CALIBRATION CENTERS

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Abstract

Quartz and rubidium oscillators disciplined by the signals of the Global Positioning System satellites (GPSDOs) are increasingly used as reference standards in calibration centers and in telecommunication networks, thanks to their cesium-like long-term instability, and several investigations are undergoing in the metrological laboratories of different countries concerning their use for the traceability to the national standards of time. Some of these devices were tested in the past at the Time and Frequency Laboratory of IEN, as regards to their use as frequency and time references in secondary laboratories and their traceability to the Italian standard of time.

In further investigations performed, evidence was found of short-term frequency instabilities, not previously detected, mainly due to temperature effects and to the disciplining algorithms used, that must be taken into account especially in the frequency calibration field. The long and short-term instability results obtained at IEN on some GPSDOs, that show the real uncertainty limits in calibration, are reported in this paper. They are also checked by means of a field-trial on frequency, carried on among some Italian Calibration centers equipped with GPSDOs or other frequency references, using either a free rubidium or a quartz oscillator as travelling standards.

INTRODUCTION

The traceability in Italy to the national time standard UTC(IEN), realized by IEN, of the secondary standards maintained in the calibration centers accredited by the Italian Calibration Service (SIT), can be obtained by means of different synchronization systems, one of the most used now being the GPS in the common-view technique or as a disciplining medium to stabilize the frequency of high quality oscillators [1].

In these disciplined oscillators, the frequency offset and the drift are continuously compensated and therefore a specific approach for the traceability issue has to be followed especially if, as in the case under study, the time signals used in the disciplining process are not originated by the national standard.

The problem of establishing the traceability of the GPSDOs was faced in the past at IEN performing several tests on devices of different manufacturers, leading to a definition of their accuracy and stability limits and of a measurement protocol for their on site calibration [2].

In 1998, the issue of the frequency accuracy and stability of GPSDOs as stand-alone frequency standards, over the observation times involved in the calibration process, has been examined at IEN through an extensive investigation on eight GPSDOs of different manufacturers, equipped either with a quartz or a rubidium oscillator. The results of these studies and the consequences on the uncertainty budget of the centers accredited for frequency are reported in the following, together with the evaluation of the long-term behavior of some of these devices operating in Italian laboratories, as obtained by implementing the daily measurement protocol agreed upon. Future work envisaged in this field is also outlined.

LONG-TERM CHARACTERIZATION OF GPSDOs

The frequency and time interval measurements performed to estimate the GPSDOs specifications have been referred to UTC(IEN), and the differences between UTC(IEN) and the GPS time scale have been determined with the NBS/GPS receiver used for the international traceability and performing the BIPM common-view (CV) tracking schedule for Europe. The mean frequency deviation between the IEN and the GPS time scales has always been well below $1 \cdot 10^{-13}$ during the instruments testing periods.

The measurement results reported in the following were obtained by means of a Stanford SR620 Time Interval and Frequency Counter, supplying an external 10 MHz derived from UTC(IEN) as a time base. For observation times up to 1000 s, frequency measurements were performed using an additional phase difference multiplier to increase the resolution; meanwhile for longer observation times, time interval measurements were used, started by a 1PPS from UTC(IEN) time scale and closed by a 1PPS supplied by the GPSDO under test.

The indoor equipment and the measurement system was inside the Time and Frequency Laboratory where the temperature has been maintained at (23 ± 1,5) °C and the AC power stabilized at (220 ± 5) V.

Eight devices from three different manufacturers have been analyzed: two equipped with an ovenized crystal oscillator (OCXO) and labeled in the following as A and B, two with a low drift crystal oscillator (BVA) and labeled as C and D, and four with a rubidium frequency standard (Rb) named E, F, G and H. They have been checked as regards their capability to reproduce GPS time, their short- and long-term instability, their frequency accuracy and the supplying of information useful to establish a traceability to an external reference standard. In some cases the devices have been operated under their default conditions, in others the reference coordinates of the IEN site have been inserted and the receiver forced to operate in "time mode."

The results obtained from daily time measurements and the statistics about the long-term frequency behavior of the GPSDOs under evaluation at the IEN laboratory are reported in Table 1, which clearly shows the effect of the GPS disciplining process, that has compensated for the oscillators frequency offsets and drifts. It can be noticed in fact that the mean relative frequency deviations $\bar{y}$ of the GPSDOs, computed over the whole period from a set of daily averaged frequency deviations, are always negligible in comparison with their uncertainty s_y estimated as the standard deviation of the daily frequency values, and in most cases approach GPS.

Some of these devices have been afterwards remotely tested in the calibration centers where they are operating as reference standards. The measurement protocol for the remote frequency calibration of GPSDOs versus the national time and frequency standard, that requires a calibration center to perform a daily series of 24 time interval measurements between the local 1PPS and the GPS time signals provided by the GPSDO, has been already implemented in six calibration centers that send the results monthly to IEN. Each measurement cycle starts at the beginning of the hour and consists of 60 consecutive time interval measurements; at IEN, 48 daily GPS measurement – lasting 13 minutes each – are performed according to the BIPM CV schedule for Europe. From these two data ensembles, a mean daily time difference between UTC(IEN) and the 1PPS/GPSDO is computed and the daily average frequency deviation of the disciplined oscillator is determined. Plots of Fig. 1, 2 and 3 show samples of the daily normalized frequency deviations of three GPSDOs computed using the measurement protocol previously described, over a period of three months. Some statistics performed on the data above is summarized in

Table 1 – Long-term frequency behavior of the GPSDOs

GPSDO	A OCXO	B OCXO	C BVA	D BVA	E Rb	F Rb	G Rb	H Rb
days of measurement	98-02-11 98-02-23	98-06-05 98-06-28	98-04-23 98-05-08	98-05-08 98-05-25	98-03-14 98-03-27	98-04-01 98-04-22	98-04-08 98-05-04	98-07-13 98-08-07
$\bar{y}$ relative freq. deviation	$-0{,}9\cdot10^{-13}$	$0{,}1\cdot10^{-13}$	$-0{,}6\cdot10^{-13}$	$-0{,}2\cdot10^{-13}$	$-0{,}6\cdot10^{-13}$	$0{,}1\cdot10^{-13}$	$3{,}3\cdot10^{-13}$	$0{,}2\cdot10^{-13}$
s_y standard dev. (24 h)	$1{,}9\cdot10^{-12}$	$2{,}8\cdot10^{-13}$	$5{,}1\cdot10^{-13}$	$6{,}6\cdot10^{-13}$	$2{,}4\cdot10^{-13}$	$4{,}6\cdot10^{-13}$	$6{,}9\cdot10^{-13}$	$6{,}5\cdot10^{-13}$
Nr. of samples	12	23	15	17	13	21	26	25

Table 2 that gives the standard deviation of the daily frequency deviations versus UTC(IEN), their upper an lower limits and the number of samples. The mean frequency deviations of the three oscillators, averaged over the same observation time, have not been reported because they are smaller than $1\cdot10^{-13}$.

Table 2 – Statistics on remote calibration of GPSDOs

GPSDO	A OCXO	C BVA	E Rb
s_y Standard dev. (24 h)	$0{,}5\cdot10^{-12}$	$1{,}1\cdot10^{-13}$	$1{,}6\cdot10^{-13}$
y_{min}	$-1{,}7\cdot10^{-12}$	$-2{,}6\cdot10^{-13}$	$-3{,}8\cdot10^{-13}$
y_{max}	$1{,}2\cdot10^{-12}$	$2{,}8\cdot10^{-13}$	$4{,}3\cdot10^{-13}$
Nr. of Samples	90	84	79

The fact that the standard deviations computed over 24 hours are smaller than the correspondent ones listed in Table 1, may be due to the smoothing process performed in this case on the data, originated by averaging over the 24 hourly data.

From this long-term analysis of the GPSDOs frequency behavior comes a confirmation that the measurement protocol adopted is adequate to trace these devices to the national time standard, at least at the level of parts in 10^{-13}, which is perfectly acceptable in most calibration centers.

SHORT-TERM CHARACTERIZATION OF GPSDOs

In the frequency calibration field it is of the utmost importance to characterize the short-term behavior of the oscillator used as a reference in the calibration process. As a sample, in Fig. 4 to 6 have been reported the short-term frequency instabilities of the GPSDOs under test, equipped with different types of oscillators, for averaging times τ of 10 s, 100 s and 1000 s.

The plots show that the instantaneous frequency of the GPSDOs can exceed by orders of magnitude its long-term value, and for $\tau = 1000$ s the frequency deviations values improve significantly over those obtained for $\tau = 10$ s. There is also evidence of periodic variations probably related to the oscillator frequency steering process and to thermal effects.

To get a more complete representation of the short-term behavior of the GPSDOs considered, some statistics over the frequency measurement data has been performed and the results are reported in Table 3.

Table 3 – Short-term frequency behavior of the GPSDOs

GPSDO		**A OCXO**	**B OCXO**	**C BVA**	**D BVA**	**E Rb**	**F Rb**	**G Rb**	**H Rb**
$\sigma_y(\tau)$ (ADEV)	1 s	$7,2\cdot10^{-12}$	$4,6\cdot10^{-11}$	$5,9\cdot10^{-12}$	$5,6\cdot10^{-12}$	$6,2\cdot10^{-12}$	$7,9\cdot10^{-12}$	$6,1\cdot10^{-12}$	$7,8\cdot10^{-12}$
	10 s	$4,0\cdot10^{-12}$	$1,0\cdot10^{-10}$	$3,3\cdot10^{-12}$	$3,1\cdot10^{-12}$	$2,7\cdot10^{-12}$	$3,5\cdot10^{-12}$	$3,1\cdot10^{-12}$	$3,6\cdot10^{-12}$
	100 s	$4,2\cdot10^{-12}$	$2,2\cdot10^{-10}$	$1,8\cdot10^{-12}$	$1,7\cdot10^{-12}$	$8,2\cdot10^{-13}$	$8,9\cdot10^{-13}$	$8,8\cdot10^{-13}$	$2,1\cdot10^{-12}$
	1000 s	–	$5,2\cdot10^{-11}$	$2,1\cdot10^{-12}$	$1,9\cdot10^{-12}$	$5,1\cdot10^{-13}$	$9,0\cdot10^{-13}$	$5,6\cdot10^{-13}$	$1,6\cdot10^{-12}$
s_y	1 s	$2,6\cdot10^{-11}$	$3,9\cdot10^{-10}$	$8,3\cdot10^{-12}$	$8,4\cdot10^{-12}$	$7,5\cdot10^{-12}$	$9,2\cdot10^{-12}$	$7,8\cdot10^{-12}$	$9,7\cdot10^{-12}$
	10 s	$1,7\cdot10^{-11}$	$2,8\cdot10^{-10}$	$5,5\cdot10^{-12}$	$6,9\cdot10^{-12}$	$3,0\cdot10^{-12}$	$5,6\cdot10^{-12}$	$3,0\cdot10^{-12}$	$4,9\cdot10^{-12}$
	100 s	$1,6\cdot10^{-11}$	$2,4\cdot10^{-10}$	$5,5\cdot10^{-12}$	$5,6\cdot10^{-12}$	$1,6\cdot10^{-12}$	$3,5\cdot10^{-12}$	$1,0\cdot10^{-12}$	$3,7\cdot10^{-12}$
	1000 s	–	$4,3\cdot10^{-11}$	$4,7\cdot10^{-12}$	$5,7\cdot10^{-12}$	$1,6\cdot10^{-12}$	$3,9\cdot10^{-12}$	$8,6\cdot10^{-13}$	$2,0\cdot10^{-12}$
y_{min}	1 s	$-7,5\cdot10^{-11}$	$-2,1\cdot10^{-9}$	$-4,6\cdot10^{-11}$	$-2,9\cdot10^{-11}$	$-2,2\cdot10^{-11}$	$-2,7\cdot10^{-11}$	$-2,5\cdot10^{-11}$	$-4,3\cdot10^{-11}$
	10 s	$-5,3\cdot10^{-11}$	$-1,2\cdot10^{-9}$	$-1,7\cdot10^{-11}$	$-2,0\cdot10^{-11}$	$-1,1\cdot10^{-11}$	$-1,6\cdot10^{-11}$	$-1,1\cdot10^{-11}$	$-1,5\cdot10^{-11}$
	100 s	$-4,8\cdot10^{-11}$	$-8,2\cdot10^{-10}$	$-2,5\cdot10^{-11}$	$-1,7\cdot10^{-11}$	$-4,9\cdot10^{-12}$	$-1,1\cdot10^{-11}$	$-3,6\cdot10^{-12}$	$-1,3\cdot10^{-11}$
	1000 s	–	$-1,2\cdot10^{-10}$	$-2,4\cdot10^{-11}$	$-2,3\cdot10^{-11}$	$-5,2\cdot10^{-12}$	$-1,2\cdot10^{-11}$	$-4,2\cdot10^{-12}$	$-8,4\cdot10^{-12}$
y_{max}	1 s	$7,2\cdot10^{-11}$	$1,4\cdot10^{-9}$	$1,1\cdot10^{-11}$	$3,8\cdot10^{-11}$	$3,2\cdot10^{-11}$	$3,6\cdot10^{-11}$	$3,9\cdot10^{-11}$	$3,4\cdot10^{-11}$
	10 s	$4,7\cdot10^{-11}$	$1,2\cdot10^{-9}$	$1,9\cdot10^{-11}$	$2,2\cdot10^{-11}$	$1,0\cdot10^{-11}$	$1,7\cdot10^{-11}$	$9,8\cdot10^{-12}$	$1,8\cdot10^{-11}$
	100 s	$4,1\cdot10^{-11}$	$8,3\cdot10^{-10}$	$1,6\cdot10^{-11}$	$2,2\cdot10^{-11}$	$6,7\cdot10^{-12}$	$9,4\cdot10^{-12}$	$2,5\cdot10^{-12}$	$2,0\cdot10^{-11}$
	1000 s	–	$1,2\cdot10^{-10}$	$1,3\cdot10^{-11}$	$2,4\cdot10^{-11}$	$4,3\cdot10^{-12}$	$8,2\cdot10^{-12}$	$5,0\cdot10^{-12}$	$5,6\cdot10^{-12}$
y_β (β=99,7%)	1 s	$5,2\cdot10^{-11}$	$1,3\cdot10^{-9}$	$6,0\cdot10^{-11}$	$3,0\cdot10^{-11}$	$2,6\cdot10^{-11}$	$3,0\cdot10^{-11}$	$2,3\cdot10^{-11}$	$2,6\cdot10^{-11}$
	10 s	$4,2\cdot10^{-11}$	$8,6\cdot10^{-10}$	$1,5\cdot10^{-11}$	$1,7\cdot10^{-11}$	$8,0\cdot10^{-12}$	$1,3\cdot10^{-11}$	$7,8\cdot10^{-12}$	$1,3\cdot10^{-11}$
	100 s	$3,7\cdot10^{-11}$	$6,7\cdot10^{-10}$	$1,5\cdot10^{-11}$	$1,9\cdot10^{-11}$	$4,3\cdot10^{-12}$	$8,2\cdot10^{-12}$	$2,3\cdot10^{-12}$	$1,2\cdot10^{-11}$
	1000 s	–	$1,2\cdot10^{-10}$	$1,2\cdot10^{-11}$	$2,0\cdot10^{-11}$	$3,9\cdot10^{-12}$	$7,4\cdot10^{-12}$	$3,1\cdot10^{-12}$	$5,1\cdot10^{-12}$
Nr. of samples	1 s	4856	4000	3000	4000	3000	3000	4000	4000
	10 s	3000	4000	4000	4000	3000	4000	4000	4000
	100 s	2109	2706	3394	2792	2453	3446	1950	3488
	1000 s	–	689	749	982	694	626	601	851

The frequency supplied by the devices under test has been characterized for averaging times of 1 s, 10 s, 100 s and 1000 s using a frequency difference multiplier and an electronic counter. For each GPSDO has been reported in the table the following data:

a) the Allan deviation (ADEV) $\sigma_y(\tau)$,
b) the standard deviation s_y of the experimental frequency deviations y;
c) the minimum y_{min} and the maximum y_{max} value of y;
d) the y_β percentile, that represents the interval including the 99,7% (3σ) of the experimental data;
e) the number of samples.

According to the ISO Guide on Uncertainty in Measurements (GUM) and to Document EAL –R2 of the European cooperation for Accreditation of Laboratories, the calibration centers must declare in their calibration certificates the expanded uncertainty of the results obtained as the standard uncertainty multiplied by the coverage factor $k = 2$, that for a normal distribution corresponds to a coverage probability of about 95%. This means that in our case we have to determine the standard uncertainty of the experimental data, for the observation times commonly used in calibrations, that satisfies the previous requirement.

In all cases, if we compare the ADEV with the y_{min} and y_{max} values, it appears that the first nearly always underestimates the real frequency deviations for every averaging time, and therefore it is not a reliable representation of the uncertainty of the GPSDOs to be used in the computation of the uncertainty budget of a calibration center. The same is also verified if the ADEV values are compared with the y_β ones, that are a more realistic representation of the behavior of the oscillators because they exclude the possible outliers present in the y_{min} and y_{max} values.

On the other hand, also the standard deviation s_y, that in most cases copes better with the range of frequency deviations represented by the y_β values, does not seem to satisfy completely to the criteria of a Gaussian distribution.

Some tests were performed on three sets of experimental data, relative to different observation times, to check their probability density distribution; the corresponding histograms are reported in Fig. 7 to 9, where the continuous line represents the Gaussian fit to each set of data. There is evidence for observation times of 1 s and 10 s that the fit is not representative of the distribution of the experimental data, whereas this works fine for $\tau = 100$ s. But tests performed on the same data sets to check their compliance with a triangular distribution, that in some cases seemed to give a better interpretation of the experimental data, showed that the Gaussian distribution fits better our case.

Coming back to the Allan deviation values, in the frequency stability curve shown in Fig.10 and computed on the experimental data of quartz GPSDO (A) for continuous averaging times τ multiples of $\tau_0 = 100$ s, it can be observed that the value of the maximum frequency deviation $\sigma_y(\tau = 4700\ s) > 3 \cdot \sigma_y(\tau = 100\ s)$ and next to the correspondent s_y value. Therefore the uncertainty estimation given by ADEV versus s_y can be improved by applying the same procedure to all data sets and looking for the maximum ADEV values.

The behavior observable in Fig.10 is typical of disciplined systems that show periodic variations in their output frequencies related to the time constant implemented in the disciplining processes.

FIELD TRIAL FOR FREQUENCY

A first verification of the assumptions of above has been made during an interlaboratory comparison organized in the summer of 1998 among ten calibration centers accredited for frequency by the Italian Calibration Service SIT, to verify the measurement capabilities of these laboratories.

Two kinds of traveling standards with different uncertainty levels were used for this purpose, a rubidium and a high performance quartz oscillator, that have been circulated among the laboratories. The devices have been characterized at the beginning and at the end of the circulation in the reference laboratory, the IEN, as regards to their frequency deviation and frequency drift. Detailed information about the devices specifications, the measurement procedure and the uncertainty evaluation criteria to be followed by the calibration centers were also supplied. Each laboratory was allowed one week time to calibrate the crystal oscillator and two weeks for the rubidium.

The measurement results were reported by the participants in formal calibration certificates that have been evaluated by IEN. Four out of the ten laboratories are equipped with GPSDOs as reference standards; two of them had to characterize the quartz oscillator and the others the rubidium standard. For both devices, the frequency deviations reference values and frequency drift have been determined by IEN, compared with the calibration data received and the compatibility coefficient computed.

This coefficient has been found compliant (<0,5) for both centers involved in the quartz calibration, but only in the case of the rubidium GPSDO the evaluation of the frequency drift was reliable, the short-term frequency deviation of the quartz GPSDO in fact, as previously shown, being at a level that inhibits the evaluation of the quartz daily drift ($2{,}6 \cdot 10^{-11}$) for the measurement period allowed.

Due to a failure occurred to the circulating rubidium that was replaced afterwards by another device, the data reduction of this loop has not yet been completed, but also in this case we expect that the compatibility of the measurement results is positive in the case of the frequency deviation data, but some problems are foreseen for the drift evaluation.

CONCLUSIONS

The studies, the experiments and the field verifications performed at IEN and in other metrological laboratories [3] on different types of GPSDOs to assess their performances as reliable means of standard frequency and time dissemination and their traceability to a national standard have demonstrated that this goal can be achieved.

To get a reliable uncertainty evaluation on the frequency deviation values that can be reached by a GPSDO in the averaging times from 1 s to 1000 s, commonly used in frequency calibrations, it has been found that the standard deviation or the maximum value of ADEV seem to be the better estimators to be taken into account for the uncertainty budget in calibrations.

A field verification of the assumptions presented in this paper, by means of a circulation of a rubidium oscillator between the calibration centers equipped with GPSDOs, is still ongoing and the first results confirm the assumptions made.

REFERENCES

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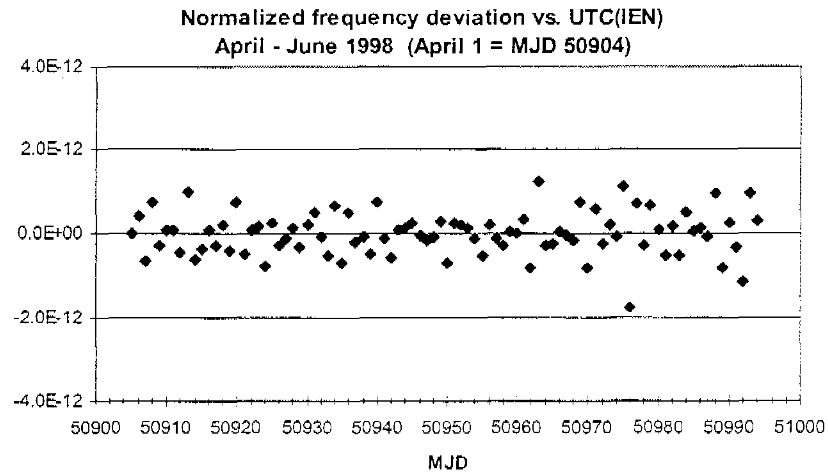


Fig. 1 – Remote calibration of a GPSDO (A) with an OCXO

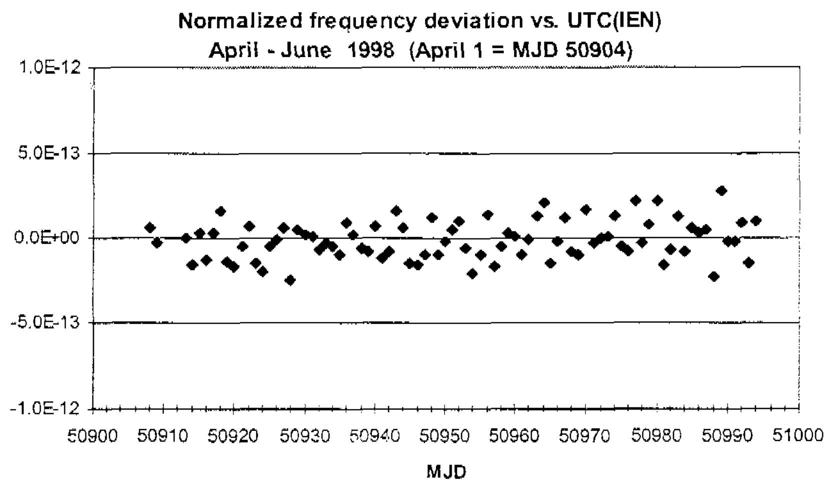


Fig. 2 – Remote calibration of a GPSDO (C) with a BVA

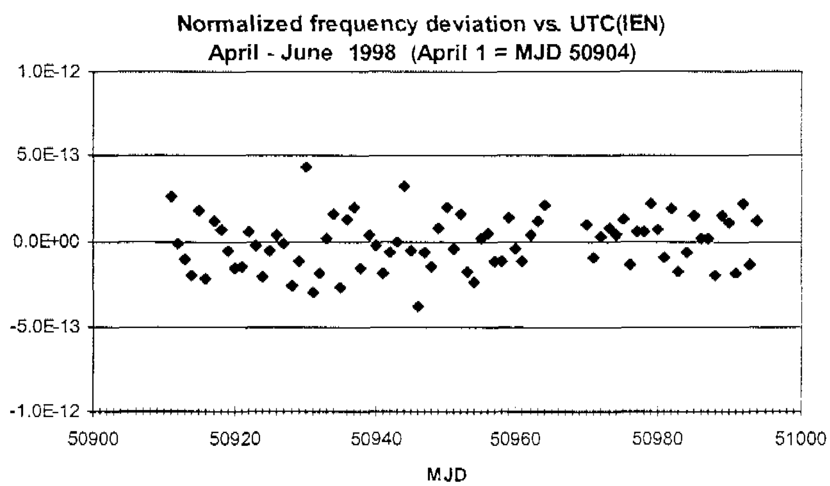
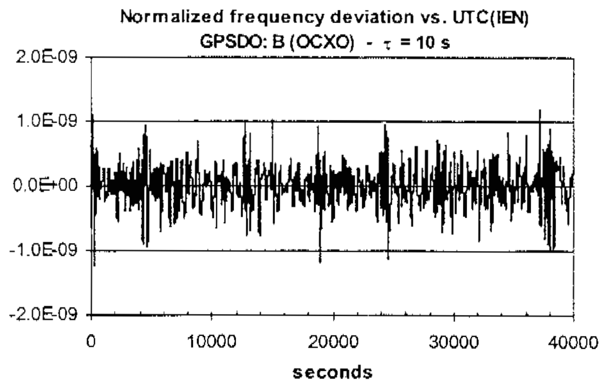
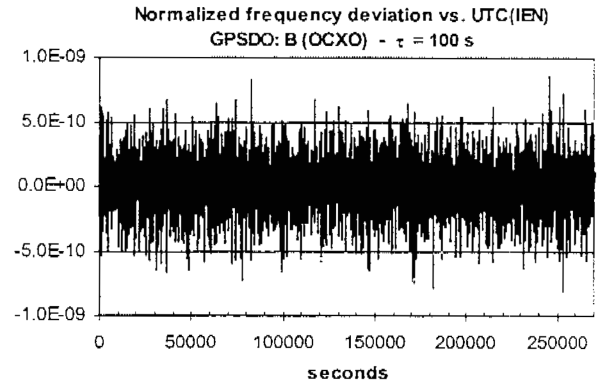


Fig. 3 - Remote calibration of a GPSDO (E) with a Rb





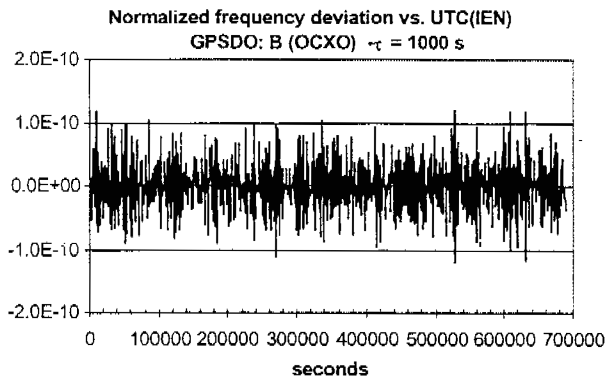
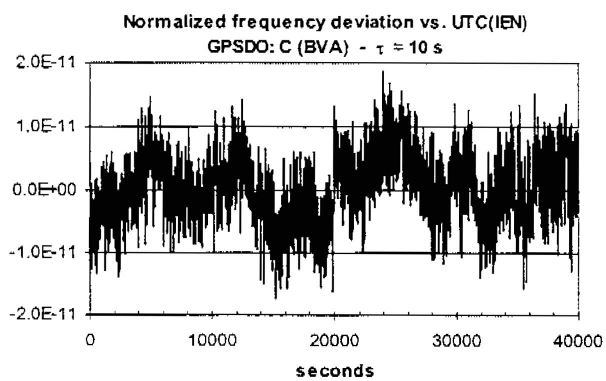
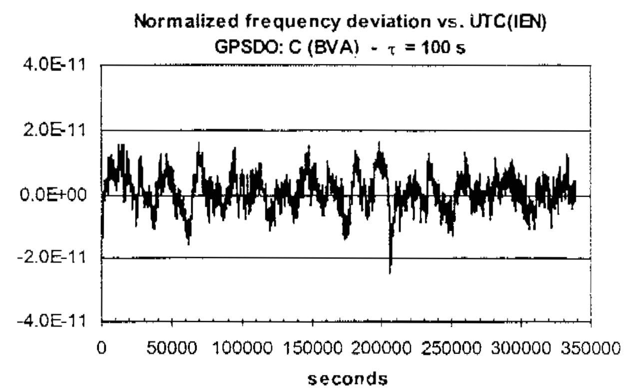


Fig. 4 – GPSDO (B), with an OCXO, for different measuring times





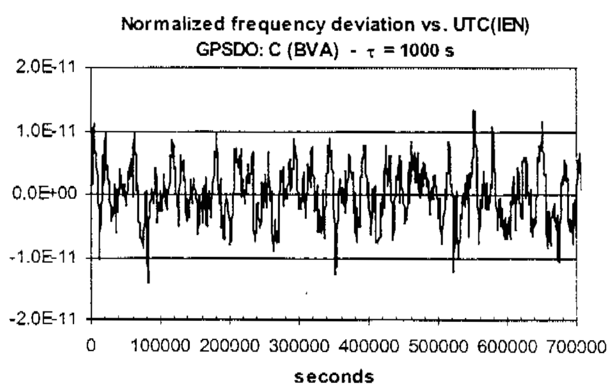
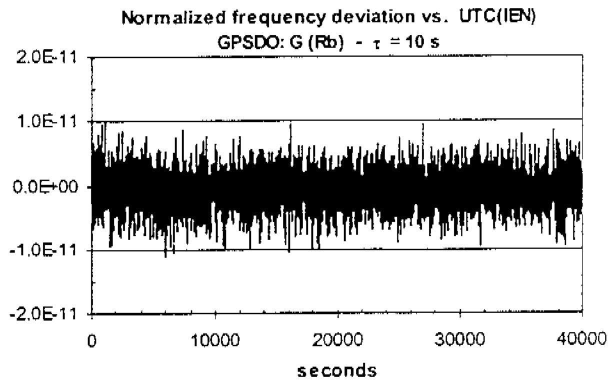
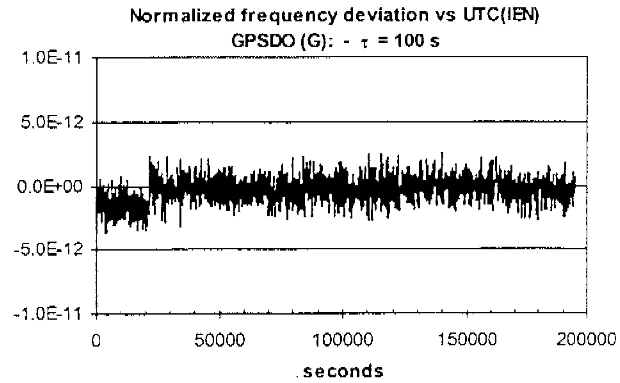


Fig. 5 – GPSDO (C), with a BVA, for different measuring times





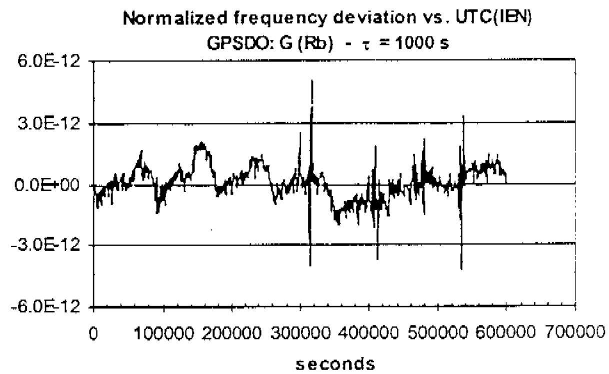


Fig. 6 – GPSDO (G), with a Rb, for different measuring times

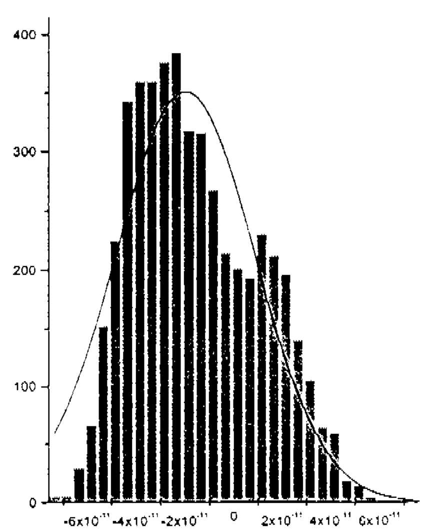


Fig. 7 – Frequency output histogram of GPSDO (A) for measuring time of 1 s

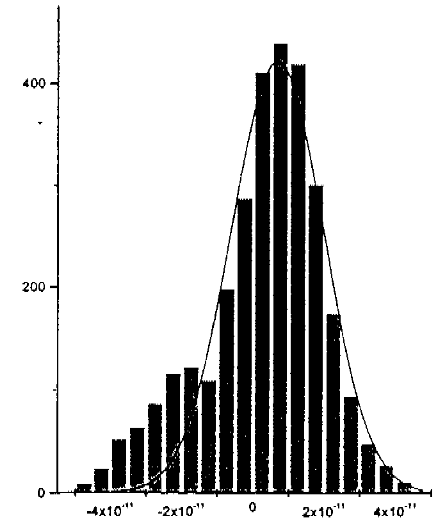


Fig. 8 – Frequency output histogram of GPSDO (A) for measuring time of 10 s

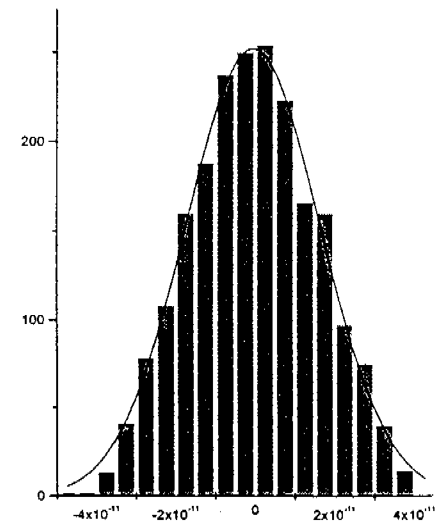


Fig. 9 - Frequency output histogram of GPSDO (A) for measuring time of 100 s

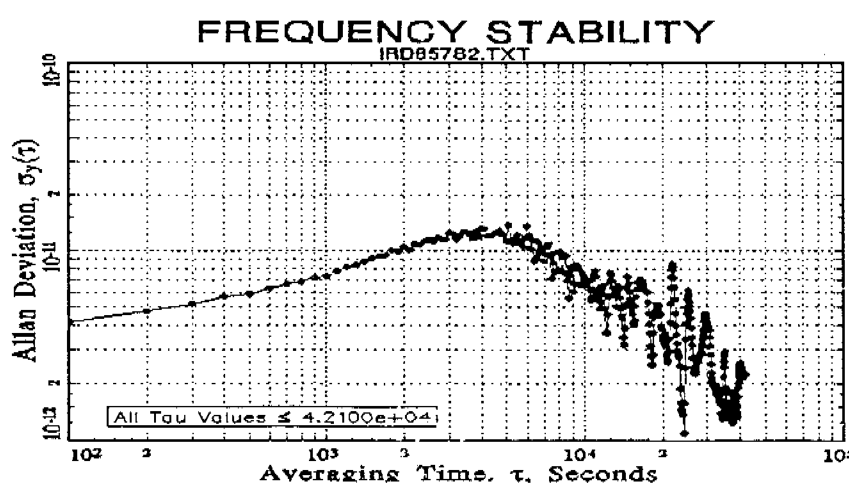


Fig. 10 - ADEV vs. time of GPSDO (A), equipped with an OCXO, for measuring time of 100 s

Questions and Answers

ROBERT DOUGLAS (NRC): That is very beautiful work. I am interested in your feelings about the statistical control of the other variables. Your calibration certificate is something which has evaluated some things, but there is a question of monitoring the stationarity of things like multipath, interference, even spoofing, or the GPS system itself. I am wondering how you integrate your calibration certification with a program for assurance that these elements, are in fact, under statistical control.

FRANCO CORDARA (IEN): Well, of course, what you are saying is something that can be done in the National Lab on each device. But I cannot foresee, in the case of secondary centers, that there are the quality of oscillators to continue this kind of observation to improve what we get. Of course, there are uncertain limitations in the way of evaluating them. I would call it a good compromise to leave these oscillators, after initial calibrations, in the National Laboratory completely free running. So, it is a compromise solution between the optimum and the worst.

I do not know if it has been clear – one thing that is very important to be aware of is not to look in the specifications of this kind of oscillator, only to the long-term accuracy of these devices when they work in the short term. In the short term, you have even two-times worse figures you have to take into account; and to make a proper characterization, at least once for all.