Long-Term Behavior of Operational Amplifiers

Enrico Rubiola, Claudio Francese, and Andrea De Marchi

***Abstract*—The voltage and current offsets of two typical precision operational amplifiers (OPAs) with BJT and FET input, respectively, were continuously measured for two years. The paper presents the experiment, explains the method of data analysis, and discusses the results. The long-term stability turns out to be limited mainly by random walk processes.**

***Index Terms*—Aging, amplifier noise, analog circuits, bipolar transistor amplifiers, FET amplifiers, operational amplifiers, random noise.**

I. INTRODUCTION

IN SPECIFYING precision operational amplifiers (OPAs), manufacturers usually report equivalent input noise spectral densities $\sqrt{S(f)}$, including white (WN) and flicker (FN) noise processes. On the contrary, information on long-term behavior is commonly quite incomplete. To describe the latter a single parameter is used, called *long-term stability*, *long-term drift* or *aging* (these terms are to be considered synonymous), which indicates the expected offset change over a given time interval. This parameter is always specified for the offset voltage $V_{\rm os}$ at one month. On the contrary, no information about long-term change of the current offset $I_{\rm os}$ was ever found, searching through some 25 to 30 databooks.

Aging is often regarded a secondary problem compared to other effects, the main of which is temperature if thermal excursion is allowed to be greater than a few kelvin. Yet, in high demanding applications temperature, power supply, and other environment or circuit parameters may be stabilized, while aging remains. Understanding the nature of aging is therefore relevant for applications of precision OPAs in metrology, when a true continuous operation is needed for a long time, and autozero techniques or chopper stabilization should be avoided because of noise or residuals of the chopper frequency. This is typical of any kind of electrical standard, but may have applications in high technology fields of industry.

Two basic processes may be included in the aging: random walk (RW) and linear drift (LD); obviously, both cannot be described by a single parameter. In databooks, the long-term stability limit is usually presented as a drift process. This is never stated clearly, but is suggested by the fact that the long-term stability parameter is almost always expressed in *microvolt per month* (μV/Mo), which is the physical dimension of LD. Few exceptions were found to this general rule, where the long-term stability is expressed in $\mu\text{V}/\sqrt{\text{Mo}}$ [1], [2] which clearly indicates that the aging process is RW. These exceptions always refer to chopper stabilized OPAs: the manufacturer clearly underlines the *zero drift* feature of these devices.

TABLE I
RELEVANT SPECIFICATIONS OF THE SELECTED OPERATIONAL AMPLIFIERS

parameter	OP 27	OPA 111
offset $V_{\rm os}$	30 μV	100 μV
offset $I_{\rm os}$	12 nA	500 fA
bias $I_{\rm b}$	15 nA	800 fA
thermal drift	300 nV/K	2 μV/K
	130 pA/K (os)	n. a.
	160 pA/K (bias)	n. a.
PSRR	2 μV/V	110 dB
		(> 100 dB)
white noise	3 nV/$\sqrt{\text{Hz}}$	6 nV/$\sqrt{\text{Hz}}$
	0.4 pA/$\sqrt{\text{Hz}}$	0.5 fA/$\sqrt{\text{Hz}}$
flicker noise	4.9 nV/$\sqrt{\text{Hz}}$	125 nV/$\sqrt{\text{Hz}}$
@ 1 Hz	4.7 pA/$\sqrt{\text{Hz}}$	n. a.
ageing	400 nV/Mo	n. a.

A number of physical phenomena can be responsible for a slow offset change. A sort of piezoelectric effect induced in the silicon by mechanical or thermal stresses of the package, combined with hysteresis, may cause aging when the device is randomly stimulated. A poisoning effect from the package is also possible, although recent technology seems to make this hypothesis unlikely. Trapped protons are good candidates to explain the aging because of their relatively high mobility in the silicon lattice. In fact, it is known [3] that during the chemical vapor deposition process—which is made with SiN plasma—some hydrogen ions are trapped in the Si lattice and in the interfacing surface between the Si lattice and the SiO_2 coating. However, OPA technology is not further investigated in this work, focused on the measurement of aging phenomena.

The experiment described here was carried out with two OP 27 and two OPA 111, chosen because they had been considered representative of two important classes of amplifiers widely used in precision electronics. The former is a general-purpose low-noise BJT device while the latter is a very low bias current FET input amplifier. A summary of the most relevant specifications of the selected OPAs is reported in Table I.

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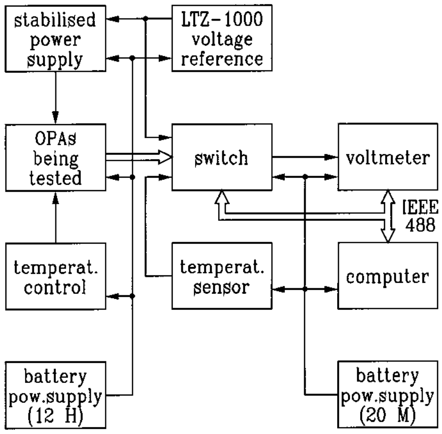

Fig. 1. Experimental configuration for the aging measurement.

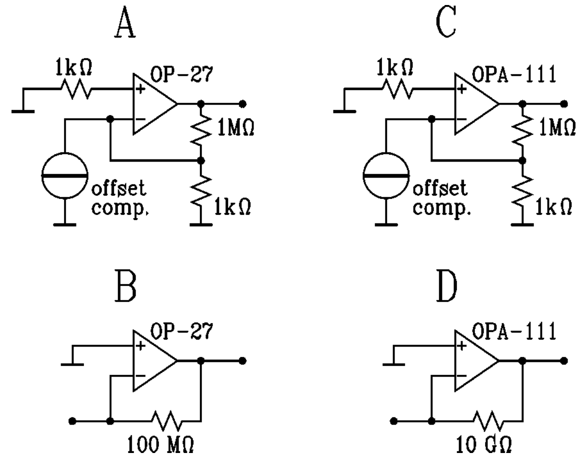

Fig. 2. Operational amplifier test circuits. The circuits A and C are used to measure the offset voltage, while B and D are used for the offset current.

II. Analysis Method

We first discuss the analysis method, which impacts on the hardware design prior to perform long acquisitions.

The classical variance cannot be used to characterize fluctuations in the presence of flicker and random walk processes, or drift. This occurs because the limit value of the sample variance estimate (N sample variance) is a function of the number of samples N, increasing with N. Therefore, we described flicker and random walk in terms of Allan variance $\sigma^2(\tau)$ [4], as a function of the measurement time τ, and we use the Allan deviation $\sigma(\tau)$ to report the results. In our case $\sigma(\tau)$ has the physical dimension of voltage or current, which is emphasized by the appropriate subscript. The Allan variance is a simple tool suitable to LD, RW, and FN, and can be regarded as a simple case of wavelet analysis [5]. The modified Allan variance mod $\sigma^2(\tau)$ [6] was not considered because its main advantage, as compared to the Allan variance, consists of improved capability in distinguishing between the *fast* noise processes, which is not relevant for our purposes.

Given a stream of M data $\overline{y}_k$, each representing a measure of the quantity $y(t)$ averaged over a duration τ ending at time $t = k\tau$, the Allan variance is

$$\sigma_y^2(\tau) = \frac{1}{2(M-1)} \sum_{k=1}^{M-1} (\overline{y}_{k+1} - \overline{y}_k)^2. \tag{1}$$

Contiguous data of a single file of rough instrument readings can be joined to form new streams related to longer τ values, preferably in power-of-two sequence. A dead time between measurements, that can not be avoided in our experiment, introduces excess noise in short term due to aliasing. This problem is irrelevant here because the focus is on long term. In order not to confuse the issues, short-term results are therefore suppressed in $\sigma(\tau)$ plots.

III. Description of the Experiment

The complete measurement system is shown in Fig. 1. In the measurement cycle, which lasts 10 seconds, the computer sets the switch and reads the offset signals, together with the environmental temperature and the reference and supply voltages. The measurement time of the voltmeter was set to 100 ms. Data stored onto the disk also include time labels and information on the system, such as the status of the power supply, failures of the mains, etc.

Test circuits, shown in Fig. 2, were designed according to the following criteria:

1) Circuits A and C are voltage amplifiers with grounded inputs. Resistance values are such that the output signal is proportional to the offset voltage, with a negligible contribution of the offset current. Similarly, circuits B and D are transresistance amplifiers with open input; their output voltage is proportional to the offset current. Where considered necessary, offset compensation was introduced because OPAs tend to behave better with improved symmetry.
2) The resolution design specification for our system turned out to be mainly determined by the OPA flicker noise. In fact, from specified OP 27 offset voltage FN (see Table I), we expect a flicker floor $\sigma_V \simeq 5.8$ nV. Consequently, a resolution of 1 nV must be ensured. Similarly, a resolution of 100 fA and 1 nV are sufficient for the OP 27 current offset and for the OPA 111 voltage offset. As regards the OPA 111 current, we supposed that a resolution of (0.1–1) fA would be adequate; anyway, we did our best because no specification was available.
3) The voltmeter resolution of 100 nV must be made negligible by choosing sufficiently high gain values.
4) The thermal noise of resistors, which is of the $1/\sqrt{\tau}$ type in the $\sigma(\tau)$ plane, should not hide the flicker floor. Noise spectra of the test circuits were carefully evaluated according to [7] and converted into $\sigma(\tau)$.

Voltage across all the critical resistances is close to zero, which attenuates the effect of resistance fluctuations. Nonetheless, the resistance flicker was evaluated on the basis of data available in [8] prior to consider the resistance fluctuations negligible.

Temperature stability is a critical point of our experiment, mainly because of the OP 27 thermal drift, which is 300 nV/K. A thermal stability of 3.3 mK must then be ensured in order to guarantee that measurements be meaningful at the 1 nV level. This stability is guaranteed by placing the test circuits

TABLE II
NOISE ESTIMATES AND MEASURES FOR THE TEST CIRCUITS

FLICKER NOISE @ 1 Hz		OP 27		OPA 111	
		voltage	current	voltage	current
1	amplifier alone: specifications	$4.9\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$	$4.7\ \mathrm{pA}/\sqrt{\mathrm{Hz}}$	$125\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$	n. a.
2	whole circuit: measured PSD	$5.3\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$	$6.2\ \mathrm{pA}/\sqrt{\mathrm{Hz}}$	$60\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$	—
3	$\sigma(\tau)$ expected from the measured PSD	6.2 nV	7.3 pA	71 nV	—

in a thermostat consisting of a 3-mm thick aluminum box, thermally insulated by a 20-mm thick polystyrene foam layer which also prevents heat exchange due to air flow. This assembly also keeps the inner temperature uniform, which is important to prevent parasitic thermocouples inside the circuits; for example, the Seebeck coefficient between the chips Kovar pins and the copper is as high as 30 μV/K [9]. The aluminum box is thermally stabilized within a few millikelvins to the room temperature by means of a house-built PID control and a Peltier cell.

Current leakage is another critical point. For this reason, we decided to keep the test circuits as simple as possible. For example, we avoided all low-pass filtering. For the same reason, circuit D (OPA 111 current offset), which is the most critical one because the OPA bias current is smaller than 1 pA, was mounted as a "dead bug", thus avoiding the presence of any board surface which would collect humidity. Finally, silica gel desiccant was inserted in the thermostat box, which is also nearly sealed.

The stability of the $\pm$15 V OPA power supply turned out to be a critical parameter. As the PSRR of the OPA 111 can be as low as 100 dB, a voltage stability of 10^{-5} was required to keep the effects of supply voltage variations in the nV range. For this reason we built a power supply driven by an LTZ-1000 voltage reference, which can be considered perfectly stable for our purposes [10]. This voltage reference is also used for system diagnostics and to check the long-term stability of the digital voltmeter.

In laboratory conditions, the mains failure probability is expected to be so small that it would cause a negligible data loss in our experiment. However, it is really important to keep the analog circuits in operation in order to prevent hysteresis that could take place in case of switching off. For this reason we chose a two-battery power supply configuration, as shown in Fig. 1. The first supply, with a power of a few hundred watts and a lifetime of 20 min, allows the computer to properly shut down in case of blackout; the second one, whose power is about 100 W, can keep the analog circuits in operation for at least 12 hours.

Most of the experience on temperature control, voltage references, resistors, and precision analog design comes from [11].

The computer operates under OS-2 operating system. This is a true multitasking system which allows monitoring, maintenance and backup operations while the measurement task is running.

The system has been working for two years without any failure of the analog circuits. The computer system stopped five times because of blackouts, planned maintenance and human errors, causing the loss of two weeks of data.

IV. EXPERIMENTAL RESULTS

Table II reports a summary of the flicker parameters of our experiment. The OPA specifications (row 1) are in reasonable agreement with the measured power spectrum densities (PSD) reported in row 2. The PSD was obtained by means of a fast Fourier transform (FFT) analyzer connected at the test circuit outputs when the system was not in operation. The results of two years of measurements are reported in Figs. 3–8 discussed below. The last reported point in Allan deviation plots $\sigma(\tau)$ is at $\tau = 10^7$ s, which corresponds to four months. This is done in order to maintain good statistical significance. The confidence intervals reported onto Figs. 3, 5, 6 and 8 have been calculated with the χ^2 method. Finally, the relationships between $\sigma(\tau)$ and $S(f)$, used to relate some of our results to the frequency-domain specifications of the OPA noise, are obtained from [12].

A. OP 27

Fig. 3 reports the measured Allan deviation of the OP 27 voltage offset. Experimental data (□) in log–log scale are well approximated by the dashed straight lines with slope 0 and $+1/2$, analytically described by

$$\sigma_V(\tau) = 5\ \mathrm{nV} + 30\sqrt{\tau}\ \mathrm{pV}. \qquad (2)$$

For $\tau \leq 4 \times 10^4$ s the main process is flicker noise with a deviation $\sigma_V = 5$ nV, which is in good agreement with the value of Table II, calculated from the spectrum. Short-term data, for $\tau < 80$ s, have been suppressed from that plot because they are affected by aliasing.

For τ values higher than a few hours the deviation is well approximated by $\sigma_V = 30\sqrt{\tau}$ pV. This slope indicates that random walk is the main process.

A least squares linear fit performed with time-domain data shows that drift, if any, is no more than 1.6 fV/s, which is negligible compared with the experimental data of Fig. 3. In fact, this LD value would be represented by a straight line with slope $+1$, at least 16 dB lower than the $\sigma(\tau)$ plot at its extreme right in Fig. 3.

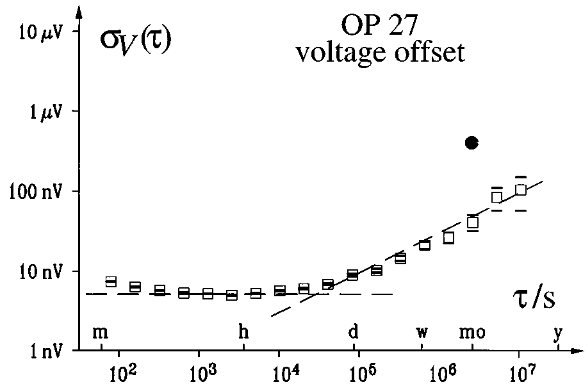

Fig. 3. Measured Allan deviation $\sigma_V(\tau)$ of the OP 27 voltage offset. The dashed lines are $\sigma_V(\tau) = 5$ nV (flicker), and $\sigma_V(\tau) = 30\sqrt{\tau}$ pV (random walk). The black spot reports the specified aging parameter, i.e., 400 nV at 1 month.

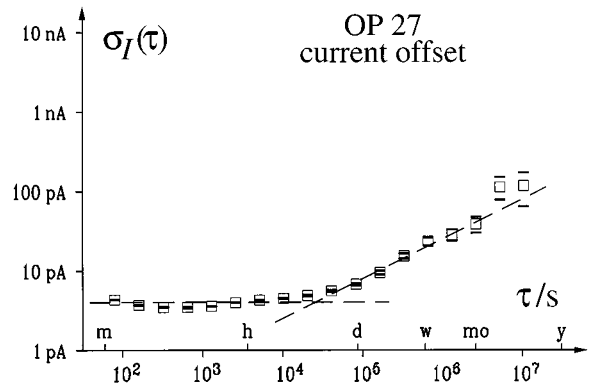

Fig. 5. Measured Allan deviation $\sigma_I(\tau)$ of the OP 27 current offset. The dashed lines are $\sigma_I(\tau) = 4$ pA (flicker), and $\sigma_I(\tau) = 25\sqrt{\tau}$ fA (random walk).

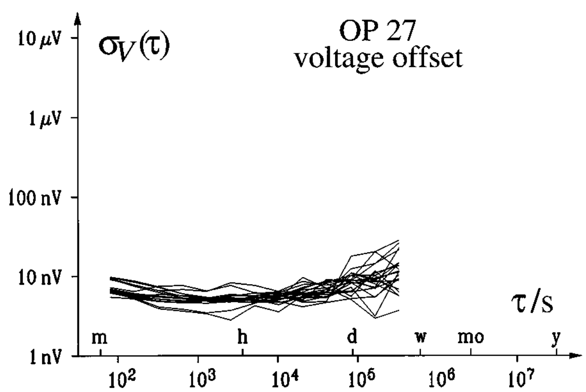

Fig. 4. Allan deviation $\sigma_V(\tau)$ of the OP 27 voltage offset. Each plot is obtained from 1 month of data acquisition.

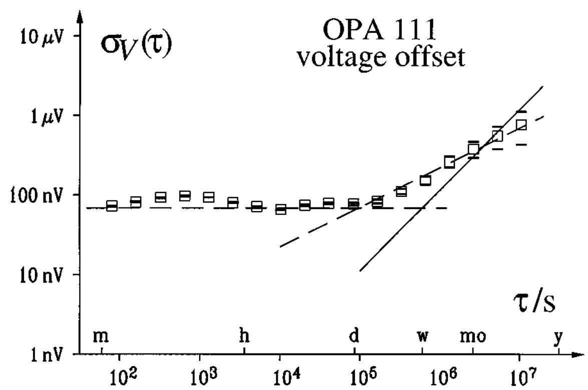

Fig. 6. Measured Allan deviation $\sigma_V(\tau)$ of the OPA 111 voltage offset. The dashed lines are $\sigma_V(\tau) = 70$ nV (flicker), and $\sigma_V(\tau) = 220\sqrt{\tau}$ pV (random walk). The linear drift $\sigma_V(\tau) = 120\tau$ fV, reported as a solid line, has been detected by means of a least square linear fit in the time domain.

In order to compare our experimental data with the aging specification of the OP 27, we have reported this specification as a black spot in the right part of Fig. 3. The specified aging, 400 nV at 2.5×10^6 s (1 month) is about 20 dB higher than the measured $\sigma_V(\tau)$ for the same τ. This difference, although relevant, is not astonishing because of two reasons. First, our amplifiers are kept in an exceptionally quiet environment, with no load at their outputs and with a stable power supply that has never been switched off. These cautions prevent any possible stress phenomena that would be present in a more realistic situation and that would contribute to the aging. Second, the aging appears not to be well understood (in fact, in many circumstances it is hidden below other effects, mainly the thermal drift), and consequently it looks reasonable to find conservative specifications in data sheets.

Finally, Fig. 4 reports a number of $\sigma(\tau)$ plots, each obtained from one month of data acquisition. As all the curves are close to one another, we can conclude that the involved noise processes are stationary, at least over the considered τ span.

The Allan deviation of the OP 27 offset current, reported in Fig. 5, is well approximated by

$$\sigma_I(\tau) = 4 \text{ pA} + 25\sqrt{\tau} \text{ fA}. \quad (3)$$

The presence of white noise, enhanced by aliasing, can be recognized in the leftmost point, at $\tau = 80$ s, where the plot has been truncated.

In the central part of the plot of Fig. 5, for 160 s $< \tau < 2\times10^4$ s the main process is flicker noise, characterized by $\sigma_I(\tau) = 4$ pA. This is in reasonable agreement with the prediction based on spectral data reported in Table II, with a discrepancy smaller than 4 dB.

For $\tau > 2 \times 10^4$ s, as shown in Fig. 5, the measured Allan deviation fits to $\sigma_I(\tau) = 25\sqrt{\tau}$ fA, which is random walk. Observing the last three points to the right, the presence of LD could be inferred. In fact, due to the asymmetry of the χ^2 distribution when a small number of data is available, in the absence of LD we would expect the last point well below the extrapolation line, as shown. Nevertheless, at least in this case the above general rule fails and probably no drift is present. In fact, a least square fit on time-domain data does not reveal any drift.

B. OPA 111

The experimental results of voltage offset measurements, shown in Fig. 6, can be approximated by the law

$$\sigma_V(\tau) = 70 \text{ nV} + 220\sqrt{\tau} \text{ pV}. \quad (4)$$

For $\tau \leq 10^5$ s, the statistics of voltage changes is of the flicker type ($\sigma_V = 70$ nV). This is in close agreement with the value of $\sigma_V = 60$ nV reported in the Table II, and expected from PSD measurements. In the region around $\tau \simeq 10^3$ s, for unexplained reasons, σ_V turns out to be about 2 dB higher than the estimated floor of 70 nV.

The rightmost experimental points, for $\tau \geq 10^5$ s, are well approximated by the line $220\sqrt{\tau}$ pV, which represents a random walk process.

Inspecting the plot of Fig. 6, the presence of the LD can be inferred from the rightmost point, which is aligned to the previous ones instead of being lower. In fact, a least-squares linear fit on all the data file reveals the presence of a linear drift of 120τ fV, which exceeds the RW at long-term, for $\tau = 3.4 \times 10^6$ s. The above indicated drift is reported as a solid line in Fig. 6.

Allan deviation evaluations performed on slots of 5 weeks of data overlap perfectly for τ values up to 10^4 s, and show a peak-to-peak excursion smaller than 3 dB for higher τ values; the corresponding plot, not reported here, is similar to Fig. 4. This fact suggests that the noise processes are stationary in the considered conditions.

It has been discovered that the Fourier transform of the offset voltage shows a spectral line of 30 nV rms at $f = 1.16 \times 10^{-5}$ Hz, which is the reciprocal of one day. Common sense suggests that this is an environmental temperature effect, acting either directly or through humidity. No similar phenomena were observed in the OP 27. Anyway, because the reported perturbation is 7 dB below the flicker floor, we have no means to further investigate on it.

Finally, it should be pointed out that taking the one month Allan deviation $\sigma_V(\tau)$ as the *aging* parameter would be completely unclear in this case. In fact, random walk and true drift contribute to the OPA 111 offset voltage fluctuations measured at one month.

The OPA 111 current offset measurement turned out to be less fortunate than the other ones because we got a great dispersion of experimental values. Observing the current offset as a function of time (Fig. 7), there are two peaks whose duration is about one month, both occurring in the summer. These peaks are clearly due to a systematic effect. In spite of this, we could not find any relationship between these peaks and recorded environmental parameters or their derivatives. The Allan deviation of the OPA 111 current is shown in Fig. 8. Evaluating the deviation on several one-month time slots when the amplifier is "quiet," we get the results reported as solid lines in the lower part of the figure. In the leftmost parts ($\tau \leq 2000$ s), where the solid lines are perfectly overlapped, WN is still present, due to the feedback resistance [Fig. 2(D)], and enhanced by aliasing. The Allan deviation evaluated on the whole data file, hence including the peaks, yields the experimental points (□) of Fig. 8. The overall aspect, fits the dashed line

$$\sigma_I(\tau) = 63\sqrt{\tau}\ \text{aA} \tag{5}$$

and looks like a random walk process.

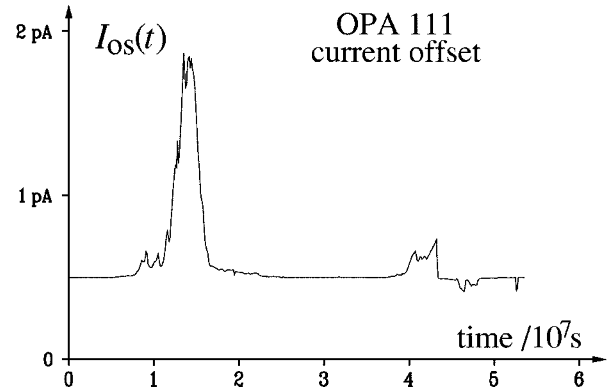

Fig. 7. Current offset of the OPA 111, as a function of time. The two peaks occurring in the summer are due to a systematic, although not identified, effect.

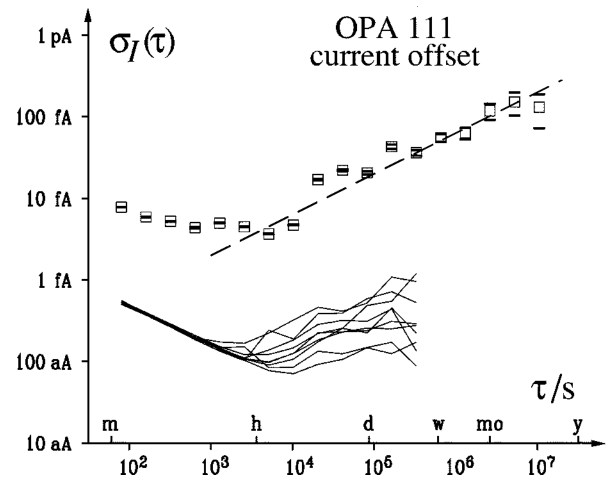

Fig. 8. Measured Allan deviation $\sigma_I(\tau)$ of the OPA 111 current offset. The upper plot, approximated by the dashed line $\sigma_I(\tau) = 63\sqrt{\tau}$ aA, is related to the whole duration of the experiment, thus including the anomalous summer behavior. The solid plots in the lower part come from 1 month time slots where the amplifier is "quiet."

V. Conclusions

A search through several operational amplifier databooks reveals that aging is specified with a single parameter—the offset change in one month—which leads one to think of a drift. No information is given on the process type. Moreover, no indication about the current offset aging was ever found.

In order to better understand aging, we monitored four operational amplifiers collecting offset data every 10 seconds for two years. The experiment was designed with provisions to ensure that observed fluctuations, both in short- and long-term, come from OPAs and not from the system. These provisions include power back-up to guarantee system integrity, thoughtful circuit design to minimize noise contributions from resistors, supply and voltmeter,and environmental stabilization. Measured aging is described in terms of Allan deviation, which allows a clear distinction between flicker, random walk, and drift processes.

In three cases, the ones that have been well understood, the offset change in one month turns out to be due to a random walk process, although linear drift may be present at longer term.

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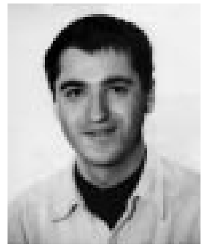
Enrico Rubiola, photograph and biography not available at time of publication.



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Dr. De Marchi was the recipient of the 1991 Rabi Award for his achievements in the improvement of Cesium standards.