Simple techniques to restore time-averaged Langmuir probe characteristics

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Abstract. We present three simple techniques that enable restoring time-averaged Langmuir probe characteristics measured under time-varying plasmas, in the sense that plasma parameters (electron density and average energy, electron energy distribution function, and plasma potential) will be deduced more accurately than what otherwise can be retrieved from averaged data.

1. Introduction

All kinds of data acquisition have to deal with the finite integration time problem. In the simplest case the output is the result of an average, but it is not unusual the (time) Instrumental Function (IF) to depart from a rectangular one. In addition, most acquisition system manufacturers make devices that have only convoluted outputs, i.e., the standard deviation is not available. As a result, users commonly choose integration times based on “looks nice” criteria, which fosters a tendency to be unaware of the amount of distortion introduced by averaging in non-linear systems. Spectroscopy is a potential candidate since integration times may have to be very long and can be changed at a touch of a button. Conversely, integration times are usually shorter in Langmuir probe diagnostics and, for using less-commercial systems, users have more hardware control and are more aware of restoring problems, which explains why such an important, general issue is hereby raised concerning probes.

Although it is relatively easy to perform time-resolved Langmuir probe measurements, it may not be known at acquisition time that the plasma under analysis is not in steady state, which may be due to the onset of striations or to deficiently mains-filtered power supplies, namely those of microwave generators. Conversely, the existence of fluctuations may be known in advance but still average plasma characteristics are only sought for due to its simplicity vs. the extra burden associated with time-resolved ones. A typical case is when industrial applications use plasmas as “black boxes” and assume that average plasma parameters are enough to describe on-going processes. The moving striations case is another example since it may not be feasible to get a time-reference to lock the data acquisition system.

As a result of the probe characteristic distortion, the second derivative no longer mirrors the electron energy distribution function (EEDF), and even simpler quantities, like the density and the
mean energy of electrons, and the position of the plasma potential, cannot be accurately deduced in a straightforward way due to the additional inverse integral problem.

In the continuation of authors’ previous works on inverse problems on probes [1-3], here we analyze the conditions that must be satisfied and the procedures that can be used to retrieve as much information as possible from time-averaged probe characteristics, namely, the values of the average electron density and mean energy, as well as their modulation amplitudes, and a meaningful EEDF.

2. Basic requirements
A naked-eye analysis of the time variation of plotted probe characteristics measured in non-steady plasmas looks like anamorphically deformed plots as current is rescaled by electron density and average speed, and as voltage is rescaled by the electron energy. Besides, plots will be shifting along the voltage axis due to a non-steady floating potential. A deeper analysis reveals second derivative changes due to the EEDF variation at the corresponding energy, as well as to energy-integrated contributions, e.g. due to collisions. In addition, since we are dealing with non-linear effects, the actual spectra of all plasma parameters would be expected to be a key parameter to any restoring technique.

The inverse problem is virtually impossible to solve under the general picture described above. Hence, though some effects can be circumvented as shown below, we still have to impose constrains. First, the value of the RMS deviation (RMSD) of any time-averaged measured quantity must be known, which is rather a good general practice than an imposition. Conversely, the actual spectra may not need to be known. Indeed, we can readily obtain the RMSD, \( \sigma \), of a periodic function, \( f(x) \), and the DC shift, \( \Delta \), of its time-averaged value, from a second order expansion as:

\[
\sigma^2 \equiv x_{\text{RMS}}^2 f'' + \delta \Delta^2
\]

\[
\Delta \equiv \frac{x_{\text{RMS}}^2}{2} f''
\]

where \( x_{\text{RMS}} \) is the RMS value of \( x \), and \( \delta \), which is usually a small quantity, accounts for the actual form factor of \( x \) (\( \delta = 0 \) and \( \frac{1}{2} \), respectively, for a square and a sinusoid, but its value becomes \( >1 \) for spiky signals). As a result, a RMS approach provides a fair description if amplitudes are small enough and a pertinent \( \delta \) value is chosen. Although information on the form factor of modulations can be retrieved using \( \delta \) as a fitting parameter, in the current work we shall assume \( \delta = 1 \) for the sake of convergence speed. The fact that we can reduce time-variations to square-wave ones does not mean that the phase difference, \( \varphi \), between the density and the mean energy is a negligible parameter. In this work we assume that the value of the phase is either 0 or \( \pi \), which is typical under hysteresis-free, low-frequency situations.

The time variation of the floating potential can be eliminated using either a prior-to-average software shifting or active probe–auxiliary electrode differential measurements under a triple-probe arrangement, which are again good practices instead of constrains. Yet, the above latter solution is not an absolute guarantee that the probe–auxiliary electrode voltage is time-modulated free, namely when electrodes have different sizes and/or are located at different spatial positions and a time-varying electric field is present. In the former situation, the problem arises due to the influence of the ratio probe-radius/Debye-length on the value of the floating potential (see e.g. [4]) and is more noticeable when electrodes are located close to the walls. Anyway, such effect can readily be detected by a non-zero RMSD when the averaged probe current is zero and can be minimized by the inclusion of a potential modulation as an additional fitting parameter in the procedures suggested below.

Although it is common to parameterize solutions when solving inverse integral problems, we prefer to try to avoid constrains on the EEDF itself.

3. Methods of solution
Our aim is to retrieve values of the plasma parameters at the time when the instantaneous value of the electron density and mean energy modulation is zero. In this direction we suggest three methods to solve the inverse problem under analysis: 1) a semi-analytical method (SAM), based on analytic
expressions of the first and second derivatives of the probe characteristic, which only requires the RMSD of the measured probe current, i.e., the probe characteristic itself is not needed; 2) a numerical method, based on an anamorphic deformation of the probe characteristic (ADM); 3) a numerical method, based on a linear deformation of the low-energy part of the EEDF (BDM).

Unless otherwise stated, EEDFs are deduced from second derivatives of probe characteristics, and the normalizing constants provide the value of the electron density (multiplied by the probe area, $A$). Conversely, electron average speeds (hence probe characteristic) and mean energies are calculated as moments of the EEDFs.

3.1. Semi-Analytical Method
Analytical expressions for the RMSD and the DC shift are not known except in very few cases of practical interest, and the Maxwellian EEDF case is one of such exceptions. In addition, as a peculiarity of exponential functions, derivatives in equations (1)-(2) can readily be expressed as simple functions of $f$. So, we shall use the Maxwellian EEDF as an example, in which case, neglecting non-linear contributions from the ion saturation current and within the exponential part of the probe characteristic,

$$ f(t) = I(t) \equiv Bn(t)\sqrt{V_0(t)}\left(\frac{V}{e^{V_0(t)}} - 1\right), \quad (3) $$

where $t$ is the time, $I$ and $V$ are, respectively, the probe current and the bias voltage referred to the floating potential, $n$ is the electron density, $V_0 = kT_e/e$ ($k$ is the Boltzmann constant, $T_e$ is the electron temperature, and $e$ is the modulus of electron charge), and $B$ is the appropriate scaling constant. The RMSD and the DC shift can then be expressed analytically as:

$$ \sigma^2 \equiv \left( \pm \frac{\Delta n}{n} + \frac{1}{2} \frac{\Delta V}{V_0} - V \frac{\Delta V_0}{V_0} \frac{\partial I}{\partial V} \right)^2 + \Delta^2 \quad (4) $$

$$ \Delta \equiv \frac{1}{2} \left[ -\frac{I}{4} + \frac{V}{2} \frac{\partial I}{\partial V} + \frac{V V_0}{2} + V^2 \right] \frac{\partial^2 I}{\partial V^2} - IC^2 \pm C \left( \frac{1}{2} - V \frac{\partial I}{\partial V} \right) \left( \frac{\Delta V_0}{V_0} \right)^2, \quad (5) $$

where $\Delta n$ and $\Delta V/V_0$ are the RMS relative variations of the electron density and average energy, and $C = V_0 n \Delta n/\Delta V_0$ accounts for the fact that $n$ and $V_0$ are correlated, functions of time. The + and − signs apply, respectively, to $\phi = 0$ and $\pi$.

The method of solution is then simple: an arbitrary probe characteristics is used as a starting $I(V)$; $\Delta n$ and $\Delta V/V_0$ are used as parameters to fit $\sigma$ to the measured RMSD; the differential equations (4)-(5) are numerically solved and provide a new $I(V)$; the procedure is repeated until convergence. Mild regularization may be required to avoid numerical instabilities around the floating potential, which sometimes do not vanish after a couple of iterations. Otherwise convergence is very fast in the $\phi = \pi$ case. Conversely, convergence may become problematic in the wide maximum–zero region of the second derivative, which averaging introduces when $\phi = 0$. Although the above problem can be solved in several ways (see §5), namely by hard regularization, we currently do not suggest this method to be used when density and energy fluctuations are in phase.

Equations (4)-(5) show that the actual value of $V_0$, which only appears explicitly once in (5), is not a crucial parameter and may be adaptively adjusted when dealing with stepwise exponential EEDFs. As a result, the applicability of the current method is not confined to a Maxwellian EEDF situation.

3.2. Anamorphic Deformation Method
The Maxwellian EEDF case, which we analysed analytically in §3.1 as an example, can be handled in a purely numerical way using its exponential variation of the electron current. Indeed, $y/a = \exp(x/b)$ is a two-parameter function, having one parameter allocated to $x$ and the other to $y$, which means that each parameter, though not independent, acts as a rescale factor, i.e., once anamorphically deformed
one single exponential represents any other else. So, whenever the EEDF is such that the probe characteristic can be assumed as:

\[ I(V, \Delta n, \Delta V_0) = I(V_1, 0, 0)(1 \pm \Delta n/n)(1 \pm \Delta V_0/V_0)^{1/2}, \]

where \( V_1 = V/(1 \pm \Delta V_0/V_0) \), we have another way to recover the undisturbed probe characteristic that provides RMSDs and DC shift values equal to those measured (the + and – signs before \( \Delta n \) apply, respectively, to \( \varphi = 0 \) and \( \pi \)). Yet, under a square-wave approach, the above quantities for each value of \( V \) result from two values of \( V_1 \), i.e., those resulting from the + and – signs that appear before \( \Delta V_0 \) in (6), meaning, broadly speaking, that the number of unknowns is equal to the number of equations plus 2. Hence, there is a mathematical problem that must be overcome first. Hopefully, under the assumptions made in §2, \( \sigma \) and \( \Delta \) become vanishing small in the vicinity of the floating potential, which means that the measured probe characteristic is not distorted and provides accurate values when \( V \to 0 \). The method of solution is then straightforward: the measured probe characteristic is used as a seed for \( I(V) \); \( \Delta n/n \) and \( \Delta V_0/V_0 \) are adjusted to fit \( \sigma \) to the measured RMSD; we start from the points closer to \( V = 0 \); the value of \( I \) at \( V_1 = V/(1 + \Delta V_0/V_0) \) is obtained by interpolation from the seeded \( I(V) \); the measured current and (6) provide a corrected value of \( I \) at \( V_1 = V/(1 - \Delta V_0/V_0) \); as soon as \( V \geq (1+\Delta V_0/V_0) V_{\text{step}}/2 \), where \( V_{\text{step}} \) is the voltage step, we already have corrected values for the current that should be used instead of averaged ones; the new \( I(V) \) replaces the seed and the procedure is repeated until convergence.

Since equations (6) is valid for exponential \( I(V) \) functions, we may again generalise its use for stepwise exponential EEDFs as stated in §3.1.

3.3. Body Deformation Method

Here, we assume that the tail temperature of the EEDF remains constant in time below a given probe potential, \( V_x \), while the body suffers a linear deformation, an assumption that is more general than a Maxwellian EEDF one. In the framework of our basic requirements, the above is equivalent to a change of \( \pm \Delta V_p \) on the plasma potential, \( V_p \). The method of solution is again simple: the averaged characteristic is used as a starting \( I(V) \); \( V_x, \Delta n/n \) and \( \Delta V_p \) are used as parameters to fit the measured RMSD to that numerically calculated; a new \( I(V) \) is calculated by averaging the probe characteristics having their plasma potentials at \( V_p \pm \Delta V_p \); the procedure is repeated until the fitting error reaches a minimum. Unfortunately, regularization is obligatory in the vicinity of the plasma potential, which unavoidably destroys the sharpness of the maximum-to-zero transition of the EEDF. As a result, the amount of regularization becomes a fourth fitting parameter, which we adjust by making runs with different filters. Conversely to the previous methods, BDM convergence is slow since \( I(V) \) must be updated smoothly, which is particularly important when \( \varphi = 0 \).

4. Application examples

The above methods were tested using Maxwellian and tri-Maxwellian EEDFs as model cases and actual data measured in a Surface Wave (SW) discharge.

4.1. Model cases

In order to show how easily methods can be implemented, we made all the calculations using a PC spreadsheet. The measured probe characteristics and RMSDs were calculated from 100 characteristics derived from electron densities and average energies with sinusoidal modulations. Modulation depth values are 50% and 20%, respectively for the density and the mean energy. The model characteristics were built assuming ion saturation currents proportional to the square root of the electron mean energy, \( <u> \), and second derivatives symmetrical around the plasma potential. The voltage step was 0.1 V. A summary of the results achieved for the model case study is presented in table 1, where the “Solution” row stands for the non-modulated probe characteristic.

In the Maxwellian case EEDFs were modulated changing the value of \( V_0 \). Considering that a Maxwellian EEDF satisfies the requirements for all methods, it is not too surprising that results are
similar in accuracy. For $\phi = \pi$, SAM missed the correct value of the normalized electron density, $n$, electron average energy, and $V_p$ respectively, by 10%, 0.8%, and $-0.4$ V, while the above errors are 10%, 2%, and $-0.11$ V for ADM and 11%, 1%, and $-0.31$ V for BDM. The information retrieved from the raw probe characteristic, which is also shown for comparison in the “Average” rows of Table 1, is definitely much less accurate: errors on $n$, $\langle u \rangle$, and $V_p$ are, respectively, 10%, 2%, and $-0.11$ V for ADM and 11%, 1%, and $-0.31$ V for BDM. The information retrieved from the raw probe characteristic, which is also shown for comparison in the “Average” rows of Table 1, is definitely much less accurate: errors on $n$, $\langle u \rangle$, and $V_p$ are, respectively, 2.5, 5, and 15 times larger when compared to our best results. A similar degree of inaccuracy occurs for $\phi = 0$, as the above errors are now 1.4, 5.5, and 12 times larger than those associated to the ADM.

Table 1. Summary of model case results.

| Solution | Maxwellian EEDF | Tri-Maxwellian EEDF |
|----------|-----------------|---------------------|
| $\Delta n/n$ | $\Delta V_p/V_0$ | $n$ | $V_p$ (V) | $\langle u \rangle$ (eV) | $\Delta n/n$ | $\Delta V_p/V_0$ | $N$ | $V_p$ (V) | $\langle u \rangle$ (eV) |
| Solution | 0.354 | 0.141 | 1 | 4.5 | 1.5 | 0.354 | 0.141 | 1 | 6.24 | 2.08 |
| Average | $\pi$ | $\pi$ | 0.74 | 3.84 | 1.40 | $\pi$ | $\pi$ | 0.90 | 5.87 | 1.89 |
| SAM | 0.351 | 0.120 | 0.90 | 4.10 | 1.49 | 0.287 | 0.051 | 1.20 | 6.06 | 1.74 |
| ADM | 0.333 | 0.141 | 0.89 | 4.39 | 1.53 | 0.352 | 0.047 | 0.95 | 6.08 | 1.93 |
| BDM | 0.337 | 0.129 | 0.81 | 4.16 | 1.49 | 0.314 | 0.110 | 0.97 | 6.47 | 2.09 |
| Average | 0 | $\pi$ | 0.92 | 4.97 | 2.16 | $\pi$ | $\pi$ | 0.94 | 6.35 | 2.28 |
| ADM | 0.340 | 0.135 | 0.95 | 4.54 | 1.62 | 0.305 | 0.174 | 1.54 | 7.25 | 2.40 |
| BDM | 0.396 | 0.112 | 0.98 | 4.88 | 2.14 | 0.372 | 0.181 | 1.00 | 6.21 | 2.32 |

As can be seen in figure 1, where the restored second derivatives are plotted for the Maxwellian case, ADM curves overlap and accurately reproduce the exact solution. It can also be seen in this figure that BDM curves become rounded in the vicinity of the plasma potential due to regularization. All curves converge to the exact solution at high energies.

The Maxwellian EEDF assumption, widely used in probe methods, is not valid in many situations, namely in low-pressure, low-density discharges. Hence, we decided to test the current methods beyond their validity limits using a tri-Maxwellian EEDF (see solid curve in figure 2), which satisfies neither SAM nor BDM assumptions and which we are forcing not to satisfy (6) by imposing a peculiar time-variation. Indeed, the semi-log slopes, form low to high-energy, correspond to 0.1, 5, and 1 eV, and modulation was achieved changing the relative importance of the 5 eV component.

For the tri-Maxwellian case, SAM is globally least accurate predicting plasma parameters, which is explained for using the RMSD only. For $\phi = \pi$, the errors associated to ADM and BDM calculations of $n$, $\langle u \rangle$, and $V_p$ are, respectively, 5%, 7%, and $-0.16$ V for the former method, and 3%, 0.5%, and

Figure 1. Restored second derivatives for the Maxwellian case.

Figure 2. Restored second derivatives for the tri-Maxwellian case.
0.23 V for the latter, which is noticeable when compared to 10%, 9%, and −0.37 V from similar values calculated from averaged data. Although ADM accurately predicts the value of $\Delta n/n$, it clearly underestimates that of $\Delta V_0/V_0$, while BDM provides globally more reliable modulation depth values.

The RMSD presents characteristic oscillations when $\phi = 0$, which ADM was not able to fit adequately in the current model case conditions. As a result, though the prediction of modulation depths is rather acceptable, the other results are worst than those achieved from the raw averaged characteristic. Conversely, BDM predictions are very close to target values.

In figure 2 we present the restored second derivatives for the tri-Maxwellian case. BDM curves are rounded near the plasma potential but the other methods could somewhat recover the sharp peak.

As an overall model test summary, we shall emphasise here that all methods provide a simultaneous set of six parameters ($\phi$, $\Delta n/n$, $\Delta V_0/V_0$, $n$, $V_p$, $<u>$), and that each parameter has its own degree of accuracy. Although table 1 provides guidance for the choice of a particular method when aiming the highest accuracy concerning one particular parameter, figures 1-2 should be taken into consideration if the aim is to recover a specific energy range of the EEDF.

### 4.2. Experimental results

The SW discharged that provided the data for the test was operated in Argon (1 mBar) inside a pirex tube surrounded by a metal shield (radii: 22.5/25/48 mm) at 500 MHz. The incident power, $P$, as shown in figure 3, was triangle-like time-modulated between 6 and 10 W by the acquisition system via the control of the HV supply of an EPSCO Microwave generator. The repetition period, $T$, was 3.5 s. Data was acquired using a triple-probe arrangement with a temporal resolution of 28 probe characteristics/period (1024 points/characteristic; 117 $\mu$s integration time; total acquisition time/period $\approx$ 700 s; 30 mV bias step). The active probe was located close to the plasma end since this is the region where modulations are more intense [5]. Restoration of the characteristics was performed by means of a BDM-dedicated PC program using Hann filters for EEDF regularization (1.5 and 0.3 V full-width half-maximum (FWHM), respectively, for the determination of $V_p$ and as general Algebraic Reconstruction Technique filter). Second derivatives of probe characteristics, namely those corresponding to the “solution”, i.e., for $P = 8$ W, and to the time-averaged measurements, were obtained by numerical differentiation using adaptive FWHM values in order to keep signal and noise within the same order of magnitude [1].

![Figure 3](image_url)

**Figure 3.** Time-variation of the discharge power (solid line), and resulting time-variations of the plasma parameters: plasma potential (dash), electron average energy (dash dot), and electron density x probe area (dot).

As can be seen in figure 3, all plasma parameters became deeply time-modulated (see also table 2 below), and the plasma potential and the electron average energy time-variations, though globally in-phase with that of the electron density, are not monotonic functions during each ramp, i.e., in the time-domain $n$ and $V_0$ have different relative harmonic contents, which was not considered in the basic
equations (1)-(2). As a result, the small-perturbation assumption, and the implicit frequency-independent phase, cannot be assumed as still valid under the current experimental conditions.

A summary of the results achieved for the SW discharge is presented in table 2, where we can see that the restoring technique was able to identify this was a $\varphi = 0$ case, and to provide values of the electron density and plasma potential RMS relative modulations accurate, respectively, within 1 and 5%. In addition, the absolute values of the plasma potential and of the electron average energy are, respectively, 2 and 2.4 more accurate than those deduced from measured, averaged data. Conversely to model cases, real data has noise, which tangles with convergence, hence decreasing the number of converging iterations. As a result, BDM could only recover a fair value of the electron density (represented in table 2 by the $nA$ product).

| $\Delta n/n$ | $\Delta V_p/V_p$ | $\Delta V_0/V_0$ | $NA$ (10$^{16}$m$^{-3}$) | $V_p$ (V) | $\langle \nu \rangle$ (eV) |
|--------------|------------------|------------------|---------------------------|-----------|---------------------------|
| Solution     | 0.344            | 0.676            | 0.422                     | 3.201     | 8.28                      | 3.647 |
| Average      | ?                | ?                | 3.330                     | 8.40      | 3.820                     |
| BDM          | 0.340            | 0.645            | 0.280                     | 3.343     | 8.34                      | 3.716 |

Figure 4. Experimental test: detailed view of the second derivatives in the vicinity of the plasma potential.

5. Conclusions
We have shown that it is possible to restore time-averaged probe characteristics, in the sense that basic plasma parameters can be retrieved more accurately than from raw averaged data. The increased accuracy is achieved by restoring the probe characteristic at the time when the instantaneous values of modulations are zero and by inferring modulation depths. Hence, it is also possible to deduce EEDFs partially corrected from averaging effects. In this direction, three restoring methods, mostly non-parametric, were suggested. Although each method is based on some restrictive assumption, our basic requirements are essentially good general practices and proved to be able to solve more general situations.

Although figure 1, some parameters in table 1, and the convergence problems already mentioned when $\varphi = 0$ may suggest that SAM is not a good general restoring technique, authors have an opposite point of view, which is based on what they think are simply limitations due to how the current work was implemented. The reason is twofold: 1) convergence problems arose from difficulties in solving a set of non-linear differential equations inside a PC spreadsheet, which can be readily avoided using a dedicated program; 2) calculations were carried out based on the RMSD only, which immediately suggests that accuracy will receive a huge boost if actual probe characteristics are taken into consideration also. Anyway, considering that standard deviations are usually considered as being just noise, once again [6], we hereby urge the reader not to neglect the amount of information that can be retrieved from “noise”.

As can be seen in figure 4, where second derivatives deduced for the same IF are compared in the vicinity of the plasma potential, the BDM curve is simultaneously closer to that of the solution and its variation is sharper than the average one.
The current deformation methods are the result of graphical analysis of EEDFs deduced from time-resolved probe measurements, which too often look like as if one original EEDF was being deformed in some simple way. Restoring accuracy is directly connected to how models describe actual EEDF modulations, which ADM and BDM do not use for the sake of generality. As a result, more accurate methods can be readily implemented if pertinent theoretical information is a priori disclosed.

Concerning the experimental test, authors think it proves that it is worthwhile to spend extra time restoring averaged characteristics. Indeed, though the added accuracy here is not as impressive as in model cases, which is a direct result of what is stated in the above paragraph and of huge modulations, the used method provided accurate modulation values, which otherwise could not be obtained unless by time-resolved measurements.

The accuracy of restoring methods can be increased under an experimental point of view by making data acquisition closer to time-resolved measurements. Indeed, simple filters and more ADC channels may be enough to gather valuable information on $I(V)$ fluctuations spectra, which multi-frequency versions of equations (1)-(2) will handle.

It should be stressed again that time-resolved measurements are neither always possible nor they are always carried out when they should. Hence, as a bottom line, there are situations when restoring techniques are irreplaceable.

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