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Model-Based Processing for the Estimation of Space-Charge Distribution from Non-Contact Pulsed Electro-Acoustic Measurements

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ABSTRACT
Estimating the space-charge distribution using the pulsed electro-acoustic method requires a calibration procedure, in which a reference voltage signal is measured and used to divide the output voltage signal of the piezoelectric sensor. Such a procedure is time consuming and generally involves manually setting filter parameters whose values should be chosen to reduce ringing artifacts in the charge profile and, at the same time, preserve the bandwidth of the profile. This paper proposes a model-based estimation method called the matrix pencil that does not require a calibration procedure to retrieve the charge distribution, albeit with normalized amplitudes, and thus it paves the way for reducing data acquisition and processing times. Results on simulated and experimental data confirm the effectiveness of the proposed method in estimating the space-charge distribution in irradiated polymers.

Index Terms — charge distribution, dielectric materials, matrix pencil method, parameter estimation, pulsed electro-acoustic method, space polymers.

1 INTRODUCTION
Insulators are extensively used in satellites for electrical protection, mechanical support, and heat management. Dielectric materials must withstand the irradiation from space particles, which leads to stimulate an electrostatic discharge on these elements, resulting in satellite abnormalities. To avoid damage, the irradiation influence on the device and its effect on physical attributes should be analyzed. Understanding charging and discharging operations is usually achieved through irradiation and testing in high vacuum conditions [1]. SIRENE, a multi-energetic vacuum chamber, was constructed to recreate the geostationary environment of the space electron during the intensive geomagnetic activity [1]. SIRENE includes contactless surface potential computational device (Kelvin probe). This technique enables the categorization of materials used in space and demonstrates its feasibility in several physical studies, such as radiation-induced conductivity that may be used to drive material charging in space [2-8]. However, an overarching interpretation of these physical phenomenon calls for the use of an additional characterization method for calculating the material charge profile. Various apparatus such as thermal [9], pressure wave [10] and pulsed electro-acoustic (PEA) system [11] have been developed for these purposes over the past 15 years. Some of the above methods were used to
estimate in open air the electric charge inside insulators after irradiation, which means that the specimen should be detached from the irradiation facility [12]. Such methods have significant drawbacks. There is no vacuum effect on gaseous molecules such as water vapor that can impair relaxation of the radiated material [12]. In fact, depending on the measuring system, the field applied to the collected loads is likely to be variable in amplitude and path. In-situ measurement provides more useful information for understanding spatial phenomena. Contactless PEA device was developed in SIRENE chamber in order to study the space charge evolution of insulators regarding different values of irradiation energies [11-13]. However, reproducing space-charge distributions requires a calibration procedure, in which a reference voltage signal is measured and used to divide the output voltage signal of the piezoelectric sensor. The calibration process for a non-contact PEA cell is different from that of the traditional cell. First, the sample should be irradiated at a low energy level to ensure a surface charge only (20 keV in our case) inside the vacuum irradiation chamber. After irradiation, the output signal of the contactless PEA measurement will be saved and adopted as the calibrated signal. Finally, the chamber should be opened to replace the sample by another one (same thickness and material) then make the vacuum again and irradiate the material at different energy level to estimate the profile of the implanted charge. Indeed, this calibration process is time consuming and generally involves manually setting filter parameters whose values should be chosen to reduce ringing artifacts in the charge profile and, at the same time, preserve the bandwidth of the profile. To this end, we propose the matrix pencil method, a model-based estimation algorithm, that does not require a calibration procedure to extract the charge distribution, albeit with normalized amplitudes. Such a method paves the way for reducing data acquisition and processing times and could also improve the spatial resolution of the estimated charge distribution given its high-resolution capability. Results on resolved simulated and experimental data confirm the effectiveness of the proposed method in estimating the space-charge distribution.

The rest of the paper is as follows. Section 2 presents the signal model and the calibration-less parameter estimation procedure. Sections 3 and 4 describe the proposed procedure on simulated and real signals, respectively. Finally, section 5 draws the conclusions of this work.

2 CALIBRATION-LESS ESTIMATION

This section describes the model for the output voltage of the piezoelectric transducer and explains the parameter estimation procedure. The procedure involves a model-based estimation algorithm, called the matrix pencil method, followed by optimizing a nonlinear objective function.

2.1 SIGNAL MODEL

Under the assumption of a linear system, the output voltage signal \( v(t) \) of the piezoelectric transducer can be approximated by the following signal model shown in Equation 1:

\[
v(t) = e(t) * h_s(t) * h_e(t) * h_t(t)
\]  

(1)

where \( * \) is the convolution operator, \( e(t) \) is the input electric pulse, \( h_s(t) \) is the impulse response of the sample under test, \( h_e(t) \) is the impulse response of the electrode, and \( h_t(t) \) is the impulse response of the piezoelectric transducer. Assuming \( h_s(t) \) to consist of a train of \( n \) Gaussian pulses having the same width allows to write

\[
h_s(t) = e^{-\frac{t^2}{2\sigma^2}} \sum_{i=1}^{n} a_i \delta(t - T_i)
\]  

(2)

where \( \sigma \) controls the width of the Gaussian, \( a_i \) is its \( i^{th} \) amplitude and \( T_i \) is its \( i^{th} \) time delay. \( h_e(t) \) contributes only a delay \( \hat{T} \) related to the thickness of the electrode, to the output voltage signal and hence is given by

\[
h_e(t) = \delta(t - \hat{T})
\]  

(3)

As a result,

\[
h_s(t) * h_e(t) = e^{-\frac{t^2}{2\sigma^2}} \sum_{i=1}^{n} a_i \delta(t - T_i - \hat{T})
\]  

(4)

In the frequency domain, the signal model is given by:

\[
V(\omega) = E(\omega) H_s(\omega) H_e(\omega)
\]

\[
= E(\omega) \sigma e^{\frac{1}{2} \sigma^2 \omega^2} \sum_{i=1}^{n} a_i e^{-j\omega(T_i + \hat{T})} H_e(\omega)
\]  

(5)

where \( \omega \) is the angular frequency in rad/s.

Dividing \( V(\omega) \) by \( V_e(\omega) \), where \( V_e(\omega) \) is the Fourier transform of the first arriving pulse in \( v(t) \) given by

\[
V_e(\omega) = E(\omega) \sigma e^{\frac{1}{2} \sigma^2 \omega^2} \sum_{i=1}^{n} a_i e^{-j\omega(T_i + \hat{T})} H_e(\omega)
\]  

(6)

over a limited bandwidth bounded by the cutoff frequency of the transducer low-pass filter gives \( V_w(\omega) \), a whitened version of \( V(\omega) \), which can be approximated as follows:

\[
V_w(\omega) = \sum_{i=1}^{n} r_i e^{-j\omega \tau_i}
\]  

(7)

where \( r_i = \frac{a_i}{a_k} \) and \( \tau_i = T_i - \hat{T} \) are the \( i^{th} \) normalized amplitude and the \( i^{th} \) shifted time delay, respectively.

After sampling, the angular frequency variable, \( \omega \), is replaced by \( \omega_k = \omega \omega_0 \), where \( \omega_0 \) is the chosen angular frequency shift between consecutive samples. The discrete signal becomes:

\[
V_w(k) = \sum_{i=1}^{n} r_i e^{-j\omega_k \tau_i} = \sum_{i=1}^{n} r_z e^{j\omega_k z_i}, \; k = 1, 2, \ldots, m
\]  

(8)

where \( z_i = e^{-j\omega_0 \tau_i} \) is referred to as the \( i^{th} \) complex pole.

In matrix form, the signal model is represented as:

\[
v_w = P r
\]  

(9)

where

\[
v_w = [V_w(1) \; V_w(2) \; \ldots \; V_w(m)]^T
\]

\[
P = [p_1 \; p_2 \; \ldots \; p_n]
\]
\[ \mathbf{p}_t = \begin{bmatrix} z_1 \\ z_1^2 \\ \vdots \\ z_1^m \end{bmatrix} \]
\[ \mathbf{r} = \begin{bmatrix} r_1 \\ r_2 \\ \vdots \\ r_n \end{bmatrix} \]

The superscript \( T \) denotes the transpose operator.

The problem of reconstructing the charge density can now be stated as follows. Given the voltage data sequence \( \{V(k)\}_{k=1}^m \), estimate the normalized amplitudes \( \{r_i\}_{i=1}^n \), the shifted time delays \( \{r_i\}_{i=1}^n \), and the width-controlling parameter of the Gaussian \( \sigma \). To this end, a two-step procedure, which involves a model-based parameter estimation algorithm applied to the whitened voltage data sequence \( \{V_w(k)\}_{k=1}^m \), and a nonlinear optimization of a one-parameter objective function based on the first arriving pulse \( V_1(\omega) \), is employed, as explained in the next two subsections.

### 2.2 Model-Based Parameter Estimation

This subsection briefly recalls the principle of the matrix pencil method (MPM), which is a linear-prediction algorithm that exploits the pencil structure of the underlying damped/undamped exponential model to estimate the parameters. MPM has found applications in various fields, including material characterization of dispersive media through the joint estimation of time delays and quality factors [14-16], two-dimensional direction-of-arrival estimation using nonlinear least squares [17], identification of observables from scattering data [18], and resolution of frequency-dependent multipath channels [19]. An advantage of MPM over other high-resolution algorithms such as MUSIC and ESPRIT is that estimation relies on just one measurement of the data vector. As a result, MPM does not require the estimation of a covariance matrix and the reduction of signal coherency through spatial smoothing techniques. These features of MPM contribute significantly to reducing its computational burden. In this paper, MPM will be employed to estimate the amplitudes and time delays of the charge profile resulting from the sample under test.

The following steps summarize the principle of MPM.

Step 1. Using the whitened voltage data sequence \( \{V_w(k)\}_{k=1}^m \), construct a Hankel data matrix:

\[
\mathbf{H} = \begin{bmatrix}
V_w(1) & V_w(2) & \cdots & V_w(L) & V_w(L+1) \\
V_w(2) & V_w(3) & \cdots & V_w(L) & V_w(L+1) \\
\vdots & \vdots & \ddots & \vdots & \vdots \\
V_w(m-L) & V_w(m-L+1) & \cdots & V_w(m-1) & V_w(m)
\end{bmatrix}
\]

Step 2. Estimate \( n \), the number of Gaussian kernels, as the number of the first singular values of \( \mathbf{H} \) representing 99% of the sum of all singular values. As for \( m \), it is obtained by dividing the sample length of \( V_w(\omega) \) by \( a_s \).

Step 3. Select the pencil parameter, \( L \), such that \( n \leq L \leq m - n \). The proper choice of \( L \) makes MPM robust against noise. In this work, \( L = m/2 \).

Step 4. Remove the first and last columns of \( \mathbf{H} \) to obtain the following two matrices, which is MATLAB notation given by:

\[
\mathbf{H}_1 = \mathbf{H}(\cdot, 1: L), \quad \mathbf{H}_2 = \mathbf{H}(\cdot, 2: L + 1)
\]

Step 5. Use \( \mathbf{H}_1 \) and \( \mathbf{H}_2 \) to form a matrix pencil defined as:

\[
\mathbf{H}_1 = \mathbf{Z}_1 \mathbf{R} \mathbf{Z}_1^T_{\omega} \quad \text{and} \quad \mathbf{H}_2 = \mathbf{Z}_1 \mathbf{R} \mathbf{Z}_2^T_{\omega} \quad (10)
\]

where \( \mathbf{Z}_1 = \begin{bmatrix} z_1 & z_2 & \cdots & z_n \\
1 & z_1 & z_2 & \cdots & z_n \\
\vdots & \vdots & \ddots & \vdots & \vdots \\
1 & z_n & \cdots & z_n^{L-1} \end{bmatrix} \)

\[
\mathbf{Z}_2 = \begin{bmatrix} z_1 & z_2 & \cdots & z_n \\
1 & z_2 & \cdots & z_n^{L-1} \\
\vdots & \vdots & \ddots & \vdots \\
1 & z_n & \cdots & z_n^{L-1} \end{bmatrix}
\]

\[
\mathbf{Z}_0 = \text{diag}(z_1, z_2, ..., z_n) \quad \mathbf{R} = \text{diag}(r_1, r_2, ..., r_n)
\]

The Vandermonde decomposition reveals the shift-invariance property along the column and row spaces and allows to write the matrix pencil as:

\[
\mathbf{H}_2 - \lambda \mathbf{H}_1 = \mathbf{Z}_1 \mathbf{R} [\mathbf{Z}_0 - \lambda \mathbf{I}] \mathbf{Z}_2 \quad (11)
\]

where \( \mathbf{I} \) is the identity matrix. Therefore, each value of \( \lambda = z_i \) is a rank-reducing number of the pencil.

Step 6. Estimate the complex poles, \( \{z_i\}_{i=1}^n \), as the generalized eigenvalues of the matrix pair \( \{\mathbf{H}_2, \mathbf{H}_1\} \). The shifted time delays can then be estimated from the poles.

Step 7. Estimate the normalized amplitudes using a least squares fit having the following solution:

\[
\mathbf{r} = (\mathbf{P}^H \mathbf{P})^{-1} \mathbf{P}^H \mathbf{v}_w \quad (12)
\]

where the superscript \( H \) denotes the conjugate-transpose operator. These amplitudes, however, still include the effects of the acoustic impedance mismatch between the electrodes, the sample, and the transducer. To compensate for these effects, the amplitudes are divided by the factors detailed in [21].

### 2.3 Gaussian Width Estimation

To estimate \( \sigma \), we consider the magnitude of the Fourier transform of the first arriving pulse given by:

\[
\left| V_1(\omega) \right| = \left| E(\omega) \right| a_s \sqrt{2\pi} e^{-\frac{1}{2}a_s^2 \omega^2} \left| H_1(\omega) \right| \quad (13)
\]

and we make the following two assumptions:

1. The input electric pulse \( e(t) \) is known and so its Fourier transform \( E(\omega) \) is known.
2. The transducer acts as a low-pass filter implying that its transfer function maintains a relatively constant magnitude at sufficiently low frequencies: \[ |H_i(\omega)| \approx K, \]
where \( K \) is a constant.

Dividing \( |V_i(\omega)| \) by \( |E(\omega)| \) for sufficiently low frequencies and then normalizing the result give the following expression of a Gaussian whose:

\[
\frac{|V_i(\omega)|}{K a_1 \sigma \sqrt{2\pi} |E(\omega)|} \approx e^{-\frac{1}{2} \sigma^2 \omega^2} \quad (14)
\]

\( \sigma \) is estimated by solving a non-linear least squares problem that fits the above Gaussian to normalized data in the low-frequency region.

3 SIMULATION RESULTS

A charge distribution in a 300-\( \mu \)m sample is fed to the electroacoustic model detailed in [13]. As shown in fig.1, this charge distribution has one negative peak distant in the middle of the sample along with two image charges at the electrodes. Feeding this distribution to the model yields the output voltage in fig.2. MPM was then used to estimate the normalized amplitude and shifted time delay for each of the three peaks, whereas \( \sigma \) was estimated by solving the nonlinear least squares problem described in subsection 2.3. These estimated parameters enable to reconstruct the impulse response of the sample as shown in fig.3, where the Gaussians of the reconstructed charge distribution are in good agreement with those of the simulated distribution in terms of location, amplitude, and width.

![Figure 1. The simulated normalized charge distribution within the 300-\( \mu \)m sample, showing one negative peak and two positive peaks.](image1)

![Figure 2. The normalized output voltage signal of the piezoelectric transducer.](image2)

![Figure 3. The simulated and estimated normalized charge distributions within the 300-\( \mu \)m sample.](image3)

4 EXPERIMENTAL SETUP AND RESULTS

The experimental apparatus is based on: (1) the irradiation chamber, which reproduces a space environment with a special equipment assembly and (2) the PEA system, which gives an estimation on the production of the embedded electric charges in dielectric insulators.

4.1 IRRADIATION APPARATUS

SIRENE experimental simulation facility reproduces the dispersed continuum of electron sites throughout spatial ranges between 0 and 400 keV, allowing for the calculation of space materials charging capacity and electric charges under GEO orbit configuration. For the electron spectrum simulation, two mono-energetic electron beams (20 and 400 keV) are diffused to create a space-like electron flow with adequate flux homogeneity in a diameter of 20 cm on the sample holder. Figure 4 shows the electron beam spectrum features of the SIRENE facility, which are identical to those of the charging behavior of GEO environment. SIRENE has the benefit of mixing low and high energies [2-8]. The rated flux values for the mono-energetic 20 keV beam and the dispersed 400 keV beam are 250 pA cm\(^{-2}\) and 50 pA cm\(^{-2}\) respectively, it could be increased to 200 pA cm\(^{-2}\) and 1 nA cm\(^{-2}\). The specimen temperature holder may be controlled between -180°C and +250°C, allowing for temperature modulation for on-flight materials. The samples taken from the chamber walls are around 20 cm wide. Experiments in a vacuum of roughly 106 hPa are possible thanks to a pumping apparatus. SIRENE ensures that the charge levels at geostationary orbit are precisely and adequately approximated, and that the many physics mechanisms involved are properly recognized, thanks to its stability and representativeness. The samples are studied at roughly 3–8 mm from their surface using an X–Y motion device, and the surface voltage of the specimen is measured using a contactless electrostatic probe “TREK 3455 ET paired with an electrostatic Voltmeter TREK 341 B”. The surface potential is given on a continuous basis using the following formula:

\[
\sigma(E) = \varepsilon_0 \varepsilon_r \frac{V}{V_s} \quad (15)
\]
where \( \varepsilon \) and \( \varepsilon_0 \) are, respectively, the relative permittivity of the material and the permittivity of vacuum, and \( V_s \) is the surface voltage of the material.

**Figure 4.** SIRENE standard spectrum and reference KP > 5.

### 4.2 CONTACTLESS PEA DEVICE

To measure the charge distribution inside dielectric materials, the pulsed electro-acoustic approach (fig. 5) was adopted. The interaction of high voltage pulses with the accumulating charge layers of insulators produces acoustic pressure waves that propagate through the material [12]. Briefly, acoustic pressure waves are created when an external electric pulse interacts with the electrodes charging layers and the substrate. Acoustic waves proportional to electric charge levels are transformed to an electric signal by a piezoelectric transducer and transferred to a digital oscilloscope for recording. The charge distribution inside the insulator under test can then be determined using an appropriate signal processing approach.

### 4.3 EXPERIMENTAL RESULTS AND DISCUSSION

The experimental validation of the suggested approach by means of high-energy electron irradiation from utilized space polymers such as FEP, Polytetrafluoroethylene (PTFE) and Kapton is described below in addition to the experimental validation of the suggested approach. PEA measurements were taken during the 250 \( \mu \)m irradiation of FEP and PTFE, as well as the 127 \( \mu \)m irradiation of Kapton. The goal was to confirm the movement of the electric charge in the sample as the electron beam's energy value increased.

ESTAR tool was used to conduct theoretical penetration depth for each radiation [22]. NISTPL offers this computational tool online. For FEP, PTFE and Kapton, the computed values of 20 keV are 3.5, 4.3 and 6.6 \( \mu \)m. The charge penetration depths observed by the non-contact PEA are estimated by 3.6, 4.9 and 5 \( \mu \)m without using the actual PEA calibration step. We realize that the values evaluated are extremely similar to those of the experiment. In other words, a strong agreement is shown between the theoretical and the suggested methodology.

The second step aims to ensure the reliability of the approach by calculating the electron penetration depth produced from the high-energy beam. In this procedure, the 20 keV charging profile should be sharply decreased or shifted as clarified in the charge distribution measurements. Table 1 provides the experimental setup used for the various validation procedures. It also includes information on penetration depth, which is hypothetically evaluated and appraised for each irradiation stage. Three samples were irradiated at various intensities to achieve this:

1. FEP of 250 \( \mu \)m thickness was irradiated for 2.5 minutes with 20 keV, three minutes with 125 keV, seven minutes with 145 keV and three minutes with 165 keV.
2. PTFE of 250 \( \mu \)m thickness has also been irradiated at 20 keV for 2.5 min and at 125 keV for 3 min.
3. For 9 min under the 20 keV energy and 12 min at 70 keV the electron-beam was submitted to a Kapton 127 \( \mu \)m.

All irradiation is done by a 100 pA.cm\(^{-2}\) stream. After every irradiation, electron charge depth was measured directly without adopting the calibration procedure as illustrated in Table 1 and Figures 6–16 (direction of irradiation is from right to left).

As predicted, the penetration of electrons rises with the increase of the irradiation energy. If the sample is thick enough, the implanted particles lose their energy and velocity before being injected in the bulk [23]. As shown, the estimated charge penetration depth is very close to the theoretical value computed by ESTAR.
Figure 6. The estimated charge distributions (normalized profiles) by the conventional and proposed methods for a 250 μm FEP irradiated at 20 keV.

Figure 7. The estimated charge distributions (normalized profiles) by the conventional and proposed methods for a 250 μm FEP irradiated at 125 keV.

Figure 8. The estimated charge distributions (normalized profiles) by the conventional and proposed methods for a 250 μm FEP irradiated at 145 keV.

Figure 9. The estimated charge distributions (normalized profiles) by the conventional and proposed methods for a 250 μm FEP irradiated at 165 keV.

Figure 10. The estimated charge distributions by the proposed method normalized with respect to the maximum of the charge distribution for a 250 μm FEP irradiated at 20, 125, 145, and 165 keV.

Figure 11. The estimated charge distributions (normalized profiles) by the conventional and proposed methods for a 250 μm PTFE irradiated at 20 keV.

Figure 12. The estimated charge distributions (normalized profiles) by the conventional and proposed methods for a 250 μm PTFE irradiated at 125 keV.

Figure 13. The estimated charge distributions by the proposed method normalized with respect to the maximum of the charge distribution for a 250 μm PTFE irradiated at 20 and 125 keV.
We can get useful knowledge about the physics that governs charge transfer. In the case of the materials, we can see a near-instantaneous elimination of the charge peak at 20 keV. It is totally disappeared after irradiation at 125 keV for FEP and PTFE, and at 70 keV for Kapton: the effective charges are swiftly transported from their starting location to the bottom border of the irradiated zone. This movement is due to the radiation induced conductivity [2] caused by 125 keV for FEP and PTFE and 70 keV for Kapton. Along the several irradiation phases, we can also observe a constant increase in the strength of the induced peak (left-hand positive peak): this peak is certainly related to the overall injected charges in the dielectric material [12].

Furthermore, an experimental validation was performed using three distinct insulators (FEP, PTFE, and Kapton). The samples were irradiated at various energy levels. Following that, an estimation study between the theoretical and experimental charge penetration depths has been made after each irradiation. The results indicate a perfect correlation between the estimated and theoretical values.

This work also highlights the use of the PEA approach in assessing the radiation-induced conductivity (RIC) that was detected for FEP, PTFE and Kapton.

Finally, we can figure out the importance of the new approach by providing accurate values that could be used to describe and validate the charge transport phenomenon and the ionization impact.

5 CONCLUSIONS

The goal of this research was to provide a calibration-free methodology that could be utilized in the contact-less PEA cell branching in the irradiation facility SIRENE that aims to analyze the transport of electric charge inside dielectric materials. First, a full discussion of the theoretical approach idea that leads to the appropriate PEA model-based parameter estimate was addressed. This strategy was then tested using a numerical simulation using COMSOL® multi-physics. The simulation results demonstrate the novel approach’s capacity by calculating the right charge distribution without employing the standard PEA calibration technique.

Table 1. Comparison between ESTAR, the conventional method, and the proposed method in terms of penetration depth in a 250-μm FEP and PTFE in addition to a 127-μm Kapton for different electron beam energies and irradiation times.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Electron Beam Energy (keV)</th>
<th>Irradiation on Time (min)</th>
<th>Penetration Depth (μm)</th>
</tr>
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<tr>
<td></td>
<td></td>
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<td>ESTAR</td>
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<tr>
<td>FEP</td>
<td>20</td>
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<td>3.5</td>
</tr>
<tr>
<td></td>
<td>125</td>
<td>3</td>
<td>115</td>
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