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ELECTROSTATIC NOISE IN THE PLASMA ENVIRONMENT AROUND THE SHUTTLE

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Abstract

The Langmuir probe flown as a part of the SAMPIE package aboard the space shuttle flight STS-62 was used to determine plasma potential fluctuations in the vicinity of the shuttle. The broadband noise was observed at frequencies 250-20,000 Hz. Measurements were performed in ram conditions; thus, it seems reasonable to believe that the influence of spacecraft operations on plasma parameters was absolutely negligible. The average spectrum of fluctuations is in agreement with theoretical predictions. The influence on the observed spectra of arcing generated by high negative bias voltages applied to solar cell samples is briefly discussed.

Nomenclature

B	magnetic field strength
$D(\omega)$	observed spectrum
f	frequency of plasma density fluctuations
I, i	LP current
k	wave vector
$J_0(\alpha)$	Bessel function
n_e	electron number density
n_i	ion number density
N_{arc}	number of arcs per one experiment
t	time
T_e	electron temperature
U	output voltage
V	spacecraft velocity
x	vector of spatial coordinates

$\delta(x,t)$	amplitude of plasma density fluctuations
Φ	angle between velocity vector and z axis
μ	azimuthal angle of wave vector
Θ	angle between wave vector and z axis
τ_{exp}	duration of individual experiment with arcing
τ_{dwell}	duration of one dwell
ω	wave frequency

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1.Introduction

As a part of the SAMPIE (The Solar Array Module Plasma Interactions Experiment) program, the Langmuir probe (LP) was employed to measure plasma characteristics during the experiment[1]. The whole set of data could be divided into two parts: i) low frequency sweeps to determine voltage-current characteristics and to find electron temperature and number density; ii) high frequency turbulence (HFT dwells) data caused by electrostatic noise. It is known that spacecraft operations influence LP data [2]. To provide measurements of plasma density fluctuations caused by turbulence in the LEO plasma itself, we analyze LP data that were obtained in ram conditions only. According to purposes of SAMPIE, the samples of solar cells were placed in the cargo bay of the shuttle, and high negative bias voltages were applied to them to initiate arcing between these cells and surrounding plasma. The arcing onset was registered by special counters, and data were obtained that included the amplitudes of current,

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duration of each arc, and the number of arcs per one experiment. This organization of the experiment allows analysis of the LP data (HFT) for two different situations: i) with arcing on samples of solar cells; ii) without arcing. HFT data were obtained during the dwells lasting for 4 ms each, and experimental data were represented in digital form: 80 points with 50 μs intervals. This means that we are able to study the spectra of plasma turbulence within the narrow frequency interval $\Delta f=250-10,000$ Hz. We may suggest that there is an influence of arcs on HFT data. This influence could be caused by changes in plasma parameters as well as fluctuations of spacecraft potential. Electrostatic noise spectra for both situations (with arcing and without arcing) , analysis of correlation properties of different signals, and the preliminary theoretical explanation of the observed differences of these spectra will be discussed below.

2. Plasma parameters

The electron number density and electron temperature were obtained during sweeps that

lasted for 4 s each. During this time interval the bias voltage on LP was changed twice: down from +10 V to -5V, and up from -5V to +10 V. An example of the sweep data is shown in Fig.1. The current flowing throughout the LP can be calculated according to the following formula:[3]

```
I=exp(1.0226 U - 9.3866) mA    (1)
```

where U is output voltage on the OP amplifier.

Thus, changes of electron number density and electron temperature were registered for ram conditions: $n_e=(5-80)\times10^5$ cm^{-3} and $T_e=0.05-0.3$ eV. It should be noted that the magnetic field strength changed within a narrow range B=0.25-0.5 Gs during the flight, and the angle between the spacecraft velocity and magnetic field vector changed from -60° to -80°. The variations in the basic plasma characteristics caused variations in such important plasma parameters as electron and ion plasma frequencies, Debye length, Alfven velocity , and the speed of ion acoustic waves (IAW). For our purposes it seems convenient to represent all of these parameters in the form of simple formulae in Table 1, below.

Table 1

Electron Langmuir frequency	$f_e = 9\sqrt{\dfrac{n_e}{10^6\,cm^{-3}}}$ MHz
Ion Langmuir frequency (for ions O$^+$)	$f_i = 56\sqrt{\dfrac{n_i}{10^6\,cm^{-3}}}$ kHz
Debye length	$D_e = 0.3(\dfrac{T_e}{3000K})^{0.5}(\dfrac{n_e}{10^6\,cm^{-3}})^{-0.5} - cm$
Alfven velocity	$W_A = 2.7\cdot10^7\left(\dfrac{B}{0.5Gs}\right)\cdot\left(\dfrac{n_e}{10^6\,cm^{-3}}\right)^{-0.5}$ cm/s
Speed of Ion Acoustic Waves	$W_s = 1.27\cdot10^5\left(\dfrac{T_e}{3000K}\right)^{0.5}$ cm/s
Electron gyrofrequency	$f_H = 1.4\cdot\dfrac{B}{0.5Gs}$ MHz
Ion gyrofrequency	$F_H = 48\cdot\dfrac{B}{0.5Gs}$ Hz
Lower hybrid frequency	$f_{LH} = 8.2\cdot\dfrac{B}{0.5Gs}$ kHz

To analyze the LP data, particularly HFT dwells, we should take into account the motion of spacecraft through the surrounding plasma.

The Fourier integral for fluctuations of the plasma density can be written in the following form:

$$\delta(x,t) = \int \delta(k,\omega)\cdot\exp(-i\cdot\omega\cdot t + i\cdot k\cdot(x - V\cdot t))\cdot d\omega\cdot d^3k =$$

$$\int_0^\infty d\omega \int_0^\infty k^2 dk \int_0^\pi \sin\theta\cdot d\theta \int_0^{2\pi} d\mu \cdot \delta(k,\omega)\cdot\exp(-i\cdot\omega\cdot t + i\cdot k\cdot x\cdot\cos\theta - i\cdot k\cdot V\cdot t\cdot\cos\Phi\cdot\cos\theta)\cdot$$

$$\exp(-i\cdot k\cdot V\cdot t\cdot\sin\Phi\cdot\sin\theta\cdot\cos\mu) \qquad (2)$$

Finally, after performing some simple algebra, we can write the observed frequency spectrum in the form:

$$D(\Omega) = 4\cdot\pi\cdot\int_0^\infty k^2 dk\cdot\int_0^\infty d\omega\cdot\delta(k,\omega)\cdot\int_0^\infty dt\cdot\frac{\sin kVt}{kVt}\cdot\exp(i\Omega t - i\omega t) \qquad (3)$$

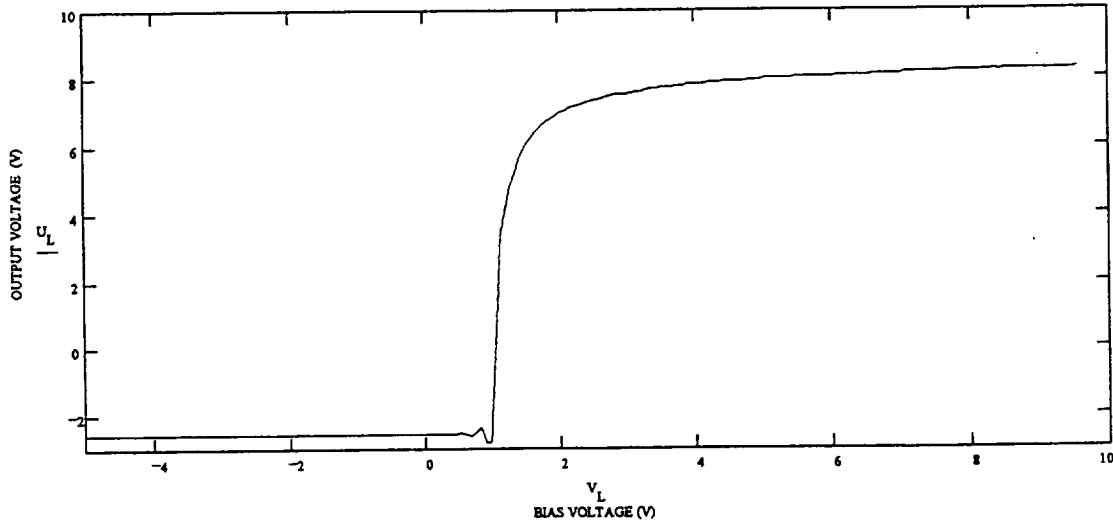To obtain the Eq. (3) we suggest LP is placed in the point $x=0$ of the coordinate system.

Fig.1. Langmuir characteristic for density $n_e=10^6$ cm^{-3}

It is easy to see that the major contribution to the integral (3) is provided by two shifted frequencies $\Omega_{1,2}=\omega\pm kV$. For Ion Acoustic waves (IAW) within the frequency interval $F_H < f < f_{LH}$, the wave numbers can be estimated as $k=2\pi f W_s^{-1}=0.0002-0.4$ cm^{-1}, and the following inequality is fulfilled always: $kD_e \ll 1$. This implies that the temporal attenuation rate of IAW is very small:[4]

$$\frac{\gamma}{f} = 2\cdot\pi\cdot\left(\frac{\pi\cdot m_e}{8\cdot m_i}\right)^{0.5} \ll 1 \qquad (4)$$

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Expression (4) is valid for almost all waves except waves that propagate perpendicularly to magnetic field. Of course, IAW are attenuated due to absorption by ions on frequencies $f \geq f_i$.

3. Observations

As was mentioned above we possess data obtained by the LP for two different situations : with arcing and without arcing. One example of an HFT dwell is shown in Fig.2. One can see that the amplitude of current flow reaches the value $i_{max}=0.155$ μA, and the average value is equal to $i_{ave}=0.076$ μA. The electron number density fluctuations can be estimated according to the following equation:

$$\delta = \frac{\delta n_e}{n_e} \approx \frac{i_{max}}{I_{sat}} \qquad (5)$$

The saturation current was equal to $I_{sat}=300$ μA (Fig.1). Thus, the amplitude of fluctuations is $\delta = 5 \times 10^{-4}$. The spectrum of this signal is shown in Fig. 3. The sharp decline of amplitude for frequencies $f > 6.5$ kHz is seen very clearly. The average spectrum was built using data of twelve dwells (Fig.4). No peculiarities can be established in this average spectrum. Figure 5 illustrates the signal that was registered when arcs occurred. First of all, it is seen that there is a significant difference in amplitudes between signals with arcing and without them. For this dwell, the amplitude of current fluctuations is as large as 2 μA. Moreover, the average spectrum that had been calculated by using data of twelve dwells with arcing is almost flat for frequencies $f > 500$ Hz. We did not find correlations between plasma parameters and spectral characteristics either for dwells with arcing or dwells without arcing. However, the peak current depends on number of arcs rather strongly (Fig.6). We believe that the large amplitude of LP current is caused by changes in the spacecraft potential due to arcing. When arcing occurs, the difference of potentials between the shuttle and the surrounding plasma changes $\Delta V \approx 2-3$ V for the moment of each arc. Because the duration of each arc is equal to $0.1-0.5$ μs, the measured value of LP current can be estimated

as

$$\Delta I_{max} = \frac{N_{arc}}{\tau_{exp}} \cdot \tau_{dwell} \cdot \left(\frac{\partial I_{sat}}{\partial V} \cdot \Delta V \right) \qquad (6)$$

For example, during one experiment there were $N_{arc}=1500$, the duration of the experiment $\tau_{exp}=60$ s, and $\tau_{dwell}=4$ ms. The value of the expression in the parenthesis can be obtained from appropriate sweep data (Fig.1). The result of the calculation, $\Delta I_{max} \approx 2$ μA, is in agreement with the measurements.

4. Conclusion

According to theoretical considerations the spectrum of noise in the ionospheric plasma should have the following form:[4]

$$D(f) = \frac{A}{f} \cdot F\left(\frac{f}{f_e} \right) \qquad (7)$$

where A=Const, and F(f) is a slow function of frequency. In reality, we obtained $D(f) \propto f^{-0.76 \pm 0.2}$ for the average spectrum without arcing, in agreement with expectations.

Electrostatic noise with such parameters was observed early [2], and those authors suggested that there were IAW generated in the vicinity of the lower hybrid resonance and shifted due the Doppler effect by $\Delta f = 2-3$ kHz. Moreover, they proved that the reason for the IAW instability was the so called "ring distribution" of water ions that were sublimated from spacecraft surfaces. These last conclusions were based on the data obtained by the Plasma Diagnostic Package (PDP) operating in wake of the shuttle (advanced analysis and new data are published in Ref.5,6).

We see from the present work that fluctuations with a broad spectrum are developed in the plasma itself. It might be suggested that the reason for their generation and instability exists in the surrounding medium (convective flows, solar cosmic rays, or something else). More measurements of LP current fluctuations should be done in ram conditions to understand the nature of the observed electrostatic noise. It seems particularly important to measure fluctuations at frequencies up to 60 kHz where attenuation due to absorption by ions at the ion plasma frequency is practically negligible.
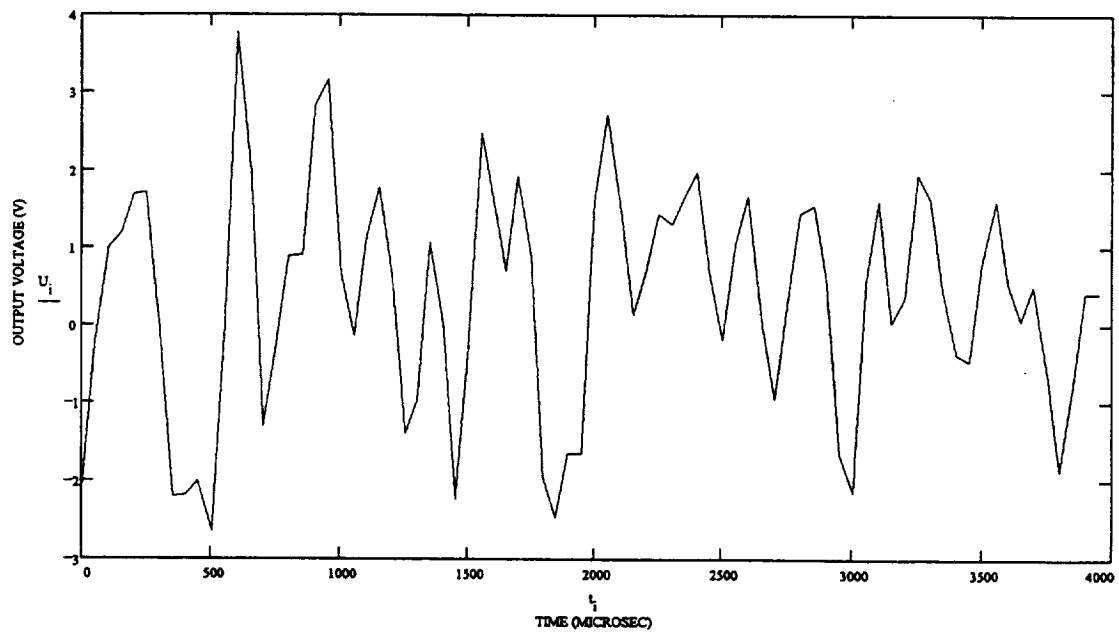
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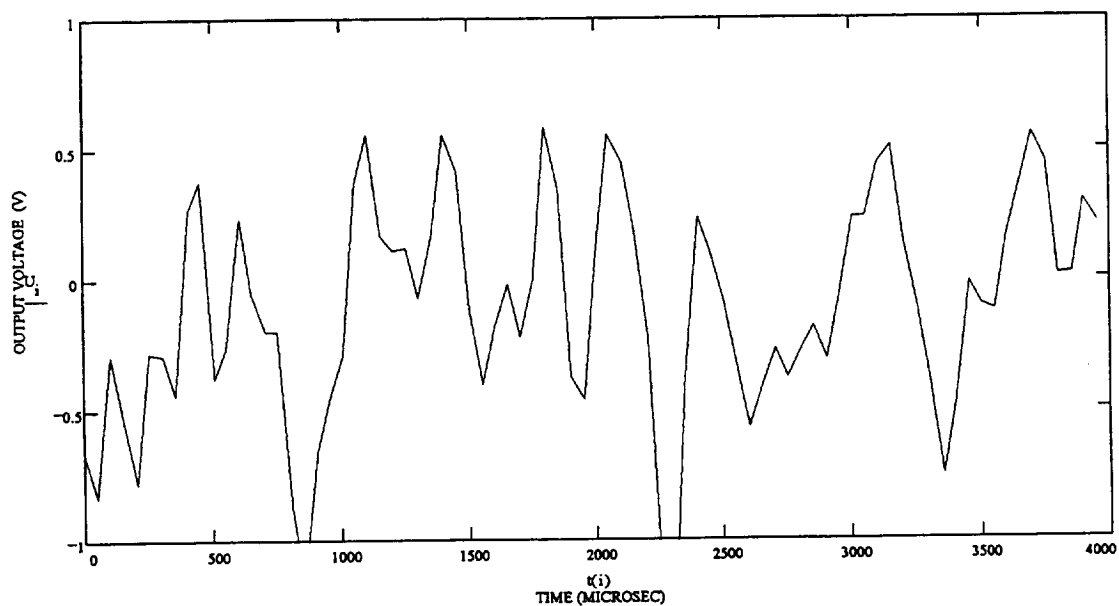
Fig.2 LP output voltage fluctuations measured during a dwell in ram conditions (MET 23:39:47)
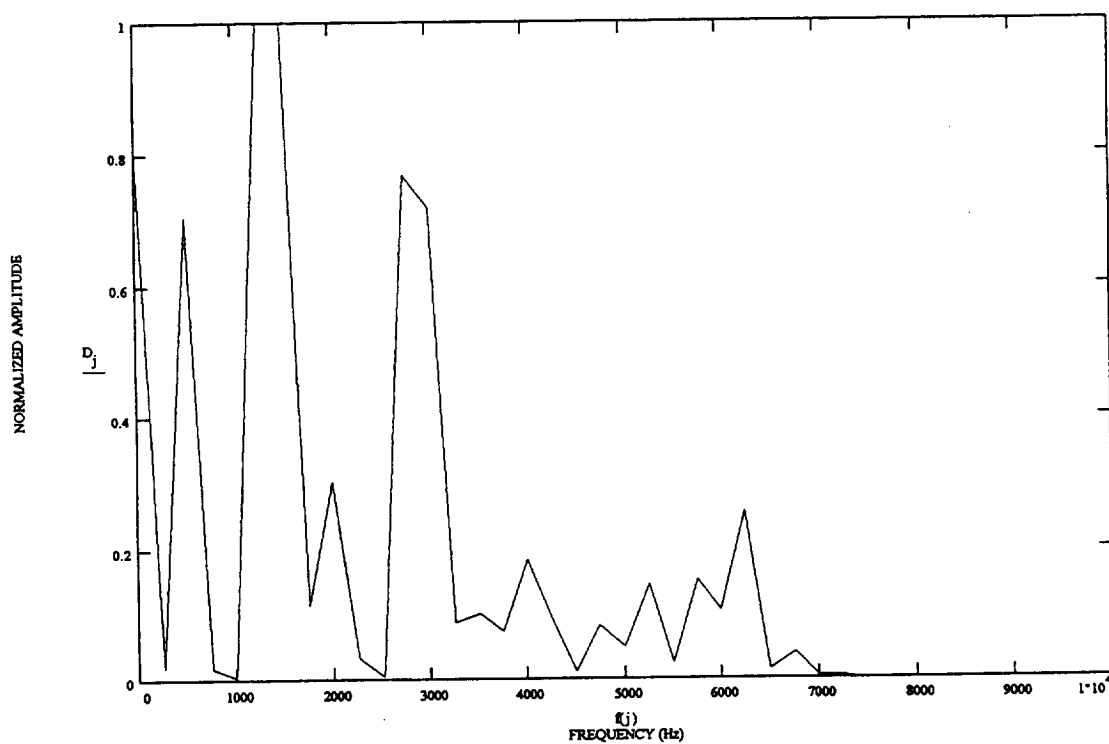

Fig.3. Spectrum of fluctuations that are shown above. The sharp decline for f>6.5 kHz is seen very well.

5
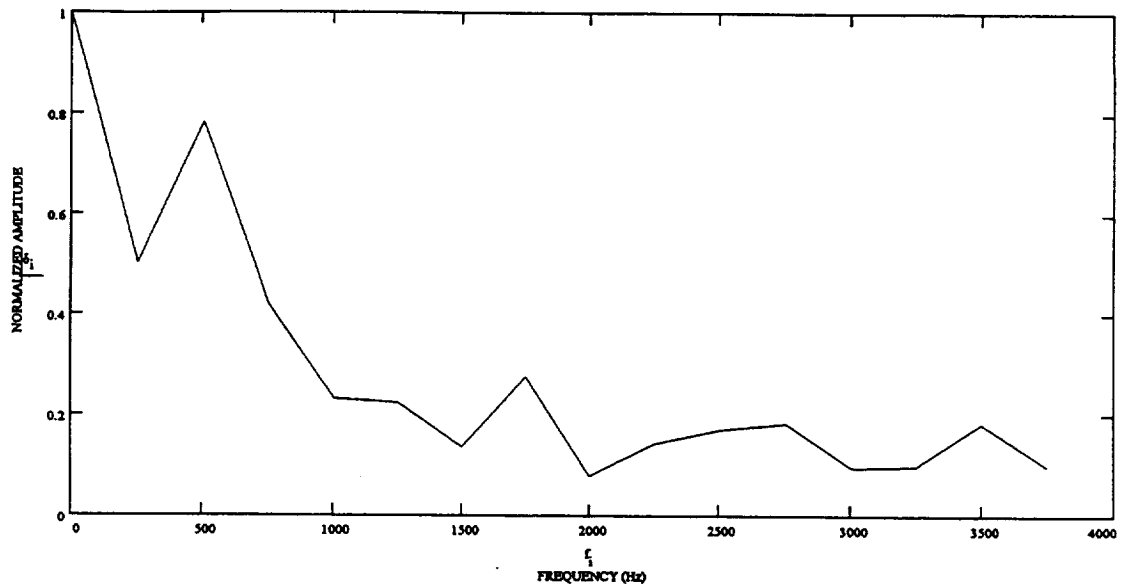
Fig.4. Average spectrum that was build by using data from twelve dwells. The best fit approximation $\delta \propto f^{0.76\pm0.2}$ is in good agreement with theoretical predictions.

Fig.5. LP output voltage fluctuations measured during the dwell in ram conditions when arcing occurred (MET 17:21:40). This plot demonstrates the large amplitude caused by arcing.

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PEAK OUTPUT VOLTAGE U_{pk}

lgN$_i$
LOG NUMBER OF ARCS
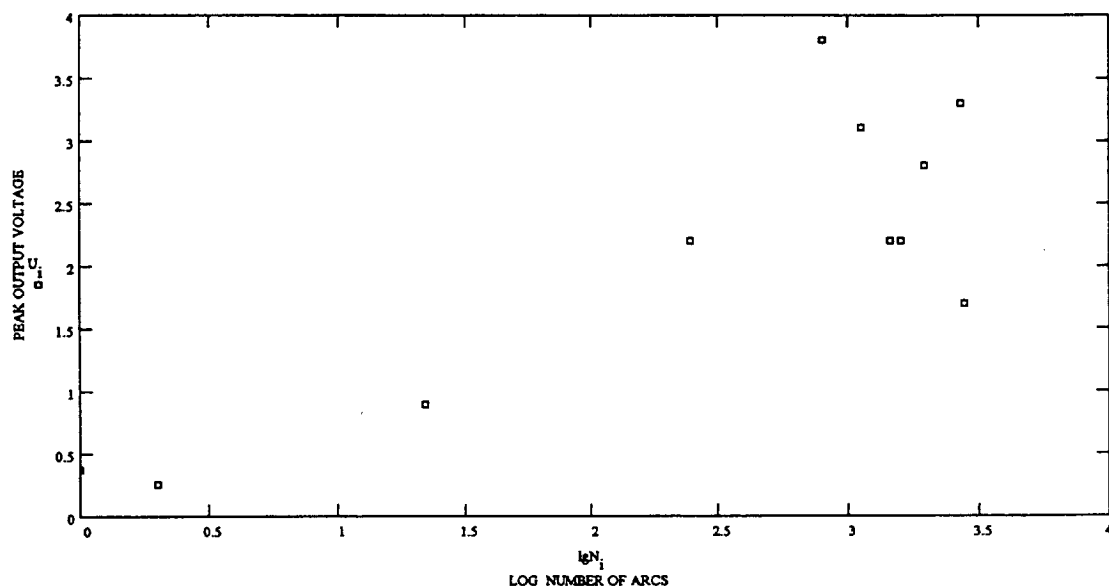
Fig.6. LP peak voltage vs. the number of arcs per one experiment. Twelve dwells are used to draw this chart. No correlations were found between the peak voltage and the distance of the LP from biased solar cell samples.

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