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Aeronautical University
DAYTONA BEACH, FLORIDA

Contamination Effects on a Sweeping Langmuir Probe in Earth's Ionosphere

SAIL
Space and Atmospheric
Instrumentation Lab
sail.erau.edu

Rachel Conway (conwayr2@erau.edu)   Aroh Barjatya   Shantanab Debchoudhury

Abstract

Langmuir probes are frequently used on sounding rockets and satellites to provide measurements of plasma density, electron temperature, and spacecraft floating potential. In Earth's ionosphere, however, Langmuir probes often experience surface contamination as a result of water adsorption, dust or oil contaminants, or oxidation of the surface due to the atomic oxygen environment. In these cases, the current-voltage (IV) curve becomes distorted and produces disagreements in derived parameters dependent on the voltage sweep direction. There is general agreement within the science community that in such circumstances upsweep is more accurate. This work presents simulations for a sounding rocket in Earth's ionosphere with both a floating potential probe and a Sweeping Langmuir Probe onboard. The system's behavior is investigated as a function of the five primary parameters controlling contamination effects. We explore effects on derived plasma parameters as a function of different sweep profiles and find that the ion dwell between IV curve sweeps presents the most unaffected results despite the presence of contamination.

Langmuir Probes in Earth's Ionosphere

Langmuir probes are used to measure plasma densities and temperatures in both Earth's ionosphere as well as interplanetary space. In the case of a Sweeping Langmuir Probe (SLP), a voltage is swept across both negative and positive potentials with respect to the spacecraft chassis, and the resulting current is measured. Each current-voltage (IV) curve, shown in Figure 1, gives a single measurement of electron and ion density, electron temperature, and can even provide insight into spacecraft charging.

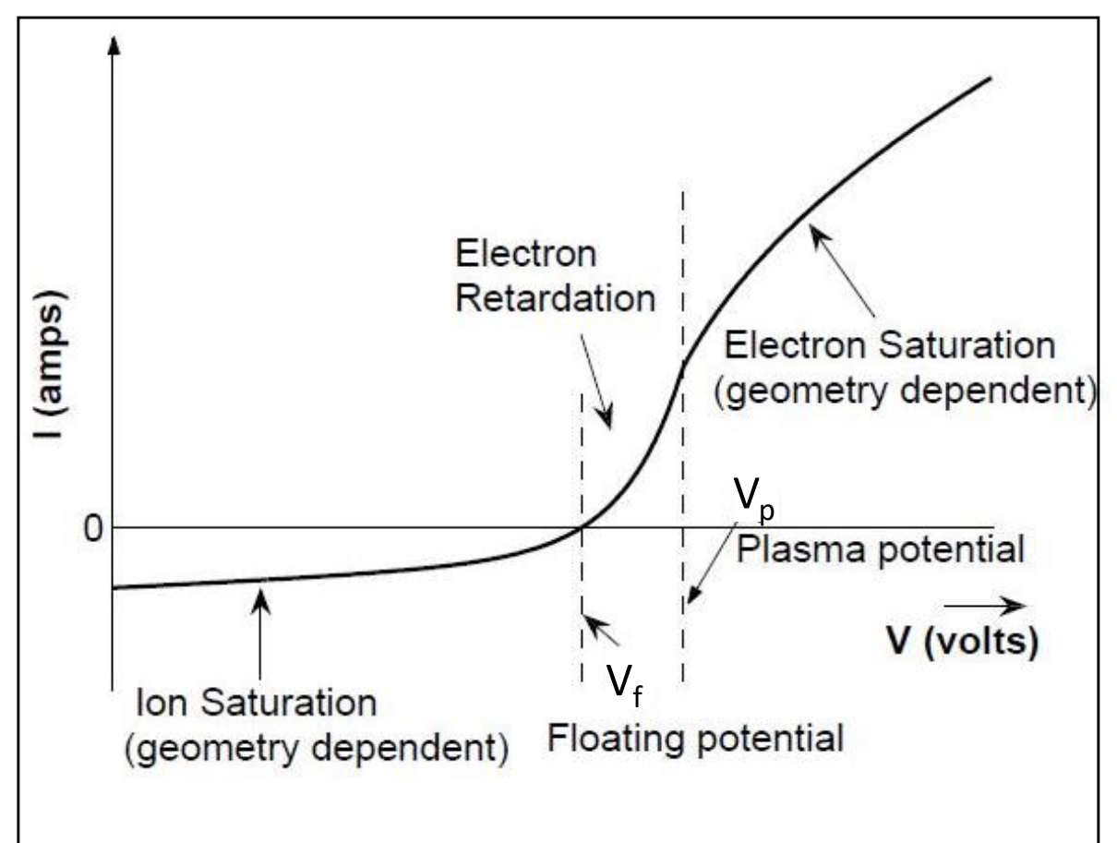
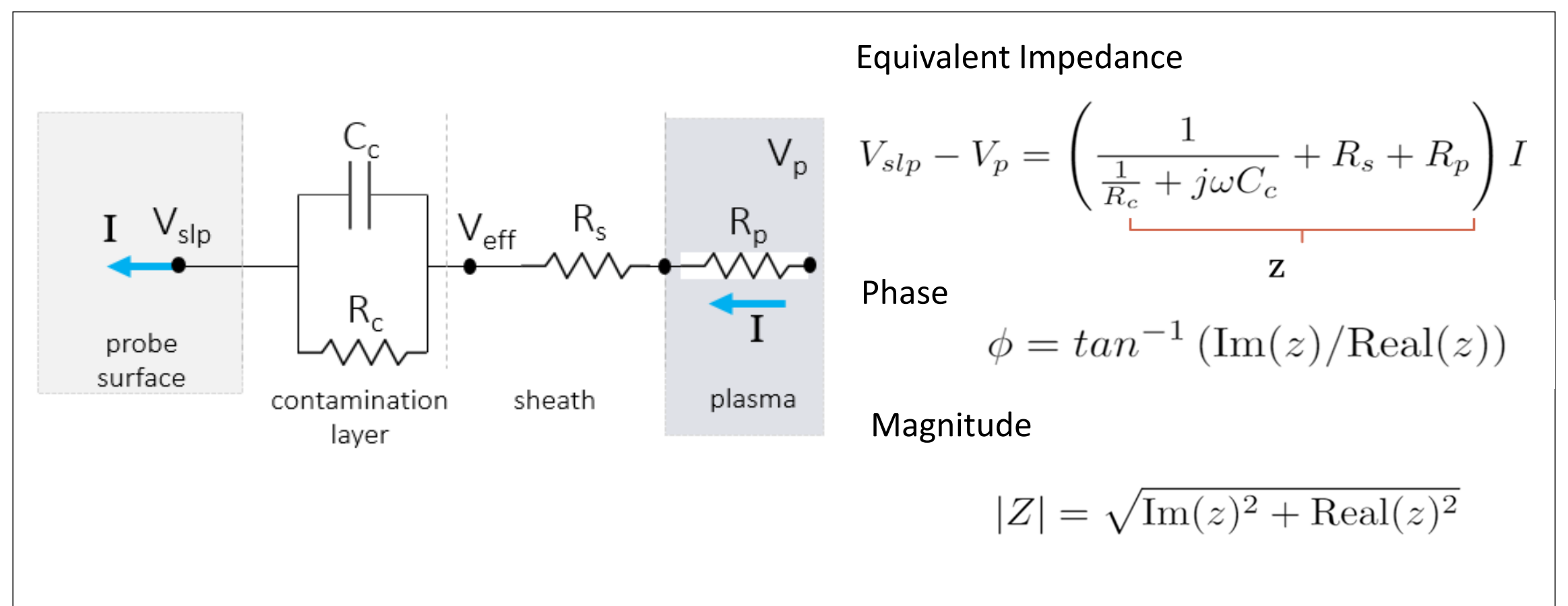


Figure 1: General IV curve shown the three main collection regions. Ion saturation current is amplified for ease of viewing. Figure adapted from Barjatya [2007].

Ideally the IV curve should be independent of the sweep direction. However, in the presence of surface contamination the resulting derived plasma parameters can have disagreements between the upsweep and downsweep, and could both be wrong even if they do have agreement. Oyama et al. [2012] point to the downsweep, Piel et al. [2001] point to the upsweep, and Oyama [1976] suggests the uncontaminated solution falls somewhere in between. This work addresses the issue of surface contamination and its effect on derived plasma density and temperatures as well as charging measurements.

Surface Contamination on Langmuir Probes



Equivalent Impedance

$$V_{slp} - V_p = \left(\underbrace{\frac{1}{\frac{1}{R_c} + j\omega C_c} + R_s + R_p}_{z} \right) I$$

Phase

$$\phi = tan^{-1}\left(\mathrm{Im}(z)/\mathrm{Real}(z)\right)$$

Magnitude

$$|Z| = \sqrt{\mathrm{Im}(z)^2 + \mathrm{Real}(z)^2}$$

Figure 2: Equivalent circuit for a probe with a contamination layer. The contamination layer is represented by R_c and C_c ,Vslp is the voltage applied to the probe, and Veff is the potential seen by the plasma. The sheath and plasma can be represented by some equivalent resistance, given by Rs+Rp.

Contamination layer on the probe surface is typically modeled as a resistor and capacitor in parallel (Figure 2). The impedance between the voltage applied to the probe and the current collected is shown in the equations above. This results in not only a phase difference, but also a magnitude component in the collected current. The contamination effects can thus be separated into four regimes, as follows:

1. Phase and Magnitude,
2. Phase Only,
3. Magnitude Only,
4. Neither Phase nor Magnitude.

Example IV curves representing each regime can be found in Figure 3.

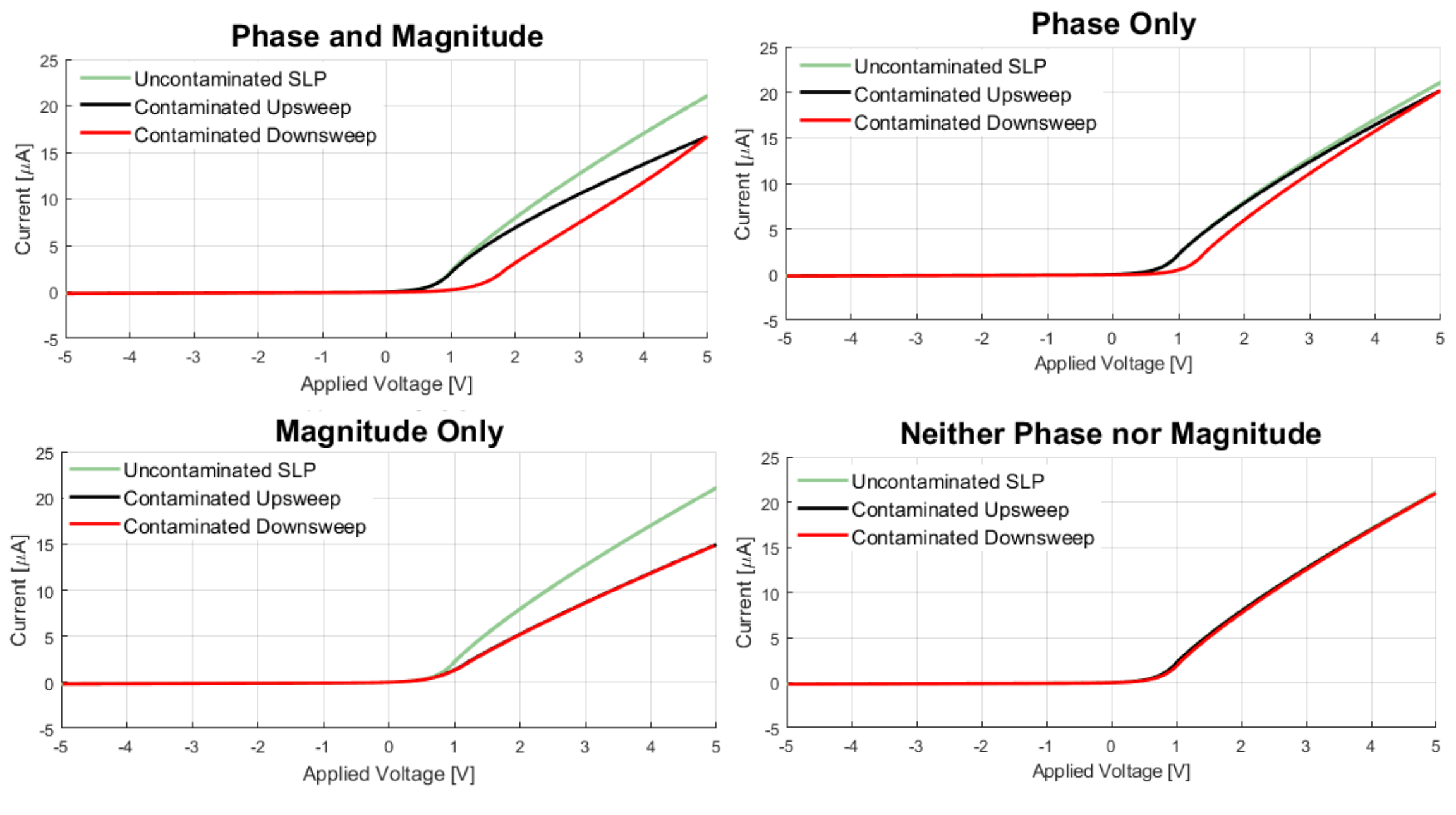


Figure 3: Arbitrary IV curves representing the four contamination regimes.

The contamination effects experienced by a Sweeping Langmuir Probe are influenced by 5 primary parameters. They are as follows:

1. R_C : Contamination layer resistance
2. C_C : Contamination layer capacitance
3. *f* : Sweep Rate of the applied voltage
4. |I| : Magnitude of collected current
5. Sweep Profile

SPICE Simulation

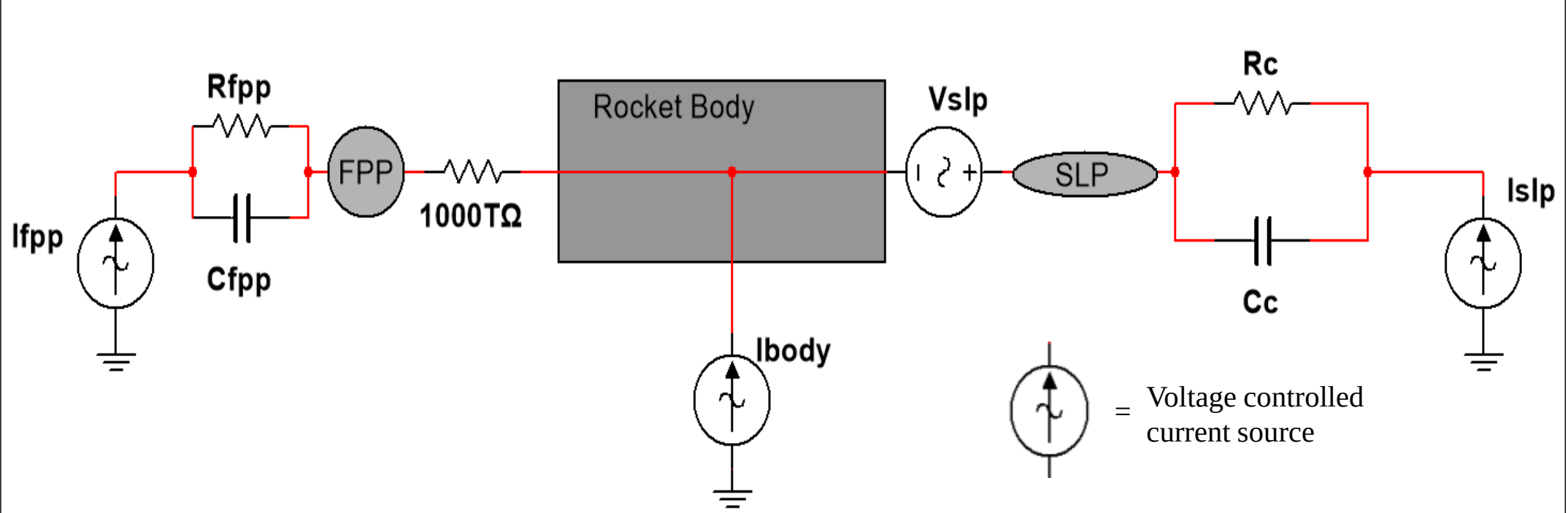


Figure 4: Visual depiction of LTSpice model. The voltage controlled current sources are modelled using Orbital Motion Limited current collection expressions.

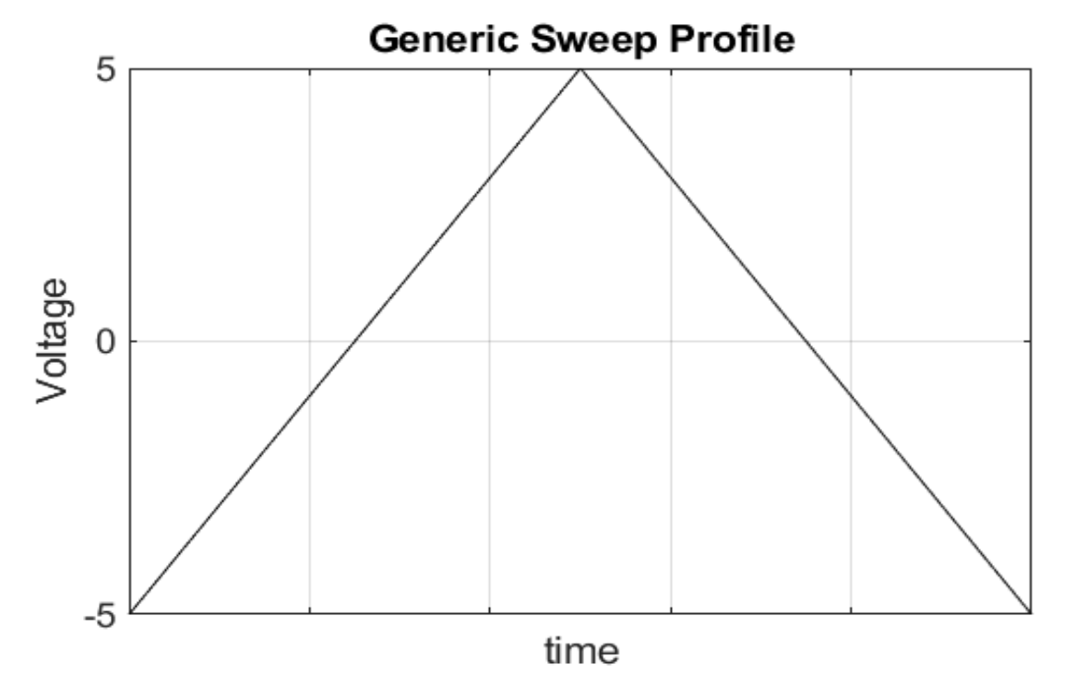


Figure 5: Generic voltage profile applied to SLP.

LTSpice, a SPICE simulation software, is used to model a contaminated Sweeping Langmuir Probe (SLP) onboard a sounding rocket. SPICE, Simulation Program with Integrated Circuit Emphasis, uses numerical solvers to evaluate current and voltage values and allows for transient analysis of both linear and non-linear components.

A visual depiction of the simulation model is shown in Figure 4 and contains both an SLP and a Floating Potential Probe (FPP). Vslp is the voltage applied to the SLP and follows the generic single sweep profile shown in Figure 5, where the duration of the sweep is equal to t =1/f. A contamination layer is modeled as a resistor and capacitor in parallel on both probes. The current to all probes, as well as the rocket body, is represented by a voltage-controlled current source that uses following equations:

if $V < V_p$,

$$I_e(V) = I_{th_e} exp(-|\frac{e(V-V_p)}{k_B T_e}|)$$

$$I_i(V) = -I_{th_i} \left(1 - \frac{e(V-V_p)}{k_B T_i}\right)^{\beta}$$

$$I_{ram}(V) = -eN_i A_{ram} v_{ram}$$

if $V > V_p$,

$$I_e(V) = I_{th_e} \left(1 + \frac{e(V-V_p)}{k_B T_e}\right)^{\beta}$$

$$I_i(V) = -I_{th_i} exp(-|\frac{e(V-V_p)}{k_B T_i}|)$$

$$I_{ram}(V) = -eN_i A_{ram} v_{ram} H(\frac{(0.5 m_i M v_{ram}^2)}{e} - V)$$

Where $I_{th,j} = N_j e A \sqrt{(k_B T_j/(2\pi M m_j)}$ is the random thermal current to the probe, e is electron charge, k_B is Boltzmann's constant, $m_{i,e}$ is ion/electron mass, V is the voltage applied to the SLP, and V_p is the plasma potential. The remaining parameters are given in *Table 1*.

The above equations account for both ion and electron thermal currents as well as ion ram current, where the SLP is perpendicular to the ram direction. Modeled SLP is cylindrical in shape with radius of 1.5mm and length of 7cm. The surface area ratio between the rocket body and SLP is modeled as 10,000 in order to avoid effects due to dynamic charging during voltage sweeps. *Table 1* shows the parameters that are constant across all simulations.

Parameter	Symbol	Value
Ion and electron temperature	T_e, T_i	3000K
Ion and electron beta	β	0.8
SLP Surface Area	A	$3.3\text{x}10^{-4}$ m^2
SLP ram facing area	A_{ram}	$1.05\text{x}10^{-4}$ m^2
Ram Velocity	v_{ram}	400 m/s
Ion Mass	M	16 amu

Table 1: Constant parameters used in simulations.

Isolated Sweep: Contamination Effects on Derived Parameters

The first set of simulations consider only a single upsweep and downsweep, as shown in *Figure 5*, therefore removing the influence of a sweep profile. The contamination capacitance, C_c, is fixed at 1μF, and the remaining parameters (R_c, *f*, and current magnitude) are allowed to vary within reasonable ranges for Earth's ionosphere. It should be noted that plasma density is chosen to represent current magnitude for the purposes of simplicity, since it is directly proportional to current.

After simulating all valid ranges of our three parameters, the resulting IV curves are fit in a nonlinear-least squares sense to the above equations. As shown in Figure 3, the electron saturation region is extremely sensitive to contamination effects, and therefore, this work presents results from a non-linear least squares fit to the ion saturation and electron retardation regions only [Debchoudhury 2021]. The following plots show absolute percent error in derived plasma parameters for both the upsweep and downsweep of a single isolated sweep with C_c= 1μF. Downsweep percent error in both temperature and density can be seen to increase for both increasing density and decreasing frequency, as expected. As expected, upsweep derived plasma parameters remain unaffected.

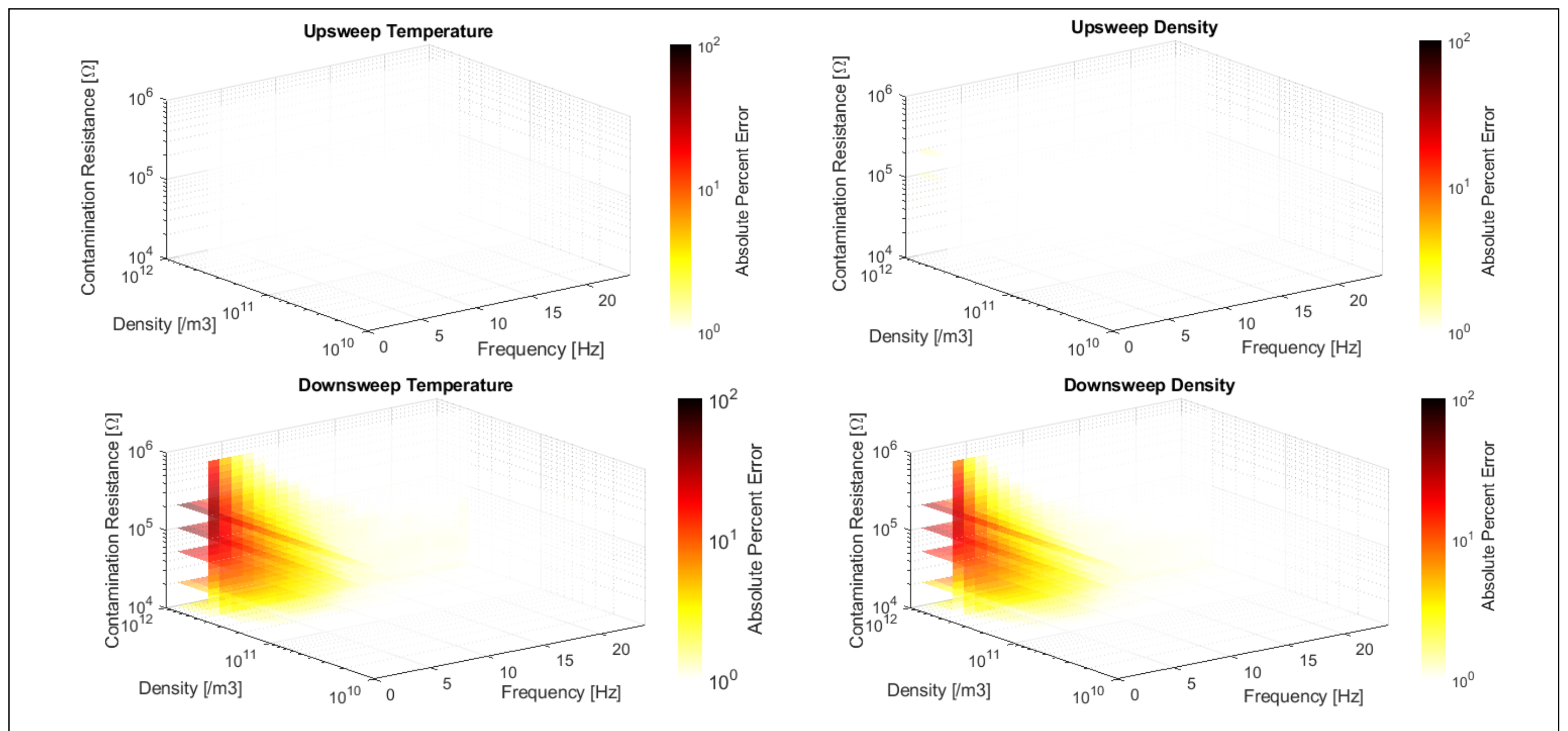


Figure 6: Derived absolute percent errors as a function of plasma density, SLP sweep frequency, and contamination resistance for both the upsweep and downsweep. The contamination capacitance is fixed to 1μF. All other fixed parameters can be found in Table 1.

The simulation is repeated, this time holding density constant at N = 1e12 m^{-3}. Results are shown in Figure 7. As capacitance decreases, more of the parameter space is affected by contamination effects. Regardless, the upsweep remains unaffected in the ion saturation and electron retardation region. Therefore, in the case of a single, isolated sweep the upsweep will produce accurate density and temperature measurements for all reasonable values of the parameter space.

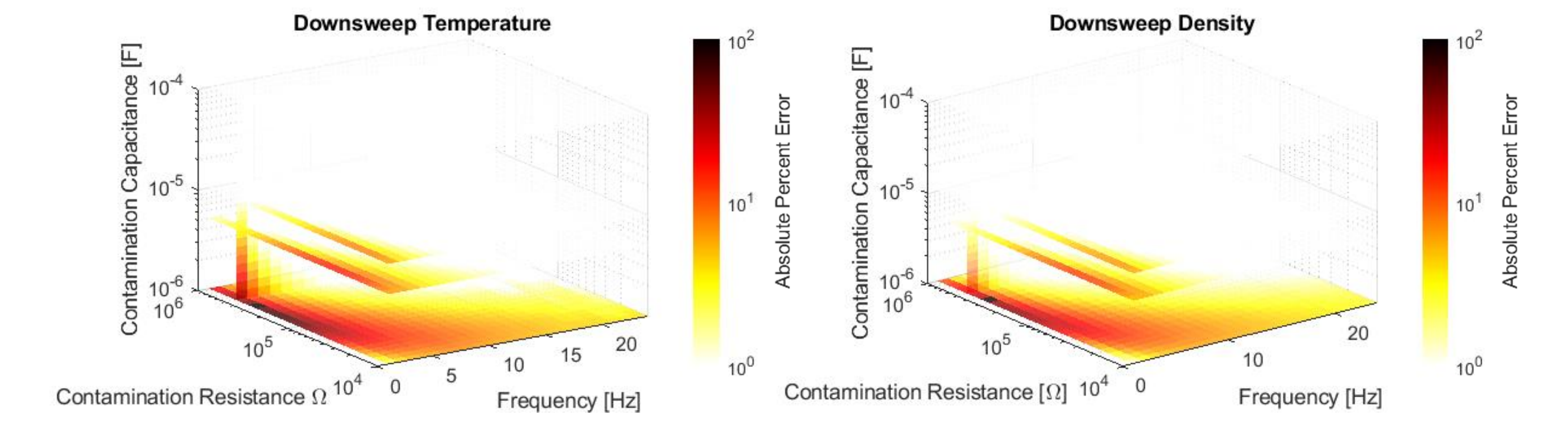


Figure 7: Derived absolute percent errors as a function of SLP sweep frequency, contamination capacitance and contamination resistance for the downsweep only. The upsweep results remain unchanged.. The plasma density is fixed to 1e12 m^{-3}. All other fixed parameters can be found in Table 1.

Various Sweep Profiles: Effects on Derived Plasma Parameters

In flight, performing a single isolated sweep is not possible as the SLP is continuously taking measurements. There are, however, different methods for continuously sweeping, as shown in Figure 8.

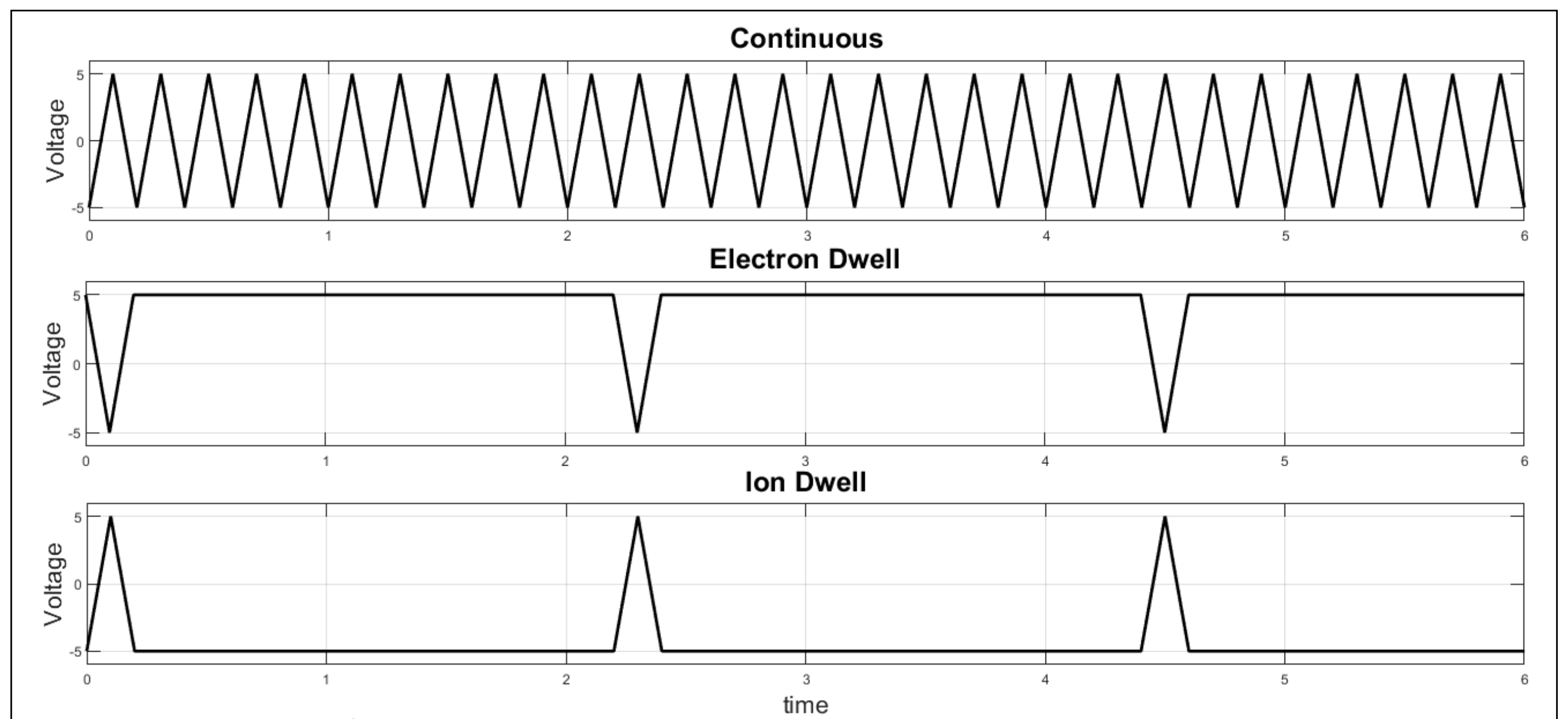


Figure 8: Sweep profiles applied to the SLP in SPICE.

We simulate each of these voltage profiles of the SLP, where both electron and ion dwell last for two seconds. The simulation considers a single set of parameters as follows:
N = 1e12m^{-3}, C_c = 1μF, R_c =100kΩ, and *f* = 5 Hz, where R_c and C_c values are those suggested by Oyama [2012]. The resulting IV curves are presented in Figure 9.

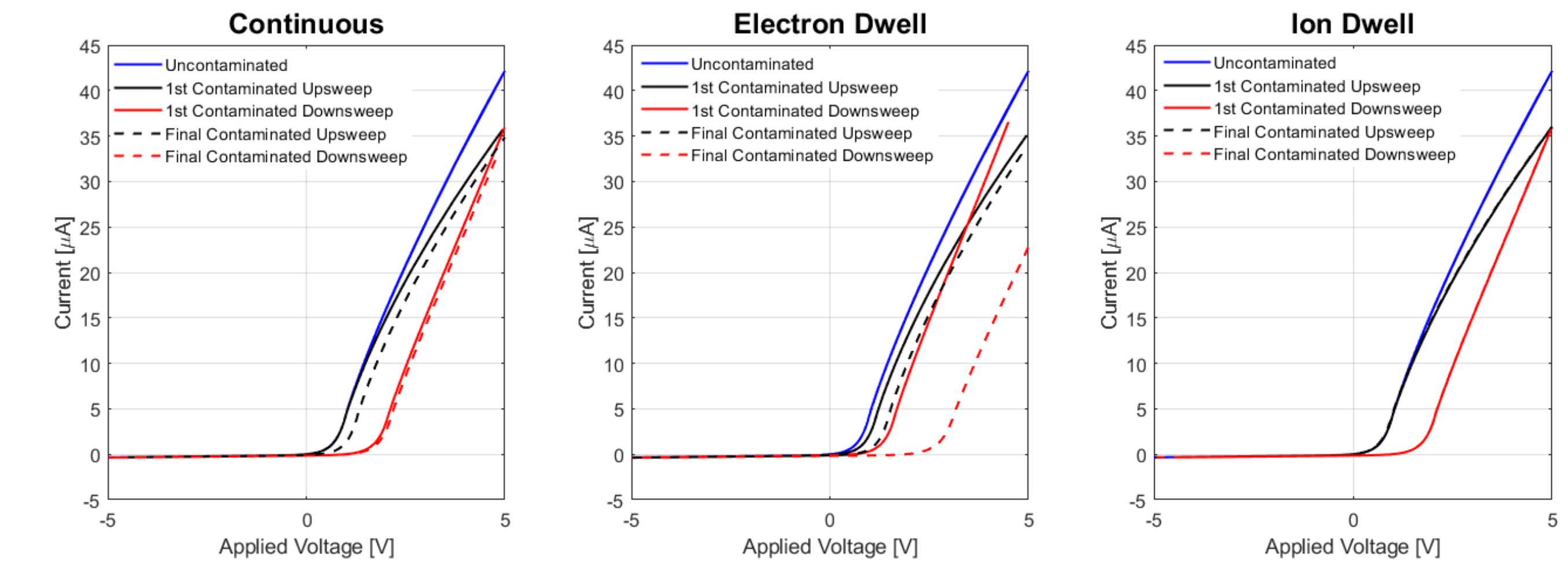


Figure 9: Simulated IV curves for three different sweep profiles. Solid lines show the first sweep while dashed lines show the final sweep. An uncontaminated SLP, representing the ideal case, is also plotted in blue.

The results show the characteristic rightward shift mentioned by Szuszczewics and Holmes [1975]. Both the continuous and electron dwell profiles experience extreme rightward shifts because the SLP sees high voltages for a large portion of its profile, allowing for significant charge buildup across the contamination layer. The ion dwell, however, is held at -5V, where currents are two orders of magnitude smaller. This allows the contamination capacitor time to discharge and avoids any long-term transient effects.
The same simulation is repeated, but this time the sweep frequency is increased to 20 Hz, as the literature suggests that high sweep rates will bypass all contamination effects. The resulting IV curves can be found in Figure 10.

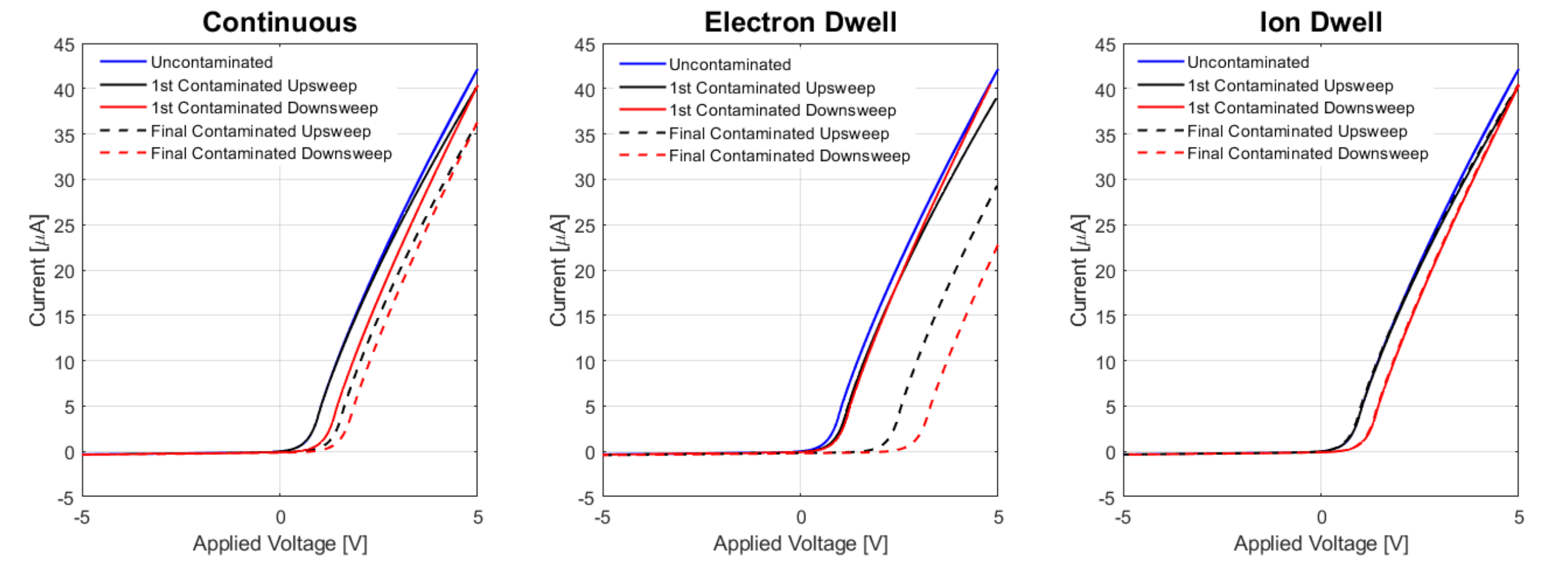


Figure 10: Simulated IV curves at increased sweep rate (f = 20Hz). Solid lines show the first sweep while dashed lines show the final sweep. An uncontaminated SLP, representing the ideal case, is also plotted in blue.

Derived Parameter		Percent Error in Final Sweep at 20Hz [%]		
		Continuous	Electron Dwell	Ion Dwell
N_i	up	0.25	1.16	-0.40
	down	-1.35	-3.24	-0.76
T_e	Up	-1.64	-3.44	-0.02
	Down	1.19	5.89	1.25
V_{sc}	Up	58.2	150.1	-3.5
	Down	82.5	223.5	39.3

Table 2: Percent Error in derived parameters for all three sweep profiles at 20Hz.

Takeaways

- In the case of a single, isolated sweep, the upsweep will produce accurate densities and temperatures for all reasonable values of the parameter space when the ion saturation and electron retardation region are analyzed. That said, no spaceflight mission does a single sweep, rather, there is a sweep profile.
- At high sweep rates, the upsweeps from all three sweep profiles produce plasma density and temperature values with less than 5% error. However, only the ion dwell results in accurate measurements of spacecraft charging from the upsweeps.

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