

ダスト衝突に伴う衛星電位変動現象に関する 計算機シミュレーション

Computer Simulation of Spacecraft Potential Variations Induced by Dust Impacts

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担当 : 本研究全般の研究指導

研究目的 (Research Objective):

Microscopic dust particles in space can collide with satellites at hypervelocity, generating transient plasma clouds. These dust impact events cause sudden and significant perturbations in the spacecraft's electric potential, which can interfere with onboard electric field instruments like those on the STEREO and ARTEMIS missions. Currently, most theoretical models used to explain these potential variations are empirical and based on waveform fitting. They lack a first-principles description of the complex spacecraft-plasma interactions, particularly regarding sheath dynamics and the timescale of the potential fluctuations.

The primary objective of this study is to investigate the physical mechanisms governing these potential variations using the 3D electromagnetic Particle-in-Cell (PIC) code, EMSES. By developing and comparing quantitative models of plasma cloud generation and particle dynamics, we aim to deepen the physical understanding of dust impact phenomena and clarify the dominant mechanisms behind the characteristic pulse waveforms observed by satellites.

計算手法 (Computational Aspects):

This study utilizes the 3D electromagnetic PIC simulation tool, EMSES, running on the KDK supercomputer system. EMSES allows for the detailed modeling of complex spacecraft structures as inner boundaries within the plasma simulation domain. To understand the potential variations, we employed two distinct modeling approaches, the current model and the plasma cloud model.

In the current model approach, we simulated the dust impact by defining a specific area on the spacecraft surface and injecting a flow of electrons and ions to replicate the influx of current, which was based on an existing empirical model. [Zaslavsky et al., 2015]

In the plasma cloud model, we introduced a new custom function, "pcloud," into EMSES. This function allows us to directly generate a plasma cloud with a fixed charge, a specific number of electrons and ions, within the simulation space. The velocity distribution is assumed to be Maxwellian, while the spatial distribution is modeled as a point source expansion [Fig.1]. This enables precise control over the spatial and velocity distributions of the generated plasma cloud, allowing us to simulate its interaction with the spacecraft body under various physical parameters.

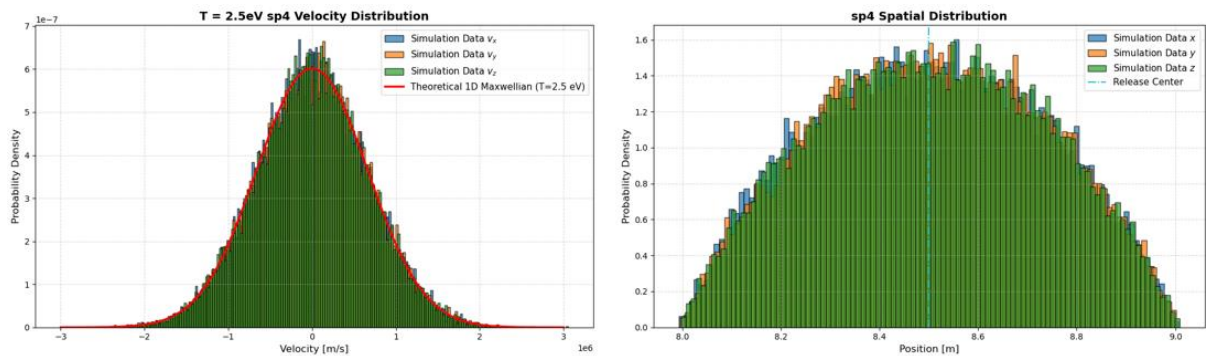


Fig.1 Velocity and spatial distributions of the plasma cloud generated using the “pcloud” function in EMSES.

研究成果 (Accomplishments) :

Consistent with previous observational and theoretical studies, our comparative analysis using both models successfully reproduced the characteristic three-stage evolution of a dust impact signal: an initial pre-drop potential rise (pre-pulse structure), a main potential drop, and a subsequent recovery phase [Fig.2]. Both the current model and the plasma cloud model captured the initial pre-pulse structure. The plasma cloud model demonstrates that the pre-pulse structure is primarily driven by the space-charge effects of the generated plasma cloud ions, which aligns with earlier theoretical predictions [Fig.3]. Meanwhile, the current model provides an additional perspective, suggesting that photoelectron currents also contribute to this pre-pulse phase [Fig.4]. Following the pre-pulse, the simulations show that the rapid main potential drop is caused by the accumulation of surface charges as electrons from the plasma cloud are absorbed by the spacecraft body. Subsequently, the relatively long recovery phase is governed by the relaxation of these accumulated surface charges.

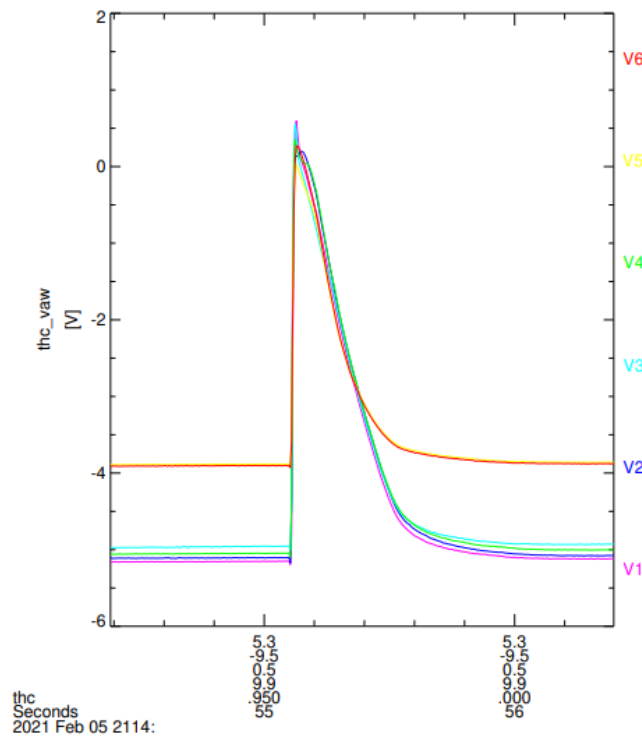


Fig.2 Observational data from the electric field instrument onboard the ARTEMIS satellite, showing the pre-pulse structure, main potential drop, and recovery phase. [Takaramoto, 2025]

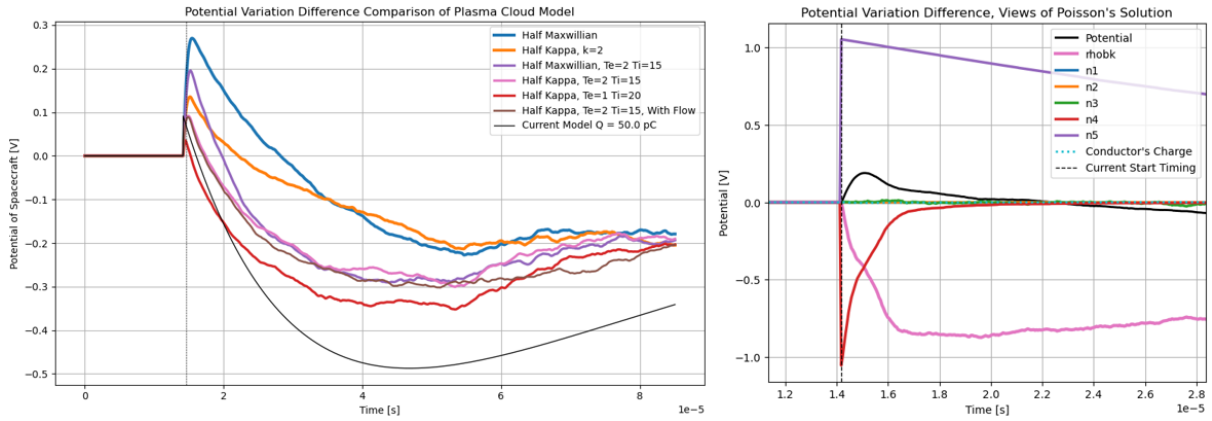


Fig.3 Simulation results from the plasma cloud model, showing a clear pre-pulse structure under various settings. Solutions to Poisson's equation indicate that this structure is induced by ions within the plasma cloud.

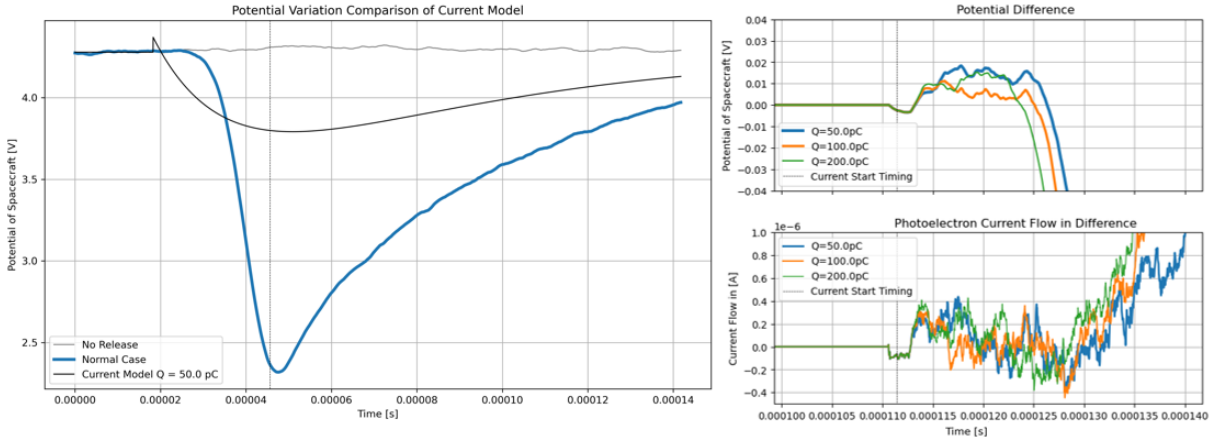


Fig.4 Simulation results from the current model across different charge release scenarios, showing a main potential drop, a subsequent recovery phase, and a small pre-pulse structure.

Although both approaches provided valuable insights, they exhibited distinct strengths and limitations. The current model, which relies on empirical formulations, successfully recreated the general waveform shape but showed a mismatch in the time scale when compared to ARTEMIS observational data. This discrepancy is likely because the underlying parameters of the current model were originally proposed for the STEREO satellite. Conversely, the newly developed plasma cloud model successfully reproduces the qualitative three-stage evolution from first principles. However, our current primary focus is addressing a quantitative deviation where the simulated magnitude of the main potential drop does not fully align with observational data. The underlying physical reasons for this discrepancy are currently under active investigation and require further verification. Nevertheless, this approach already offers a more physically accurate picture of complex particle interactions.

Although this research is still ongoing, our results thus far have clearly demonstrated that 3D PIC simulations provide an effective and valuable approach for deepening our understanding of dust impact events. Moving forward, we will continue to refine our models and further investigate these complex spacecraft-plasma interactions.

公表状況 (Publications) :

(口頭)

1. T.J. Lin, S. Kurita, H. Kojima, T. Taniguchi, J. Nakazono, Y. Miyake, H. Usui, Computer Simulation of Dust Impact signals Detected by Electric Field Instruments Onboard Satellites, SGEPPSS, Kobe, Nov. 2025
2. T.J. Lin, S. Kurita, H. Kojima, J. Nakazono, Y. Miyake, H. Usui, Computer Simulations of Spacecraft Potential Variations Caused by Hypervelocity Dust Impacts: Two Models Approach, URSI-JRSM, Tokyo, Mar. 2026
- 3.