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Instrumental modeling of Mutual Impedance experiments and validation tests in plasma chamber

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Mutual impedance experiments are in situ space plasma diagnostic techniques for the determination of characteristic plasma parameters, such as the plasma density and the electron temperature. These electric experiments rely on the coupling between two emitting and two receiving antennas embedded in the plasma to be diagnosed.

Different versions of mutual impedance instruments are included in the scientific payload of past, present and future exploratory planetary space missions, such as the RPC-MIP instrument onboard the Rosetta spacecraft that explored the cometary environment of comet 67P/CG, the PWI/AM2P experiment onboard the Mio spacecraft of the BepiColombo mission that will investigate the Hermean environment, the RPWI/MIME experiment onboard the JUICE spacecraft that will characterize the magnetosphere and ionosphere of Ganymede, and the DFP/COMPLIMENT instrument onboard the Comet Interceptor spacecraft that will map the ionized environment of a pristine comet and its interaction with the solar wind.

The next step in planetary exploration shall rely on small satellite platforms and the concept of multi-point measurements missions. In particular, by mapping the investigated plasma environment, multi-point measurements shall improve our understanding of the investigated physical phenomena by enabling the distinction between spatial and time dependent variations, a distinction that is not possible with current single-point measurements configurations.

In this context, mutual impedance instruments are now being adapted to better fit small satellite platforms. Instrumental development efforts are put into various and complementary directions. First, we are increasing the signal emission amplitude of the mutual impedance instrument in order to improve the signal-to-noise ratio of the measurements and to relax EMC (i.e. electromagnetic compatibility) constraints on the small satellite platform while maintaining robust plasma density and electron temperature diagnostic performances. Second, we are optimizing the time-resolution of the instrument to facilitate the coupling of mutual impedance experiments with different plasma experiments, such as the Quasi-Thermal Noise and the Langmuir Probe experiments, all using the same electric sensors to perform their measurements. Indeed, coupling between different experiments and sharing of sensors is crucial for nanosatellite applications, where the limited mass and volume strongly constrain the design of the payload instrumentation.

To reach such goals, we use two complementary tools. Our first tool is a numerical 1D-1V full-kinetic electrostatic Vlasov-Poisson model that enables to simulate the propagation of electric perturbations generated in the plasma by mutual impedance experiments and address both the effect of nonlinearities and inhomogeneities in the instrumental response. Our second tool is the plasma chamber of CNRS-LPC2E space laboratory (Orléans, France) that enables experimental tests of space plasma instruments and nanosatellites in typical plasma conditions encountered in planetary ionospheres. We use this plasma chamber to test both mutual impedance miniaturized instrument prototypes and new mutual impedance instrumental modes.

The results of our investigation are the following.

First, using our new instrumental model in both linear and non-linear regimes, we identify for the first time the maximum emission amplitude that can be used in mutual impedance experiments without introducing spurious nonlinear perturbations in the plasma and show the robustness of both plasma density and electron temperature diagnostics even when non-linear effects such as wave-wave and wave-particle interactions are triggered in the plasma. We find on optimal threshold of the electric energy injected in the plasma to be smaller than 10% of the electron thermal energy, to be applied to the design of future mutual impedance experiments.

Second, using both our numerical model and the plasma chamber facility, we show that the sensor occupation can be drastically reduced without loss of plasma density diagnostic, thus potentially enabling a significant increase of time resolution for future mutual impedance experiments. This result enables the design of a new mutual impedance instrumental mode, called "chirp mode", for which the measurement time duration is reduce by a factor 10-100 compared to typical space applications such as the RPC/MIP onboard the Rosetta spacecraft.

These new instrumental developments will be at the basis of significant improvements in the design of future mutual impedance experiments for planetology exploration.