Numerical studies of space plasma electrodynamics with the help of parallelised codes for Maxwell-Lorentz and kinetic equations

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We report recent results from a project, started in the late 1990's and aimed at the development of numerical codes for detailed modelling of the nonlinear interactions between beams of electromagnetic fields, plasma waves, and particles with space plasmas. Particular emphasis is put on the possibility of studying the evolution of a turbulent saturated stage of the processes where satisfactory analytical and/or numerical models describing experimental results obtained from the past 25 years are still sorely lacking.

We will describe the parallelisation of an existing two spatial and two velocity dimensional (2+2D) Vlasov-Maxwell solver for UNIX/Linux, which uses pseudospectral methods and high-order compact difference schemes to approximate derivatives. The parallelization of the four-dimensional phase-space is performed by transposing the data over the processor grid so that single-processor algorithms can be used for the pseudo-spectral and compact difference scheme algorithms, thereby reducing the complexity of the program and increasing the efficiency of the data communication. The expanded code provides opportunities to look closer at many of the theoretical problems connected with the study. Examples are the nonlinear interaction between antennas and plasmas, the kinetic effects of trapped upper-hybrid waves in two-dimensional plasma cavities, nonlinear waves and kinetic structures in the lower-hybrid range, etc, where a parallelized code is needed to overcome both memory and simulation time demands.

Under way is also an extension of the two-dimensional code into three dimensions. With a full three-dimensional (3+3D) code, one can compare the results with those obtained with 3D PIC codes used by other research groups and to test the applicability of approximate fluid- and Zakharov models. Our resulting kinetic code will be able to simulate the central parts of the radiation, and in this way answer questions that have not been answered in many of the earlier projects. It is anticipated that we will at the same time be able to incorporate a code for the rest of the atmospheric volume, from ground up to the ionosphere. One example of ionospheric experiment planned for LOIS is the injection of several EM waves at very high frequencies, but separated by typical resonance frequencies of the plasma. This situation resembles many natural and anthorpogenic processes, beat-wave particle acceleration experiments in elementary particle physics, and the nonlinear response of the surrounding plasma during synchronous multi-channel satellite communication transmissions. Results from a 2+2D Vlasov/Maxwell simulation have already been obtained but the limitation of these simulations, not allowing the prediction of the complete ordinary and extraordinary plasma mode response, will be removed with the higher-dimensional codes under development.

The long-term main goal of the project described here is to continue and expand the computer modelling line of development and to create a full-scale numerical model, based on kinetic plasma theory and Maxwell-Lorentz theory, of the interaction between the ionospheric plasma and beams of particles (electrons and ions) resulting in weak and strong electrostatic and electromagnetic turbulence in the ionosphere and the magnetosphere. Such interactions have for over twenty years been studied remotely in experiments by injecting radio waves into the ionosphere and the subsequent observation and analysis, of the reflected wave and associated secondary radio emissions. Recent results from the EISCAT Svalbard radar, interpreted as Langmuir turbulence excited by "natural" electron beams, belong to the very same category of non-linear plasma physics radiation problems. Attempts have been made to try to explain the results with the help of the Zakharov approximation but self-consistent results seem impossible to obtain from Zakharov-type equations. Kinetic electromagnetic codes of the type developed in our project do not suffer from such limitations.

The project is of particular importance for the new-generation digital radio telescope LOFAR and its Scandinavian outrigger, LOIS. This system, consisting of more than 25 000 sensor nodes currently under deployment in the Netherlands, Germany, and southern Sweden will, by far, be the world's most powerful ground-based netted radio and radar facility for fundamental solar, interplanetary, magnetospheric, ionospheric and atmospheric physics. In particular, the LOIS/LOFAR combination will be the first attempt to actively probe coronal mass ejections (CMEs) from the Sun using radar techniques, aiming at producing reliable predictions of particle storms which seriously affect technological systems and may be harmful to biological systems. In order to correctly interpret the observations in the LOIS radio project, it is of importance to model and understand the processes responsible for the observational results.