Stable dispersion analysis of an arbitrary distributed plasma system with noise

V.A. Frantsuzov[1,2], A.V. Artemyev[2], A.A. Petrukovich[1]

1. Space Research Institute of the Russian Academy of Sciences (IKI), Moscow, Russia

2. Faculty of Physics, National Research Institute Higher School of Economics, Moscow, Russia

3. Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, USA

Plasma micro-instabilities, although driven by the kinetic properties of charged-particle distribution functions, largely control the dynamics of large-scale plasma systems. These instabilities are responsible for releasing the free energy stored within particle distributions and for driving their relaxation toward more stable states. In the absence of collisions – such as in space plasmas – micro-instabilities provide the primary mechanism for particle energy and momentum exchange, enabling the system to evolve toward equilibrium.

The basic theoretical framework used to investigate plasma instabilities is perturbation theory, which treats instabilities as spatially and temporally growing perturbations of an initial plasma state. Applied to particle velocity distributions, this approach encompasses a wide range of instabilities and yields their dispersion relations (frequency as a function of wave number) and growth rates. Historically, perturbation theory has been applied to model distributions described by analytical functions designed to mimic characteristic features of realistic plasmas. However, with the rapid development of in-situ charged-particle measurements from space missions, this approach is increasingly being used directly on spacecraft data interpolated onto velocity.

The integration of spacecraft observations with perturbation theory for instability identification introduces several new challenges. First, distribution functions measured by spacecraft contain finite – and sometimes significant – noise associated with measurement techniques, and this noise must be properly treated to minimize its impact on the resulting wave modes. Second, unlike idealized model distributions tailored for the study of a specific instability, real measured distributions may be unstable to multiple modes simultaneously, requiring accurate identification and separation of these modes within perturbation analyses. Third, the natural boundaries of the measured velocity-space domain must be handled carefully to avoid artificial effects on the computed wave modes.

Today, several well-developed numerical codes address these challenges from different perspectives, however, the most general case remains problematic. In this work we present an advanced version of such a dispersion solver that combines the most desirable features of existing tools and provides improved capability for recognizing and separating multiple wave modes in spacecraft-measured distribution functions.