

Fast numerical treatment of nonlinear wave equations by spectral methods

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A method is presented that accelerates spectral methods for numerical solution of a broad class of nonlinear partial differential wave equations that are first order in time and that arise in plasma wave theory. The approach involves exact analytical treatment of the linear part of the wave evolution including growth and damping as well as dispersion. After introducing the method for general scalar and vector equations, we discuss and illustrate it in more detail in the context of the coupling of high- and low-frequency plasma wave modes, as modeled by the electrostatic and electromagnetic Zakharov equations in multiple dimensions. For computational efficiency, the method uses eigenvector decomposition, which is particularly advantageous when the wave damping is mode-dependent and anisotropic in wavenumber space. In this context, it is shown that the method can significantly speed up numerical integration relative to standard spectral or finite difference methods by allowing much longer time steps, especially in the limit in which the nonlinear Schrödinger equation applies. © 2011 American Institute of Physics. [doi:10.1063/1.3551464]

I. INTRODUCTION

Nonlinear interactions of large-amplitude waves frequently occur in laboratory, space, and astrophysical plasmas,¹ as well as in nonlinear optics,² fluid dynamics,³ pattern formation in active media,⁴ and other branches of physics. In plasmas, the associated dynamics is typically analyzed via nonlinear partial differential equations, in which the electromagnetic fields are treated using approximations to the Euler equations of motion for each species (treated as a fluid), together with the Maxwell equations. One such approach is via the Zakharov equations,⁵ which describe the nonlinear coupling between Langmuir waves and ion-acoustic waves (and also transverse electromagnetic waves when the electromagnetic version is used). These equations have been remarkably successful in modeling a wide range of different physical phenomena involving three- and four-wave processes including decay, coalescence, and modulational instabilities, which play major roles in plasma turbulence.⁶ In studying strong turbulence, the Zakharov equations are usually solved numerically by spectral methods, in which the dependent variables are expressed in terms of a carefully chosen set of orthogonal basis functions,⁷ most often spatial Fourier modes. When applicable (e.g., for systems where the physical quantities are sufficiently smooth that they can be well represented via a finite Fourier or Chebyshev series expansion), spectral methods are often greatly superior to finite difference schemes because they provide much faster convergence rates and are computationally more economical. Nevertheless, many implementations of spectral methods to solve nonlinear wave equations in the plasma physics literature spend a considerable amount of computational time on handling the linear wave

evolution,^{8–11} which is generally neither desirable nor necessary, since this step can be minimized by using exact analytic formulas.

In this paper, we present an algorithm, termed the linear phase removal (LPR) scheme, that can speed up spectral computations by several orders of magnitude while maintaining or improving accuracy. The scheme constitutes a generalization of an unpublished solution method for the electrostatic Zakharov equations, which was developed and used extensively by Robinson and Newman,^{12–17} and is applied to the electromagnetic Zakharov equations. The approach is to solve exactly for the linear part of the high-frequency wave evolution, including thermal effects in the terms for the dispersion and linear growth and damping, and incorporate this knowledge in an algorithm that then need only advance the nonlinear terms. The algorithm is further optimized by re-expressing the electric field in terms of the eigenvectors for the matrix coefficient in front of the linear term in the Fourier-transformed equations. The benefit of the method is particularly great for cases where the time evolution of the fields is dominated by linear effects (as opposed to nonlinear self-focusing and ponderomotive effects), and the damping depends on the wave vector and polarization of the normal modes. In applications to wave collapse, for example, the method enables fast computation of the linear dynamics so that computational resources can be concentrated on the later stages of collapse, where nonlinear effects are maximal.

Some of the fundamentals behind the proposed LPR scheme have been discussed previously in the plasma literature, in various levels of detail, and in a variety of contexts.^{18–21} In an early paper, Payne *et al.*¹⁸ provided a rigorous derivation of a numerical algorithm to integrate the Zakharov equations using analytical expressions to handle the linear terms. They also checked the accuracy of their scheme for various time steps in terms of conserved quanti-

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Algebraic And Spectral Methods For Nonlinear Wave Equations

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