IMPLICIT SCHEMES IN A MULTI-PHYSICS AND MULTI-APPLICATION CODE: BALANCING EFFICIENCY AND FLEXIBILITY

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ABSTRACT

Over the last 16 years our group at the University of Michigan has been developing a general use global MHD code, the Block-Adaptive Tree Solarwind Roe-type Upwind Scheme (BATSRUS), and the Space Weather Modeling Framework (SWMF) that couples domain models extending from the Sun all the way to planetary upper atmospheres. BATS-R-US and the SWMF have been extensively used to simulate a broad range of space science phenomena, including the solar corona, coronal mass ejections (CME); propagation of CMEs through the heliosphere; interaction of the solar wind with planets, moons, and comets; and the termination shock of the outer heliosphere. More recently, in the Center for Radiative Shock Hydrodynamics, BATSRUS has been further extended to model laser induced radiative shocks that propagate through a small plastic tube in a few nanoseconds.

There are several applications when the system of partial differential equations become stiff, and the simple explicit time stepping method becomes inefficient. In some cases the whole system of equations is stiff in the whole domain, e.g. for strongly magnetized planets like Jupiter or Saturn. In these cases we use a fully implicit time stepping based on the Jacobian-Free Newton-Krylov-Schwarz (JFNKS) algorithm. In other cases only part of the domain is stiff, and we can employ an explicit/implicit time-stepping scheme: only grid blocks that are unstable for a given time step are advanced by the implicit scheme, the rest of the blocks are advanced by the explicit scheme. Radiative transfer as well as heat conduction can be extremely stiff but this involves a few variables only. We have developed a semi-implicit approach where the advection is handled explicitly, while the parabolic source terms are solved with the JFNKS method. Finally, chemical reactions, photoionization and recombination processes in the ionosphere of planets and moons can be stiff. Here a point-implicit approach can be utilized to speed up the calculations.

Due to the multitude of the equations and applications, it is advantageous to develop general-purpose methods instead of highly tuned special algorithms. We employ numerical derivatives and matrix free approaches as much as feasible. We also use a modular software design. For example the equation variables are defined in a small equation module, and the numerical schemes apply to all equations. The implicit solvers reuse the explicit flux and source evaluations to construct the preconditioners as well as to obtain the matrix-free matrix-vector products. Although the general algorithms are necessarily less optimal than specialized algorithms, we have achieved very significant speed-ups compared to explicit time stepping in several applications.

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