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An Analysis of Source Tilting and Sub-cell Opacity Sampling for IMC

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Abstract

Implicit Monte Carlo (IMC) is a stochastic method for solving the radiative transfer equations for multiphysics application with the material in local thermodynamic equilibrium. The IMC method employs a fictitious scattering term that is computed from an implicit discretization of the material temperature equation. Unfortunately, the original histogram representation of the temperature and opacity with respect to the spatial domain leads to nonphysically fast propagation of radiation waves through optically thick material. In the past, heuristic source tilting schemes have been used to mitigate the numerical teleportation error of the radiation particles in IMC that cause this overly rapid radiation wave propagation. While improving the material temperature profile throughout the time duration, these tilting schemes alone do not generally alleviate the teleportation error to suitable levels. Another means of potentially reducing teleportation error in IMC is implementing continuous sub-cell opacities based on sub-cell temperature profiles. We present here an analysis of source tilting and continuous sub-cell opacity sampling applied to various discretizations of the temperature equation. Through this analysis, we demonstrate that applying both heuristics does not necessarily yield more accurate results if the discretization of the material equation is inconsistent with the Monte Carlo sub-cell transport.

Outline

- Introduction
- Teleportation and Source Tilting
- Some Attempts at Improving Tilts
- Test Problem Description
- Histogram Temperature Results
- Linear Discontinuous Equations
- Results
- Conclusions

Introduction

- Radiation Transport Equations:

$$\frac{1}{c} \frac{\partial I}{\partial t} + \mu \frac{\partial I}{\partial x} + \sigma_P I = \frac{1}{2} \sigma_P a c T^4$$

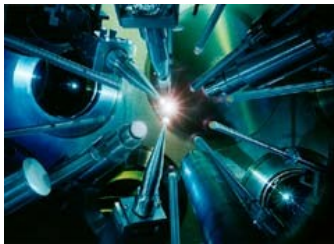
$$C_v \frac{\partial T}{\partial t} = \sigma_P \int_{-1}^1 I d\mu - \sigma_P a c T^4$$

- IMC Equations:

$$\frac{1}{c} \frac{\partial I}{\partial t} + \mu \frac{\partial I}{\partial x} + \sigma_{P,n} I = \frac{1}{2} (1 - f_n) \sigma_{P,n} \int_{-1}^1 I d\mu + \frac{1}{2} f_n \sigma_{P,n} a c T_n^4$$

$$C_v \frac{\partial T}{\partial t} = f_n \sigma_{P,n} \left(\int_{-1}^1 I d\mu - a c T_n^4 \right)$$

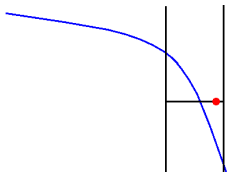
$$f_n = \frac{1}{1 + \alpha \beta_n c \Delta t \sigma_{P,n}}$$



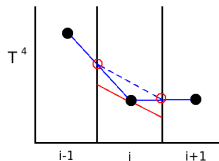
ICF radiation (aries.ucsd.edu)

Teleportation and Source Tilting

- Numerical teleportation error is prominent in IMC computations.
- Energy propagates too quickly near large gradients.
- Source tilting is a means of sampling particle source locations with a heuristic sub-cell profile.
- The current scheme in the Jayenne IMC Project employs a linear discontinuous T^4 tilt.



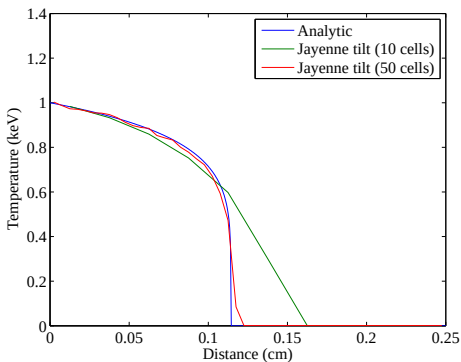
Teleportation error



Linear discontinuous tilt

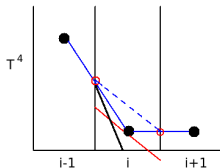
Teleportation and Source Tilting (continued)

- The current source tilting methods converge as $\Delta x \rightarrow 0$.
- But, we wish to improve the methods at lower spatial resolutions.

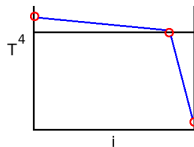


Some Attempts at Improving Tilts

- Recent attempts to improve upon original tilt scheme include:
 - Sub-cell representation of wavefront
 - Linear-continuous tilts
 - Variable Inflection Point
 - Continuous sub-cell opacities



Sub-cell tilt



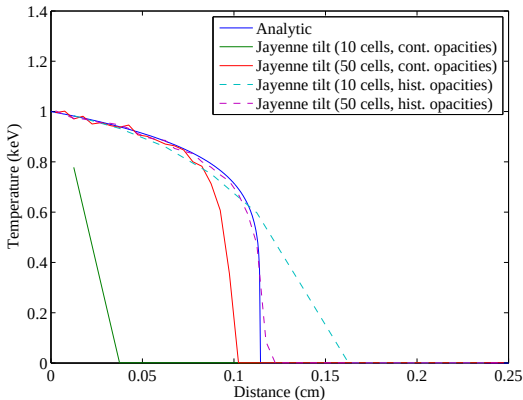
Variable Inflection Point

Marshak Wave Test Problem

- We consider the following problem:
 - $\{x \mid 0.0 \text{ cm} \leq x \leq 0.25 \text{ cm}\}, \{t \mid 0.0 \text{ ns} \leq t \leq 20.0 \text{ ns}\}$
 - Isotropic boundary source, $T(0,t) = 1 \text{ keV}$
 - $\sigma_P = \frac{1000}{T^3} \text{ cm}^{-1}$
 - $C_v = 3.0\text{e}15 \text{ erg/cm}^3\text{keV}$
- For IMC, we specify the following conditions:
 - 10 and 50 spatial cell tests
 - 2000 time steps, or $\Delta t = 0.01 \text{ ns}$
 - $\alpha = 1.0$
- We apply both source tilting and sub-cell continuous opacities.

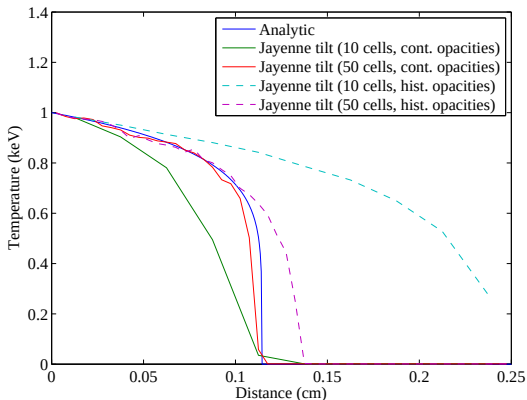
Histogram Temperature Results

- The following results are for a T^4 tilt.



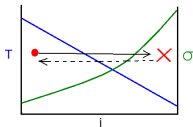
Histogram Temperature Results (continued)

- The following results are for a $\sigma_P T^4$ tilt.



Linear Discontinuous Equations

- The original discretization with tilting and sub-cell opacity continuity produces nonphysical results.
- For low spatial resolution, "photon trapping" occurs.



- We apply a linear discontinuous (LD) trial space to
 - the T^4 profile
 - the $\sigma_P T^4$ profileto remove the inconsistencies.
- The Monte Carlo transport is kept continuous.

Linear Discontinuous Equations (continued)

- The trial space functions for each cell are

$$V_L(x) = \frac{(x_{i+\frac{1}{2}} - x)}{\Delta x_i}, \quad V_R(x) = \frac{(x - x_{i-\frac{1}{2}})}{\Delta x_i}$$

and $\vec{V}$ denotes the column array with $V_1 = V_L$ and $V_2 = V_R$.

- The LD equation employed for T^4 linearity is

$$\frac{C_v}{4} \mathbf{A} \frac{\partial \vec{T}^4}{\partial t} = \left(f_n \sigma_0 \int_{x_{i-\frac{1}{2}}}^{x_{i+\frac{1}{2}}} \vec{V}(x) \left(\int_{-1}^1 I(x, \mu) d\mu \right) dx \right) - \sigma_0 f_n a c \mathbf{A} \vec{T}_n^4$$

where

- $\vec{T}^4$ is the array consisting of T_L^4 and T_R^4
- $\mathbf{A}$ is the 2x2 sub-cell system matrix
- $\sigma_0 = 1000 \text{ keV}^3 \text{cm}^{-1}$ ($\sigma_P = \frac{\sigma_0}{T^3}$)

Linear Discontinuous Equations (continued)

- The LD equation employed for $\sigma_P T^4$ linearity is

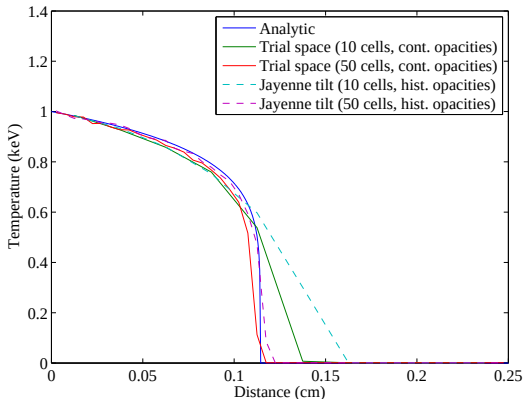
$$C_v \mathbf{A} \frac{\partial \vec{T}}{\partial t} = \left(f_n \int_{x_{i-\frac{1}{2}}}^{x_{i+\frac{1}{2}}} \vec{V}(x) \sigma_{P,n}(x) \left(\int_{-1}^1 I(x, \mu) d\mu \right) dx \right) - \sigma_0 f_n a c \mathbf{A} \vec{T}_n$$

where

- $\vec{T}$ is the array consisting of T_L and T_R
- $\mathbf{A}$ is the same 2x2 sub-cell system matrix
- Both LD schemes weight energy deposition to the material by the trial space functions, V_L and V_R .
- Moreover, solving the equations produces a sub-cell tilt that is consistent with the discretization.

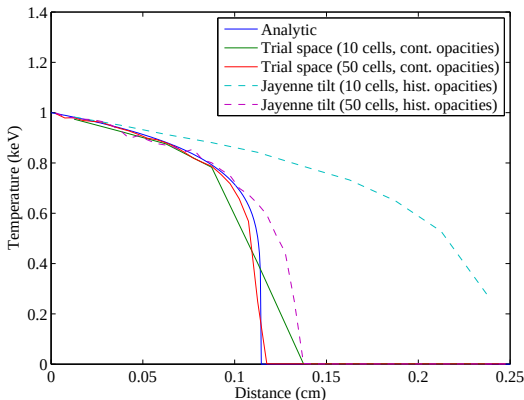
Results

- The following results are for a T^4 tilt with LD temperatures.



Results (continued)

- The following results are for a $\sigma_P T^4$ tilt with LD temperatures.



Conclusions

- We have demonstrated the importance of consistency between the material equation discretization and the radiation dynamics at the sub-cell level.
 - The LD results are superior in quality relative to the original material equation discretization.
- Inconsistency errors can dominate benefits from improved tilt methods.
- Future:
 - Investigate approaches to consistency when IMC is coupled to cell-centered hydrodynamics.
 - Develop discretizations for multi-dimensional IMC.
 - Couple LD IMC to LD-style hydrodynamics.

References

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