Laser Ray Tracing in a Parallel Arbitrary Lagrangian-Eulerian Adaptive Mesh Refinement Hydrocode

N D Masters¹, T B Kaiser¹, R W Anderson¹, D C Eder¹, A C Fisher¹, A E Koniges²
¹Lawrence Livermore National Laboratory, Livermore, CA U.S.A.
²National Energy Research Scientific Computing Center, Lawrence Berkeley National Laboratory, Berkeley, CA U.S.A.
E-mail: masters6@llnl.gov

Abstract.
ALE-AMR is a new hydrocode that we are developing as a predictive modeling tool for debris and shrapnel formation in high-energy laser experiments. In this paper we present our approach to implementing laser ray tracing in ALE-AMR. We present the basic concepts of laser ray tracing and our approach to efficiently traverse the adaptive mesh hierarchy.

1. Introduction
Shrapnel and debris with the potential of damaging expensive optics, diagnostics, or fixturing, may be generated by the extreme conditions present in high energy laser facilities such as the National Ignition Facility (NIF), Laser Mégajoule (LMJ) and Omega. The ALE-AMR multi-physics hydrocode has been developed as a predictive modeling tool to identify and assess sources of shrapnel and debris and the hazards they pose so these may be mitigated [1–6]. Such simulations generally require large computational domains in which to track fragment formation and trajectories. ALE-AMR implements arbitrary Lagrangian-Eulerian (ALE) hydrodynamics within an adaptive mesh refinement (AMR) framework. This allows the mesh to be adapted in response to the current state: applying additional mesh resolution in regions with rapidly changing dynamics while a coarser mesh may be used in regions that are currently less interesting—enhancing computational efficiency without sacrificing accuracy or resolution. In evaluating debris and shrapnel formation we need to be concerned not only with the energy deposited by the 3ω (UV) light—critical to target design—but also the unconverted 1ω and 2ω (red and green) that may irradiate support and diagnostic structures. Laser ray tracing is an efficient means for simulating laser propagation and energy deposition and provides a realistic energy source for hydrodynamic simulations.

2. ALE-AMR
The Structured Adaptive Mesh Refinement Application Infrastructure (SAMRAI) [7, 8] framework on which ALE-AMR is implemented provides a hierarchy of logically rectangular patches on which the problem physics are advanced. The simulation resolution can be improved in areas of interest, e.g., large gradients or fragmentation, by overlaying refined meshes that represent subsets of the domain
Figure 1. Rays traverse a virtual composite mesh. Rays are passed to the appropriate patch which may be at a higher, lower, or the same level of refinement

(see Figure 1). The hydrodynamics are evolved using a Lagrange-plus-remap algorithm. After problem initialization (mesh generation and initial conditions) the problem is advanced by repeating the following steps:

**Lagrange Step** The mesh is deformed by evaluating the forces (pressures and stresses) acting on the nodes and the resulting accelerations and displacements.

**Remap Step** Periodically the current Lagrange solution is remapped to an new mesh to avoid tangling, this may be either the original mesh (Eulerian) or some arbitrary mesh (ALE), usually a relaxed mesh intermediate to Lagrange and Eulerian configurations.

**Adaptive Mesh Refinement** Zones are tagged for coarsening or refinement by evaluating the current solution with respect to user defined criteria. A new mesh hierarchy is then created (regridding) onto which the current solution in mapped through coarsening or refining the solution variables.

**Additional Physics** If additional physics (heat conduction, radiation diffusion, or in this case laser ray tracing) are required they are performed at this point and the cumulative result is used for the next Lagrange step.

The code is designed to run on large parallel machines, therefore each processor is responsible for only a small subset of the problem, with communication limited to the information necessary to correctly synchronize adjacent or underlying patches through patch ghost cells or coarsened and refined solutions.

### 3. Laser Ray Tracing

Ray tracing is a powerful technique applied to high-energy laser simulations by Friedman [9] and Kaiser [10]. The key assumption is that the length scale of variations in the medium is larger than the laser wavelength over most of the computational domain. This allows the wave equations to be simplified as an equation of motion for rays and tracked through each zone. The electron density gradient is considered to be linear within each zone resulting in parabolic ray trajectories. Discontinuities at zone faces are treated via Snells law and energy deposition is computed as an inverse bremsstrahlung process. For a detailed description of the application of laser ray tracing to high energy laser simulations the reader is referred to the papers cited above.

Lagrangian or ALE modes result in deformed meshes consisting, in general, of quadrilateral elements in 2D and hexahedral elements in 3D (bounded by lines and doubly ruled surfaces, respectively). The intersections of the parabolic ray trajectories with these zones results in quadratic (2D) and quartic (3D) equations that must be solved for each face of the current zone. Although several solutions to these equations may exist valid solutions must fall within the boundaries of the current face. The exit face is identified as the one with the shortest exit time. Ambiguities may arise if a ray passes close to edges and/or corners. Incorrect selection of the exit face will result in a lost ray in the next zone as no valid exit points will be found. Such ambiguities are removed by reevaluating the ray traversal in the current zone after slightly perturbing the entry point within the entry face.
4. Logical Patches and AMR

We implemented laser ray tracing in ALE-AMR by considering the AMR hierarchy as a virtual composite mesh, i.e., rays are only propagated through the finest representation of the physical space as shown in Figure 1. The composite mesh is never explicitly constructed, rather at the end of each zone traversal an exit point and apparent destination zone are identified. The destination zone may be either: (a) on the same patch, but a finer representation exists, (b) on a different patch possibly at a different level (coarser or finer), or (c) on the same level and patch. As a ray enters a new zone (from a neighboring zone, a different patch, or when introduced to the computational domain) we determine if the zone is the finest representation of the physical space by querying the is_finest variable. This variable is updated each time the structure of the AMR grid is modified as follows: (1) is_finest patches on Level 0 and Level 1 are filled with ones and zeros, respectively, (2) the finer level is coarsened to fill any underlying coarse regions with zeros, and (3) the process is repeated with each successively finer pair of coarse-fine levels (e.g., Levels 1 and 2). Therefore if is_finest = 0 for a given zone, then a finer representation exists to which the ray should be passed. In ALE-AMR, fine nodes in faces that lie on coarse-fine boundaries are constrained to be equally distributed within the parametric space of the coarse face. The face touching a domain boundary on the coarsest level. In subsequent timesteps we search in the neighborhood of the last valid entry zone. This local search may fail if the domain boundaries are allowed to move, in which case the search region may be expanded or an exhaustive search again applied. Searching the coarsest level reduces the number of face crossing evaluations and avoids needing
to determine which patches touch domain boundaries prior to ray insertion as only the coarsest level
is guaranteed to exist at all points in the simulation domain. If the insertion zone is not the finest
representation we repeat the face crossing search to accurately determine the entry point on the fine
zones that replace the coarse zone.

One additional difficulty arises when rays insertion passes close to patch boundaries during start up.
If a ray passes too close to an edge (in 3D, or a corner in 2D) we remove any ambiguity by applying a
small random perturbation to the ray trajectory. At startup, such rays will receive independent random
perturbations on different processors—possibly leading to multiple copies of the same ray. We avoid
this by identifying potential duplicates (any that enter zones along patch boundaries) and compare this to
the list of suspects on all other processors and remove the duplicates (preferring those from lower rank
processors). Once an initial entry point (and associated search neighborhood) has been found, duplicate
rays become very rare.

Current load balancing involves processing rays in batches that cascade to neighboring
patches/processors. This evens the load on the processors that will participate in ray tracing. However,
some processors may hold patches or levels that are traversed by few if any rays and may remain idle
during a given laser ray tracing step. Future work will seek to address load balancing issues.

To illustrate the AMR laser ray tracing algorithm we will follow a ray through the mesh in Figure 1(a).
The ray is introduced on the left side of the mesh into a zone on Level 0. After traversing one zone a finer
representation of the destination is found Figure 1(b). The ray is passed to the appropriate Level 1 patch
and ray propagation continues until a patch boundary is encountered (see Figure 1(c)). The ray is then
passed to the neighboring Level 1 patch. After one zone traversal a finer representation is again indicated
and the ray passed to Level 2. After traversing this Level 2 patch the ray leaves and no patch exists at the
current level to receive it (see Figure 1(d)), the destination is coarsened and the process continued until
the ray leaves the domain (or is fully depleted).

5. Conclusions and Future Work
We have implemented laser ray tracing in the ALE-AMR hydrocode to provides an efficient means for
modeling laser energy deposition. This provides the means to deposit energy in a realistic manner as we
seek to mitigate potential damage through predictive modeling of debris and shrapnel. Future work will
explore load balancing and present applications of the ALE-AMR laser ray tracing package in simulating
debris formation in high energy laser experiments.

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