CODE VERIFICATION AND VALIDATION IN IMPACT CRATERING.

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Introduction: As the capability of computer models surpasses the regime of physically feasible experiments, insuring the accuracy of the models becomes increasingly vital. Methods for insuring the reliability of the models include verification and validation (V&V) as described by ASME [1]. Verification involves quantifying the numerical approximation errors in a discrete solution relative to the exact solution [2]. Validation is concerned with whether the numerical model is appropriate to the physical process it represents.

In the context of impact crater modeling, validation efforts have been undertaken with hydrocode modeling, including the Pierazzo et al. benchmarking study in which distinct hydrocodes were used to model peak shock pressure decay with distance and crater geometry for small-scale cratering experiments and large-scale simplified impact scenarios [3].

Oberkampf and Roy outline 5 distinct levels of V&V [2]:

1. Simple tests, including conservation, symmetry, and Gallilean invariance
2. Code-to-Code comparisons
3. Discretization error quantification
4. Convergence analysis
5. Order of accuracy test

Currently, in the field of impact cratering there are publications on V&V up to level two and four [3, 4]. In other computation heavy fields, the minimum standard of rigorous V&V is level four [1, 2]. The traditional method for code verification is the third level, the discretization error quantification. In this test, the exact solution is compared to a simulation at a step in time and/or space. A convergence test assesses whether the error in the simulated solution relative the exact solution reduces with increased spatial and temporal resolution. The most rigorous test in code verification is the order of accuracy test, which seeks the formal order, or rate, of convergence through a convergence analysis [2].

Verification Methodology: Order of accuracy tests are performed by running the simulation and comparing to the analytic solution. This involves first finding a analytic solution, or manufacturing a solution, that tests the fundamental physics of the model. This is followed by taking the L1 Norm, which involves running the simulation on meshes that are successively resolved by dx/(2*n). The total error of the simulation is taken with regard to the exact solution and plotted logarithmically against the spatial resolution. The order of accuracy is then represented by the linear fit.

One useful tool for verification studies is LANL's ExactPack, which is a verification test suite for hydrocodes [6]. The test problems include spherical collapses, shockwaves, and radiation transfer among others. It also includes framework for running a convergence analysis and order of accuracy test. These tests are typically undertaken with the spatial and time step held constant within a given simulation.

Spatial convergence was also addressed in Pierazzo et al. (2008).

Validation Methodology: Validation studies test the appropriateness of the numerical model by comparing to experiments, observational data, or code-to-code comparisons. This methodology has been presented in depth [3, 4]. Validation is a much more common practice in computational planetary science.

Proposal: Numerical models in computational planetary science inform researchers where experimental and observational data is incomplete or infeasible to collect. V&V offers a way to test numerical models through simplified test cases that have applicability to physical phenomena. While most of the common test problems focus on the behavior of fluids, there is an increasing interest in solid mechanics and constitutive models. Example for purely elastic materials includes both the Hunter and Blake problems [5]. Test problems for fracture mechanics are being explored [6, 7]. Verification tests for solid materials, rather than fluids and the ideal gas, are vital for modeling impact processes and other geophysical phenomena.

While material models in geophysical simulations undergo validation, a comparison to data will not catch bugs in the underlying physics. Verification tests are useful for this because they examine specifically the underlying framework of the numerical model. Due to the scale of lab experiments and the unknown scalability of the material models that they inform, rigorous verification is important for testing that they extend to the correct scales in impact cratering simulations.

One such study that would benefit from rigorous V&V is that of the Inca City structure at 82 S, 67 W on Mars [8]. This structure is thought to be an 86 km diameter impact structure, but a close numerical study has yet to be undertaken. The unknowns in this problem require that the model have a rigorous physical response before a parameter study is undertaken. Differences between the model and the structure can then be indicative of composition, rather than limitations of the physical models. For an analogous problem, see [4], where Caldwell looked at differences in crater morphology caused by differences in impactor composition.

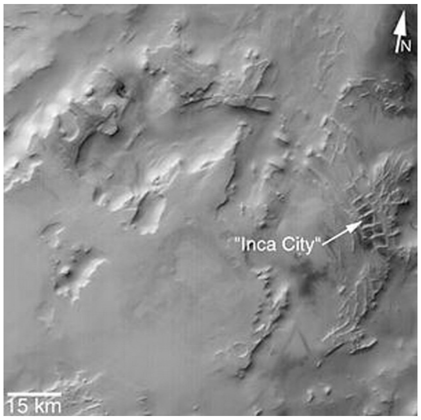

Figure 1. Image of Angustus Labyrinthus, the region informally known as Inca City.

Within impact cratering, verification studies could start from ExactPack and expand to include studies based on exact solutions obtained from relations presented in Melosh, 1989, and Housen and Holsapple 1993 [9, 10].

The ideal verification test problem examines a specific aspects of the physics of the numerical model in a simplified test case that is easy to implement. Ensuring that the basis of the model is physically representative in simplified test problem lends credibility to intensive calculations that build on those foundational relations.

Example verification test: A standard verification test problem for hydrocodes is the Sedov spherical blast problem. This problem tests the ability of the code to handle a simple shockwave expanding in an ideal gas that originates from a high energy density pill at the origin. The energy is released at the first time step to produce a shockwave that expands into the ambient material. We have used this test problem to inform airburst simulations, specifically to ensure that the shockwave does not artificially accelerate throughout the simulation caused by the varying levels of refinement in a given simulation. While the verification of AMR schemes through order of accuracy and convergence tests persists as a question in V&V, we compared the total error of the runs with AMR to those without at different spatial resolutions within the LANL hydrocode XRAGE.

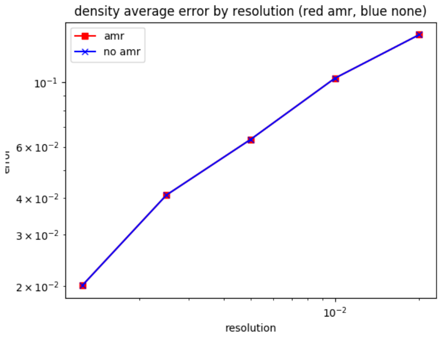

Figure 2. Overlay of absolute error from Sedov spherical blast in xRAGE simulations with and without AMR implemented.

Through this simple test, we showed the appropriateness of using AMR in airburst simulations as it reduced runtime without sacrificing the accuracy of the model.

Conclusion: Rigorous V&V of numerical models demonstrates both the accuracy of the underlying physics and their appropriateness in modeling the physical process. It offers credibility to models that are outside of the feasible experimental regime.

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