Visualization and Analysis of Threats from Asteroid Ocean Impacts

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***Abstract*—An asteroid colliding with earth can have grave consequences. An impact in the ocean has complex effects as the kinetic energy of the asteroid is transferred to the water, potentially causing a tsunami or other distant effect. Scientists at Los Alamos National Laboratory are using the xRage simulation code on high performance computing (HPC) systems to understand the range of possible behaviors of an asteroid impacting the ocean. By running ensembles of large scale 3D simulations, scientists can study a set of potential factors for asteroid-generated tsunamis (AGTs) such as angle of impact, asteroid mass and air burst elevation. These studies help scientists understand the consequences of asteroid impacts such as water dispersement into the atmosphere, which can impact the global climate, or tsunami creation, which can place population centers at risk. The results of these simulations will support NASA's Office of Planetary Defense in deciding how to best track near-Earth objects (NEOs).**

I. Asteroids and Impacts

NASA is currently tracking 1,717 near-Earth objects that are considered Potentially Hazardous Asteroids (PHAs) due to their size and orbits. These objects are possible Earth-impact threats [1].

Large asteroids can have devastating impact effects, but even modest-sized asteroids can be destructive. For example, the 2013 Chelyabinsk meteor, perhaps only 20 meters across, exploded in a fireball above Russia, damaging over 7,200 buildings and prompting nearly 1,500 hospital visits [2].

To help NASA understand more about PHAs, scientists from NASA, NOAA, and the NNSA Tri-Labs gathered in August of 2016 for the Second International Workshop on Asteroid Threat Assessment: Asteroid-generated Tsunami (AGT) and Associated Risk Assessment [3]. NASA's Planetary Defense Coordinating Office is posing two questions [4]:

- What is the smallest size of near-Earth Objects (NEOs) that should be tracked?
- Is there a transition size above which one catalogs all the objects and below which NASA simply provides a warning?

Since approximately 70% of the Earth is covered by the oceans, asteroid impacts are likely hit water, sending water and water vapor into the atmosphere, and possibly causing destructive tsunamis. Scientists at Los Alamos National Laboratory (LANL), led by Dr. Galen Gisler, are studying the effects of asteroids impacting deep ocean water with a particular focus on the potential to generate a tsunami that could endanger coastal communities. High Performance Computing (HPC) resources at the Los Alamos National Laboratory (LANL) in conjunction with LANL's xRage HPC physics code were used to simulate a variety of factors and produce datasets that could be passed to scientists that study tsunami generation and propagation. Visualization is used to aid intuition building and communication of the different impact scenarios.

Simulations show that an ocean impact results in shock waves and high temperatures in the atmosphere, the dispersion of water and water vapor to high altitudes, and creation of waves in the ocean (Fig 1). The splash waves that are produced by an impact can be hundreds of meters to kilometers high, and near-shore impacts can therefore be devastating. A more important question, and harder to answer, is whether such waves can develop into tsunamis and propagate across oceans.

A. *Studying Asteroid-generated Tsunamis (AGTs)*

A tsunami caused by landslides from steep cliffs into bodies of water can be devastating. The 1958 Lituya Bay event in Alaska [5], [6] and the Norwegian fjord events at Loen in 1906 and 1936 and at Tafjord in 1934 [7] produced spectacular waves, and (in the Norwegian events) resulted in dozens of deaths. But as dangerous as impact tsunamis are in the near field, their propagation to

(a) Approach **(b)** Impact **(c)** Aftermath

Fig. 1: A 250 meter wide asteroid impacting deep water at 45deg with no airburst. High concentrations of asteroid are shown in reddish tones while water is indicated in blue and temperature in yellow. In the simulation, ocean depth is 5km with 23 km of atmosphere. Total simulation spatial dimensions span 28 km vertically with an area of 46 km by 24 km.

the far field is strongly attenuated because of their short wavelengths and origin as point sources. The effect on distant shores, if felt at all, is no more deadly than the wave effects from tropical storms. Earthquake-generated tsunamis, on the other hand, begin as line sources with long wavelengths, and they are known to propagate all the way across ocean basins.

However, for an asteroid impact the kinetic energy transmitted to the water and the atmosphere can be orders of magnitude greater, allowing for other mechanisms of generating waves. A possibility is that an airburst like that observed in the 2013 Chelyabinsk event or the 1908 Tunguska event [8] might induce a broad pressure pulse in the atmosphere that leads to a wave with a much longer wavelength than the transient impact crater. Our preliminary results indicate that the waves produced by atmospheric airbursts are in fact even less likely to propagate over long distances than the waves produced by direct ocean impacts.

Whether an airburst occurs, and how effective it is at reducing the asteroid's kinetic energy depends on many characteristics of the asteroid, including its mass, the angle of the impact, characteristics of the atmosphere, and elevation of its airburst, if any. There are millions of possible combinations of these factors, but scientists can use an ensemble of simulations to understand how they interact to transfer kinetic energy to the water.

B. *Simulations at LANL*

Dr. Gisler is leading the effort at LANL to quantify the characteristics of asteroids that could trigger events of concern. His ensemble of simulation consider the asteroid mass, angle of entry, composition and elevation of airburst, all of which determine the magnitude of kinetic energy transferred into the ocean. This in turn determines the repercussions of the impact.

A surprisingly significant factor is the elevation at which the asteroid explodes. Some asteroids explode on impact with the water. Others *airburst*, exploding prior to entering the water. The pressure pulse generated by the airburst propagates in all directions from the source of the explosion. The momentum of the asteroid enhances its downward (generally oblique) impulse, spreading it over a wide area. The pressure pulse attenuates as it spreads, however, and the depression of the water surface is slight, depending on the altitude at which the explosion occurs. If the airburst does not completely destroy the asteroid, a transient impact crater may occur in the water. In an airburst, pressure pulse is transmitted to the surface of the water by the incoming projectile's momentum. It is spread over a larger area and displaces less water, so the wave is more coherent as it moves through the water. This produces a wave that travels further. A surface water explosion causes colliding energy, canceling out the impact on the wave propagation [9].

Winds and high temperatures generated in the atmosphere are complicating effects that are difficult to consider except in the context of a complete hydrodynamic simulation such as is possible with xRage. Colliding shockwaves in the atmosphere and in the water, and the winds that interact with the waves on the water's surface generally prove to be deleterious to the generation of a propagating wave, whether due to airburst or impact. But direct impacts produce waves that are more likely to be measurable at great distance simply because of the greater amplitudes produced by the splash. Their effect on distant shores must still be assessed using wave propagation codes such as the MOST model [10].

Our scientists use Lagrangian tracers in the code to identify the frequency and the amplitude of the waves produced by the impact. This is done by analyzing the pathlines that the tracers make as they move over time. These tracers can also be used to generate an estimate of the amount of water reaching the stratosphere.

A good approximation of the near field (close to the impact) behavior can be obtained from the behavior of the Lagrangian particles, but for wave behavior outside the domain of the simulation, the data must be used as an input to different wave propagation codes, which can then simulate the behavior of the resulting wave.

II. Relevance to the HPC Community

The simulation used in these asteroid studies is xRage [11], a parallel multi-physics Eulerian hydrodynamics code developed and maintained by the ASC program at LANL. xRage uses a continuous adaptive mesh refinement technique that allows smaller computational cells in areas of interest and larger, thus fewer, cells in other areas. This results in more efficient use of the supercomputer. These simulations typically run on 512-2048 nodes of a production supercomputer at LANL. These runs can take several weeks. The entire ensemble at the time of this writing was 226 TB. The largest three runs produced 86 TB, 54 TB and 52 TB of data.

Scientists are using *in situ* analysis techniques to couple analysis and visualization capabilities directly with codes, so that more valuable data artifacts can be extracted during the simulation [12], [13]. In this instance, we ran xRage coupled with ParaView v4.3.1, and executed Catalyst analysis scripts to write out unstructured grid data derived from xRage's native AMR grid data structures. These VTK unstructured grids were then down sampled onto regular grids of VTKImageData so that we could use parallel volume rendering pipelines to render the entire dataset.

III. Visualization and Scientific Discovery

Visualization of this data is critical to understanding the science of the simulation. We note, however, that is often difficult for the scientist to create visualizations of the large data, due to the computing demands and the time it would take away from their simulations. The need for integrated *in situ* pipelines that include visualization is clear, though the easy integration may prove unwieldy.

A ParaView Catalyst [14] adapter was developed for the xRage code. This adapter allowed Dr. Gisler to execute a ParaView pipeline at run time. The xRage adapter translates the AMR grid to an unstructured grid representation. Both the unstructured grid and a resampling to regular structured grids was used for different visualizations and analysis. Volume rendering was the primary use of the sampled data.

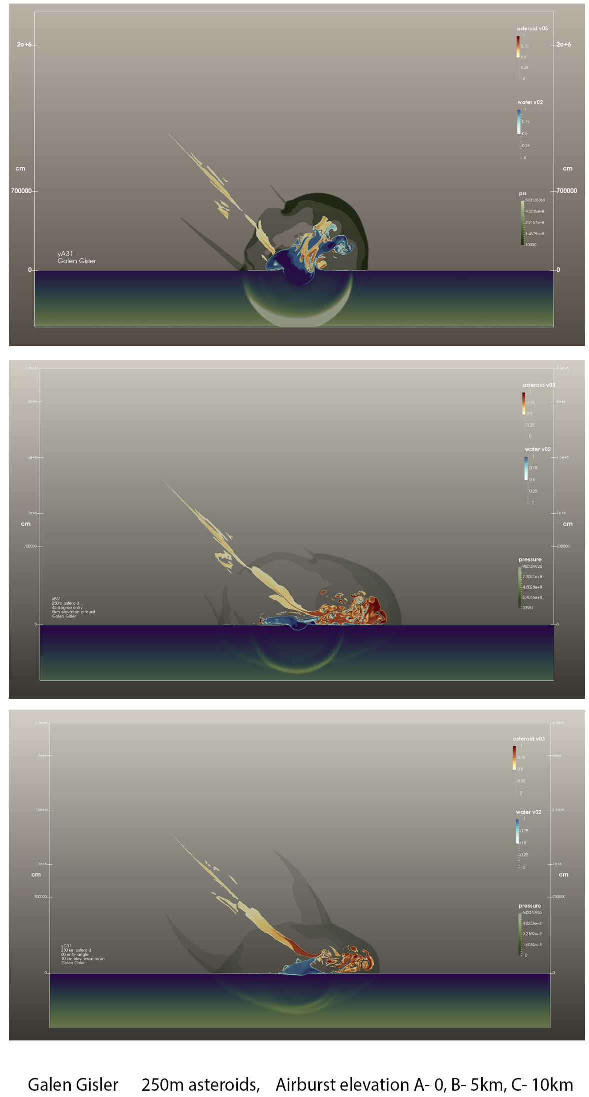

Fig. 2: Visualization showing asteroid material (reddish), water (blue and green), and pressure wave (transparent circle) for three different simulations in which the height of the airburst was varied. The images are from the same timestep (20) in each simulation. In the top image, the airburst was at 0 km (impacting the surface), in the middle the airburst was at 5km, and at the bottom the airburst was at 10km. Note the profiles of the pressure waves, showing the difference in how the kinetic energy was transferred to the water.

Dr. Gisler used these visualizations as evidence that the simulations support his conclusions. He presented both his conclusions and the visual evidence to a diverse set of peers at the Second International Workshop on Asteroid Threat Assessment. The variety of visualizations showed that the current understanding is supported and that hypothesized forces were accounted for in the simulation (i.e. leading high pressure from the airburst).

The visualizations are compelling evidence that the simulations accounted for the correct physics at the correct scales, the scientist is seeing what they are expecting in the details. In addition, the visualizations effectively show the different factors, especially the differences in airburst events on the transfer of energy from the asteroid to the water. In some simulations, this resulted in lofting as much as 250 metric megatons of water into the atmosphere. Because water vapor is a potent greenhouse gas, this may have a significant impact on climate.

Figure 2 shows three different heights for the airburst in three different runs, showing asteroid material (reddish), water (blue and green) and pressure wave (transparent circle) for three different simulations in which the height of the airburst was varied. In the top image, the airburst was at 0 km (impacting the surface), in the middle the airburst was at 5km, and at the bottom the airburst was at 10km. Note the difference in the profile of the pressure wave, showing the difference in how the kinetic energy was transferred to the water.

Scientists are interested in viewing important variables side-by-side with simulations, to better understand the behavior of the system. Density, pressure and temperature combine to give a full view of the state of each kind of matter in the simulation.

IV. Conclusion

This research contributes to NASAs Asteroid Detection, Hazard Mitigation Mission. The first goal is to compare simulations to understand differences and gain confidence in the modeling results for both formation and propagation of asteroid-generated tsunami. A second goal is to better understand the role of asteroid-generated tsunami effects to advance the overall impact threat risk assessment capabilities. By visualizing runs from this ensemble, scientists were able to better understand the interaction of the different parameters explored, and communicate these to peers at the Second International Workshop on Asteroid Threat Assessment.

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