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Physical and Infrastructure Modeling for the 2015 PDC Asteroid Threat Exercise

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Abstract— **The 2015 Planetary Defense Conference (2015 PDC) was held in Frascati, Italy on April 13-17 by the International Academy of Astronautics (IAA). In addition to customary technical sessions, we performed the first week-long threat exercise designed to simulate and examine the process of decision making that would accompany the discovery and response to an asteroid on a collision course with Earth. Our role in the exercise was to develop and present a plausible scenario that would be of interest to as many participants as possible while considering the broad diversity in technical expertise, approach, values, missions, and national affiliations of the conference attendees. Moreover, we strove to present a reasonable sequence of events spanning several years that would provide many opportunities for collective decision making under uncertainty by parties likely to have conflicting interests. In order to hold the attention of the participants throughout the week we tried to create a scenario that would be as dramatic as possible—including "cliffhangers" and unexpected turns of events—but without sacrificing realism. This allowed us to discuss a wide range of potential responses, including kinetic and nuclear deflection, and potential outcomes, including tsunami-forming ocean impacts, crater-forming land impacts, and airbursts by objects over a large size range. In addition to creating the scenario, members of our team served on an expert panel in a role-playing exercise that included participants acting as world leaders of nations, both directly and indirectly affected members of the public in at-risk areas, and the media. This paper summarizes the exercise, focusing on physical and infrastructure modeling.**

The exercise spanned the entire week, with daily "injects" (or updates) of new observed data about what was currently known on the imaginary date. We presented models of potential physical effects and resulting infrastructure damage, with emphasis on the uncertainties. Seven updates spanned most of the time between when the asteroid (dubbed "2015 PDC") was discovered on April 13, 2015, and its impact date of September 3, 2022. Information about the orbit and technical response options were presented as a set of faux press releases that were made available to participants prior to each briefing. The scenario was based on an actual calculated orbit to provide as much realism as possible. The physical effects at each stage were predicted by using simulations for airburst and tsunami generation, and a shallow water model for tsunami propagation. Maps were generated using tools developed for the National Infrastructure Simulation and Analysis Center (NISAC), and were presented by expert panelists as part of a mock press briefing at each inject. We present the contents of those press briefings and put them into context with the threat exercise.

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1. INTRODUCTION

The 2015 IAA Planetary Defense Conference (PDC) provided the opportunity to design and execute an international tabletop exercise for the purpose of practicing and assessing the process of decision making in the face of a hypothetical but realistic asteroid impact scenario in which a large number of nations would be directly or indirectly threatened. An exercise development team of experts was assembled to generate a challenging and realistic threat scenario based on actual orbital calculations, physical effects modeling, and deflection mission design. Paul Chodas of the Jet Propulsion Laboratory (JPL) formulated the scenario, and the physical and modeling was performed by staff at Sandia National Laboratories (SNL) and Lawrence Livermore National Laboratory (LLNL). This is the same team that was responsible for creating the scenarios used in past tabletop exercises, including the 2013 and 2014 tabletop (TTX) exercises conducted for the Federal Emergency Response Agency (FEMA), described by Boslough et al. [1] and Ezzedine et al. [2]. A webpage was created on JPL's Near Earth Object (NEO) Program website [3, http://neo.jpl.nasa.gov/pdc15/] to provide the details of the 2015 PDC hypothetical asteroid impact scenario, including a table of impact circumstances for 303 possible impact points.

The information provided prior to the conference was intended to encourage the attendees to conduct their own research into the threat and its possible outcomes and present their findings, mitigation proposals, and concerns in a public-forum-like lead by a board of experts at the conference. Attendees were randomly assigned to four different groups.

- Group 1: Political leaders of nations that might be directly affected by impact.
- Group 2: Political leaders of nations that would not be directly affected by impact.
- Group 3: Residents of areas that might be directly affected by impact.
- Group 4: Members of the media.

In addition, three attendees were selected as world leaders (individuals whose role was to make decisions as to what actions should be taken given the information presented on each threat). Five to seven expert advisors were also identified who would provide expert advice and counsel to the world leaders as they deliberated on their decision. Both the expert advisors and world leaders changed as the threat evolved.

Groups 1 through 4 were invited to meet during lunchtime and breaks to develop their perspectives on the threat and recommendations for actions that could be taken. Each group selected a member to present condensed version of their thoughts to the world leaders at the end of each day. The last day of the conference was dedicated to completing the threat exercise, and three "injects" were provided on that day. It should be noted that the exercise was designed–and updates in the form of press releases were drafted–prior to the conference so the outcome and details were predetermined.

This paper summarizes the scenario and its evolution. Each section describes what we presented to the participants for each of the eight injects, with emphasis on the physical modeling provided by our JPL/SNL/LLNL sub-group of the impact scenario development team.

2. JUNE 9, 2015: SMALL THREAT OF IMPACT

The scenario began with the discovery of the hypothetical asteroid by the Catalina Sky Survey (CSS) on April 13, 2015 (the first day of the actual conference). The apparent magnitude of the asteroid at first sighting was 20.9, a typical discovery magnitude for current asteroid search programs. After a second night of observations, the asteroid was assigned the designation "2015 PDC" by the Minor Planet Center (to reinforce the fact that this was not a real asteroid, we used three letters in the designation, something which would never be done for an actual asteroid). Based on the initial orbit calculation and a rough size estimate, the asteroid was classified as a Potentially Hazardous Asteroid (PHA).

Table 1. Heliocentric orbital elements for 2015 PDC

Semi-major Axis	1.775 AU
Perihelion Distance	0.905 AU
Eccentricity	0.4903
Inclination to ecliptic	5.347°
Right Ascension of Ascending Node	340.39°
Argument of Perihelion	313.44°
Orbital Period	2.366 yrs

The asteroid's orbital elements could be computed with reasonable accuracy even after only a few days of tracking (Table 1). The orbit was somewhat eccentric, but quite typical for a Near-Earth Asteroid (Fig. 1). The key parameter which made this object "potentially hazardous" was its MOID (Minimum Orbit Intersection Distance), the minimum distance in three dimensions between the asteroid's elliptical orbit and the Earth's elliptical orbit. Even the preliminary calculation for 2015 PDC yielded a very small MOID of less than 0.001 AU, indicating that the asteroid could potentially approach very close to the Earth. The MOID point on the asteroid orbit occurred when it was moving outbound from the Sun.

While the asteroid's orbit was fairly well determined, very little was initially known about its physical properties. The absolute magnitude *H*, a measure of the object's intrinsic brightness, was estimated to be about *H* = 21.3 +/- 0.4. Assuming a typical range of values for albedo, this corresponds to an asteroid size of roughly 100 to 500 meters. The large size uncertainty was due to uncertainty in the estimated *H* value and the wide range of possible albedos.

The asteroid was discovered at a distance of about 0.34 AU (51 million kilometers or 32 million miles), approaching the Earth and brightening. The asteroid had not been this bright since 1996, which explained why it had not been previously detected by asteroid search programs. As it approached a little closer to our planet and brightened over the next few weeks, it was observed extensively. but it peaked in brightness at only magnitude 20.3 on May 4th, and then began to fade. Its closest approach to Earth was at about 0.19 au (28 million km) on May 12. The asteroid did not get close enough to the Earth to be observed by Goldstone radar and it was too far south at close approach to be observed by Arecibo radar.

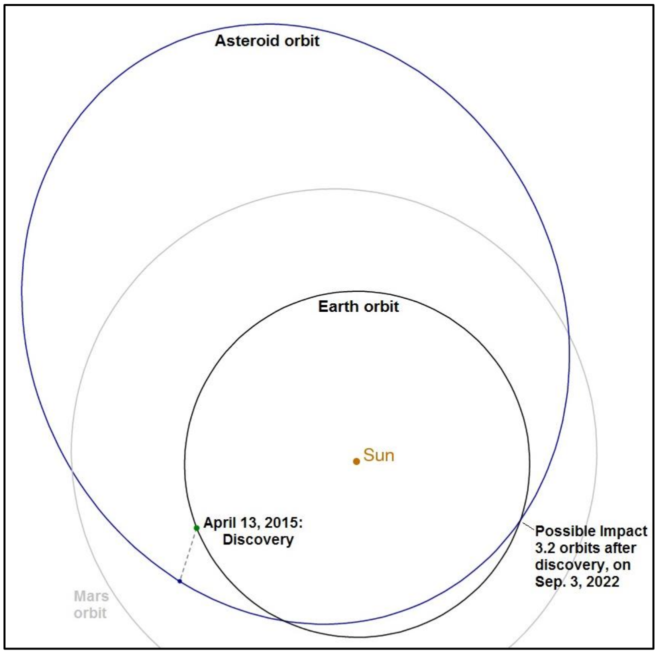

Figure 1 – Orbit of Asteroid 2015 PDC

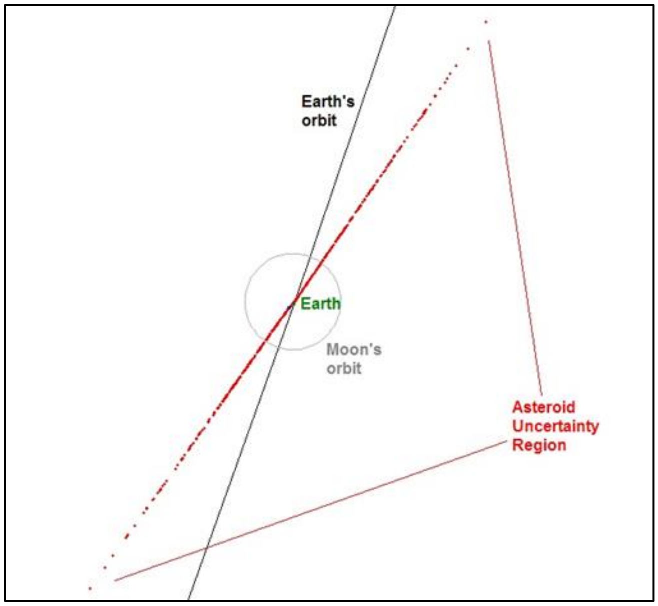

Figure 2 – Close-up of the asteroid uncertainty region, as traced by Monte Carlo points, when the Earth crosses the asteroid orbit on Sep. 3, 2022

Only two days after discovery, the NASA/JPL Sentry impact monitoring system [3] and the University of Pisa's CLOMON system [4] both identified numerous future dates on which 2015 PDC could potentially impact the Earth, but the chance of impact was extremely small. The most likely potential impact date was Sept 3, 2022, although the probability of impact was very small in the first week after the asteroid was discovered (less than 1 chance in 10,000). As astronomers tracked the object over the next few weeks, however, the impact probability for 2022 continued to increase. Ten days after discovery, for example, the impact probability surpassed 1 chance in 10,000, and the asteroid's hazard rating on the Sentry Risk Page [3] moved up to level 1 (Green) on the Torino Scale [5]. By a month after discovery (mid-May, 2015) the chance of impact in 2022 had risen to 1-in-500, a concerning level but still not unprecedented for an asteroid of this size. The asteroid was slowly fading from view as it receded, dimming below magnitude 22 in early June, but astronomers simply resorted to larger, 4-meter-class telescopes in order to continue tracking it.

A mock press briefing was given on Day 1 of the Planetary Defense Conference, summarizing the scenario status as of June 9, 2015. Presenters spoke on behalf of the new International Asteroid Warning Network (IAWN), a worldwide partnership of agencies that detect, monitor and track potentially hazardous asteroids. Established at the direction of the United Nations in 2013, IAWN links together the institutions that discover, monitor, and physically characterize the potentially hazardous NEO population. The IAWN partners include the Minor Planet Center (MPC), which maintains an internationally recognized clearinghouse for the receipt, acknowledgment and processing of all NEO observations, and NASA's NEO Program Office and the European NEODyS group, which specialize in high precision orbit calculation and computation of impact probabilities.

For this first scenario briefing, the probability of impact on Sept. 3, 2022 had reached 0.9 percent, or 1 chance in 110. The nominal close approach distance in 2022 was quoted as about 30,000 km, which would be well within the ring of geosynchronous satellites. But the close approach distance was highly uncertain, and the possibility of impact could not be ruled out. The size of the object, based on magnitude measurements, could only be determined to a range of "roughly 140 to 400 meters". The potential impact was now rated at 2 on the Torino Scale of 1 to 10. Note that 2015 PDC would not be the first asteroid to reach Torino level 2: asteroid (99942) Apophis reached level 2 and moved up to level 4 in late 2004 before additional observations uncovered in sky-image archives eliminated the possibility of impact in 2029.

As shown in Fig. 1, the potential impact would occur just over three complete asteroid orbits after discovery (its orbital period was 864 days). While the asteroid's orbit track was fairly well known, its position along the orbit could not be precisely predicted 7 years into the future. Fig. 2 shows Monte Carlo points spanning the asteroid's positional uncertainty region at the moment when the Earth crosses the asteroid's orbit in 2022. The region is very long, spanning several times the diameter of the Moon's orbit, but it is also very thin, since the asteroid orbital plane is quite well determined. When the uncertainty region intersected the Earth surface, it produced a "risk corridor" that wrapped more than halfway around the globe, as depicted by the red dots on Fig. 3. The corridor extended from the eastern Pacific Ocean, across the South Pacific, through the Philippines, South China Sea, Southeast Asia, Myanmar,

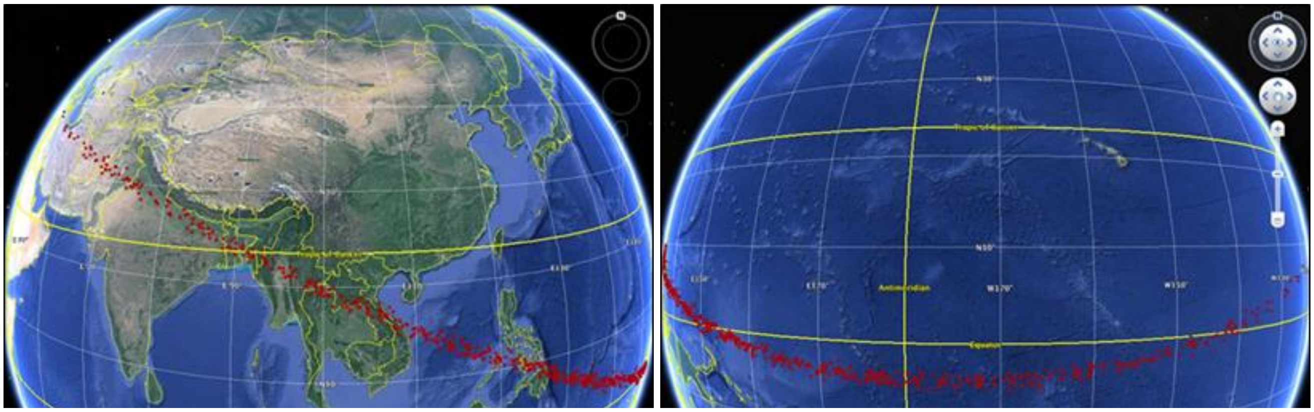

Figure 3 – Left: Western portion of risk corridor; Right: Eastern portion of risk corridor

Bangladesh, India, Pakistan, Afghanistan, Iran, and all the way to Turkey. If the asteroid were to impact in 2022, it would hit somewhere along this corridor.

Based on the orbit, astronomers could predict that the asteroid would be continue to be observable through the rest of 2015, although it would be very faint (22nd and 23rd magnitude) and observers would require fairly large (2-meter-class) telescopes to track it. In December 2015 and January 2016, the asteroid would fade through 24th and 25th magnitudes, requiring even larger telescopes such as the 4- and 8-meter class facilities of CFHT, Keck, Gemini, Subaru, VLT, etc. But, in the spring of 2016, the asteroid would move too close to the Sun to be tracked any further, and it would remain unobservable for about 7 months.

Because of the small likelihood of impact and large uncertainty in the size of the asteroid, we presented only a very rough approximation of the damage footprint for various target locations along the risk corridor (Fig. 3). We used the online Purdue impact calculator of Collins et al. [6] which is based on scaling laws and nuclear weapons effects literature [7] but modified the damage definitions for this exercise to illustrate the primary infrastructure damage mechanism to lateral dynamic loading from the winds associated with the blast wave (Figs. 4 & 5).

Figure 4 -- Impact damage footprints on risk corridor

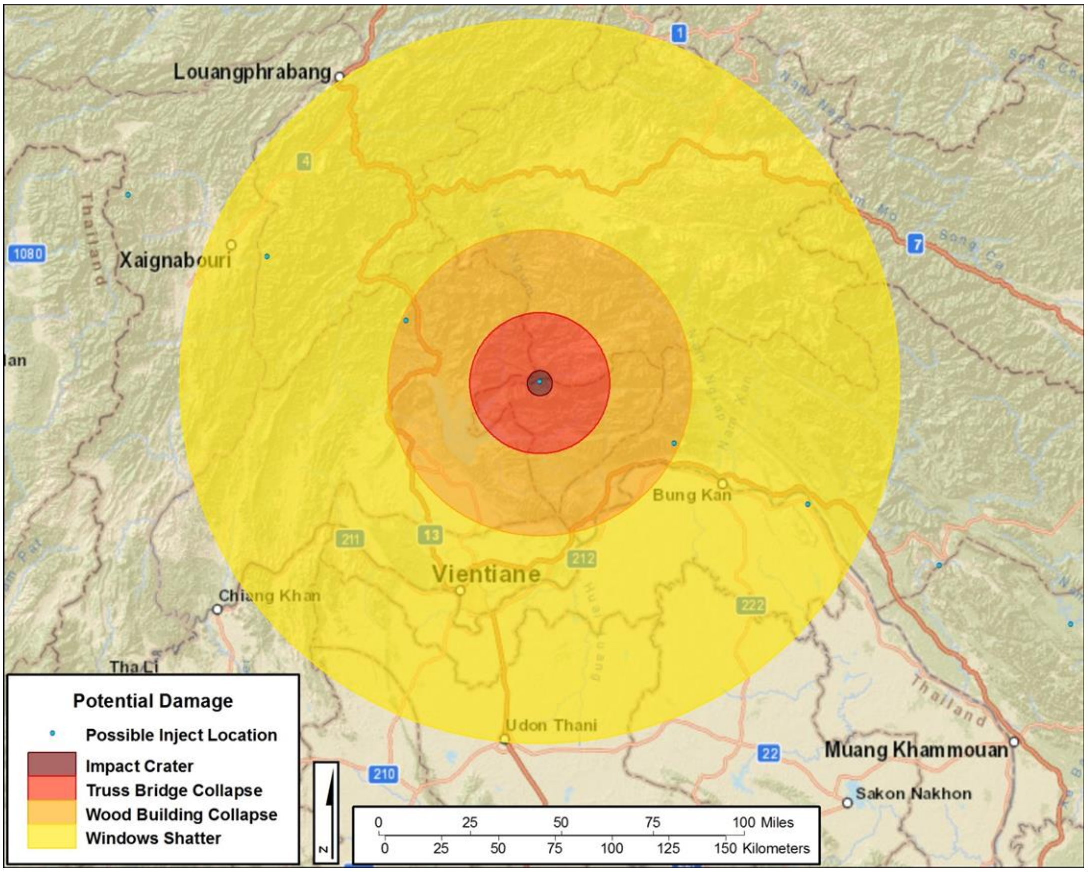

Figure 5 -- Damage footprint north of Vientiane, Laos

3. APR. 4, 2016: CHANCE OF IMPACT 43%

On Day 2 of the PDC meeting, we gave our second mock press briefing, which moved the scenario story forward to April 4, 2016. After almost a full year of tracking 2015 PDC, it had become clear that the asteroid posed a serious risk of impacting Earth in 2022. Based on the complete set of tracking observations, the impact probability was estimated to be 43 percent. Further updates to this estimate would not be possible for eight months, as the asteroid would pass on the other side of the Sun as viewed from Earth, and therefore could not be tracked. The asteroid had been favorably positioned during mid- to late-2015, and it had been observed extensively by large-aperture telescopes. The new data, however, had not eliminated the possibility of impact, as had been expected. Instead, the impact probability rose above 5 percent in August 2015, reached 30 percent in October, and would now remain fixed at 43 percent until late 2016, when the asteroid would become observable again. The Torino Scale rating had moved up to 5 (Orange).

The positional uncertainty region at the time the Earth was predicted to cross the asteroid orbit in 2022 was now much smaller, but still larger than the diameter of the Earth. Fig. 3 shows the possible positions of the asteroid at the time of the potential impact. The updated estimate of the risk corridor along the surface of the Earth followed the same path as before, wrapping around the globe from the eastern Pacific Ocean to Turkey, only now it was somewhat narrower.

Based on the available information at this point in the scenario, we presented our estimate of the blast effects caused by the entry and impact of 2015 PDC. The blast could create a crater 5 to 7 km (3 to 4 miles) in diameter and up to 500 meters (1600 feet) deep and generate a 6.8 magnitude earthquake. The impact would immediately cause damage over an area of approximately 70,000 square kilometers (27,000 square miles, about the size of the Republic of Ireland). If the impact were to occur in open ocean, it would create a wave as high as 10 meters (30 feet) that could inundate populated coastal areas with waves as high as 3 to 4 meters (10 to 13 feet). A near-shore impact would generate a much stronger local tsunami.

Our simulations suggested that an ocean impact would affect a far larger area than a land impact, but with less predictability. All nations with Pacific coastlines would be vulnerable to tsunami, but the magnitude would depend critically on impact location because of the varying impact angle and ocean depth. The modeled event released energy of approximately 500 kilotons of TNT. Should the object in the estimated size range of 2015 PDC enter our atmosphere, it could release energy of as much as 2250 megatons (Mt) of TNT, about 4500 times more powerful than the airburst over Chelyabinsk, Russia, in 2013. Clearly this would be the largest explosive event in recorded history.

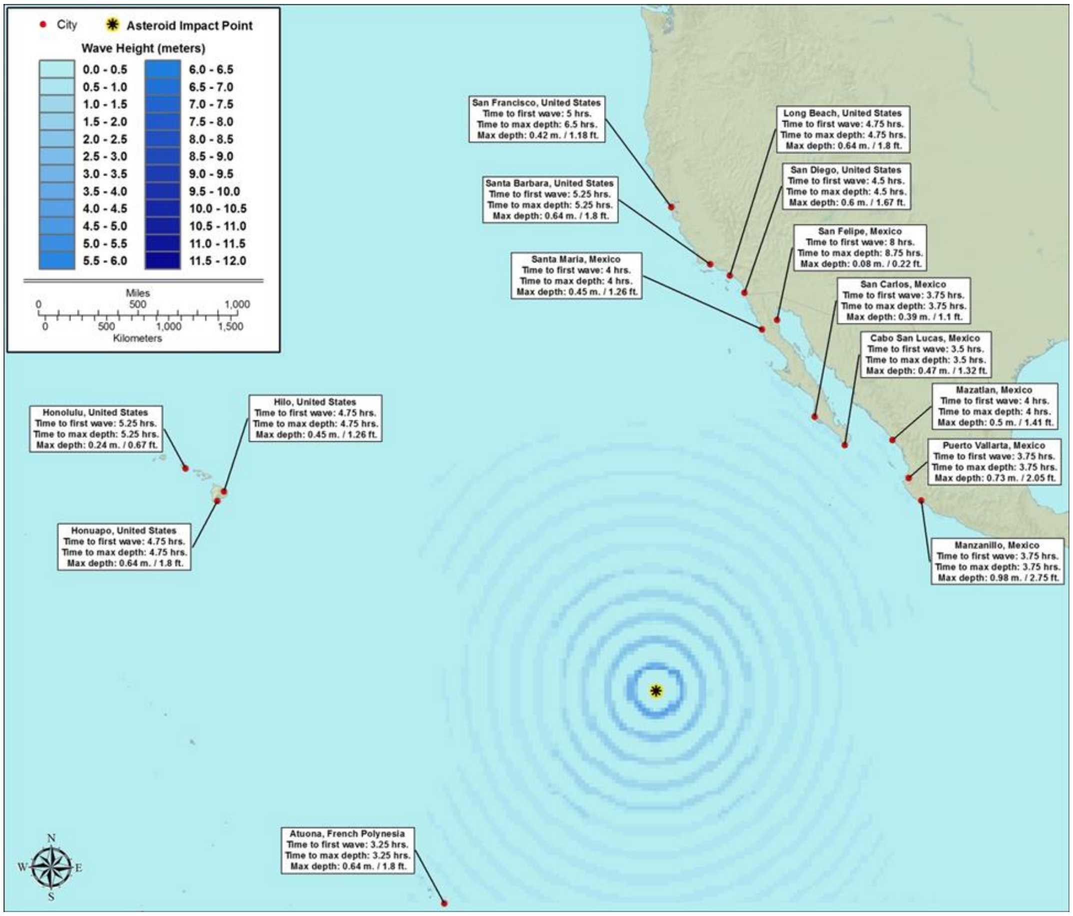

Figure 6 -- –Eastern Pacific impact: shallow entry

As the hazard in the scenario posed by asteroid 2015 PDC rose to unprecedented levels in September and October 2015, several spacefaring nations begin studying how this asteroid might be deflected. The deflection method of choice was the Kinetic Impactor (KI), in which as large a spacecraft as possible is launched to impact the asteroid, thereby changing its velocity. This approach was considered the simplest method and the quickest to develop. The next favorable launch opportunity for a KI mission to deflect 2015 PDC was only about a year away, in late 2016, and that would be too soon to be feasible. But a second favorable launch opportunity wasn't available for another three years, in August 2019, and that would be enough time to prepare the spacecraft and launch vehicle. The large uncertainty in the mass estimate of for 2015 PDC remained a key concern, however, and it was possible that many such KI missions would be required, working in tandem to completely deflect the asteroid from its collision course.

3.1. Introduction to tsunami simulations

Impact of asteroids on the ocean surface can lead to the generation of high amplitude long water waves that propagate to shorelines with possible catastrophic consequences such as flooding the coasts, destroying infrastructure and industrial assets, and disrupting any emergency evacuations. In the next subsections we discuss the coupling between a hydrodynamic code, GEODYN, and a shallow water wave code, SWWP, both built under the same adaptive mesh refinement (AMR) structure. First, we simulated the high velocity impact of the asteroid on the ocean surface. This step is essential to create the source of the wave. In a second stage, we initiated SWWP with the source previously created. SWWP propagates the surface waves to shorelines. To the best of our knowledge, this was the first attempt to couple a hydrocode with a surface water wave code. As the first in its kind, this method opens new opportunities in modeling the nonlinear dynamics at the impact location with the linear long wave propagation of water waves and, in particular, tsunami.

3.2. Brief description of GEODYN and SWWP

3.2.1. Overview

Following Lomov et al. [8] and Vorobiev et al. [9], simulations presented in this paper were conducted using GEODYN – a parallel Eulerian compressible solid and fluid dynamics code with AMR capabilities [10, 11]. Among its many features are high-order material interface reconstruction algorithms [12] and advanced constitutive models that incorporate salient features of the dynamic response of geologic media [13]. GEODYN is capable of:

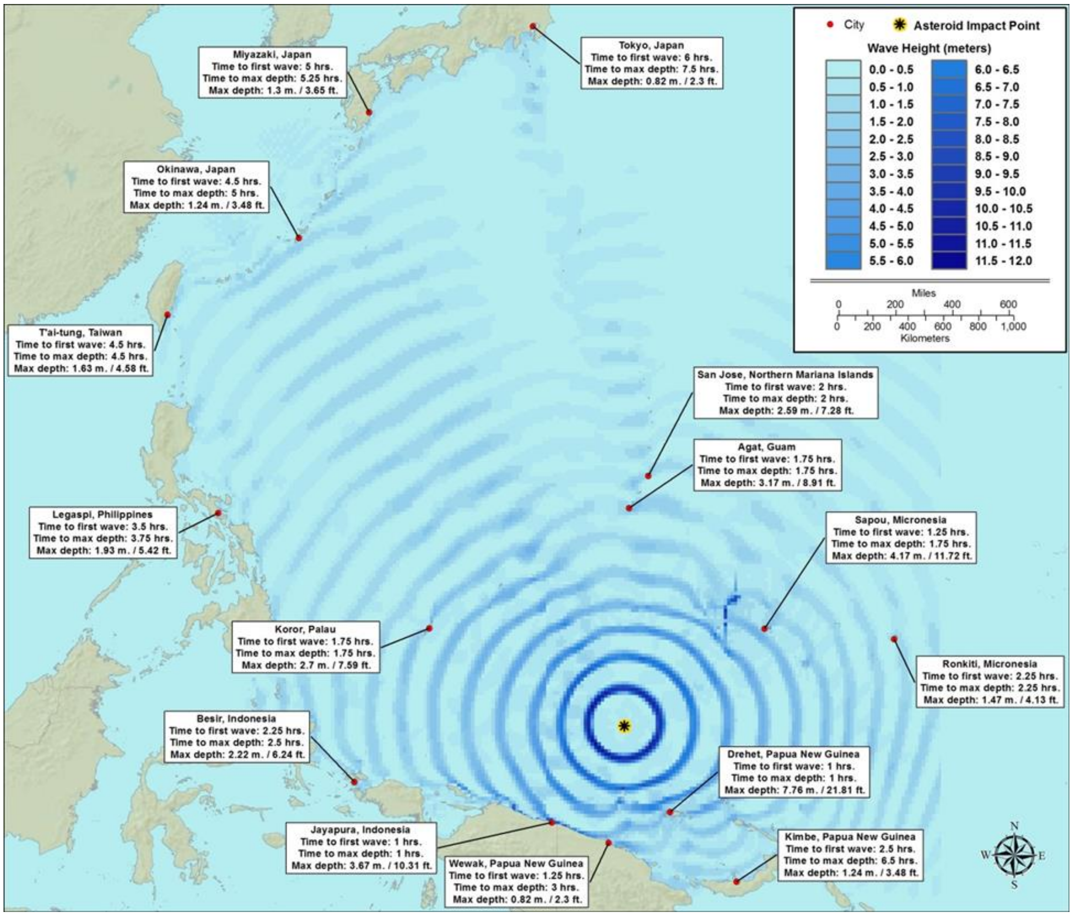

Figure 7 – Western Pacific Impact: steep entry

a) simulating materials under extremely large deformations, b) resolving details of wave propagation within grains with high accuracy, and c) using a continuum damage mechanics approach to represent fracture. The Eulerian framework of adaptive mesh refinement [11] is a relatively mature technique. Adaptive mesh refinement can help simulate the entire domain while allowing focus on greater details in regions of interest. In combination, Eulerian Godunov methods with AMR have been proven to produce highly accurate and efficient solutions to shock capturing problems. The method we used is based on several modifications of the single-phase high-order Godunov method, which is not as straightforward as Lagrangian FEM. For completeness we briefly summarize the method. For solid mechanics, the governing equations consist of the laws of conservation of mass, momentum and energy, equation of distortional elastic deformation, and a number of equations that represent specific rheological time-history dependent parameters (i.e. porosity, plastic strain). The visco-plasticity is modeled with a measure of elastic deformation as a symmetric, invertible, positive definite tensor which is determined by integrating the correspondent evolution equation [15]. The numerical scheme for a single fluid cell is based on the approach of Miller [16], with some modifications to account for the full stress tensor associated with solids. The multidimensional equations are solved by using an operator splitting technique, in which the one-dimensional Riemann problems for each direction are solved using Strang-splitting order to keep second-order accuracy, while the source term is always applied at the end of the time step. Each directional operator is the update of the cell from two-consecutive present-future time steps with fluxes computed at the edges of the cell. The approach to modeling multi-material cells is similar to that of Miller [16] but extensively improved [8,9].

3.2.2. Shallow water wave propagation code SWWP

It is often assumed that any source of disturbance, in particular tsunamis, propagates in the open ocean as linear, non-dispersive surface waves [17]. Therefore, the shallow water equations (SW) have often been used. Assumption of linearity of the waves stems from the fact that the ratio of water surface displacement to the depth is small. For non-dispersive waves, the propagation speed does not depend on their frequency. Dispersion alters wave speeds leading to waves with shorter wavelength to travel more slowly. In the long-wave limit (or hydrostatic approach), all waves travel with the same speed $C=(g\ H)^{1/2}$, where g is the acceleration of gravity, and H is the local water depth [17]. This wave speed relationship makes it relatively easy to estimate travel-time for a tsunami event. Tsunami modeling based on

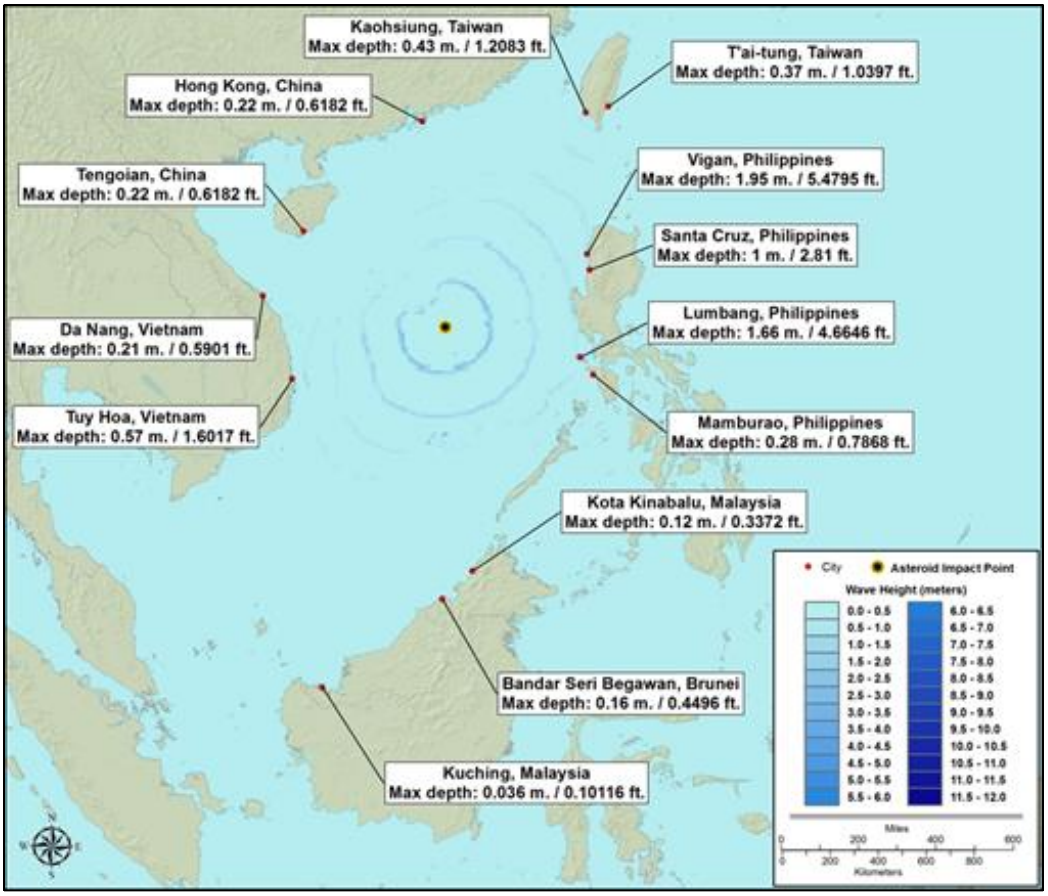

Figure 8 – South China Sea tsunami wave propagation

linear shallow water equations (LSW) can predict initial arrival times quite accurately, because the leading wave in a real wave train is the longest and propagates with the highest wave speed. The models that include nonlinearity but still neglect effects of frequency dispersion are governed by the nonlinear shallow water equations (NLSW). NLSW-based models can provide good prediction of run-up heights of the leading wave [18]. The principal limitation of their accuracy in predicting shoreline inundation in tsunami application stems from factors that are not covered by the basic theory: a) frequency dispersion that can lead to different wave heights and wave forms, b) inability of wave breaking simulation due to singularity in the free surface description, c) interaction with fixed structures, and the interaction with the mass of transported debris resulting from destruction of structures. While the effect of dispersion can still be included as an extension to the SW equation, other effects mentioned above require more complicated approach [18, 19]. One of the most advanced examples of NLSW modeling is MOST (Method of Splitting Tsunami; [20]) used at National Oceanic and Atmospheric Administration (NOAA). A number of applications of this model to different tsunami scenarios are described in the literature (e.g. [20, 21]). Another model that uses NLSW using Godunov method and Adaptive Mesh Refinement technique was proposed by LeVeque [22]. SWWP is essentially a Godunov NLSW implementation using LLNL's SAMRAI (Structured Adaptive Mesh Refinement Application Infrastructure [23]).

3.3. Water wave source generation using GEODYN

We set up GEODYN to simulate the source wave at the impact site. In all cases the asteroid is assumed spherical. The density of the asteroid is assumed to be 2.2 g/cm^3 throughout all scenarios. The 3D simulation required ~9 million cells, 4 levels of AMR and a total of ~10,000 CPU-Hrs.

Due to the uncertainty in the size of the asteroid and its impact location we defined three different impact cases for demonstration and simulation purposes, as follows:

1. The first case assumed an asteroid diameter of 400 m impacting in the eastern Pacific as depicted on Fig. 6. We prescribed an asteroid density of 2.2 g/cm^3. We used an entry angle of 4° from horizontal and velocity of 15.3 km/s which is consistent with the hypothetical orbit for an impact in that location.

2. The second impact case (Fig. 7 was in the western Pacific and assumed the same size and density as before, but with an entry angle of 72^o and a velocity of 15.7 km/s (also consistent with the hypothetical orbit).

3. The third case assumed a 100 m asteroid in the South China Sea (Figs. 8 & 9 with an entry angle of 54^o and a velocity of almost 16 km/s). For the simulation we used a 100 m asteroid but our illustration is for the 50 m asteroid case which had been adopted prior to the PDC TTX 2015 public release of the final script.

Fig. 6 is a snapshot of the numerical simulation of ocean wave generation and propagation due to asteroid impact at site #1 of the risk corridor established by Chodas [http://neo.jpl.nasa.gov/pdc15/]. The heights of the waves reach +/- 5m and attenuate with time when reaching the shorelines. Waves reach Baja California, Ecuador and Peru within 2 hours from impact. The waves get attenuated as they travel north reaching as far as the west coast of the USA and Alaska.

Fig.7 is a snapshot of the numerical simulation of ocean wave generation and propagation due to asteroid impact at site #151 of the risk corridor. The impact location is off of the coast of Papua New Guinea, which waves reach within 1 hour from impact. The waves are +/- 7m in height and attenuate with time when reaching the shorelines. This impact takes place in shallower ocean compared to the previous scenario. The long waves reach as far as the Philippines, Japan and China among other south-east Asian countries.

Fig. 8 is a snapshot of the numerical simulation of ocean wave generation and propagation due to asteroid impact at site #229 of the risk corridor. The impact location is within South China Sea. Waves reach Vietnam and then the south coast of China within 1 hour from impact. The wave amplitudes are +/- 2m. The ocean is shallower than in scenario #1 but deeper than that of #2; one main long wave reaches the Philippines, China and Taiwan among other southeast Asian countries (Fig. 9).

4. DEC. 27, 2016: IMPACT CERTAIN

Our third mock press release was given on Day 3 and updated the scenario to December 27, 2016. The asteroid had just emerged from behind the Sun, as viewed from the Earth, and the new tracking observations indicated that it was indeed on a collision course with the Earth. Impact was now certain, and less than 6 years away. The precise location of the impact could not be narrowed down just yet, but it would lie somewhere within a shortened risk corridor (Fig. 10). Nations at risk from the direct effects of a land impact or an airburst would be: Philippines, Vietnam, Laos, Thailand, Myanmar, Bangladesh, India, Afghanistan, Pakistan, Iran, Iraq and Turkey. Nations at risk from a tsunami in the Pacific or South China Sea include all those with coasts on those bodies of water, including Indonesia, Malasia, Philippines, Taiwan, Japan, Papua New Guinea, Australia, New Zealand, coastal nations of mainland Asia, North America, South America, and all other island nations and territories in the Pacific (as shown on Fig. 7). Weaker tsunamis would propagate into other ocean basins but would not be expected to be dangerous. The probability and consequence-weighted risk would be greatest for equatorial western Pacific nations (Southeast Asia and Oceania). Although the asteroid would be observable until mid-2017, it would be very distant and faint, and it would take at few more months of continuous tracking before the approximate location of the impact point would not be narrowed down. Further tracking in late 2018 and early 2019 would refine the impact location.

World leaders were meeting in Frascati, Italy to assess options for deflecting the object and to initiate planning for emergency response and humanitarian aid in case of an impact. A total of seven kinetic impactor (KI) missions to deflect 2015 PDC were under development worldwide, all to be launched during the favorable August 2019 launch opportunity. Fig. 11 shows the interceptor trajectories; the deflection would occur more than one full asteroid revolution before the potential Earth impact. Four missions would be developed by the U.S. and one each by Europe, Russia and China. An important limiting factor on the number of KI missions was the number of launch pads available for heavy lift launch vehicles: only one mission was planned for each pad because the on-pad preparation time for each mission was longer than the launch period.

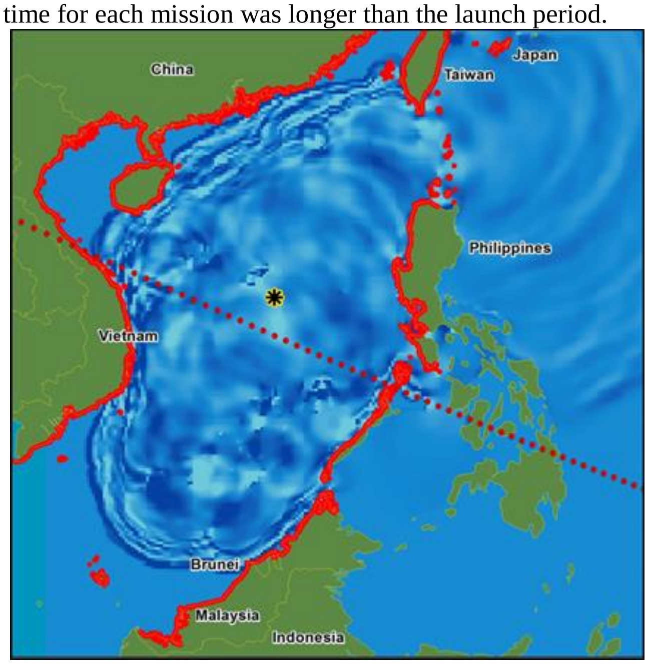

Figure 9 – Risk from impact tsunami

It was not yet known how many KI deflections would be needed to deflect the trajectory off the Earth. Not only was the displacement required for the deflection still very uncertain, the key parameters of asteroid size and mass were also largely uncertain. Based on photometric color measurements, the asteroid was believed to belong to the S-class, which has a higher average albedo. This reduced the asteroid size estimate to roughly 150 to 250 meters, but a size of 400 meters still could not be ruled out. The asteroid mass was therefore uncertain by more than an order of magnitude. If the asteroid turned out to be massive and/or

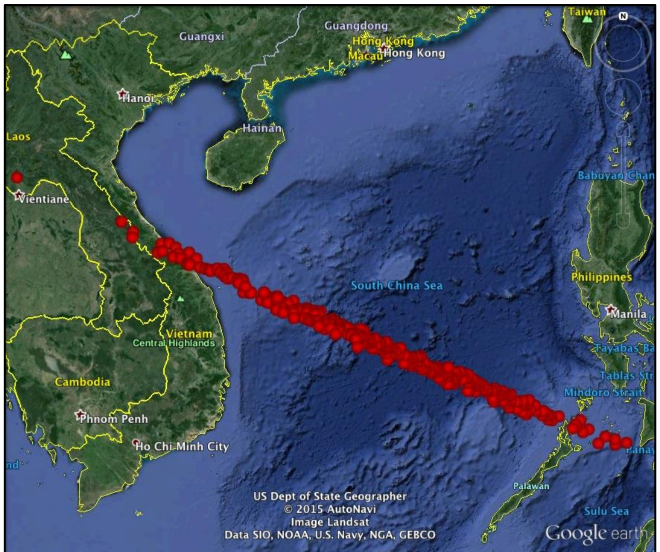

Figure 10 – Impact footprint when the Kinetic Impactor missions were launched

the impact point was on the eastern end of the risk corridor, it was very possible that 7 KI missions would not be sufficient to move the trajectory off the Earth. Note that KI deflection is only effectiove in pushing the trajectory in one direction off the Earth, in this case towards the leading edge of the Earth (westwards along the risk corridor). Fortunately, the size and mass would become better determined well before the KI launch period, in late 2017, when 2015 PDC would pass near the Spitzer Space Telescope, which could accurately measure the object's size. The impact location would be known much better by that time as well, and therefore the size of the required deflection.

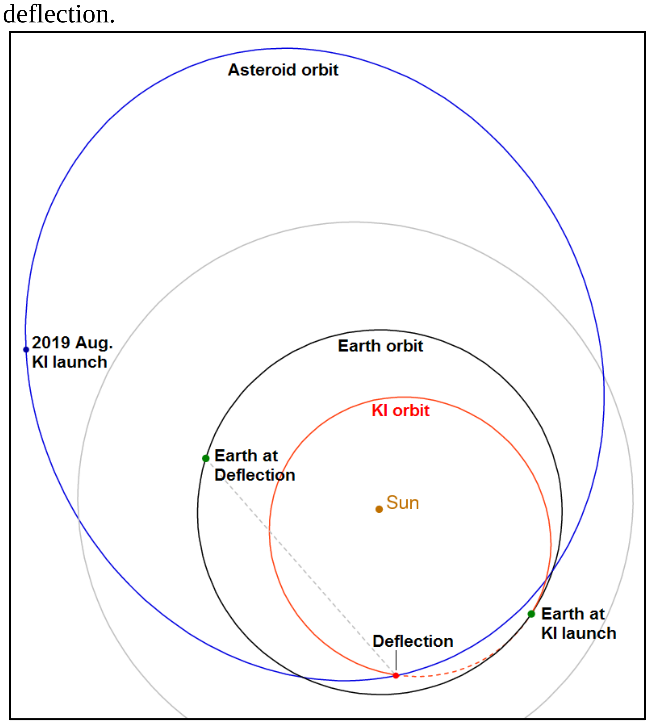

Figure 11 – Trajectory followed by the kinetic impactors to deflect the asteroid in early March, 2020

5. Aug. 1, 2019: Deflection Missions

Our fourth scenario press release, given on Day 4 of the PDC meeting, advanced the scenario a full 19 months forward to August 1, 2019, just before the armada of kinetic impactor spacecraft were due to be launched. Over the almost two years since the previous update, the trajectory of 2015 PDC had become much more precisely known, and the likely location of the September 3, 2022 impact was predicted to occur in the South China Sea (Fig. 11) at about 3:51 UTC, or 11:51 am local time. The Spitzer Space Telescope observation of the asteroid had been successful, confirming the asteroid size was in the range of 150 to 250 meters. The location of the projected impact point near the leading edge of the Earth and the smaller size estimate were both favorable for a successful outcome of the deflection effort.

Figure 12 – Impact footprint of the asteroid fragment in early 2021

A total of six spacecraft missions to deflect the oncoming asteroid were ready for launch. The U.S. would launch 3 missions, using a Delta IV-Heavy, a Falcon Heavy, and an Atlas V 551. A larger spacecraft to be launched on NASA's first Space Launch System (SLS) vehicle had to be scrapped because the launch vehicle could not be readied in time. Europe, Russia and China would launch missions on the Ariane 5, Proton, and Long March vehicles. The spacecraft would all follow similar trajectories and the deflections would occur over a 7-day period in early March, 2020. India joined the effort and would launch a trailing flyby observer spacecraft to assess the effectiveness of the deflection.

The impactor spacecraft would hit the asteroid at a closing velocity of about 15 km/s, so the total amount of momentum which could be delivered to the asteroid by the six spacecraft was roughly known. The asteroid mass, however, was still quite uncertain, as was the momentum enhancement that could be expected from ejecta from the spacecraft impacts. But even under conservative

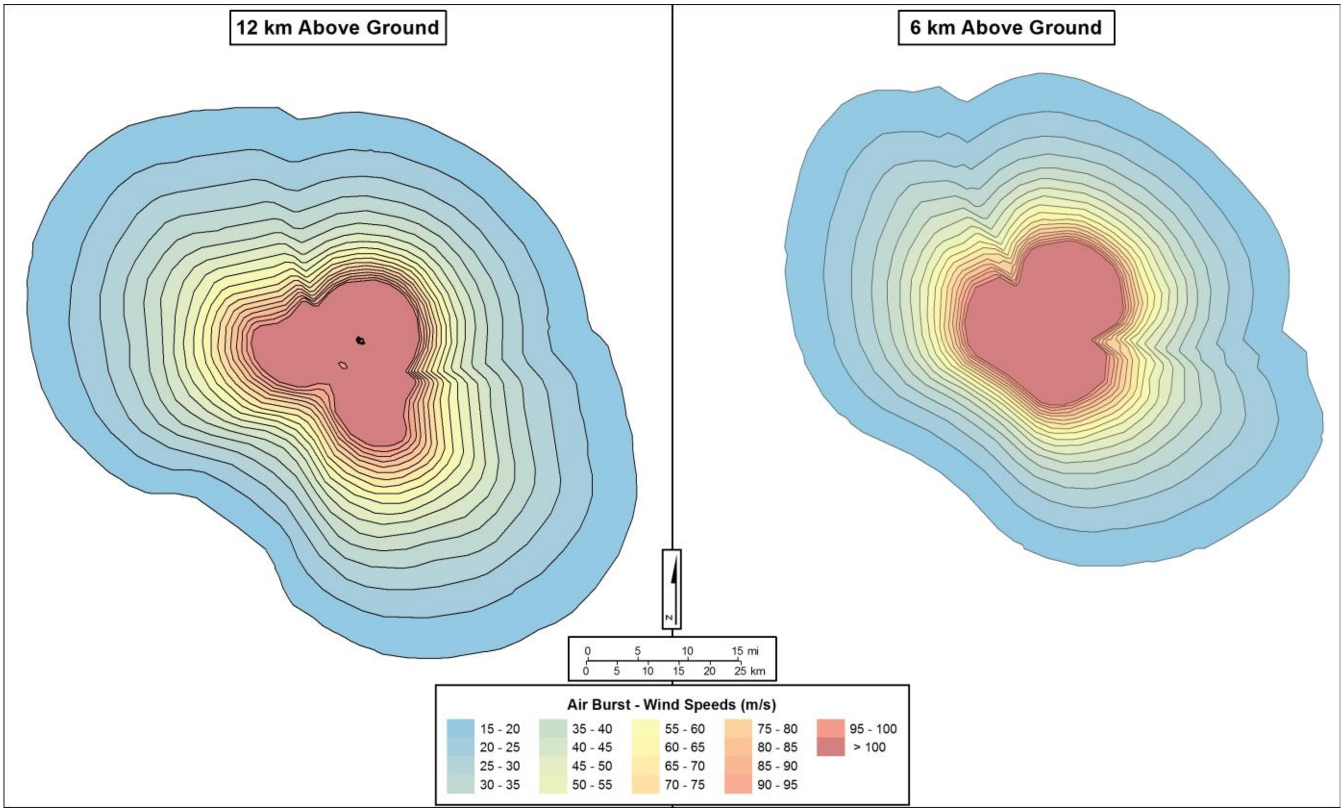

Figure 13– Airburst wind speeds for two burst heights

assumptions, it was felt that the six interceptor missions would be more than enough to impart 20 mm/s of velocity change to the asteroid, the minimum required to deflect it away from its collision course with the Earth.

Unfortunately the effectiveness of the deflection effort would be difficult to assess directly from the Earth because the asteroid would be nearly on the other side of the Sun, and too close to the Sun for observations. For that reason, an observer spacecraft would be launched to assess the size of the imparted deflection. The deflected asteroid would be observable from Earth again in late 2020.

6. Jan. 18, 2021: Incomplete Deflection

Three scenario press briefings were given on the final day of the PDC meeting, which was devoted entirely to scenario discussions. The first briefing, dated Jan. 18, 2021, discussed the outcome of the deflection campaign and the aftermath. Five of the six Kinetic Impactors had been successfully launched on their missions, although one of them failed during a trajectory correction maneuver en route to the asteroid, leaving only 4 spacecraft to perform the deflection. Images from the leading spacecraft revealed the asteroid to be a 300-meter-long rubble pile looking much like the asteroid Itokawa. The first KI mission impacted, successfully changing the velocity of the asteroid, but it also fractured the body. The second KI spacecraft also successfully hit the asteroid, but a loosely connected fragment split off without much of a velocity change. The third and fourth kinetic impactors hit the main part of the asteroid, probably delivering enough momentum to move it away from Earth impact, but the impactors did not affect the smaller fragment. Images taken from the observer flyby spacecraft two days after the final KI impact detected both the main asteroid and a sizeable fragment, embedded within a cloud of debris. The spacecraft lost attitude control near closest approach due to impacts from debris particles, so the fragment was only observed as it approached. The fragment was estimated to be roughly 60 to 100 meters in size. It was not possible to accurately determine the deflection velocity change impacted to the fragment, but it was clear that the fragment had not received much deflection and could still be on an Earth-impacting trajectory.

The deflection events could not be imaged directly from the ground because the asteroid was too close to the Sun, as viewed from the Earth. Eight months elapsed before ground-based observations of the asteroid and fragment resumed in late 2020 while the objects were still very distant. Two distinct objects were barely resolved, the smaller fragment being very faint. Only a few months of ground tracking of the objects could be obtained, and at the time of this press briefing the objects were again heading behind the Sun as viewed from the Earth. With such limited post-deflection tracking, the modified trajectories of the two bodies could not be accurately estimated. While the impact probability of the main asteroid had been reduced to less than 1 percent, the impact probability of the fragment was 54 percent. No further updates to this result were possible for almost a full year, while the asteroid remained unobservable from the

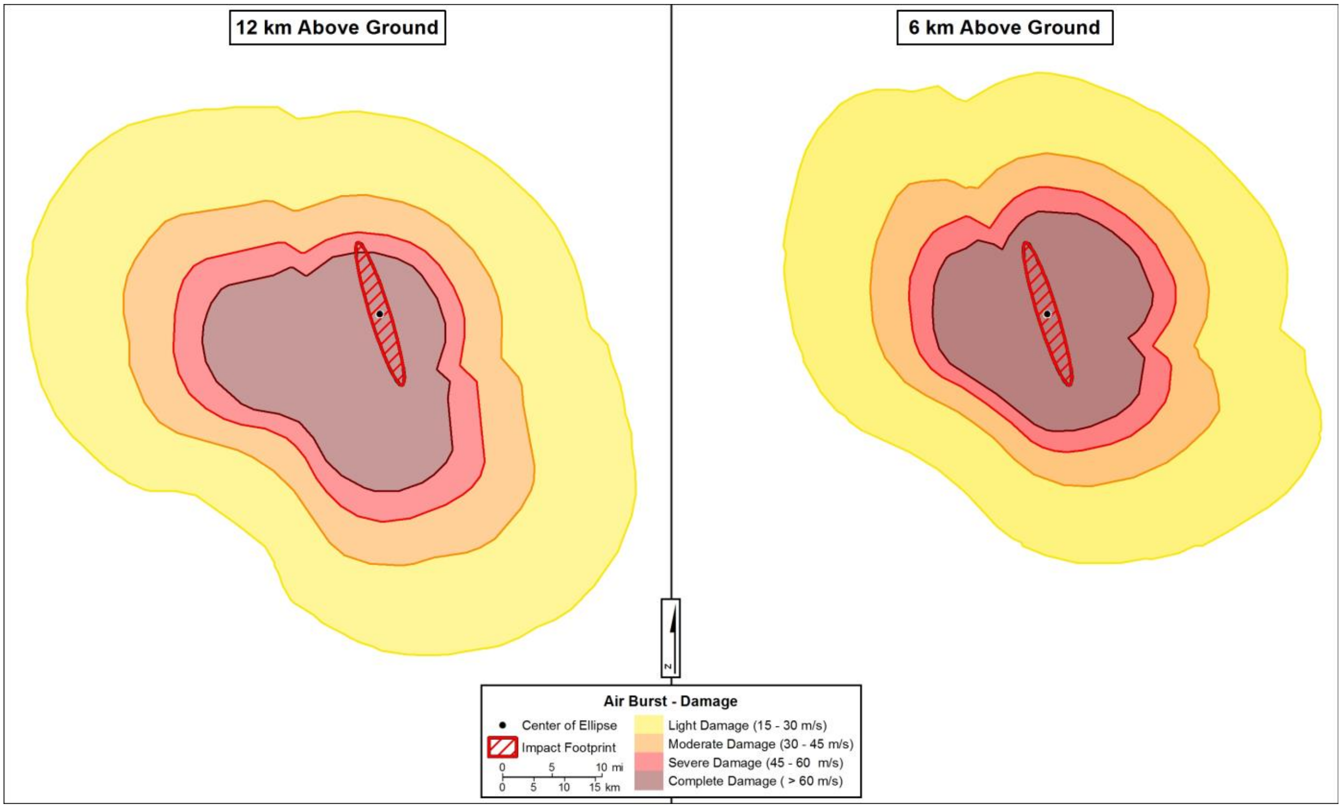

Figure 14 – Damage zones with impact uncertainty

Earth. Fig. 12 shows the impact footprint of the fragment, larger now because of the uncertainty in the amount of deflection imparted to the fragment. Nations that could be directly affected by the impact of the fragment were: Vietnam, Laos, Thailand, Myanmar, Bangladesh, India, Afghanistan, Pakistan, Iran, Iraq and Turkey.

Assuming a worst-case fragment size of 100 meters and a predicted entry speed of about 16 km/s, we calculated that the impact would produce an explosion with energy of about 50 megatons, much smaller than that predicted for the original object, and the region of total devastation would also be much smaller. If the fragment were to impact on land, wood frame buildings would almost completely collapse out to a radius of 10 km, and windows would shatter out to a radius of 25 km. The equivalent earthquake magnitude would be 5.3, and a crater between 1 and 2 km diameter would be created. The event would release approximately 10 times more energy than that delivered by the 30 to 50-meter asteroid that damaged over 2000 square kilometres of forest in Siberia in 1908.

If the fragment were to impact in water, it would produce a tsunami, but one considerably smaller than a tsunami from the original object. At 270 km from the impact point, the tsunami height would be about 1 meter, and it would drop to 25 cm at a distance of 1000 km. The tsunami would no longer be a Pacific-wide threat but if the strike were to occur near a coastline, there could be potential widespread regional destruction. The worst-case impact would be in the South China Sea.

To analyse the impact effects for this stage of the scenario, we performed the tsunami simulation in the South China Sea (Figs. 8 & 9). We also ran a matrix of airburst simulations for various possible burst heights, for the largest possible fragment size of 100 m. The impact location was still highly uncertain but we were able calculate the surface winds relative to the projected impact point (Fig. 13) and converted that to a map of damage zones (Fig. 14). These damage maps for various asteroid sizes, entry angles, and burst heights can be placed and oriented on an actual geographic map, once the impact location was better determined.

There was considerable discussion from the conference participants after this scenario update. Although the deflection attempt was well intentioned, the space-faring nations had quite possibly shifted the impact threat from one area of the world to another, and the risk corridor which had collapsed nicely to the South China Sea was now uncertain again. The possibility was raised that the nations responsible for the KI missions might be liable for any damages caused by the partially deflected fragment.

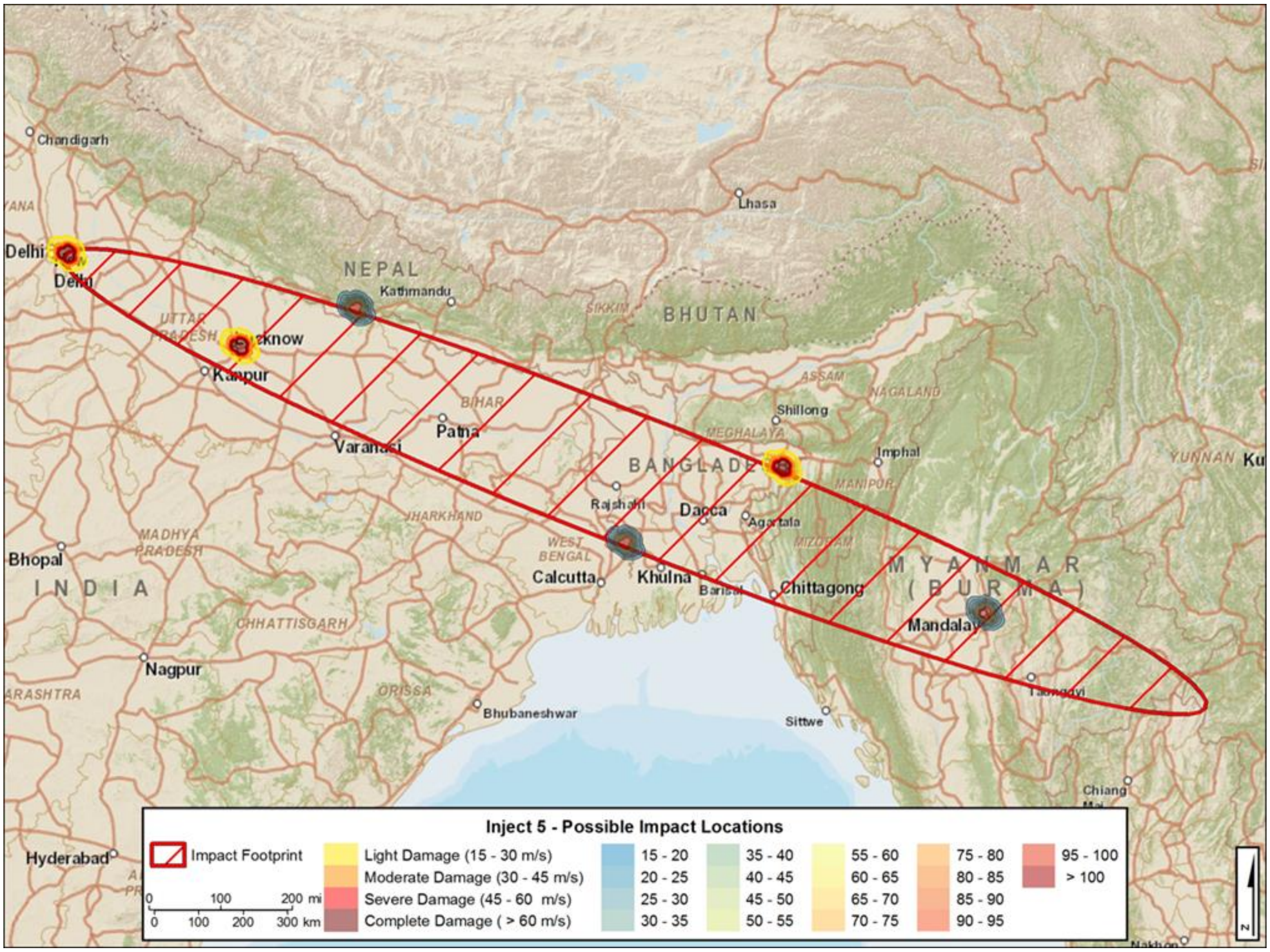

Figure 15 – Wind and damage zones with uncertainty

7. Feb. 4, 2022: Asian Impact or Airburst

The sixth scenario update was dated Feb. 4, 2022, over a year since the last update, and only seven months before the potential impact event. The broken asteroid had just recently emerged from behind the Sun after being unobservable for a year, and the new observations confirmed that although the main asteroid would miss our planet, the smaller fragment was on course to collide with the Earth on September 3, 2022 at about 03:50 UTC. As shown in Fig. 12 the impact would occur somewhere in the region of northern India, Bangladesh, Myanmar, or northern Thailand, and would therefore be a land impact.

The asteroid pieces were now approaching much closer to the Earth, and brightening. Further tracking observations over the next two months were expected to dramatically shrink the size of the impact footprint to within 100 km or so. Observations could be expected to continue until a month before impact, when the objects would again move too close to the Sun as viewed from the Earth. The impact location would be known to within about 50 km by then.

Even more accurate predictions would be possible when the asteroid came within range of NASA's Goldstone radar about a week before the impact. Those observations would also produce a more accurate estimate of the size and shape of the fragment. The larger and more powerful Arecibo radar facility could not observe this asteroid because the asteroid would not pass within its pointing window.

The size of the fragment was still somewhat uncertain. Evacuation and shelter-in-place plans would therefore have to assume the worst-case estimate of an asteroid as large as 100 meters with and corresponding impact energy of up to 50 Megatons.

For this update, we projected our wind speed maps onto the impact uncertainty ellipse as it continued to shrink in the months before impact (Fig. 15 & 16). We used the Glasstone and Dolan [7] study of the effects of nuclear weapons to transform wind speed to damage. We included four damage zones indicated on the general damage potential on the maps we presented.

The participants were able to narrow down the potential risk to population and infrastructure and add this information in their response plan. The predicted population in danger was approximately 80 million people. Many were residents of

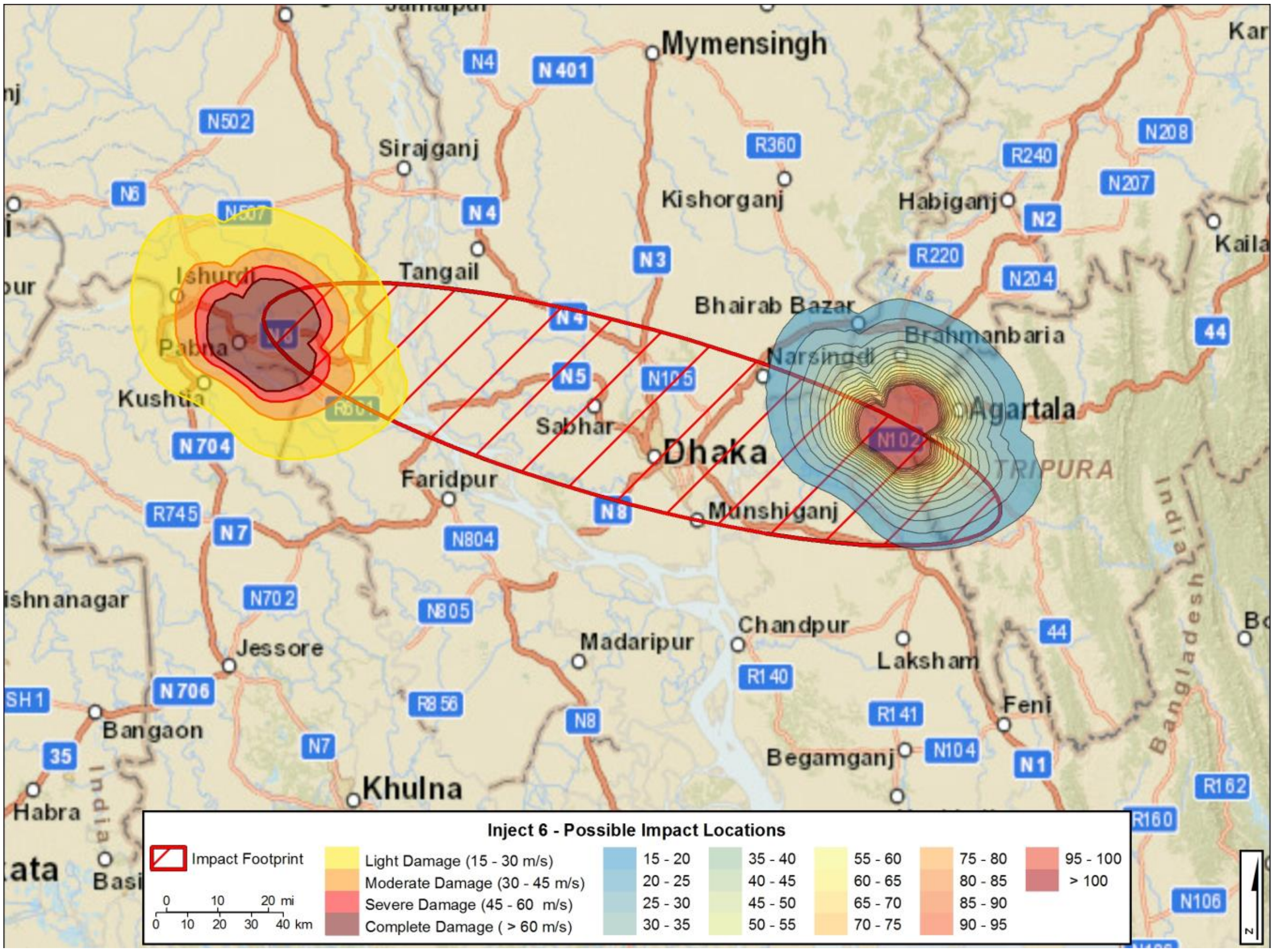

Figure 16 – Last footprint before Goldstone data

the megacity of Dhaka but some were farmers in surrounding rural areas. Political leaders were concerned with getting aid from non-affected nations, planning to provide civil protection and mitigate panic among the population.

8. Aug. 27, 2022: Dhaka, Bangladesh

The seventh and final press briefing updated the scenario to only a week before the impact date, and announced the location with a high degree of certainty. The fragment of 2015 PDC was now within range of Goldstone radar, and based on the highly accurate range and Doppler measurements, the object was predicted to enter the atmosphere in the vicinity of Dhaka, capital city of Bangladesh, on September 3, 2022 at 9:50 a.m. local time (Fig. 16). Dhaka is the 10^{th} largest city in the world and more than 15 million people are estimated to live in the greater Dhaka area. The radar measurements of the asteroid fragment also revealed that it was about 80 meters in diameter.

The fragment would enter the atmosphere at about 16 km/s (almost 36,000 miles per hour) at an angle of about 36 degree from the horizontal. The energy produced by the event would most likely be about 18 Megatons, but a crater-forming impact was very unlikely. The object would almost certainly explode in the atmosphere as an airburst, much like the Tunguska explosion of 1908.

We convolved the footprint with the impact uncertainty ellipse to get a composite risk map (Fig. 17) on which the evacuation plan was based because it must commence immediately. This map would be provided to officials who are responsible for shutting down utilities and dealing with infrastructure and economic losses.

With only a week until impact, planning was focused on continuity of operations for necessary infrastructure and safe shut-down of power plants and other facilities to mitigate damage and enable them to be safely started up again. Authorities were also occupied with evacuation and shelter plans. Extreme weather events are common in Bangladesh, so an existing notification system could be exploited.

A final press release was given and the panel addressed the risk area and the potential damage zones. Panel members representing world leader's (India, China, Europe and the US) discussed their plans and responses. Affected nations

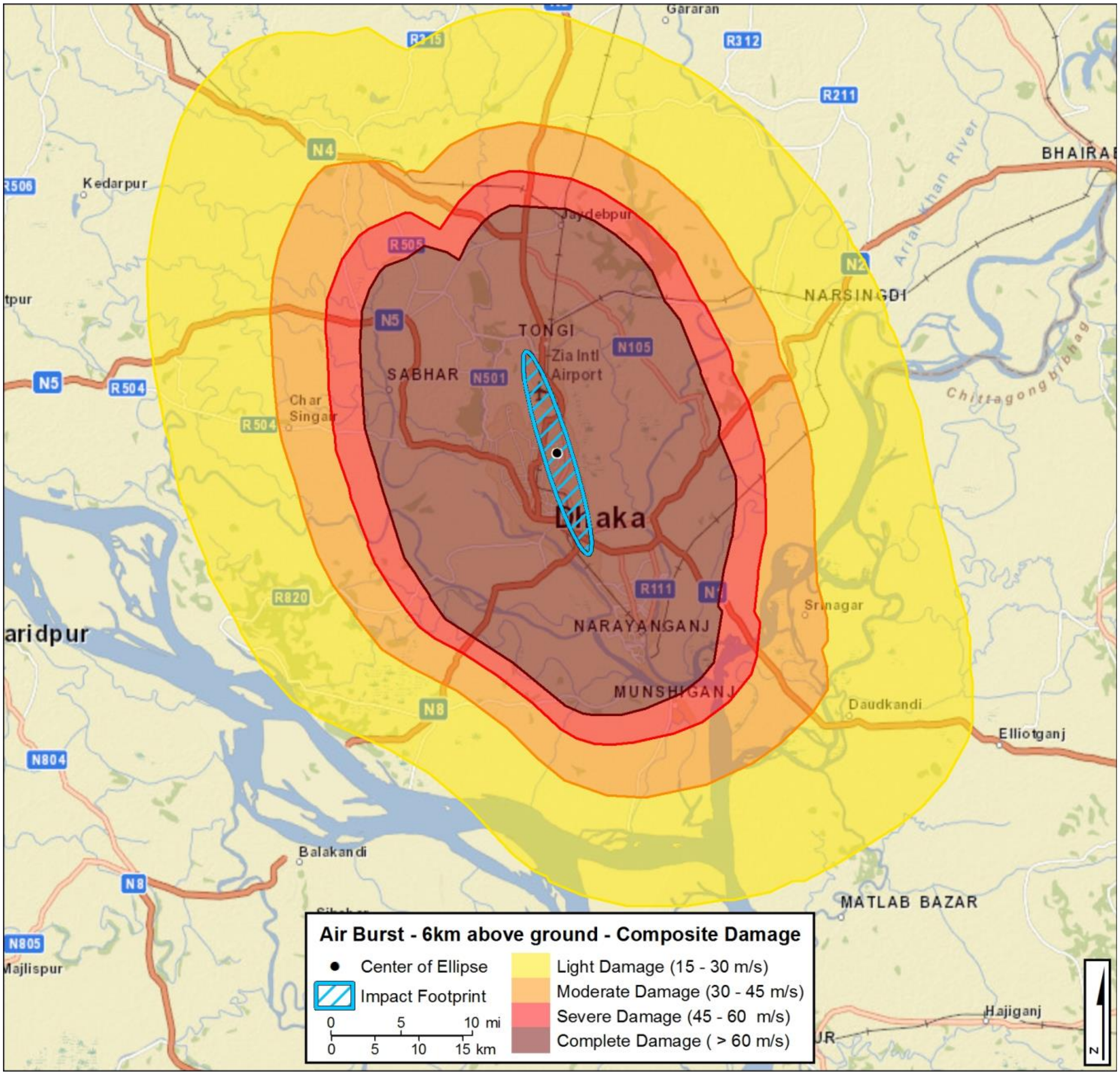

Figure 17 – Composite damage map just before impact

identified the need to notify, evacuate and support the impacted population and secure infrastructures at risk. A general consensus was reached that Bangladesh can address a disaster of this magnitude. The rest of the international communities, not directly affected, were on standby to provide support as needed. These included representatives from NASA and FEMA and neighbouring nations.

This was the final update before the exercise was concluded.

9. Conclusions

This was first time that a week-long asteroid threat exercise has ever been attempted. We designed it to simulate and examine the process of decision making that would accompany the discovery and response to an asteroid on a collision course with Earth. We developed and presented plausible scenarios that would be of interest to as many participants as possible while considering the broad diversity in technical expertise, approach, values, missions, and national affiliations the attendees. Moreover, we strove to present a reasonable sequence of events spanning several years that would provide many opportunities for collective decision making under uncertainty by parties likely to have conflicting interests. Some of the participants were surprised by the high level of uncertainty present through much of our scenario, in the predicted location of impact as well as the size and mass of the asteroid. But we felt that these uncertainties were entirely plausible and possibly even typical.

A "hot debrief" was conducted at the end of the exercise with participants being asked to provide their thoughts on the exercise and a summary of the most important lessons learned from the exercise:

- Having deflection and characterization space missions already pre-planned would have been very helpful.
- A space-based asset for infrared characterization of asteroids would have been very helpful.
- Communication at all levels is very important (inter-governments and governments to their citizens).
- It is to get easily misinformed, even in this controlled exercise.
- Linkages between UN and IAWN would be involved in a large international crisis.
- We need to pre-plan some aspects in advance of a real event and look at all possibilities, including the potential for space mission failure.
- The problem has a dynamic character; the exercise was initially about asteroids and deflection, but then evolved to impact and disaster response.
- More research into the nature and structure of asteroids is needed in order to understand whether a kinetic impactor might fracture an asteroid.
- Development of a fast-response low cost characterization mission should be explored.

It was emphasized that the daily press releases given must be consistent and frequent in order to keep the public informed and assured and that the press not sensationalize the potential disaster.

Participants generally appreciated the exercise, learned from it, and had the opportunity to work with individuals with whom they may not have otherwise interacted. Most attendees would like to see such exercise scenarios included as part of future PDC conferences.

Links to original presentation files, photographs, and daily webcast videos are archived by the European Space Agence [24].

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References

[1] Boslough M.B. et al., 2015, FEMA asteroid impact table-top exercise simulations, Proceedings of the 13th Hypervelocity Impact Symposium.

[2] Ezzedine S. et al., 2015, Simulation of Asteroid Impact on Ocean Surfaces, Subsequent Wave Generation and the Effect on US Shorelines, Proceedings of the 13th Hypervelocity Impact Symposium.

[3] Jet Propulsion Laboratory's Near Earth Object Program Sentry Risk Page: http://neo.jpl.nasa.gov/risk/

[4] Milani A., et al. 2002. Asteroid close approaches: Analysis and potential impact detection. Asteroids III, 55-69.

[5] Binzel R.P., 2000. The Torino Impact Hazard Scale, Planetary and Space Science, 48, 4, 297-303.

[6] Collins G., et al., 2005, Earth Impact Effects Program: A Web-based computer program for calculating the regional environmental consequences of a meteoroid impact on Earth, Meteoritics & Planetary Science, 40, 6, 817–840.

[7] Glasstone S. & P.J. Dolan, 1977, The Effects of Nuclear Weapons 3rd edn, 100–105. US Gov. Printing Office.

[8] Lomov I., et al., 2013, Influence of Mechanical Properties Relevant to Standoff Deflection of Hazardous Asteroids, Procedia Engineering 58, 251 – 259, Proceedings of the 12th Hypervelocity Impact Symposium.

[9] Vorobiev Yu, et al., 2007. Simulation of penetration into porous geologic media. International Journal Of Impact Engineering, 34(4):721-731..

[10] Antoun T., et al., 2001, Development and application of a strength and damage model for rock under dynamic loading, in: D. Elsworth, J. Tinucci, K. Heasley (Eds.), Proceedings of the 38th U.S. Rock Mechanics Symposium, Rock Mechanics in the National Interest, Balkema Publishers, pp 369–374.

[11] Lomov I., & M. Rubin, 2003, Numerical simulation of damage using an elastic-viscoplastic model with directional tensile failure, Journal De Physique IV 110: 281–286.

[12] Hertel E., & R. Bell, 1992, An improved material interface reconstruction algorithm for Eulerian codes, Sandia National Laboratory report.

[13] Rubin M.B. & I. Lomov, 2003, A thermodynamically consistent large deformation elastic-viscoplastic model with directional tensile failure, International Journal of Solids and Structures 40 (17) 4299 – 4318.

[14] Berger M.J., P. Colella, 1989, Local adaptive mesh refinement for shock hydrodynamics, Journal of Computational Physics 82 (1) 64–84.

[15] Rubin M.B., et al., 2000, Mechanical and numerical modeling of a porous elastic-viscoplastic material with tensile failure, International Journal of Solids and Structures 37 (13) 1841–1871.

[16] Miller G. H., & E. G. Puckett, 1996, A high-order Godunov method for multiple condensed phases, Journal of Computational Physics 128 (1) 134–164.

[17] Stoker J.J., 1992, Water Waves: The Mathematical Theory with Applications, Wiley International, 600 pages.

[18] Liu P., & H. Yeh, 2008, Advanced Numerical Models For Simulating Tsunami Waves and Runup. 334 pages, Publisher: World Scientific Publishing Company

[19] Titov V.V. & C.S. Synolakis, 1998, Numerical modeling of tidal wave runup. Journal of Water, Port Coastal Eng., 124(4), 157-171.

[20] Tang L., et al., 2009. Development, testing, and application of site-specific tsunami inundation models for real-time forecasting. Journal of Geophysical Research, 114(C12), 1-22.

[21] Gonzalez, F.I., et al., 2009. Probabilistic tsunami hazard assessment at Seaside, Oregon, for near- and far-field seismic sources, Journal of Geophysical Research, 114, 1-19.

[22] LeVeque, R., et al., 2011. Tsunami modeling with adaptively refined finite volume methods. Acta Numerica, 20, 211-289. Arieh Iserles, eds.

[23] Gunney, B.T., et al., 2006, Parallel Clustering Algorithms for Structured AMR, Journal of Parallel and Distributed Computing, 66(11):1419-1430.

[24] European Space Agency Rocket Science Blog: http://blogs.esa.int/rocketscience/2015/04/16/planetary-defense-conference-2015-media-briefing/

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Barbara Jennings *received her PhD in Organizational Learning and Instructional Technology from the University of New Mexico in 2011. She has been with Sandia for 25 years where she has contributed to a wide range of research. Barbara has designed secure inter-lab knowledge sharing systems, worked with simulation and visualization codes using leading edge super-computers, and developed early Internet application technologies. Her recent research interests/expertise comprise contributing to the study of several critical areas including: near earth object impact effects on infrastructure, resilience in commercial building, and design of a mobile application to provide augmented reality in text.*

Bill Fogleman *is the president of GRIT Inc.; In his role as senior consultant in Spatial and Data Analytics for GRIT he has participated in projects in a wide range of subject areas to include: critical infrastructure analysis, network optimization, food safety, defense & security, local and global supply chain modeling, facility assessment & siting, water and resource development & management, environmental assessments, groundwater modeling and contaminate transport modeling. Projects have been conducted for all levels of government, private industry, and NGOs. Clients include the U.S. Department of Justice, the U.S. Forest Service, The U.S. Bureau of Indian Affairs, the U.S. Department of Homeland Security, Sandia National Laboratories, and the Sierra Club. He obtained his BS in geography and international relations from James Madison University and pursued graduated studies in Geography and GIS at the University of Idaho.*