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USING INFORMATION FROM RENDEZVOUS MISSIONS FOR BEST-CASE APPRAISALS OF IMPACT DAMAGE TO PLANET EARTH CAUSED BY NATURAL OBJECTS

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ABSTRACT

The Asteroid Threat Assessment Project (ATAP), a part of NASA's Planetary Defense Coordination Office (PDCO) has the responsibility to appraise the range of surface damage by potential asteroid impacts on land or water. If a threat is realized, the project will provide appraisals to officials empowered to make decisions on potential mitigation actions. This paper describes a scenario for assessment of surface damage when characterization of an asteroid had been accomplished by a rendezvous mission that would be conducted by the international planetary defense community. It is shown that the combination of data from ground and in-situ measurements on an asteroid provides knowledge that can be used to pin-point its impact location and predict the level of devastation it would cause. The hypothetical asteroid 2017 PDC with a size of 160 to 290 m in diameter to be discussed at the PDC 2017 meeting is used as an example. In order of importance for appraising potential damage, information required is: (1) where will the surface impact occur? (2) What is the mass, shape and size of the asteroid and what is its entry state (speed and entry angle) at the 100 km atmospheric pierce point? And (3) is the asteroid a monolith or a "rubble pile"? If it is a rubble pile, what is its sub and interior structure? Item (1) is of first order importance to determine levels of devastation (loss of life and infrastructure damage) because it varies strongly on the impact location. Items (2) and (3) are used as input for ATAP's simulations to define the level of surface hazards: winds, overpressure, thermal exposure; all created by the deposition of energy during the object's atmospheric flight, and/or cratering. Topics

presented in this paper include: (i) The devastation predicted by 2017 PDC's impact based on initial observations using ATAP's risk assessment capability, (ii) How information corresponding to items (1) to (3) could be obtained from a rendezvous mission, and (iii) How information from a rendezvous mission could be used, along with that from ground observations and data from the literature, could provide input for an new risk analysis capability that is emerging from ATAP's research. It is concluded that this approach would result in appraisal with the least uncertainty possible (herein called the best-case) using simulation capabilities that are currently available or will be in the future.

INTRODUCTION

NASA's Planetary Defense Coordination Office (PDCO) [1] sponsors the Asteroid Threat Assessment Project (ATAP) to appraise devastation of the Earth's surface that could arise from impacts of any Near-Earth Object (NEO). The ATAP's function is exemplified herein by describing an assessment of damage caused by the impact of the hypothetical asteroid 2017 PDC, based on initial knowledge of the atmospheric impact corridor and its intrinsic magnitude of 21.9 +/- 0.4 (see http://neo.jpl.nasa.gov/pdc17). The predicted location of the impact is uncertain and the range of estimated devastation is large, owing to imprecise knowledge in 2017 PDC's orbit and its physical characteristics. This initial assessment is based on ATAP's Probabilistic Asteroid Risk Assessment (PAIR) capability [2,3] that includes an asteroid generated tsunami (AGT) model. The discussion goes on to describe how the ATAP could reduce the uncertainty in their risk assessment of the threat as more information about 2017 PFC becomes available, including that from a rendezvous mission conducted by the international planetary defense community (assuming time to impact is sufficient). To this end, it is pointed out how data from a rendezvous mission could be obtained, and how it would be used in an emerging model within the PAIR capability being described at PDC 2017 [4]. It is shown that information from a rendezvous mission, combined with that from ground observations and data from the literature could use as input to ATAP's PAIR capability, enabling delivery of the best-case appraisals to decision makers chartered to implement planetary defense mitigation actions.

INITIAL RISK ASSESSMENT OF 2017 PDC

The hypothetical asteroid 2017 PDC was "discovered" on March 6, 2017. As of March 7, 2017, the most likely impact date for 2017 PDC was reported by the JPL Center for Near Earth Object Studies (CNEOS) to be on July 21, 2027 - approximately ten years in the future. Shortly after it was discovered, the impact probability of 2017 PDC was estimated by the CNEOS to be 1 in 40,000, and that it would occur somewhere along the very long surface impact corridor shown by red dots on Figure 1.

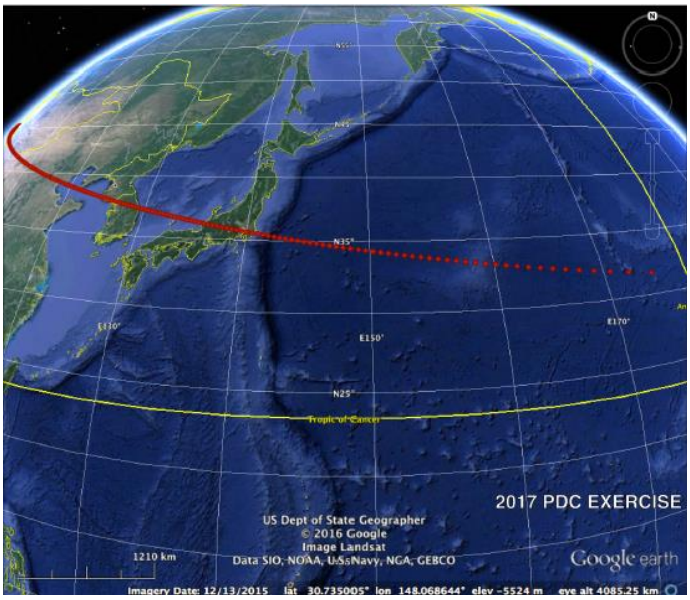

Figure 1. *Initial impact corridor for the hypothetical asteroid 2017 PDC as of May 15, 2017. As of this date, the probability of the asteroid's impact was predicted to be 1 in 100.*

Based on the apparent visual magnitude, 2017 PDC's absolute (intrinsic) magnitude was estimated by the CNEOS to be about 21.9 +/- 0.4. Since its albedo (reflectivity) is unknown, the asteroid's mean size could range from 160 to 290 m using ATAP's analysis. For more detail, visit https://cneos.jpl.nasa.gov/pd/cs/pdc17/. ATAP personnel secured from the CNEOS all that would be known as of May 15, 2017 about 2017 PDC's impact on July 21, 2027. Specifically, 2017 PDC's absolute magnitude, predicted speed and entry angle at the atmospheric pierce points (100 km altitude) and the predicted impact corridor as it was known on May 15, 2017.

The assessment of devastation along the May 15 impact corridor of 2017 PDC is shown in Figure 2. These results are based on application of ATAP's PAIR capability and the project's asteroid generated tsunami (AGT) model [3]. The plot shows the overall "Affected Population", a metric that accounts for different fractions of the affected population and infrastructure within four over pressure ranges down to 68 mbar (1 psi), as defined in Table 1 and described in reference [3]. This assessment assumes the asteroid is of a spherical shape varying in size from 160 to 290 m and its composition is unknown. Owing to lack of information, the asteroid's density, porosity and materials strength are unknown, so Monte Carlo sampling of characteristics for stony and carbonaceous classes for the ensemble of asteroids was used for the PAIR analysis. This approach is similar to that used for the recent Science Definition Team (SDT) study [3]. The entry angle for 2017 PDC relative to the local horizontal gets as high as 47.7 degrees at the mid-corridor. The entry speed at the Atlantic end of the corridor is 17.48 km/s, and at the Pacific end it is slightly to 16.92 km/s.

As shown in the Figure 2, devastation along the impact corridor depends strongly on location. The mean location of the blast is plotted in latitude and longitude coordinates on the figure. The width of the curve is related to the lateral breadth of the blast, while the mean value of affected population at that location is identified by color. As can seen from the upper plot in Figure 2, corresponding to the impact corridor over land, Affected Population values span 4 orders of magnitude from 10^4 to 10^7. The variation in the magnitude of Affected Population about the mean is large, as two orders of magnitude, owing to the range of diameters (160 to 290 m) deduced from variation of the albedo and density (1.1 to 2.4 g/cc) selected from the ensemble of asteroid properties following methodology used in Reference [3]. Not shown is the minimum level of affected population on land ~ 10^3 predicted to be in Northern China, in the Gobi Desert, while the maximum is over Japan, slightly over 10^7. Two areas with low values of affected population in Kazakhstan and China (with predicted minima of ~ 10^3) might be considered by decision makers as places where "taking the hit" on land would be acceptable (given there is ample time for civil defense measures). The predicted devastation for 2017 PDC along the rest of the corridor on land is quite sobering, and illustrates the challenge decision makers would be face for a real threat posed by asteroid of size similar to that of 2017 PDC, not knowing where the strike would happen on land.

Table 1: Affected Population percentages within different overpressure levels

Overpressure Range	Affected Population, Percent	Expected Damage
68 - 136 mbar 1 -2 psi	10	Window breakage
136 - 272 mbar 2 - 4 psi	30	Partial collapse of roofs/walls
272 - 680 mbar 4 - 10 psi	60	Partial building destruction
680+ mbar 10+ psi	100	Total building destruction and fatalities

Now consider the consequences of a strike on water by 2017 PDC along the corridor that stretches from Japan, far out into the Pacific. From results discussed at the AGT workshop [5] in August 2016, it was concluded for both airbursts and monolithic impacts from asteroids of size less than 250 m, that most damage to coastal populations is limited to impacts close to the shore, where direct blast damage is added to inundation. This result is based on the risk from the ensemble, but it should hold true for individual cases, for impacts far from shore. The risk from such near-shore impacts may be important when considering specific cases. The low values of Affected Population created by an ocean impact by 2017 PDC across the Pacific shown in Figure 2 is consistent with the conclusions from the AGT Workshop[5].

This initial risk assessment of the threat posed by the hypothetical asteroid 2017 PDC depicted in Figure 2 is greatly compromised by lack of information. The impact corridor is extremely long, and it remains long for years, even as more ground-based observations are made. The asteroid's physical characteristics represent those from the ensemble, whereas the risk assessment should be based on those for 2017 PDC. ATAP would want decision makers have the best possible and timely information for their deliberations for taking mitigation action. To this end, the benefits to reduction of uncertainty in risk assessments that could be realized from a characterization mission to PDC 2017 are described below. Options would be either a flyby or a rendezvous mission. Note that a rendezvous mission provides the most powerful reduction of uncertainty because the observations can be made over a long period of time.

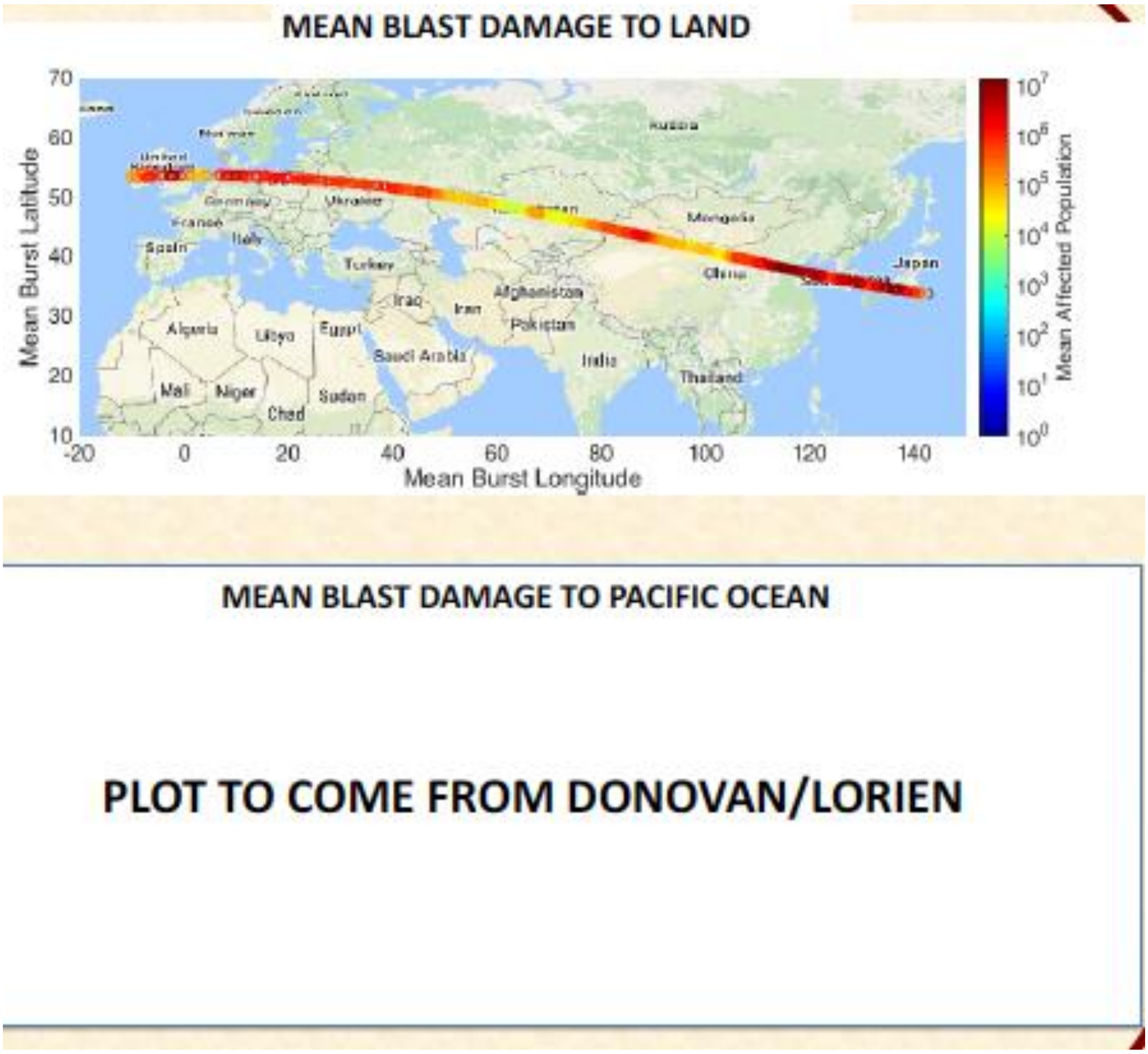

Figure 2. *Prediction for Affected Population as a function of location for asteroid 2017 PDC, based on information available on May 15, 2017.* https://cneos.jpl.nasa.gov/pd/cs/pdc17/. ***Waiting for Pacific Ocean results from Donvan and Lorien.***

DATA FROM RENDEZVOUS MISSIONS COULD PROVIDE IMPROVED RISK ASSESSMENTS

Since 2017 PDC's impact is ten years in the future, there is time for the international planetary defense community to conduct a rendezvous mission, possibly concurrently with, or followed by, a deflection mission similar to the Asteroid Impact and Deflection Assessment (AIDA) mission [6,7].

Data from a rendezvous mission to 2017 PDC, combined with ATAP's PAIR capability would enable the best-case assessment of risk because: (a) Long term optical navigation data from the rendezvous spacecraft, combined with ground observations not described at https://cneos.jpl.nasa.gov/pd/cs/pdc17/ would allow powerful improvement in knowledge of the asteroid's orbit. The improved orbit would dramatically reduce the length of the impact length to probably less than 100 km. (b) In-situ optical measurements would provide information about 2017 PDC's shape, size, spin rate and spin orientation* as well as details of the surface regolith, and (c) **t**he effective mass of the asteroid could be determined from the orbit of the rendezvous space craft while (d) radar tomography [8] would enable determination of the structure of the asteroid, including boulders in the sub surface to depths of tens of meters and large fragments throughout the deep interior, answering the question: Is 2017 PDC a heterogeneous "rubble pile", intact monolith or something in between?

With this information, it would be possible to precisely define the initial conditions of 2017 PDC at its entry point into the Earth's atmosphere at 100 km: Time, location, entry angle, speed and a rather complete description of its physical characteristics including the asteroid's interior structure and its orientation with respect to the objects flight path if it was a rubble pile.

**Given precise information of 2017 PDC's spin rate and spin axis from a rendezvous mission, modified CNEOS software would enable the prediction of the orientation of the structural fragments within the asteroid with respect to its flight path at the 100 km pierce point to within a degree or so. The importance of having this information to simulate 2017 PDC's atmospheric entry and breakup is described below.*

HOW A RENDEZVOUS MISSION COULD DETERMINE THE INTERIOR STRUCTURE OF THE HYPOTHETICAL ASTEROID 2017 PDC

How? Radar sounding is the only technique capable of characterizing the internal structure and heterogeneity of an asteroid [8]. Performance is determined by the choice of the frequency and bandwidth of the transmitted radio signal: Frequency drives the penetration with lower attenuation at the lowest frequencies. Bandwidth drives resolution while the bandwidth is necessarily lower than the highest frequency. Estimated values of resolution quoted below assume a radar instrument as proposed for FANTINA (MarcoPoloR, AIDA/AIM-MASCOT2) [7]. The resolution of the monostatic radar (200-800 MHz) would be about 1 m. The resolution for the bistatic radar (30-70 MHz) would be in the range of 10 - 15 m. Density of fragments is deduced indirectly from a parameter called epsilon. See Figure 3 and the following discussion for a description of the instrumentation.

Deep Interior of objects to size to ~290 m with resolution of fragments of 10 - 15 m. Measurement of the deep interior structure requires low-frequency radar to reduce the dielectric scattering losses and penetrate through the complete body. Radar wave penetration delay and received power are related to the composition and microporosity while small scale heterogeneities are related to scattering losses. Spatial variation of the signal and multiple paths provide information on the presence of heterogeneity (variations in composition) or porosity, layers, voids or large blocks. Partial coverage provides "cuts" of the body while dense coverage enables tomography. Two Instrument concepts for radar measurements are shown in Figure 3: (1) Monostatic radar like MARSIS on board Mars Express ESA [9] that analyzes radar waves transmitted by the orbiter and received after reflection by the asteroid, its surface and internal structures. (2) Bistatic radar like CONSERT on Philae and Rosetta ESA, DLR, CNES [10] that analyzes radar waves transmitted through the body between the lander and orbiter**.**

Regolith and Shallow Subsurface to ~ 10 m depth with ~ 1 m resolution.
These measurements can be achieved with a monostatic radar with a 200 - 800 MHz frequency range.

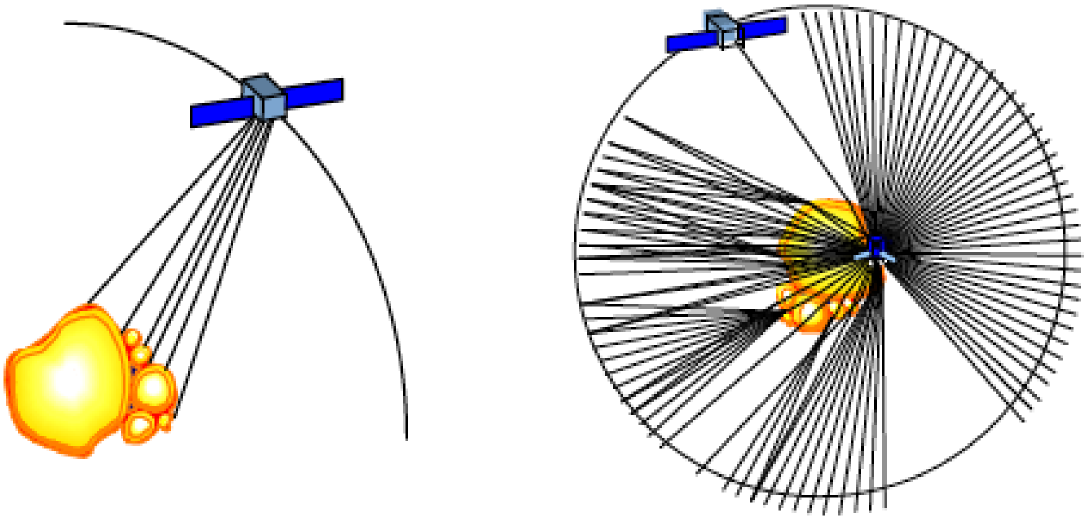

Figure 3. *Radar sounding techniques to measure the sub and interior structure of asteroids: Monostatic (left) and Bistatic (right) [8].*

The paper by Michel, *et al*., [7] describes what could be learned from radar sounding to determine the structure of small asteroids. Plans for the currently (May 2017) unfunded ESA Asteroid Impact Mission (AIM) included the use of two radar instruments to collect direct information on the subsurface and interior structure of the ~160 m secondary in the Didymos binary asteroid system. The AIM mission was to be a part of the combined NASA-ESA AIDA mission [6]. High-frequency radar would sound the surface of the secondary (referred to as “Didymoon”) at depths to the first tens of meters at 1 m resolution to detect potential layering and embedded large rocks. A low frequency radar would be used to probe the deep interior of Didymoon to probe its structural homogeneity and to discriminate monolithic versus aggregate internal structure and to characterize the size distribution of constitutive blocks.

FRAGMENT CLOUD MODEL – RUBBLE PILE

An emerging ATAP model [4] being presented at PDC 2017 extends the current PAIR capability as it will include simulations of the entry and breakup of “rubble piles”- it is called the FCM Rubble Pile Model. Rubble piles are considered to be a heterogeneous ensemble of fragments varying in size, density and strength held together by gravity, or perhaps by other cohesive forces [11]. Figure 4, adopted from [4] depicts the FCM Rubble Pile approach. Time constraints do not allow presentation of 2017 PDC's entry and breakup, modelled as rubble pile at this year's conference. However, it is possible to describe how data from in-situ and ground observations, along with knowledge from the literature could be used as input to the new PAIR capability, and to describe how the approach could minimize uncertainty in the assessment of the risk created by the impact of 2017 PDC.

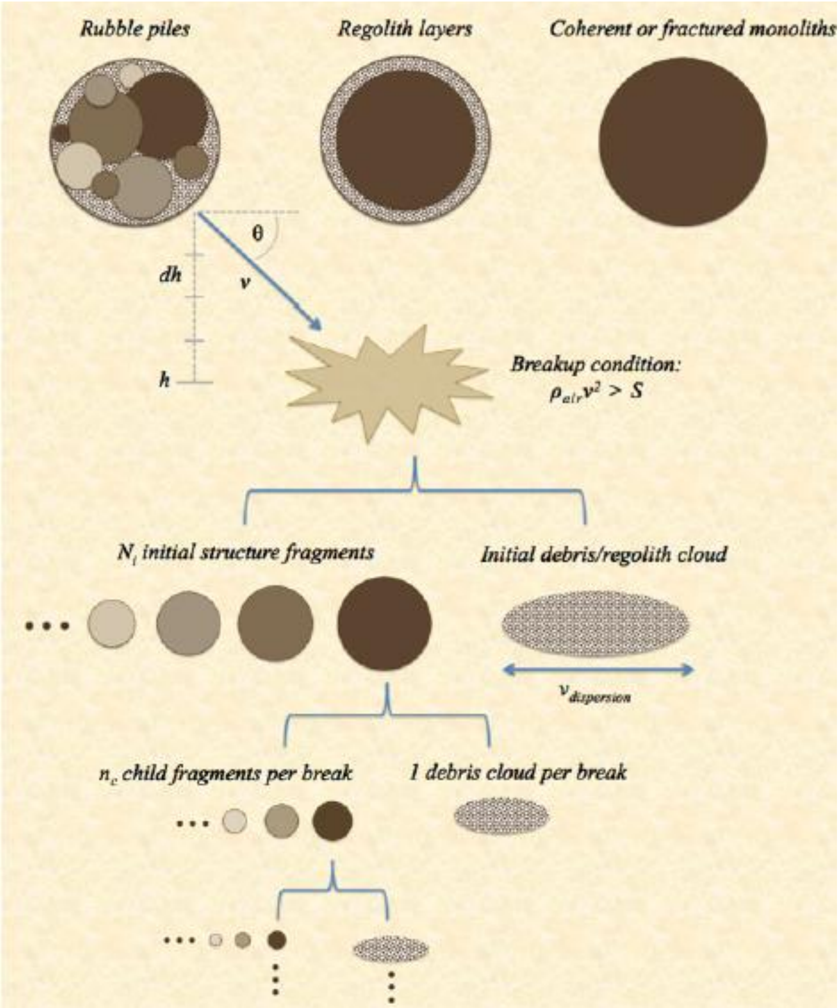

Figure 4. *Schematic of the Fragment Cloud Model Rubble Pile Model. See [4] for more information.*

2017 PDC's Impact: Where and When?

Given data about 2017 PDC from a rendezvous mission, ground observations of the asteroid and general knowledge from the literature, the set up for the FCM Rubble Pile simulation with respect to determining the location and timing of the impact would be: (1) define the location of the pierce point at 100 km and the initial entry velocity vector (speed *v*, entry angle (θ) and the heading). As discussed above, knowledge regarding the asteroid's orbit from the rendezvous mission, combined with data from ground observations will enable location of the atmospheric pierce point within 100 km or less. (2) The PAIR capability would be exercised to simulate the entry and breakup of the asteroid, appropriate to one of the three structural models shown in Figure 4. Solutions for the entry and breakup, specific to 2017 PDC from the atmospheric entry pierce point to the surface enables pin-pointing the location of the impact location along the very long corridor shown in Figures 1 and 2. Since the orbit is well known, the timing of the impact should be readily available. This answers the first order question, where will the devastation occur, and when?

Level of Devastation Created by 2017 PDC's Impact

If the rendezvous mission established 2017 PDC to be a monolith, the existing PAIR capability would suffice to model the asteroid's entry, breakup and surface damage as described in [2] where the FCM simulations would be based on its specific physical characteristics.

If the rendezvous mission determined 2017 PDC to be a rubble pile the analysis would be more complicated. The PAIR assessment would start by defining the location, shape, size, density and materials strength S_i associated with the N_i initial structural fragments. As discussed above, regolith and boulders in the sub surface would be defined by monostatic radar measurement to depths of ~ tens of meters at a resolution of meter or so. Structure throughout the deep interior would be defined by bistatic measurements to within 10 - 15 m and the density of the fragments could be specified as described above. Information from the literature would provide the materials strength of the fragments, inferred from their size and density. The next step in the set up would be to orient the ensemble of fragments comprising 2017 PDC with respect to the initial flight path at the 100 km atmospheric pierce point. The importance of the orientation can be visualized by inspection of rubble pile schematic in Figure 4. If the rubble pile 2017 PDC entered in an orientation rotated clockwise about 45 degrees in plane of Figure 4 from that shown, the largest, dark (dense) fragment would strike the atmosphere first and the subsequent break up probably would be much different than that for the orientation as shown, where two smaller, less dense fragments would strike the atmosphere first. The initial breakup of a rubble pile will result from aerodynamic forces that are created by shock heated gases flowing over and between the fragments.

Given this set up of initial conditions, the FCM Rubble Pile simulation would be run, with breakup of the initial configuration of the fragments and their "children" in accordance with the condition at the altitude h where the product of the free stream air density and the velocity exceeds the materials strength, i.e., $\rho_i v^2 > S_i$. The variability of the strength with size of the "child" fragments (stronger at smaller sizes), that defines the altitude of the fracture of the "children" is accounted for using the Weibull approach, as described in [2]. The question now is what information of significant importance relevant to the level of devastation of 2017 PDC would come from FCM Rubble Pile simulations of its entry and breakup? The answer is that, similar to the FCM modeling, the results would provide details of the deposition of energy into the atmosphere along the entry trajectory and subsequent propagation of the disturbance that result in surface hazards: overpressures, winds and thermal exposure. While results for the FCM Rubble pile model are not yet available for 2017 PDC, results from existing FCM simulations can help understand the relation between level of hazards and the altitude of peak Energy Deposition that will be provided by the new PAIR capability. This understanding comes from Figure 5, and the associated discussion, adopted from [2] and another ATAP presentation [12] at PDC 2017. As pointed out by those authors, FCM simulations, and likewise FCM

Rubble Pile simulations must account for the dispersal of fragments in order to produce realistic energy deposition profiles. They are quantified [12] by the empirical relation $vdisp = \frac{\sqrt{Cdisp\rho A}}{\rho m}$ where ρ_A air is the free stream air density and v_{disp} is the lateral sperad velocity. Rubble pile asteroids will airburst, and C_{disp} strongly influluences the altitude of the energy deposition as shown in Figure 5, adopted from [12] for a 50 m airbursting asteroid.

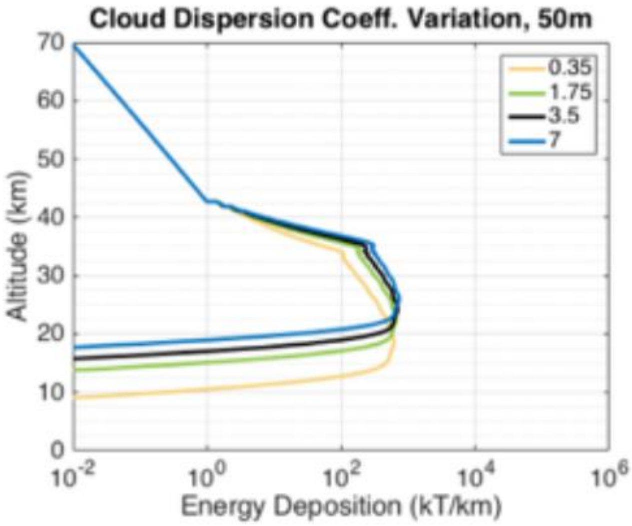

Figure 5. *FCM model of the variation of the height of peak Energy Deposition for a 50m airbursting asteroid as a function of altitude corresponding to values of the lateral dispersion coefficient C_{disp} ranging from 0.35 to 7. Figure adopted from [12].*

As can be seen, the variation in the altitude of peak Energy Deposition is from about 25km to 18km over a range of values for C_{disp} from 0.35 to 7, respectively. The variation in altitude is important in the resulting prediction of surface devastation. For example [2,12] the area of overpressures roughly doubles as the altitude of peak energy deposition is reduced from 25 to 18 km. At "ground zero" thermal radiation varies inversely with the square of altitude, *h.* From this example for a 50 m rubble pile asteroid, it is seen that variation in the altitude of peak energy deposition can result in increases by factors of about two for both the area of surface overpressures and thermal exposure. Each of them would result in significant increases in the level of Affected Population. This information for a 50 m asteroid illustrates how important it is to to know for risk assessments of 2017 PDC, the details of its sub and interior structure, how the constitutive fragments break up and how the "children" disperse laterally. This is because of their influence the altitude of peak energy deposition and the resulting surface damage. This knowledge is of great importance for determining the magnitude of the Affected Population on land impacts of 2017 PDC pin-pointed location along the impact corridor (See Figure 2). As stated above, sub and interior structure of asteroids like 2017 PDC, can only be determined by radar sounding via a rendezvous mission [8].

It is noted that care should be undertaken for the assessment of Affected Population that could happen on land impacts. If 2017 PDC was a rubble pile, it could quickly evolve into several objects reacting to aerodynamic forces, flying independently with larger ones possibly creating dispersed surface craters. On the other hand, depending on the initial orientation, some of the fragments could be captured in the wake of the leading body, staying there until striking the surface. This would lead to a more compact area of cratering, possibly similar to that caused by a coherent or a fractured monolith. Note that ATAP is conducting collaborative research with DLR Cologne on the subject of multi-body hypersonic aerodynamics relevant to this topic, and initial results [12] will be presented at PDC 2012. Dispersion of landed fragments of tens of km could be very important in evaluating levels of affected population along an impact corridor on land. For example, the largest meteorite from Chelyabinsk (~ 600 kg) fell in Lake Chebarkul, 78 km away from the damage that occurred within the city [131]. Damage by impacts could be very different for cases with and without crater dispersions at narrow boundaries between cities and unpopulated areas or at coast lines. The other extreme would be a strong monolith that strikes the surface after only undergoing surface ablation during entry.

If a rendezvous mission could establish the orbit and physical characteristic of a threat like 2017 PDC to provide high confidence by the CNEOS that the strike would happen in the Pacific, far from populated coastlines and the ATAP predicted the resulting Affected Population to be small, it seems that decision makers would have sufficient information to evaluate if “taking the hit” in the Pacific ocean could be a viable option for 2017 PDC across its ranges in size (160 – 290 m). ATAP would conduct extensive simulations for expected damage with their PAIR capability accounting for water depths and bathymetry in the area of the ocean strike. This work would include their own hydrocode simulations that would be compared to that from the FCM Rubble Pile based risk assessment and to those involving hydrocode based simulations by other groups from the DoE tri-labs.

The intent of these cases for 2017 PDC is to illustrate how information from a rendezvous mission could be combined with that from ground observation and data from the literature could be used to provide optimum or best-case assessments to decision makers who would be considering “taking the hit” that had a high probability to strike in the ocean far from shore, or in remote land areas versus approving an in-space mitigation. If the strike is predicted to be at a densely populated area, the best-case risk assessment will provide a good idea of the expected levels of the Affected Population. Finally, at the risk of stating the obvious, two things are noted that if “taking the hit” is an accepted solution that would be good: (1) It would eliminate the risk that the post mitigation 2017 PDC could make matters worse, owing to uncertainty in the outcome of the in-space mitigation and (2) 2017 PDC or its residual fragments from a mitigation exercise would be completely eliminated from the list of potentially hazardous asteroids. Indeed that would be a good thing for future generations of planetary defenders.

CONCLUSION

Based on early information on the hypothetical strike of 2017 PDC provided by the JPL CNEOS, an initial risk assessment was presented using ATAPs risk assessment capability. Owing to lack of information, the initial assessment is of high uncertainty with respect to both the location and magnitude of the inflicted damage. A rendezvous mission would dramatically improve the prediction of the strike location as well as information regarding the physical characteristics of the hypothetical asteroid 2017 PDC. A brief discussion of the methodology to determine physical characteristics from a rendezvous mission, including sub surface and the deep interior structure of an asteroid by radar mapping was provided. Also presented was a description of how ATAP's PAIR capability will include emerging FCM Rubble Pile modeling, and how data from a rendezvous mission would be used for risk assessments of asteroids like 2017 PDC. Because of the benefits to reducing uncertainty in risk, it becomes clear that a rendezvous mission followed by, or concurrently with, a mitigation action should be considered by decision makers in the event that a real threat, similar to 2017 PDC materializes.

FUTURE WORK

Clearly, the emerging Fragment Cloud Model (FCM) Rubble Pile capability described herein using data from rendezvous missions and ground observations can enable the Asteroid Threat Assessment Project's (ATAP's) ability to minimize uncertainties in assessments of threats from potential impacts of Near Earth Asteroids. As was done for the development of the existing FCM capability, sensitivity studies with the model should be conducted to prioritize how the project should conduct inclusion of associated of detailed physics based models into the PAIR capability, focus its ground testing and continue its measurements of meteorite properties. Some aspects of the current paper are conjectural. After sensitivity studies are mature, the information and conclusions made herein should be updated and documented in a appropriate journal. After the work is peer reviewed and published, it should be made available to those in the community that are (or will be) empowered to decide upon mitigation of actual threats of impact to the Earth by natural objects.

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