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UNCERTAINTY EFFECTS FROM AN ASTEROID RISK ASSESSMENT PERSPECTIVE FOR THE PDC25 IMPACT SCENARIO

Ashley Coates[1], Lorien Wheeler[2], and Jessie Dotson[3]
[1][2][3]*NASA Ames Research Center, MS 258-5, Moffett Field, CA 94035, USA,*
[1] *ashley.m.coates@nasa.gov, +1 (650) 604-5949,*
[2] *lorien.wheeler@nasa.gov,* [3] *jessie.dotson@nasa.gov*

ABSTRACT

Uncertainties in asteroid properties and entry parameters can lead to large ranges for asteroid damage and risk estimates. NASA's Probabilistic Asteroid Impact Risk (PAIR) model uses a Monte Carlo framework to assess possible damage across these potentially wide input ranges. In this work, a value-of-information study is conducted to determine the expected benefit to risk knowledge from asteroid property and entry parameter refinements resulting from additional information sources. The 2025 Planetary Defense Conference hypothetical asteroid impact exercise is used as a case study. The study found that for every 100% asteroid property range refinement, ~70% damage radius range refinement was observed meaning, for example, for every factor of two reduction in the range of possible asteroid diameters, we obtain a factor of 1.7 reduction in the range of possible damage radii. For every 100% entry parameter range refinement, ~30% damage radius range refinement was observed. The roles reversed when looking at affected population. For every 100% asteroid property range refinement, ~30% affected population range refinement was observed. And finally, for every 100% entry parameter range refinement, ~65% affected population range refinement was observed. Overall, by 2028 in the PDC25 scenario, ~10-20% output refinement would be forfeited by forgoing asteroid property refinements from the flyby mission and ~65-75% would be forfeited by forgoing both JWST and flyby refinements. Results provide valuable context for decision makers when faced with choosing how to act.

Keywords: asteroid, impact risk, modeling uncertainty

INTRODUCTION

A big challenge in asteroid impact risk assessment is the large uncertainties involved, particularly early on when there is limited data. Limited observational data leads to uncertainties in asteroid properties, orbital uncertainties affect the impact location, and the entry and damage models all have some inherent modeling uncertainty. Combining these sources of uncertainty in an asteroid impact assessment results in wide ranges for damage and risk estimates. Modeling uncertainty, along with uncertainty from properties and parameters that we can't measure, will remain. However, there are asteroid properties and entry parameters that can be refined with additional observations. The value of potential refinements to these properties and parameters in terms of overall risk knowledge will be discussed in this work.

The effects of uncertainty on hazard and risk calculations are highlighted by the ranges of results in the 2025 Planetary Defense Conference (PDC) hypothetical impact exercise scenario where output ranges can span multiple orders of magnitude at some points along the timeline (CNEOS Hypothetical Impact Scenario). In this study, we use PDC25 results generated using the NASA-developed Probabilistic Asteroid Impact Risk (PAIR) model (Mathias et al. 2017, Wheeler et al. 2024) as a case study to evaluate the expected benefit of additional sources of information. Corresponding to the PDC25 scenario, information sources in this study include hypothetical ground-based observations, James Webb Space Telescope (JWST) observations, and flyby reconnaissance mission observations across several time epochs. Understanding the expected benefit to our risk knowledge from different actions will provide valuable context for decision makers when faced with choosing when and how to act.

VALUE OF INFORMATION STUDY

In this section we describe the value of information study process, including the sources of additional information considered, parameters of interest, and how we quantified uncertainty for the purposes of this study.

Information Sources

Value-of-information studies in general aim to estimate the expected benefit from getting more information. In this study, we are specifically assessing how additional sources of asteroid property and entry parameter information – the inputs to PAIR – add to our overall risk knowledge. Based on the PDC25 scenario, sources of information include ground-based, James Webb Space Telescope (JWST), and flyby reconnaissance mission observations. This results in three asteroid property sets and two entry parameter sets, all of which are described in Table 1 (CNEOS Hypothetical Impact Scenario).

Table 1: Asteroid property and entry parameter sets used in combination as inputs to PAIR. Sets are based on the PDC25 scenario

Asteroid Properties	Set 0	Initial ground-based observations estimated size based on brightness
	Set 1	JWST refined diameter estimates and identified type S taxonomy
	Set 2	Flyby obtained direct size measurement and confirmed taxonomy
Entry Parameters	Set 1	Ongoing astrometric observations through August 2024 resulted in an impact corridor spanning Antarctica, the South Atlantic, Africa, the Mediterranean, and Eastern Europe
	Set 2	Ongoing astrometric observations and flyby orbital tracking in April 2028 refined the impact corridor to span Angola and the Democratic Republic of the Congo

Together, these inputs combine into three main epochs, of which the latter two directly match the PDC25 scenario epochs. Epoch 0 is a baseline epoch using Asteroid Set 0 and Entry Set 1, corresponding on the scenario timeline to just before JWST observations were obtained. Epoch 1 uses Asteroid and Entry Set 1, representative of just after JWST observations occurred. Epoch 2 falls just after the flyby mission in the timeline and uses Asteroid and Entry Set 2. Two additional “what if” epochs are considered to evaluate the potential changes in April 2028 risk knowledge that would result from forgoing property updates from the flyby mission or both the flyby mission and JWST. Because entry parameters will continue to be updated by ongoing astrometric observations regardless of whether JWST or flyby observations occur, we focus on the loss of asteroid property updates in this part of the study. The case with no flyby mission uses Asteroid Set 1 and Entry Set 2, and the case with no flyby mission or JWST observations uses Asteroid Set 0 and Entry Set 2. All combinations are summarized in Table 2. PAIR model results were generated for each of these five epochs using 5000 property samples and 5000 entry samples as inputs, resulting in 25 million cases per epoch.

Table 2: Asteroid property and entry parameter combinations for five epochs of interest. Epoch 1 and Epoch 2 directly match the PDC25 hypothetical scenario epochs

	Epoch 0	Epoch 1	Epoch 2	“What if” Yes JWST, No Flyby	“What if” No JWST, No Flyby
Asteroid Properties	Set 0	Set 1	Set 2	Set 1	Set 0
Entry Parameters	Set 1	Set 1	Set 2	Set 2	Set 2

Outputs of Interest

The PAIR model outputs a variety of information about types of damage, damage sizes, the number of affected people, the likelihood that a location will be impacted, etc. This study focuses on two parameters of interest – local damage radius and affected population. Based on the PAIR model results, the local damage in this scenario is dominated by blast overpressure, so value-of-information determinations are based on the blast overpressure damage models. The blast damage model in PAIR is based on Height of Burst (HOB) maps, the inputs of which are energy and burst altitude (Glasstone and Dolan 1977, Aftosmis et al. 2019, Wheeler et al. 2021). These are not direct inputs to PAIR. Instead, energy is calculated from diameter, density, and velocity, while the burst altitude is determined by propagating the object through the atmospheric entry and break up model (Wheeler et al. 2017). That model requires information about both the asteroid properties and the entry parameters, along with additional modeling parameters representing uncertainties in ablation and breakup rates. Damage radius is determined at four severity levels: serious (1 psi), severe (2 psi), critical (4 psi), and unsurvivable (10 psi) (Wheeler et al. 2024). Affected population calculations depend on damage radius at the four severity levels and the population within the area. The population density in an area depends on the location. Scaling factors of 10%, 30%, 60%, and 100% are used to determine the total affected population in the serious, severe, critical, and unsurvivable damage severity regions, respectively (Wheeler et al. 2024).

For the PDC25 scenario used in this work, the dominant PAIR inputs for the damage radius calculation are diameter (asteroid property affecting energy) and entry angle (entry parameter affecting burst altitude). The dominant inputs for the affected people calculation are diameter and entry latitude (entry parameter affecting population density). Latitude represents the location of the impact region along the potential impact corridor, which is mostly vertical across the populated damage region. Other asteroid property and entry parameter inputs (such as density, strength, and entry modeling parameters) play a role but are secondary to the effects of the dominant inputs listed either because they are not as influential or there was limited refinement from the added information sources. Modeling parameters were also excluded as dominant inputs since they received no refinement from observable properties.

Uncertainty Calculations

To quantify the expected benefit from additional information, we track changes in the overall size of the uncertainty range (min to max) in the inputs (Equation 1), the intermediate calculated values, and the outputs of interest (Equation 2). Minimum and maximum uncertainty range values represent the smallest and largest values modeled for this scenario, not the absolute theoretical limits on any one parameter. Working from inputs to outputs and among different epochs, we calculate the expected refinement in output from either an asteroid property or entry parameter update (Equation 3). As will be seen in the results, comparing the different epochs highlights the benefits of each of the additional information sources.

$$r_i = \frac{max_b - min_b}{max_a - min_a} - 1 \qquad [1]$$

$$r_o = \frac{max_b - min_b}{max_a - min_a} - 1 \qquad [2]$$

$$expected\ benefit = \frac{r_0}{r_i} \qquad [3]$$

RESULTS

This section highlights the results of the value-of-information study. We present comparisons of inputs, calculated inputs, and our outputs of interest for each epoch. We also include an analysis of the expected benefit to our risk knowledge from asteroid property and entry parameter refinements, highlighting what would be lost by forgoing a given set of information.

Inputs

Uncertainty ranges (min, max) for asteroid properties and entry parameters are included in Table 3 and
Table 4, respectively, for each of the three epochs. Epoch 0 to Epoch 1 only benefits from asteroid property refinements coming from JWST. Entry parameters are not refined between these two epochs because they are essentially at the same point on

the timeline, one just before JWST and one just after JWST observations. Minor variations in entry parameters are from sampling a different set of 5000 points from the same distribution. Epoch 1 to Epoch 2 benefits from both asteroid property and entry parameter updates from a combination of the flyby and continued ground-based observations.

Table 3: Asteroid property ranges modeled at each epoch

		Asteroid Properties	
	Case	Diameter [m]	Density [kg/m^3]
Min	Epoch 0	42	800
	Epoch 1	48	1206
	Epoch 2	141	1128
Max	Epoch 0	896	8263
	Epoch 1	278	3594
	Epoch 2	159	3705

Table 4: Entry parameter ranges modeled at each epoch

		Entry Parameters			
	Case	Entry Angle	Entry Latitude	Entry Longitude	Velocity [km/s]
Min	Epoch 0	1	-80	-144	14
	Epoch 1	1	-81	-145	14
	Epoch 2	67	-9	21	14
Max	Epoch 0	87	80	61	14
	Epoch 1	87	80	61	14
	Epoch 2	71	-4	22	14

Looking at the most influential property and parameter refinements, diameter saw a 73% reduction in range from Epoch 0 to Epoch 1, a 98% reduction from Epoch 0 to Epoch 2, and a 92% reduction from Epoch 1 to Epoch 2. Entry angle saw a 95% reduction and entry latitude saw a 97% reduction in range by Epoch 2. All three parameters were very well refined by the Epoch 2 analysis point. Other parameters, including entry longitude and velocity (well constrained from the beginning), were also very well refined by Epoch 2 (near 100%), although the refinements proved less influential on the outputs of interest for this scenario. Density saw about a 65% reduction in range from Epoch 0 to Epoch 2 but again was less dominant than other properties and parameters in terms of benefitting the outputs.

Calculated Inputs

As introduced in the Outputs of Interest section, the final outputs are not directly calculated from the asteroid property and entry parameter PAIR inputs. Instead, they are based on calculated inputs like energy, or outputs of a PAIR sub-model, like burst altitude which requires propagation through the entry and fragmentation model. Population density is based on impact location and the associated population in that area. Uncertainty ranges for each of these are provided in Table 5.

Table 5: Parameters of interest input ranges calculated for each epoch

Case		Energy [Mt TNT]	Burst Altitude [km]	Population Density [ppl/km^2]
Min	Epoch 0	1	0	0
	Epoch 1	3	0	0
	Epoch 2	45	1	10
Max	Epoch 0	21686	39	26188
	Epoch 1	716	35	6128
	Epoch 2	158	16	131

Starting with energy, a 97% reduction in range was observed from Epoch 0 to Epoch 1, 99% reduction from Epoch 0 to Epoch 2, and an 84% reduction from Epoch 1 to Epoch 2. Refinement in energy was largely driven by the diameter refinement given the D^3 term in the $E = \frac{1}{2}mv^2 = \frac{\pi}{12}\rho D^3 v^2$ energy calculation. Burst altitude only saw an 11% reduction in range from Epoch 0 to Epoch 1 in the absence of entry parameter refinement, a 62% refinement from Epoch 0 to Epoch 2, and a 57% reduction from Epoch 1 to Epoch 2. The improved refinement in estimated burst altitude between Epochs 1 and 2 was largely due to entry angle refinement. Population density was refined 77% from Epoch 0 to Epoch 1, ~100% from Epoch 0 to Epoch 2, and 98% from Epoch 1 to Epoch 2. Diameter largely contributed to refinement from Epoch 0 to 1, reducing the damage area, and impact location (latitude) contributed heavily between Epoch 1 and 2, with some additional contributions from diameter refinement.

Ranges for the two additional "what if" epochs were also calculated. For the Yes JWST/No Flyby epoch, energy ranged from 3 to 706 Mt TNT, burst altitude ranged from 0 to 25 km and population density ranged from 1 to 130 ppl/km^2. These ranges correspond to a 97%, 38%, and ~100% reduction in range from Epoch 0. The No JWST/No Flyby epoch ranged from 1 to 21,395 Mt TNT for energy, 0 to 24 km for burst altitude, and 1 to 130 ppl/km^2 for population density. Compared to Epoch 0, the energy range is reduced by 1%, burst altitude is reduced by 39%, and population density is reduced by ~100%.

Outputs

Uncertainty ranges and comparisons are visualized in a couple of different ways throughout the Outputs section of the Results. We provide a brief introduction here. Probability histograms show the probability that the damage radius or affected population values fall within a given bin range. Associated horizontal bar graphs flatten the histogram to better highlight the min and max values making up the uncertainty range, the median value (solid black vertical line) and the most likely range (dashed box) based on the 68% Highest Probability Density Interval (HPDI). Color coding remains consistent throughout with Epoch 0 in blue, Epoch 1 in orange, and Epoch 2 in green. The two additional cases are light green to represent that they occur at the same time on the timeline as Epoch 2. The outlines are either blue or orange to indicate the property information that is known.

Bringing everything together towards our outputs of interest, Figure 1 shows the probability that the serious damage radius is within a given bin, along with bar graphs that compare the ranges. As described above, the solid vertical lines represent the median value in the distribution and the dashed box represents the most likely range given by the 68% HPDI. The 47% reduction in range from Epoch 0 to Epoch 1 and the 66% reduction from Epoch 1 to Epoch 2 for a combined 82% reduction in range from Epoch 0 to Epoch 2 is largely a result of energy refinement tracing back to diameter refinement.

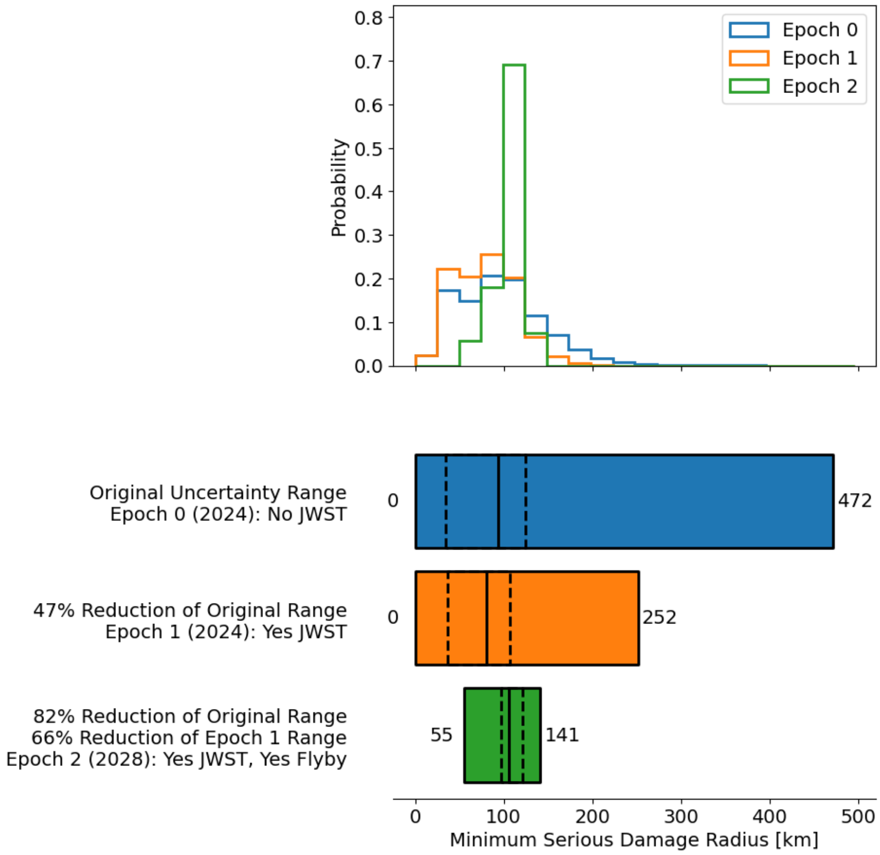

Figure 1: (Top) Histogram showing probability that the serious damage radius is within a given size range. (Bottom) Bar graphs comparing ranges between epochs. Solid vertical lines represent the median and the dashed box represents the most likely range

The damage radius results in Figure 1 only include results for the serious damage severity level; however, Table 6 lists the ranges for all damage severity levels. Listed in order from serious through unsurvivable, these values indicate a 47%, 31%, 28%, and 60% reduction in range from Epoch 0 to Epoch 1 and an 82%, 79%, 75%, and 77% reduction from Epoch 0 to Epoch 2.

Table 6: Damage radius ranges calculated at each epoch across all four damage severity levels

		Damage Radius [km] by Severity Level			
	Case	Serious	Severe	Critical	Unsurvivable
Min	Epoch 0	0	0	0	0
	Epoch 1	0	0	0	0
	Epoch 2	55	35	19	0
Max	Epoch 0	472	204	127	91
	Epoch 1	252	140	92	36
	Epoch 2	141	78	52	21

Additionally, we can consider what happens to damage radius estimates in our "what if" epochs. Figure 2 highlights serious damage radius results for the Yes JWST/No Flyby case where the flyby mission was omitted, but the JWST observations were included. This represents a scenario where a wait-and-see approach was taken following JWST. The 0 to 180 km range is a 62% reduction of Epoch 0 and falls between the Epoch 1 and Epoch 2 refinements. While asteroid property updates were omitted with elimination of the flyby, continued ground observations did provide entry property refinements. The refinement beyond the Epoch 1 range is largely due to entry angle refinements. In particular, the shallow entry angles were eliminated as Earth-impact location was refined, lowering the burst altitude. As the burst altitude was lowered, the highest energy cases were shifted farther away from the optimal burst altitude on the HOB map, reducing the damage radius and refining the range. See Wheeler et al. 2025 for further discussion on optimal burst altitude.

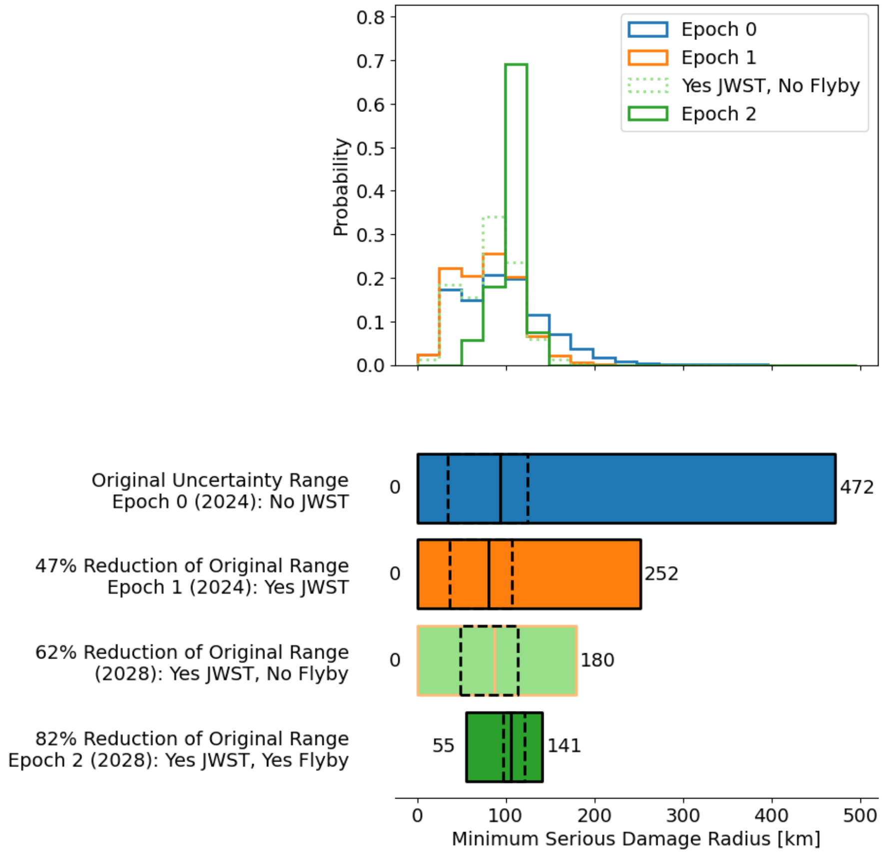

Figure 2: (Top) Histogram showing probability that the serious damage radius is within a given size range for the scenario where flyby is omitted. (Bottom) Bar graphs comparing ranges between epochs. Solid vertical lines represent the median and the dashed box represents the most likely range

The second "what if" epoch, No JWST/No Flyby, omitted property updates from both JWST and the flyby. This represents a wait-and-see approach from the start. A 39% reduction in range from Epoch 0 resulting in a range of 0 to 289 km is presented for the serious damage radius in Figure 3. Like the previous case, the continued entry parameter updates from ground observations refined the entry angle between Epoch 0 and the No JWST/No Flyby case, leading to reduced burst heights and points on the HOB map farther from optimal. Many of the larger energy cases moved away from airbursting scenarios and towards ground impacting scenarios with reduced damage radii.

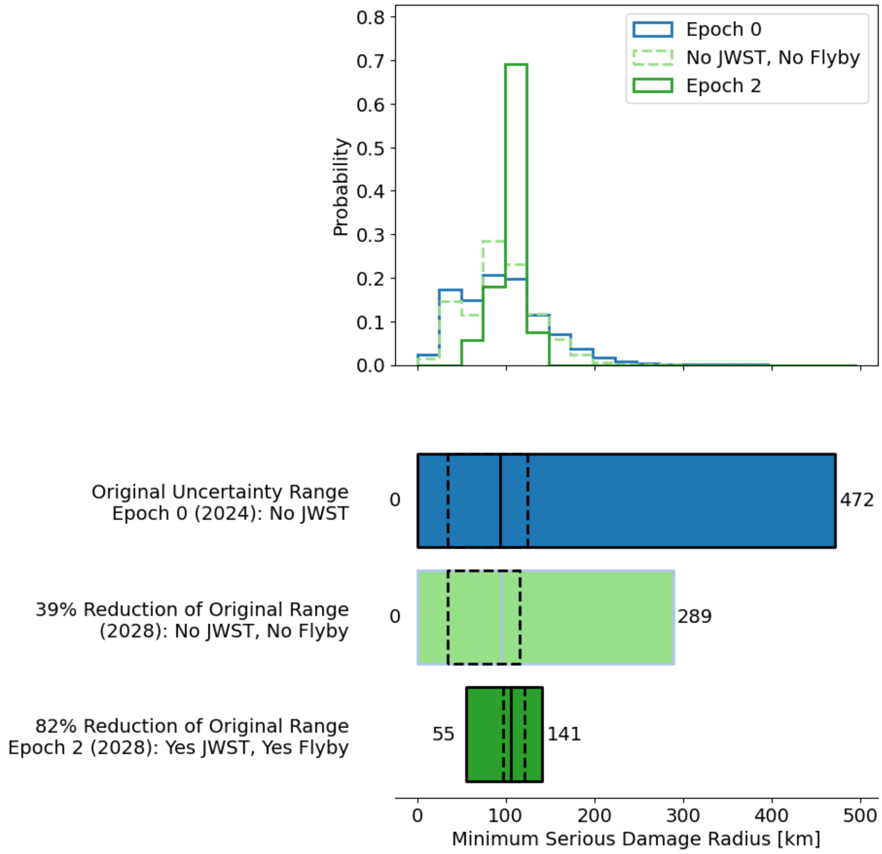

Figure 3: (Top) Histogram showing probability that the serious damage radius is within a given size range for the scenario where flyby and JWST are omitted. (Bottom) Bar graphs comparing ranges between epochs. Solid vertical lines represent the median and the dashed box represents the most likely range

For both "what if" epochs and across all severity levels, damage radius ranges are included in Table 7. Listed in order from serious through unsurvivable, these values indicate a 62%, 52%, 50%, and 65% reduction in range from Epoch 0 to Epoch Yes JWST/No Flyby and a 39%, 15%, 4%, and -12% reduction from Epoch 0 to Epoch No JWST/No Flyby. The unsurvivable level for the No JWST/No Flyby epoch increases.

Table 7: Damage radius ranges calculated for the "what if" scenarios across all four damage severity levels

Case		Damage Radius [km] by Severity Level			
		Serious	Severe	Critical	Unsurvivable
Min	Yes JWST, No Flyby	0	0	0	0
	No JWST, No Flyby	0	0	0	0
Max	Yes JWST, No Flyby	180	97	63	32
	No JWST, No Flyby	289	172	122	102

Moving on to our second output of interest, Figure 4 presents affected population histograms and bar graphs on a log scale, highlighting the uncertainty range progressions from Epoch 0 through Epochs 1 and 2. The 23% reduction in range from

Epoch 0 to Epoch 1 is driven by damage radius refinements resulting from energy range improvements following JWST diameter updates. Epoch 1 to Epoch 2 includes entry refinements which account for most of the 75% reduction in range. In particular, latitude refinement leading to a better understanding of population density at the impact location plays a big role. To a much lesser degree, damage radius refinements propagating from diameter refinements through energy also help refine the Epoch 2 range. Overall, an 81% reduction in range is observed between Epoch 0 and Epoch 2, primarily from a combination of diameter and latitude refinements from JWST, Flyby, and ground observations.

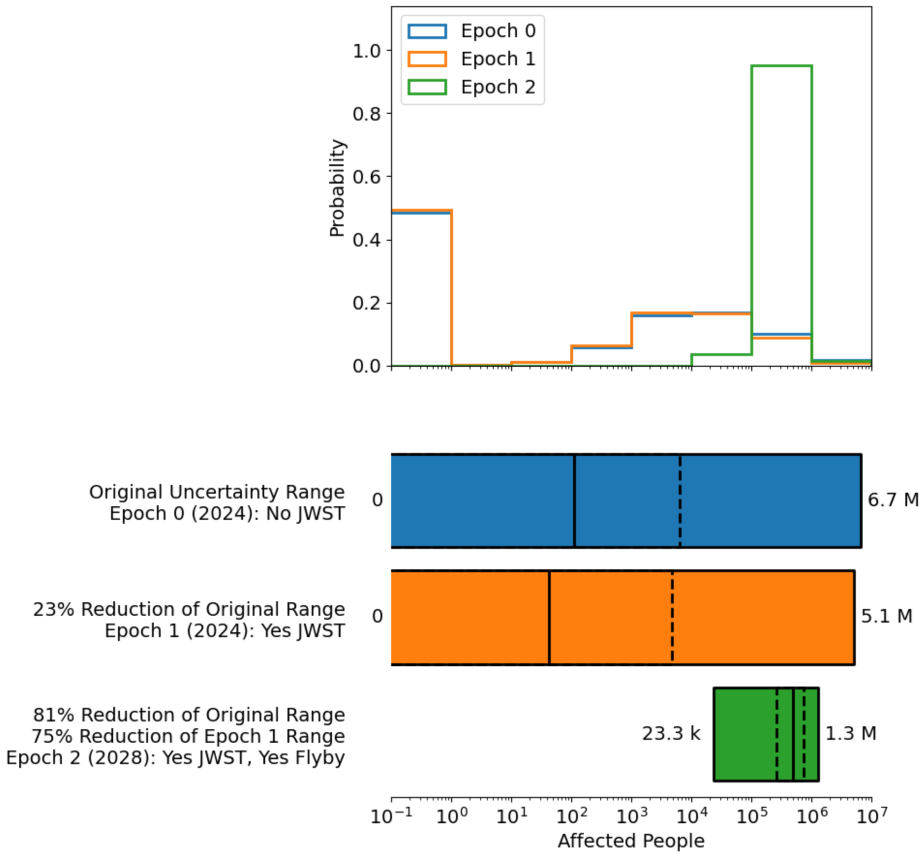

Figure 4: (Top) Histogram showing probability that affected population is within a given magnitude range. (Bottom) Bar graphs comparing ranges between epochs. Solid vertical lines represent the median and the dashed box represents the most likely range

Both of the “what if” epochs also leveraged latitude refinements updating population density ranges to refine the affected population range. Results for the Yes JWST/No Flyby epoch are presented in Figure 5 and show a reduction in range of 71% in comparison to Epoch 0. While the range minimum may still look like previous epochs, the median and most likely range show a distinct shift towards the Epoch 2 distribution. The most likely range extends to zero for Epoch 0 and Epoch 1, which gets cut off on the log scale axis.

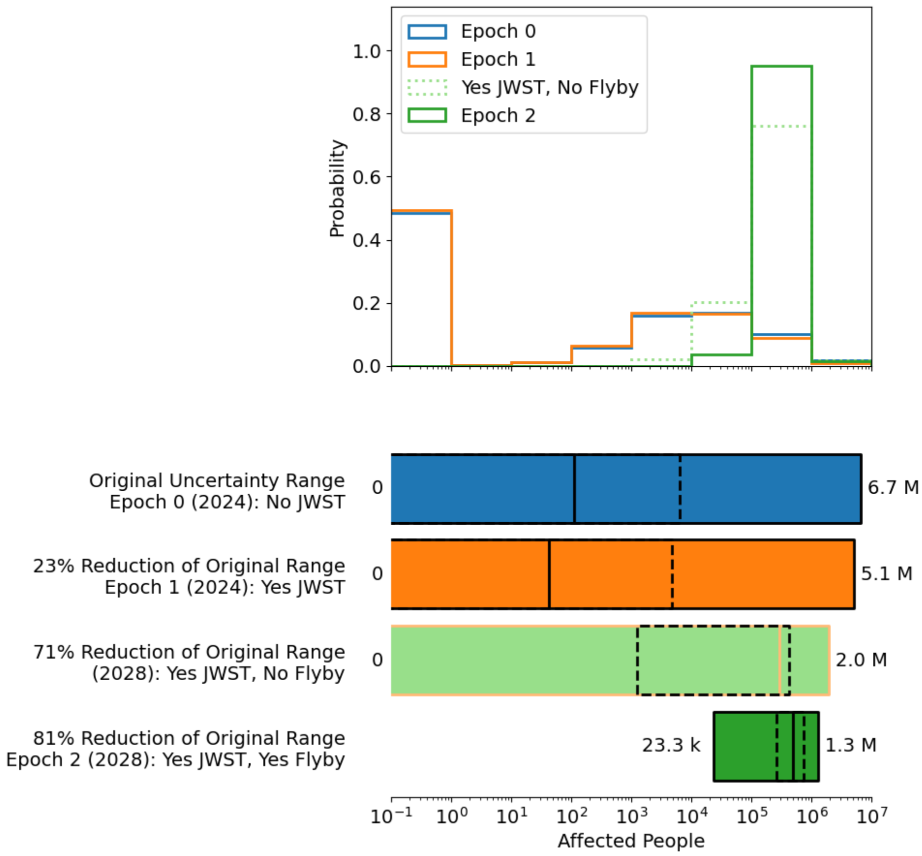

Figure 5: (Top) Histogram showing probability that affected population is within a given magnitude range for the scenario where flyby is omitted. (Bottom) Bar graphs comparing ranges between epochs. Solid vertical lines represent the median and the dashed box represents the most likely range

Leaving out the JWST observations, the No JWST/No Flyby results in Figure 6 show significantly less overall range refinement with just a 4% reduction from Epoch 0. The median and most likely values have again moved towards the Epoch 2 distribution, despite the overall range remaining seemingly unrefined on both ends. Higher energy, airbursting cases that remained in the distribution by omitting JWST information kept the upper end of the affected population range high.

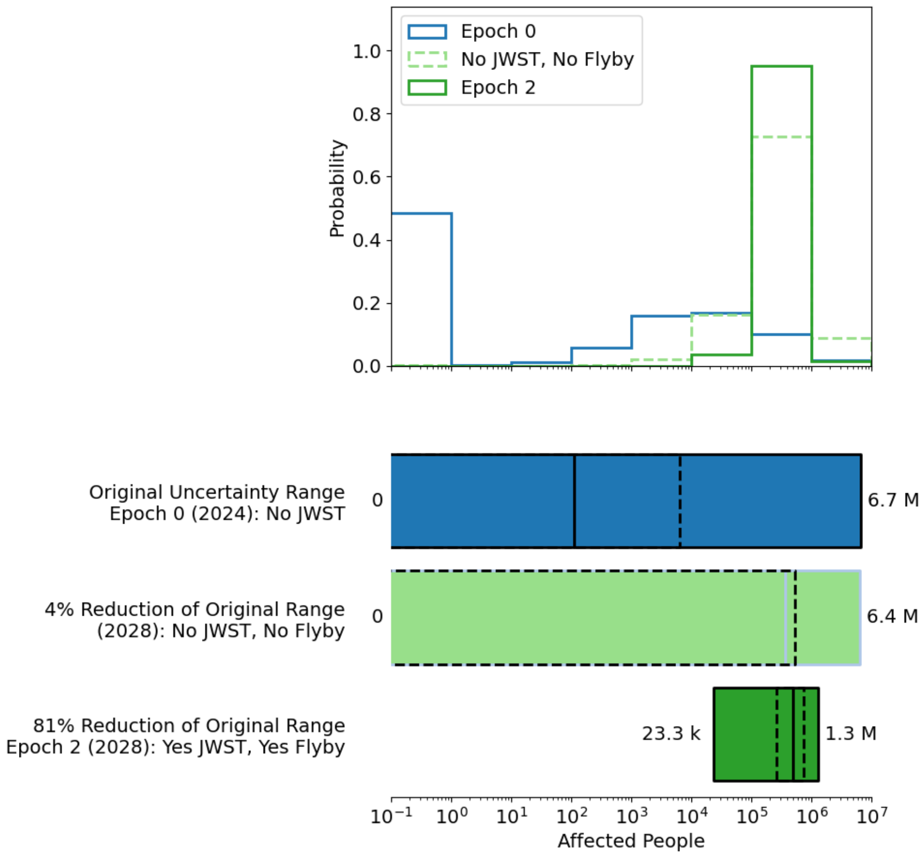

Figure 6: (Top) Histogram showing probability that affected population is within a given magnitude range for the scenario where flyby and JWST is omitted. (Bottom) Bar graphs comparing ranges between epochs. Solid vertical lines represent the median and the dashed box represents the most likely range

For completeness, the affected population ranges are included in Table 8 for the three main epochs as well as the two "what if" epochs.

Table 8: Affected population ranges calculated at each epoch and for the "what if" scenarios

Case		Affected Population [ppl]
Min	Epoch 0	0
	Epoch 1	0
	Epoch 2	23.3 k
	Yes JWST, No Flyby	0
	No JWST No Flyby	0
Max	Epoch 0	6.7 M
	Epoch 1	5.1 M
	Epoch 2	1.3 M
	Yes JWST, No Flyby	2.0 M
	No JWST, No Flyby	6.4 M

Expected Benefit

In the preceding sections we have laid out in detail input refinements from ground, JWST, and flyby observations along with the observed output refinements. These numbers allow calculation of the expected benefit of an information source, where expected benefit is defined in this context as the expected output refinement for a given property or parameter input refinement. Calculating these values for this scenario is step one in building a database of expected benefits that could be used in future scenarios to estimate refinements prior to running a case.

Table 9 and
Table 10 provide details on the expected benefit to damage radius knowledge from asteroid property and entry parameter updates, respectively. Diameter and entry angle were the dominant variables in terms of affecting damage radius uncertainty and are used in the calculations, but other properties are also changing. The top number in each set is the average value across all four damage severity levels and the remaining values are specific to the listed damage level. The overall calculations include the average followed in parentheses by the damage level specific values from serious through unsurvivable.

For every 100% diameter (asteroid property) refinement, 70% damage radius refinement is expected on average for the PDC25 scenario. Using Equations 1, 2, and 3, this means that if diameter was known exactly, the expected refinement in damage radius would be 70%. The “what if” case that omitted the flyby averaged a 57% return. Because there were no property updates after Epoch 1, only the Epoch 0 to 1 column contributed. The final “what if” case that eliminated both JWST and flyby had no property input refinements to base a calculation on.

Table 9: Expected benefit to damage radius knowledge from asteroid property refinement between each epoch and across all damage severity levels. Primary value is the average across damage levels

For every 100% Diameter (Asteroid Property) Refinement, Expect X% Damage Radius Output Refinement				
Severity Level	Epoch 0 to 1 (JWST)	Epoch 1 to 2 (Flyby)	Epoch 1 to Yes JWST/No Flyby	Epoch 0 to No JWST/No Flyby
Average	57	50	--	--
Serious	64	61	--	--
Severe	43	54	--	--
Critical	38	42	--	--
Unsurv.	83	42	--	--
			Overall Epoch 0 to 1 to 2	70 (78, 67, 57, 77)
			Overall Epoch 0 to 1 to Yes JWST, No Flyby	57 (64, 43, 38, 83)
			Overall Epoch 0 to No JWST, No Flyby	-- (--, --, --, --)

For every 100% entry angle (entry parameter) refinement, 27% damage radius refinement is expected on average for the PDC25 scenario. The “what if” case that omitted the flyby also averaged a 27% return. In both of those cases, there were no entry parameter updates between Epoch 0 and 1 so that column did not contribute to the calculation. The second “what if” case where both JWST and flyby were omitted only had entry parameter updates resulting in an averaged 12% return.

Table 10: Expected benefit to damage radius knowledge from entry parameter refinement between each epoch and across all damage severity levels. Primary value is the average across damage levels

For every 100% Entry Angle (Entry Parameter) Refinement, Expect X% Damage Radius Output Refinement				
Severity Level	Epoch 0 to 1 (2024-2024)	Epoch 1 to 2 (2024-2028)	Epoch 1 to Yes JWST/No Flyby (2024-2028)	Epoch 0 to No JWST/No Flyby (2024-2028)
Average	--	27	27	12
Serious	--	30	30	41
Severe	--	32	32	16
Critical	--	33	33	4
Unsurv.	--	12	12	-13
			Overall Epoch 0 to 1 to 2	27 (*30, 32, 33, 12*)
			Overall Epoch 0 to 1 to Yes JWST, No Flyby	27 (*30, 32, 33, 12*)
			Overall Epoch 0 to No JWST, No Flyby	12 (*41, 16, 4, -13*)

Table 11 and Table 12 provide similar information to the previous tables but for affected population. For affected population, diameter and latitude were the dominant input parameters in terms of affecting the output. For every 100% diameter (asteroid property) refinement, a 31% improvement in affected population is expected for the PDC25 scenario. The “what if” case omitting the flyby is expected to have a 32% return based solely on information from Epochs 0 to 1 since no further property updates are made. The second “what if” did not include any property updates.

Table 11: Expected benefit to affected population knowledge from asteroid property refinement between each epoch

For every 100% Diameter (Asteroid Property) Refinement, Expect X% Affected Population Output Refinement			
Epoch 0 to 1 (JWST)	Epoch 1 to 2 (Flyby)	Epoch 1 to Yes JWST/No Flyby	Epoch 0 to No JWST/No Flyby
32	10	--	--
		Overall Epoch 0 to 1 to 2	31
		Overall Epoch 0 to 1 to Yes JWST, No Flyby	32
		Overall Epoch 0 to No JWST, No Flyby	--

For every 100% impact location (entry parameter) refinement represented by latitude refinement for this vertical swath, a 64% refinement in affected population is expected for both the PDC25 case and the “what if” case where flyby was omitted. In both scenarios, calculations were only based on information post Epoch 1 since no entry parameter updates were made prior to that. And finally, the “what if” case that omitted JWST and flyby is expected to have only a 4% return. Larger airbursting cases that remain by omitting size refinements strongly influence this number.

Table 12: Expected benefit to affected population knowledge from entry parameter refinement between each epoch. Impact Location represented by latitude for vertical swath in this scenario

For every 100% Impact Location (Entry Parameter) Refinement, Expect X% Affected Population Output Refinement				
Epoch 0 to 1 (2024-2024)	Epoch 1 to 2 (2024-2028)	Epoch 1 to Yes JWST/No Flyby (2024-2028)	Epoch 0 to No JWST/No Flyby (2024-2028)	
--	64	64	4	
			Overall Epoch 0 to 1 to 2	64
			Overall Epoch 0 to 1 to Yes JWST, No Flyby	64
			Overall Epoch 0 to No JWST, No Flyby	4

The results so far have focused on what was gained at each step. The remaining results focus on what is forfeited by forgoing property updates from either flyby or both JWST and flyby. Calculations are based on the difference between the "what if" cases and Epoch 2, where the 'a' subscript in Equations 1 and 2 corresponds to the "what if" case and the 'b' subscript corresponds to Epoch 2. The "what if" cases and Epoch 2 have the same 2028 entry parameter information, so forfeits are a result of asteroid property differences. Starting with damage radius, the Yes JWST/No Flyby Epoch forfeits on average 52% damage radius output refinement for every 100% property input refinement forfeited by forgoing flyby. Damage severity level specific values are 57%, 60%, 52%, and 37% corresponding to serious through unsurvivable severity levels. Overall, an average of 21% damage radius refinement is forfeited for the Yes JWST/No Flyby Epoch or 20%, 26%, 24%, and 12% for individual damage levels. The second "what if" scenario where both JWST and flyby were omitted, forfeits on average 76% (72%, 77%, 75%, 81%) for every 100% property input refinement lost. Overall, an average of 66% (43%, 63%, 70%, 89%) damage radius refinement is forfeited for the No JWST/No Flyby Epoch.

Similar calculations for affected people show 37% output refinement is forfeited for every 100% property refinement lost from forgoing flyby with an overall affected population forfeit of 10% for the Yes JWST/No Flyby case. The No JWST/No Flyby case forfeits 82% output refinement for every 100% property refinement lost by forgoing JWST and flyby leading to an overall 77% forfeit in output refinement.

DISCUSSION

The results presented in this work are specific to the PDC25 hypothetical exercise scenario. This exercise sees JWST observations followed by a flyby mission. With this order of events, JWST observations look to be very beneficial in comparison to flyby. For the outputs of interest, ~65-75% was forfeited by omitting both property updates while only ~10-20% was forfeited from flyby. Ultimately, the results are about how the properties and parameters were refined, not what did the refining. In this case, JWST observations eliminated the largest object sizes, but had a flyby occurred without JWST, those size refinements likely would have resulted in a more drastic change than what was seen from flyby in this case. General trends, however, should extend beyond this scenario. As expected, asteroid property refinements show a larger expected benefit for damage radius and entry parameter refinements show a larger expected benefit for affected population calculations.

These results are also solely described in terms of the expected benefit to risk knowledge; however, there is value to the information beyond just risk within context of the larger problem. For example, the differences between 150 m, 300 m, and 900 m asteroids would be quite significant with respect to mitigation efforts and the potential mitigation options. Another example would be evacuation preparations should the asteroid hit Earth. It would presumably be easier to plan an evacuation of up to 1.3 M people from an area 55 to 141 km in radius than up to 6.4 M people from an area 0 to 289 km in radius.

FUTURE WORK

Future work for this study includes extending the analysis to more general results. This will include multiple size regimes (e.g. small, transitional, large) and entry conditions (e.g. impact points on land versus water, low populations, high populations), additional sources of information (e.g. ground-based and space-based telescopes, flyby, rendezvous), different orders of refinement, etc. with the goal of building a database to give decision makers an estimate of how risk knowledge would be improved with different sources of information. Taking into consideration timelines of when different options are available, along with other driving factors (cost, etc.), decision makers could use this resource to help determine what information they need or want to be able to make better-informed decisions regarding risk and perhaps more broadly.

The question remains for this scenario, would this understanding of the expected knowledge-gain have affected the decision making? Would a PDC25 decision maker have changed their response based on what was expected from JWST or flyby observations? Future work may provide opportunities to find out.

CONCLUSION

In this study, we assessed the value of different sources of information, looking at how input uncertainty affected the risk model results and the potential benefits to our risk knowledge of reducing those uncertainties. We specifically focused on diameter, entry angle, and latitude as input parameters and damage radius and affected population as output parameters, with input refinements coming from JWST and flyby observations to correspond with the PDC25 scenario.

For the PDC25 scenario, we found on average a 70% return on asteroid property refinements and a 27% return on entry parameter refinements for damage radius. Affected population showed the opposite trend with 31% return on asteroid property updates and a 64% return on entry parameter updates. The large diameter refinement in Epoch 1 eliminating the largest sized objects had a noticeable effect on the results, and omitting that refinement limited the expected benefit of additional entry parameter refinements. Further study on a wide variety of objects and scenarios is being continued to build more general conclusions about the expected benefit to risk knowledge from information sources and the reductions in uncertainty they provide. Moving forward, this work will help decision makers to understand the benefits of taking certain actions, or the losses from inaction, leading to better-informed decisions.

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