PDC 2023 simulated impact threat scenario
SMPAG(*) mission option analysis
And:
SMPAG recommendation

B. Barbee, D. Koschny

Apr 2023

(*)Space Mission Planning Advisory Group

IAWN notification update

SMPAG

EXERCISE EXERCISE EXERCISE

INTERNATIONAL ASTEROID WARNING NETWORK (IAWN)

POTENTIAL ASTEROID IMPACT NOTIFICATION – HYPOTHETICAL SIMULATION

Date: October 23, 2024

From: International Asteroid Warning Network

To: Chair, Space Mission Planning Advisory Group (SMPAG);
United Nations Office of Outer Space Affairs

Title: Potential for Impact of Near-Earth Asteroid 2023 PDC

Impact Probability:	100% as calculated by NASA JPL CNEOS and ESA NEOCC
Impact Date:	22 OCTOBER 2036
Impact Risk Corridor:	West Africa, extending from south of the Canary Islands southeast to the southern Congo River region
Approximate Size:	300 - 880 meters (970 - 2980 feet) determined from observations of brightness and color, and an assumed range of surface reflectivities
Expected Damage Level if Impact Occurs:	Uncertain – Regional to Continental. Energy release estimated to be 76 MT to 10 Gt.

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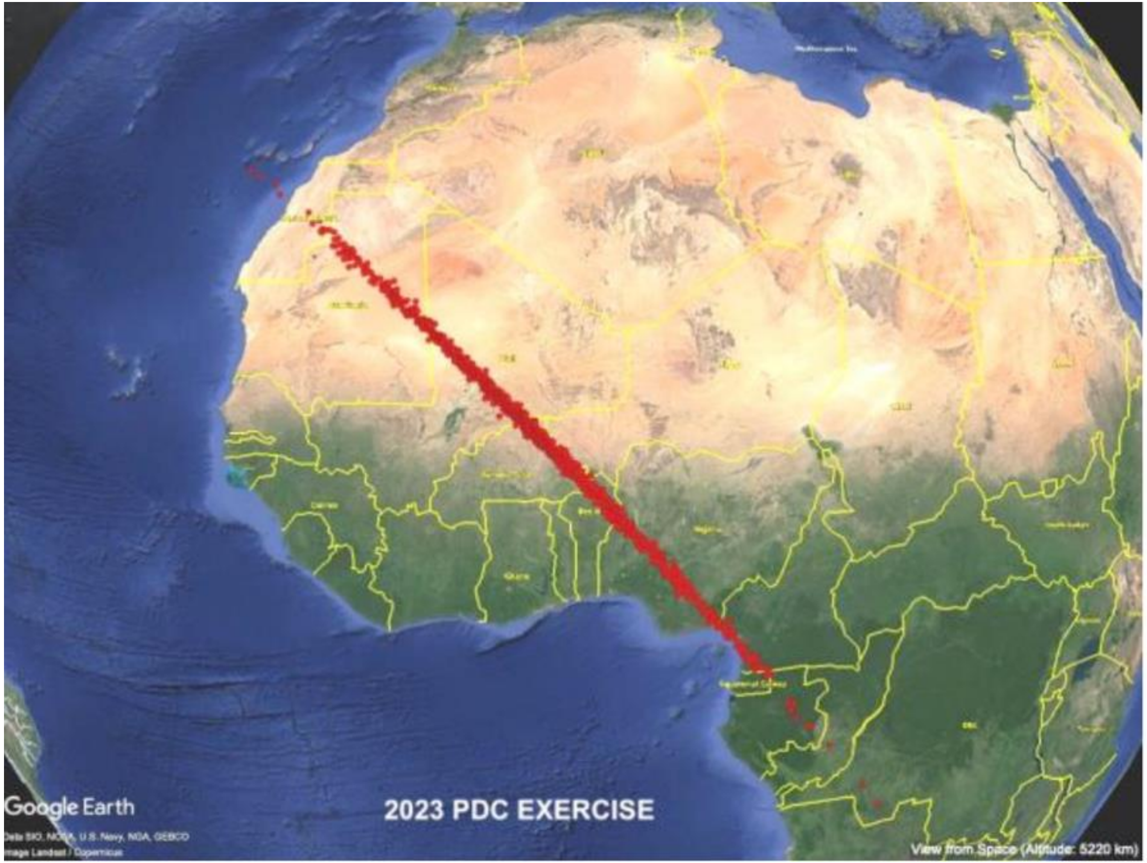
IAWN notification update - impact risk corridor map

SMPAG



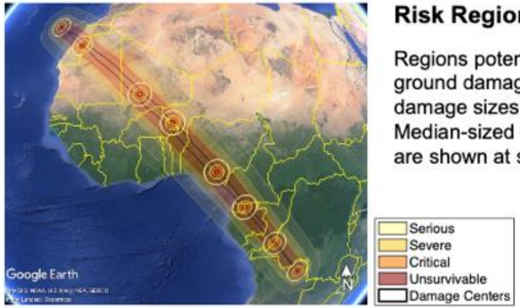
HYPOTHETICAL EXERCISE

Impact Risk Summary

Assessment Date: 23 October 2024 (Epoch 2)

Asteroid Characterization Summary

- 100% chance of impact on 22 Oct. 2036 (12 years)
- Diameter: 170–2100 m (550–6900 ft), most likely 300–880 m (970–2890 ft), median 620 m (2020 ft)
- Impact Energy: 76–190,000 megatons (Mt)
- Remote observation data have increased likelihood of larger sizes, but potential size range remains very uncertain
- Reconnaissance space missions would enable further size and property refinements that are not possible from remote observation



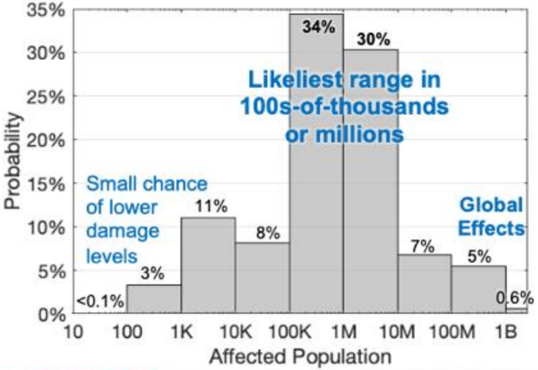
Risk Region Swath Map

Regions potentially at risk to local ground damage, given range of damage sizes and locations. Median-sized damage footprints are shown at sample locations.

Hazard Summary

- Damage risk has increased substantially due to confirmed Earth impact likely over land, and higher likelihood of larger asteroid sizes
- Significant damage is likely for all potential impact sizes & locations
- Impact would cause large blast & thermal damage reaching unsurvivable levels, with serious damage likely extending ~100–240 km (~60–150 mi) outward, and possibly 600 km (400 mi) or more
- Tsunami could cause significant damage if large impactors were partially deflected into the ocean
- Largest impacts could cause catastrophic global effects (9% chance)
- Large uncertainties remain in potential damage extents & severities

Affected Population Risks



Probabilities of how many people could be affected by the potential damage

Total avg. risk: 32M

Median: 712K

Likely 100s-of-thousands or millions

Possibly up to ~2B for global effects

HYPOTHETICAL EXERCISE

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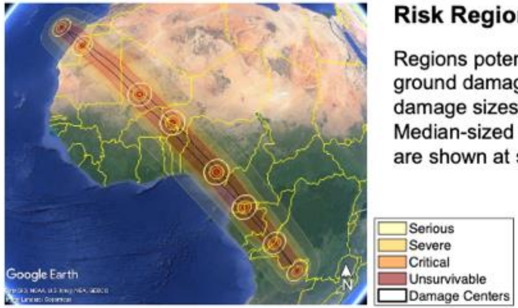

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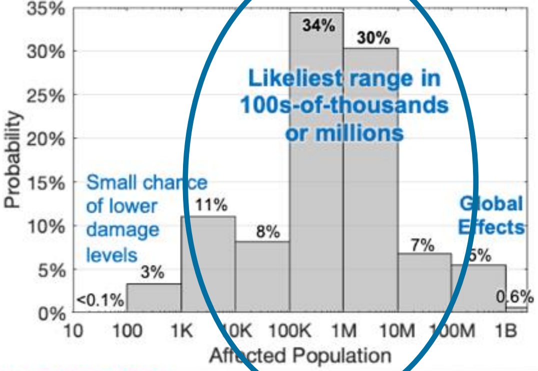

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HYPOTHETICAL EXERCISE

Reminder – Relevant tasks of SMPAG

SMPAG

- From the terms of reference (available at https://www.smpag.net):

1. Purpose

The purpose of the SMPAG is to prepare for an international response to a NEO impact threat through the exchange of information, development of options for collaborative research and mission opportunities, and NEO threat mitigation planning activities.

....

3. Scope

The SMPAG may address the following main areas:

....

4) Mitigation planning activities

a. Recommend operational responsibilities for a space-based NEO mitigation campaign.

b. Work in coordination with the relevant actors potentially involved in the implementation of the threat response.

c. In case of a credible threat, recommend viable concepts for a possible mitigation campaign and directly inform those governments that would coordinate and fund space mission activities and request that they in turn inform UN COPUOS, via the UN Office for Outer Space Affairs if necessary.

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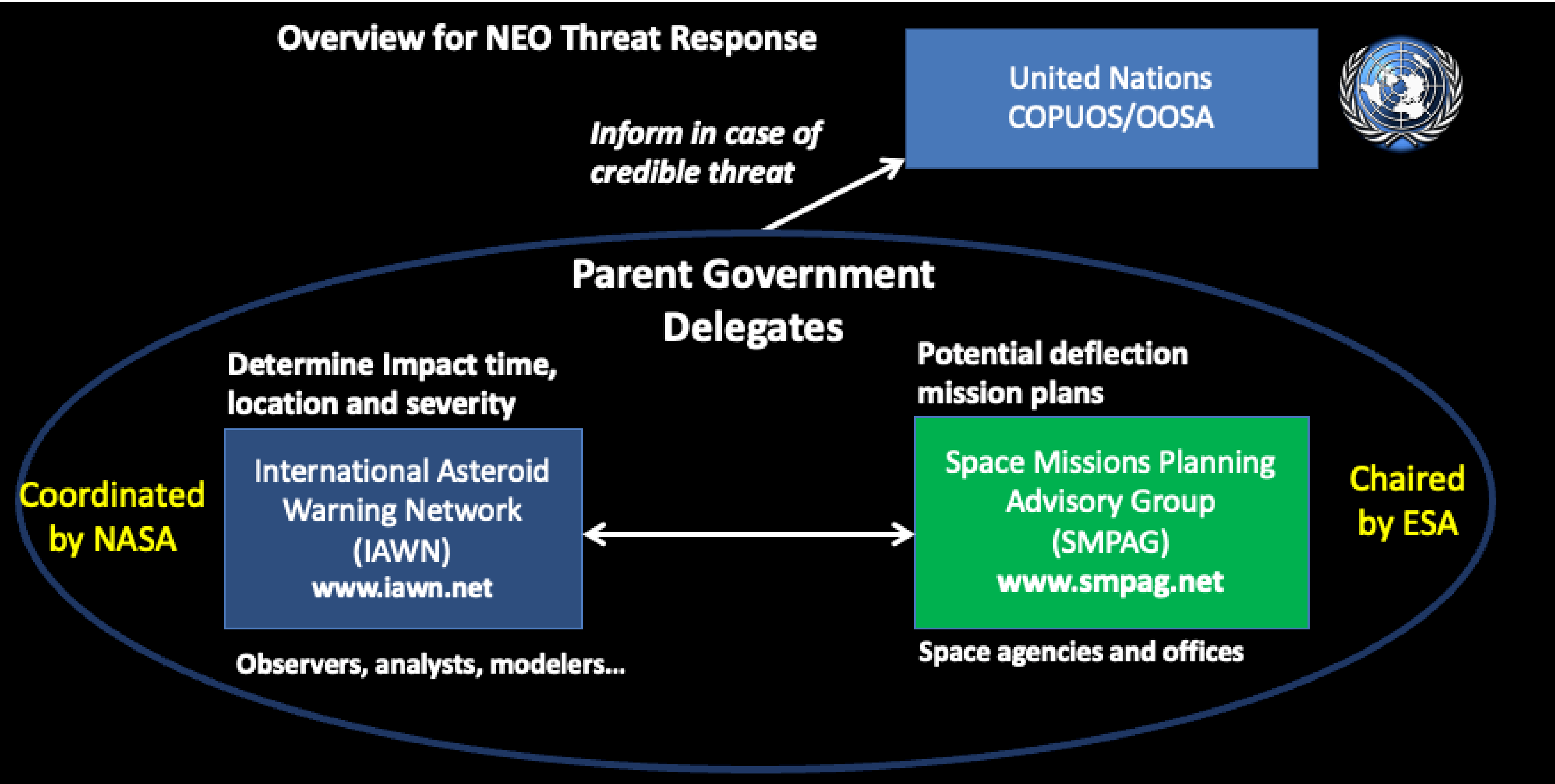
Reminder – Context

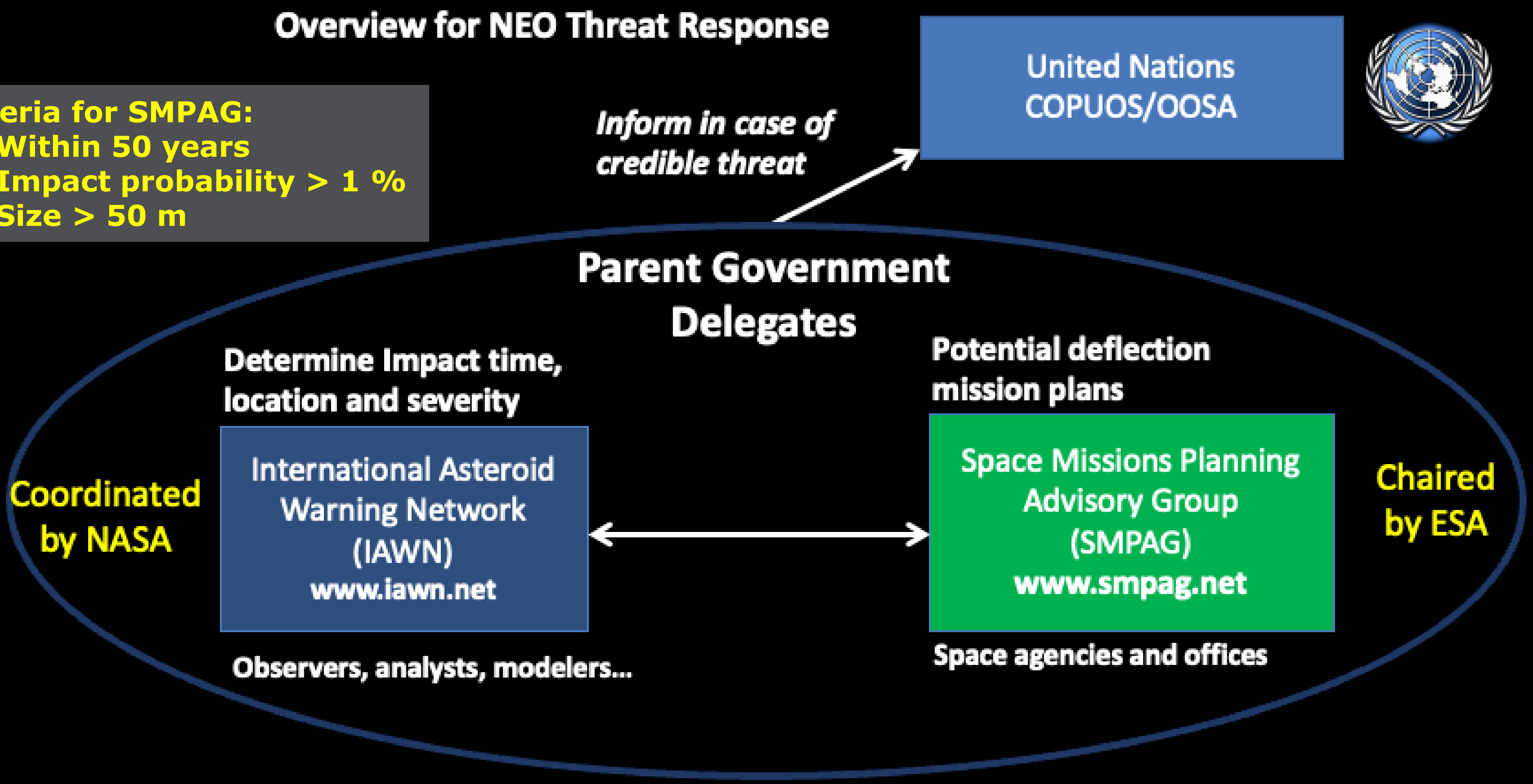
SMPAG



Reminder – Context

SMPAG

Criteria for SMPAG:
- Within 50 years
- Impact probability > 1 %
- Size > 50 m



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Steps within SMPAG

- SMPAG was informed about the threat via IAWN.
- Thresholds for action are reached/exceeded already at epoch 1.
- Ad-hoc meeting took place with first discussions:
  - Future actions were agreed.
  - A first advisory statement was prepared, to be passed to member countries and the UN Office of Outer Space Affairs together with IAWN statement (see next page).
- After epoch 1, detailed studies were ongoing – remember the recommendation:
  - Quickly develop and launch a reconnaissance mission.

PDC 2023 simulated impact threat scenario

SMPAG(*) mission options analysis

Epoch 2: 23 October 2024

Brent Barbee, NASA/GSFC

Apr 2023

(*)Space Mission Planning Advisory Group

Analysis Team

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- Mary Burkey, LLNL
- Paul Chodas, JPL/CNEOS
- Jessie Dotson, NASA/ARC
- Katie Kumamoto, LLNL
- Josh Lyzhoft, NASA/GSFC
- Rob Managan, LLNL
- Catherine Plesko, LANL
- Bruno Sarli, NASA/GSFC
- Matt Vavrina, NASA/GSFC
- Lorien Wheeler, NASA/ARC

Reconnaissance Mission Options Assessed

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- **Flyby reconnaissance mission**
  - ~15 months to prepare for launch (from July 2023)
  - Asteroid flyby: 1 December 2025.
  - Flyby reconnaissance would dramatically reduce uncertainties in impact location, and modestly reduce uncertainties in asteroid size.
- **Rendezvous reconnaissance mission**
  - ~2.5 years available to prepare for launch (from July 2023)
  - Asteroid rendezvous: 23 November 2026.
  - Rendezvous reconnaissance would further reduce impact location uncertainties and all but eliminate uncertainties in asteroid size, mass, composition, rotation, and other properties.
  - The rendezvous reconnaissance spacecraft could also remain with the asteroid to provide ongoing monitoring of the situation and observe any deflection attempts.

Deflection Mission Options Assessed

Kinetic impactors (KIs) for full or partial deflection

- ~5 years available to prepare for launch (from July 2023).
- Asteroid impact: 6 July 2030.
- Any KI missions launched later would require a larger number of launches to achieve the same deflection.

Rendezvous Nuclear Explosive Device (NED) standoff detonation for full deflection

- Primary and backup launch dates identified.
- ~4.5 or 5.5 years available to prepare for launch (from July 2023).

Timeline of Exemplar Mission Options

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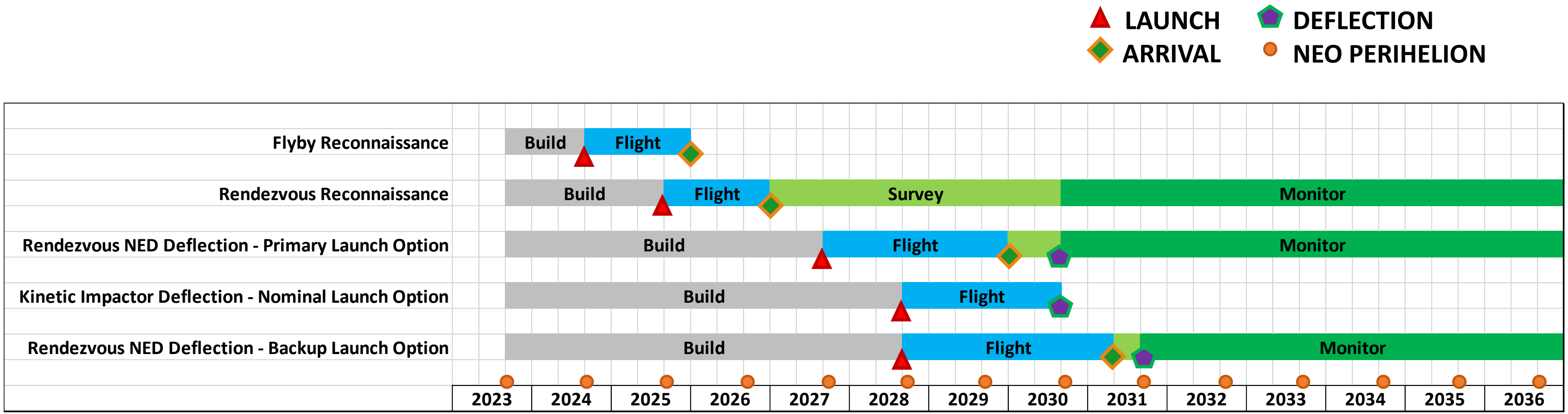
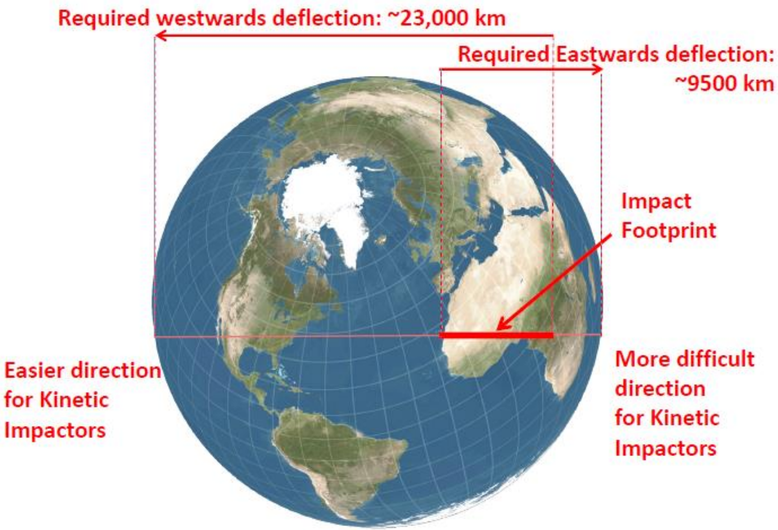
The launch times cannot move: they are fixed by the orbital dynamics.



Impact Corridor, Deflection Distances, & Asteroid Properties

Predicted Impact Corridor (3σ, 99.7% confidence)



Deflection Distances to Move the Impact Corridor Off Earth

Asteroid Physical Properties at Selected Percentile Levels

Note that an asteroid density of 2000 kg/m³ is assumed throughout this analysis for simplicity, but the actual asteroid density could of course be lower or higher. Asteroid diameter affects asteroid mass much more strongly than density does.

	5th%	50th%	95th%
Diameter (m)	290	617	1539
Density (kg/m³)	2000	2000	2000
Mass (kg)	2.6E+10	2.5E+11	3.8E+12

Numbers of Falcon Heavy Rocket Launches Required for Asteroid Deflection

	Nuclear, Full Deflection	Kinetic Impactor, Full Deflection	Kinetic Impactor, Partial Deflection
5th percentile asteroid (290 m)	1	4 to 9	4
50th percentile asteroid (617 m)	1	39 to 85	33
95th percentile asteroid (1539 m)	1 to 2	565 to 1256	487

Notes about partial deflection:

- *Requires comparably challenging numbers of launches to full deflection;*
- *Ocean impacts even at mid-Atlantic points have a high chance of significant tsunami affecting large numbers of people, and the potential for significant global effects remains.*

SMPAG recommendation on action (in bullets)

SMPAG

- **Recommended possible courses of action, epoch 2**

  (1) Studies showed that the nuclear option seems to be the only available scenario for full deflection. SMPAG recommends to develop the nuclear option.

  (2) Partial deflection could be considered with conventional methods – attempt to move the impact to a less devastating area (e.g. ocean).

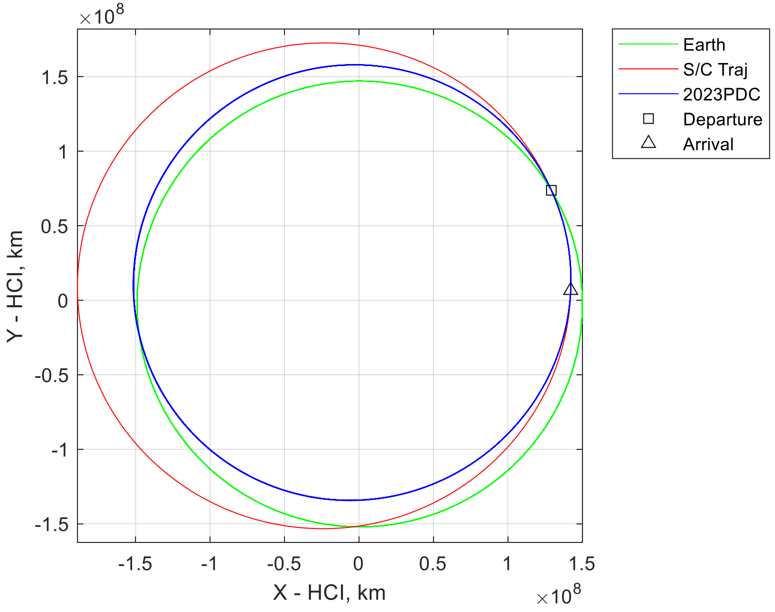
  (3) Continue to study alternatives - on a non-interference basis with recommendation (1). E.g. availability of large launchers to make kinetic impactor feasible; study options with similar unknowns as nuclear, e.g. laser ablation techniques, ion-beam sheperd.

Appendices for technical part

Flyby Reconnaissance Mission Details

SMPAG

Launch Vehicle: Falcon Heavy (recovery or expendable)
Launch: 2024-10-23
Arrival Date: 2025-12-01 (404 day TOF)
Departure C3: 46.235 km^2/s^2
Declination of Launch Asymptote (DLA): -35.614 deg
Asteroid flyby speed: 1.738 km/s
Approach phase angle: 110.53 deg
Spacecraft mass capability: >500 kg

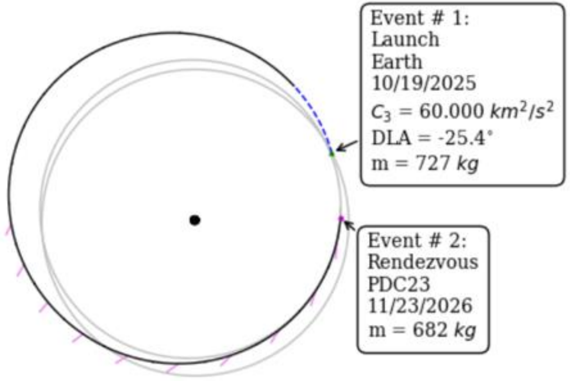


Rendezvous Reconnaissance Mission Details

SMPAG

Solar Electric Propulsion Option

LV: **Vulcan VC2***
EOL power: 5 kW
EP thruster: 1 NEXT-C
Launch: 10/19/2025
Arrive: 11/23/2026 (400-day TOF)
EP prop mass: 50 kg with 10% margin
Delivered mass: 682 kg (includes 4.5 kg of margined prop)

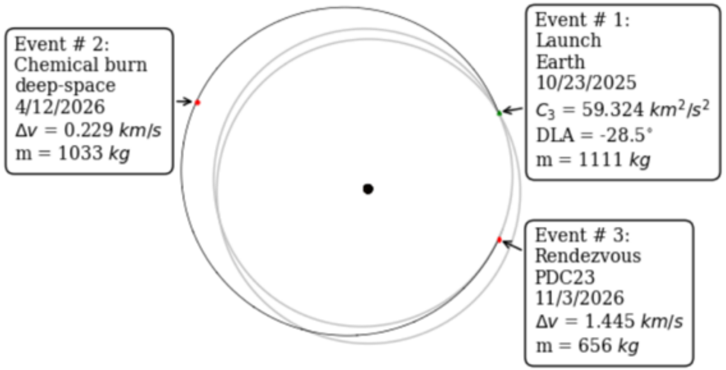


Chemical Propulsion Option

(Storable hypergolic bipropellant, Isp=324 s)

LV: **Vulcan VC2***

Thruster: 324 s Isp storable hypergolic bipropellant
Launch: 10/23/2025
Arrive: 11/3/2026
Prop mass: 500 kg with 10% margin
Delivered mass: 656 kg (includes 50 kg of margined prop)



**Note: The Vulcan VC2 has not yet flown, but would be right-sized for these missions. The currently available Falcon Heavy launch vehicle is more than capable of flying these missions.*

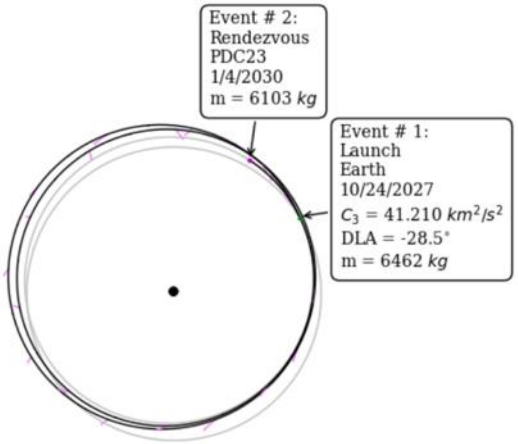
NED Deflection Mission Details

SMPAG

- FHE and 8 kW SEP bus allows for >6000 kg delivered mass with only ~400 kg of EP prop within nominal deflection mission bounds
- Backup SEP option possible with 2028 launch & 2031 deflection opportunity, allowing longer duration between recon characterization & deflection mission launch

Primary Launch Option

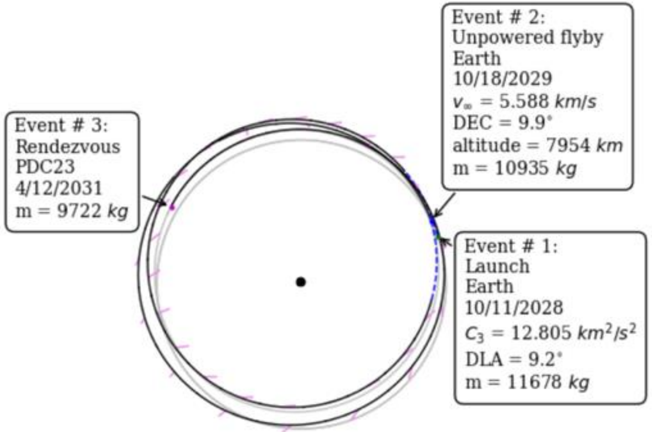
LV: Falcon Heavy Expendable
Launch: 10/24/2027
Arrive: 1/4/2030
EOL power at 1 AU: 8 kW
Thrusters: 1 active NEXT-C thruster
Prop mass: 394 kg (includes 10% margin)
Delivered mass: 6067 kg (margined prop not included)



Backup Launch Option

LV: Falcon Heavy Expendable
Launch: 10/11/2028
Arrive: 4/1/2031
EOL power at 1 AU: 15 kW (can likely be lower)
Thrusters: 2 active BPT-4000 thrusters
Prop mass: 2153 kg (includes 10% margin)
Delivered mass: 9526 kg (margined prop not included)

Pysche s/c:
4 SPT 140s
18 kW array
launch mass: 2600 kg
EP prop mass: ~1000 kg



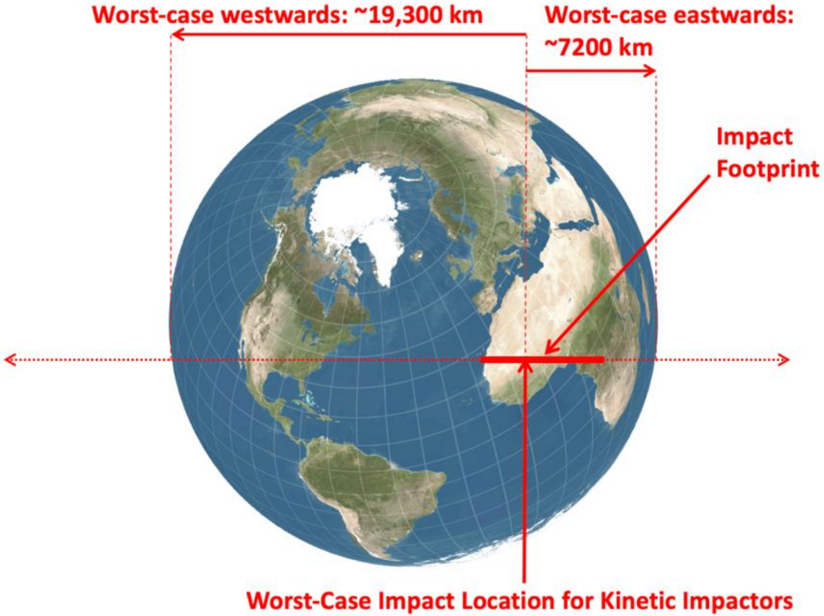
Space Mission Design Ground Rules & Assumptions

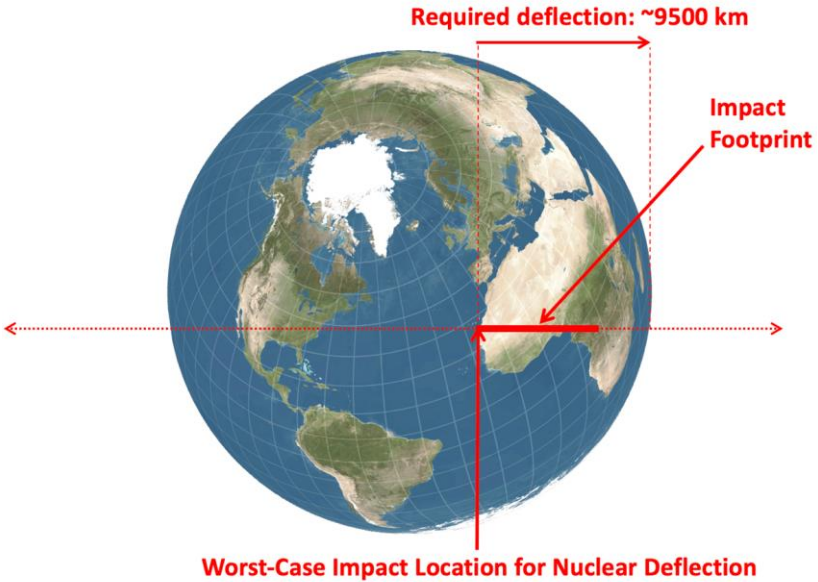
SMPAG

- Solar electric propulsion (SEP) designs
  - Duty cycle: 90%
  - Prop margin: 10%
  - Power margin: 10%
  - s/c bus power: 1 kW
  - 30 day forced coast after launch for s/c checkout
- Chemical propulsion designs
  - Bi-prop Isp: 324 s
  - Prop margin: 10% for statistical maneuvers & ACS tax
  - No mnvrs. until 30 days after launch for s/c check out
- Planetary gravity assist flybys
  - No restrictions on flyby body; up to 4 flybys evaluated w/ any combination of Earth, Venus, & Mars
  - No mnvrs. 30 days before flyby for missed thrust margin & dispersion corrections
  - No mnvrs. 2 days after flyby for navigation & mnvr. planning
- Min solar radius: 0.6 au
- Max solar radius: 2.5 au
- Declination of launch asymptote
  - +/- 28.5 deg for stock NASA Kennedy Space Center (KSC) Launch Vehicle performance curves

Deflection Directions

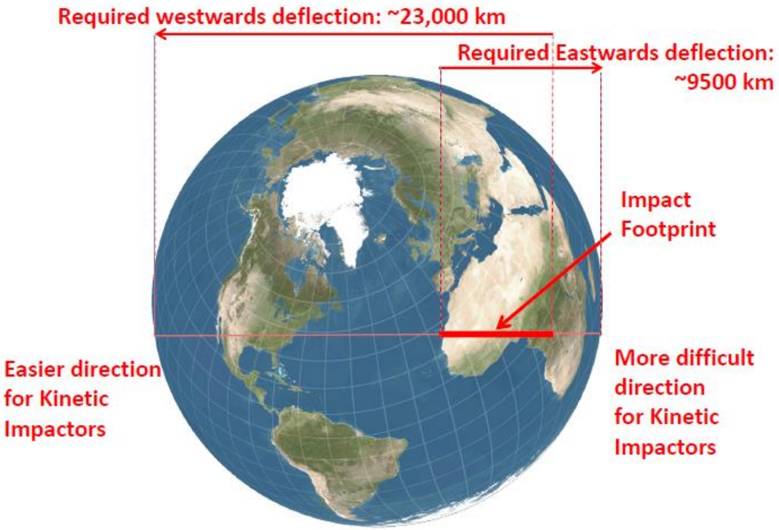
SMPAG





Nuclear Deflection Performance Summary

SMPAG



- **Eastwards deflection**
  - **1 Falcon Heavy (FH) launch delivers enough spacecraft mass to deflect the up to the 95th percentile asteroid off Earth using one to several NEDs (each with yield of 1 Mt or less)**
  - **True for either primary or backup NED rendezvous mission options**
- **Westwards deflection**
  - **1 FH launch delivers enough NED payload mass to deflect up to the 92nd percentile asteroid (1320 m size) for the primary launch option, or up to the 88th percentile asteroid for the backup launch option**
  - **So, 2 FH launches may be advisable if westward deflection were selected**
- **Copies of the NED rendezvous spacecraft could be built and launched to provide full redundancy**
  - **2 FH launches total for eastward deflection**
  - **4 FH launches total for westward deflection**

Kinetic Impactor Deflection Performance Summary (1/3)

- KI deflection dynamics result in the hardest deflection location (within the aforementioned predicted corridor) requiring the following deflection distances:
  - Eastward: 7212 km
  - Westward: 19288 km
  - Deflection from this hardest deflection location is equally difficult for KIs in either direction
  - The hardest deflection location is near Timbuktu
- A momentum enhancement factor (β) of 3 is assumed, based on the results of NASA's DART mission
  - Cheng, A. F. , Agrusa, H. F., Barbee, B. W. et al. Momentum Transfer from the DART Mission Kinetic Impact on Asteroid Dimorphos. Nature (2023). https://doi.org/10.1038/s41586-023-05878-z
- The β that would actually be achieved in a given deflection scenario could be higher or lower than 3, requiring proportionally fewer or greater numbers of launches

Kinetic Impactor Deflection Performance Summary (2/3)

- **KI launch requirements for full deflection of the asteroid off the Earth, from the hardest deflection location:**
  - **5th percentile asteroid mass: 9 FH launches (~62300 kg total KI spacecraft mass)**
  - **50th percentile asteroid mass: 85 FH launches (~588000 kg total KI spacecraft mass)**
  - **95th percentile asteroid mass: 1256 FH launches (~8.7 million kg total KI spacecraft mass)**
- **The easiest deflection location for KI performance is the easternmost edge of the impact corridor, with eastward deflection directions.**
  - **The number of FH launches required for 5th, 50th, and 95th percentile asteroids would be 4, 39, and 565, respectively.**
- **TBD additional launches beyond those listed above would be required for redundancy**

Kinetic Impactor Deflection Performance Summary (3/3)

SMPAG

- KI requirements for partial deflection of the asteroid into the Atlantic ocean:
  - The example target ocean impact point for partial deflection requirements analysis is at 24 W longitude (1663 km from the coast of Western Sahara)
  - The hardest deflection location for partial deflection performance (where deflection is equally difficult in either direction) is at the eastern end of the impact corridor
  - The deflection distance from the hardest deflection location to the targeted ocean impact location is ~7500 km
  - <u>5th percentile asteroid mass: 4 FH launches (~27672 kg total KI spacecraft mass)</u>
  - <u>50th percentile asteroid mass: 33 FH launches (~228290 kg total KI spacecraft mass)</u>
  - <u>95th percentile asteroid mass: 487 FH launches (~3.37 million kg total KI spacecraft mass)</u>
- TBD additional launches beyond those listed above would be required for redundancy
- Even before considering the potential effects of an ocean impact (tsunami, atmospheric effects, other severe global effects.), note that the number of required KI launches is of similar magnitude to the required launches for full deflection

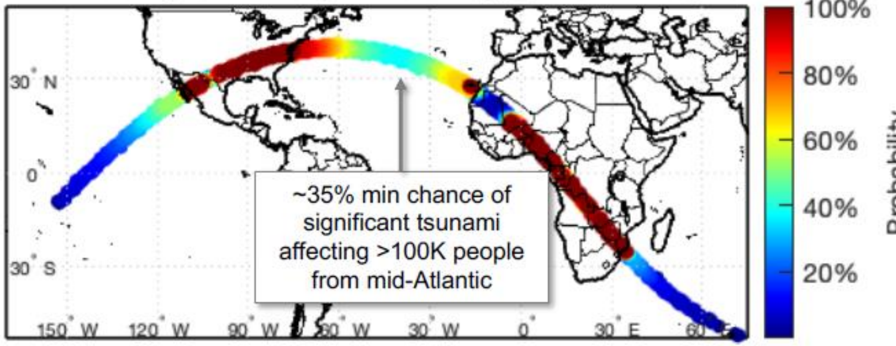
Ames Research Center

Population Damage Probabilities along Impact Locations

- **~100% chance of large damage over almost all land and near-shore locations**
- **High chance of significant tsunami even from far mid-Atlantic points:**
  - 55% chance of tsunami affecting >10K people
  - 35% chance of tsunami affecting >100K people
  - 10-15% chance of tsunami affecting >1M people

Affected Population Probability Maps:
For each location, plots show the likelihood that tsunami or local ground damage will affect at least the given number of people or more, given the potential asteroid sizes (*not including global effects*).

Probability of Damage Affecting ≥ 100K People



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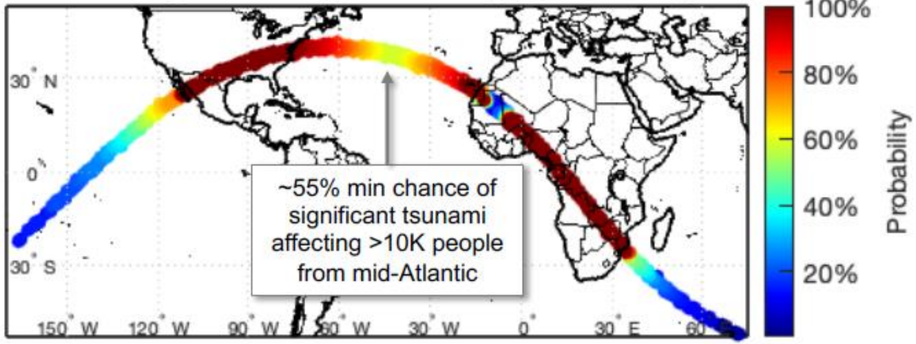

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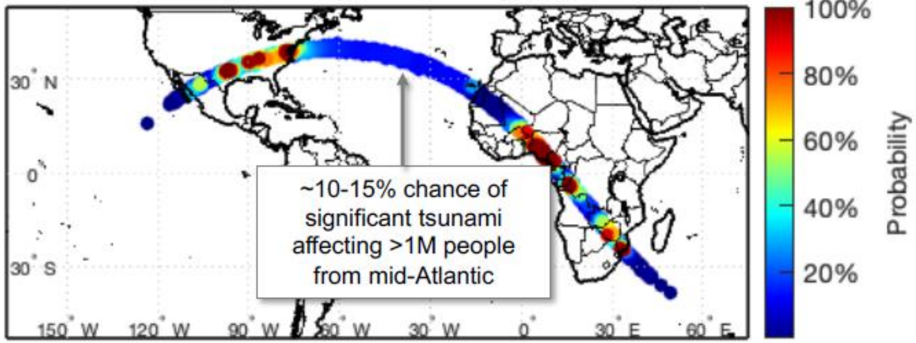


Standoff Nuclear Detonation Deflection Performance

SMPAG

	# NEDs	Yield per NED (Mt)	NED Payload Mass (kg)	# FH Launches
Westwards Deflection (23000 km) - Near Aug 2031 Perihelion - Delta-V = 4.26 cm/s				
	# NEDs	Yield per NED (Mt)	NED Payload Mass (kg)	# FH Launches
5th %tile asteroid (290 m)	1	0.109	61	1
50th %tile asteroid (617 m)	2	0.597	663	1
95th %tile asteroid (1539 m)	N/A - Would require > 7 NEDs			
Westwards Deflection (23000 km) - Near Jul 2031 Perihelion - Delta-V = 5.03 cm/s				
	# NEDs	Yield per NED (Mt)	NED Payload Mass (kg)	# FH Launches
5th %tile asteroid (290 m)	1	0.137	76	1
50th %tile asteroid (617 m)	2	0.677	752	1
95th %tile asteroid (1539 m)	N/A - Would require > 7 NEDs			
Eastwards Deflection (9500 km) - Near Aug 2030 Perihelion - Delta-V = 1.76 cm/s				
	# NEDs	Yield per NED (Mt)	NED Payload Mass (kg)	# FH Launches
5th %tile asteroid (290 m)	1	0.031	17	1
50th %tile asteroid (617 m)	1	0.410	228	1
95th %tile asteroid (1539 m)	5	0.951	2642	1
Eastwards Deflection (9500 km) - Near Jul 2031 Perihelion - Delta-V = 2.08 cm/s				
	# NEDs	Yield per NED (Mt)	NED Payload Mass (kg)	# FH Launches
5th %tile asteroid (290 m)	1	0.040	22	1
50th %tile asteroid (617 m)	1	0.519	288	1
95th %tile asteroid (1539 m)	6	0.930	3100	1

Largest asteroid size that could be deflected using 1 FH launch carrying up to 7 NEDs, each having up to 1 Mt yield:

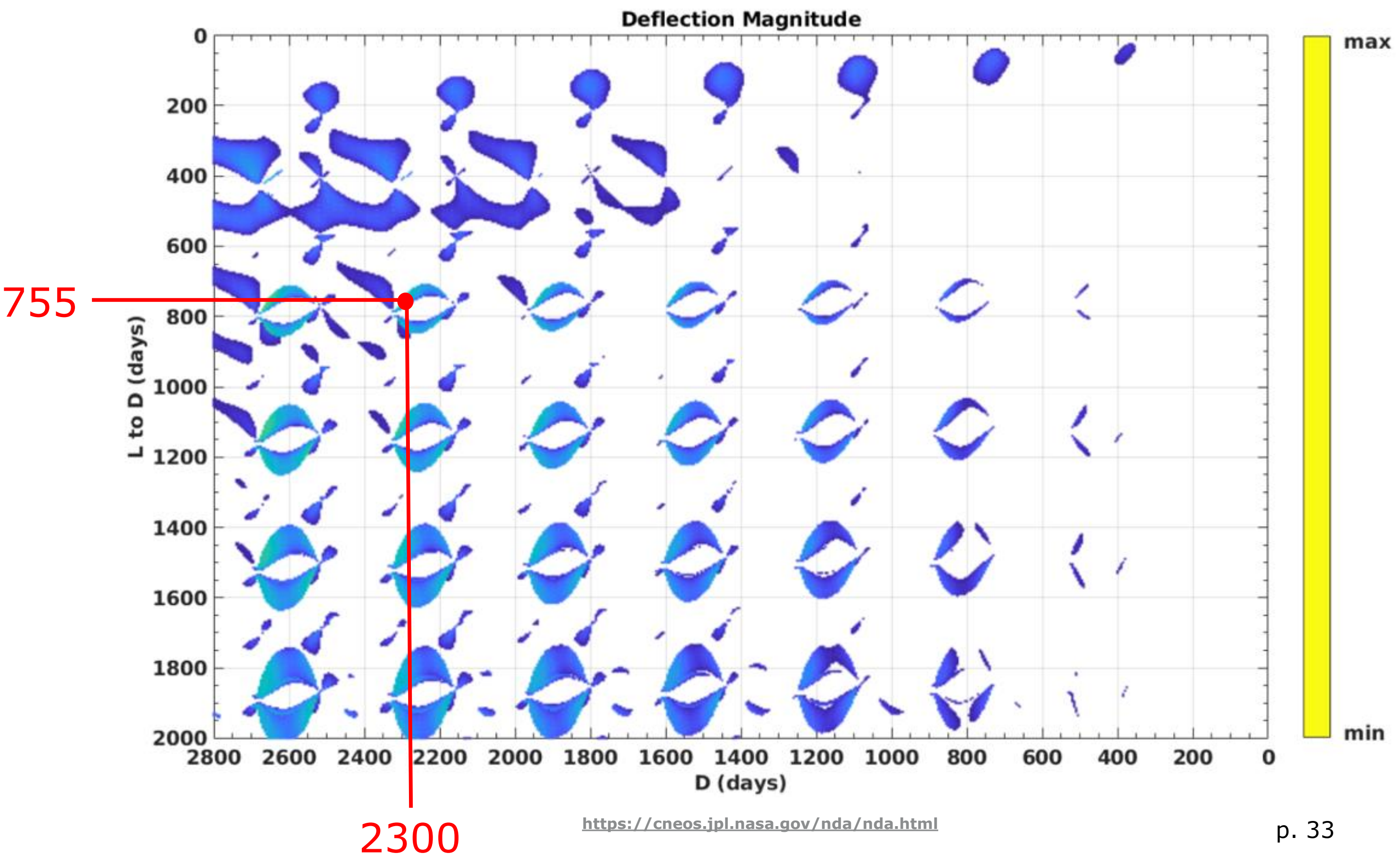
→ 1320 m (92nd percentile)

→ 1160 m (88th percentile)

Nominal Ballistic Kinetic Impactor Trajectory

SMPAG

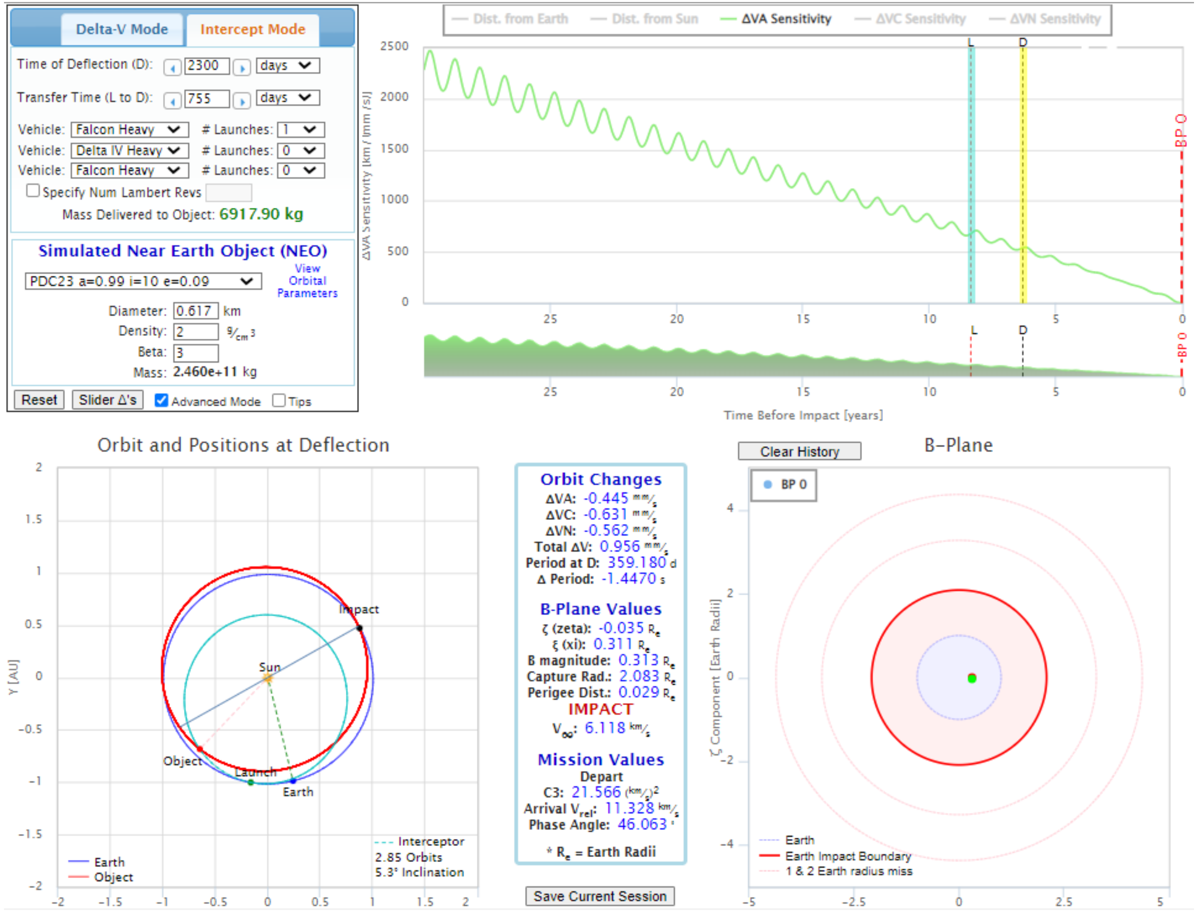
- This is the most performant ballistic kinetic impactor trajectory launching no earlier than 5 years after notional authority to proceed with mission development would be given on 2023-07-01, when Earth impact probability rose above 10%.
- Launching on later dates would require a larger number of launches to deflect the asteroid.
- 5 years is a typical interplanetary mission development time span.
- Launch date is 2028-06-11
- Asteroid impact date is 2030-07-06



https://cneos.jpl.nasa.gov/nda/nda.html

Nominal Ballistic Kinetic Impactor Trajectory

SMPAG



https://cneos.jpl.nasa.gov/nda/nda.html

KI Deflection Launch Requirements by Year

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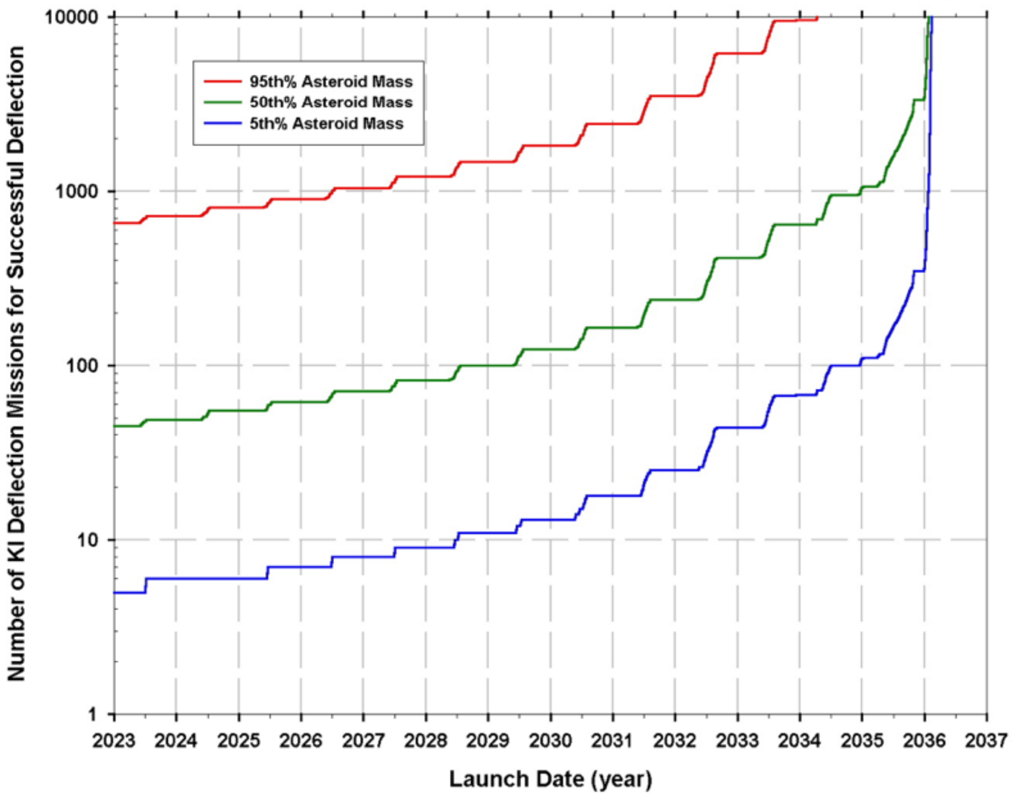
Worst-case Number of FH Launches Required for KI Deflection of Asteroid Off the Earth



SMPAG recommendation on action (in bullets)

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- **Initial analysis**
  - Object will be difficult to deflect with kinetic impactors.
  - More detailed knowledge on the properties of the asteroid are needed, difficult to impossible to obtain via ground-based observations.
- **Recommended possible courses of action, epoch 1**
  - Quickly develop and launch a reconnaissance mission.
  - Check whether rendezvous is possible - could also be used to check deflection success later.
  - Study options to ‘touch the surface’ to better determine asteroid properties.
  - Study deflection mission scenarios: Look in detail at the nuclear option, but study alternatives: e.g. availability of large launchers to make kinetic impactor feasible; study options with similar unknowns as nuclear, e.g. laser ablation techniques.

EXERCISE EXERCISE EXERCISE

This notification is issued by the International Asteroid Warning Network (IAWN) in accordance with report SMPAG-RP-003 on Recommended Criteria & Thresholds for Action for Potential NEO Impact Threat that defines the threshold for issuing warnings of possible impact effects, which is a probability of impact is greater than 1% and a rough size estimated to be greater than 10 meters (33 feet).

IAWN is a worldwide collaboration of asteroid observers and modelers that was recommended by the United Nations. https://iawn.net

Point of Contact: IAWN Coordinating Officer for the IAWN Steering Committee [email]

Graphics:

- Impact risk corridor map
- Impact Risk Summary quad chart

Details for IAWN notification epoch 2

ADDITIONAL DETAILS:

- There is a 100% probability that asteroid 2023 PDC will impact Earth on 22 October 2036 as calculated by the NASA JPL Center for Near-Earth Object Studies and the ESA Near-Earth Objects Coordination Centre, based on observations from the worldwide network of observatories.
- The impact risk corridor, which is the region of Earth where it is possible that 2023 PDC could impact, extends from south of the Canary Islands southeast across West Africa to the southern Congo River region.
- The asteroid 2023 PDC has been tracked by Earth-based telescopes except for late June – Nov. 2023 when it was too close to the Sun to observe. Since observations resumed in Nov. 2023, the impact probability of asteroid 2023 PDC has risen to 100%.
- The size of 2023 PDC is estimated to be 300 - 880 meters (970 - 2900 feet). This updated size estimate is based on color data from ground-based telescopes, which indicates something about the surface reflectivity and the type of asteroid, along with its observed brightness (absolute magnitude H is determined to be 19.4).
- The asteroid is too distant for radar observations and will not come within range until 2036.
- There is a high probability that hundreds of thousands to millions of people on the African continent could be affected by the potential damage of the impact based on the latest predicted impact corridor and risk modeling. See Impact Risk Summary quad chart below for further details.