HYPOTHETICAL EXERCISE ONLY

Space Mission Options for the 2021 PDC Hypothetical Asteroid Impact Scenario

Presented to the 7th IAA Planetary Defense Conference on Behalf of the Space Mission Planning Advisory Group (SMPAG)

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2021 PDC Hypothetical Asteroid Overview

https://cneos.jpl.nasa.gov/pd/cs/pdc21/

- Scenario developed by CNEOS/JPL/CalTech: Paul Chodas.
- Discovery: 2021-04-19.
- Potential Earth impact: 2021-10-20.
  - Only 6 months after discovery.
- 2021 PDC's physical properties are unknown:
  - Absolute (intrinsic) magnitude estimate: H = 22.4 ± 0.3 (1σ).
  - The asteroid's size could range from ~35 meters to ~700 meters – significant size uncertainty.
  - If the asteroid's albedo (reflectivity) is 13%, a typical mean value, then its size would be 120 meters.
- 2021 PDC's orbit has eccentricity of 0.27 and an inclination of 16°. Its orbit semi-major axis is 1.26 au, giving it an orbit period of 1.41 years.
- **Deflection is not practical in this scenario because it would require too much ΔV be imparted to the asteroid, and too far in advance of Earth encounter.**

Rapid Launch Capabilities are Not Yet Available

Early NEO detection and rapid response spacecraft launch are both key capabilities for an effective planetary defense.

Enhanced NEO detection systems are affordable, technologically ready, and under development now, so they are our next priority.

- Enhanced NEO detection systems, e.g., NASA’s NEO Surveyor space-based telescope mission currently under development, can prevent short warning scenarios
- Rapid launch capability is still important (comets, late asteroid detections)
- However, if confronted with the 2021 PDC hypothetical scenario in real life we would not be able to launch any spacecraft on such short notice with current capabilities
- For the sake of discussion only, we describe space mission options for the 2021 PDC scenario that ***could*** hypothetically be available **if** we had rapid spacecraft launch capabilities

Summary of Mission Options Analysis

- Because deflection is impractical, we consider disruption of the asteroid via a nuclear explosive device (NED).
- NED performance for robust disruption of the asteroid is calculated using approximate models provided by Lawrence Livermore National Lab (LLNL) and Los Alamos National Lab (LANL).
  - In an actual situation, detailed modeling would be required for the particular scenario at hand.
- We evaluated NED performance against the statistical distributions of the 2021 PDC asteroid's physical properties provided by NASA/ARC.
- However, the uncertainties in the asteroid's properties are too large to compute meaningful statistics for NED disruption likelihood of success.
  - So, we design the missions to deliver as large a NED as possible to the asteroid.
- We use a launch performance model for a re-purposed commercial intermediate class launch vehicle with a kickstage, launching from Cape Canaveral Air Force Station (CCAFS).
- Launch no earlier than 2021-05-01 (12 days after discovery).
- Reach the 2021 PDC asteroid no later than 2021-09-20 (1 month before Earth encounter).
- We calculate missions for rendezvous and flyby, both ballistic and with low-thrust solar electric propulsion.
- We consider both reconnaissance and disruption mission designs.

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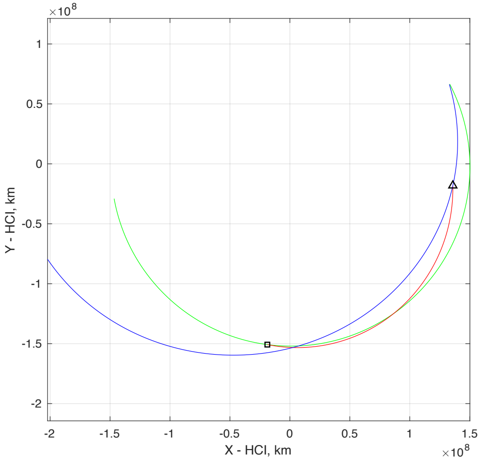
Maximum Delivered Spacecraft Mass (flyby/intercept)

Ballistic

Chemical propulsion

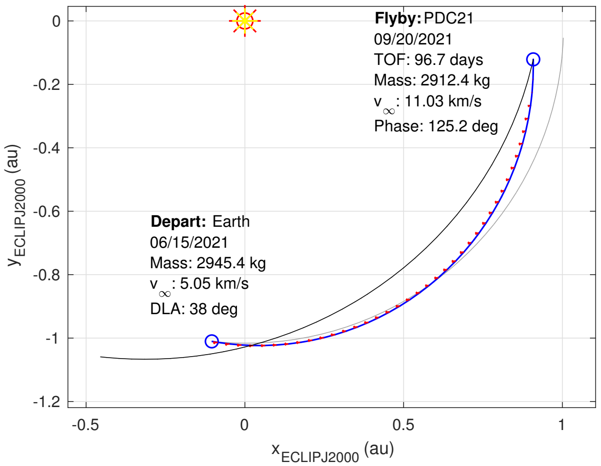


Ballistic analysis by NASA/GSFC:
Brent Barbee

Departure Date	2021-06-14
TOF (days)	98.0
Arrival Date	2021-09-20
Mass Delivered to asteroid (kg)	2787.1
Phase angle @ Intercept	125.9°
Rel. Speed @ Intercept (km/s)	10.73
Departure C3 (km^2/s^2)	27.764
Declination of Launch Asymp., DLA	39.79°

NEXT-C Propulsion (similar to DART)

Low-thrust solar electric propulsion



Flyby: PDC21
09/20/2021
TOF: 96.7 days
Mass: 2912.4 kg
v_∞: 11.03 km/s
Phase: 125.2 deg

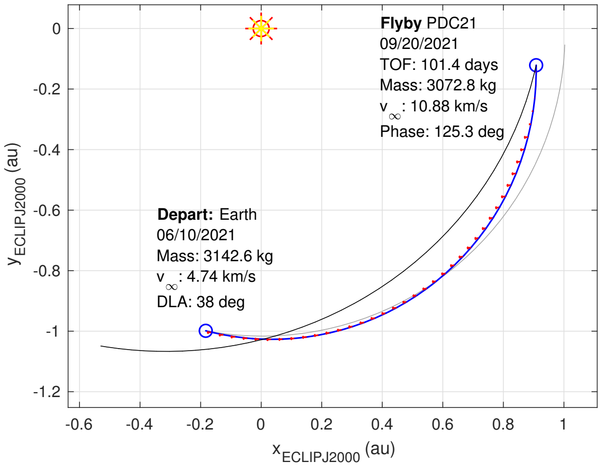
Depart: Earth
06/15/2021
Mass: 2945.4 kg
v_∞: 5.05 km/s
DLA: 38 deg

Low-thrust analysis by CNEOS/JPL/CalTech:
Javier Roa

Departure Date	2021-06-15
TOF (days)	96.7
Arrival Date	2021-09-20
Mass Delivered to asteroid (kg)	2912.4 kg
Phase angle @ Intercept	125.2°
Rel. Speed @ Intercept (km/s)	11.03
Departure C3 (km^2/s^2)	25.503
Declination of Launch Asymp., DLA	38.00°

XIPS25 Propulsion

Low-thrust solar electric propulsion



Flyby PDC21
09/20/2021
TOF: 101.4 days
Mass: 3072.8 kg
v_∞: 10.88 km/s
Phase: 125.3 deg

Depart: Earth
06/10/2021
Mass: 3142.6 kg
v_∞: 4.74 km/s
DLA: 38 deg

Low-thrust analysis by CNEOS/JPL/CalTech:
Javier Roa

Departure Date	2021-06-10
TOF (days)	101.4
Arrival Date	2021-09-20
Mass Delivered to asteroid (kg)	3072.8
Phase angle @ Intercept	125.3°
Rel. Speed @ Intercept (km/s)	10.88
Departure C3 (km^2/s^2)	22.468
Declination of Launch Asymp., DLA	38.00°

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Summary of Mission Options

- Rendezvous missions are impractical.
- The flight times are too short for low-thrust propulsion to make a significant difference in delivered NED performance.
- Flyby recon missions delivering up to ~800-900 kg recon spacecraft are available with earlier launch & arrival dates.
- The deliverable NED yield via high-speed intercept missions is ~4.5 MT.
- The largest size asteroid that can be disrupted by the NED ranges from ~100 m to ~210 m, for asteroid densities ranging from 5 g/cm^3 down to 1 g/cm^3.
- We will show how launching either a reconnaissance mission or 4.5 MT NED disruption mission would improve the statistical impact damage risk assessments.

EXERCISE

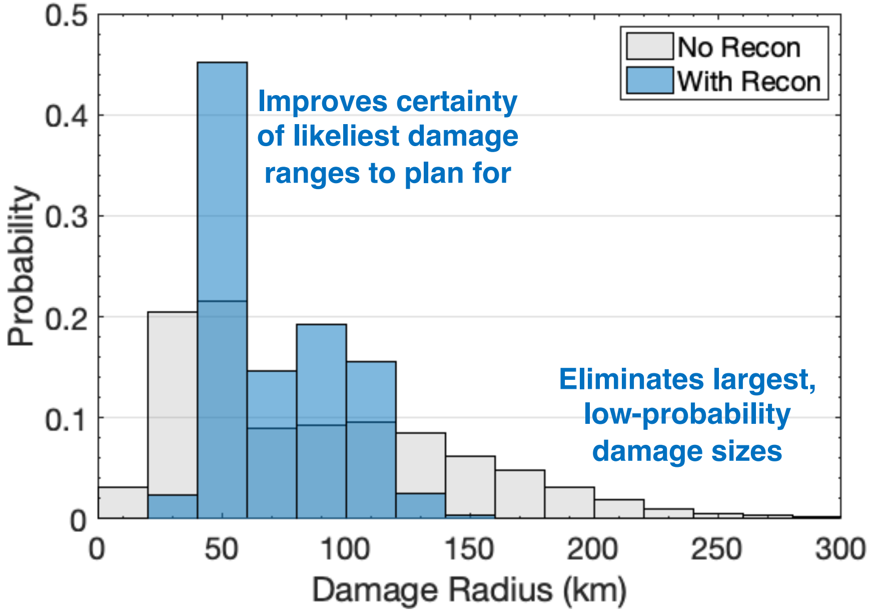
Recon Mission Benefits for Disaster Planning

How much could a hypothetical recon mission refine damage area estimates?

Assuming recon could determine diameter to within 10% for a median-sized 118 m object:

- Asteroid diameter range reduced to 118±12 m (~106–130 m vs 30–700 m without recon)
- Substantially narrows range of potential damage areas for disaster response and improves confidence in likeliest damage areas to plan for
- Reduces maximum potential radius from ~470 km to ~160 km

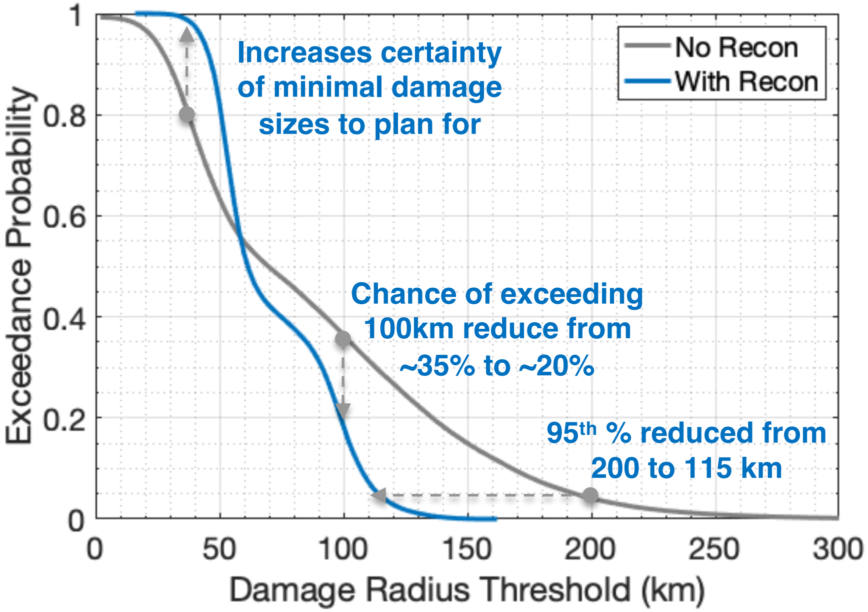
Damage radius risk histogram: Probabilities of damage radii within each range



Improves certainty of likeliest damage ranges to plan for

Eliminates largest, low-probability damage sizes

Damage radius exceedance risk: Probability of damage radii being *at least* the given size *or larger*



Increases certainty of minimal damage sizes to plan for

Chance of exceeding 100km reduce from ~35% to ~20%

95th % reduced from 200 to 115 km

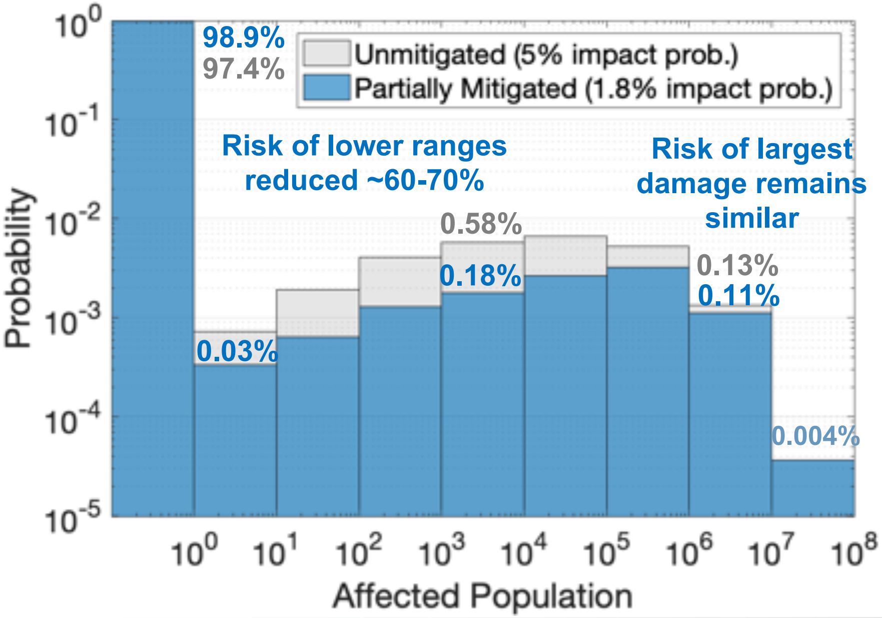
Hypothetical Risk Mitigation

How much could a hypothetical NED mission reduce risk of impact damage?

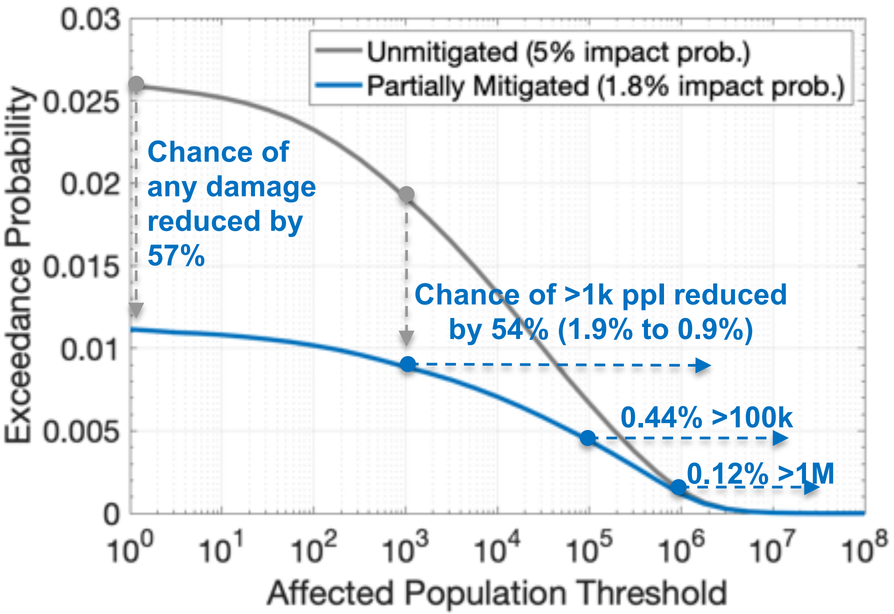
Assuming successful mitigation of all objects under mass/density disruption criteria:

- ~64% of cases successfully mitigated, reducing impact probability from 5% to ~1.8%
- Average affected population reduced by ~20%, from ~5,900 to ~ 4,700
- Chance of damage affecting any population reduced by 57% (from 2.6% to 1.1%).
- Chance of affecting lower population ranges reduced by ~60-70%
- Risk of largest population ranges (>1M or >10M) remains low but similar due to unmitigated largest objects

Population risk histogram: Probabilities of affecting the number of people within each range



Population exceedance risk: Probability of affecting *at least* the given number of people *or more*



Summary of Findings and Recommendations

- It is difficult to define mitigation mission requirements or assess the likelihood of mitigation mission success (due to 2021 PDC's uncertain properties)
- Current real-world infrastructure for spacecraft development and launch would not enable us to deploy either reconnaissance or mitigation spacecraft in such a short warning scenario if this were a real situation.
- Deflection would not be practical due to the short warning time
- Robust disruption of the asteroid would be the only practically viable in-space mitigation
- These short warning mission options require high-speed flybys at poor solar phase angles, which can pose significant guidance and navigation challenges
- **Deploying a nuclear disruption mission could significantly reduce the risk of impact damage, despite substantial uncertainties in the asteroid's properties**
- **Deploying a flyby reconnaissance spacecraft (if a disruption mission is foregone) would significantly reduce the uncertainties faced by disaster response planners**

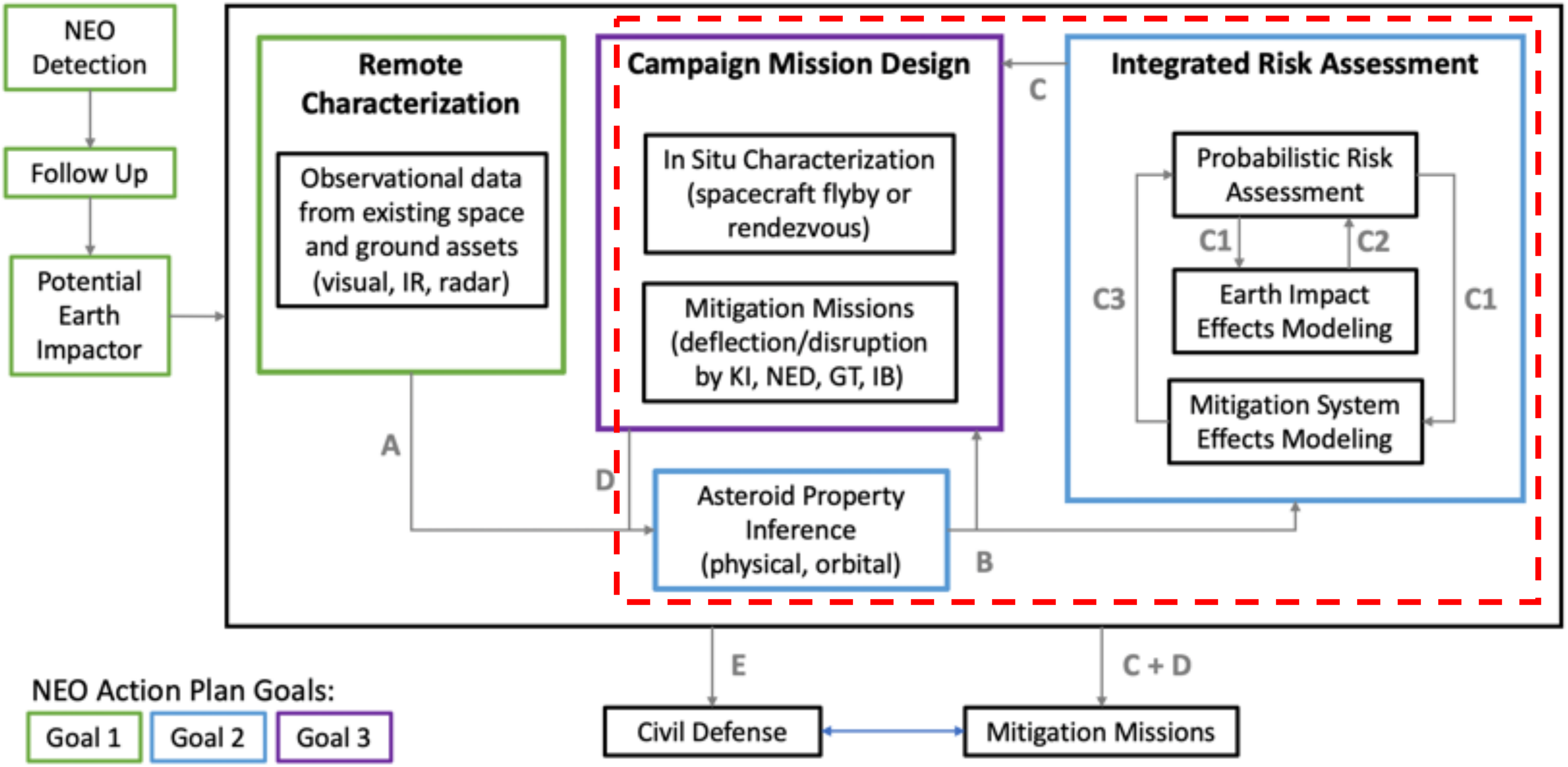
Appendices

Deflection Is Not Practical

- Deflection ΔV requirements (assuming ideally oriented ΔV vector and a geocentric impact):
  - Computed via the CNEOS NEO Deflection App: https://cneos.jpl.nasa.gov/nda/.
  - 6 months before Earth impact – 25.5 cm/s deflection ΔV required.
  - 5 months before Earth impact – 28.2 cm/s deflection ΔV required.
  - 4 months before Earth impact – 39.6 cm/s deflection ΔV required.
  - 3 months before Earth impact – 65.9 cm/s deflection ΔV required.
- The above values are shown for reference, but intercepting the asteroid earlier than ~3 months before Earth impact is not possible because the asteroid is discovered only 6 months before Earth impact.
- Imparting such large ΔV to the asteroid would be very difficult:
  - If the asteroid were ~130 meters in size with a bulk density of ~1.5 g/cm^3, deflecting it via kinetic impactors would be impractical, requiring launch ~2 weeks after discovery and sending ~294,000 kg worth of kinetic impactors to the asteroid (~37 notional NASA SLS 2B rocket launches); assumes β=1.
  - A ~1 MT NED could impart 65.9 cm/s of ΔV to a ~130 meter size asteroid with a bulk density of ~1.5 g/cm^3, but if the asteroid is larger and/or denser, then a much larger NED yield (and/or different type of NED) would be required.
- Regardless of the foregoing, imparting such large ΔV to the asteroid would almost certainly accidentally fragment it, which is undesirable because that could leave sizeable fragments on Earth collision trajectories.
  - For the range of possible asteroid sizes and bulk densities, the asteroid surface escape velocity could be 1.3 to 45 cm/s.
  - The required deflection ΔV would be ~57% to ~500% of the asteroid's surface escape velocity, depending on the asteroid's size and density, but the threshold for weak disruption is only >10% of asteroid surface escape velocity.

Risk-Informed Mission Design Process Summary

We are exercising portions of our planned risk-informed mission design process:
- **NEO properties uncertainties drive mitigation mission effectiveness uncertainties.**
- **Mitigation mission performance included in damage risk model outputs.**



NEO Detection

Follow Up

Potential Earth Impactor

Remote Characterization

Observational data from existing space and ground assets (visual, IR, radar)

Campaign Mission Design

In Situ Characterization (spacecraft flyby or rendezvous)

Mitigation Missions (deflection/disruption by KI, NED, GT, IB)

Integrated Risk Assessment

Probabilistic Risk Assessment

Earth Impact Effects Modeling

Mitigation System Effects Modeling

Asteroid Property Inference (physical, orbital)

Civil Defense

Mitigation Missions

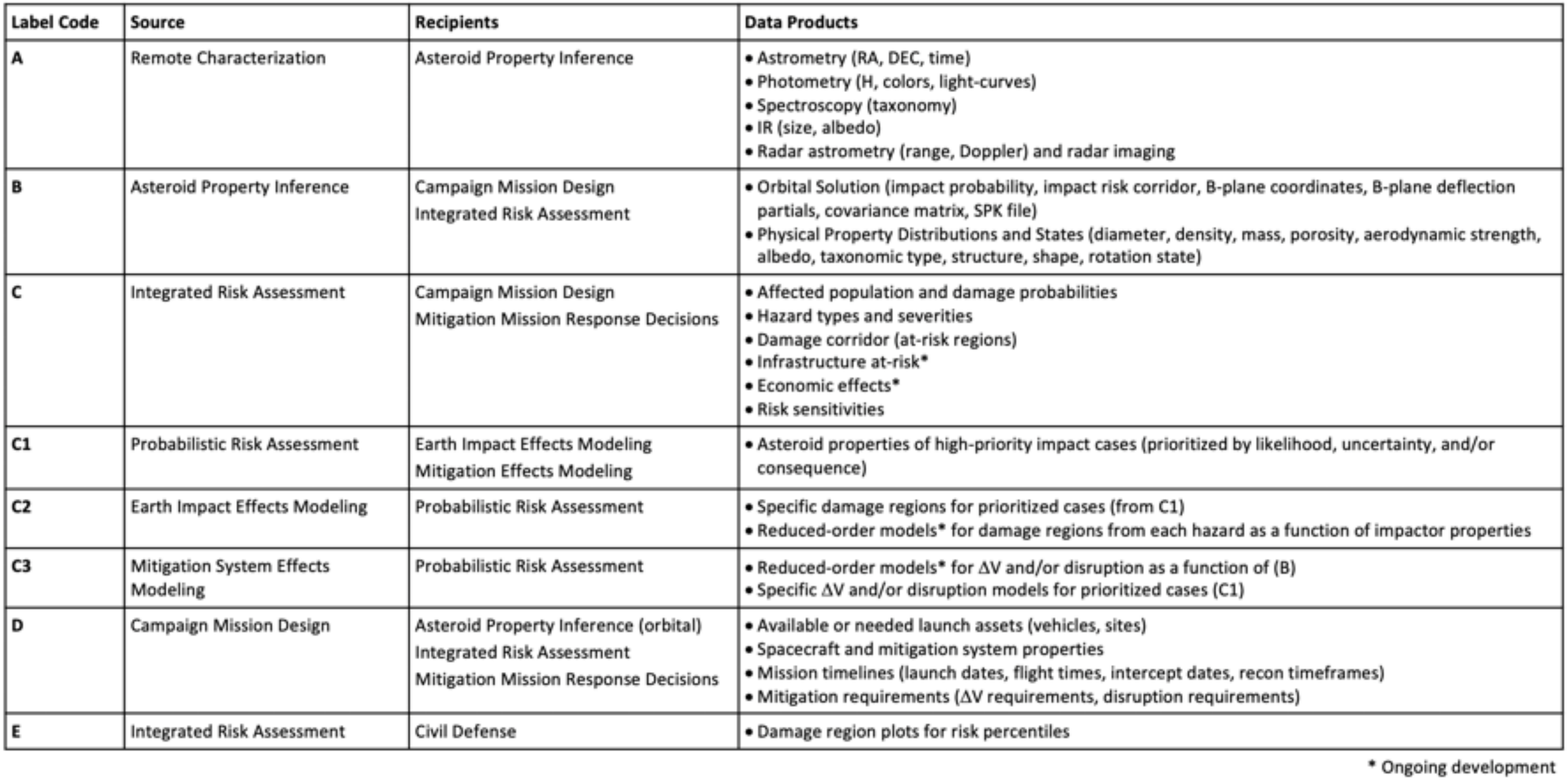
NEO Action Plan Goals:

Goal 1

Goal 2

Goal 3

Risk-Informed Mission Design Data Flow



Label Code	Source	Recipients	Data Products
A	Remote Characterization	Asteroid Property Inference	• Astrometry (RA, DEC, time) • Photometry (H, colors, light-curves) • Spectroscopy (taxonomy) • IR (size, albedo) • Radar astrometry (range, Doppler) and radar imaging
B	Asteroid Property Inference	Campaign Mission Design Integrated Risk Assessment	• Orbital Solution (impact probability, impact risk corridor, B-plane coordinates, B-plane deflection partials, covariance matrix, SPK file) • Physical Property Distributions and States (diameter, density, mass, porosity, aerodynamic strength, albedo, taxonomic type, structure, shape, rotation state)
C	Integrated Risk Assessment	Campaign Mission Design Mitigation Mission Response Decisions	• Affected population and damage probabilities • Hazard types and severities • Damage corridor (at-risk regions) • Infrastructure at-risk* • Economic effects* • Risk sensitivities
C1	Probabilistic Risk Assessment	Earth Impact Effects Modeling Mitigation Effects Modeling	• Asteroid properties of high-priority impact cases (prioritized by likelihood, uncertainty, and/or consequence)
C2	Earth Impact Effects Modeling	Probabilistic Risk Assessment	• Specific damage regions for prioritized cases (from C1) • Reduced-order models* for damage regions from each hazard as a function of impactor properties
C3	Mitigation System Effects Modeling	Probabilistic Risk Assessment	• Reduced-order models* for ΔV and/or disruption as a function of (B) • Specific ΔV and/or disruption models for prioritized cases (C1)
D	Campaign Mission Design	Asteroid Property Inference (orbital) Integrated Risk Assessment Mitigation Mission Response Decisions	• Available or needed launch assets (vehicles, sites) • Spacecraft and mitigation system properties • Mission timelines (launch dates, flight times, intercept dates, recon timeframes) • Mitigation requirements (ΔV requirements, disruption requirements)
E	Integrated Risk Assessment	Civil Defense	• Damage region plots for risk percentiles

* Ongoing development

Standoff NED Model (from J.Wasem/LLNL) (1/2)

$$A_1 = \sqrt{yrd^2/(r+d)}$$

$$A_2 = \sqrt{1 - \sqrt{(1+d/r)(1+d/r) - 1}/(1+d/r)}$$

$$A_3 = \sqrt{(2r/d)\left(1 + ln\left(y/((3.16 \times 10^{-4})d^2)\right)\right) - ((1+(2r/d))(ln(1+(2r/d))))}$$

$$\Delta v = \tfrac{2}{\varrho}\tfrac{5750}{r^3} A_1 A_2 A_3$$

where

Δv is the magnitude of the change-in-velocity imparted to the asteroid via the standoff nuclear detonation. Note that the *direction* of the Δv must be selected independently of these equations in order to specify the full Δv vector. (i.e., $\Delta \bar{v}$), which is needed for propagating the motion of the deflected asteroid and computing by how much it is deflected from Earth (i.e., its perigee altitude when it encounters Earth around the date when the undeflected asteroid would originally have hit Earth). The units of Δv given by this equation are cm/s.

y is the yield of the nuclear device in units of kT

r is the radius of the (assumed spherical) asteroid in units of meters

d is the distance between the nuclear device and the asteroid's surface in units of meters at the time of detonation

ϱ is the bulk density of the asteroid in units of g/cm^3

Standoff NED Model (from J.Wasem/LLNL) (2/2)

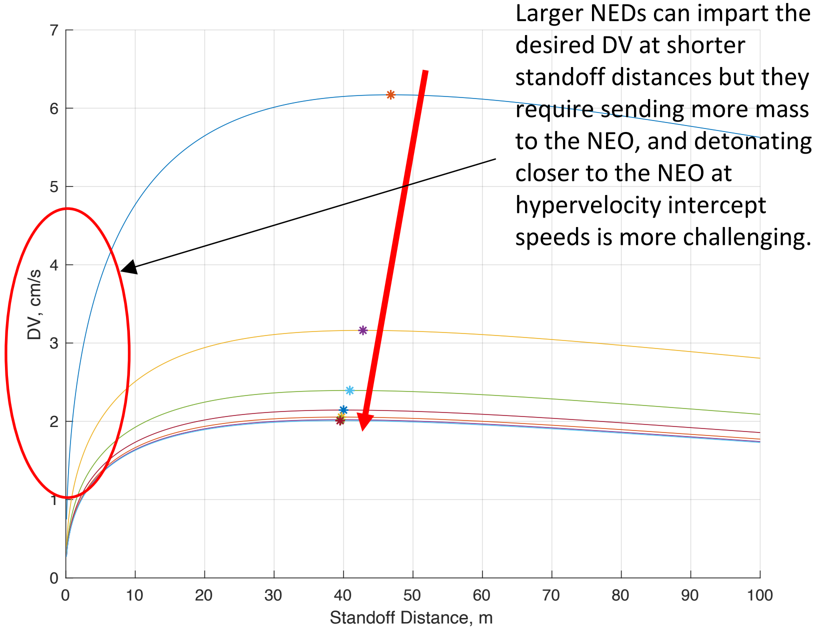
The ranges of values for y, r, and d for which this model is valid are:

- Yield can be set very low (e.g., a few kT), or very high (e.g., >100 MT), without loss of model accuracy. When yield is set too low for the given scenario, the model will give imaginary results.
- d can range from 0 (i.e., on the asteroid's surface) to larger values; the results of the model become imaginary when d is too large for the specified scenario.
- r can be set very low (e.g., a few meters). r can also be set to large values, and it is likely that the achieved deflection change-in-velocity on the asteroid will become too small to be worthwhile well before a large value of r exceeds the mathematical limits of the model.

Solving For Minimum Required NED Yield

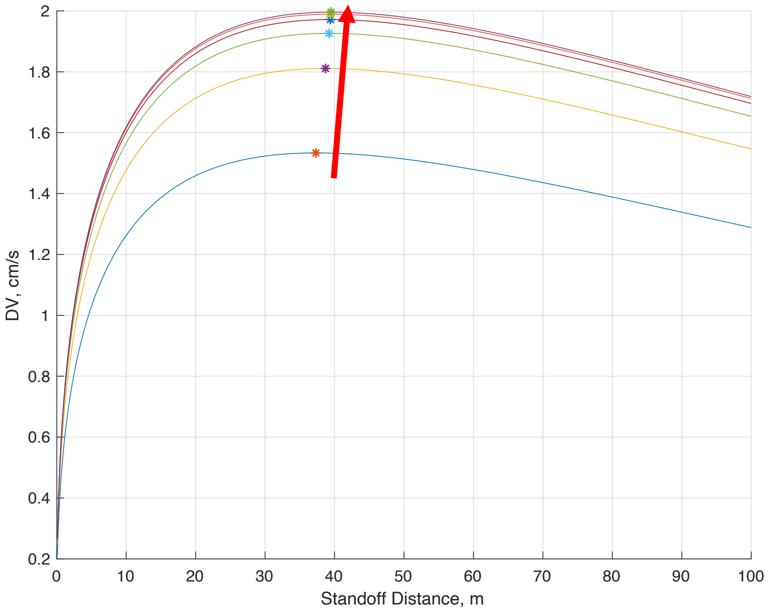
- The minimum required NED yield for imparting a given ΔV should achieve that value of ΔV at its peak (at the standoff detonation distance that maximizes ΔV imparted to the given NEO).
- The minimum NED yield with peak ΔV at the desired value can readily be solved for iteratively.
- The examples below are for an NEO with diameter and bulk density of 340 m and 2 g/cm³, respectively. The desired imparted ΔV is 2 cm/s.

Converging from above:



Larger NEDs can impart the desired DV at shorter standoff distances but they require sending more mass to the NEO, and detonating closer to the NEO at hypervelocity intercept speeds is more challenging.

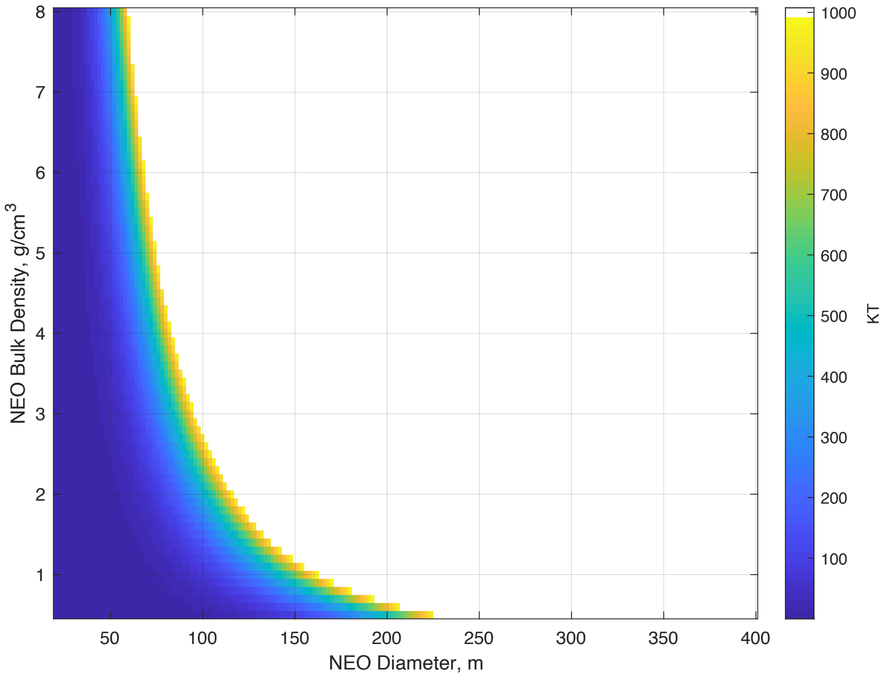
Converging from below:



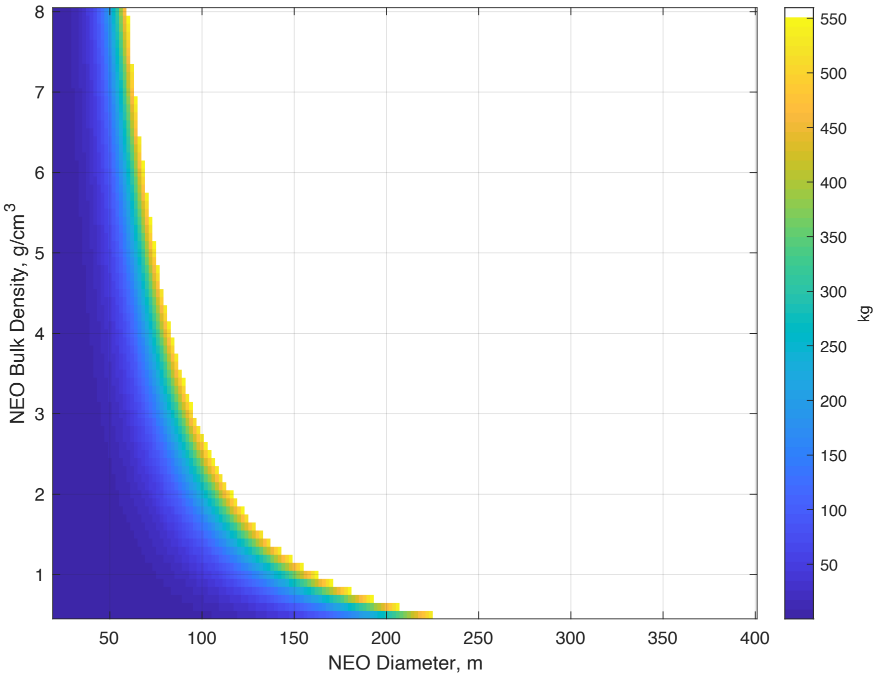
Parametric Analysis of Disrupt-able NEOs

- Several representative NED yields were studied parametrically, to ascertain the span of NEO diameters and bulk densities for which each particular NED yield can impart at least 10× NEO surface escape velocity, for robust disruption.
- NED yields of 1000, 2000, 3000, 4000 KT.
- NEO diameter spanning 20 to 400 m.
- NEO bulk density spanning 0.5 to 8 g/cm^3.
- NED mass is computed from yield using the LANL-provided heuristic of 1.8 KT/kg.

NEOs Disrupt-able with a 1000 KT NED

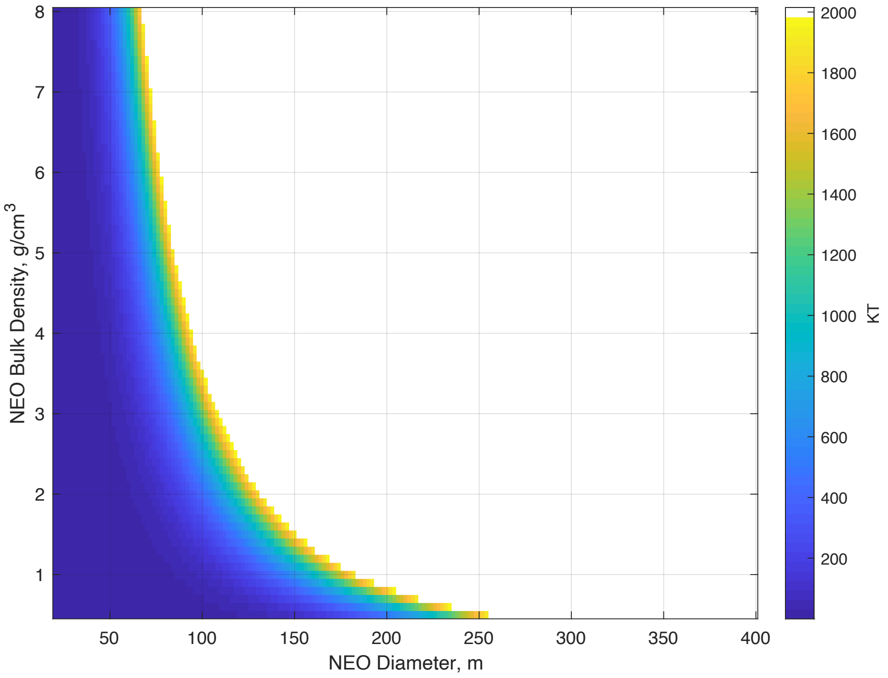


NED yield (up to 1000 KT) required for disruption NEOs of given diameter & density.

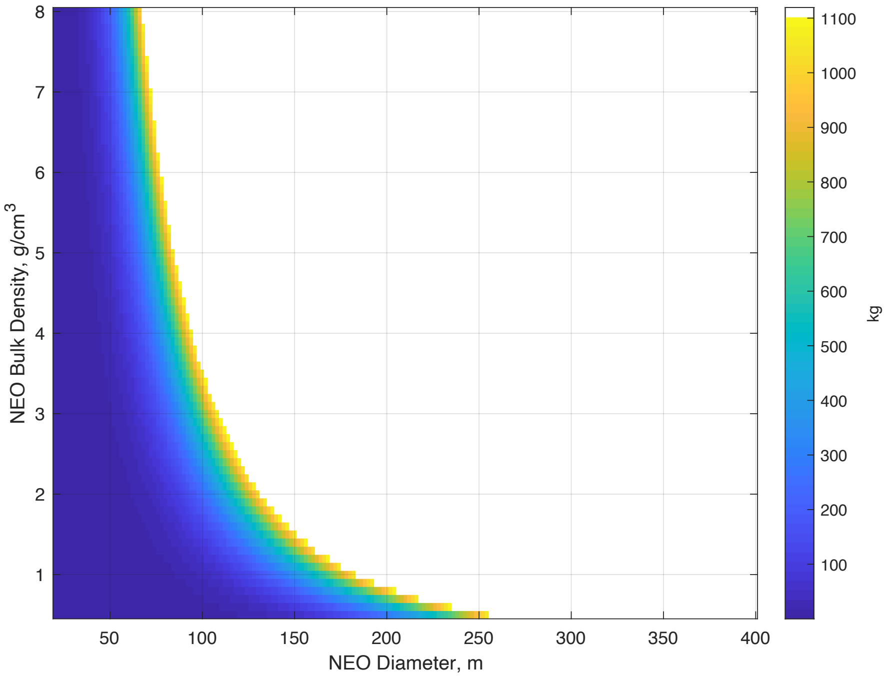


NED mass (for up to 1000 KT) required for disruption NEOs of given diameter & density.

NEOs Disrupt-able with a 2000 KT NED



NED yield (up to 2000 KT) required for disruption NEOs of given diameter & density.



NED mass (for up to 2000 KT) required for disruption NEOs of given diameter & density.

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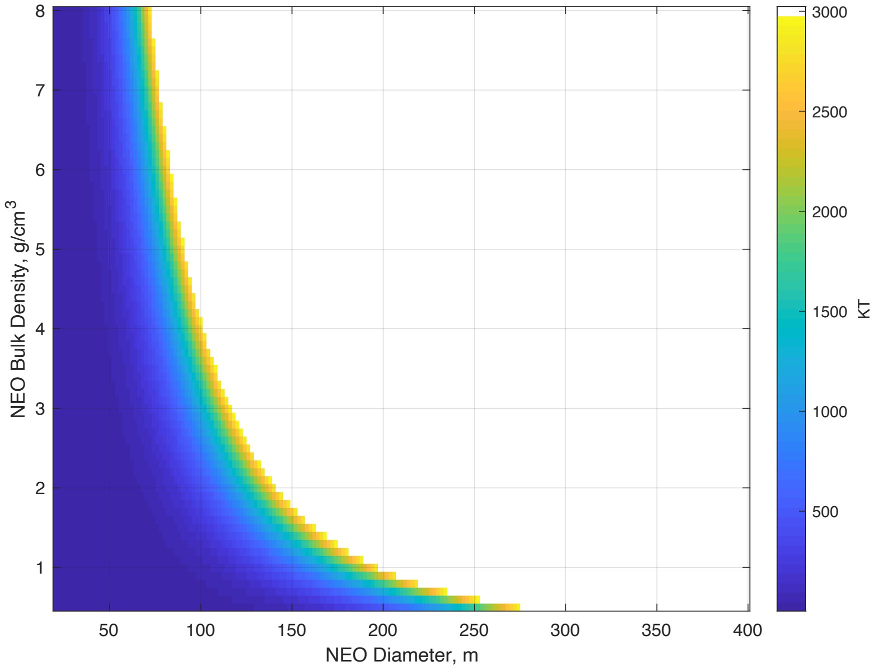
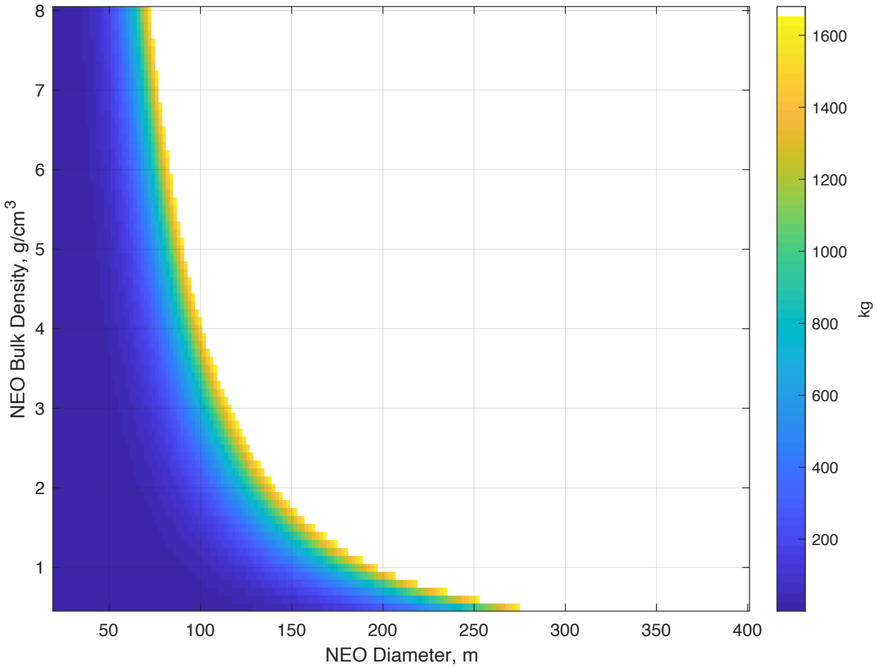
NEOs Disrupt-able with a 3000 KT NED



NED yield (up to 3000 KT) required for disruption NEOs of given diameter & density.



NED mass (for up to 3000 KT) required for disruption NEOs of given diameter & density.

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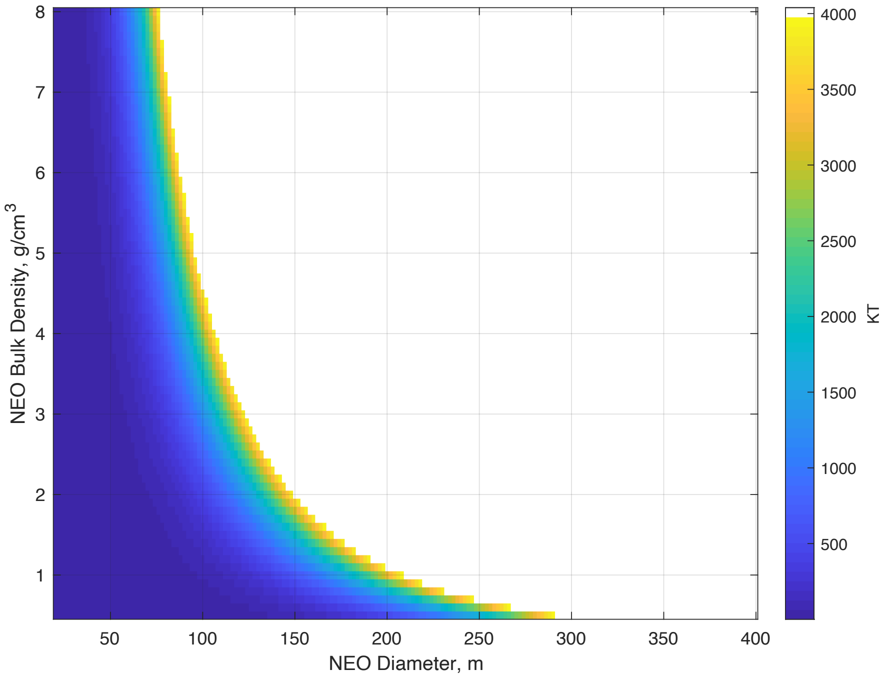
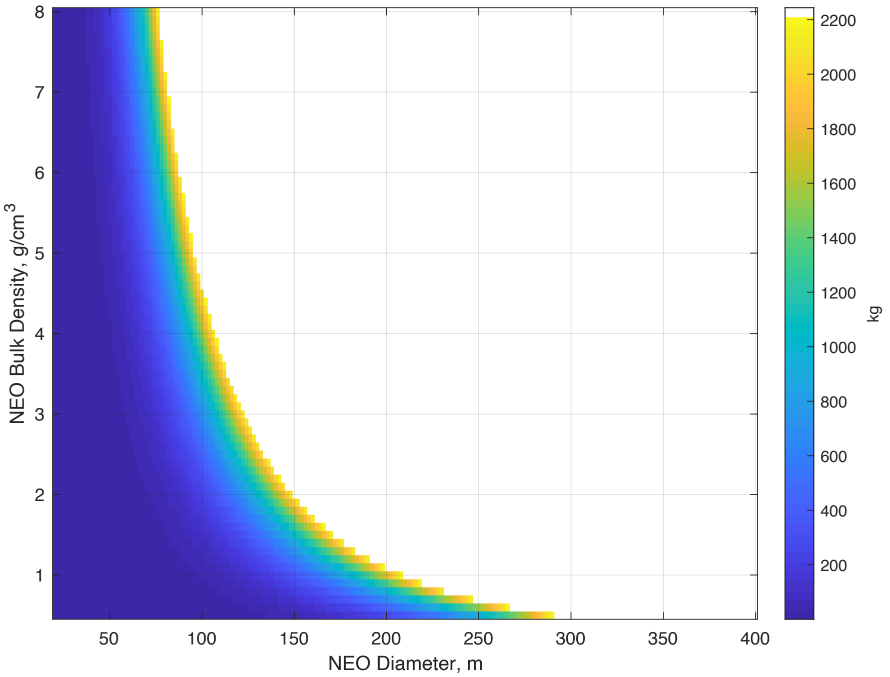
NEOs Disrupt-able with a 4000 KT NED



NED yield (up to 4000 KT) required for disruption NEOs of given diameter & density.



NED mass (for up to 4000 KT) required for disruption NEOs of given diameter & density.

Remarks on Disrupt-able NEO Analysis

- At anticipated common/average NEO bulk densities (e.g., around ~2 g/cm^3), robust disruption of an NEO via a NED with yield up to ~several MT appears to only be feasible for NEO diameters up to ~100-150 m.
- An NEO with lower bulk density closer to ~1 g/cm^3 may be disrupt-able via a ~several MT NED, up to NEO diameters of up to ~150-200 m.
  - Note that carbonaceous NEOs Bennu (B-type) and Ryugu (C-type) both have a bulk density of about 1.19 g/cm^3.
- Even very dense (e.g., iron) NEOs may be robustly disrupted up to ~70-100 m NEO diameter.
- This is all because NEO mass scales cubically with diameter but only linearly with bulk density.

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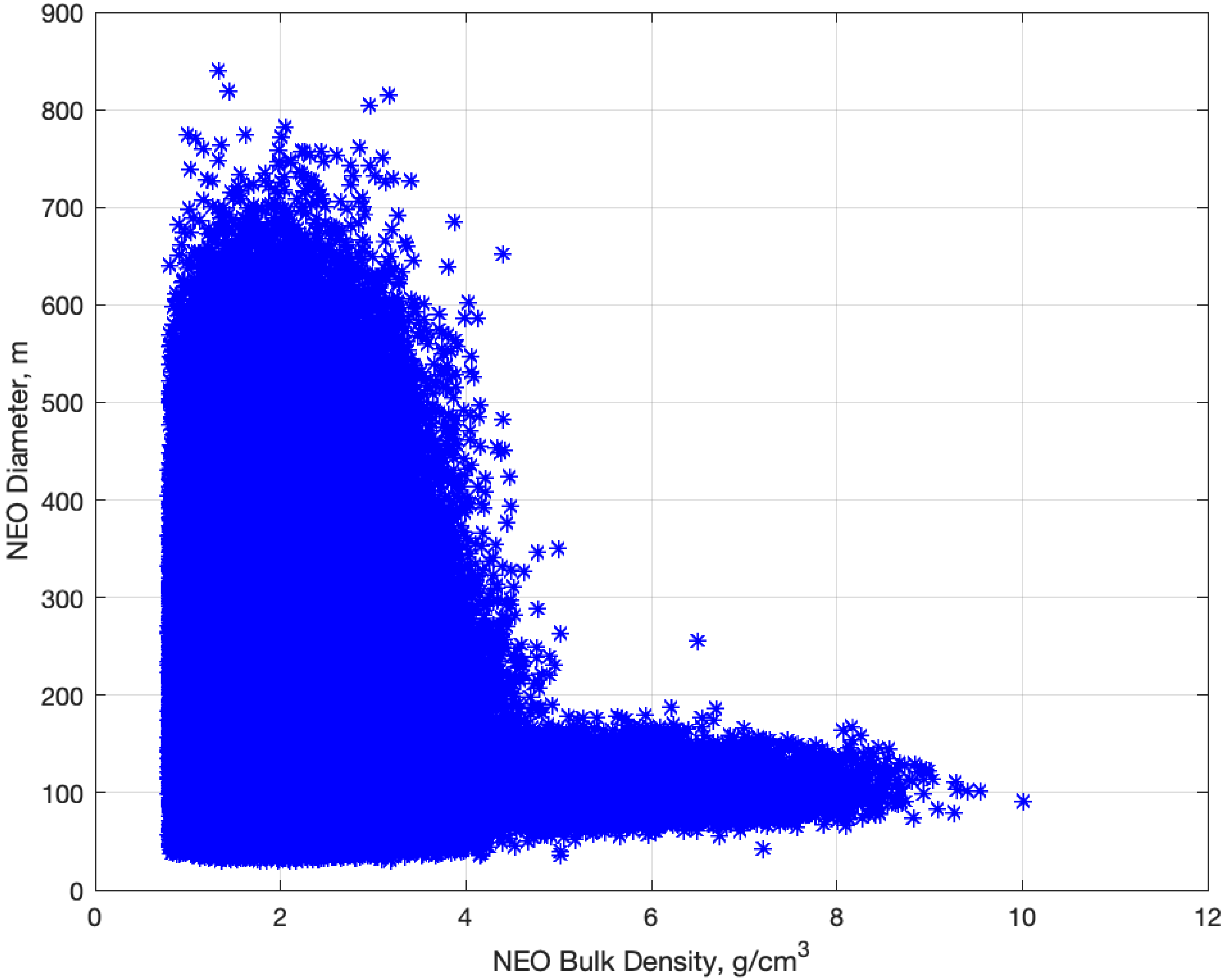
2021 PDC Asteroid Bulk Density vs. Diameter



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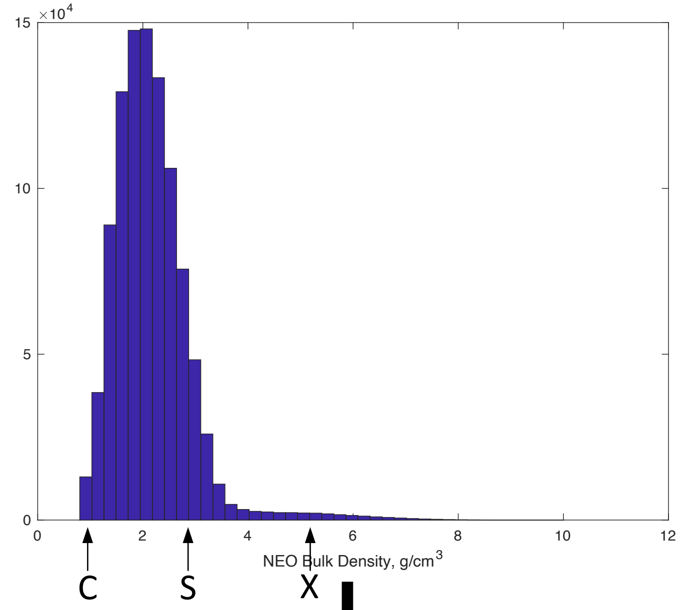
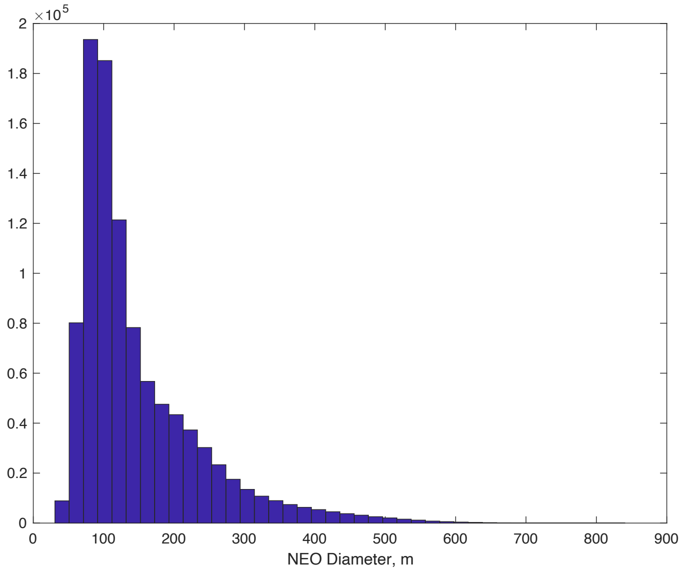
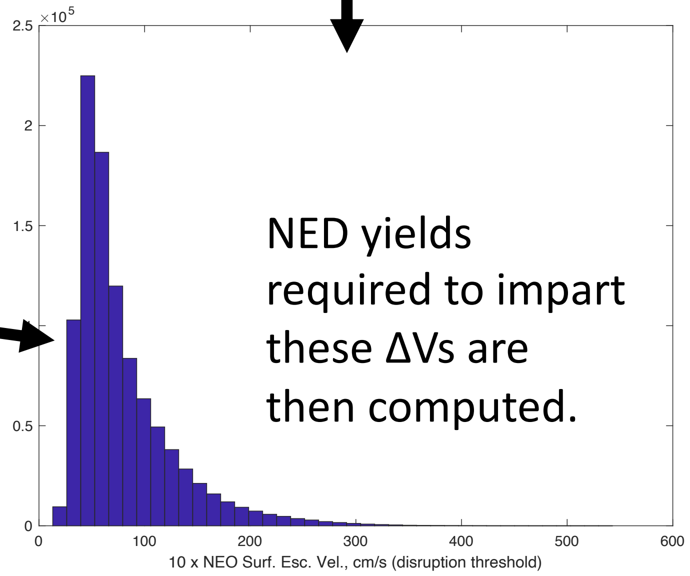
Asteroid Diameter & Bulk Density Set Disruption Requirements

- 2021 PDC physical property distributions from NASA/ARC: Jessie Dotson & Lorien Wheeler
- Note the significant uncertainties in asteroid diameter and density.
- The diameter and density are used to compute the asteroid surface escape velocity.
- **<u>The requirement for robust disruption is to impart ΔV of at least 10✕ surface escape velocity to the asteroid.</u>**
- Robust disruption means that the NEO is disrupted with sufficient energy to break it into fragments that are small enough and scattered widely enough to not pose a significant threat to the Earth-Moon system.
- This is only a heuristic, and detailed analysis is required in practice to assess disruption requirements, etc.
- For computing NED yield / mass, we use the heuristic of 1.8 KT/kg provided by Los Alamos National Laboratory (LANL).

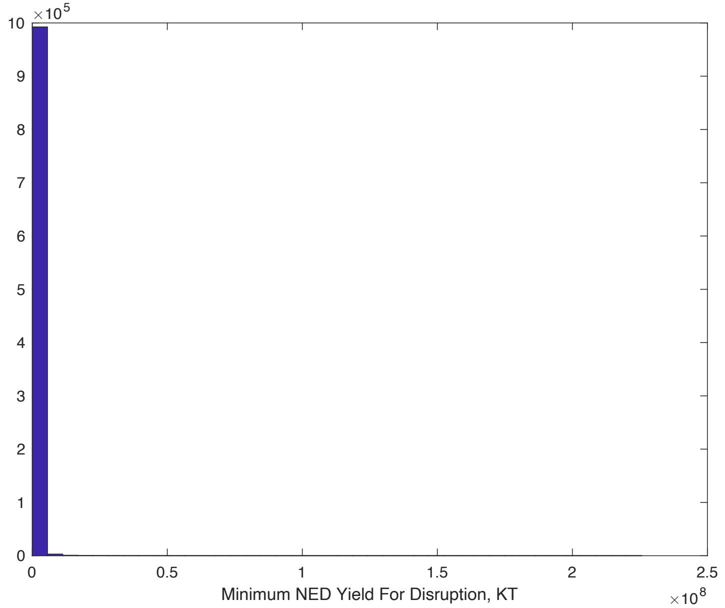


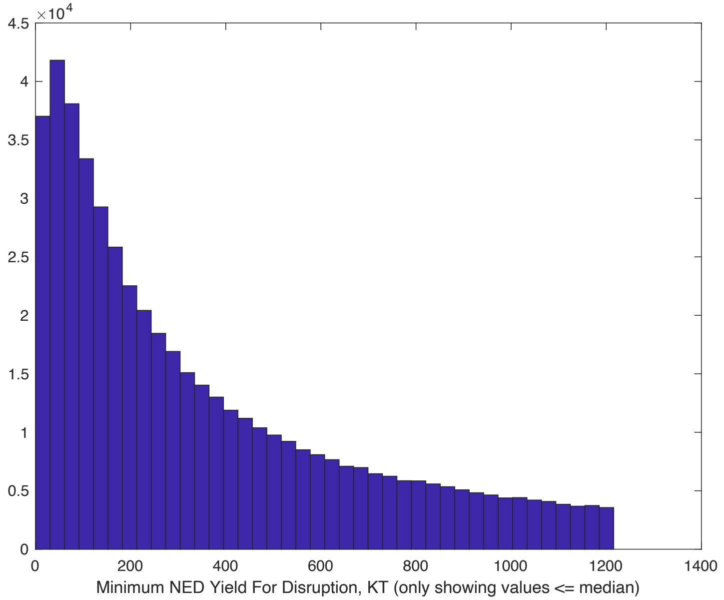




NED yields required to impart these ΔVs are then computed.

Distribution of NED Yields Required for Asteroid Disruption





Minimum required NED yield: 0.31 KT

- NEO diameter: 38.2 m
- NEO bulk density: 0.832 g/cm^3
- ΔV imparted: 13 cm/s

Mean required NED yield: 138 MT
Std. Dev. of reqd. NED yield: 1200 MT

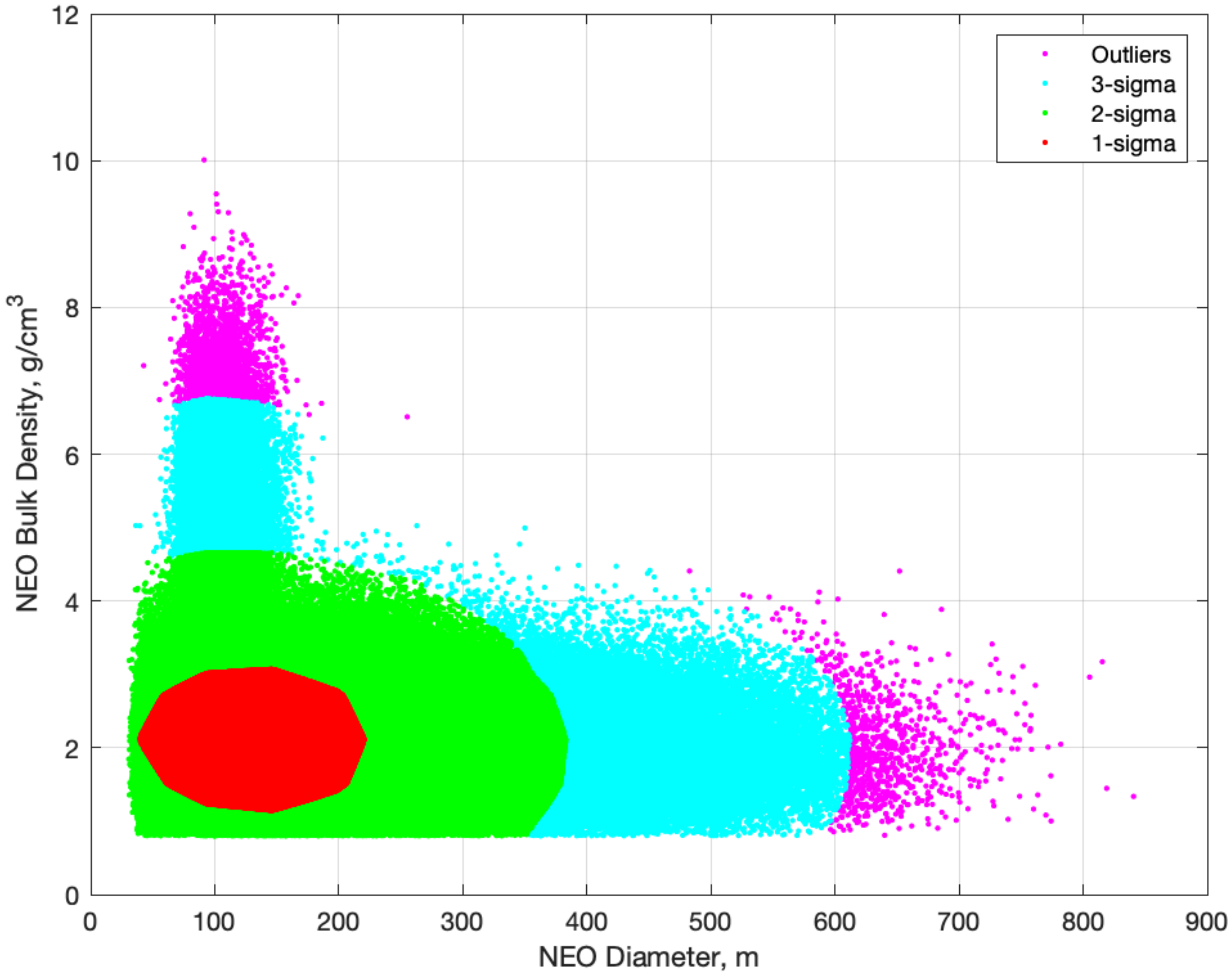
<u>Median required NED yield: 1.22 MT</u>

Maximum required NED yield: 226000 MT

- NEO diameter: 815.5 m
- NEO bulk density: 3.172 g/cm^3
- ΔV imparted: 543 cm/s

- **Remarks:**
  - For computing NED yield / mass, we use the heuristic of 1.8 KT/kg provided by Los Alamos National Laboratory (LANL)
  - <u>Both the mean and maximum required NED yield values are completely impractical.</u>
  - This distribution is quite skewed, with a very long tail, and is, therefore, difficult to deal with.
  - The <u>median</u> required NED yield value is reasonable (in terms of availability of such a NED).
  - **In practice, if the need ever arose to disrupt a large NEO, then a different type of NED may be required.**

Asteroid Diameter vs. Density (w/ confidence levels)



Statistical Analysis of NED Yield Requirements

Statistics For NED Yields Required For Asteroid Disruption

	1σ NEOs	2σ NEOs	3σ NEOs	Outlier NEOs
Minimum	3.3 KT, 1.8 kg	0.3 KT, 0.17 kg	18.6 KT, 10.3 kg	0.116 MT, 65 kg
Median	0.61 MT, 340 kg	27 MT, 15000 kg	848 MT, 470000 kg	31 MT, 17000 kg
Mean	3.2 MT, 1800 kg	100 MT, 55000 kg	2000 MT, 1060000 kg	7000 MT, 3600000 kg
Maximum	52 MT, 29000 kg	1800 MT, 1000000 kg	35000 MT, 19000000 kg	226000 MT), 126000000 kg

Remarks:

- For computing NED yield / mass, we use the heuristic of 1.8 KT/kg provided by Los Alamos National Laboratory (LANL)
- The large uncertainties in NEO physical properties drive large spreads of possible asteroid diameters and densities.
- Additionally, the ways in which asteroid diameter and bulk density are correlated in the properties model results in long tails in the distribution of NED yields required for disruption.
- Median values of required NED yield for disruption are significantly smaller than mean values.
- The required NED yield to disrupt the worst case 1σ asteroid is probably impractically large: 52 MT.
- **Thus, no practical NED yield can be recommended for confidence of asteroid disruption at the 1σ, 2σ, or 3σ level.**
- **In practice, if the need ever arose to disrupt a large asteroid then a different type of NED might be required.**

Rapid Launch Capabilities are Not Yet Available

- Enhanced NEO detection systems, e.g., NASA's NEO Surveyor space-based telescope mission currently under development, will affordably enable us to detect incoming NEOs much farther in advance and help prevent us from being confronted with short-warning scenarios in the first place. This should remain our next priority.

- However, incoming comets, by their nature, are not readily detectable far in advance by any system. Additionally, late detection of an incoming asteroid cannot be ruled out.

- If confronted with a real-life short warning situation like this 2021 PDC hypothetical scenario, our current infrastructure for spacecraft development and launch would not enable us to deploy either reconnaissance or mitigation spacecraft on such short notice.
    - Nevertheless, for the sake of discussion only, we will describe space mission options for the 2021 PDC scenario that ***could*** hypothetically be available to decision makers **if** our planetary defense space mission infrastructure were upgraded to enable mission deployment within ~2 to 6 weeks of Authority to Proceed (ATP). **Again, we currently do not have such rapid launch capability.**

Early NEO detection and rapid response spacecraft launch are both key capabilities for an effective planetary defense.

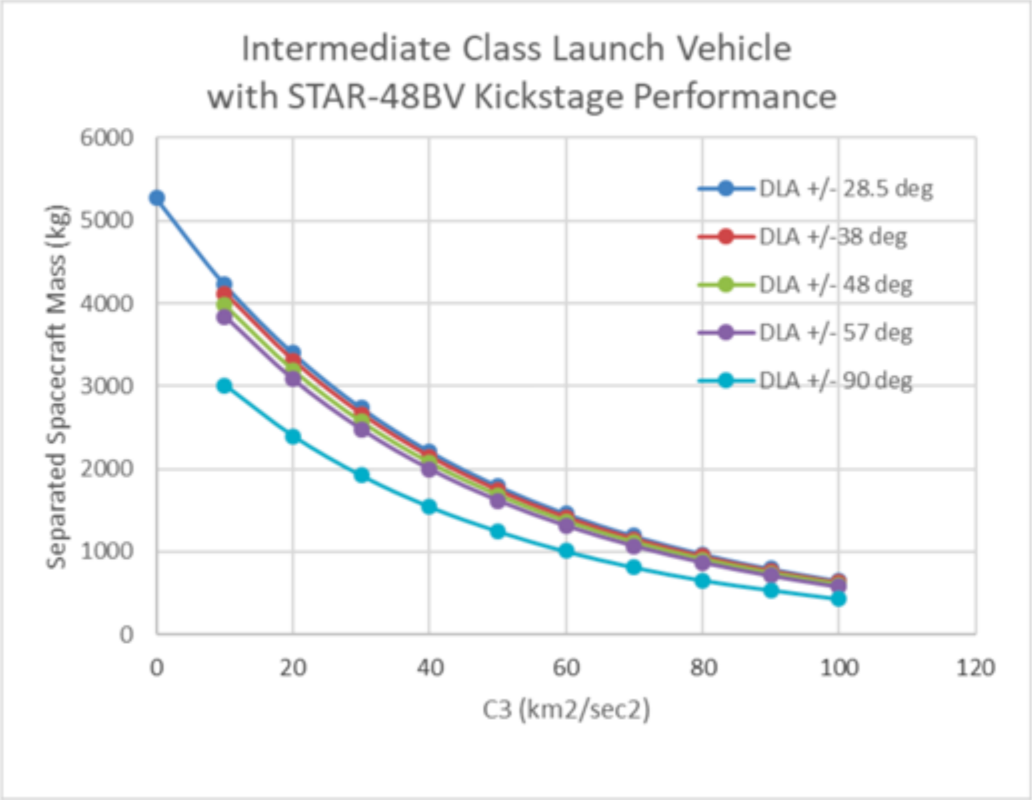
Enhanced NEO detection systems are affordable, technologically ready, and under development now, so they are our next priority.

Mission Design Constraints and Assumptions

- Launch no earlier than 2021-05-01 (12 days after discovery).
- Reach the 2021 PDC asteroid no later than 2021-09-20 (1 month before Earth encounter).
  - If a mission to disrupt the asteroid is deployed, this provides at least 1 month for the disrupted asteroid material to spread out and avoid interaction with Earth or Earth/Moon-orbiting assets.
    - Further studies are required to better understand the actual timing requirements associated with asteroid disruption.
    - In a real situation, detailed analysis and modeling of the specific scenario at hand would be required (and would be limited by the data available on the NEO).
    - The disruption impulse may be applied along the optimal deflection direction to optimize the dispersion of the disrupted asteroid material.
- No constraint on declination of launch asymptote (DLA).
  - NASA/KSC has provided preliminary performance estimates for launch with DLA up to ±90° from Cape Canaveral Air Force Station (CCAFS).
- No constraint on asteroid-relative speed for flyby missions.
  - However, the higher the flyby speed, the higher the probability of mission failure.
- No constraint on Sun phase angle @ flyby/rendezvous.
  - However, the higher the phase angle, the higher the probability of mission failure.
- Sun-Earth-Spacecraft (SES) angle @ flyby/rendezvous ≥3°.
  - Ensures a viable radio link is available with the Deep Space Network (DSN) antennas.
- Spacecraft trajectory optimization seeks to maximize the amount of spacecraft mass delivered to the asteroid, subject to the above constraints.

Launch Vehicle Performance

- We use a launch performance model for a re-purposed commercial intermediate class launch vehicle with a STAR-48BV kickstage, able to handle declination of launch asymptote (DLA) >28.5° for Cape Canaveral Air Force Station (CCAFS) launches.
  - Launch vehicle performance data provided by NASA/KSC: Bill Benson.
  - The amount of time required to prepare such a vehicle for launch during a rapid response planetary defense scenario is currently unknown but is being analyzed.

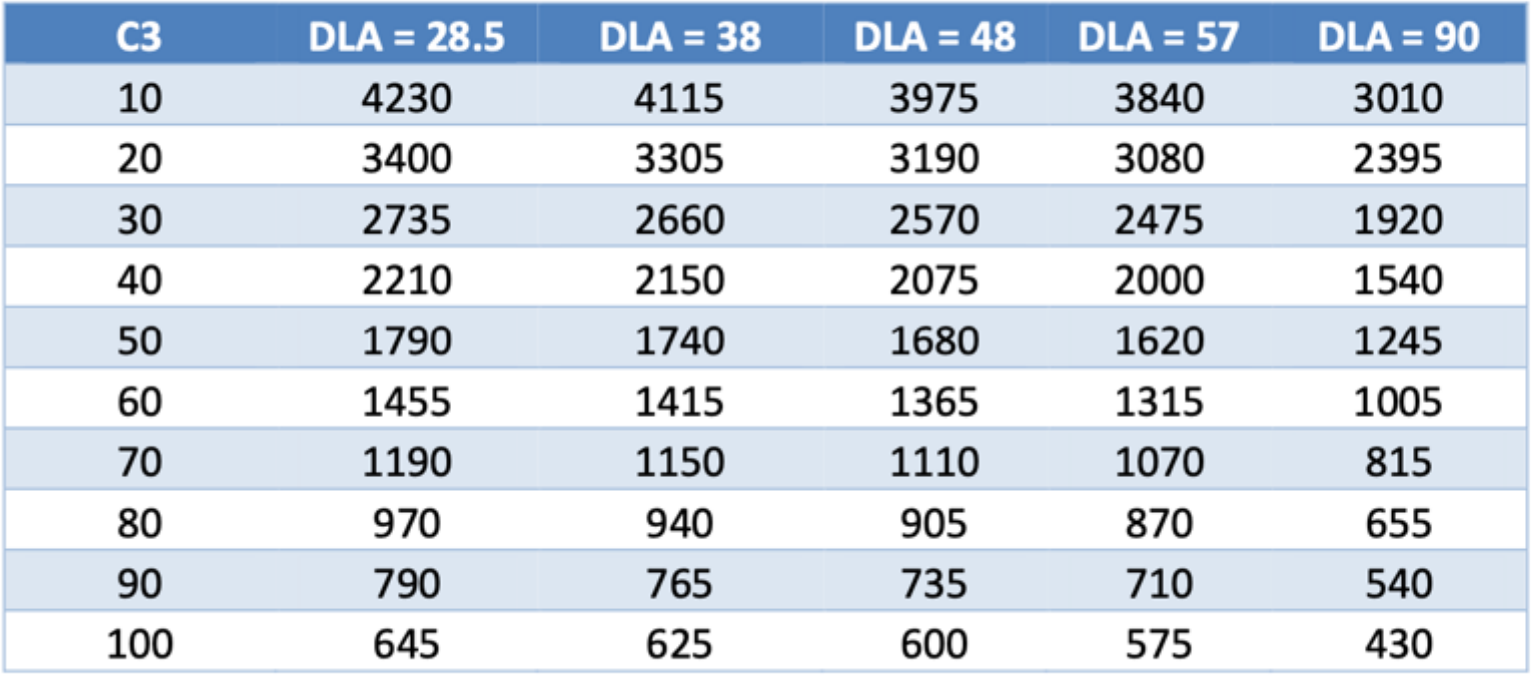


Please direct any questions regarding this performance assessment to:

William Benson
NASA Launch Services Program
Phone: 321-867-9455
Email: William.W.Benson@nasa.gov

HYPOTHETICAL EXERCISE ONLY

Intermediate Launch Vehicle w/Kickstage High Energy Performance to various DLAs



C3	DLA = 28.5	DLA = 38	DLA = 48	DLA = 57	DLA = 90
10	4230	4115	3975	3840	3010
20	3400	3305	3190	3080	2395
30	2735	2660	2570	2475	1920
40	2210	2150	2075	2000	1540
50	1790	1740	1680	1620	1245
60	1455	1415	1365	1315	1005
70	1190	1150	1110	1070	815
80	970	940	905	870	655
90	790	765	735	710	540
100	645	625	600	575	430

*Due to range safety considerations, assume DLA = 90 performance for all DLA’s higher than 57 deg

Please direct any questions regarding this performance assessment to:

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HYPOTHETICAL EXERCISE ONLY

Launch Vehicle Ground Rules / Assumptions

- 3-sigma guidance reserves.
- Instantaneous launch attempt. Finite window accommodations may significantly reduce performance for missions with inertially fixed targets.
- STAR-48BV-based kickstage is assumed. All masses required to make this a complete stage such as separation systems, vehicle adapters, avionics, attitude control systems, etc. have been accounted for in this performance quote. Note that this is a non-standard service that will incur additional cost and risk.
- 2 payload fairing doors.
- Payload mass greater than 700 kg may require heavier 3rd stage structural masses than that assumed in this performance quote, resulting in performance impacts.
- 160 km (86 nmi) park orbit perigee altitude.
- This performance does not include the effects of orbital debris compliance, which must be evaluated on a mission-specific basis. This could result in a significant performance impact for missions in which launch vehicle hardware remains in Earth orbit.
- Trajectories for DLA's higher than 57 degrees may require modification to be compliant with range safety requirements, resulting in performance impacts.
- Launch from SLC-40 at CCAFS (Cape Canaveral Air Force Station).

Please direct any questions regarding this performance assessment to:

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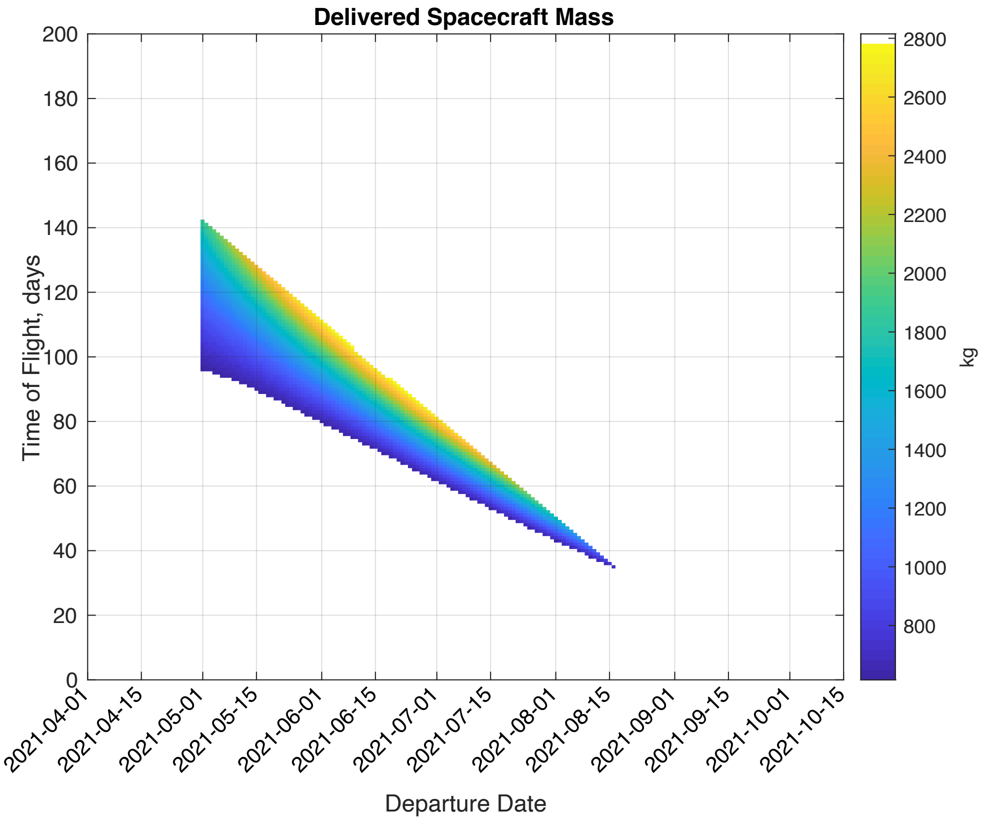
Spacecraft Assumptions

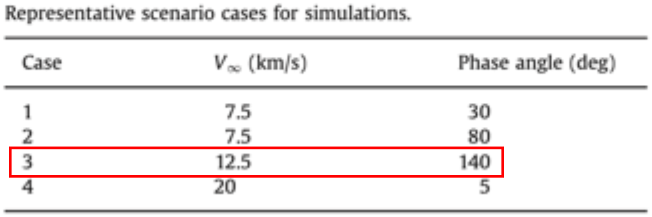
- We assume using the components of a DART-like spacecraft for purposes of estimating spacecraft mass and modeling low-thrust solar electric propulsion (SEP) system performance.
- The spacecraft components would have to be arranged around the NED payload, but the mechanical design of the spacecraft is beyond the scope of this study. This should be considered in future work.
- We also consider three spacecraft configurations:
  - DART-like, but flying ballistic trajectories using conventional chemical propulsion. (storable hypergolic bipropellant with a specific impulse (Isp) of 310 seconds for the rendezvous analysis) and not carrying the low-thrust propulsion system hardware.
  - DART-like, using the nominal DART propulsion system (NEXT-C ion engine).
  - DART-like, but using off-the-shelf commercial propulsion (XIPS-25 ion engine) and with more solar array power.
- For nuclear missions (deflection or disruption), we assume the DART-like spacecraft will carry as large a nuclear explosive device (NED) as possible, given the spacecraft mass and the delivered mass capability of the trajectory solution.
  - For computing NED yield / mass, we use the heuristic of 1.8 KT/kg provided by Los Alamos National Laboratory (LANL).

Delivered Spacecraft Mass for Flybys

- The launch date to maximize ballistic flyby delivered mass is 2021-06-14.
  - 2787 kg delivered mass, arrival phase angle 125.9°, arrival speed 10.7 km/s.
- Later launches are possible, but delivered mass performance falls off rapidly and arrival speeds increase
  - Launch 2021-07-01: 2662 kg delivered mass, arrival phase angle 123.4°, arrival speed 12.2 km/s.
  - Launch 2021-07-15: 2372 kg delivered mass, arrival phase angle 121.4°, arrival speed 13.5 km/s.
- Low-thrust propulsion can improve flyby delivered mass only slightly, due to the very short flight times. The trends in launch dates, etc., are very similar to the trends in ballistic mission options.

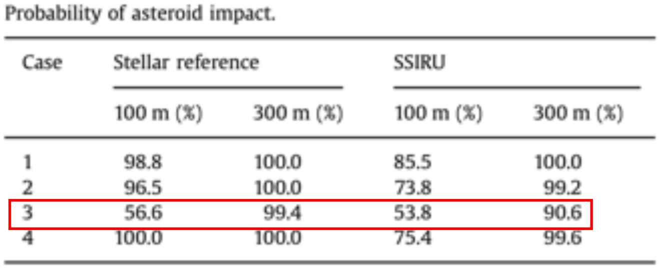


- Terminal GNC may be challenging if the asteroid's size is much less than ~300 m.



Representative scenario cases for simulations.

Case	V_∞ (km/s)	Phase angle (deg)
1	7.5	30
2	7.5	80
3	12.5	140
4	20	5



Probability of asteroid impact.

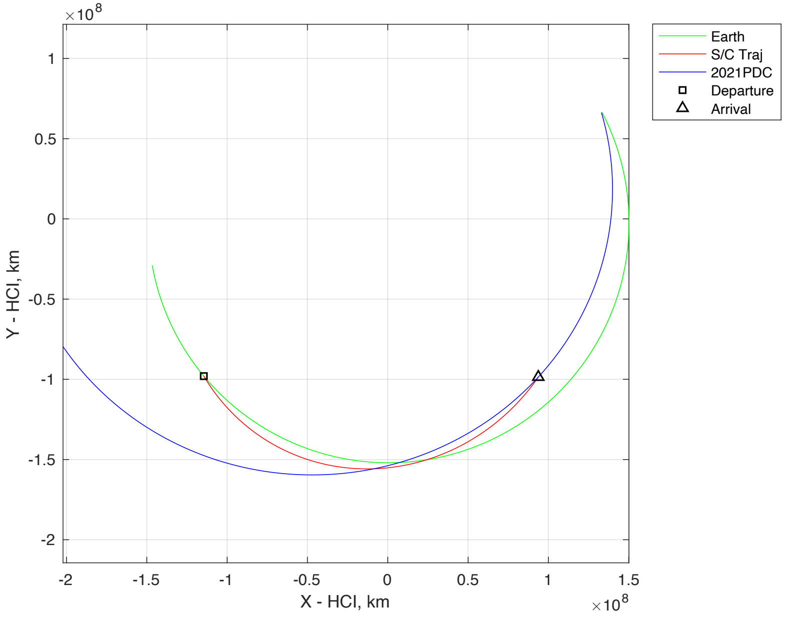
Case	Stellar reference		SSIRU	
	100 m (%)	300 m (%)	100 m (%)	300 m (%)
1	98.8	100.0	85.5	100.0
2	96.5	100.0	73.8	99.2
3	56.6	99.4	53.8	90.6
4	100.0	100.0	75.4	99.6

Tables from: Bhaskaran & Kennedy (2014). Closed loop terminal guidance navigation for a kinetic impactor spacecraft. *Acta Astronautica* 103, 322-332.

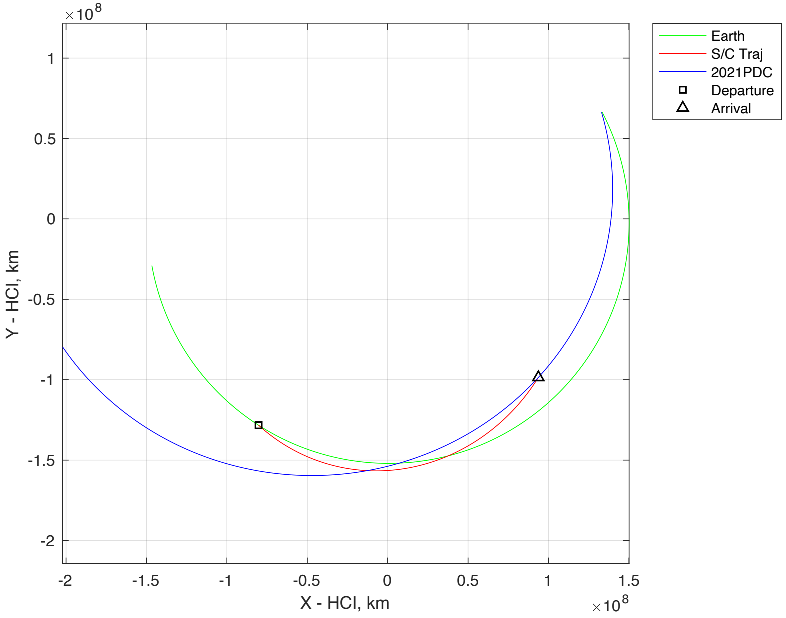
Flyby Reconnaissance Options

- Earlier launch dates / earlier arrival dates are possible, with reduced delivered spacecraft mass that should be sufficient for reconnaissance but not enough for nuclear disruption.
- Examples:

Launch 2021-05-01
Arrive 2021-08-20
919 kg delivered spacecraft mass
6.72 km/s flyby speed
118.6° flyby phase angle

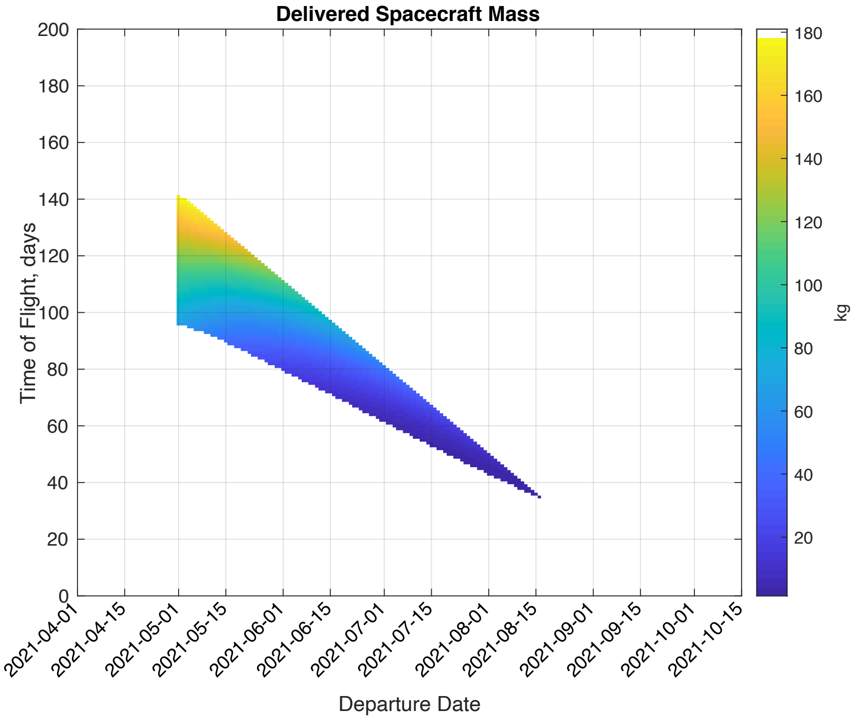


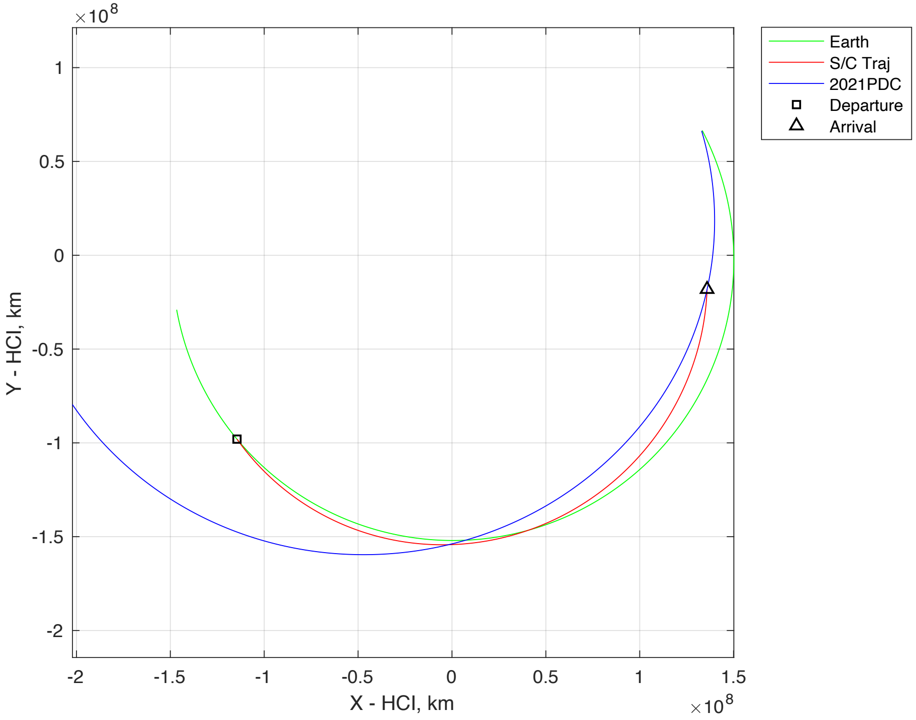
Launch 2021-05-19
Arrive 2021-08-20
823 kg delivered spacecraft mass
8.73 km/s flyby speed
115.8° flyby phase angle



Delivered Spacecraft Mass for Rendezvous Missions

- The maximum delivered mass for a ballistic rendezvous spacecraft is 179 kg, which is insufficient.
- Low-thrust propulsion improves delivered mass somewhat for rendezvous, but not enough to make a rendezvous mission practical. This is due to the very short flight times.





Summary of Mission Options

- Rendezvous missions are impractical.
- The flight times are too short for low-thrust propulsion to make a significant difference in delivered NED performance.
- Flyby recon missions delivering ~800-900 kg recon spacecraft are available with earlier launch & arrival dates.
- The deliverable NED yield is ~4.3 to ~4.5 MT.
- The largest size asteroid that can be disrupted ranges from ~100 m to ~210 m, for asteroid densities ranging from 5 g/cm^3 down to 1 g/cm^3.

	Flyby			Rendezvous		
	NEXT-C	**XIPS-25**	**Ballistic**	**NEXT-C**	**XIPS-25**	**Ballistic/Chemical**
Launch Date (Days After Discovery)	2021-06-15 (X)	2021-06-10 (X)	2021-06-14 (X)	2021-05-01 (12)	2021-05-01 (12)	2021-05-01 (12)
Flight Time (Days)	97	101	98	142	142	142
Arrival Date (Days Before Earth Encounter)	2021-09-20 (30)	2021-09-20 (30)	2021-09-20 (30)	2021-09-20 (30)	2021-09-20 (30)	2021-09-20 (30)
C3 (km^2/s^2)	25.5	22.5	27.8	100	100	43.5
DLA (degrees)	38	38		38	38	56.5
Asteroid-Relative Intercept Speed (km/s)	11	10.9	10.7	-	-	-
Sun Phase Angle (degrees)	125.2	125.3	125.9	-	-	-
Launch Mass (kg)	2945	3143	2787	210	450	1870
Total Delivered Mass (kg)	2912	3073	2787	158	344	179
Delivered NED Mass (kg)	2402	2493	2384	-	-	-
Delivered NED Yield (MT)	4.3	4.5	4.3	-	-	-
Max. Disruptable Asteroid Size (m) w/ density 1 g/cm^3	211	212	211	-	-	-
Max. Disruptable Asteroid Size (m) w/ density 1.5 g/cm^3	174	175	173	-	-	-
Max. Disruptable Asteroid Size (m) w/ density 2.5 g/cm^3	136	137	135	-	-	-
Max. Disruptable Asteroid Size (m) w/ density 5 g/cm^3	97	98	97	-	-	-

Summary of Findings and Recommendations

- The significant uncertainties in 2021 PDC’s physical properties, especially size and mass, make it very difficult to define mitigation mission requirements or assess the likelihood of mitigation mission success.
- Current real-world infrastructure for spacecraft development and launch would not enable us to deploy either reconnaissance or mitigation spacecraft in such a short warning scenario if this were a real situation.
- However, **if** rapid launch were possible then the only practically viable mitigation approach would be robust disruption of 2021 PDC via nuclear explosive device (NED).
  - Deflection is not practical in this scenario because it would require too much ΔV be imparted to the NEO, and too far in advance of Earth encounter.
- While rendezvous is generally preferred, the rapid response timeline and inclination of the asteroid’s orbit make rendezvous impractical, necessitating flyby missions that encounter the asteroid at high relative speeds and high Sun phase angles.
  - This makes spacecraft guidance, navigation, and control especially challenging.
- **Deploying a nuclear disruption mission appears to be the only realistic mitigation possibility (if launch were possible). It can significantly reduce the risk of impact damage even in the face of substantial uncertainty in the asteroid’s properties.**
- **Should a nuclear disruption attempt be foregone, we recommend at least deploying a flyby reconnaissance spacecraft because the data it would provide about the asteroid’s properties would significantly reduce the uncertainties faced by disaster response planners.**

Remarks on Forward Work

- The lack of rapid response launch systems for planetary defense is a severe capability gap.
  - Recommendation: Rapid response capabilities for planetary defense should be developed and demonstrated.
- The combination of high arrival speeds and high Sun phase angles make terminal GNC challenging and prone to error, especially for smaller NEOs (i.e., below ~300 m size).
  - Recommendation: Study the benefits of thermal infrared (IR) terminal guidance sensors for NEO intercept missions. IR sensors are also better able to ascertain the size and shape of the NEO. Uncooled microbolometers with reasonable pixel pitches are becoming more practical, and Forward Looking IR (FLIR) technology offers some lightweight options that could be assessed for performance in space.
- NEO disruption via NED is the only viable mitigation option in very short warning scenarios. However, the ability of typical NEDs to robustly disrupt NEOs may not be adequate for larger NEOs.
  - Recommendation: NED requirements for NEO disruption should be assessed in more detail, including various types of NEDs as appropriate.