Effect of Momentum Transfer Deflection Efforts on Small Body Rotational State

ePoster presentation #76

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Overview

- Introduction & Motivation
- Dynamics of kinetic deflection
- Rotation changes of rotating ellipsoids
- Nuclear detonation deflection
- Deflection results on polyhedral asteroid models
- Conclusions

Abstract

- This ePoster presents an investigation into the effects of momentum transfer deflection methods, specifically kinetic impact and nuclear detonation, on the rotational state of a deflected object. Initially, a simplified model is developed and applied on ellipsoid analogs. The model is then expanded to, and applied on, polyhedral asteroid shapes. The results show the presence of deflection side effects to rotation, introduction of precession, and change in angular velocity magnitude, with the existence of a lever arm between the deflection direction and deflection interface location with respect to the body's center of mass. At times, these rotational side effects can lead to structural instability that might counteract the deflection or completely disaggregate the object.

- Further details can be found in:

Brack, Daniel N., and Jay W. McMahon. "Effects of Momentum Transfer Deflection Efforts on Small-Body Rotational State." Journal of Guidance, Control, and Dynamics 43, no. 11 (2020): 2013-2030, https://doi.org/10.2514/1.G004963

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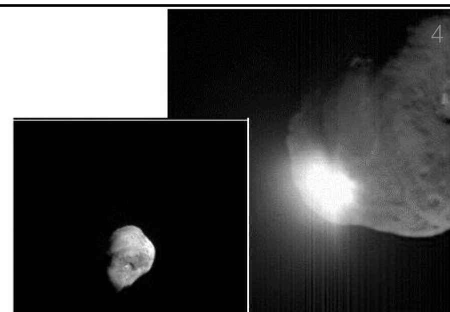
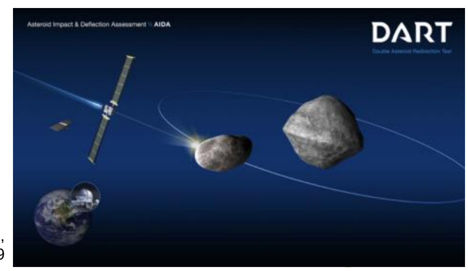
Asteroid deflection

- Perturb a Potentially Hazardous Object (PHO) in its orbit to increase Minimum Orbit Intersection Distance (MOID)
- Highest technological readiness level for direct momentum transfer deflection
  - kinetic interception (Deep Impact, DART)
  - nuclear detonation
- Past research mostly neglected shape and rotation



NASA Planetary Data System, 2006

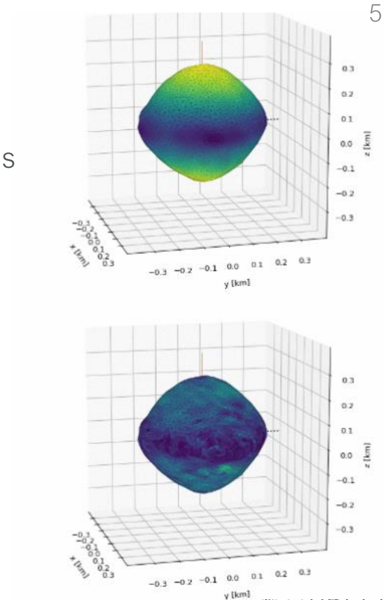


NASA Planetary Defense Office, 2019

In asteroid deflection we seek to slightly perturb a Potentially Hazardous Object (PHO) in its orbit to increase it Minimum Orbit Intersection Distance (MOID).
This type of mission has been researched extensively in the past with direct momentum transfer deflection (kinetic interceptor and nuclear detonation) being the methods with the highest technology readiness level.
For kinetic interception two actual missions can be discussed when talking about deflection – deep impact from 2005 and DART which is planned for 2022.
One aspect that had little research done into is the effect of asteroid shapes and resulting change to the rotational state.

Asteroid rotation and geopotential

- Principal Axis Rotation (PAR)
  - alignment of angular velocity with (max) inertia axis
  - minimum energy state
  - most asteroids are PAR
  - leads to stable surface environment
    - surface accelerations
    - surface slopes
- Fast rotation and/or tumble motion can lead to local fission or complete disaggregation



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When we talk about asteroid dynamical behavior and asteroid environments the link between rotational state and geopotential should be mentioned.
Most asteroids are principal axis rotators, meaning their angular velocity vector is fixed, leading the surface environment to be constant (surface acceleration and surface slopes). This is a minimum energy state that has been reached after energy dissipated from the system.
If an asteroid if led to a fast rotation or tumble state the accelerations and slopes on the surface can be altered such that their magnitude, direction and time variation lead to surface motion, material launch or even complete disaggregation of the asteroid.

Kinetic interception

- Sum of momentum transfer due to impactor and debris

$$P = P_i + P_e = m_i v_i + \frac{n}{\sqrt{2}(n-1)} \left(M_e v_{e,min}\right)$$

- Ejecta mass

$$M_e = m_i \left(\beta - 1\right) \frac{v_i}{v_{e,min}} \frac{\sqrt{2}(n-1)}{n}$$

- Change to PHO velocity

$$\Delta \boldsymbol{v} = \frac{m_i}{M_A} \left(\boldsymbol{v}_i + \left(\beta - 1\right) \left(\hat{\boldsymbol{n}} \cdot \boldsymbol{v}_i\right) \hat{\boldsymbol{n}}\right)$$

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In kinetic interception two factor of the momentum transfer are seen – the momentum introduced by the impacting spacecraft and the momentum taken away by the debris that’s created and ejected from the system.
The amount of debris is a function of the incoming impactor mass and velocity as well as the type and porosity of the asteroid structure, these qualities are empirically quantified using these n and beta factors, n being the power-law slope of the experimentally derived particle ejection velocity vs ejected mass graph and beta being the derived momentum multiplication factor.
Nominal value for n is 1.2 for a porous asteroid and 2-3.5 for beta.
For a given beta the ejecta mass is seen here, where v_e,min is the minimal velocity of ejecta that has escaped the asteroid system
The change in asteroid velocity the magnitude is proportional to the impactor and ejecta masses and velocity. The direction is in the impactor direction with consideration for the surface normal at the point of impact.

Effects on rotating ellipsoids

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- Rotating ellipsoid with point mass

$$[I_0] = [I_{ellipsoid}] + M_e[\tilde{\boldsymbol{r}}][\tilde{\boldsymbol{r}}]^T \qquad \boldsymbol{H}_0 = [I_0]\boldsymbol{\omega}_0$$

- Point mass launch as deflection equivalent

$$v_{eq} = \frac{P}{M_e} \qquad \hat{\boldsymbol{v}}_{eq} = \frac{-\hat{\boldsymbol{v}}_i + (\beta - 1)\,\hat{\boldsymbol{n}}}{|-\hat{\boldsymbol{v}}_i + (\beta - 1)\,\hat{\boldsymbol{n}}|}$$

- Change to angular velocity

$$\boldsymbol{\omega}(t = 0^+) = [I_{ellipsoid}]^{-1}\left(\boldsymbol{H}_0 - M_e\boldsymbol{r} \times (\boldsymbol{r} \times \boldsymbol{\omega}_0 + \boldsymbol{v}_{eq})\right)$$

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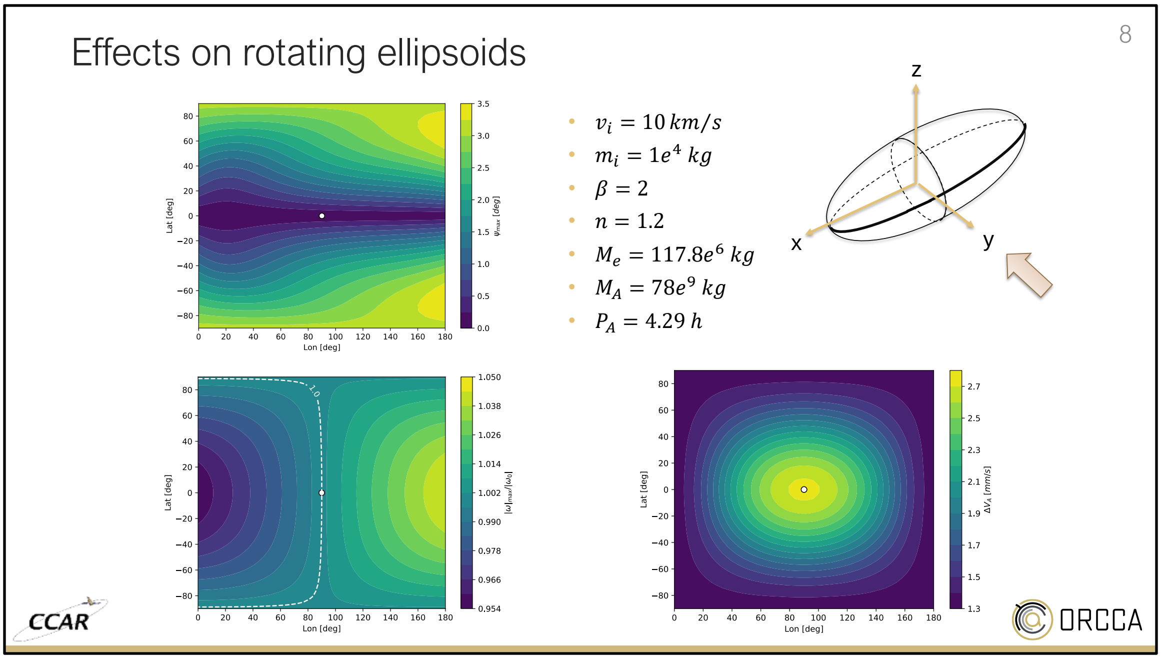
Our first simulated asteroid is a rotating ellipsoid with a point mass on its surface, this mass represents the impactor and ejecta and is launched in defined directions.
The point mass is launched in an equivalent velocity to the overall change in linear momentum over the ejecta mass, and the direction again takes the surface normal into consideration.
The change in ellipsoid (or asteroid) angular velocity is here, it accounts for both the loss of the point mass in the inertia tensor and the added impactor momentum.



Here are results for a 10 ton, 10 km/s impact of a Bennu like ellipsoid.
What you see here are the changes in rotation scheme for an impact coming from the negative y direction and hitting any point in the eastern hemisphere.
On the top left you see the precession reached for any impact, we see that high latitudes on the far trailing edge lead to the largest precession and equatorial hits lead to the lowest precession.
When it comes to torqueing of the rotation the bottom left plot shows a change of up to 5% for impacts on the edges.
The impact efficiency (assuming the impactor direction is the desired deflection direction) is seen here, we have a loss of 50% if instead of hitting the center we hit tangentially.

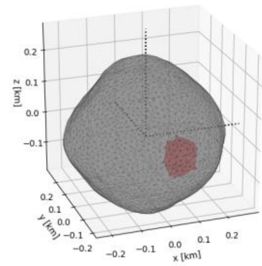
Effects on realistic asteroid shapes

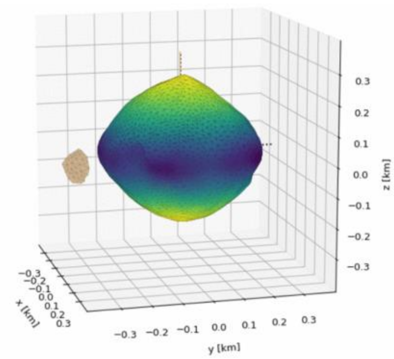
- Using the SEA RATS model developed at the University of Colorado Boulder
  - slice asteroid polyhedron shape model (M_e)
  - launch simulated ejecta (v_{eq})
- Asteroid velocity change

$$\Delta \boldsymbol{v}_A = -\frac{M_e}{M_A}\sqrt{\boldsymbol{v}_{e,\infty}^2 - 2\frac{\mu_A}{|\boldsymbol{r}_{e,\infty}|}}\,\hat{\boldsymbol{v}}_{e,\infty} \qquad \boldsymbol{v}_{e,0} = \boldsymbol{\omega} \times \boldsymbol{r} + \boldsymbol{v}_{eq}$$

- Effective velocity change

$$\Delta \boldsymbol{v}_A^* = (\Delta \boldsymbol{v}_A \cdot \hat{\boldsymbol{v}}_i)\,\hat{\boldsymbol{v}}_i$$





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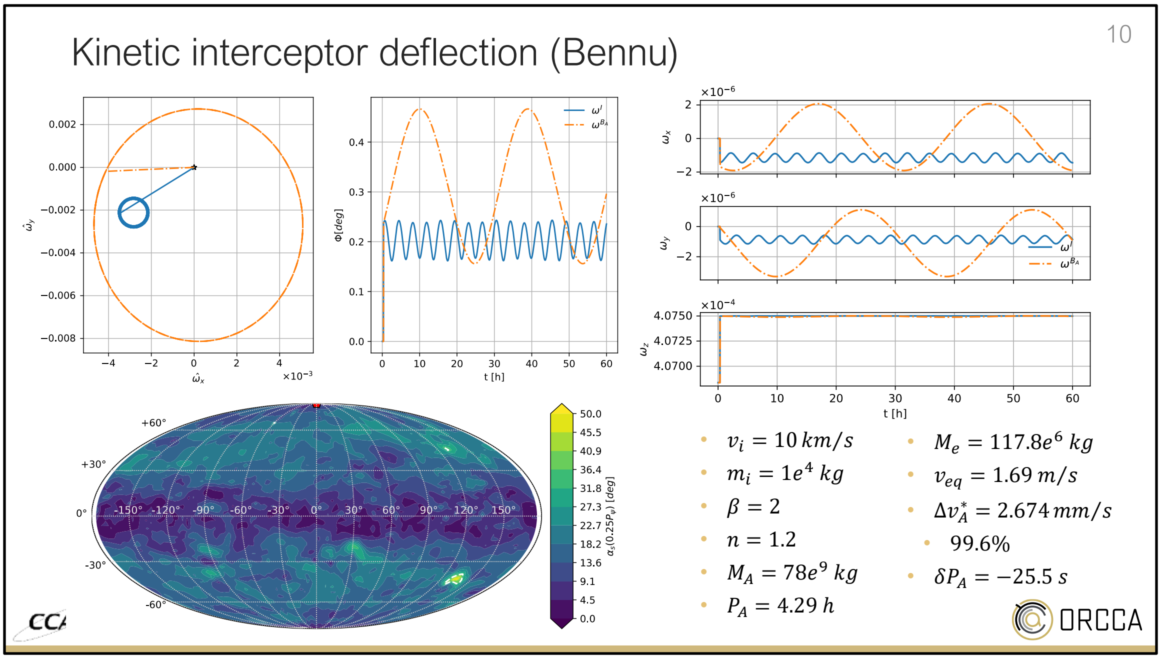
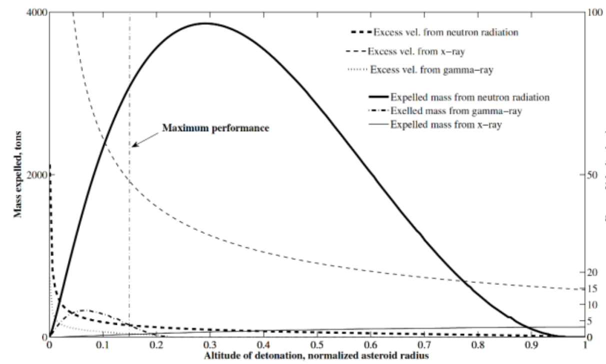
Now, we know that asteroids are not ellipsoids, so we need to implement our deflection problem on more realistic shapes
We use the SEA RATS model developed at the university of Colorado which manipulates a polyhedral asteroid's shape and rotation (see https://doi.org/10.1016/j.icarus.2019.05.038 for more details).
Here instead of launching a point mass off the surface we slice the asteroid to create a small crater and debris.
The debris cluster is launched in a velocity determined as before, but now we have the added change to the shape to account for.
We also have a more realistic change to the asteroid's velocity and a sense of the effective change in asteroid velocity, again, assuming that the deflector direction is the desired delta V.



Here are results for the 10 ton 10 km/s kinetic impactor on bennu at the equatorial point presented in the previous slide.
The top two plots show the rotation state both in the body frame (orange) and in the inertial frame (blue).
We note that precession is introduced and the body is no longer a PAR.
We also see a small increase in the rotation rate that is equivalent to 25 seconds reduced from the asteroid’s 4.3 hour rotation period.
The deflection efficiency is 99.6% at 2.674 mm/s because the impact location is well aligned with its surface normal and the incoming impactor.

Nuclear detonation

- Above surface detonation
- Radiation caused ejecta
  - Asteroid Apophis
  - $M_{e,ntrn} = 3e^6\ kg$
  - $v_{eq,ntrn} = 4\ km/s$
  - $M_{e,xray} = 0.003e^6\ kg$
  - $v_{eq,xray} = 50\ km/s$



Sanchez et al. 2009

$$M_e = 3.003e^6 \text{ kg} \qquad v_{eq} = \frac{M_{e,ntrn}v_{eq,ntrn} + M_{e,xray}v_{eq,xray}}{M_{e,ntrn} + M_{e,xray}} = 4.45 \text{ km/s}$$

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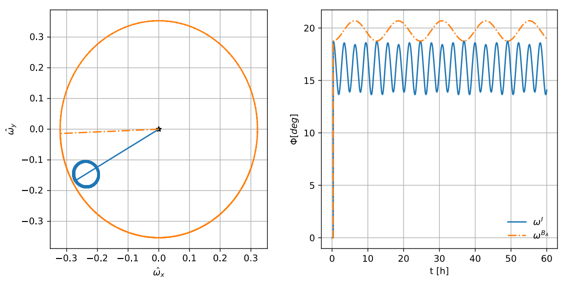
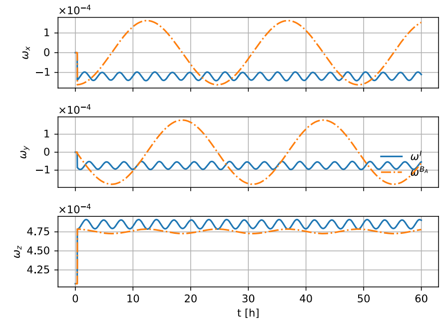
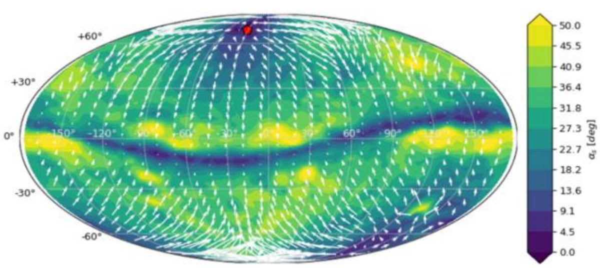
When we talk about nuclear deflection we use empirical data from the sanchez el at 2009 paper for a detonation above the surface of an asteroid.
We note that now the launch velocity is now 1000 times larger than the kinetic impactor while the mass is in the same order of magnitude.

Nuclear detonation deflection (Bennu)







- $M_A = 78e^9\ kg$
- $P_A = 4.29\ h$
- $M_e = 3.003e^6\ kg$
- $v_{eq} = 4.45\ km/s$
- $\Delta v_A^* = 189.7\ mm/s$
  - 99.6%
- $\delta P_A = -2959.9\ s\ (49.3\ m)$
  - 23%

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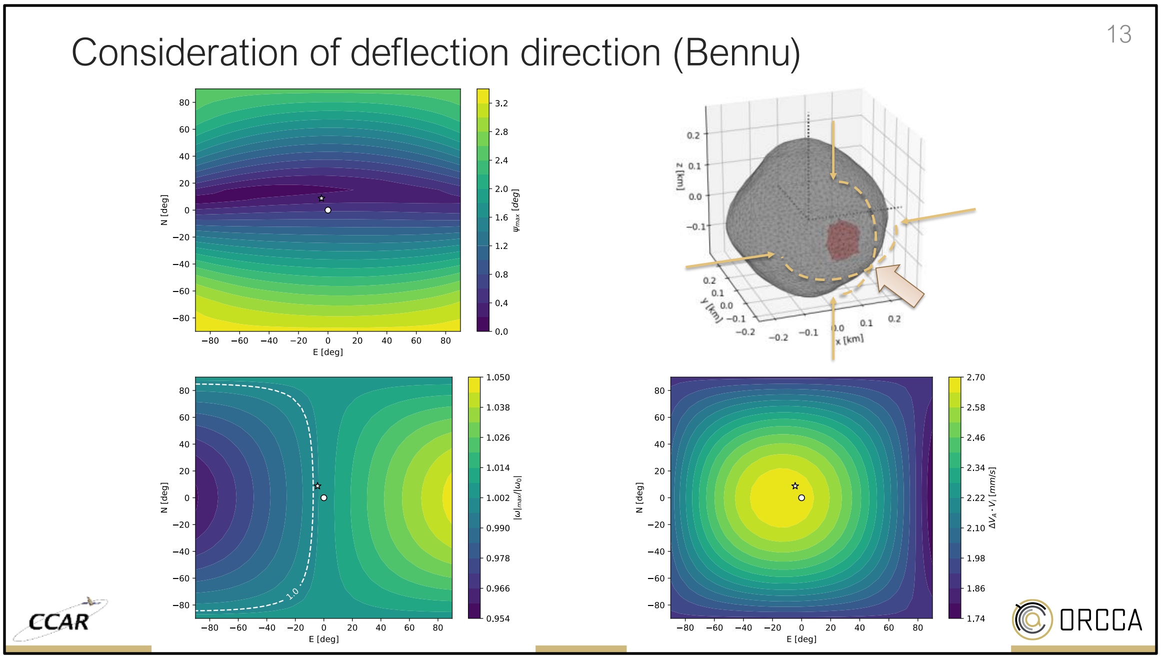
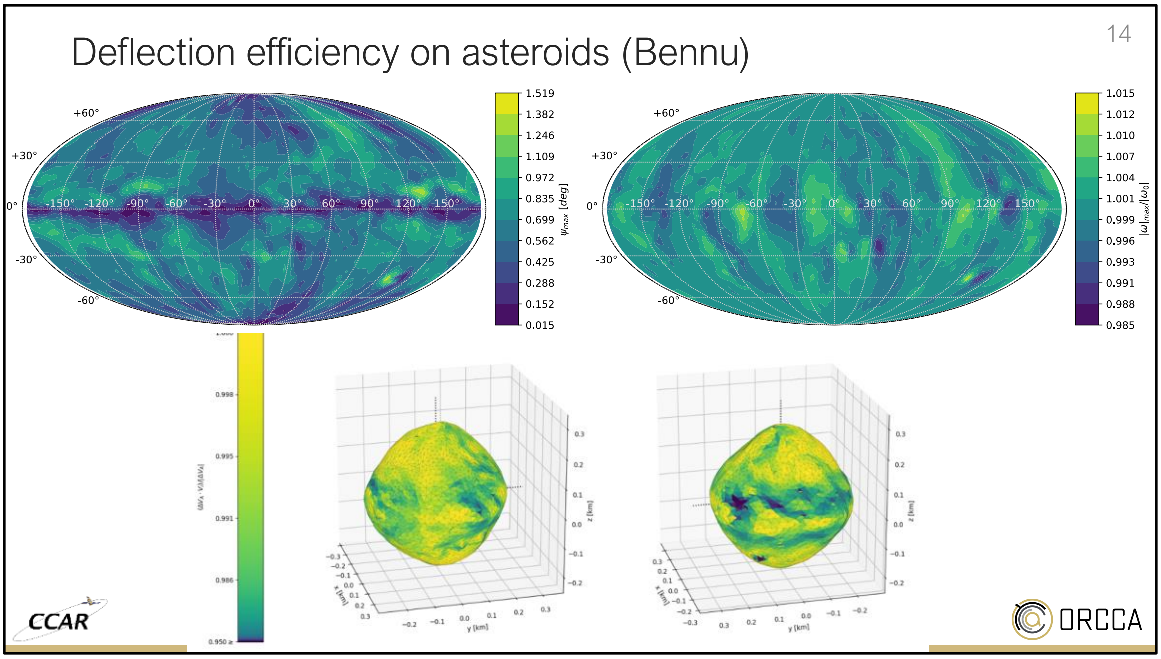
The results for a nuclear detonation in the same equatorial spot presented before on Bennu are shown here
Again, precession is introduced, but more importantly we have a speed up of 23% of the rotation rate and a shift of 20ish degrees in the rotation axis
This leads to a very active surface environment, an environment that definitely represents a dramatic change in the asteroid structure
What you see in this gif are the surface slope magnitude and directions, we can see that basically the entire surface reaches what is thought to be the motion inducing slope of 35 degrees at some point in the rotation
Again, the impact efficiency is 99.6% but this time the delta V provided is 190 mm/s (about 70 larger than the kinetic impactor)



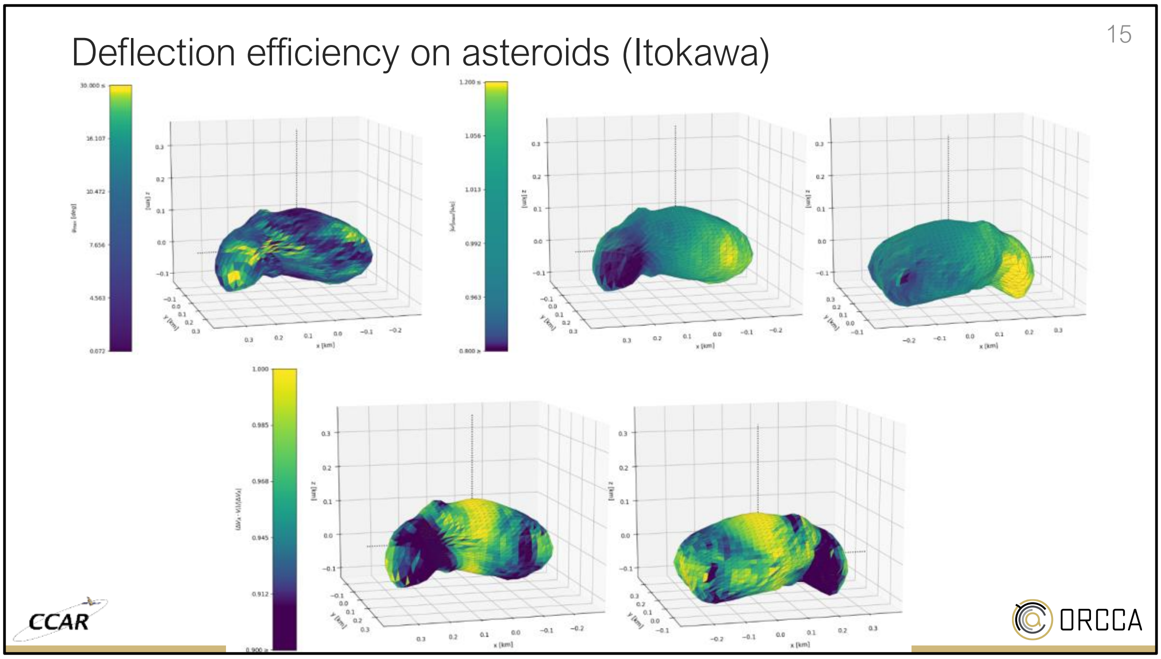
Here we go back to the kinetic interceptor case and look at how the deflection changes if we change our incidence angle.

The coordinates in these heat maps are angles with respect to the surface normal at the point of impact. The dot at each point is the surface normal and the star at each point is the position vector direction. The top left plot shows the extent of Bennu's precession for each impact direction. The bottom left shows the change to angular velocity magnitude. And the bottom right shows the effective deflection direction, its interesting to point out here that there is a western shift in max efficiency due to the asteroid's rotation.



We now look at the deflection effects for any point on the entire asteroid shape, here the incoming deflection is always in the direction of the facet position vector so the effects to deflection are due to the discrepancy between position vector and surface normal, so basically these results are best case scenarios depending on where our impactor is coming from. Top left we have the amount of precession reached for each location, for Bennu these effects are very small.

It is interesting to point our that there is a correlation between reduced precession and existing craters on the surface. Top right is the change to angular velocity with is up to 1.5%. The bottom plot shows the efficiency at every point, again for pointing the impactor in the direction of the facet position, we see that most of Bennu has close to 100% efficiency



For itokawa things are a little more interesting. Top left is the precession reached, we see that some points on the nodes' sides can lead to 30 degree precession angles. The top right shows the node sides changing the asteroid's rotation by around 20%. The bottom plot shows the impact efficiency, mostly close to 100% but again, the node sides can lead to reduced efficiency. Basically, these results show that if we're hitting an elongated asteroids we need to impact its center either on the long axis, or if necessary on the short one.

Conclusions

- Misalignment between interface position direction and deflection direction
  - Precession → Unstable surface/structure
  - Change to angular velocity magnitude (up or down) → Fission
  - Reduced efficiency in deflection → Unwanted change to OE
  - Mission failure
- Need for reconnaissance mission for deflection planning
- Guidelines for future research
  - Study DART
  - Further research variables (shapes, β, deflection s/c)
  - Examine craters as potential targets for impact

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In conclusion the results presented here show that a misalignment between surface position, surface normal and deflection direction can lead to reduced performance in the deflection and unwanted side-effects and even complete mission failure
In addition to calling for future research to be done in the matter such as performance analysis with pointing errors and connecting this analysis with the orbital requirements the results in this paper demonstrate the importance of reconnaissance missions to potentially hazardous asteroids for better a-priori knowledge in the deflection mission.

Thank you!

For more details see:

1. Brack, Daniel N. and McMahon, Jay W. (2019). "Effects of Momentum Transfer Deflection Efforts on Small Body Rotational State". 70th International Astronautical Congress (IAC, manuscript number IAC-19,C1,2,2,x50088

2. Brack, Daniel N., and Jay W. McMahon. "Effects of Momentum Transfer Deflection Efforts on Small-Body Rotational State." Journal of Guidance, Control, and Dynamics 43, no. 11 (2020): 2013-2030, https://doi.org/10.2514/1.G004963

3. Brack, Daniel N., and Jay W. McMahon. "Modeling the coupled dynamics of an asteroid with surface boulder motion." Icarus 333 (2019): 96-112, https://doi.org/10.1016/j.icarus.2019.05.038

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