7th IAA Planetary Defense Conference

26-30 April 2021, Online Event

Hosted by UNOOSA in collaboration with ESA

Session 13: Apophis and Others, Far and Near: Future Characterization Opportunities from NEO Close Approaches

Chairs: Gerbs Bauer | Larry Denneau | Michaela Blain

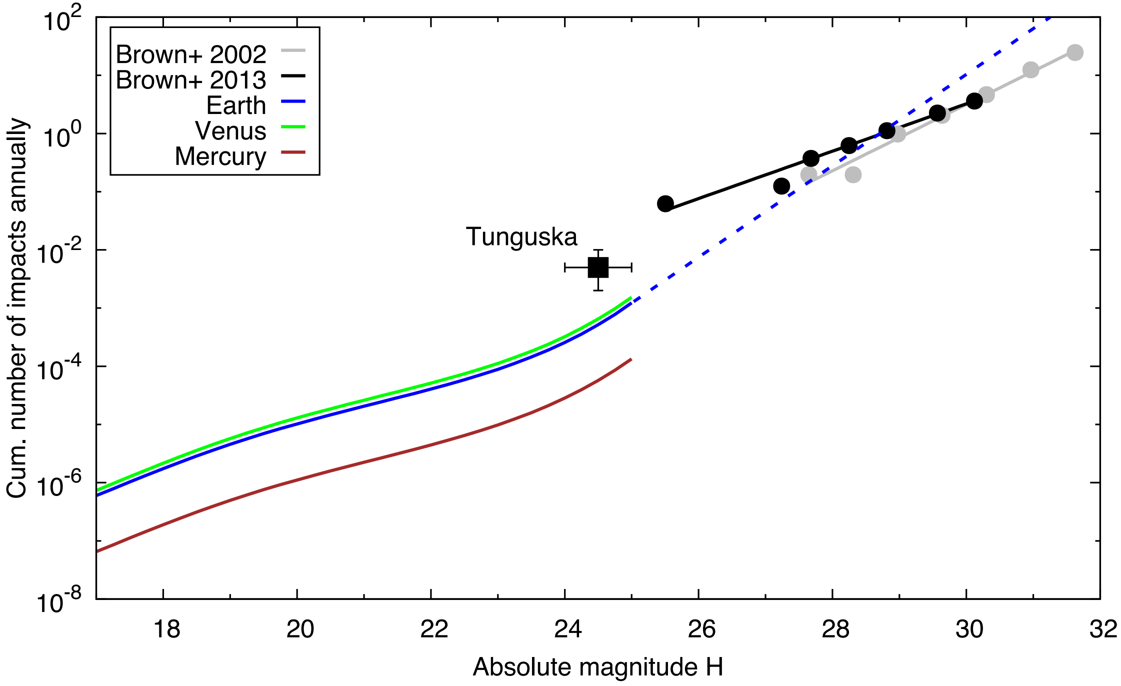
Presenters: M. Granvik | M. Kelley | D. Tholen | J. Prado | P. Taylor | V. Zubko

Frequency of Close Earth Approaches by Near-Earth Objects

Mikael Granvik
Luleå University of Technology, Sweden
University of Helsinki, Finland

Building on
Granvik, Morbidelli, Jedicke, Bolin, Bottke, Beshore, Vokrouhlicky, Nesvorny, Michel, 2018. "Debiased orbit and absolute-magnitude distributions for near-Earth objects", Icarus 312, 181–207.

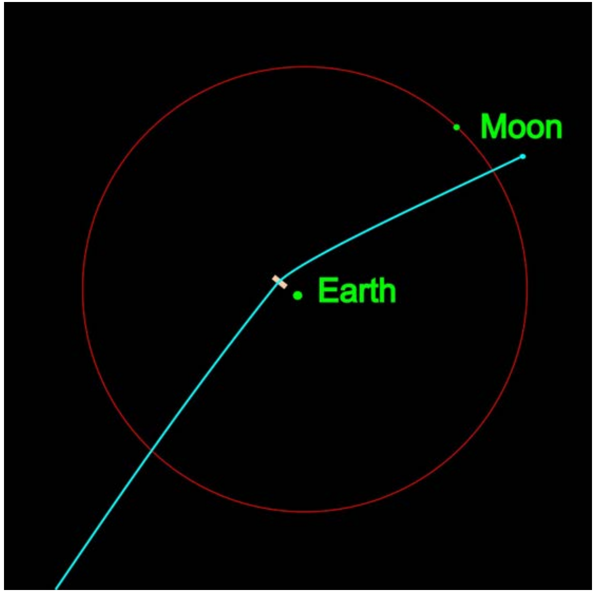
Predicted rate of impacts on the inner planets and comparison with bolides



Granvik+ (2018)

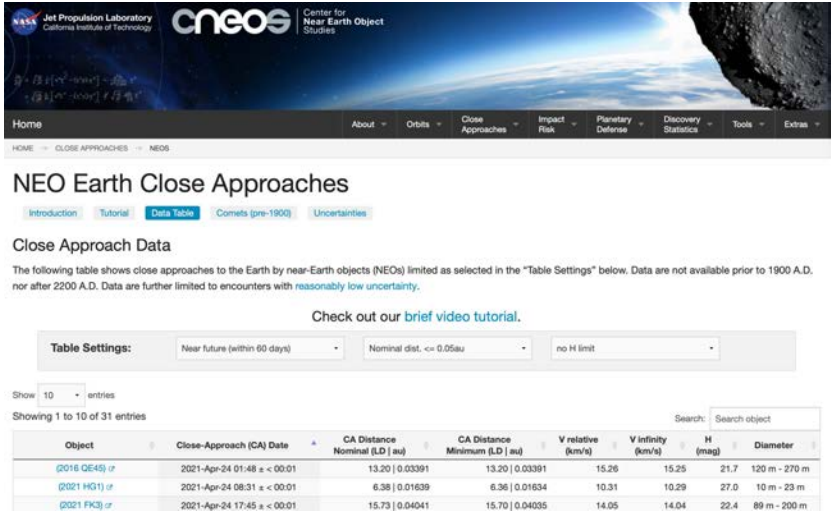
What is the frequency of encounters such as that by Apophis in 2029?

- Apophis has H≈19.1 and closest geocentric distance in 2029 is 0.00025 au.
- Frequency of Apophis-like encounters is once per 1000 yr according to casual statements – unclear where this number comes from.
- Frequency of Apophis-like encounters is once per 6500 yr according to Granvik+ (2018).

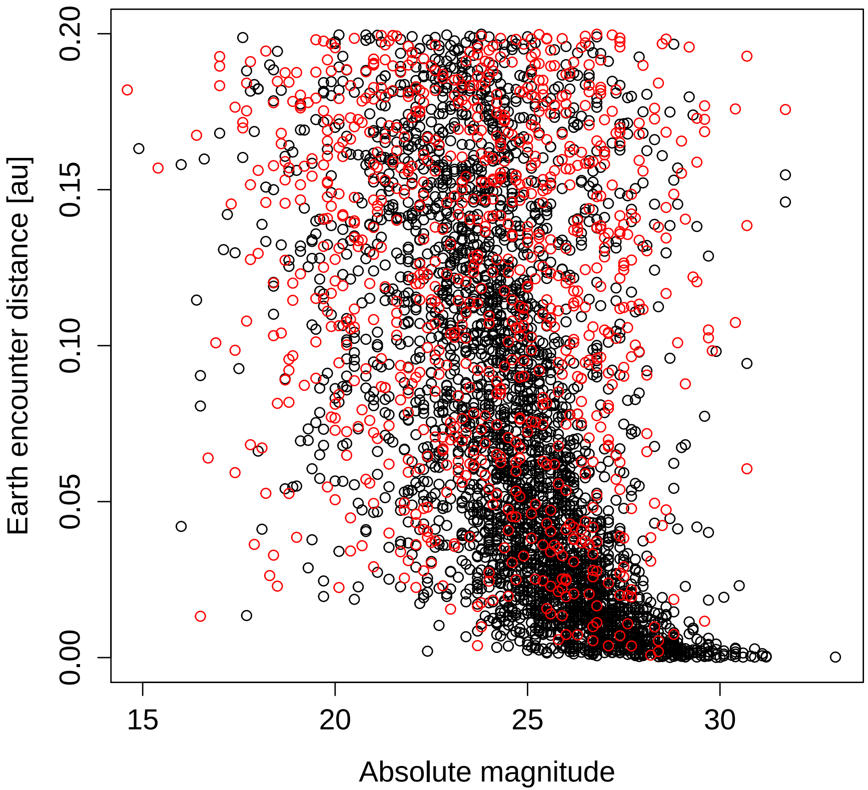


Can we rely on the Granvik+ (2018) prediction in terms of impact and close-encounter rates?

- The impact frequency in the size range of observed bolides appears to be in reasonable agreement with model prediction.
- A direct verification of the impact frequency for larger objects is, of course, impossible because impacts are rare and there is no observational data.
- We can make a direct comparison between the predicted and observed rate of close encounters, but need to use a reasonably unbiased sample to avoid being misled by observational biases.

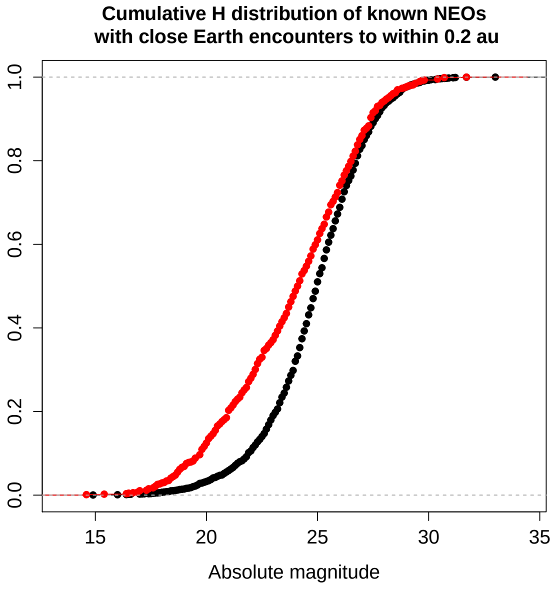


Close encounter data 2021-04-15 ± 1yr from CNEOS

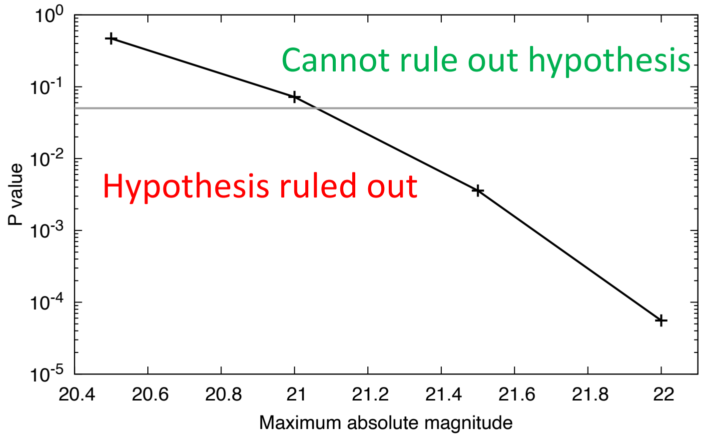


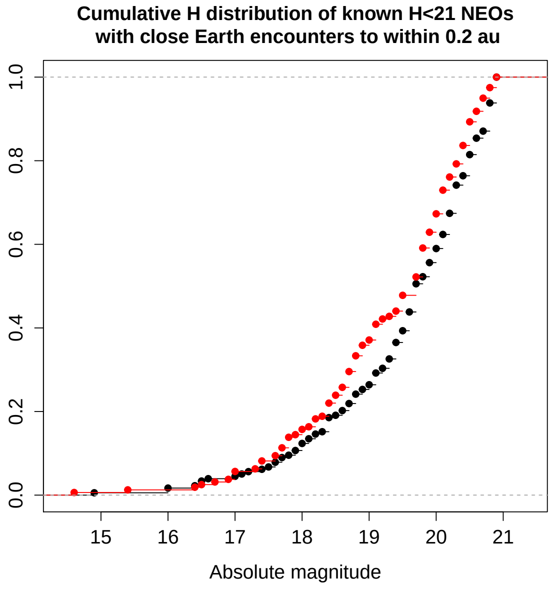
Past year (“observed”)
Next year (“predicted”)

Unbiased close encounter data 2021-04-15 ± 1yr

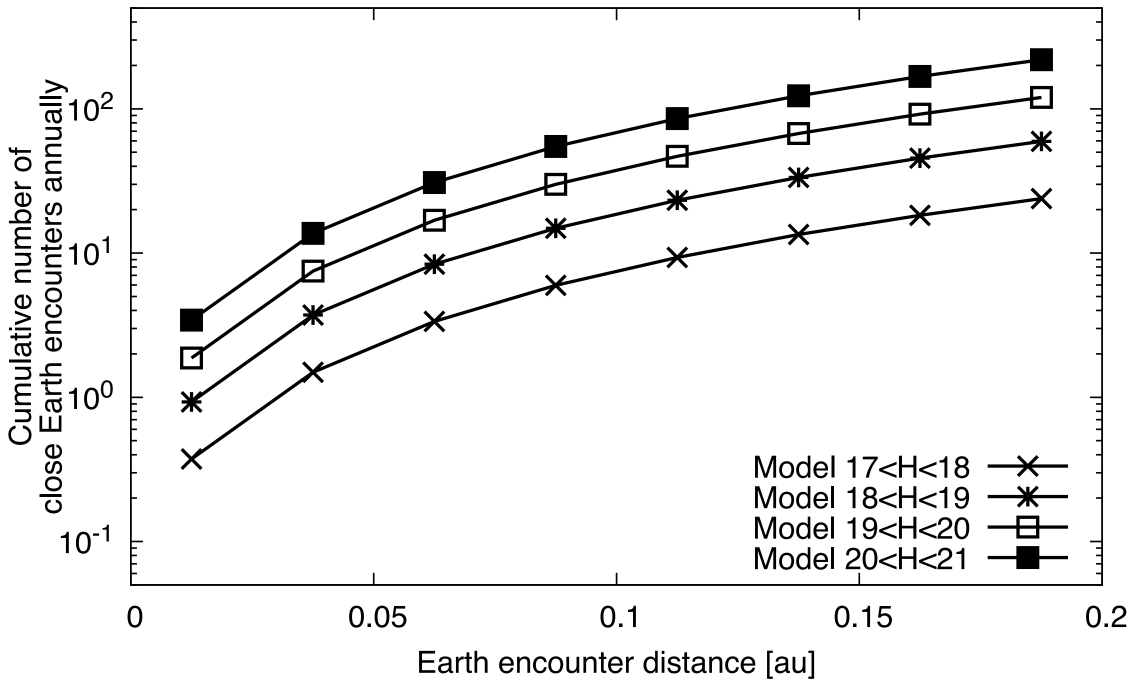


Null hypothesis for AD test:
Samples are drawn from
the same distribution

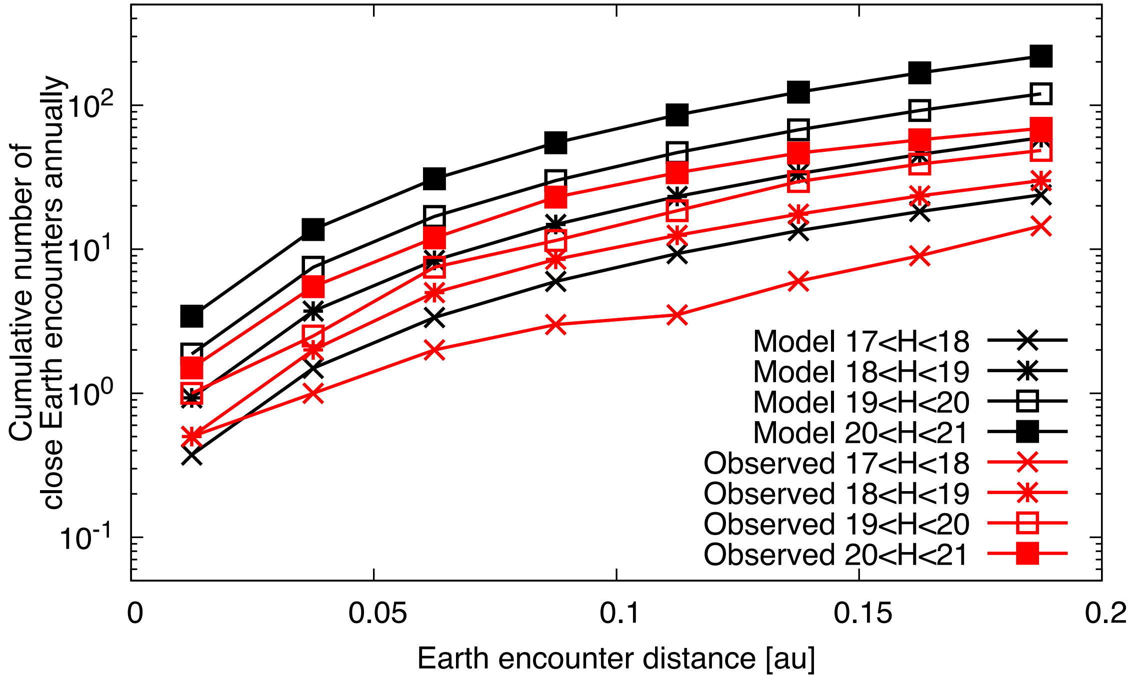




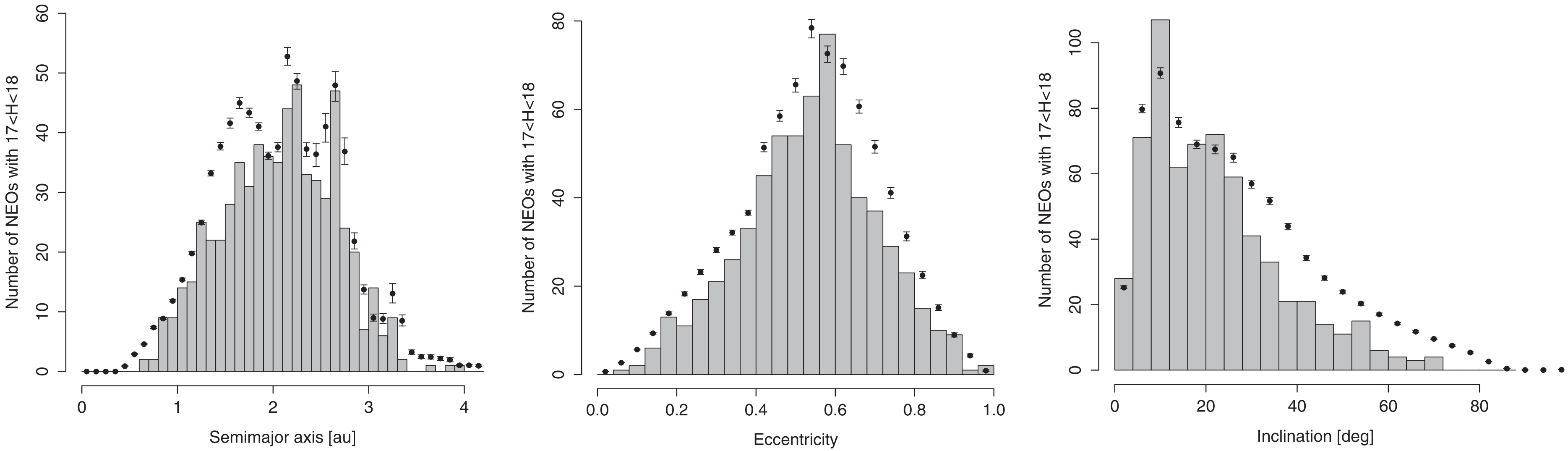
Model prediction for frequency of close encounters by large NEOs



Predicted frequency of close encounters is factor of few higher than observed frequency



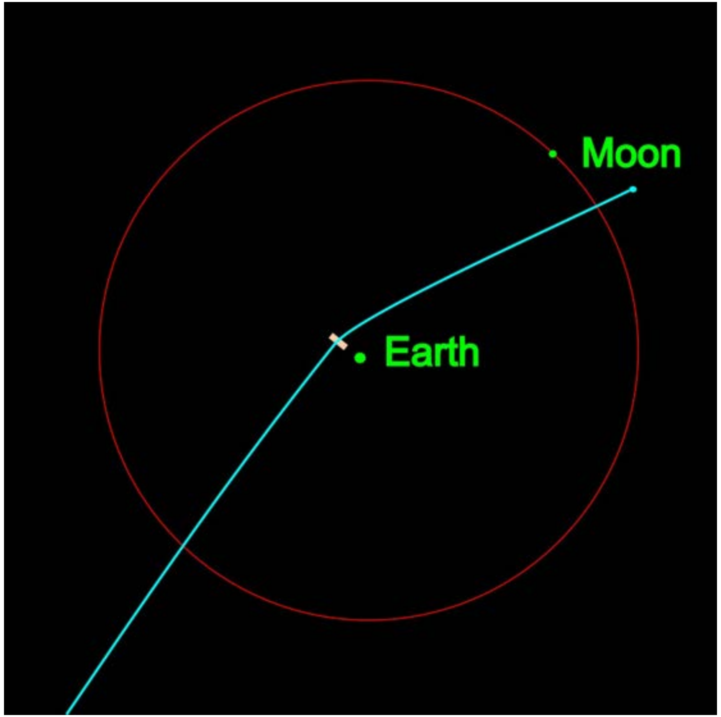
Completeness of the 17<H<18 NEO inventory in 2018



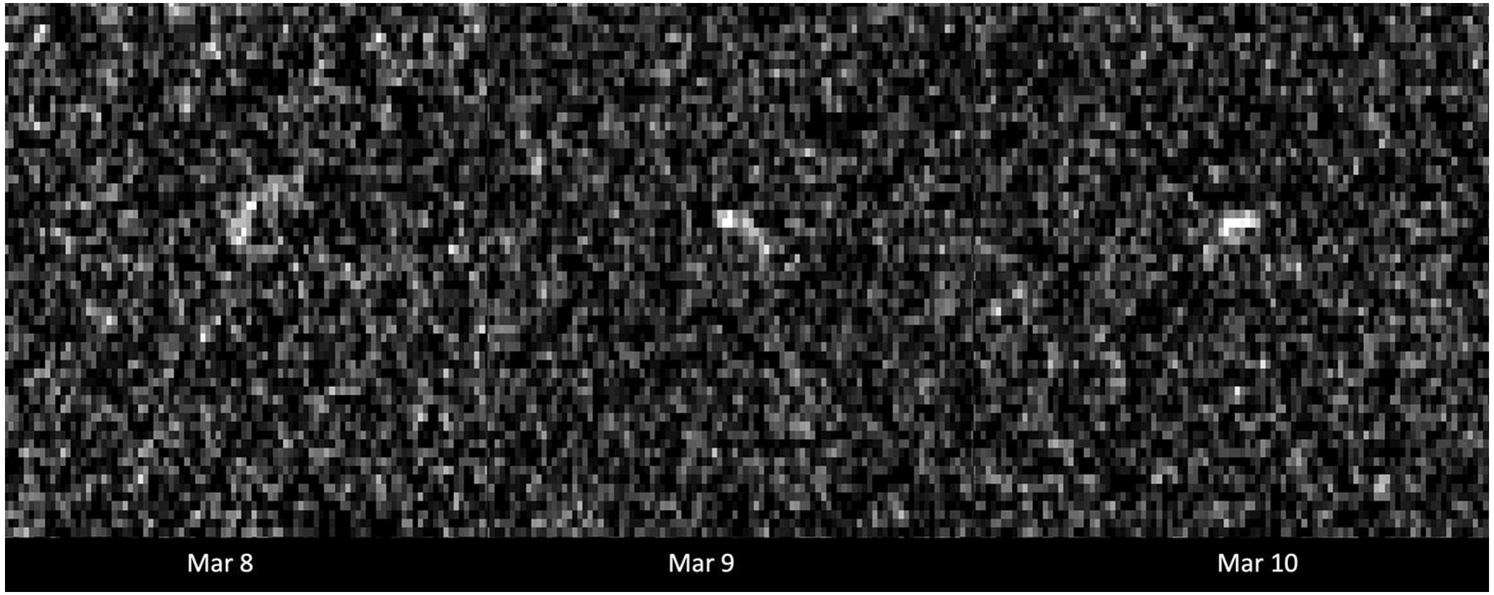
Granvik+ (2018)

Conclusions

- The observed frequency of close encounters for Apophis-scale objects is a factor of a few lower than the model predicts.
- The Apophis encounter in 2029 thus appears to be a once-in-20,000-yr event.
- The root cause for the disagreement between theory and observations is still not understood, but observational biases may be part of the explanation, in particular for smaller NEOs.



International Asteroid Warning Network (IAWN) Apophis Campaign



Credits: NASA/JPL-Caltech and NSF/AUI/GBO

NASA PDCO Lead: Mike Kelley, NASA HQ

IAWN Coordinator: Prof. Vishnu Reddy (University of Arizona)

Group Leads: Davide Farnocchia (JPL), Jessie Dotson (NASA ARC), Nicolas Erasmus (SAAO), David Polishook (WIS), Lance Benner (JPL), Joe Masiero (IPAC, CalTech), James (Gerbs) Bauer (UMD)

Hypothetical exercise

Planetary Defense Campaigns

- NASA PDCO has been conducting planetary defense tabletop exercises for several years in coordination with other federal agencies
- Planetary defense community also engaged in such activities through the Planetary Defense Conference Hypothetical Asteroid Impact Scenarios
- Those theoretical exercises do not include real world observational component with actual NEOs
- Proposal was made during the 2017 NEOO program review to use the October 2017 flyby of a small NEO, 2012 TC4, to exercise the entire global planetary defense system from observations to modeling to communication
- Since then, we have conducted two additional campaigns

Hypothetical exercise

Campaign Structure

- Participation is voluntary ("Coalition of the Willing")
- Participants organize themselves into working groups with a lead
- Working Groups: Astrometry, Photometry, Spectroscopy, Radar, Direct Imaging, Spacecraft Missions, Impact Risk Modeling
- Bimonthly telecons with updates from working groups
- Impact risk model is run at different epochs as information about the target is gathered by the observers
- Data quality/reduction timelines are set by operational rather than scientific needs

Hypothetical exercise

Probabilistic Asteroid Impact Risk (PAIR) in Apophis Exercise

Astrometry:
Davide Farnocchia
CNEOS-JPL, USA

Photometry:
Nic Erasmus
SAAO, South Africa

Spectroscopy:
David Polishook
Weizmann Inst., Israel

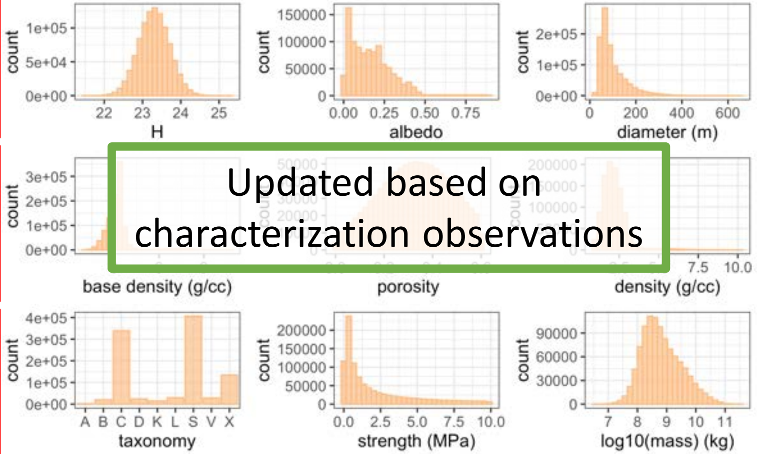
Spacecraft Missions:
Joe Masiero
IPAC-Caltech, USA

Radar:
Lance Benner
JPL, USA

Hypothetical exercise

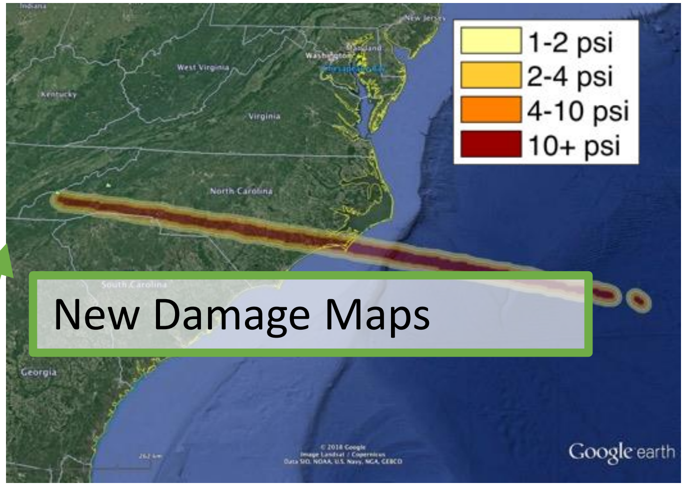
Hypothetical Entry points

Physical Property Distributions



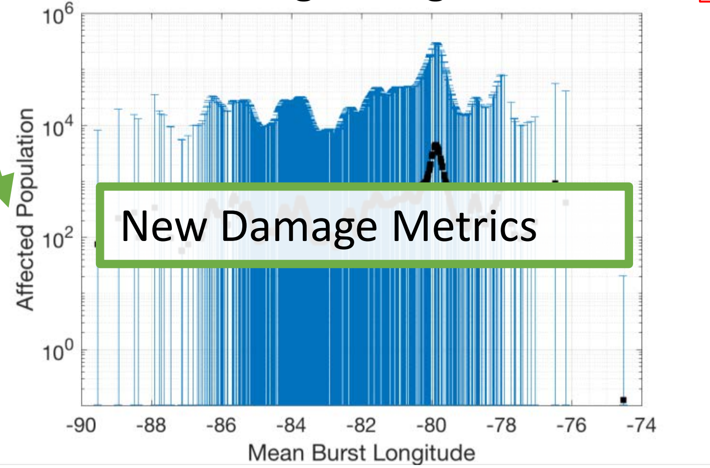
PAIR

Damage Map

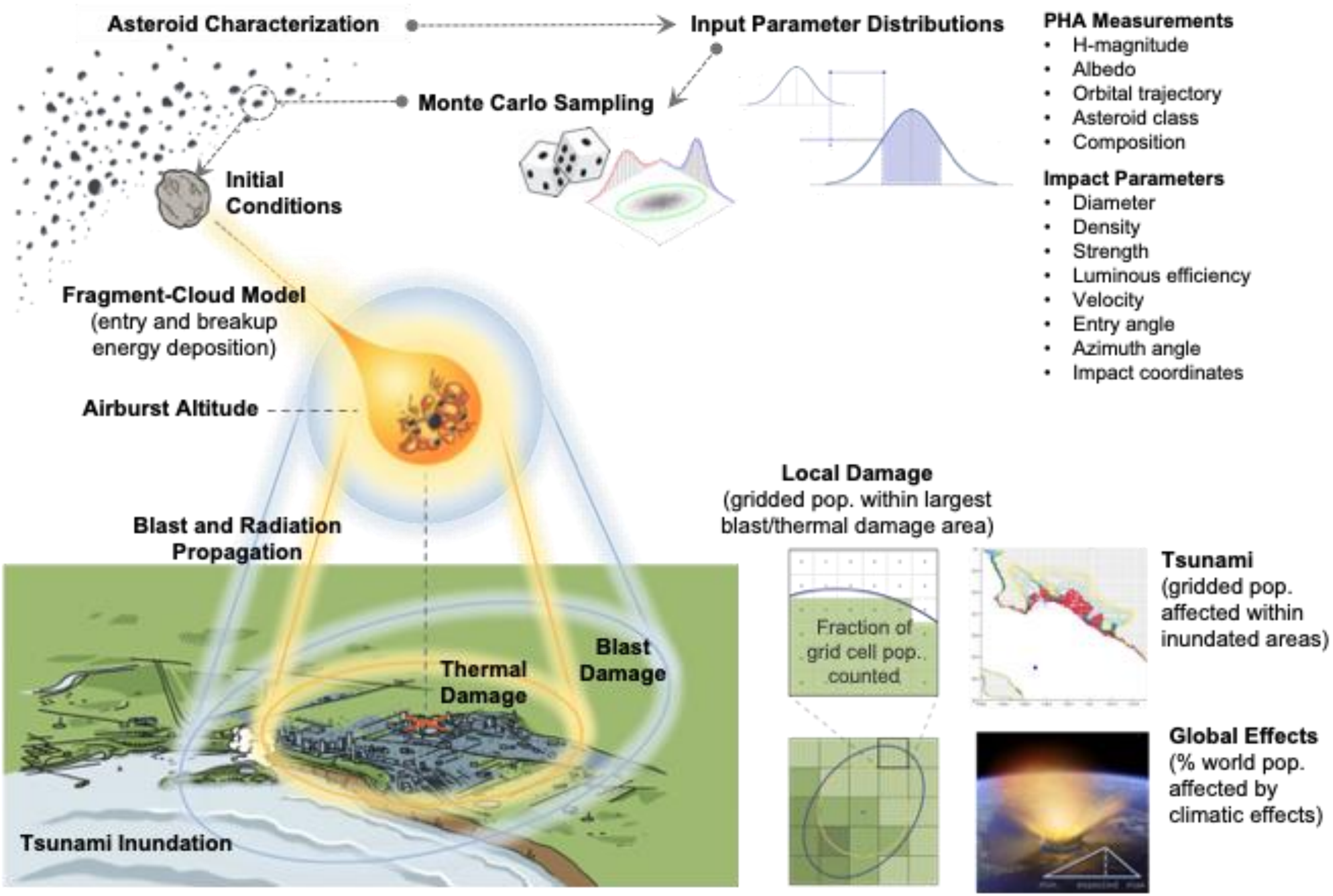


Hazard Modeling:
Jessie Dotson
NASA Ames, USA

Damage Range



Probabilistic Asteroid Impact Risk (PAIR) Model



Hypothetical exercise

Apophis Campaign (Oct. 2020-April 2021)

- Goal: *Near-Earth asteroid Apophis will make a flyby on the Earth on March 06, 2021 at a distance of 10 million miles. The goal of Apophis Observing Campaign is to discover, track, and characterize Apophis as a potential impactor in order to exercise the Planetary Defense system from observations to impact modeling and prediction, and communication. This campaign is open for participation by amateur astronomers from around the world.*

- Participants: 40 observers/modelers from 14 different countries

- Working Groups: Astrometry (Davide Farnocchia); Hazard Modeling (Jessie Dotson); Photometry (Nic Erasmus); Spectroscopy (David Polishook); Radar (Lance Benner); Spacecraft (Joe Masiero)

Hypothetical exercise

Timeline

- Apophis was 'discovered' by CSS Schmidt after NEOWISE triggered the discovery process in Dec. 2020 when it was put on NEOCP.
- Impact probability was calculated with the real Apophis as follow up observations were made. As uncertainties and impact probability decreased, we switched to hypothetical impactor for the reminder of the exercise.
- Epoch 1: Using diameter and albedo from NEOWISE observations we ran the impact risk model on Dec. 23, 2020
- NASA IRTF spectral observations helped constrain the taxonomy and identify the meteorite analog (L chondrite). This helped constrain the density for a range of assumed porosities. Photometric observations helped refine the H magnitude.
- Epoch 2: Included NASA IRTF observations for taxonomy and meteorite analog and ran the model on Jan. 22, 2021.
- Epoch 3: Included radar observations for diameter and ran the model in late March 2021.

Hypothetical exercise

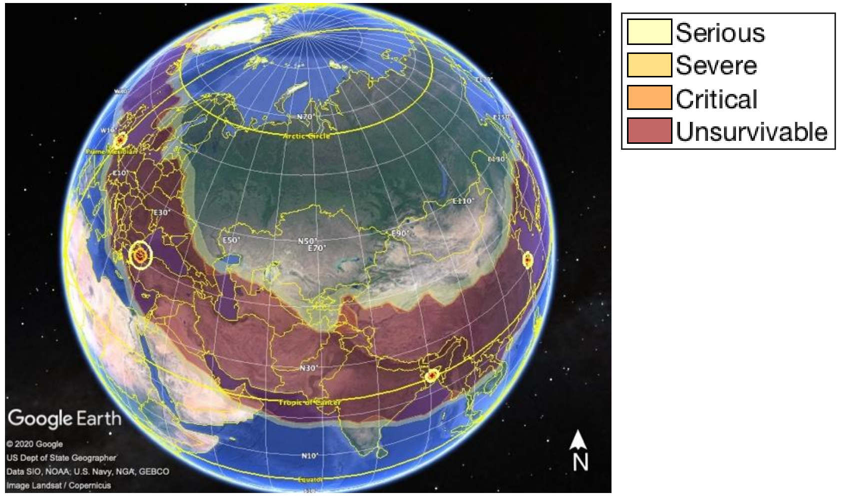
Impact Risk Summary

(Epoch 1: Initial Observations with NEOWISE, 0.6% Impact Prob)

Characterization Summary & Updates

- Assessment date: 23 Dec. 2020
- Earth impact probability: 0.6%
- Size refinement from NEOWISE data
- Diameter 300m ± 75m
- Albedo: 0.44 ± 0.19
- Energy: mean 678 Mt, full range 2 – 8220 Mt
- Entry: 12.2-12.8 km/s, at entry angles up to 54°

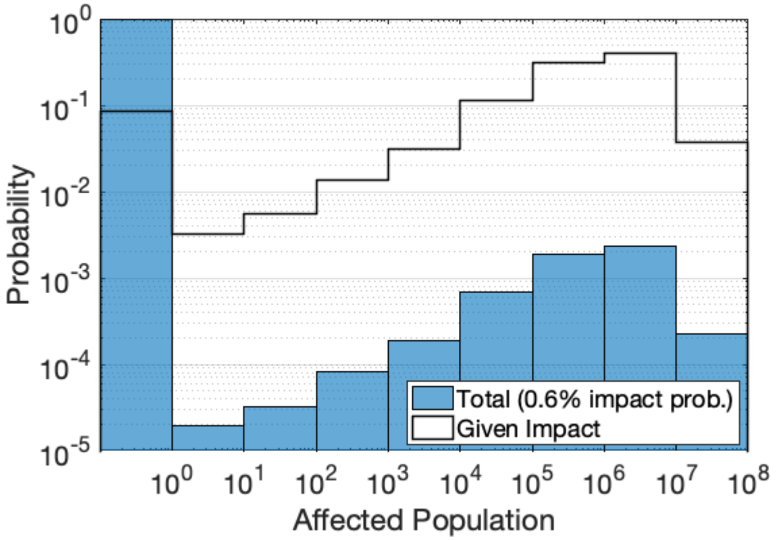
Potential Risk Regions



Hazard Summary

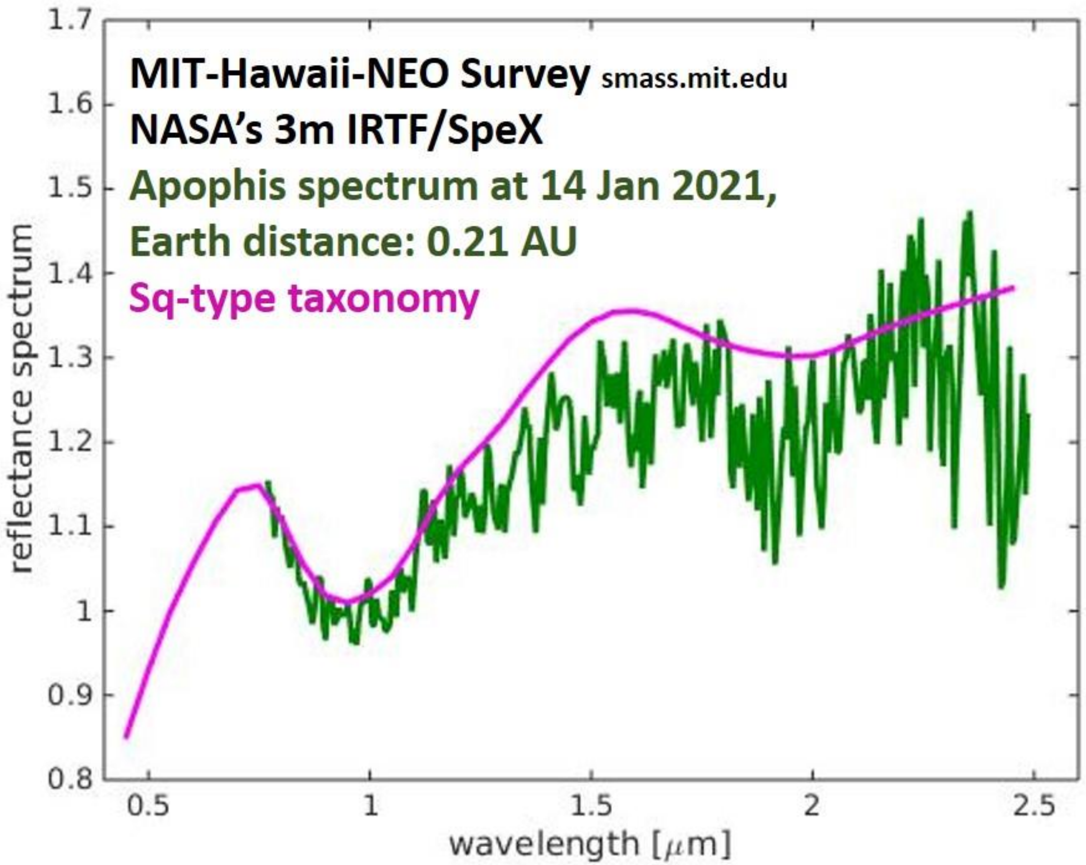
- Affected population: 0-61M, 12k average total risk with 0.6% impact prob., 2M average among impacting cases.
- No population damage for ~9% of impact cases.
- Blast overpressure is primary hazard for ~90% of impact cases.
- Local blast damage radii: 0-370 km, 150 km avg.
- Potential tsunami damage for ~4% of impact cases (primary hazard for <2%)
- No major global effects expected

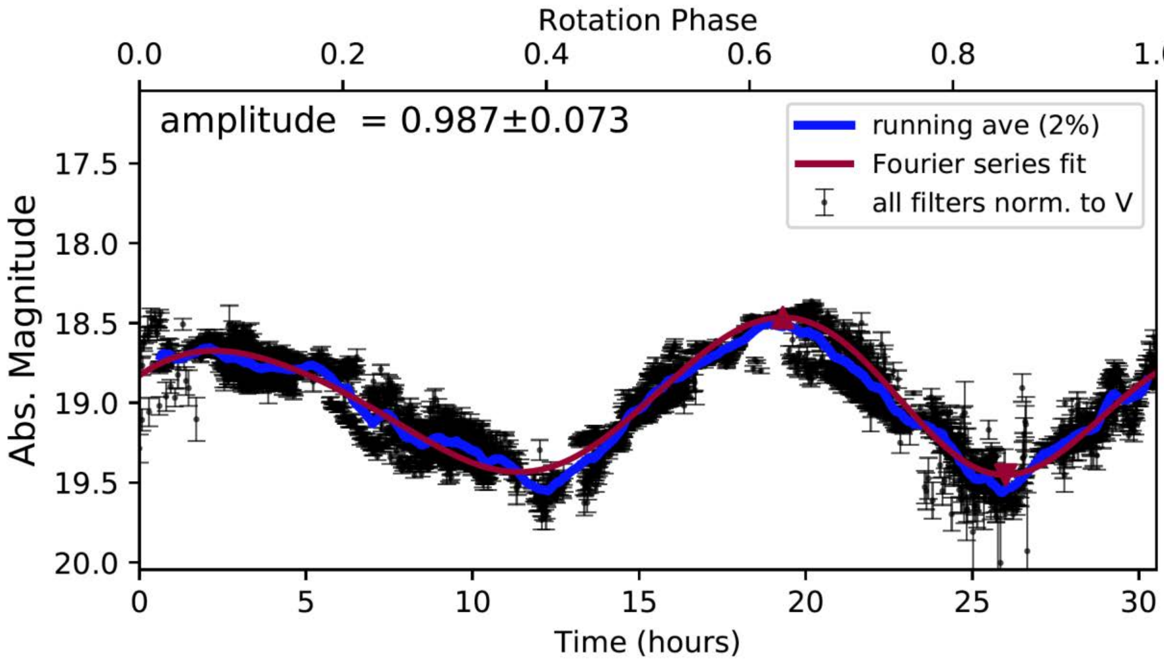
Affected Population Risk Probabilities



Hypothetical exercise

NASA IRTF and Photometric Observations





Hypothetical exercise

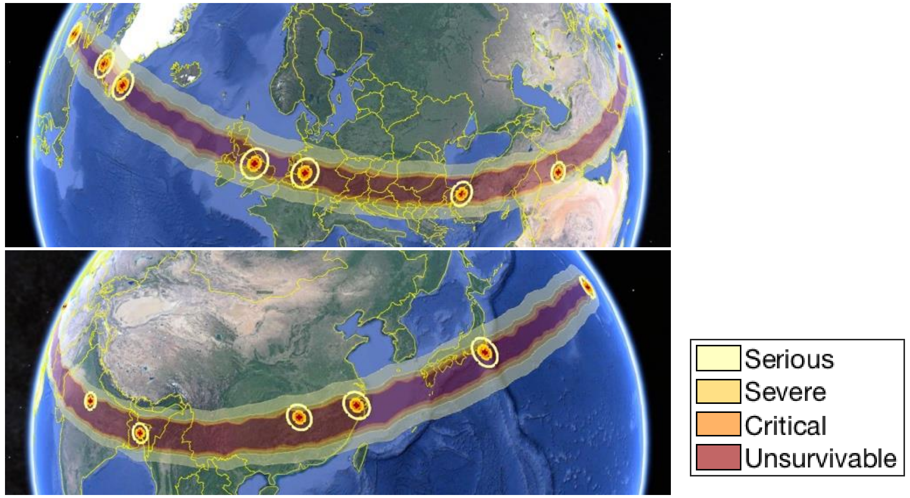
Impact Risk Summary

(Epoch 2: NEOWISE & taxonomy, 6% impact probability)

Characterization Summary & Updates

- Assessment date: 22 Jan. 2021
- Earth impact probability: 6%
- Taxonomy: Sq determination from IRTF
- Size: NEOWISE size refinement from Dec. 23
- Diameter 300 m ± 75 m, full range 44 – 550 m
- Energy: mean 670 Mt, full range 2 – 3770 Mt
- Entry: 12.2-12.8 km/s, at entry angles up to 50°

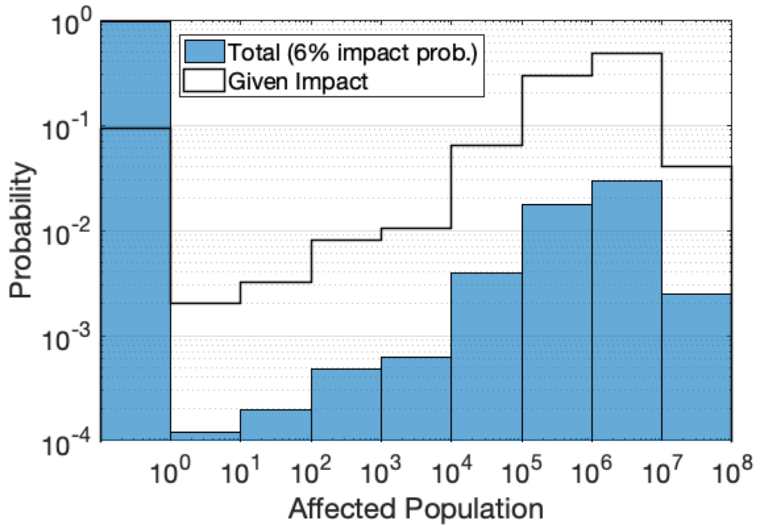
Potential Risk Regions



Hazard Summary

- Affected population: 0-54M, 138k average total risk with 6% impact prob., 2.3M average among impacting cases.
- No population damage for ~9% of impact cases.
- Blast overpressure is primary hazard for ~90% of impact cases.
- Local blast damage radii: 0-370 km, 150 km avg.
- Potential tsunami damage for ~2% of impact cases (primary hazard for <0.4%)
- No major global effects expected

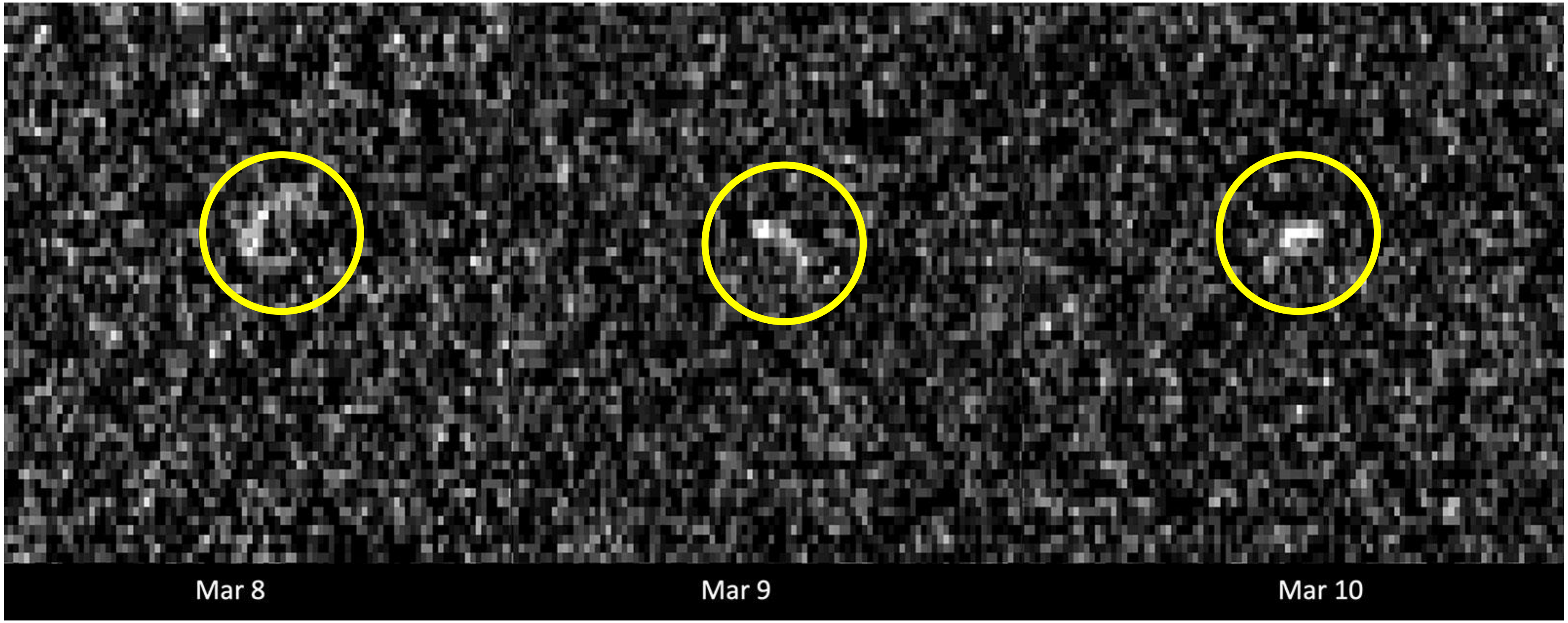
Affected Population Risk Probabilities



Hypothetical exercise

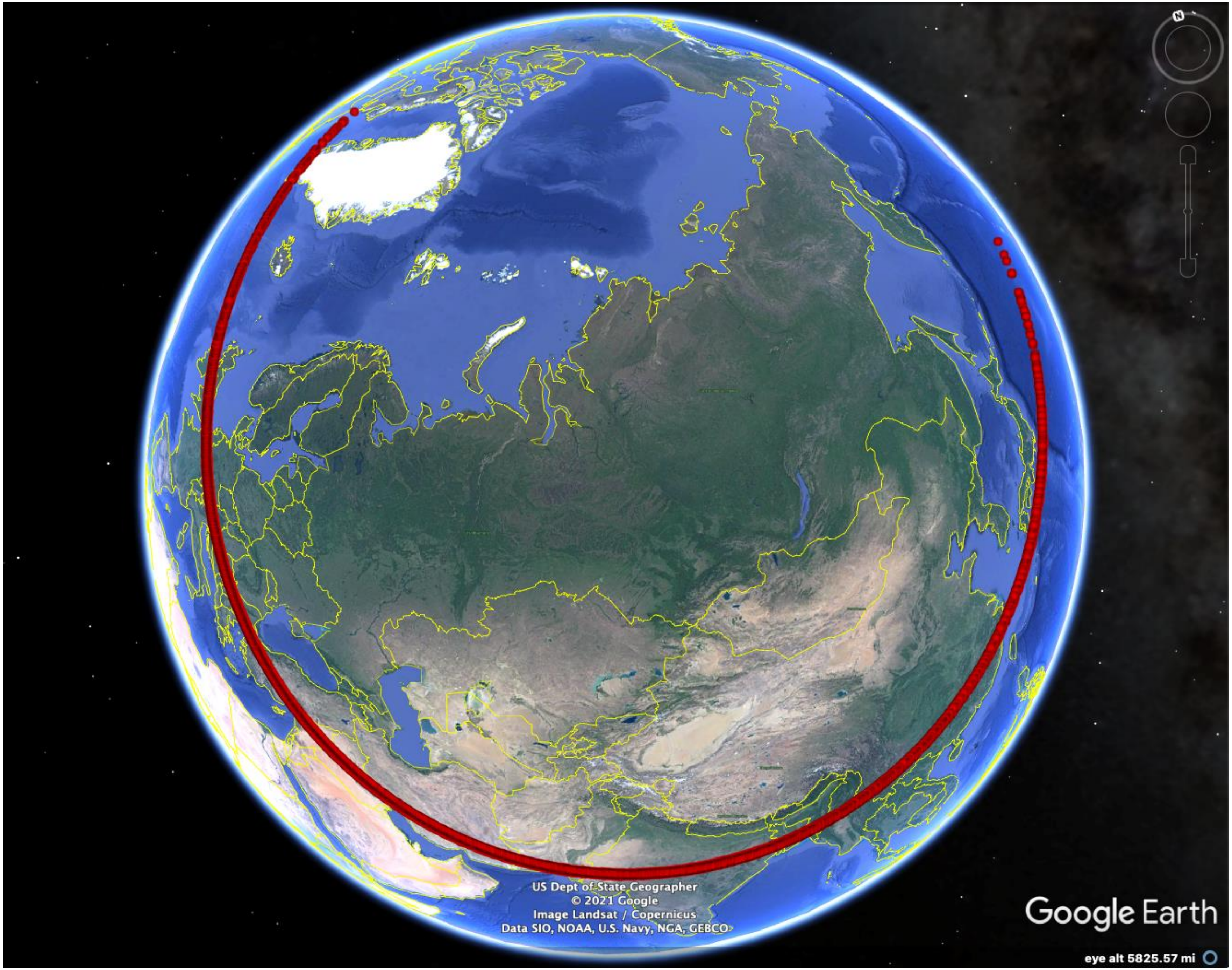
Goldstone Apophis Radar Observations in 2021

Quick Overview:
12 tracks: March 3 - 14.
Track durations: 1.25 – 8.5 hours
Some tracks will use Green Bank to receive (doubles the SNRs).
Goldstone > Green Bank SNRs comparable to those at Goldstone in 2013.



Hypothetical exercise

Impacting clone
Data cutoff Mar 1
Pre-Radar



Hypothetical exercise

Impacting clone
Data cutoff Mar. 15
With Radar data

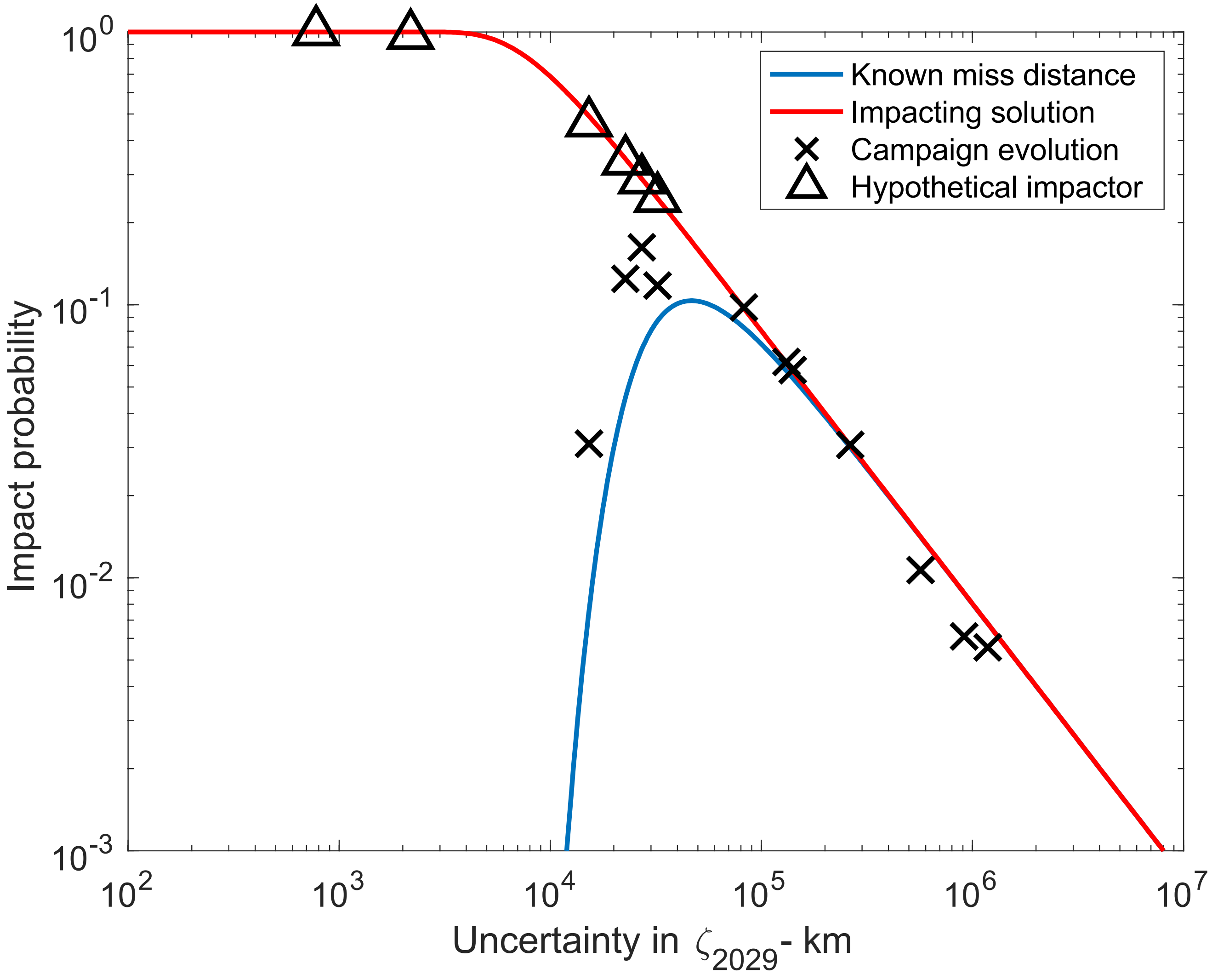
Hypothetical exercise

Impact probability for April 2029

As of March 15, 2021:

Real Apophis: 0%

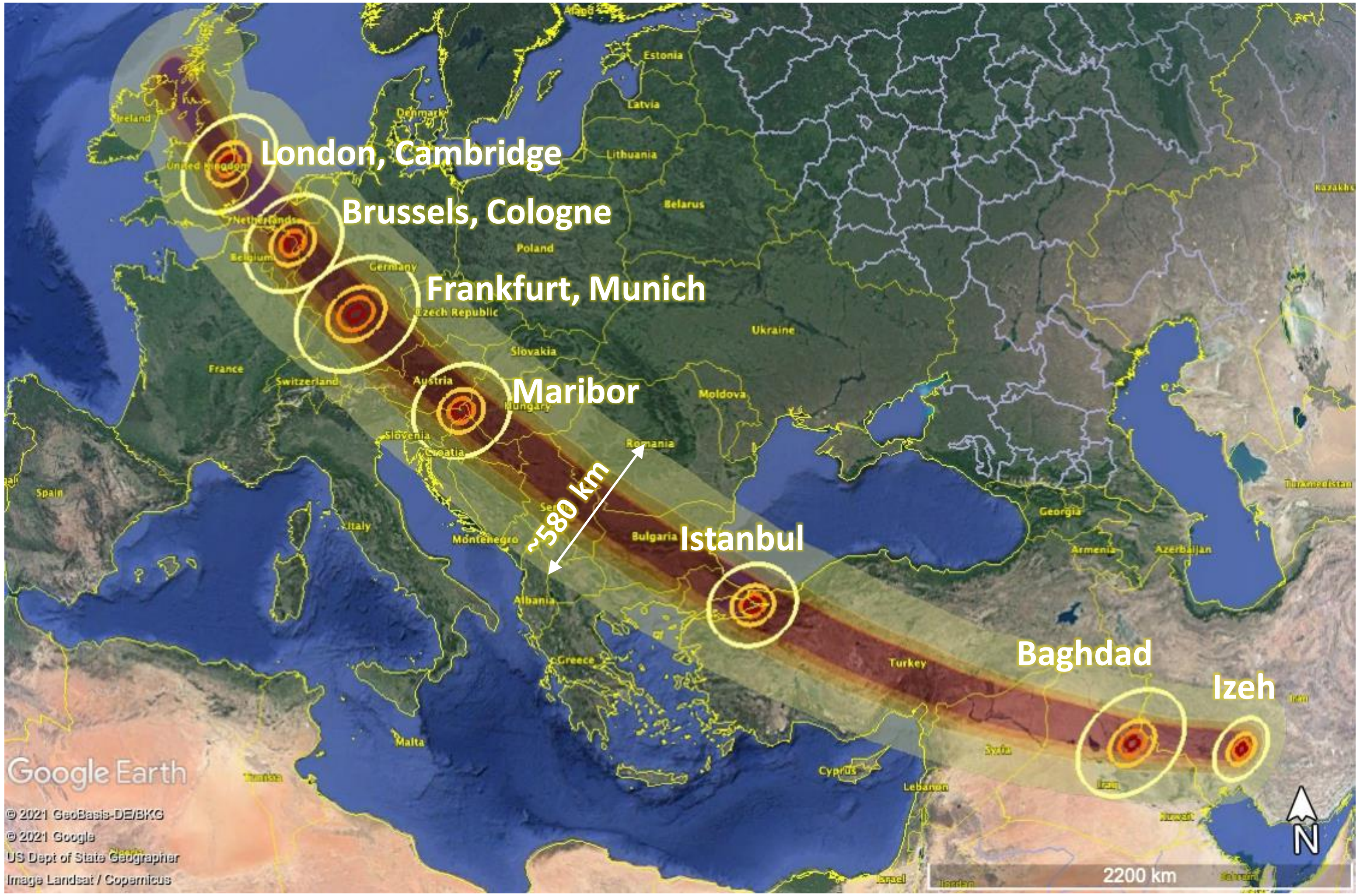
Impacting clone: 100%



Hypothetical exercise

Local Damage Swath

(Epoch 3: Radar size data, 100% virtual impact probability)



Serious
Severe
Critical
Unsurvivable

Damage swath: Full range of regions potentially at risk to local ground damage, from all modeled cases (including unlikely worst-case objects and all sampled impact locations).

Sample average damage areas: Average blast damage areas at several high-population locations across the swath.

Map image/data credit: Google Earth, © 2020 Google. Data SIO, NOAA, U.S. Navy, NGA, GEBCO. Image Landsat / Copernicus. © 2020 GeoBasis-DE/BKG.

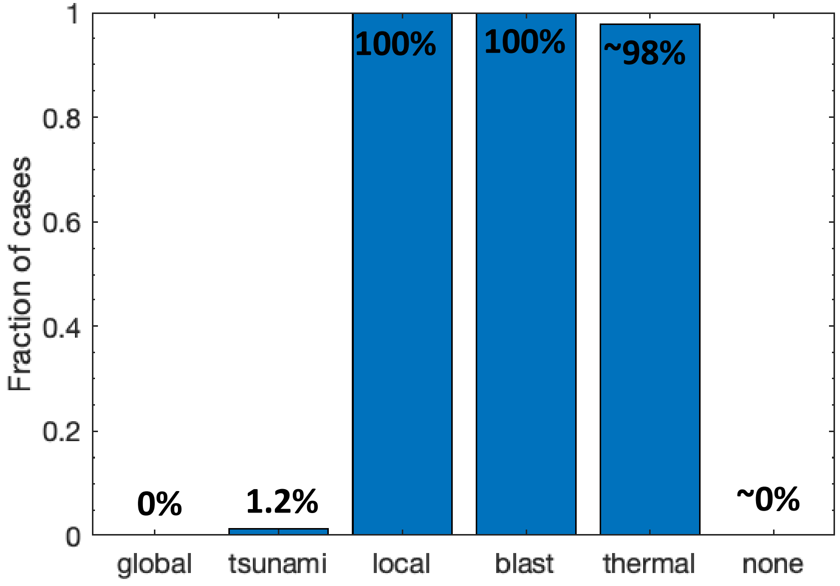
Swath extent: ~5800 km long, from UK to Iran, ~650–470 km wide (~650 W. end, 580 km middle, ~470 km E. end)

Hypothetical exercise

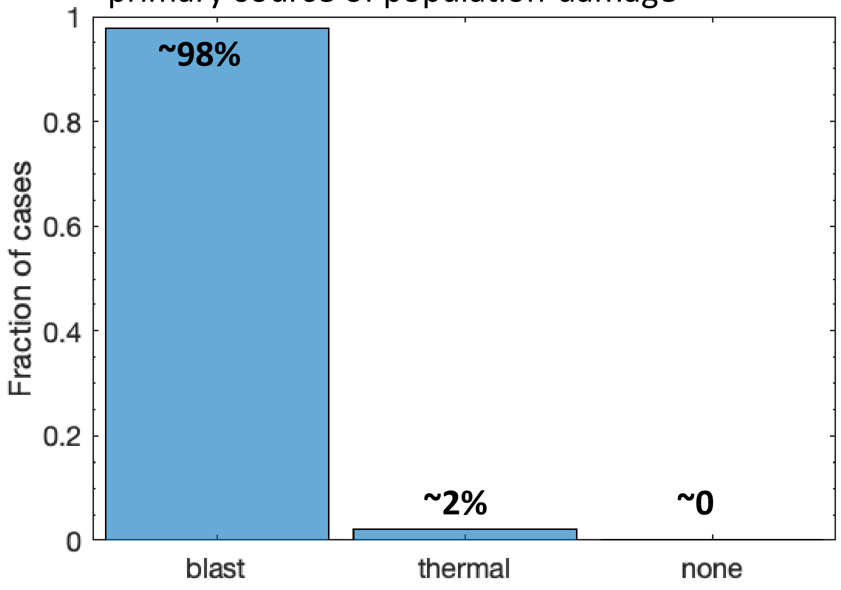
Hazard Sources

(Epoch 3: Radar size data, 100% virtual impact probability)

Occurrence of hazard sources
Fraction of Earth-impacting cases for which damage from each hazard occurs



Risk-driving hazard sources
Fraction of cases for which each hazard is the primary source of population damage

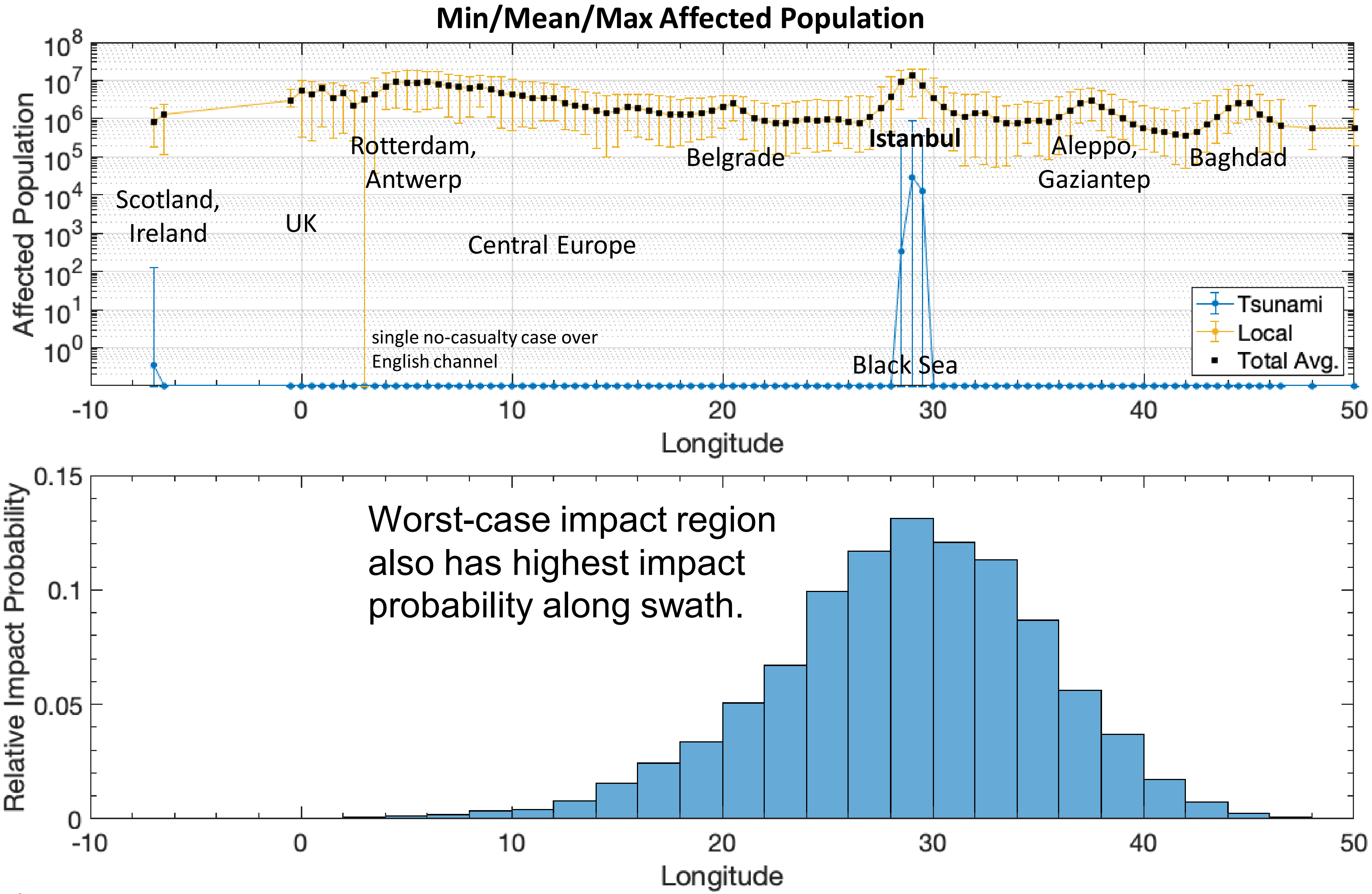


- Total affected population risk is driven primarily by local blast overpressure damage
- Blast damage occurs for all cases and is primary hazard source for ~98% of cases
- Thermal damage also occurs in 98% of cases but is smaller or less severe than the blast damage in nearly all cases (primary hazard source for only 2% of cases).
- Tsunami inundation potentially occurs for ~1% of cases, but is not primary hazard source in any cases (tsunami minor enough and blast always close enough to coast to cause more damage)
- No major global climatic effects are expected
- Only one out of 25M cases caused no population damage

Hypothetical exercise

Affected Population Ranges Along Swath

(Epoch 3: Radar size data, 100% virtual impact probability)



Hypothetical exercise

Summary

- Apophis no longer on the risk list as 2068 impact has been ruled out. No threats from Apophis in the next 100 years.
- IAWN campaigns have been very effective in identifying strengths and stress points of global planetary defense coordination efforts.
- Participants from this and previous campaigns are pleased with the process and results and express enthusiasm for participating again in future campaigns.

Hypothetical exercise

Detection of Yarkovsky Acceleration of (99942) Apophis

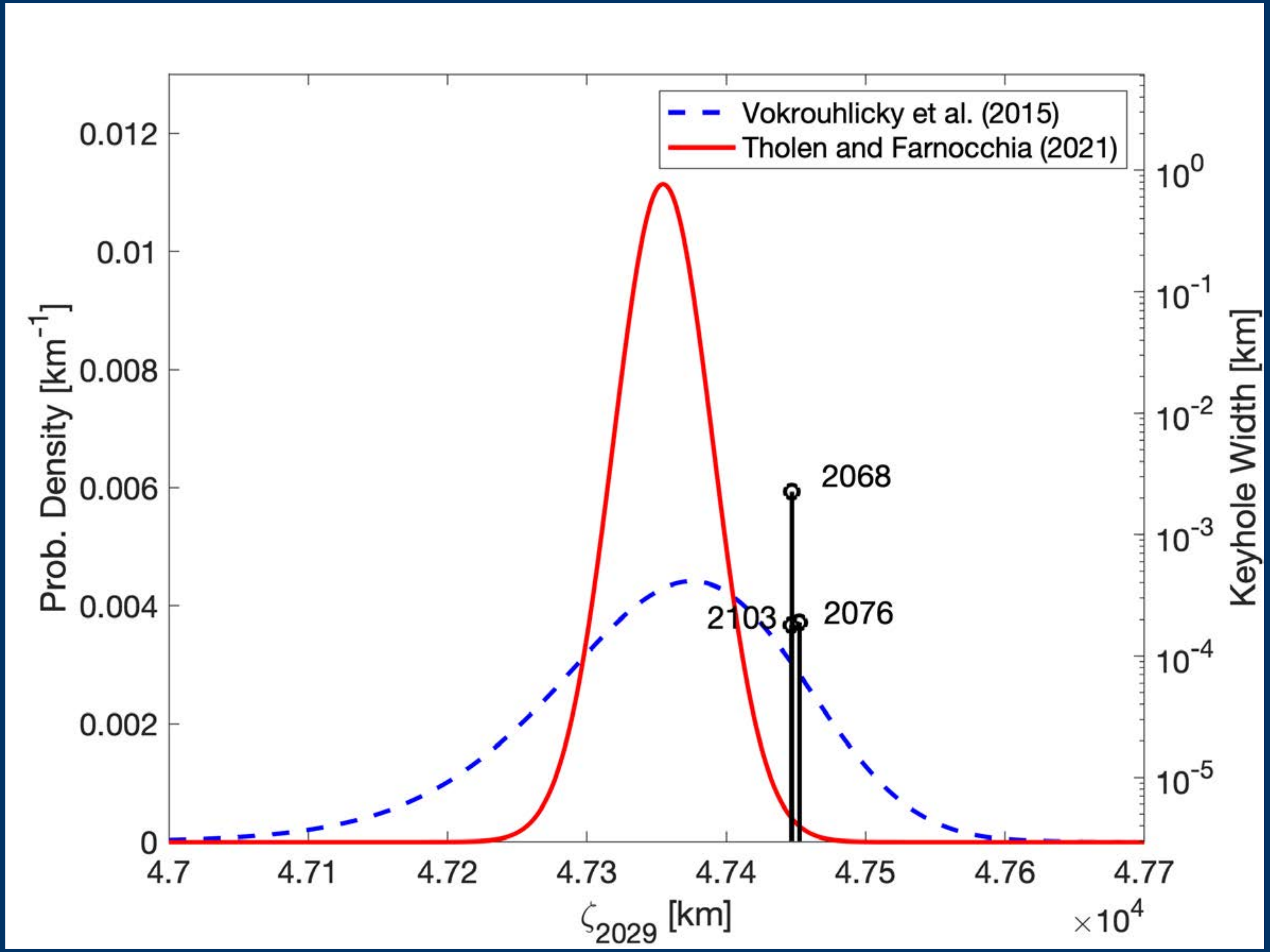
David J. Tholen
University of Hawaii

Davide Farnocchia
Jet Propulsion Laboratory

Update to DPS and Apophis T-9 Presentations

- Reflects the status of the project as of PDC abstract submission deadline
- Five additional Subaru observations in 2020 December good to 10 milliarcsec
- As of that time, our value for A2 was $-30 \pm 3 \times 10^{-15}$ AU/d^2, or slightly more negative than previous determination
- Shifted the peak of the probability distribution a little farther away from the 2068 keyhole (2029 B-plane distance of 47355 ± 36 km)

Keyhole Map for 2029 Close Approach



Impact Probabilities Over Next Century

- 10 million clone orbits were checked for Earth impacts over the next century and 13 impacts were found
- 8 of those impacts occurred on 2068 Apr 12.63 for an impact probability of slightly less than 1 in a million in 2068
- Single impacts were also found on 2075 Apr 13.21, 2079 Apr 13.65, 2079 Oct 16.81, 2083 Apr 13.31, and 2091 Apr 13.37
- More recent observations have eliminated the impact risk over the next century

Acknowledgments

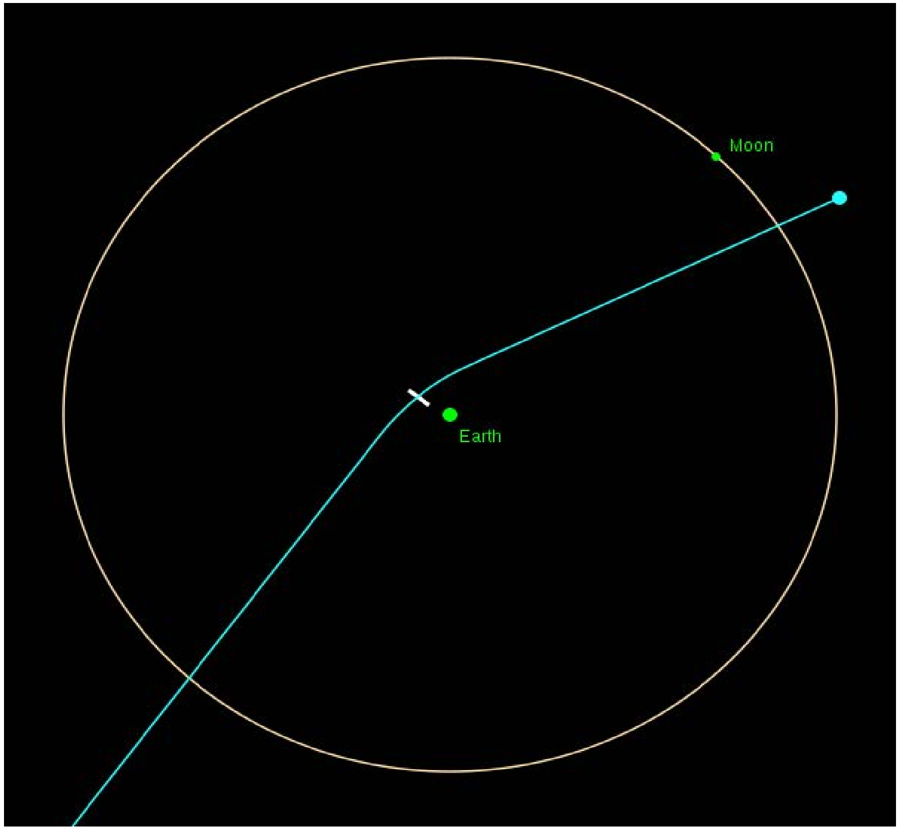
- Several people have helped to acquire observations of Apophis from Mauna Kea Observatory over the years, including Fabrizio Bernardi, Marco Micheli, Garrett Elliott, Dora Fohring, and Denise Hung.
- Most recent funding from NASA grant NNX13AI64G.

Dedication

- DJT would like to dedicate this presentation to the memory of Apophis co-discoverer and dear friend Roy A. Tucker, who passed away of pancreatic cancer on 2021 March 5, within hours of the 2021 close approach of Apophis to the Earth

APOPHIS Express

A UNIQUE OPPORTUNITY FOR VISITING APOPHIS IN 2029



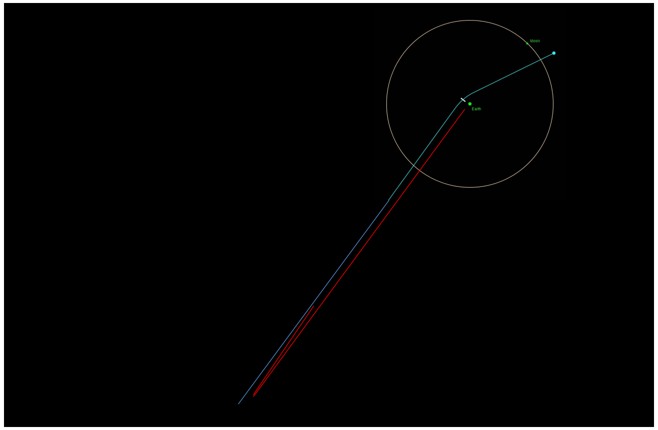
Jean-Yves Prado[1], Daniel Hestroffer[2] , Alain Herique[3]

[1]PLATINEO Suite C201 14 rue Henri Amel 17000 La Rochelle France prado@club-internet.fr
[2]IMCCE Paris Observatory, univ. PSL, CNRS hestro @imcce.fr
[3] Univ. Grenoble Alpes, CNRS, CNES, IPAG, Grenoble, France Alain.Herique@univ-grenoble-alpes.fr

APOPHIS Express Outline

. Interception and rendez-vous with APOPHIS on its incoming leg, a few days before its flyby

. Launch in March 2029 on a highly eccentric orbit with an apogee between 1 and 2 Million kilometers



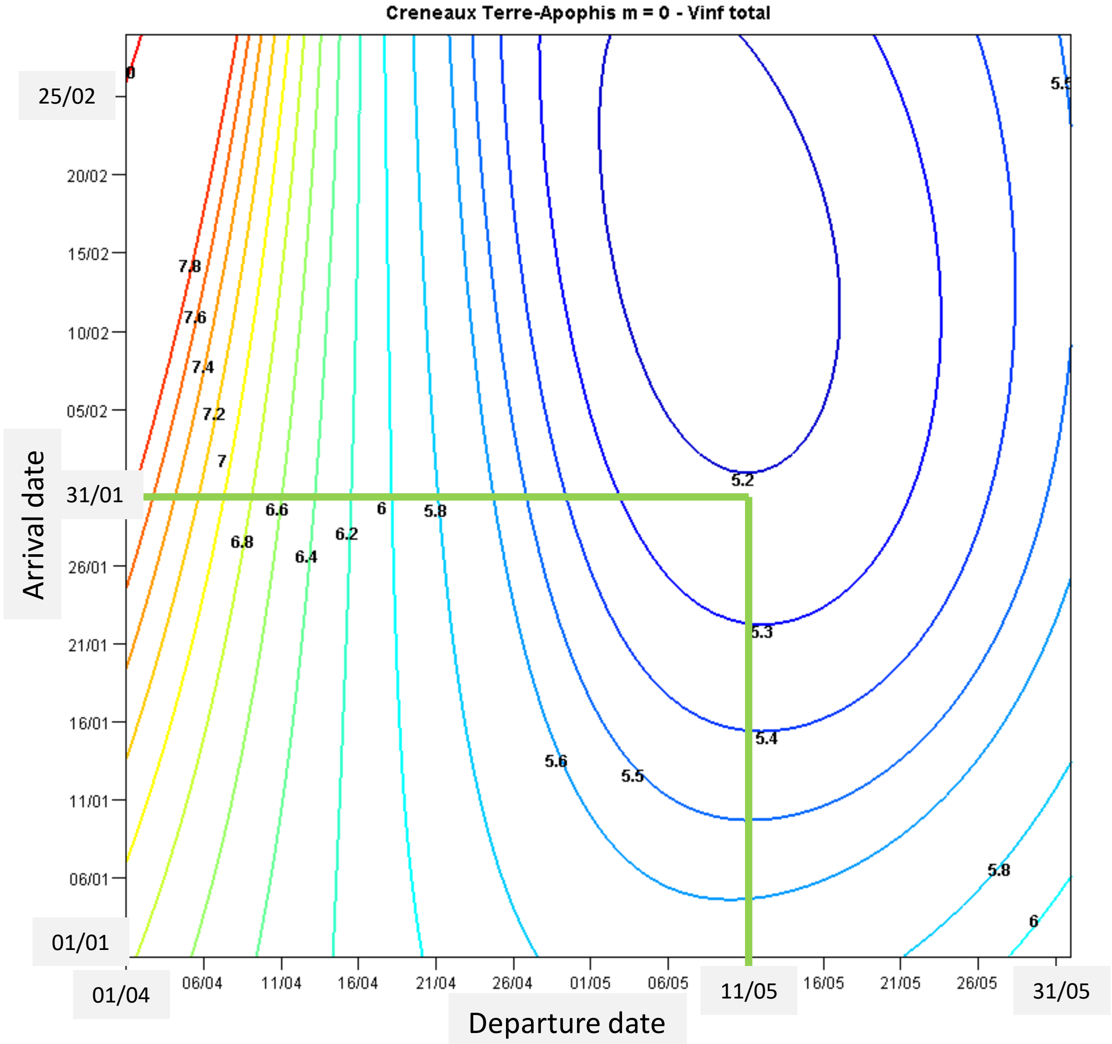
. Delivery of a set of modules for

- rendez-vous with APOPHIS (Apogee Kick Module)
- close navigation, observation and command of the other modules (Service Module)
- APOPHIS orbiter
- lander
- Return Capsule

. Main mission advantages:

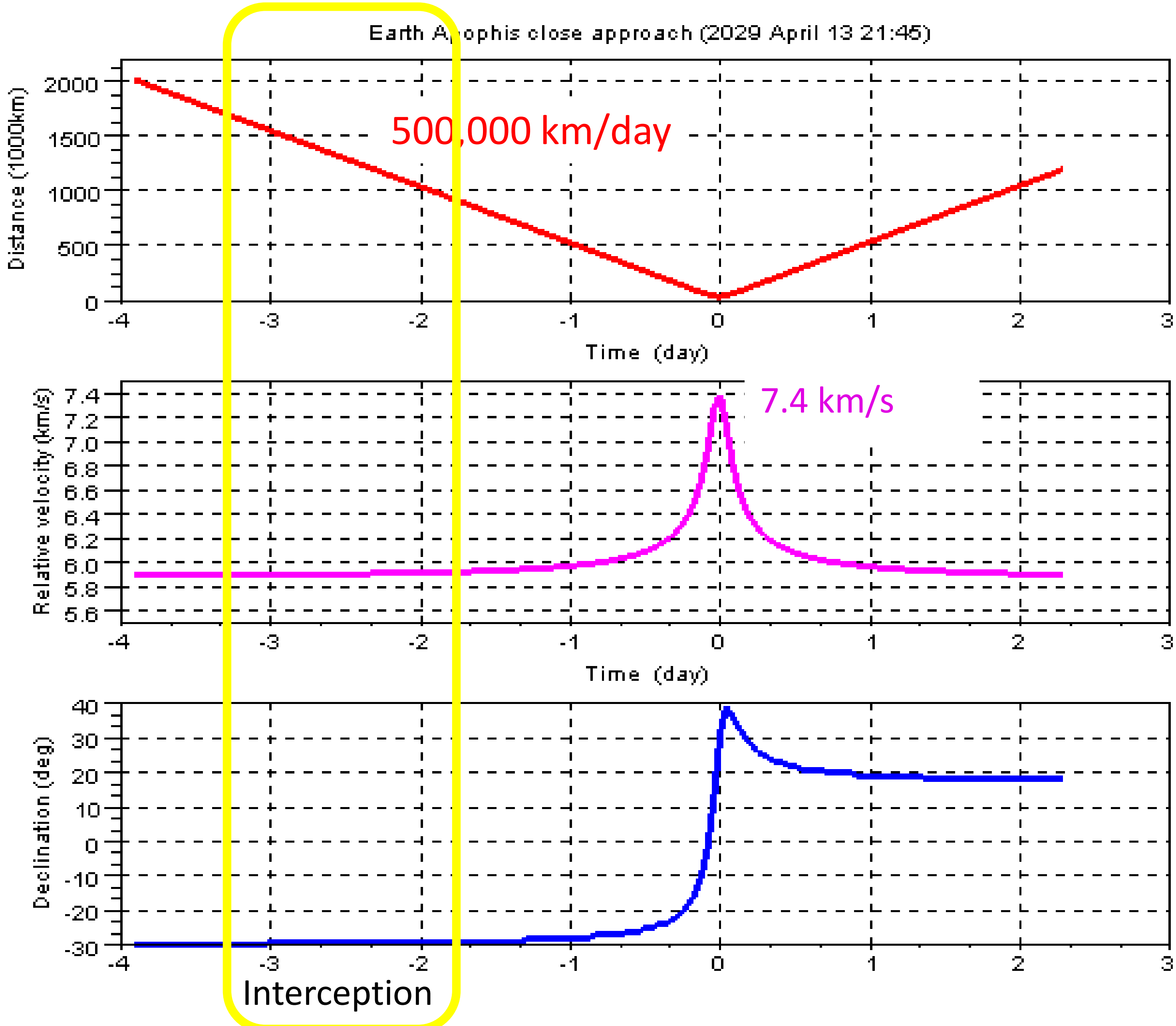
- short duration
- late departure
- system requirements similar to Sun-Earth L1/L2 missions instead of interplanetary missions

Standard Mission Scenario

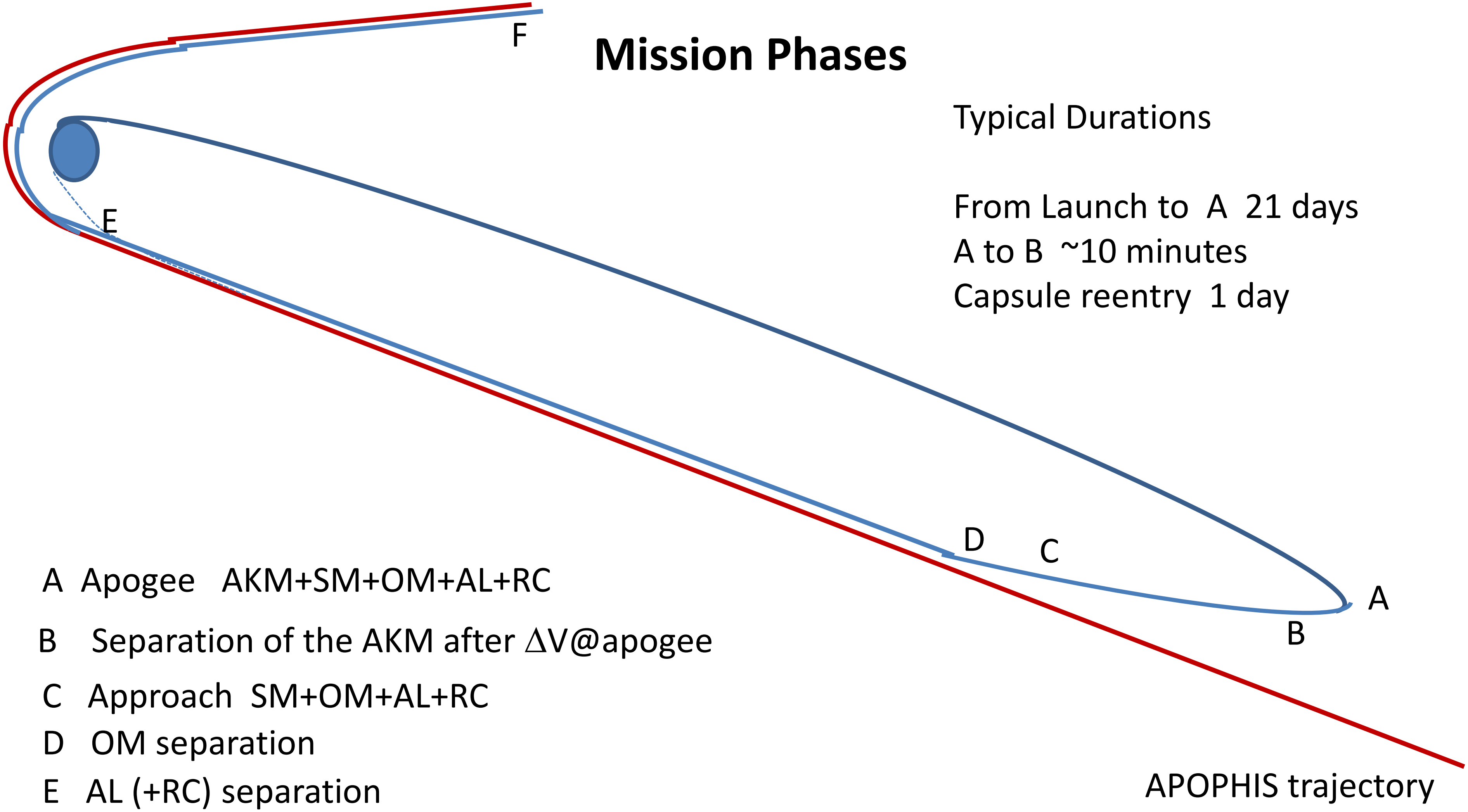


- Launch in May 2028 at the latest (V_{inf}<3.7 Km/s)
- Arrival on APOPHIS in February 2029 (V_{inf}<1.6 km/s)
- Total ΔV <5.2 km/s
- 2 months for precursor activities before the close pass

Proposed Scenario



Mission Phases



Typical Durations

From Launch to A 21 days
A to B ~10 minutes
Capsule reentry 1 day

A Apogee AKM+SM+OM+AL+RC

B Separation of the AKM after ΔV@apogee

C Approach SM+OM+AL+RC

D OM separation

E AL (+RC) separation

F Mission end

Launch Options (based on publically available data)

Launcher	Delivery capacity @ 1 Mkm	Gross mass after AKM separation	Estimated allocation (2) for instrumentation
Soyuz-Fregat	2000kg	296kg	56kg
AR 62	2500	320	60
AR5 ECA	6200	920	174
AR64	7500	1060	201
AR64-VINCI (1)	7500	1370	260

All masses in kg

(1) AKM Specific Impulse 435s except for AR64-VINCI (465s)

(2) Based on HERA mass budget (19% of the total mass available for the scientific P/L

ref https://www.cosmos.esa.int/documents/336356/1601091/SMPAG_HERA_Carnelli.pdf/f8d427cf-5ec7-95c0-1265-3fe95f89d880

Conclusions

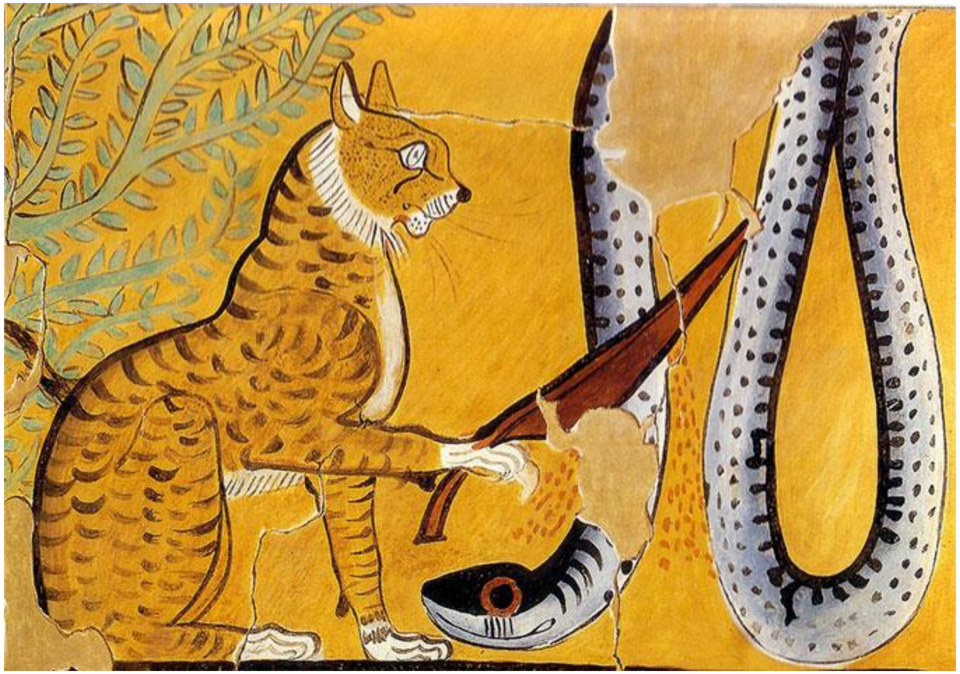
The short duration and short distance of the systems have positive effects on operation costs

Late launch has positive impact on the decision making process

It can benefit from other space missions and ground observations

Large public interest expected due to the fast sequence of events in the last 2 days before the flyby

Scientific objectives, payload and modules to be defined in coherence with the expected other missions (SMPAG?) and in adequation with the selected launcher



EXTENSION OF THE EARTH LIBRATION POINT MISSIONS BY TARGETING A SPACECRAFT TO NEAR-EARTH ASTEROIDS

***N.A. Eismont*[1], <u>*M.V. Pupkov*</u>[1,2], *K.S. Fedyaev*[1],**
***V.A. Zubko*[1,2], *A.A. Belyaev*[1,2],**
***N.A. Simbiryov*[1,2], *R.R. Nazirov*[1]**

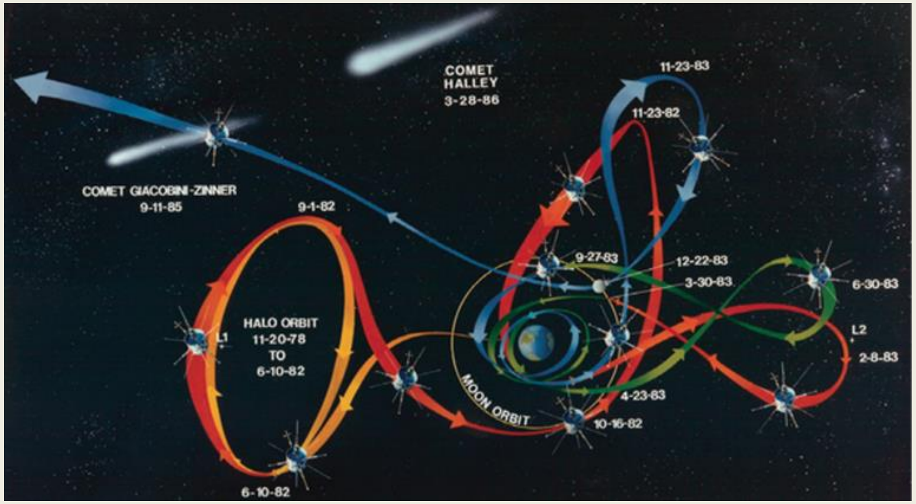
---

[1] Space Research Institute of Russian Academy of Sciences
[2] Bauman Moscow State Technical University

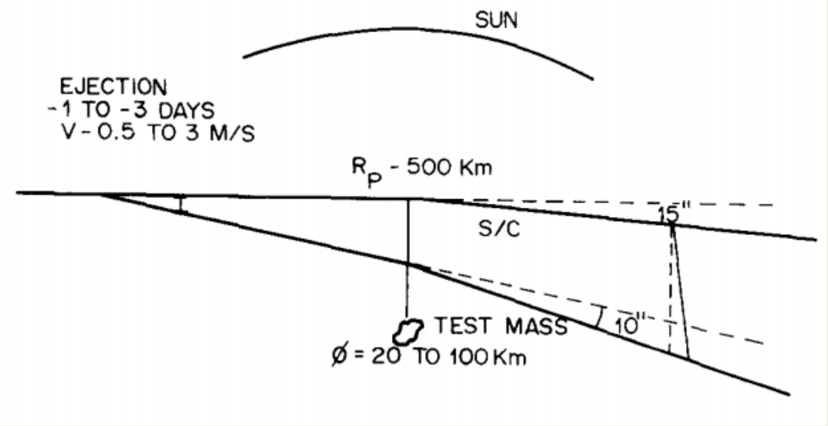
IAA PLANETARY DEFENSE CONFERENCE 2021

APRIL 26-30, 2021

ISEE-3/ICE Project[1]



An Approach to Estimate the Mass of an Asteroid[2]

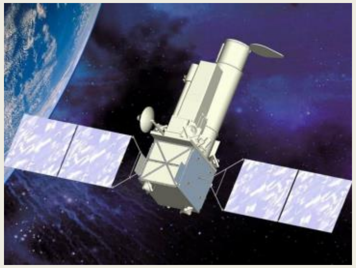


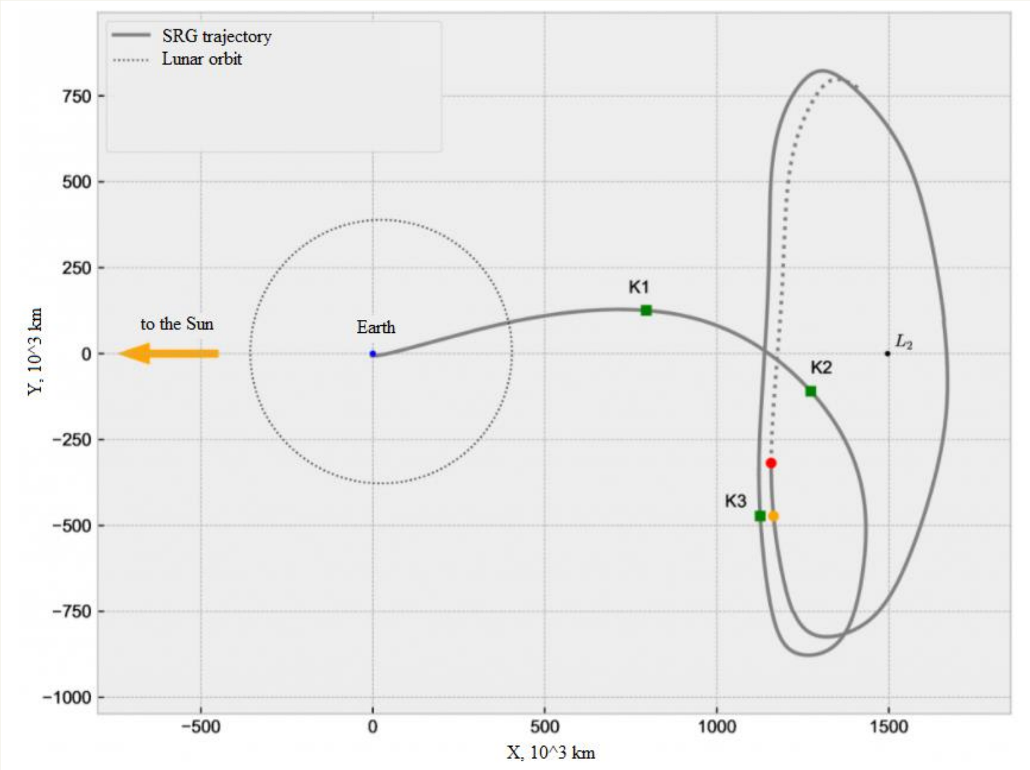
---

[1] David W. Dunham, Robert W. Farquhar et al. “The 2014 Earth return of the ISEE-3/ICE spacecraft.” Acta Astronautica. Vol. 110, 2015, pp. 29–42.
[2] A. Perret. “Mass Determination of a Small Body in Solar System by Using a Test-Mass During a Fly-By.” Acta Astronautica. Vol. 12, No. 1, 1985, pp. 41-44.

Spectrum-Roentgen-Gamma[3]

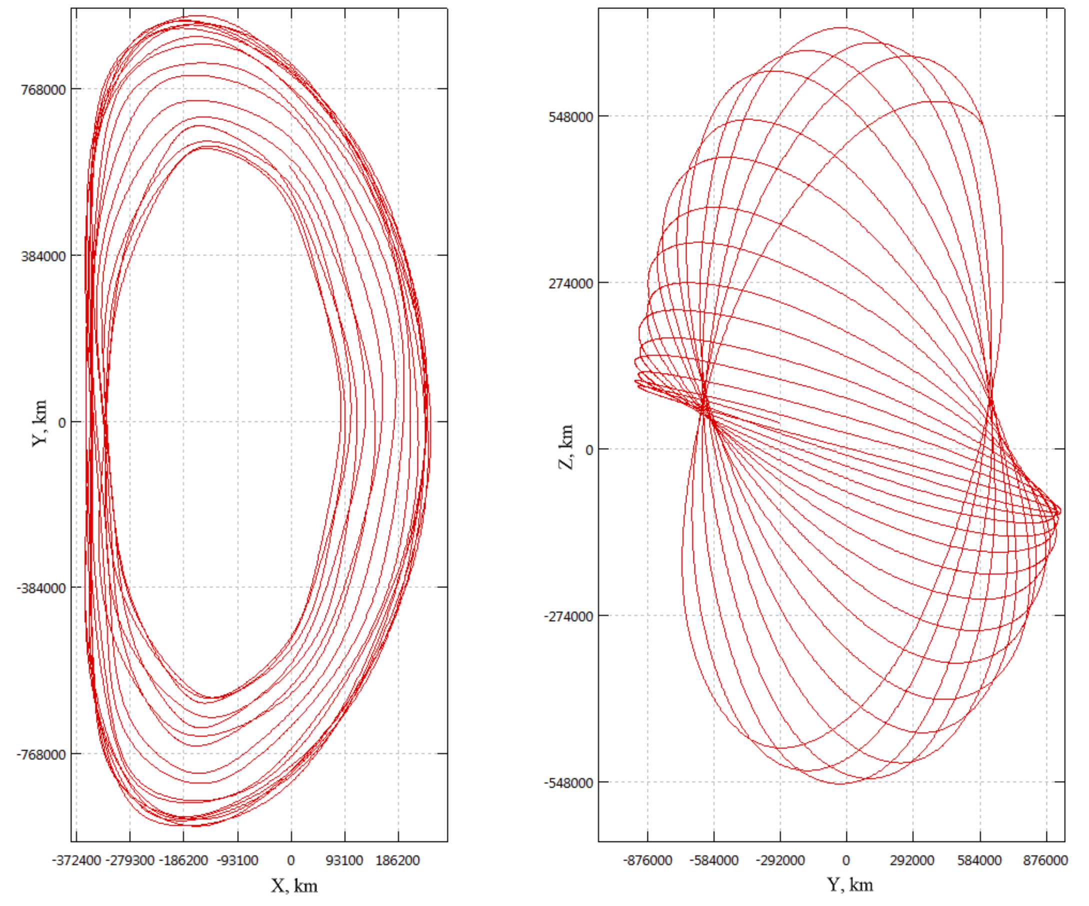
Launch: July 13, 2019
Wet mass: 2712.25 kg
Payload mass: 1210 kg
Exp. lifetime: 6.5 years





[3] Spectrum-Roentgen-Gamma, Astrophysical project.
URL: http://srg.iki.rssi.ru/

SRG Trajectory Simulating[4]



[4] Aksenov S.A., Bober S.A. "Calculation and Study of Limited Orbits around the L2 Libration Point of the Sun–Earth System." Cosmic Research, 2018, Vol. 56, Iss. 2, pp. 144–150.

General Mission Analysis Tool[5]

[5] GMAT: General Mission Analysis Tool.
URL: https://sourceforge.net/projects/gmat

Asteroids

(35396) 1997 XF11

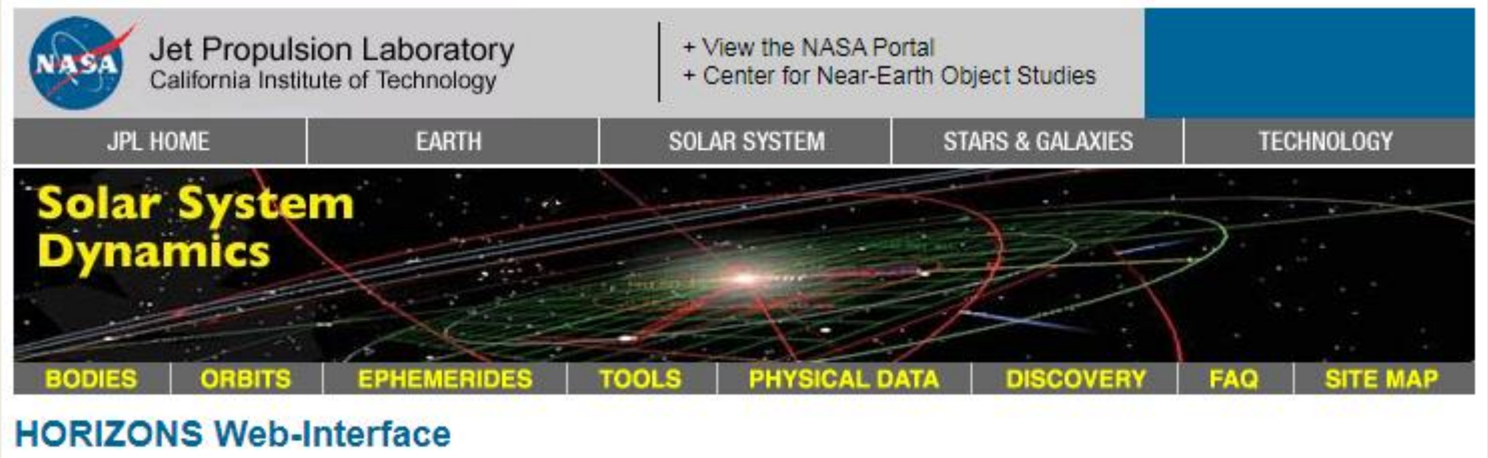
(99942) Apophis

Comets

289P/Blanpain

300P/Catalina

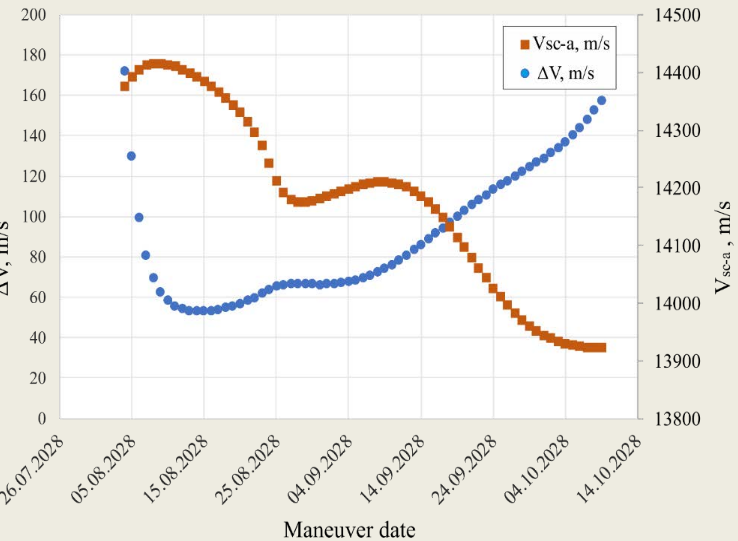
Ephemeris data – from NASA Horizons interface[6]



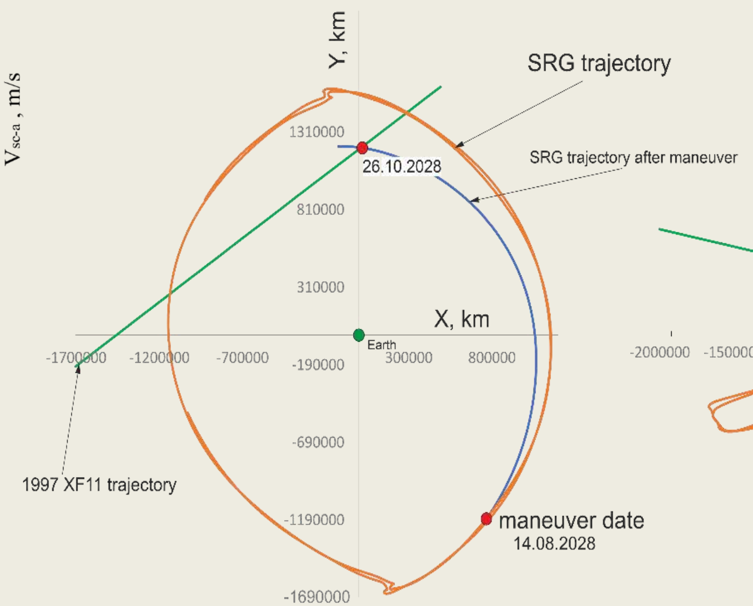
---

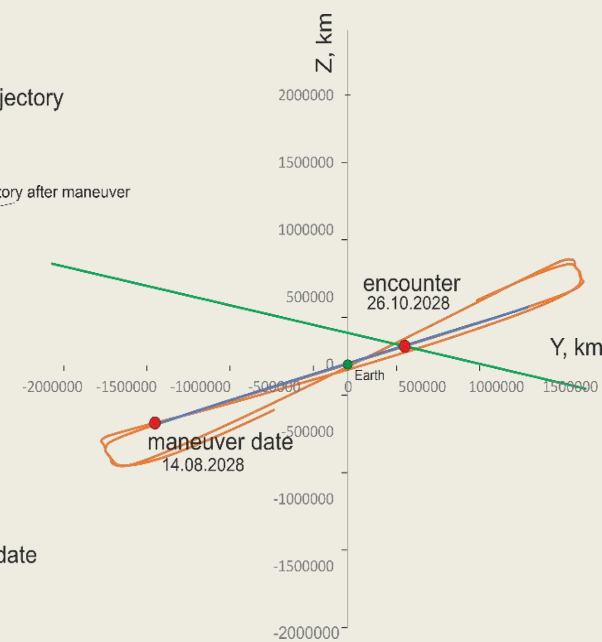
[6] **WebGeocalc: A Tool of the Navigation and Ancillary Information Facility. URL: https://ssd.jpl.nasa.gov/horizons.cgi**

Asteroid (35396) 1997 XF11

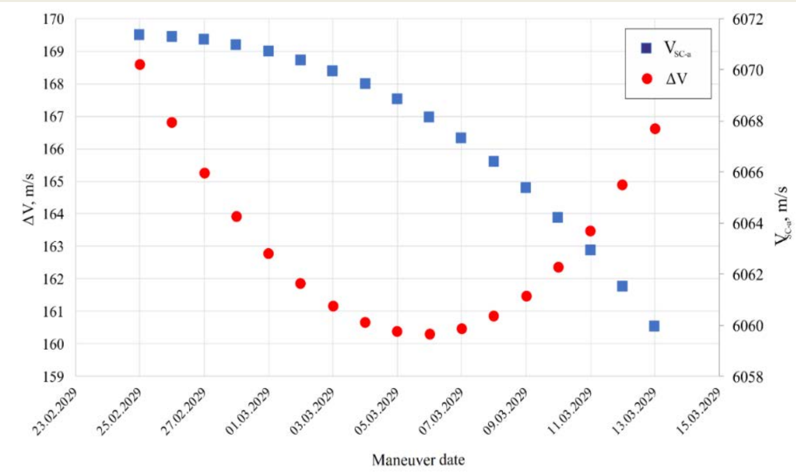


Dependence of the minimal ΔV required for the SRG transfer to the 1997 XF11 asteroid on the date of the impulse application (shown in red), and the relative velocity of the spacecraft (shown in blue)

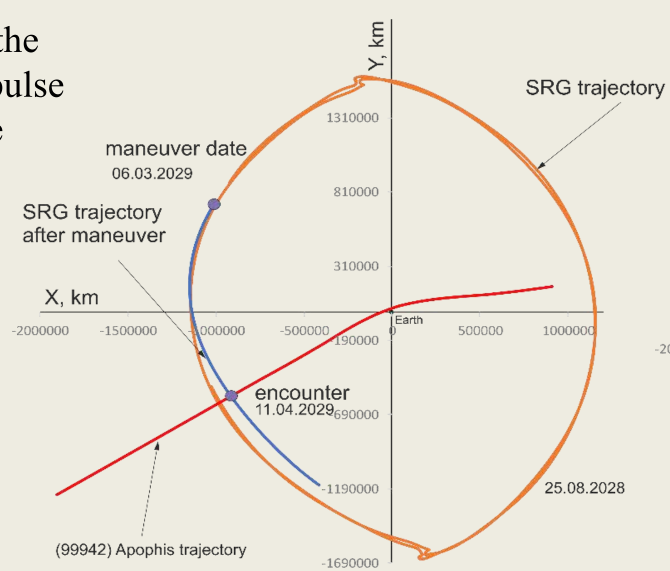


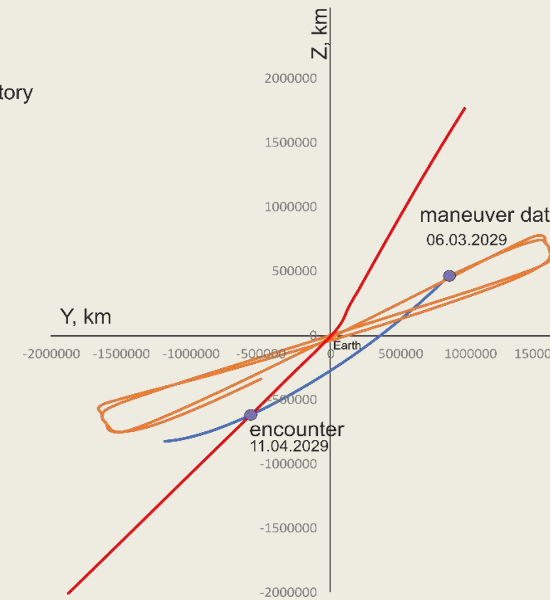


Asteroid (99942) Apophis



Dependence of the minimal ΔV required for the SRG transfer to Apophis on the date of the impulse application (shown in red), and the relative velocity of the spacecraft (shown in blue)

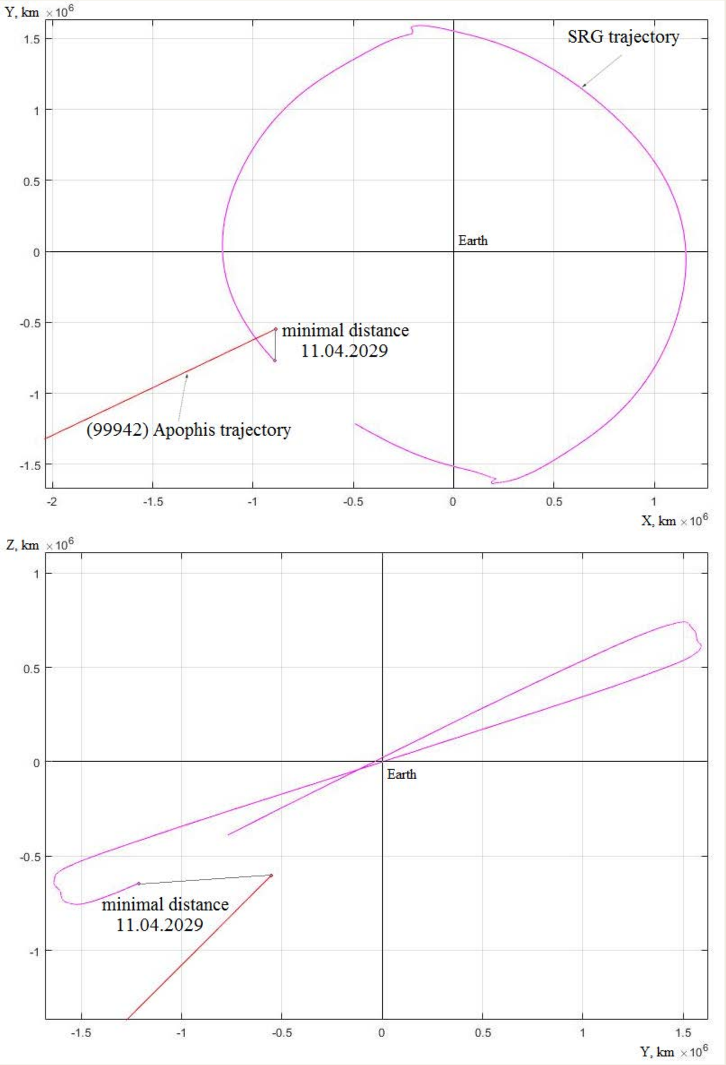




IAA PLANETARY DEFENSE CONFERENCE 2021

APRIL 26-30, 2021

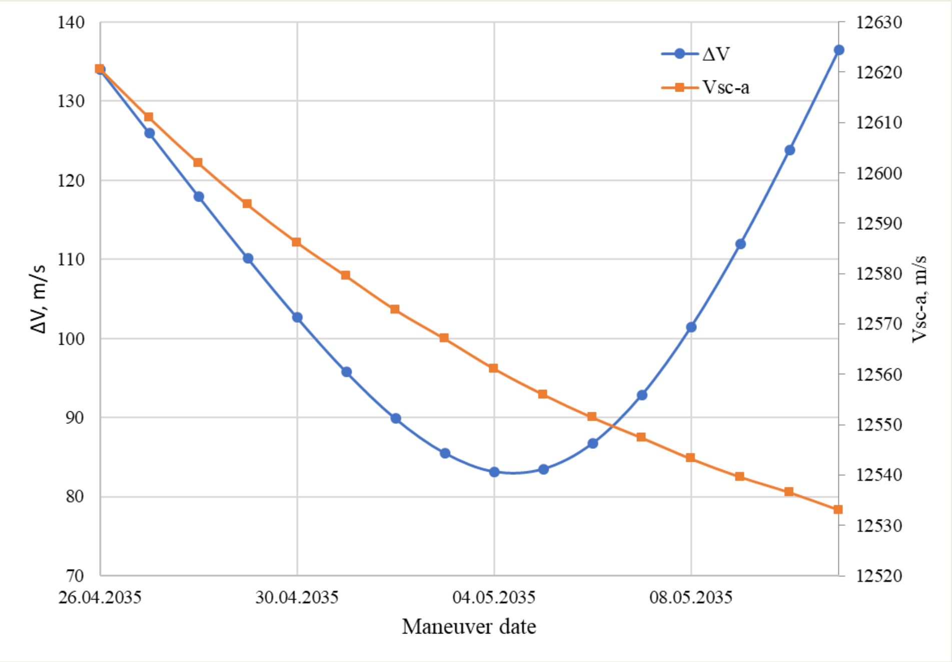
Observing Apophis from the SRG initial orbit



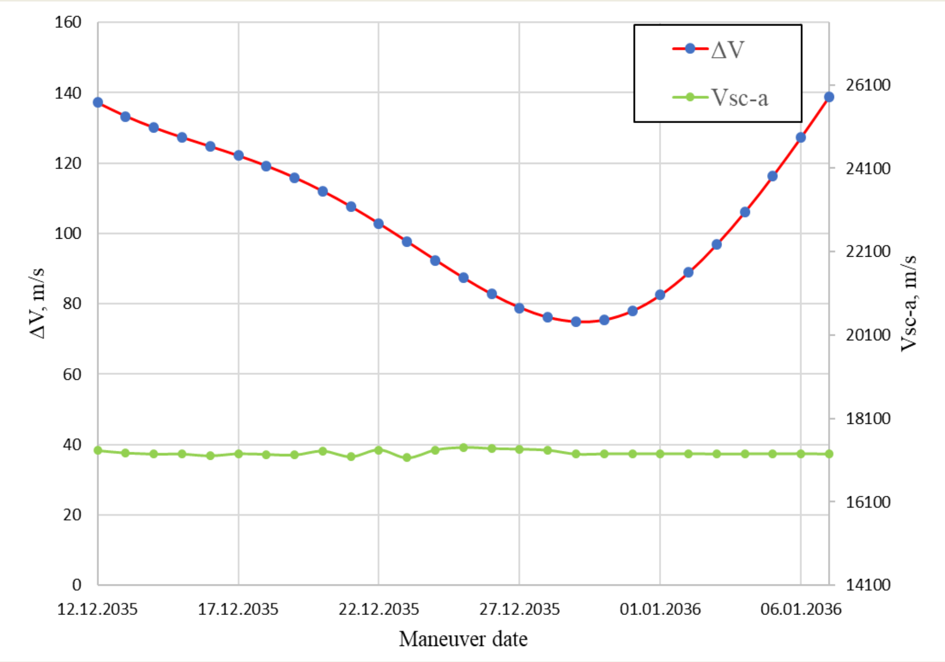
IAA PLANETARY DEFENSE CONFERENCE 2021

APRIL 26-30, 2021

Comets 289P/Blanpain and 300P/Catalina



Dependence of the minimal ΔV required for the SRG transfer to 289P/Blanpain on the date of the impulse application (shown in blue), and the relative velocity of the spacecraft (shown in orange)



Dependence of the minimal ΔV required for the SRG transfer to 300P/Catalina on the date of the impulse application (shown in red), and the relative velocity of the spacecraft (shown in green)

IAA PLANETARY DEFENSE CONFERENCE 2021

APRIL 26-30, 2021

Thank you for attention!

7th IAA Planetary Defense Conference

26-30 April 2021, Online Event

Hosted by UNOOSA in collaboration with ESA

Q&A

Session 13 – Apophis and Others, Far and Near: Future Characterization Opportunities from NEO Close Approaches

7th IAA Planetary Defense Conference

26-30 April 2021, Online Event

Hosted by UNOOSA in collaboration with ESA

Break

Up next: PANEL - PROPOSAL FOR AN INTERNATIONAL YEAR OF PLANETARY DEFENSE