SSA-SN-VII
NEO Impact Effects & Mitigation Measures Study

Final Presentation

Juan L. Cano
DEIMOS Space S.L.U.
ESRIN, 18th November 2014

Agenda

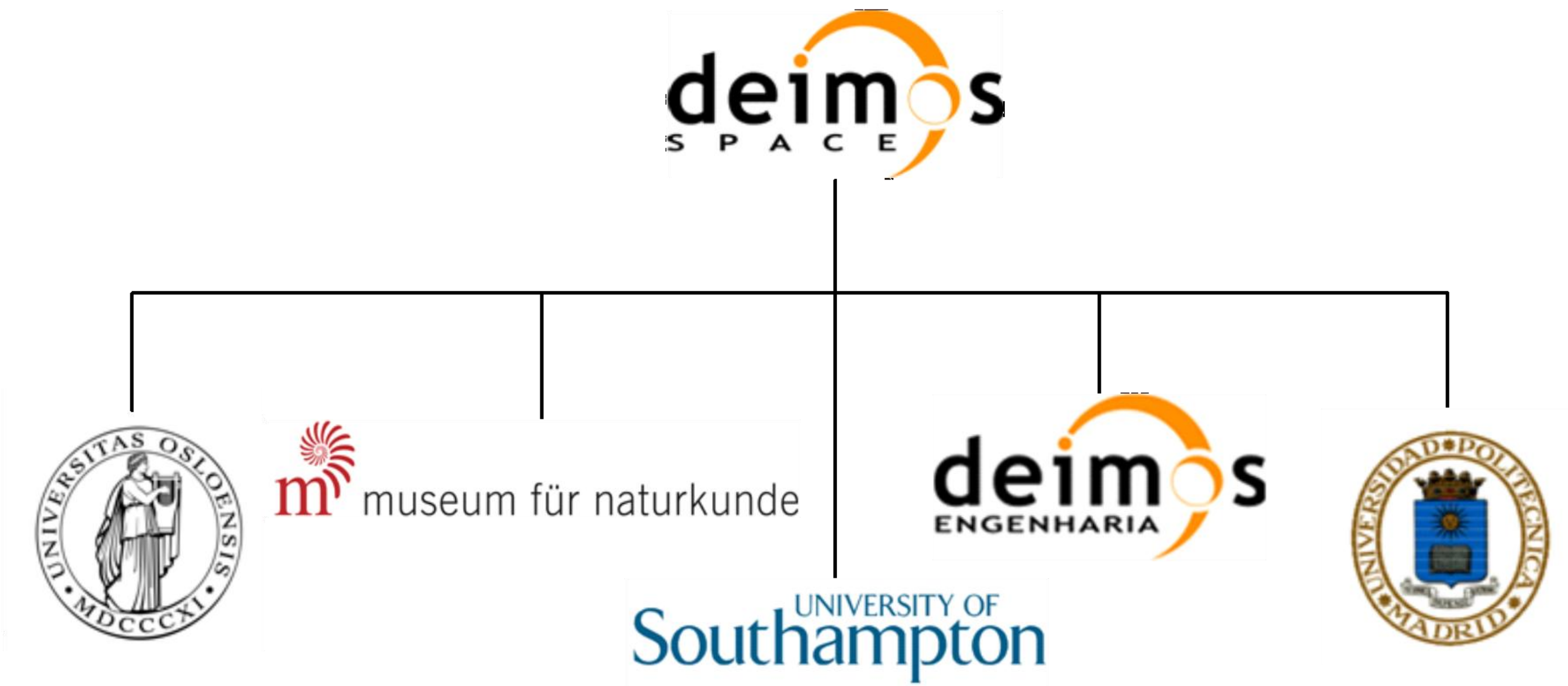
1. The Project
2. Impact Effects Activities
3. Mitigation Measures Activities
4. Workshop and Roadmaps
5. Summary

1 THE PROJECT

Study Motivation and Objectives

- Perform an assessment of the state of the art of NEO **impact effects** and potential **mitigation measures**
- Main objectives were:
  - Review the effects of **hypervelocity entries** in the atmosphere and of impacts on ground
  - Review related **simulation tools**
  - **Demonstrations** of some existing tools
  - Assess **missing capabilities** (knowledge and tools) and required measures and efforts (tests, simulation tool developments) to fill the gaps in the area of impact effects
  - Review NEO **mitigation options** and ongoing related activities
  - Analyse **potential next steps** towards a NEO mitigation space mission
  - Organize a European **workshop** on NEO impact effects and mitigation measures to support future efforts in this field

SN-VII Consortium

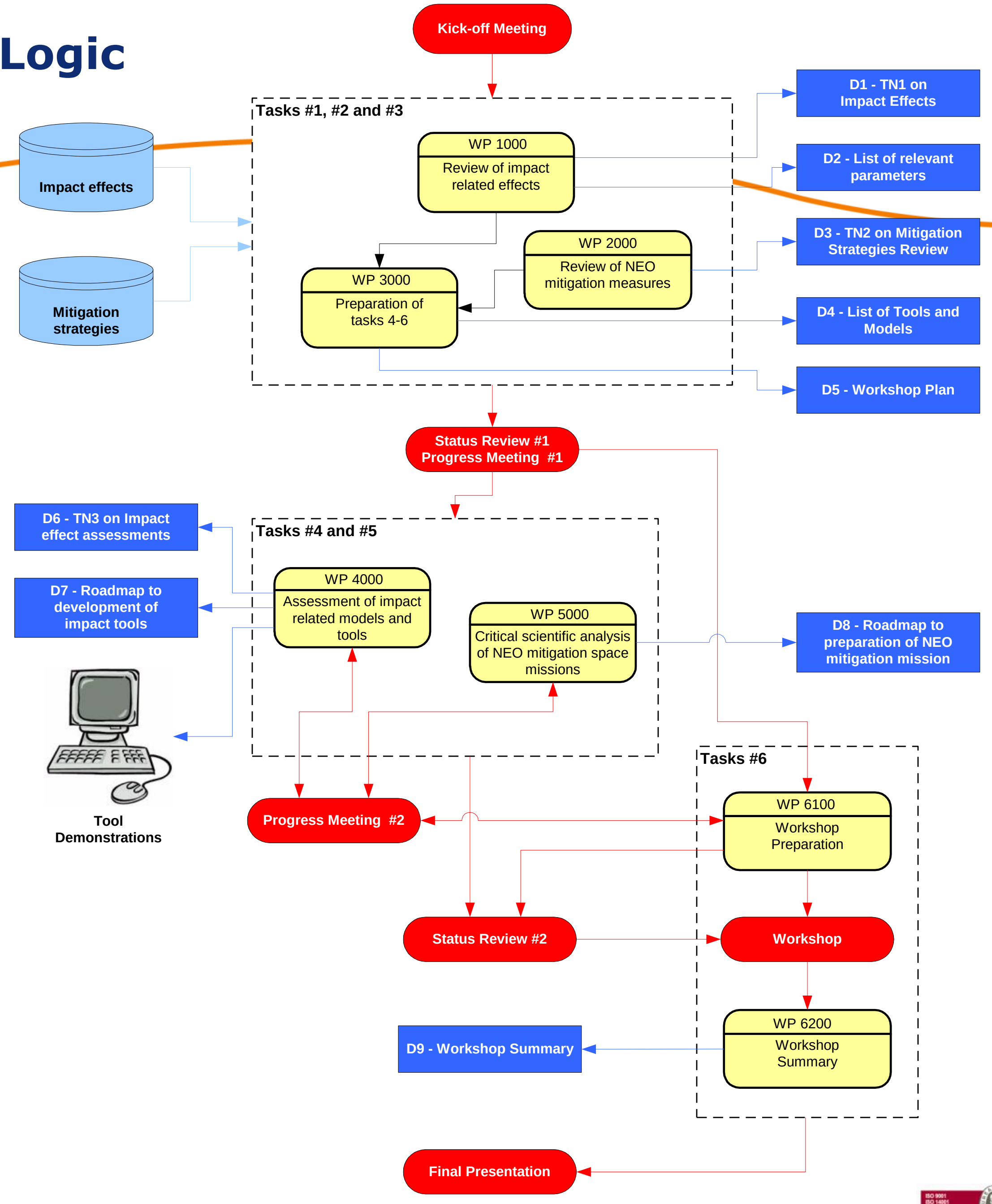


Consortium Set-up

elecnor deimos

	Impact Effects	Mitigation Measures
deimos SPACE	Asteroid and spacecraft entry effect	Kinetic impact strategy
UNIVERSITAS OSLOENSIS MDCCCXI	Low altitude atmospheric and water effects	
museum für naturkunde	Ground and long term effects	
UNIVERSITY OF Southampton	Human and economic effects	
deimos ENGENHARIA		Gravity tractor, explosive and other strategies
UNIVERSIDAD POLITECNICA MADRID		Ion Beam Shepherd strategy

Study Logic



Kick-off Meeting
Tasks #1, #2 and #3
Impact effects
Mitigation strategies
WP 1000
Review of impact related effects
WP 2000
Review of NEO mitigation measures
WP 3000
Preparation of tasks 4-6
D1 - TN1 on Impact Effects
D2 - List of relevant parameters
D3 - TN2 on Mitigation Strategies Review
D4 - List of Tools and Models
D5 - Workshop Plan
Status Review #1
Progress Meeting #1
Tasks #4 and #5
D6 - TN3 on Impact effect assessments
D7 - Roadmap to development of impact tools
WP 4000
Assessment of impact related models and tools
WP 5000
Critical scientific analysis of NEO mitigation space missions
D8 - Roadmap to preparation of NEO mitigation mission
Tool Demonstrations
Tasks #6
Progress Meeting #2
WP 6100
Workshop Preparation
Status Review #2
Workshop
D9 - Workshop Summary
WP 6200
Workshop Summary
Final Presentation

Project Timeline

- ITT release: 29 Nov 2011
- Proposal deadline: 1 Feb 2012
- Project Kick-off: 16 May 2012
- Status Review #1: 27 Sep 2012
- Status Review #2: 04 Apr 2013
- Workshop: 07-08 May 2013
- Final delivery: 23 Aug 2013
- Final presentation: 18 Nov 2014

2 IMPACT EFFECTS

Impact Effects

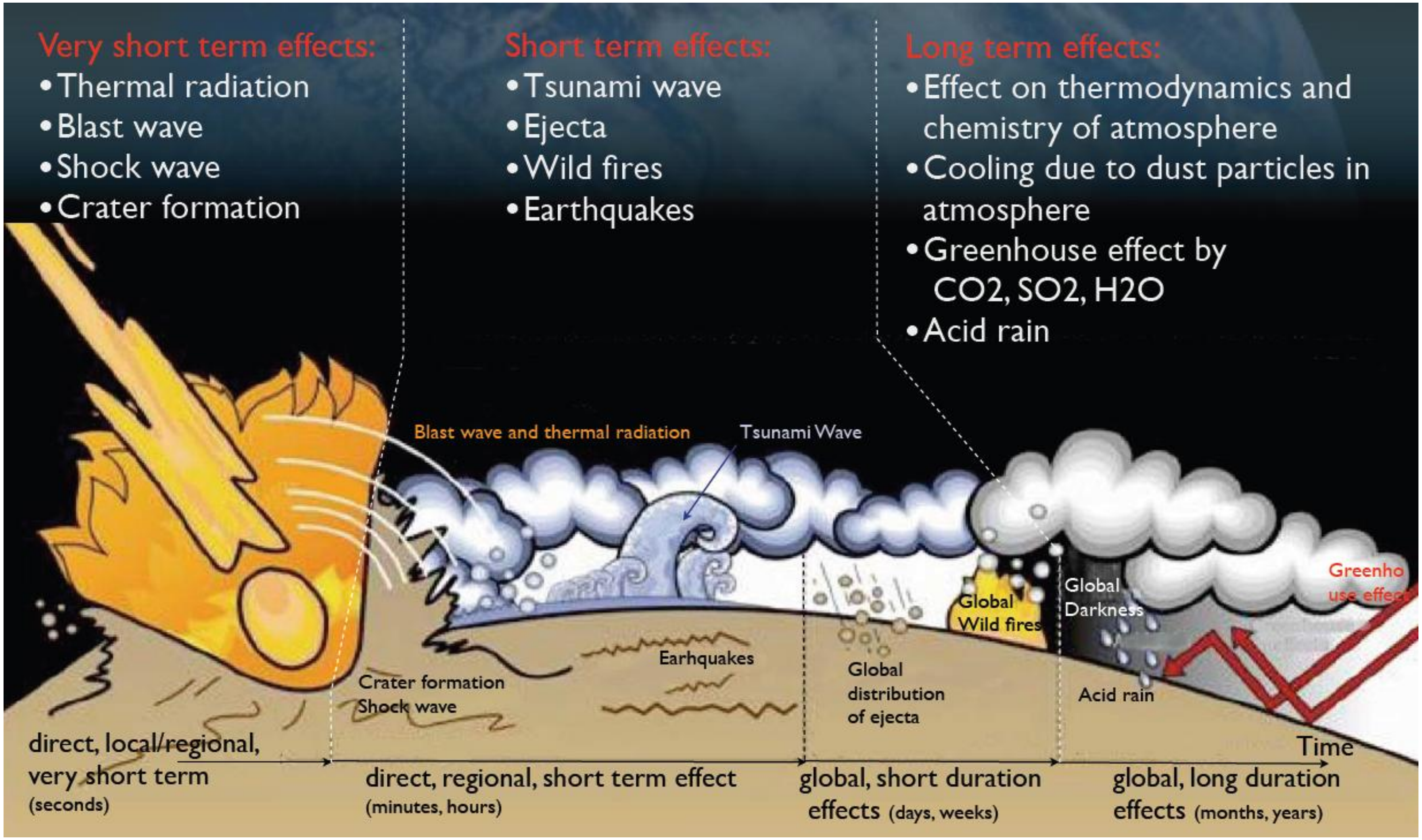


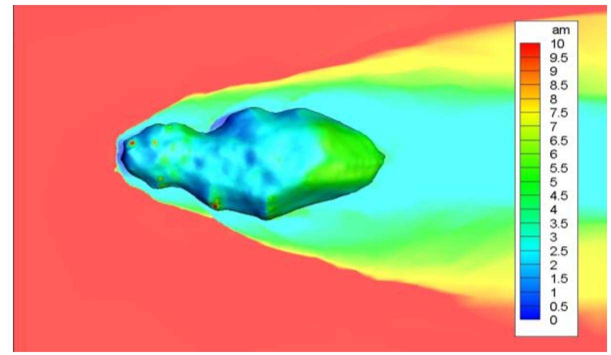
Image courtesy of Laubscher & Reimold

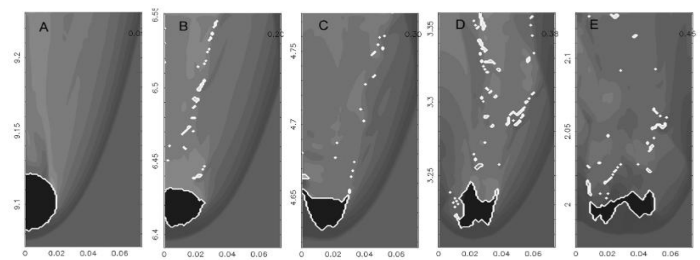
Impact Related Effects
Project Activities

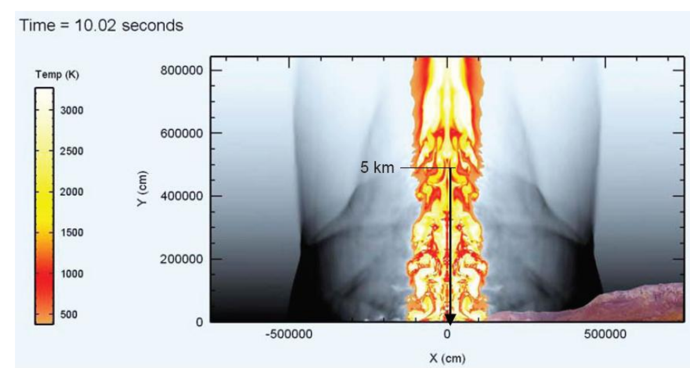
- Review of all types of impact effects:
  - Atmospheric
  - Water
  - Ground
  - Ejecta and long term
  - Societal and economic
- Review of software tools for each of the effects
- Test cases over three scenarios:
  - 140 m asteroid
  - Tunguska case (40 m asteroid)
  - Chelyabinsk case

2.1 Review of Impact Effects

- Aerothermodynamics
  - Pressure effects
  - Thermal flux
  - Chemistry
  - Ablation
- Breakup and fragmentation
  - Pancake model
  - Separated fragments model
  - Hydrodynamical approximation
- Energy dissipation
  - Steady dissipation
  - Airburst



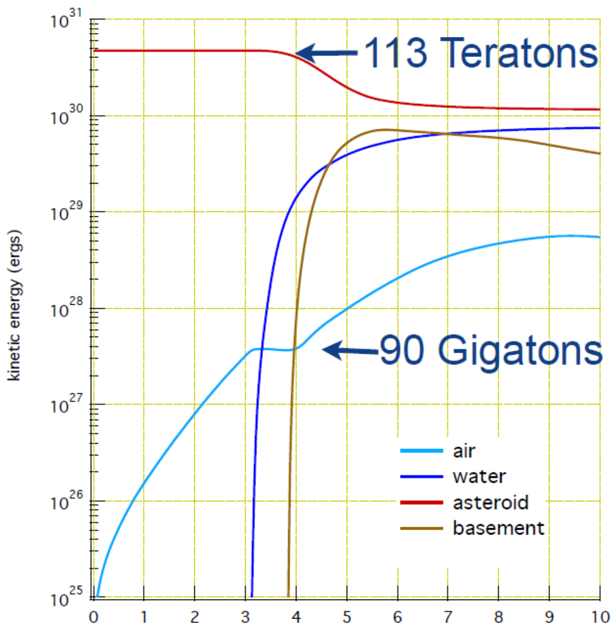




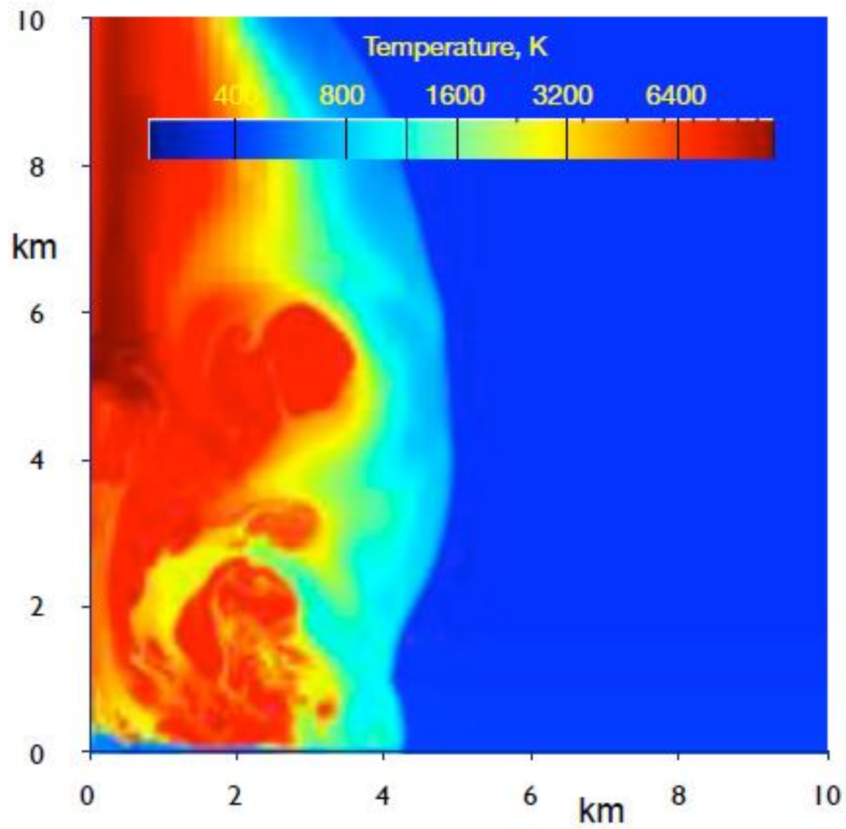
Boslough et al.

Review of Impact Related Effects
Atmospheric Entry Effects

- Energy transfer to atmosphere
- Shockwave propagation (pressure & temperature)
- Airburst



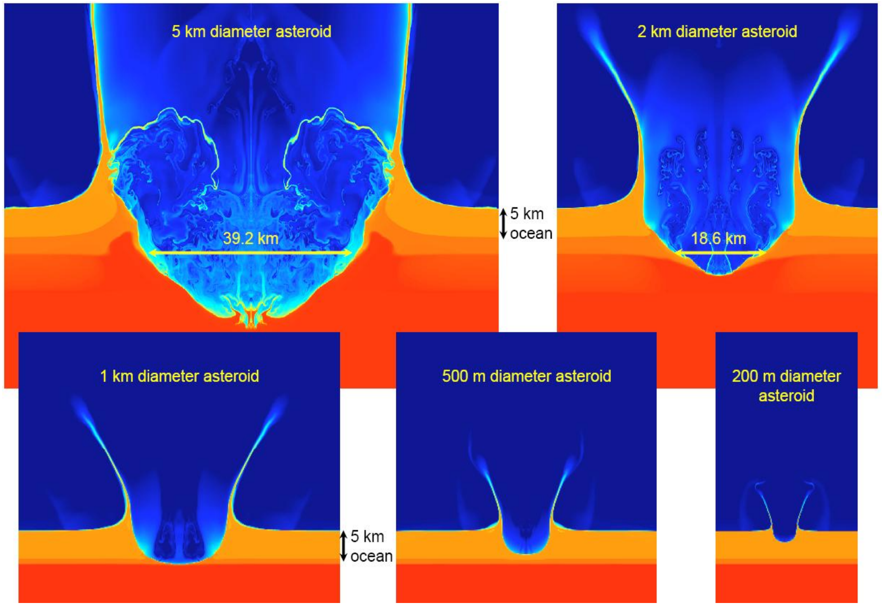
12 km asteroid at and angle of 30 deg

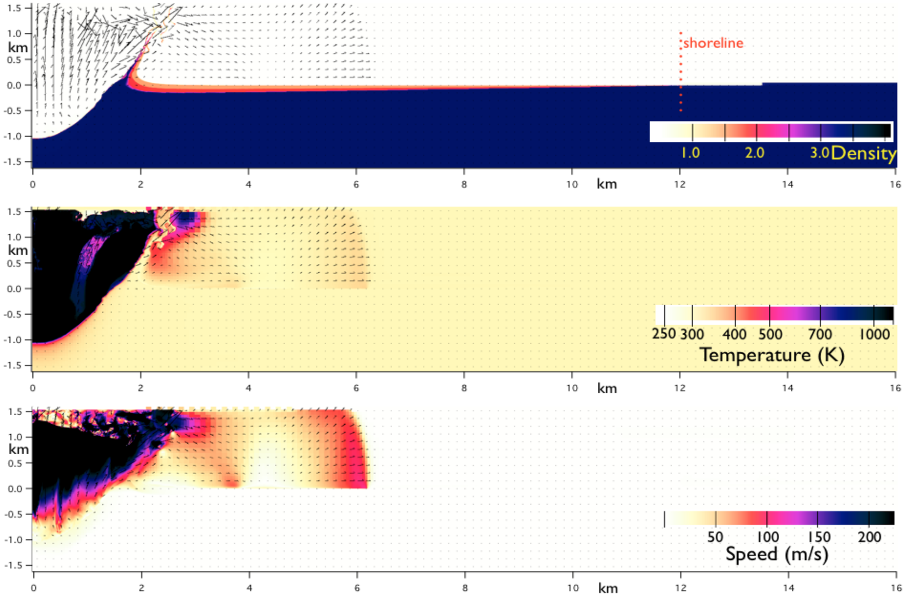


125 m stony asteroid, vertical entry at 20 km/s and airburst at 10 km altitude

Review of Impact Related Effects
Water Impact Effects

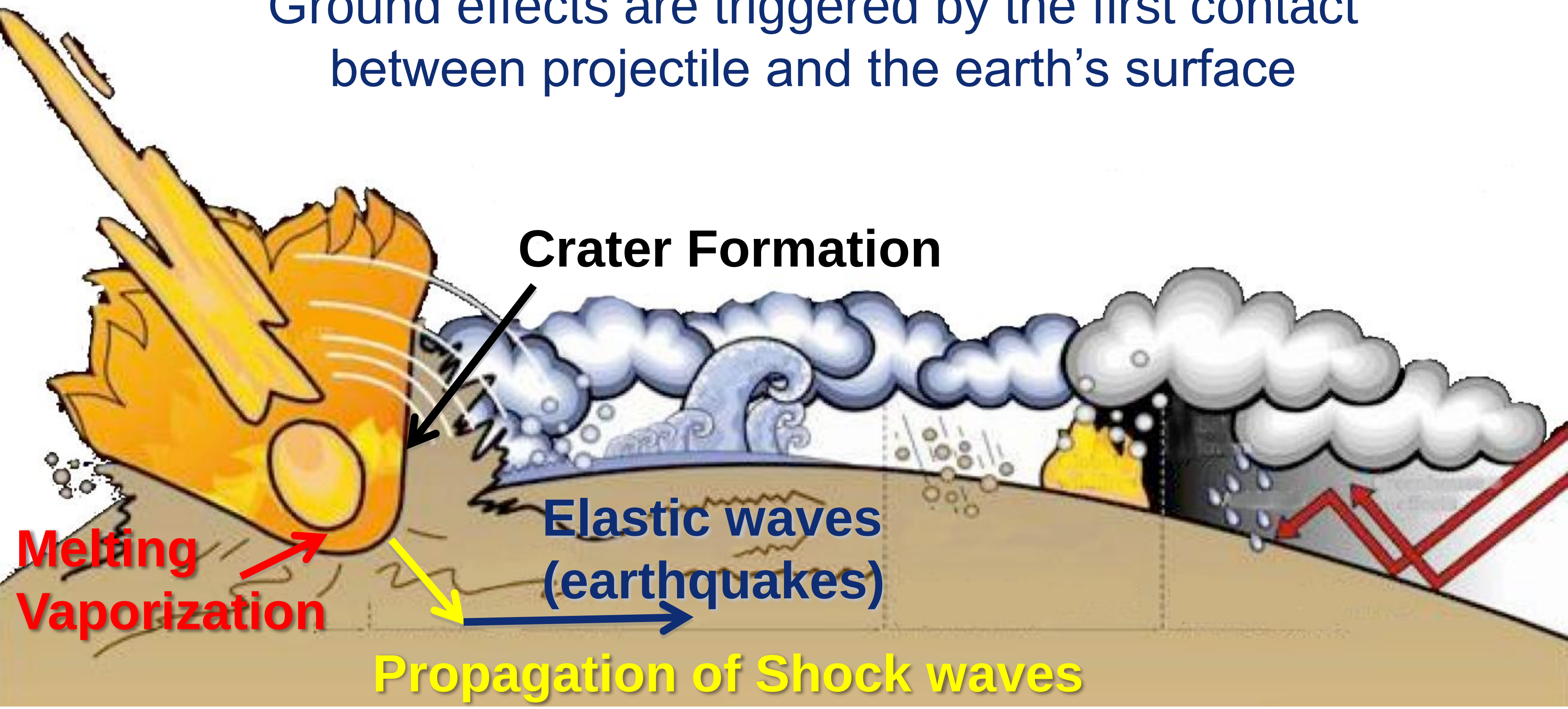
- Effects on deep and shallow waters
- Interaction with the sediment layers
- Formation and evolution of tsunamis
- Coastal effects



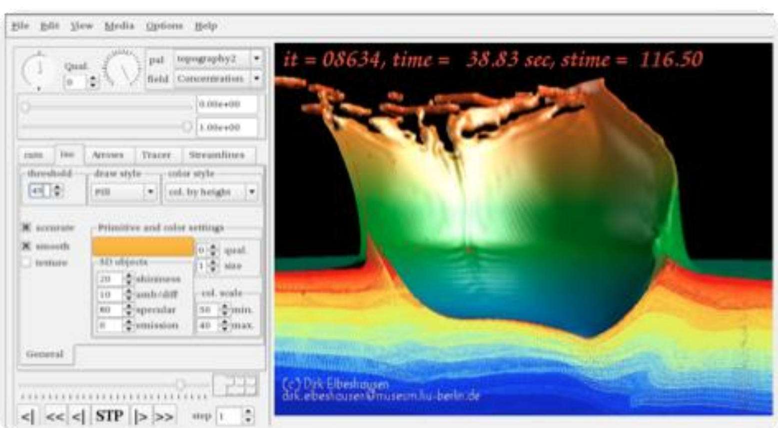


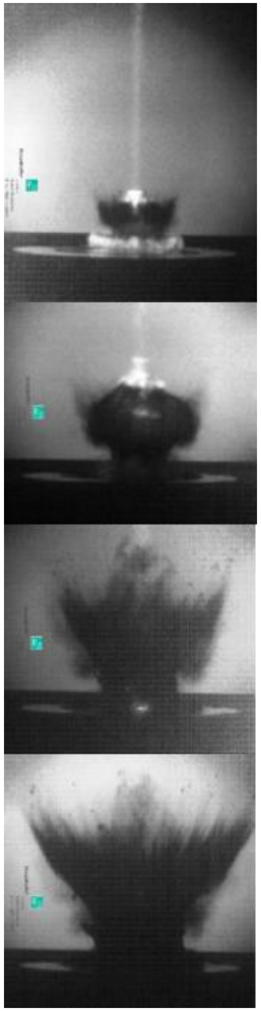
museum für naturkunde

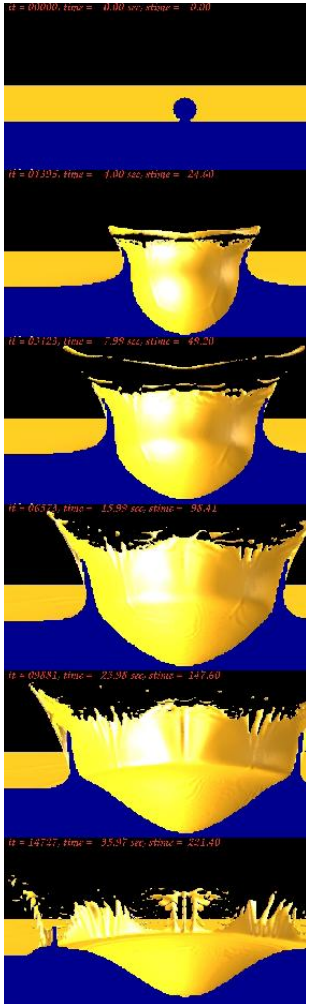
Ground effects are triggered by the first contact between projectile and the earth's surface



- Contact and compression
- Shock melting/vaporisation
- Crater excavation
  - Gravity regime
  - Strengh regime
- Shockwave propagation
- Seismic waves



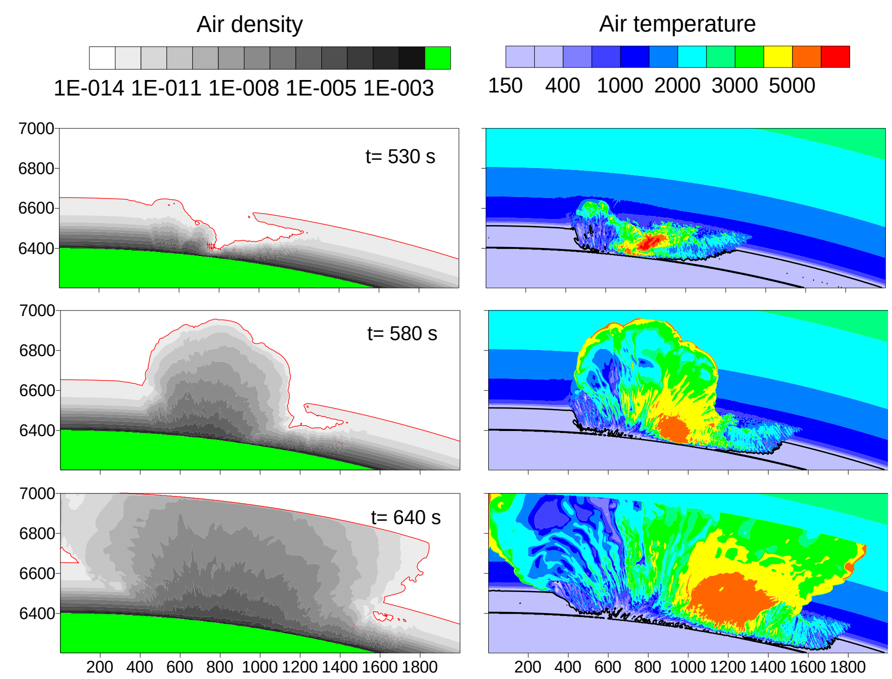




Review of Impact Related Effects
Ejecta and Long Term Atmos. Effects

museum für naturkunde

- Ejecta
- Blast wave
- Plume effects
- Thermal effects and wildfires
- Dust and gases release ➔ climate modelling



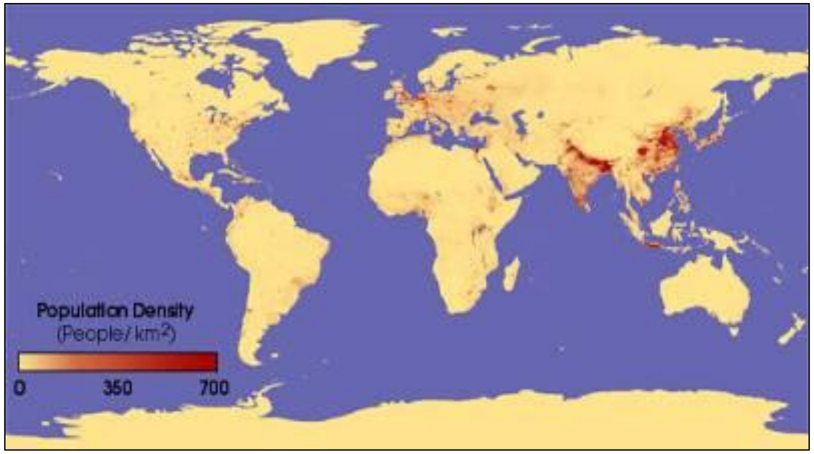
Pierazzo et al. 2010

Review of Impact Related Effects
Human and Economic Impact Effects

- Review the status of knowledge on:
  - Databases of population modelling, infrastructure and associated GIS
  - Modelling of impact effects on population and infrastructure
  - Dependency of those effects on the geography/demography of the impacted region
- Dependence of these on parameters of the impacting object
- List the relevant parameters and establish criteria for assessment of impact effects
- Overall risk is evaluated in terms of:
  - Hazard, which describes the magnitude
  - Vulnerability, which is proportional loss
  - Exposure, which describes the elements at risk

Review of Impact Related Effects
Human and Economic Impact Effects

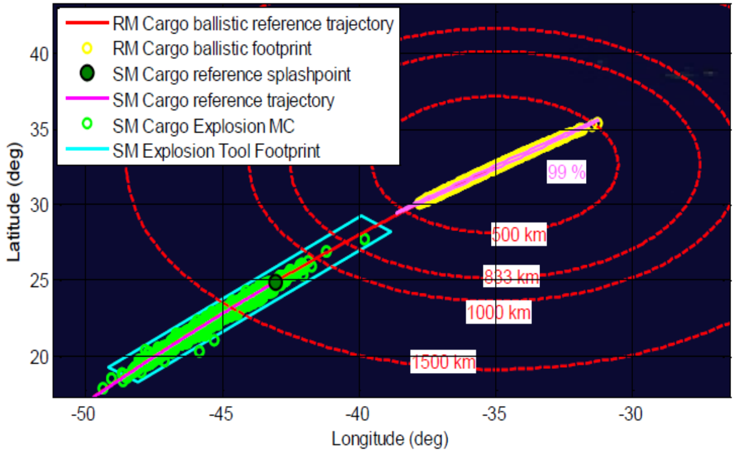
- Effects considered
  - Air blast
  - Thermal radiation
  - Craters
  - Ejecta
  - Seismic shockwaves
  - Tsunamis
  - Secondary and Cascading Hazards
  - Long term effects



- Mitigation measures: Modify vulnerability or exposure
  - Observation campaigns – warnings, preparedness
  - Deflection – modifies exposure

Review of Impact Related Effects
Spacecraft Re-Entry Effects

- Trajectory calculation
- Aerothermodynamics
- Uncertainty modelling
- Break-up and fragmentation
- Fragments characterisation and dispersion
- Risk analysis



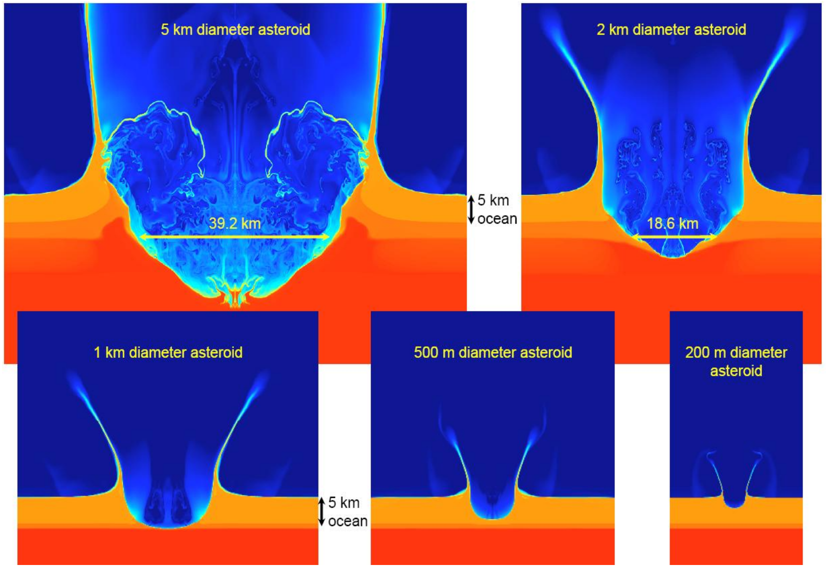
2.2 Review of Software Tools

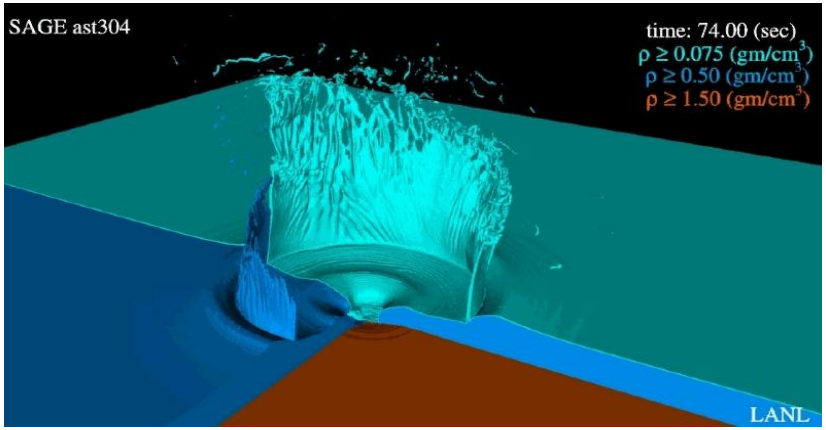
Reviewed and Demonstrated Tools

- **SAGE**, University of Oslo
- **SOVA**, Museum für Naturkunde
- **iSALE**, Museum für Naturkunde
- **NEOSIM**, University of Southampton
- **NEOImpactor**, University of Southampton
- **NEOMiSS**, University of Southampton
- **DEBRIS** , DEIMOS Space
- **CFD Tool**, DEIMOS Space

Demonstration Tools
SAGE

- Unstructured multi-material Eulerian finite-volume compressible fluid code
- Continuous adaptive mesh refinement with repartitioning
- Analytical and tabular equations of state and elastic-plastic strength model with tensile failure
- Developed by Mike Gittings at Science Applications International
- Used by G. Gisler while at UiO



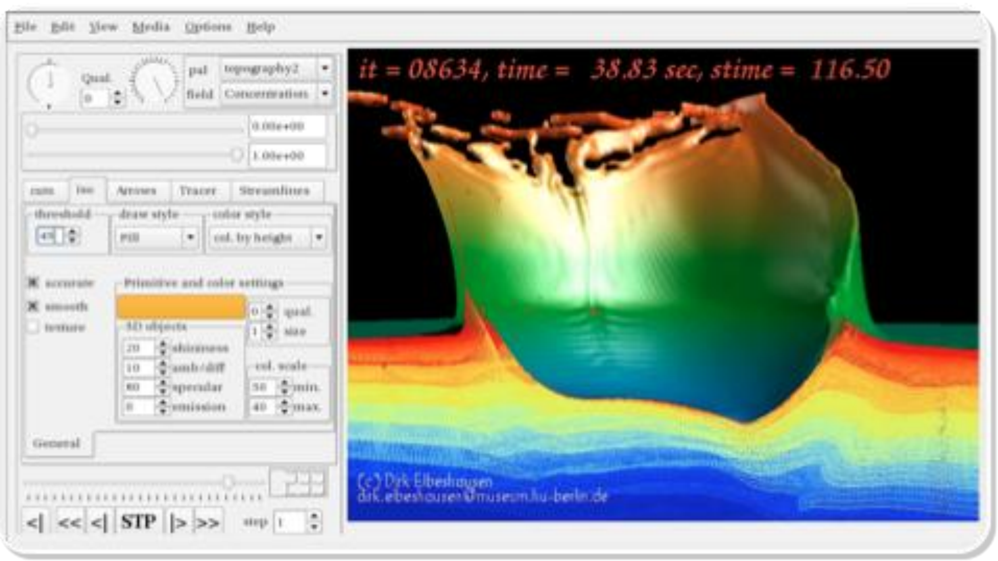


iSALE = impact Simplified Arbitrary Lagrangian Eulerian

core developers: Elbeshausen, Wünnemann (MfN), Collins (IC)

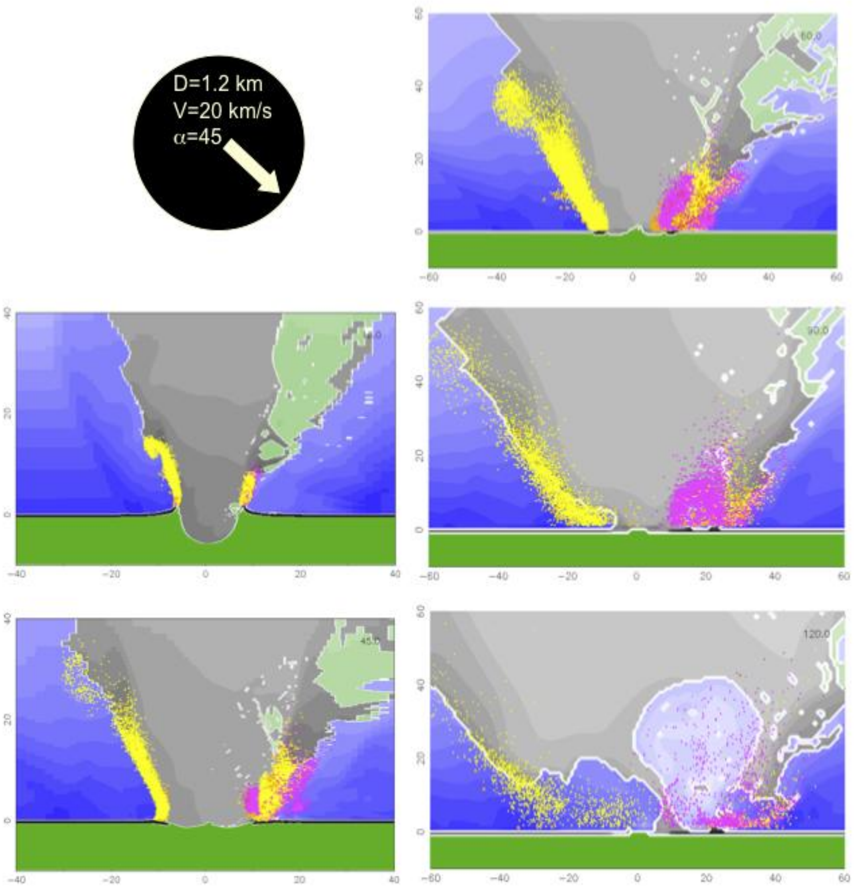
Specifically designed to model ground effects

(crater formation, shock wave, dynamic fracturing, elastic waves)



- Based on Los Alamos SALE (Amsden et al., 1980/81) and SALEB (Ivanov, 1997)
- 2D and 3D version
- 2-step Lag. Eul. Finite Diff.
- Sophisticated material models (ANEOS, brittle/ductile strength, …)
- Parallelized (MPI)
- Inter. group of developers

museum für naturkunde

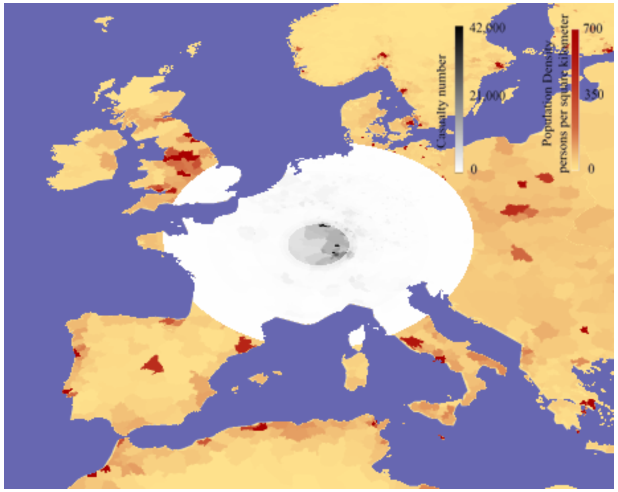


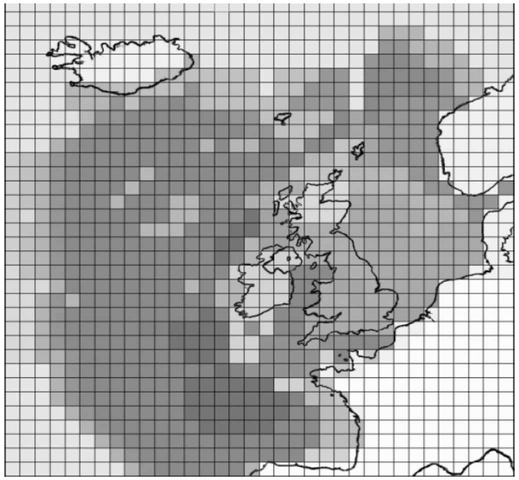
- **Two-step Eulerian code**
- **2D & 3D**
- **Multi-material**
- **Large deformation**
- **Strong shock wave physics**
- Model for atmospheric traverse
  - ➢ Mass loss
  - ➢ Deceleration
  - ➢ Deformation
  - ➢ Fragmentation
  - ➢ Particle-Atmosphere interaction
- **Applications:**
  - Object entry and ablation
  - Dusty flows
  - Tektite formation and deposition
  - Crater formation and distal ejecta

Demonstration Tools
NEO Simulator - NEOSim

UNIVERSITY OF Southampton

- Developed in 2005-2006 by University of Southampton
- Motivated by Collins et al. work, need to map impact effects and calculate human losses
- Modelling of atmospheric entry, land or ocean impact and casualty estimation
- Vulnerability figures are generated for all effects
- Outputs used in presentation to UN COPUOS STSC
- MATLAB program, subsequently redeveloped in C++

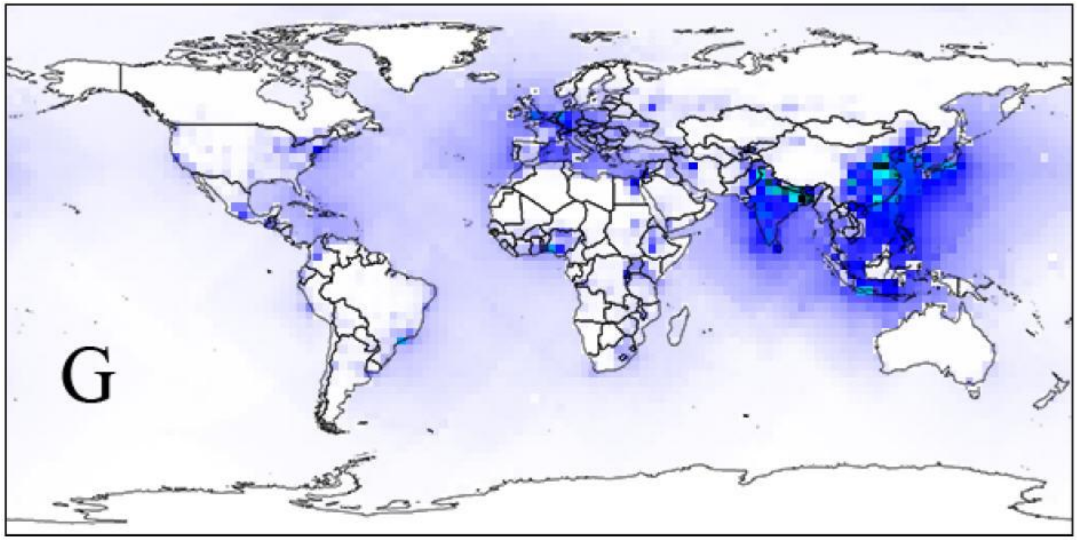




Demonstration Tools
NEOImpactor

University of Southampton

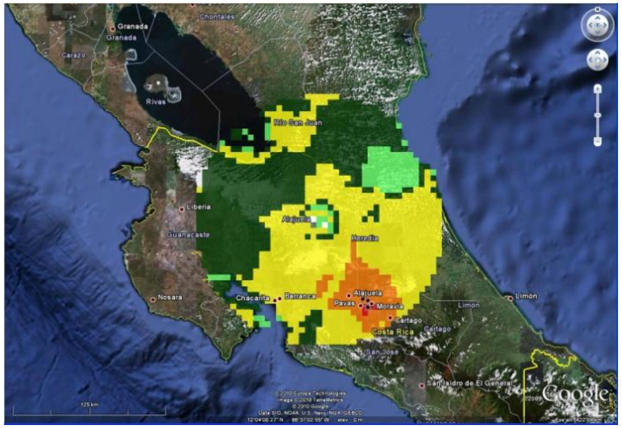
- Developed in 2006-2009 by University of Southampton
- Motivated to assess the relative risks at a global scale
- Also considers infrastructure losses
- Running assumptions: simple impact, global risk & line of risk

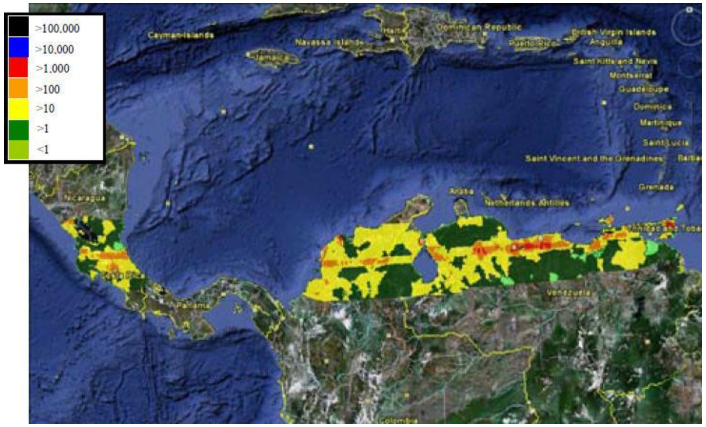


Demonstration Tools
NEO Mitigation Support Software - NEOMiSS

UNIVERSITY OF Southampton

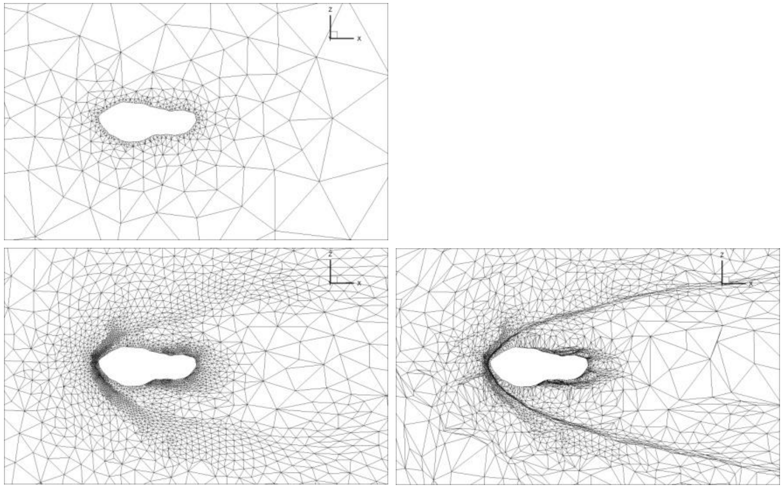
- Developed in 2009-2013 by University of Southampton
- Work by Norlund, Lewis and Atkinson
- Focuses on the treatment of vulnerability and uncertainty
- Uses NEOSim as the basis for estimating physical effects (but does not consider ocean impacts)
- It allows assessing the effect of the warning time and the evacuation in the resulting casualty figures

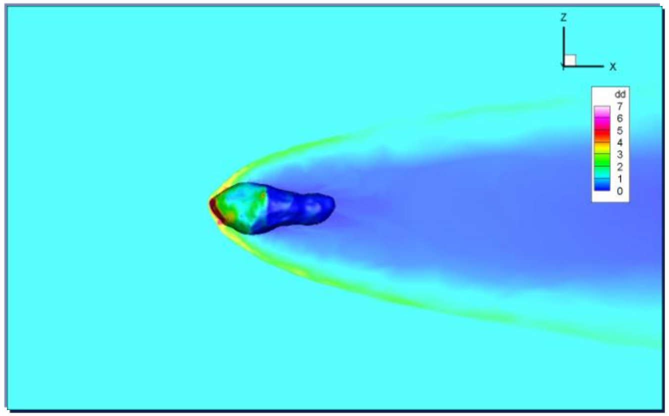




Demonstration Tools
CFD Tools

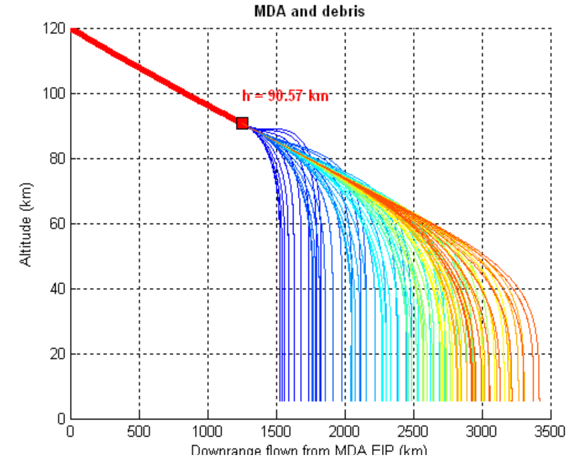
- S/W tool used at Deimos
- Determination of the flowfield solution in a specific flight regime and around an arbitrary body
- Estimation of the aerodynamic coefficients
- Finite element Euler solver with mesh adaptation



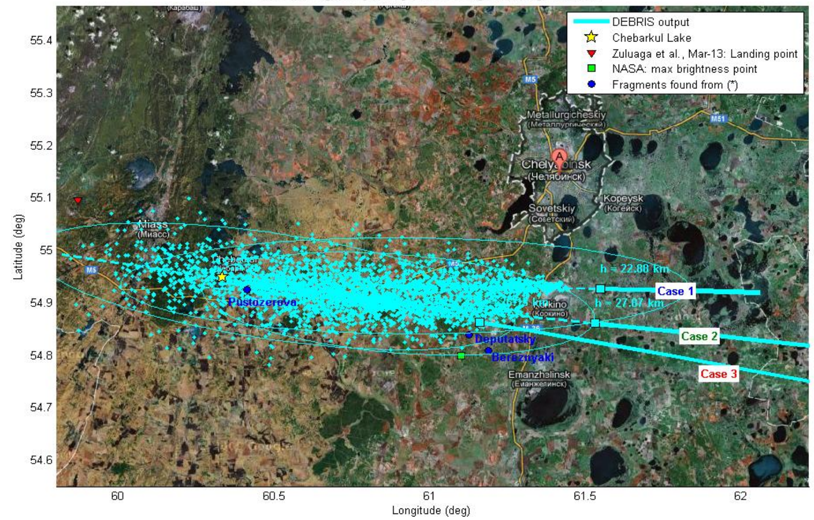


Demonstration Tools
DEBRIS Tool

- Tool used to estimate entry debris impact area and elements survivability
- Based on the Planetary Entry Toolbox (PET)
- Object oriented code that allows simulating:
  - Atmospheric entry
  - Object break-up
  - Uncertainty management
- The code was used to estimate the footprint of pieces after the Chelyabinsk event



DEBRIS tool outputs: groundtrack and fragments footprint over a Google maps image of the Chelyabinsk region, Russia



Status of Impact Effects Tools

elecnor deimos

Simulation tool	SAGE	iSALE	SOVA	NEOImpactor	NEO Sim	NEO MiSS	DEBRIS	Entry CFD
Tool operation at	**UiO**	**MfN**	**MfN**	**UoS**	**UoS**	**UoS**	**DMS**	**DMS**
Hypervelocity/high-velocity entry in atmosphere	PFD	-	PhM	EnM	EnM	EnM	EnM	PhM
Object ablation in atmosphere	PFD	-	PhM	EnM	EnM	EnM	EnM / PFD	PFD
Object break-up in atmosphere	PFD	-	PhM(2)	EnM	EnM	EnM	EnM	-
Energy release during airbursts	PhM	-	PhM	-	-	-	PFD	-
Entry effects in atmosphere (shockwaves, blastwaves, thermal radiation, etc.)	PhM	-	PhM	EnM	EnM	EnM	-	PhM
Object pieces reaching ground level	PhM	-	PhM(2)	EnM	EnM	PFD	EnM / PFD	-
Impact crater	PhM	PhM	-	EnM	EnM	EnM	-	-
Earthquakes	-	PhM / PFD	-	EnM	EnM	EnM	-	-
Tsunamis	PhM	PhM(3)	-	EnM	EnM	PFD	-	-
Electromagnetic pulses	-	-	-	-	-	-	-	-
Ejecta	PhM	PhM	PhM	EnM	EnM	EnM	-	-
Secondary hazards (e.g. fire)	-	-	-	PFD	-	PFD		
Population damage	-	-	-	EnM	EnM	EnM	-	-
Economic consequences	-	-	-	EnM	PFD	PFD	-	-
Short- and long term atmospheric and climatic effects	-	-	PhM(1)	-	-	-	-	-
Model uncertainties	-	-	PhM(1)	EnM*	PFD	EnM*	EnM	-
Evacuation	-	-	-	PFD	PFD	EnM	-	-
Deflection (risk corridor)				EnM	EnM	EnM		

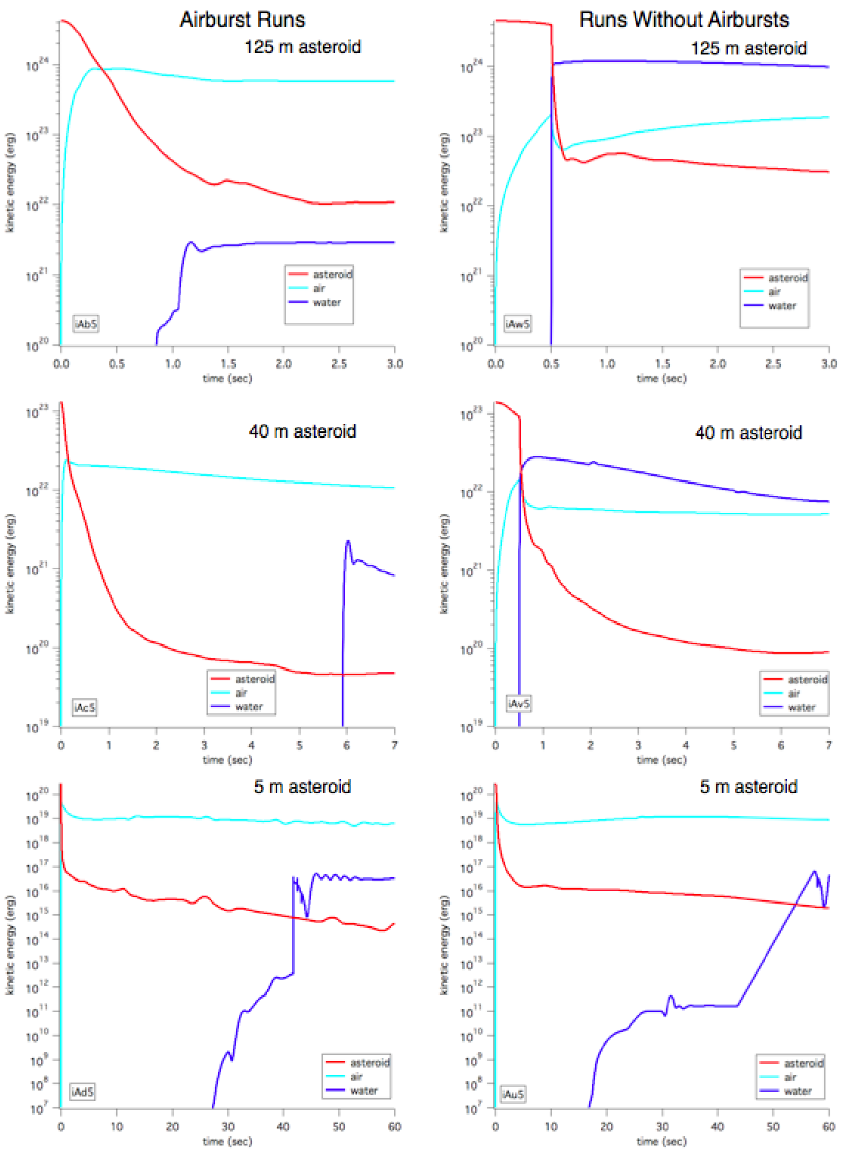
PFD = Possible with further development / (1) with WACCM=Whole Atmosphere Community Climate Model / (2) with semi-analytic break-up model / (3) far-field wave propagation model is lacking
EnM* - Partial implementation (NEOImpactor – uncertainty in impact location; NEOMiSS – uncertainty in impact effects)

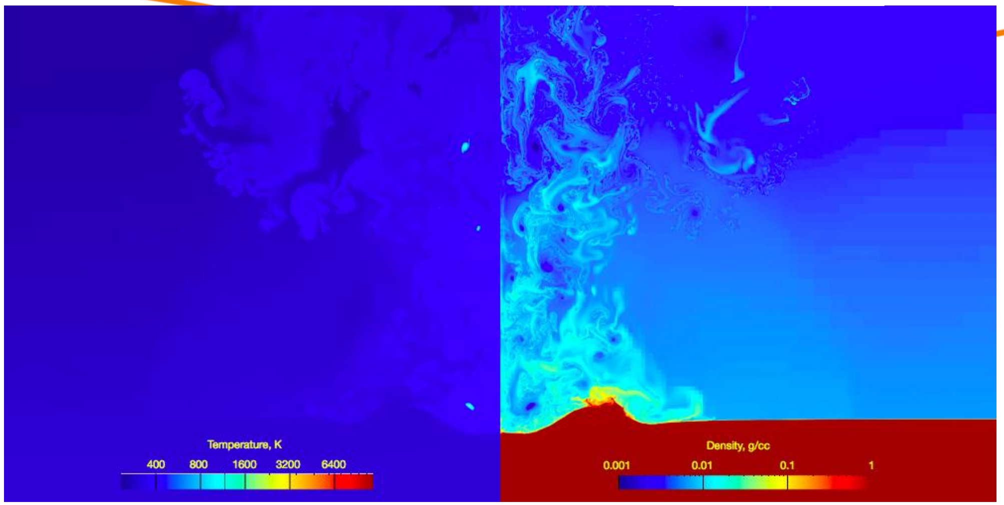
2.3 Review of Test Results

Demonstration Cases

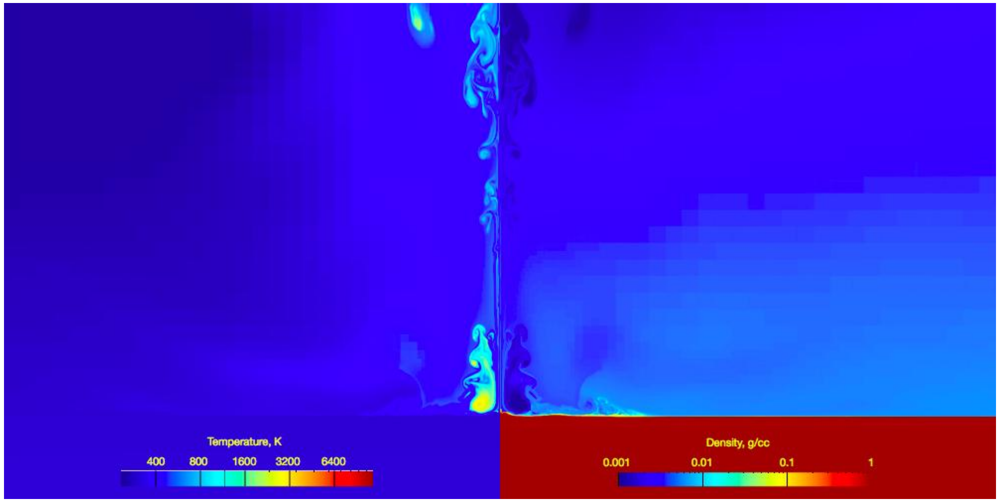
- Asteroid cases:
  - 2011 AG5 case (140 m range)
  - Tunguska size object (40 m range)
  - 2008 TC3 type case (5 m range)
  - Chelyabinsk was later added (the event occurred during the project)
- Entry conditions:
  - Entry velocities: 12.5 km/s and 25 km/s
  - Entry angles: 0 deg and 45 deg
  - Different NEO properties (density, porosity, cohesion)
- For each tool a combination of the above conditions was proposed (not all tools involve the same amount of set-up complexity and execution time)

Some Results / SAGE





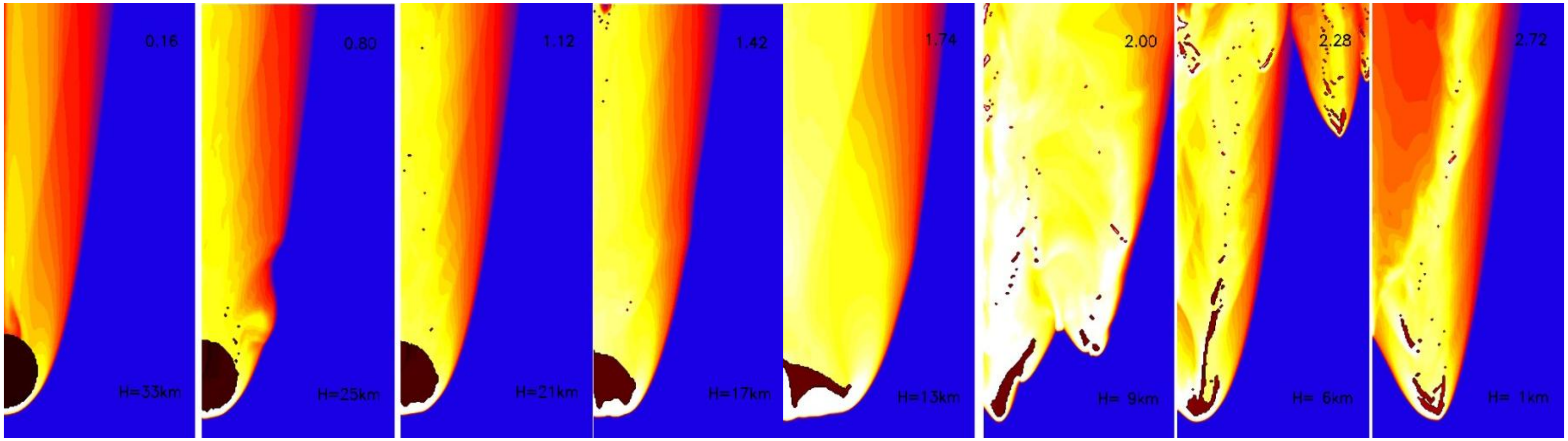
125-m asteroid vertical impact, no airburst, 63 seconds after drop

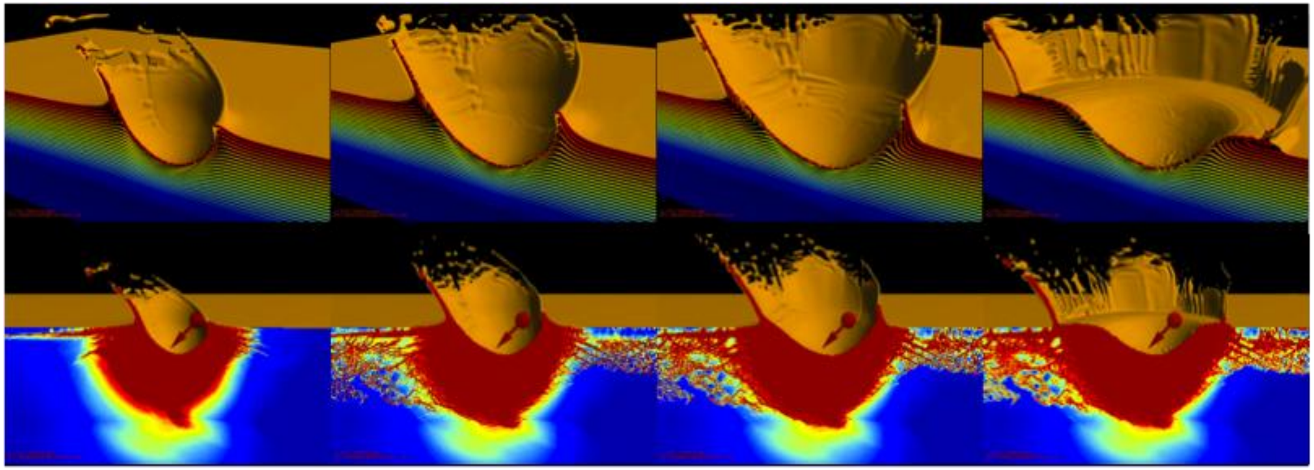


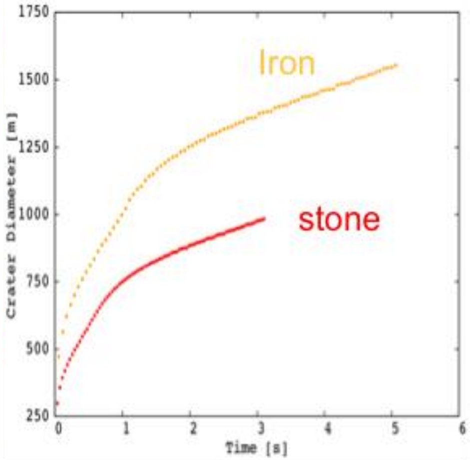
125-m asteroid vertical impact, 10 MT airburst, 49 seconds af ter drop

Some Results / SOVA & iSALE

museum für naturkunde







Some Results / NEOSim

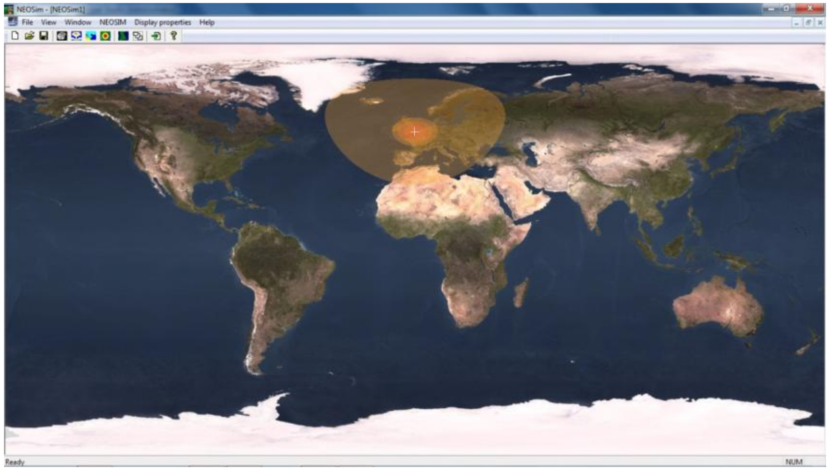
- Parametric assessment over ~144 cases. Example:

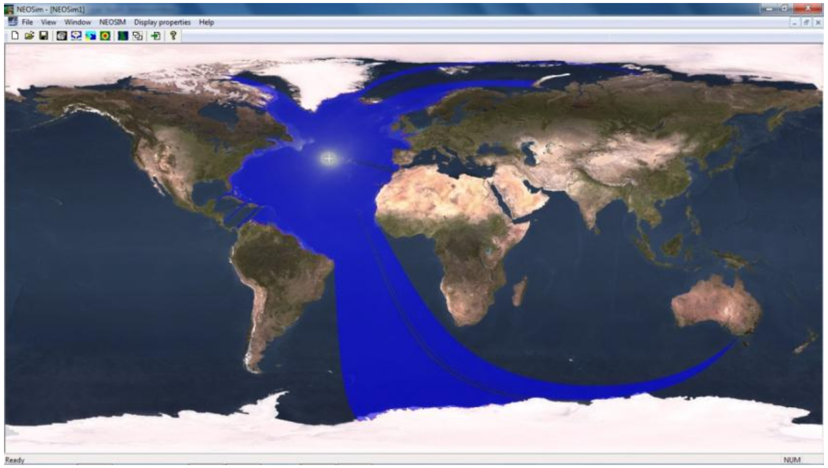
London impact (51.5° N, 0° W)

4.16 million casualties

Atlantic impact (39.5° N, 37.5° W)

10.4 million casualties



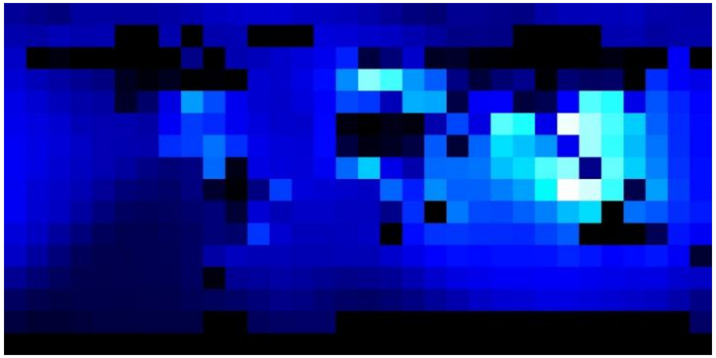


140 m iron asteroid at 25 km/s

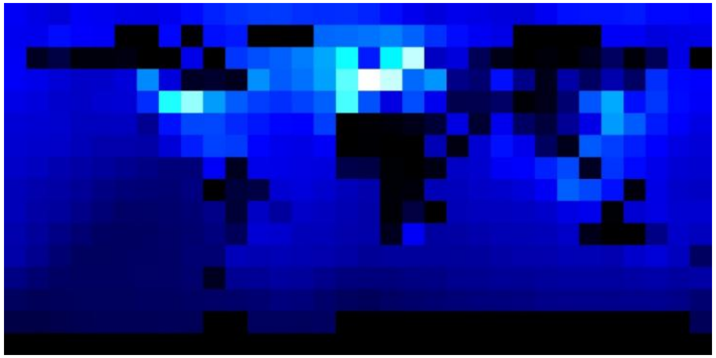
Some Results / NEOImpactor

- Parametric assessment over 36 cases (18,432 separate impacts)

140 m iron asteroid at 25 km/s



Casualties



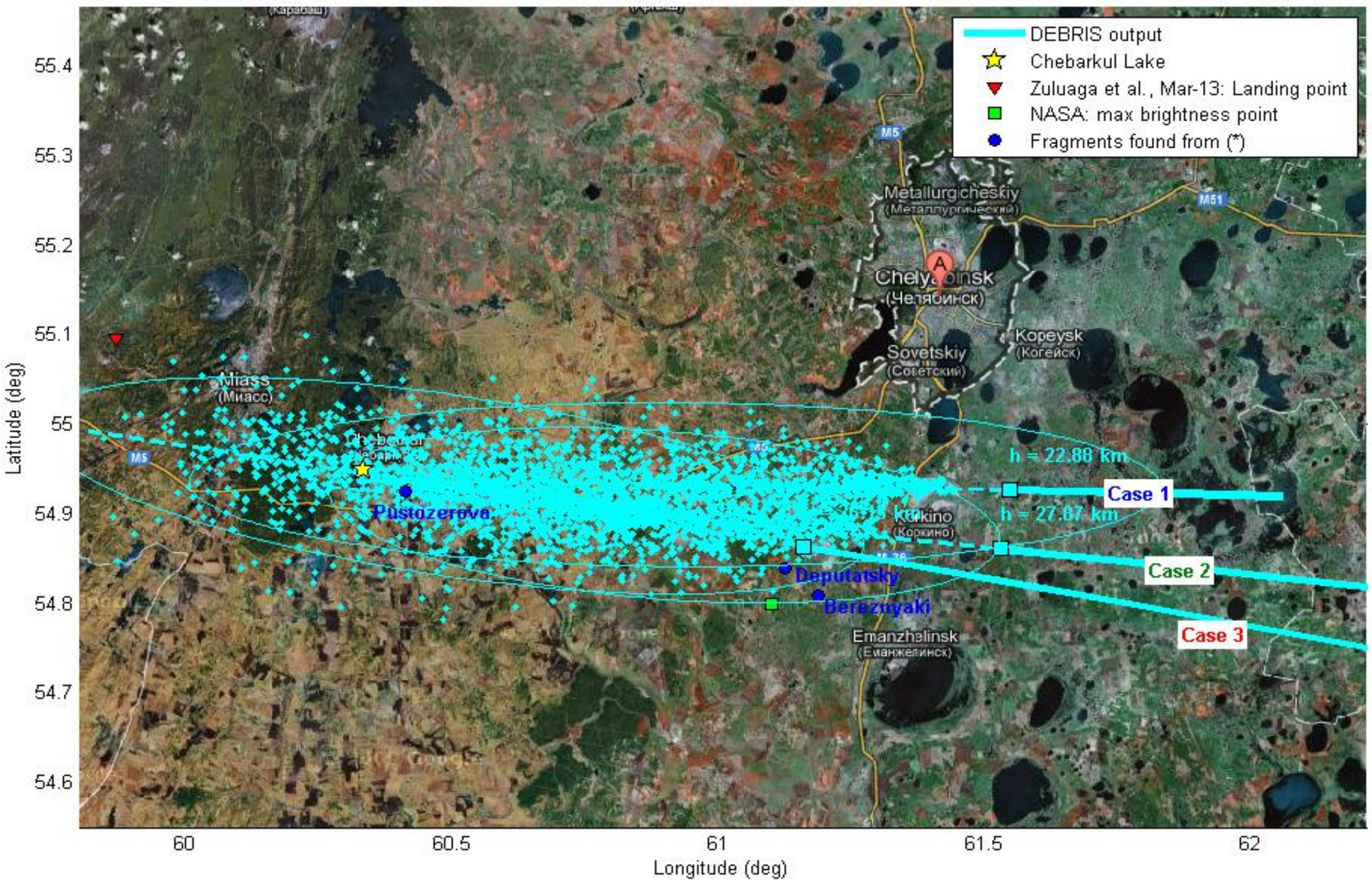
Damage

Rank	Country
1	Indonesia
2	China
3	Japan
4	Philippines
5	United States
6	Brazil
7	India
8	Mexico
9	United Kingdom
10	Australia

Rank	Country
1	United States
2	Canada
3	Norway
4	Japan
5	Russia
6	United Kingdom
7	China
8	Brazil
9	Australia
10	Indonesia

Some Results / DEBRIS

DEBRIS tool outputs: groundtrack and fragments footprint
over a Google maps image of the Chelyabinsk region, Russia



Impact Effects
Summary of demonstrations cases

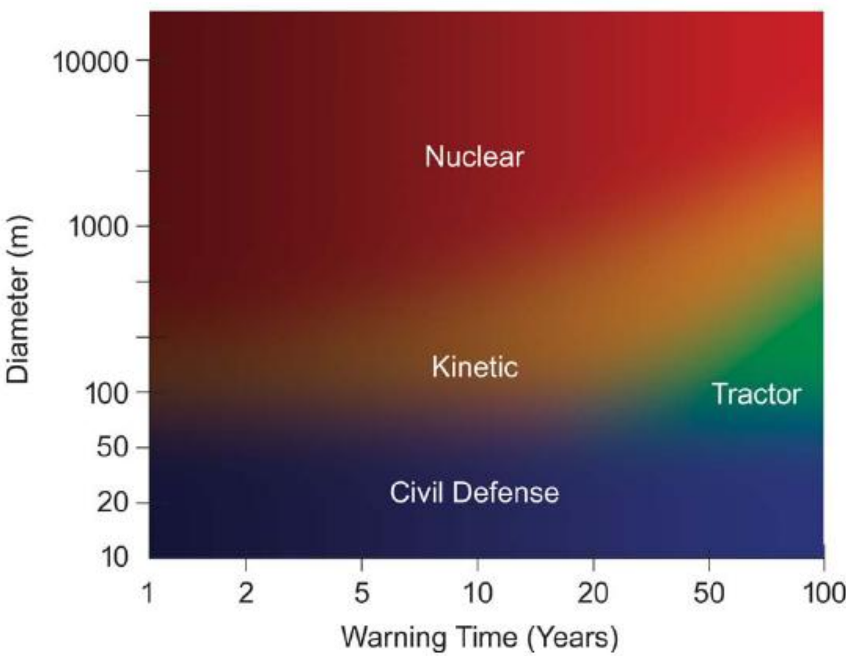
- The tools were put to work as benchmark for ESA
- Usability demonstrations were also performed for ESA TOs
- The tests helped in identifying
  - Applicability for the different scenarios
  - Performance issues
  - Usability issues
  - Identification of interfaces and missing models
- The outcome was used to prepare the impact effects draft roadmap for discussion at the workshop

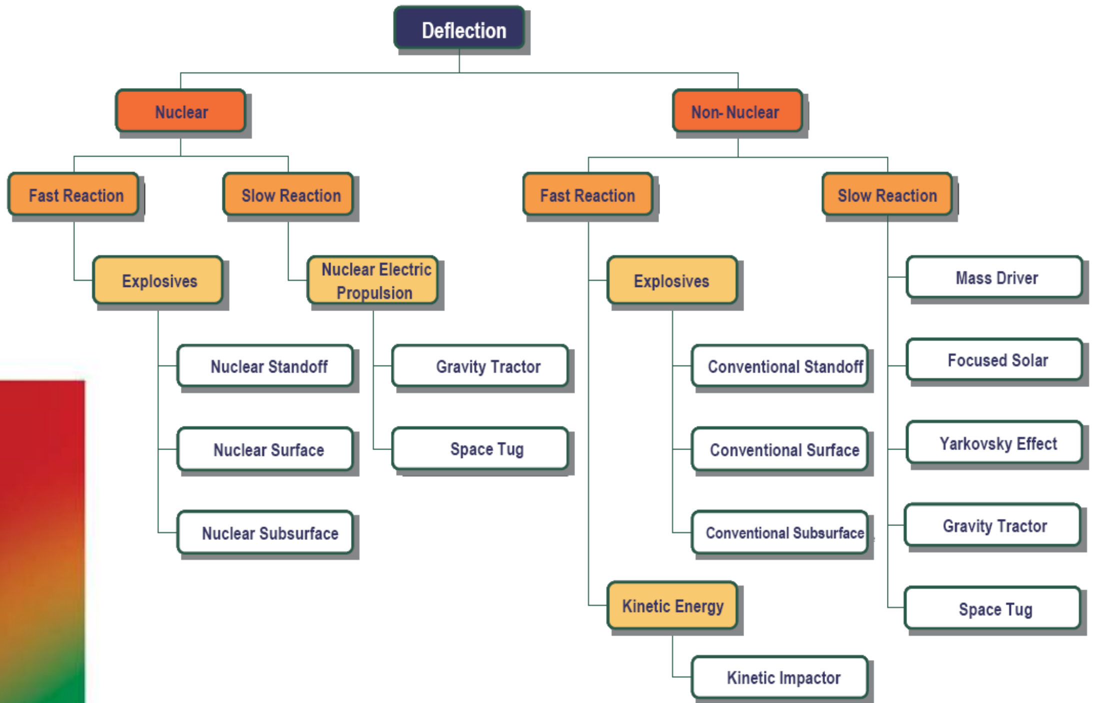
3 MITIGATION MEASURES

Mitigation Measures
Project Activities

- Review of past and ongoing activities related to NEO mitigation measures
- Assess the scientific credibility and technical maturity of the various mitigation measures
- Identification of physical parameters which determine the selection of a deflection method
- Review past space missions studies relevant for NEO mitigation (including ESA's Don Quijote mission) w.r.t. their purpose and scientific credibility
- Quantitative evaluation and critical analysis of the scientific feasibility and credibility of different NEO mitigation space mission concepts
- Provide input for a roadmap for the preparation of a NEO mitigation mission

Mitigation Measures

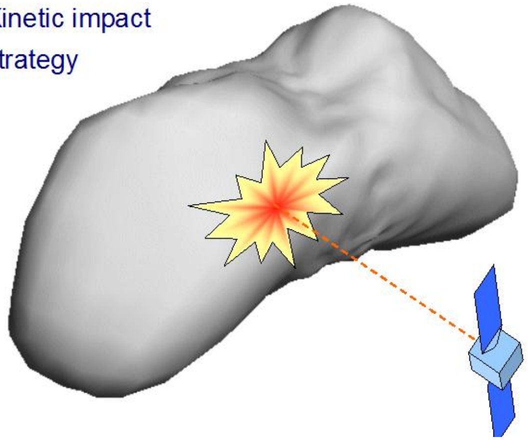




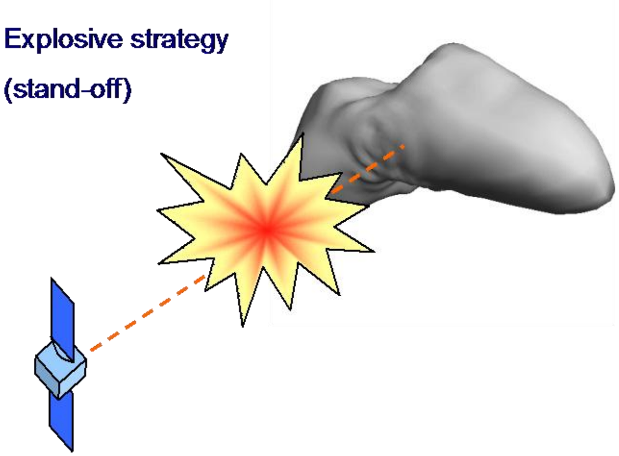
Credits: NASA

Mitigation Measures Analysed

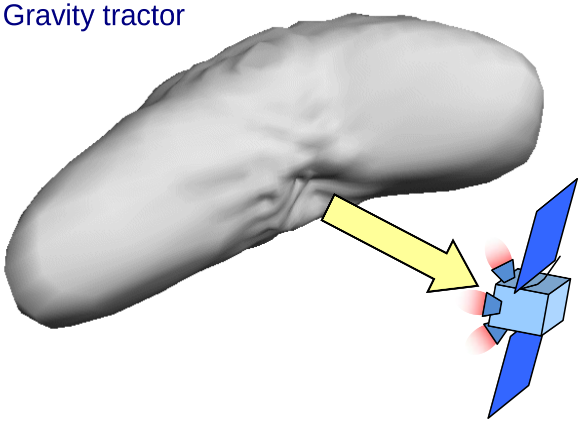
Kinetic impact strategy



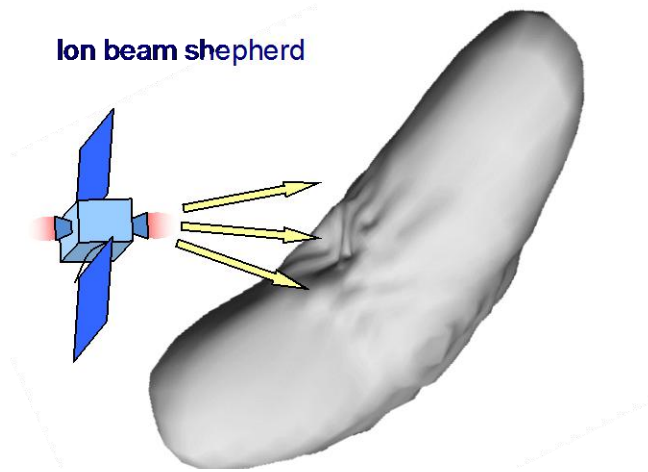
Explosive strategy (stand-off)



Gravity tractor



Ion beam shepherd



3.1 Kinetic Impact

Kinetic Impact Mitigation Concept

elecnor deimos

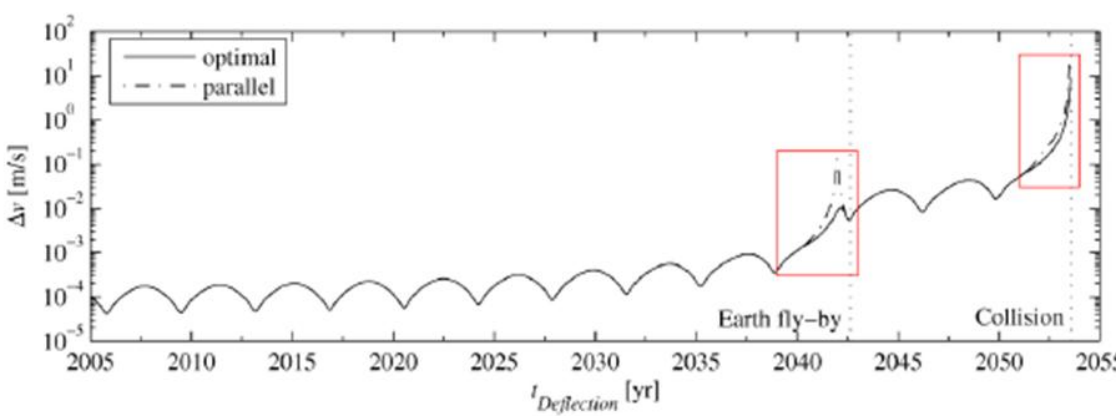
HYPERVELOCITY IMPACT → **ASTEROID DELTA-V** → **INCREASING ASTEROID DISPLACEMENT** → **SUFFICIENT MISS DISTANCE AT EARTH IMPACT EPOCH**

- **Asteroid delta-V** depends on impactor momentum ($m_{S/C} \cdot U$) and asteroid properties through a **momentum multiplication factor β**: $\Delta V = \beta \cdot m_{S/C} \cdot V_{impact} / m_{ast}$; $\beta > 1$
- **Optimal delta-V** direction depends on available **lead time Δt**:
  - **Long Lead Time** → Delta-V parallel to orbit velocity to maximize orbit period change → $\Delta X = 3\,\Delta t \cdot \Delta V$
  - **Short Lead Time** → Delta-V normal to orbit velocity → $\Delta X = \Delta t \cdot \Delta V$
- **Required delta-V** grows as the lead time reduces

DELTAVS FOR 1 EARTH RADIUS DEFLECTION

$$\Delta V_{long\,term}(\Delta t) \approx \frac{7\ cm/s}{\Delta t(years)}$$

$$\Delta V_{short\,term}(\Delta t) \approx \frac{75\ m/s}{\Delta t(days)}$$



Hypervelocity Impact Modeling (1)

- The main goal is to obtain a **scaling law** for **β**
  - Unknowns to be determined:
    - ***Coupling parameter μ*** *modelling the ejecta amount trend with impact velocity*
    - ***Functions F*** *and* ***G*** *modelling the ejecta amount trend with asteroid properties*
- **β** generally depends on:
  - **Asteroid properties**: material stress resistance **Y**, material density **ρ**, internal structure, porosity, asteroid size, surface gravity **g** and escape velocity $\mathbf{V_{escape}}$
  - **Impactor properties**: impactor velocity $\mathbf{V_{impact}}$, mass $\mathbf{M_{S/C}}$ and size **a**
  - **Collisional regime**:
    - ***Gravity regime*** *←→ ρga >> Y (lithostatic pressure is dominant)*
    - ***Strength regime*** *←→ ρga << Y (material resistance is dominant)*

GRAVITY REGIME (ρga >> Y)

$$\beta = 1 + \left(\frac{V_{impact}}{V_{escape}}\right)^{3\mu - 1} \cdot F\left(\frac{g \cdot R_{crater}}{V_{escape}^2}\right)$$

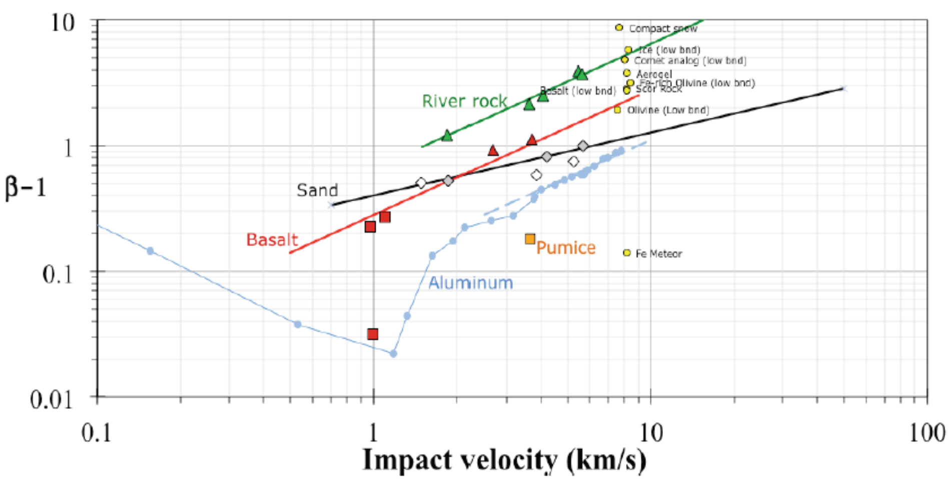
STRENGTH REGIME (ρga << Y)

$$\beta = 1 + \left(\frac{V_{impact}}{V_{escape}}\right)^{3\mu - 1} \cdot G\left(\frac{Y}{\rho \cdot V_{escape}^2}\right)$$

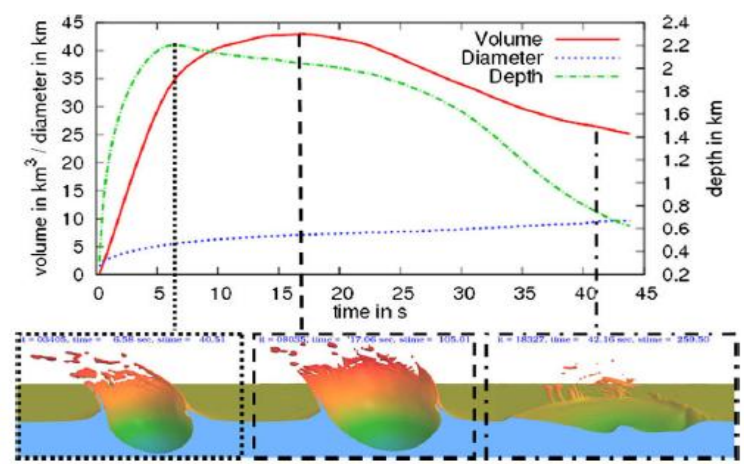
$$1/3 < \mu < 2/3$$

Hypervelocity Impact Modelling (2)

- Open Modelling issues:
  - **Internal porosity effects** → impact energy wasted to collapse pores
  - **Internal structure effects** (**rubble-pile** or **monolithic**)
  - **Rate dependent strength effects** → equivalent resistance may depend on the collisional time scale
  - **Oblique impact effects** → direction and amount of ejecta momentum
  - **Disruption energy threshold** → asteroid may be fragmented if impactor S/C kinetic energy is too high



Beta scaling law evaluation for different materials (Housen and Holsapple)



Oblique Impact Modelling (Elbeshausen)

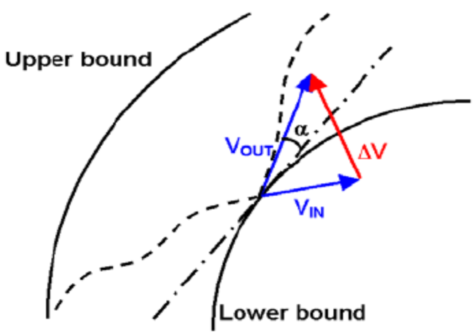
Major Impactor Challenges

- **Autonomous and Precise ADCS**:
  - Attitude reconstruction error affects the OD precision
  - Required attitude estimation precision of the order of **10s** of **µrads**
    - ***Stellar mode*** *solution: stars in the background of the optical image → near perfect attitude knowledge*

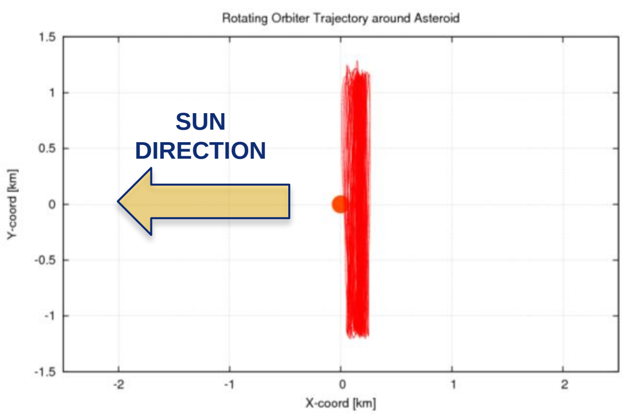
- **Autonomous Terminal Guidance GNC**:
  - Targeting precision determined by the **relative OD accuracy** at the time of the **last TCM**
  - Based on **autonomous visual navigation** with very small onboard camera iFOV (**10s** of **µrads**) → minimization of across LOS OD errors
  - A priori knowledge of the **asteroid shape** would enable realting the CoB to the CoM
  - **TCMs** executed at **predefined instants**
  - **Don Quijote studies** demonstrated a **final targeting precision** in the order of **50 m** (3-sigma)

Major Orbiter Challenges

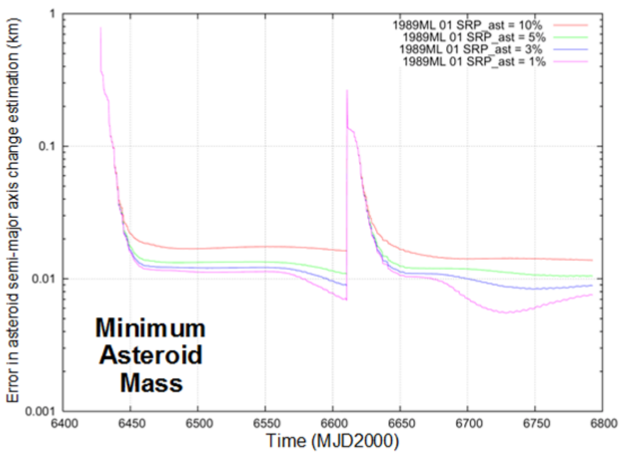
- **Autonomous In-Orbit GNC**:
  - Maintain the optimal **orbit** for the **global characterization phase** in order to determine the asteroid shape, rotation and composition
- **RTE Experiment for Asteroid OD**:
  - **Major task** of the orbiter S/C in a kinetic impact mitigation context
  - Based on **radio tracking measurements** from ground
  - OD precision affected by orbit control manoeuvres → Need of a control-free stable orbit → **Photo-Gravitationally Stable Orbit**
  - Achievable precision: **10s of m** in orbit SMA



In-orbit Control Box Proposed for Proba-IP



A Photo-gravitationally Stable Orbit around Apophis



Asteroid OD Campaign Performance Assessment

Conclusions on Kinetic Impactor

- The kinetic impactor is an **attractive mitigation method** for asteroid sizes between **50** and **500m** and lead times of a **few years**
- This concept has been analysed in Europe: **Don Quijote studies**
- Research should focus on **3 major investigation areas**:
  - **Hypervelocity impact modelling** to better predict the achieved asteroid delta-V and assess the probability of asteroid disruption
  - **Impactor S/C technologies**
  - **Orbiter S/C technologies**
- Current European TRL levels for the GNC technologies can be raised significantly with a number of possible missions:
  - **Marcopolo-R**
  - **AIDA-AIM**
  - **Proba-IP Orbiter demonstrator**
  - **Short Warning Time Impactor demonstrator**

3.2 Explosive Methods

Explosive Measure
Overview of measure

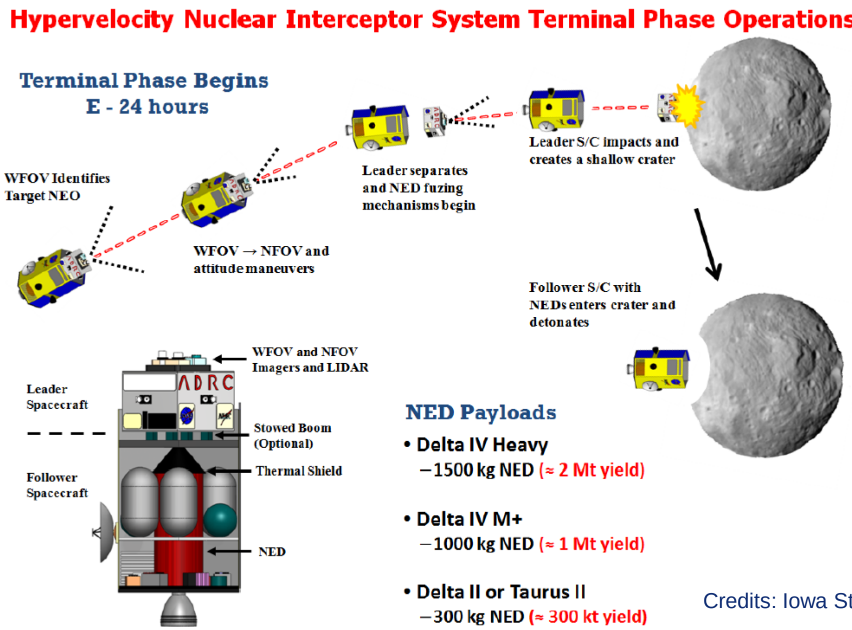
- Use of nuclear explosion to **divert** or **destroy** NEO.
- Only practical mitigation option with a **short warning time** (<10 years). Imperative for NEO with diameter >100m and detected close to Earth.
- **Most mass-efficient** mean for storing energy. Nuclear explosion is more effective than non-nuclear alternatives, especially for larger NEOs with short lead time.
- Several scenarios are possible, considering:
  - **Explosion altitude**: surface, subsurface, standoff
  - **Approach to NEO**: hypervelocity, rendezvous
  - **Objective**: deflecion, disruption

- Surface/subsurface
  - Explosion creates small crater
  - Size of the impulse depends on NEO properties
  - Momentum/energy transfer created by subsurface explosion is one order of magnitude larger than standoff
  - Higher risk of undesired NEO fragmentation

- Standoff
  - Deflection obtained through the energy transmitted to the surface by neutrons and X rays. A thin layer of the NEO surface is blown-off
  - Demands substantially less information about the NEO, than subsurface deflection
  - Mitigates the fracture problem
  - Involves a substantial increase in interceptor mass
  - Standoff distance is a key parameter. There is a optimal value that maximises momentum transfer

Explosive Measure
Overview of measure

- Hypervelocity approach
  - HNIS Concept



Credits: Iowa State University

  - Leader S/C (detonator) and a follower S/C carrying the NED
  - Leader S/C impacts first and creates a shallow crater
  - Follower S/C enters the crater and detonates the NED

Explosive Measure
Main challenges

- In general, the nuclear explosive measure is reasonably mature, but in practice this depends on the approach and objective
  - Nuclear munitions are technologically mature
  - Most of the technology involved is already at high TRL, except for the nuclear payload and the precision NEO proximity operations
  - Overall mass required is within the current space transportation capabilities
- Surface explosion approach is perhaps the most mature. Needs rendezvous and touchdown, which has been achieved before
- Subsurface approach requires rendezvous and drilling into the core to significant depth (difficult prospect for nickel-iron NEOs)
- Hypervelocity intercept approach is associated to high impact velocities that cause the destruction of the detonation device
- Proposed HNIS concept addresses this limitation, but adds technical challenge of autonomous formation flying of 2 S/C within a context of high impact velocities and small targets

Explosive Measure
Main challenges

- Standoff approach requires detonation at precise altitude which is a technically challenging task, especially in case of high intercept velocities.
- Neutron emission is more effective for standoff deflection, but current nuclear bombs deliver most of their energy as X-rays.
- Summary of Key technological challenges

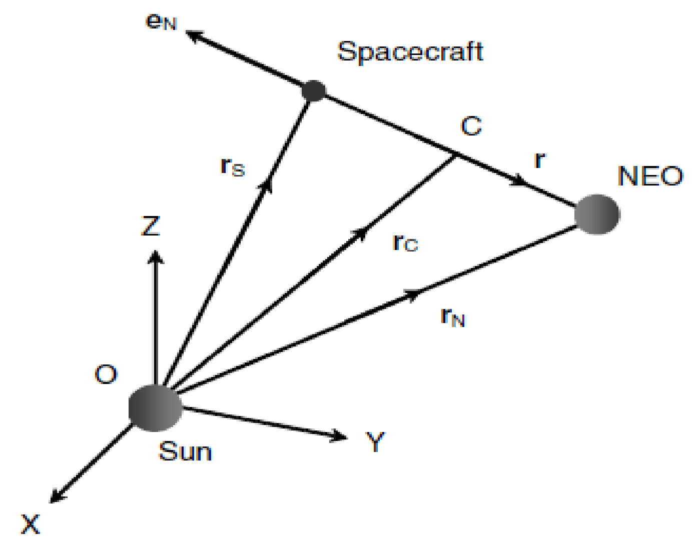
	Surface	Subsurface	Standoff
Rendezvous	• Rendezvous and touchdown.	• Rendezvous and touchdown. • Drilling.	• Rendezvous and precise altitude hovering. • Optimization of nuclear device.
Hypervelocity approach	• Precision targeting of smaller bodies with higher intercept velocities. • Timing of detonation at precise altitude.	• Precision targeting of smaller bodies with higher intercept velocities. • Detonation device robustness to high impact loads.	• Precision targeting of smaller bodies with higher intercept velocities. • Timing of detonation at precise altitude. • Optimization of nuclear device.

Explosive Measure
Main challenges

- Key **scientific aspects** requiring further development to promote and enable the explosive mitigation measure
- Essentially, these concern the **response of the asteroid to the nuclear detonation**, in all the different approaches possible.
- Assessment of nuclear blast effect and NEO modeling
  - Determining what is the **effect of the nuclear blast on the asteroid**:
    - Ejected mass and impulse provided
    - Possibility and mode of fracturing
  - These aspects are **highly dependant on the asteroid composition** (material properties, geology, and topography), and **more investigations** would be beneficial on how these aspects can be modeled and assessed for the **purpose of mitigation mission design**
  - It is also important to take into account the effect of the **modeling uncertainties**, in order to have a robust assessment of the effectiveness

3.3 Gravity Tractor

Gravity Tractor Measure
Overview of measure



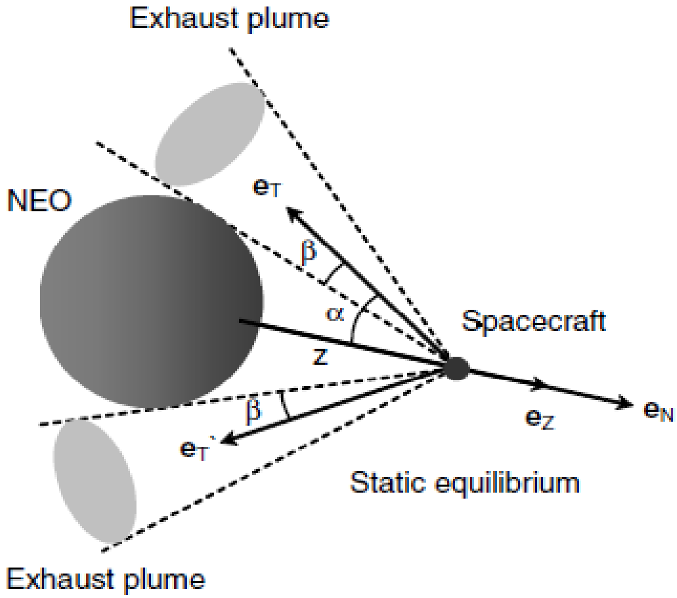
- The **S/C hovers in a static equilibrium** near the NEO surface. S/C thrusters compensate for NEO gravity pull.
- Acceleration in the centre of mass of the S/C-NEO system due to the stream of momentum transported by the plume of exhaust gas escaping the system.
- Station keeping of the S/C in the direction of towing
- **No physical contact** with the NEO. Gravity used as towline.
- Does **not require knowledge** of NEO **surface** characteristics or **internal** structure.

Gravity Tractor Measure
Overview of measure

- Approximately 15% of the NEO population is composed by **binary asteroid systems**
  - **Challenging** for deflection techniques based on **direct interaction** with the NEO
  - **GT can tractor both bodies** at the same time, even though with an increased complexity of the control tasks
- Continuous but low levels of acceleration. GT measure **valid for scenarios with sufficient time** before Earth impact, especially for those where it is possible to **exploit close Earth encounters**
- Allows **constant monitoring** of the achieved deflection

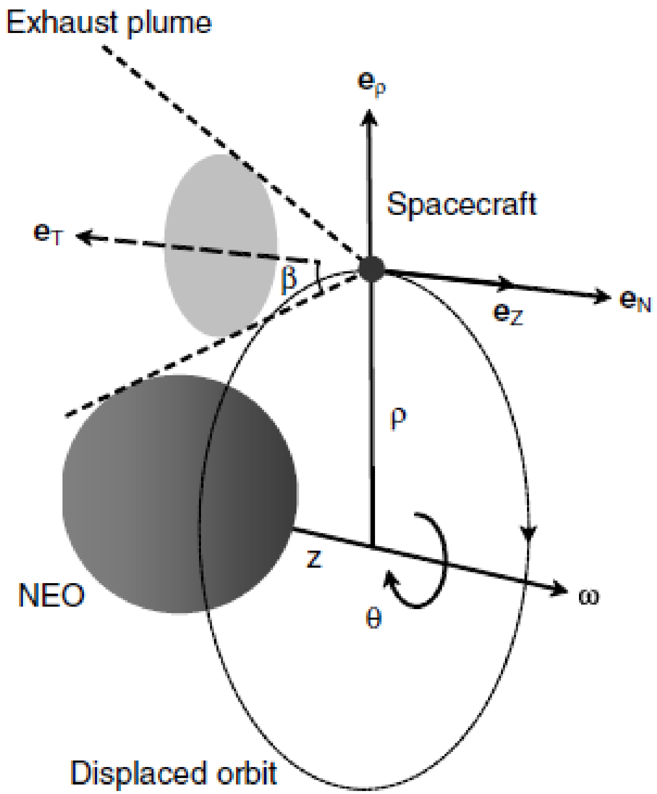
Gravity Tractor Measure
Overview of measure

- Possible architectures:
  - Solar electric or nuclear electric propulsion system:
    - 1) Static equilibrium
    - 2) Displaced orbit
  - Solar sails propulsion system
- Static equilibrium
  - Simplest scheme.
  - S/C exhaust plume must be canted to avoid impingement on the NEO surface.
    - Constrains the orientation of the S/C thrusters.
    - Required thrust level must be increased to compensate.



Gravity Tractor Measure
Overview of measure

- Displaced orbit
  - With a suitable orbit radius and displacement distance, the exhaust plume needs not be canted.
  - Potentially more efficient transfer of momentum to the CoM of the S/C-NEO system.



Gravity Tractor Measure
Main challenges

- In general, a **typical GT mission** can be performed with **current space transportation technology**
- Technology development and maturation needed for **control software**, which could require **development of dedicated algorithm** for asteroid hovering
- GT is based on continuous but low levels of acceleration, making the deflection strategy suitable for scenarios in which there is sufficient time before Earth impact and small deflections required (e.g. keyhole deflection)
- However, this comes with the drawback of **extended operation time**, leading to the need to **develop longer-lifetime electric propulsion** devices, possibly with nuclear electric power systems

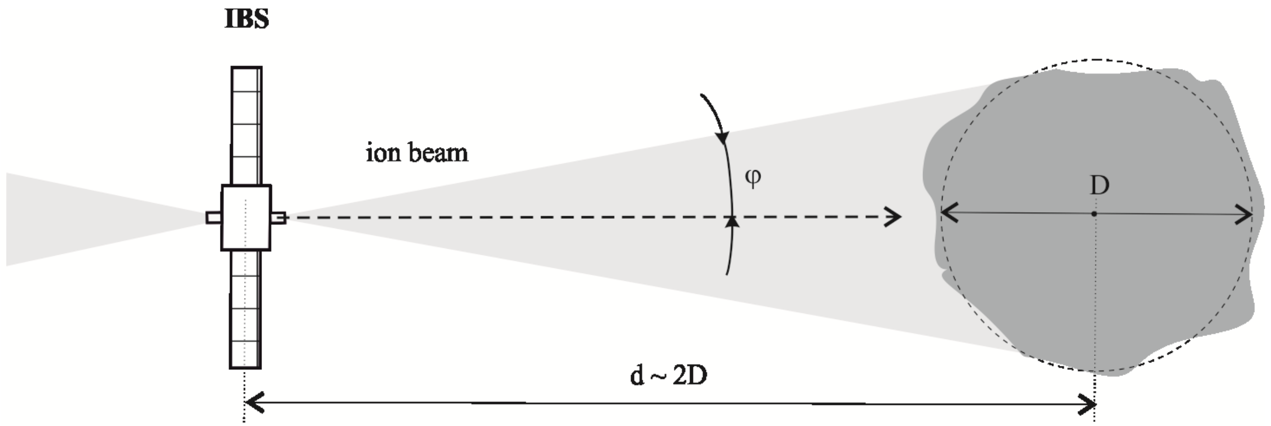
Gravity Tractor Measure
Main challenges

- The main relevant aspects for GT concerning the **characterization of the asteroid** are:
  - Notably, the modeling and determination of the **asteroid's gravitational field** and its **rotational state** are of critical importance for the GT measure.
  - Other parameters relevant for the design of a GT mission are the **diameter** and **mass** of the asteroid, together with its **orbital parameters**.

3.4 Ion Beam Shepherd

The ion beam shepherd concept

- Shepherd spacecraft hovering at safe distance from asteroid surface
  - Primary ion engine pointed at asteroid surface
  - Secondary propulsion to avoid IBS drifting away from asteroid
- Quasi-neutral plasma beam impinges on surface transmitting momentum
- Transmitted force is ~ equal of having the same thruster mounted on the asteroid (if beam is properly pointed)



- As in the gravity tractor (GT), transmitted force is applied in a **contactless** fashion

Why is contactless important?

→ Deflection can be carried out at a **safe distance** from the body surface

→ Avoid mechanical interaction with a body of unknown physical properties and possibly highly fragile (rubble pile, regoliths, “astro-quakes”,...)

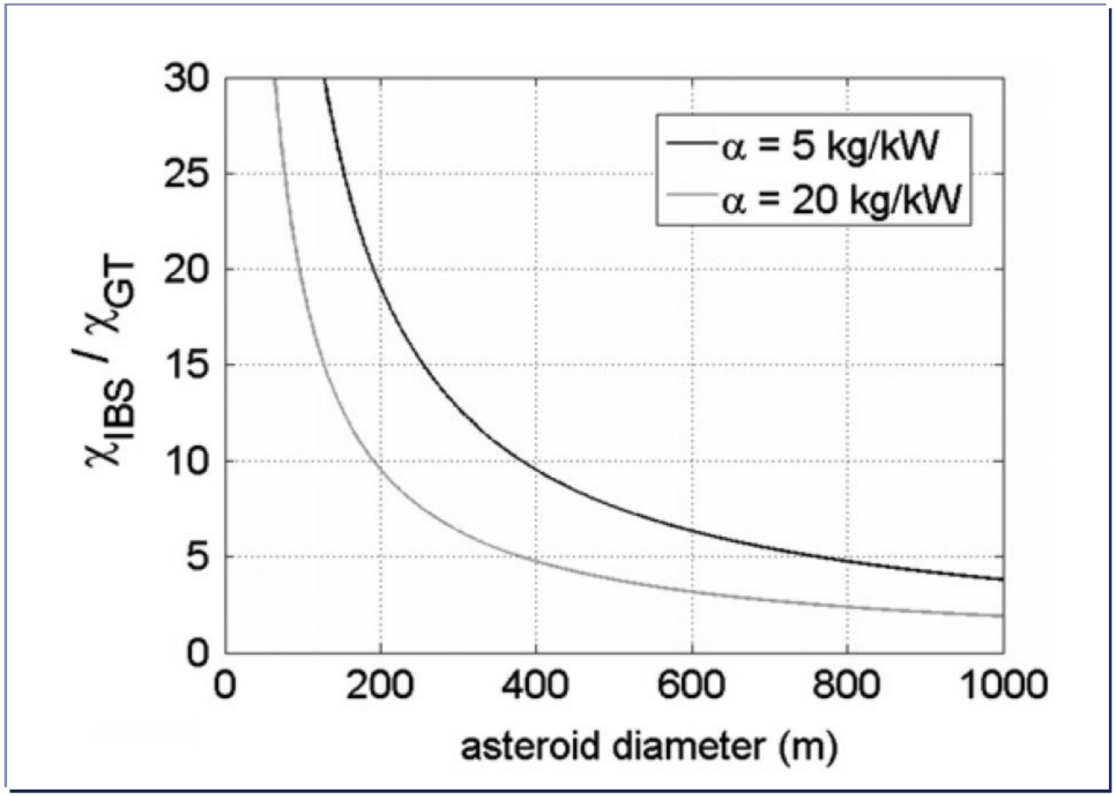
→ Avoid dealing with asteroid spin motion and thrust vector modulation

(thrust needs to be tangent to the orbit at all times for optimum long-warning-time deflection)

→ And surely you don´t need to do this:

☺

GT-IBS comparison



χ is the ratio between the deflection action and the S/C mass required for it

α is the mass of the low-thrust subsystem per kW of propulsive power

The GT performance rapidly decreases the smaller the asteroid

One order of magnitude difference for a typical 200 m diameter asteroid

Backsputtering contamination: some results

For optical devices and solar panels thickness of the deposited contamination layer should be kept below 200-300 nm [*Tribble, et al., SPIE,vol 2864, pp 4-15,1996.*]

Backsputtering simulations conducted at UPM (IBIS software): 130 m asteroid, 1N force, Xenon 15 deg divergence, 90% momentum transfer efficiency: **208 nm/year contamination**

However:

- Porosity of the asteroid not taken into account → expected reduction of sputtered flux due to trapping effects
- Reduction of thrsuter divergence greatly reduces the backsputtering flux

So, what are the IBS challenges?

- Show that the beam momentum transfer is real (vacuum chamber)
- Validate (or “calibrate”) backsputtering models at keV energies (vacuum chamber)
- Learn how to hover at “moderate” distance from the surface of small asteroids in an autonomous way
- Reduce divergence (to allow larger hovering distances and reduce backsputtering)
- Improve current electric propulsion systems performance (efficiency, specific impulse)
- Work on high-efficiency, high power density solar arrays

Conclusions

- The IBS is, potentially, the best slow-push asteroid deflection measure
- Backsputtering contamination not negligible but likely not a big issue
- Reduction in divergence would yield a dramatic improvement in the IBS capabilities by increasing the hovering distance and reducing the backsputtering flux
- Vacuum chamber tests needed

- Deflection demo mission with small asteroid is highly attractive

3.5 Other Methods

Mitigation Measures
Other Techniques

- Mass Drivers
- Attached Propulsion System
- Attached Solar Sails
- Solar Collector
- Laser Ablation
- NEO Painting/Yarkovsky Effect
- NEO To NEO Collisions
- Mini-magnetospheric Plasma Propulsion
- Magnetic Flux Compression
- Antimatter Devices
- Eaters
- Smart Cloud

4 THE WORKSHOP AND THE ROADMAPS

ESA’s Requests for this Workshop

- Invite the European community and some international experts on NEO Impact Effects and Mitigation Measures and provide feedback to ESA on the field in the form of a **roadmap**
- Discuss what **actions** could ESA SSA-NEO take in the short-medium term in those fields
- What **chances for collaboration** could be taken to foster advances on such objectives

SN-VII Workshop

- The workshop took place at Deimos premises in Tres Cantos (Spain) on the 7-8 May 2013
- 40 international experts gathered for the event
- First day devoted to impact effects and the second day to the mitigation measures
- Main goals:
  - Present the state of the art
  - Discuss the draft roadmaps prepared in advance

SN-VII Workshop Sessions

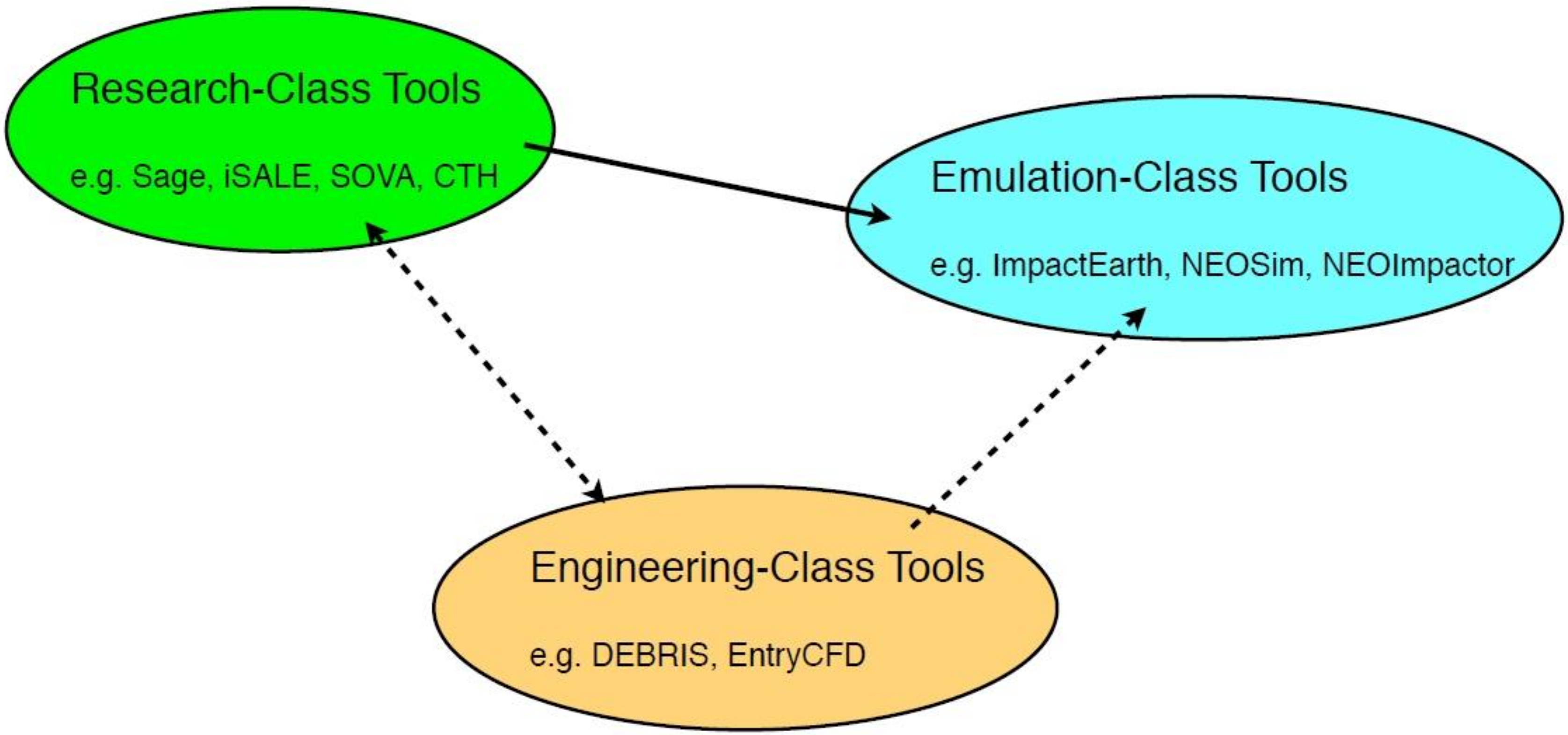
First Workshop Day: NEO Impact Effects	
8:30	Opening of Workshop registration
9:00	Workshop welcome by ELECNOR DEIMOS DG and introduction to the first day
9:10	**Workshop presentation by ESA**
9:20	Overview of the **SSA-SN-VII Project** by Juan L. Cano, DEIMOS Space, Spain
9:30	Presentation on "**General Perspectives on NEO Impact Effects**" by Dr. Clark Chapman, Southwest Research Institute, Boulder CO, USA
10:00	Presentation on "**Airburst Modelling**" by Dr. Mark Boslough, Sandia National Laboratories, Albuquerque NM, USA
10:30	Presentation on "**Preliminary Results on the Chelyabinsk Event**" by Dr. Natalia Artemieva, Museum für Naturkunde, Berlin, Germany
10:50	Coffee break
11:10	Presentation on "**Modelling of Atmospheric and Water Impact Effects**" by Dr. Galen Gisler, University of Oslo, Norway
11:30	Presentation on "**Modelling of Ground Impact Effects**" by Dr. Kai Wünnemann, Museum für Naturkunde, Berlin, Germany
11:50	Presentation on "**Modelling of NEO impact effects in Impact Earth!**" by Dr. Gareth Collins, Imperial College, London, UK
12:20	Presentation on "**Modelling of Social and Economic Effects**" by Dr. Hugh Lewis, University of Southampton, UK
12:40	Presentation on "**Preliminary estimation of the footprint and survivability of the Chelyabinsk Meteor fragments**" by Mrs. Cristina Parigini, presented by Mr. Rodrigo Haya, DEIMOS Space, Spain
13:00	Lunch break
14:20	ESA introduction to the **Impact Effects Roadmap**
14:30	Presentation of the **Impact Effects Roadmap**
14:50	Open discussion (I)
16:10	Coffee break
16:30	Open discussion (II) and roadmap update
18:00	Wrap-up
18:30	Close out of first day
19:00	Workshop cocktail
20:30	End of the cocktail

Second Workshop Day: NEO Threat Mitigation Measures	
9:00	Guidelines for the second day by DEIMOS
9:10	Introduction to the second day by ESA
9:20	Presentation on "**Overview of NEO Threat Mitigation Measures**" by Dr. Christian Gritzner, Wachtberg, Germany
9:50	Presentation on "**Characterisation of Mitigation by Kinetic and Explosive Measures**" by Dr. Keith Holsapple, University of Washington, USA
10:20	Presentation on "**Studying Asteroid Deflection in Hypervelocity Impact Laboratories**" by Dr. Martin Rudolph, Ernst Mach Institute, Germany
10:50	Coffee break
11:10	Presentation on "**Status of NEOShield and Future Perspectives**" by Dr. Alan Harris, DLR - German Aerospace Centre, Germany
11:40	Presentation on "**Kinetic Impact Measure Challenges**" by Mr. Filippo Cichocki, DEIMOS Space, Spain
11:55	Presentation on "**Gravity Tractor Measure Challenges**" by Mr. Baltazar Parreira, DEIMOS Engenharia, Portugal
12:10	Presentation on "**Explosive Measure Challenges**" by Mr. Baltazar Parreira, DEIMOS Engenharia, Portugal
12:25	Presentation on "**Ion Beam Shepherd Measure Challenges**" by Dr. Claudio Bombardelli, Universidad Politécnica de Madrid, Spain
12:40	Presentation on "**Challenges of Other Mitigation Measures**" by Mr. Juan L. Cano, DEIMOS Space, Spain
13:00	Lunch break
14:15	Presentation of a "**Summary on the Mitigation Measures activities presented at PDC**", by Dr. Alan Harris, DLR - German Aerospace Centre, Germany
14:30	Presentation on "**ESA / GSP Related Activities**" by Mr. Andrés Gálvez, General Studies Programme Manager, ESA-HQ
14:45	Presentation on "**The EC / FP7 Stardust ITN Project**" by Dr. Massimiliano Vasile, University of Strathclyde, United Kingdom
15:00	ESA introduction to the **Mitigation Measures Roadmap**
15:10	Presentation of the **Mitigation Measures Roadmap**
15:30	Open discussion (I)
16:20	Coffee break
16:40	Open discussion (II) and roadmap update
17:40	Wrap-up
18:00	Close-out of Workshop

SN-VII Workshop

4.1 The Impact Effects Roadmap

Impact Effects Tools Classification

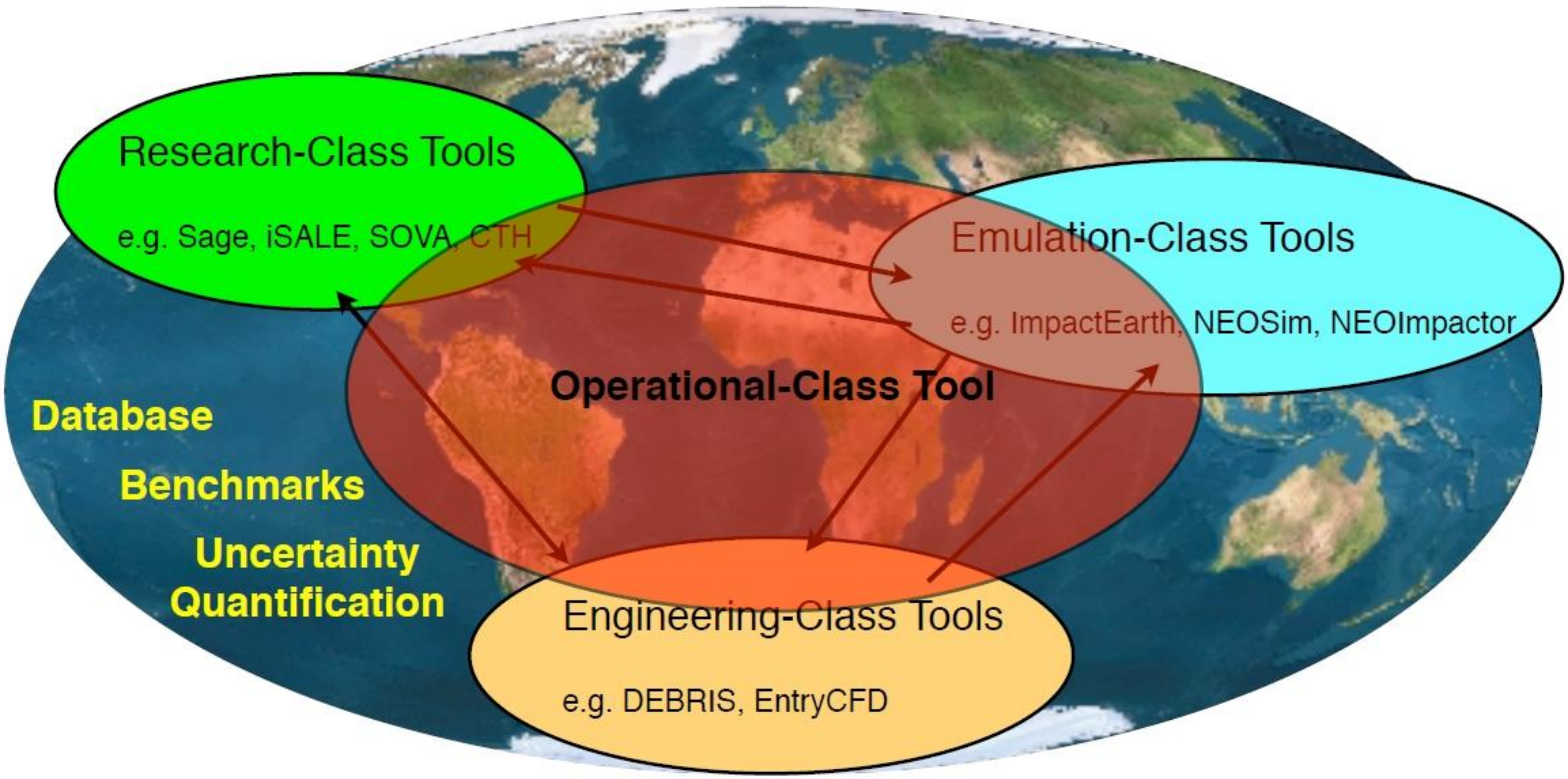


First Recommendations of the Roadmap

- Continue the maintenance of existing tools
  - Expand Verification & Validation exercises
  - Resolve intellectual-property issues
  - Ensure future portability to new architectures & operating systems
  - Establish a training methodology for the use of these tools

- Develop methods to cover other effects with these tools
  - Radiative transfer
  - Thermal conduction (present in Engineering-Class)
  - Electromagnetic pulse generation
  - Global effects — pass outputs from Research-Class tools to existing Global Models

Propose a new Operational Class Tool



Propose a new Operational Class Tool

- To bridge the gap and handle intercommunication
- Substantial database
  - of runs from Research-Class and Engineering-Class tools
  - of benchmarks from laboratory experiments and real events
  - of implied consequences from Emulation-Class tools
- Standard formats
  - for outputs
  - for accessibility protocols
- Uncertainty quantification
- Recognise this as an ecosystem

Final Recommendations (1)

1. Development of a **new tool** that would bridge the gaps between the Research-Class, Emulation-Class, and Engineering-Class models to be used as an **Operational-Class** model, for more detailed and practical use in the event of a real predicted event. This development assumes:
   - Production of a database that would consist of a substantial number of impact-effects runs done with the Research-Class and Engineering-Class tools spanning the ranges of interest.
   - Development of a methodology for the quantification of uncertainty in impact effects modelling.
   - Production of benchmarks for testing all of the models, and of standards for data interchange among the various models.
   - Incorporation of socio-economic aspects into the Operational-Class model.

Final Recommendations (2)

2. Continuing **maintenance** of the tools that already exist
3. Development of **new methods and algorithms** to be incorporated into those tools (electro-magnetic effects, radiative transfer, etc)
4. Extend the **database and benchmarks** down to very small (sub-metre) impactor sizes
5. Strengthening the **links** between the different classes of models and ensuring that they become, and remain, tightly coupled
6. Development of a policy of **education and public outreach** with special attention to frequent impacts of small bodies shall be pursued. Synergies for the use of the operational-class tool as a mean for education and public outreach should be found

4.2 The Mitigation Measures Roadmap

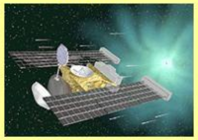
Mitigation Measures Context (as of May 2013)

USA / NASA and others

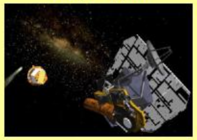
NEAR

Deep Space 1

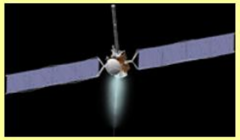
Stardust



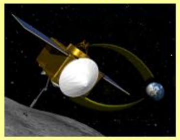
Deep Impact



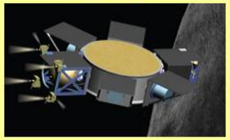
Dawn



OSIRIS-REx



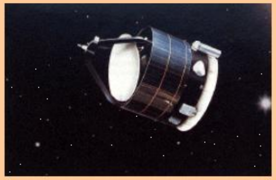
ISIS study



AIDA / DART study

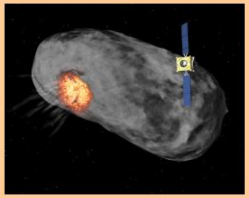
ESA

Giotto

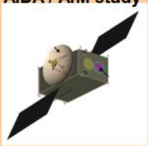


Rosetta

Don Quijote studies



AIDA / AIM study

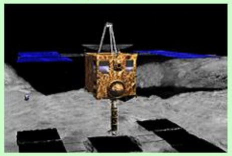


Marco Polo-R

SSA-NEO
Cosmic Vision
GSP
TRP

JAXA

Hayabusa



Hayabusa 2

Russia

Phobos-Grunt

Mission study to Apophis

EC

NEOShield

Stardust

SRCs

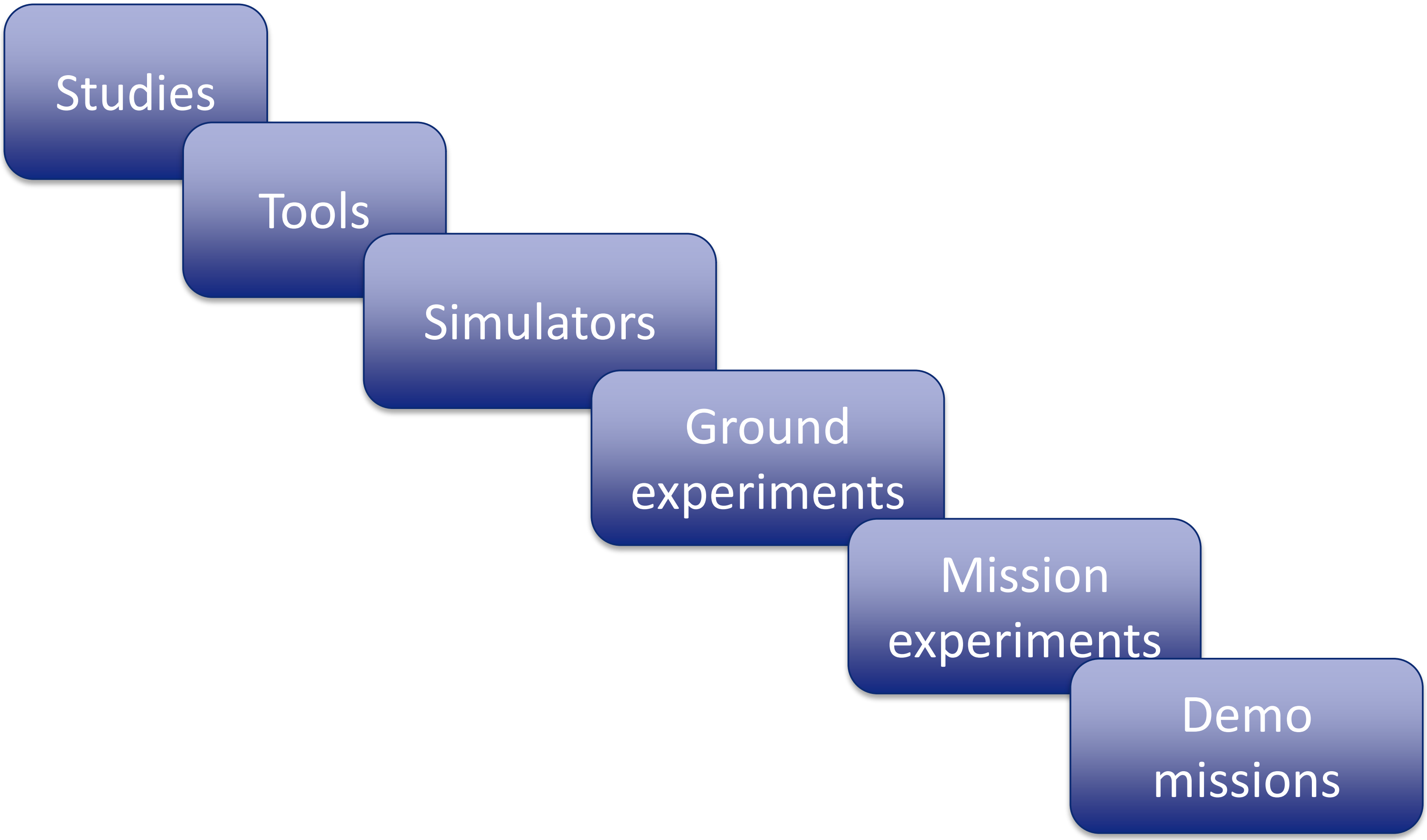
CNES

Mission study to Apophis

Others

Brazil
India
China

Concepts for Consideration



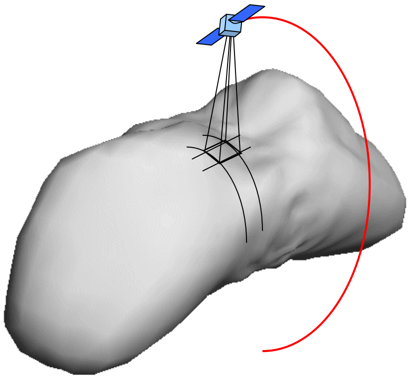
Concepts for Consideration
Studies and Tools

- Possible activities:
  - Processes and tools to help in supporting ESA's role within UNCOPOUS bodies (AT-14, IAWN, SMPAG)
  - Studies on how to raise general public awareness on NEO threat and on how to explain the complexity of the situation: PR actions, active promotion, etc.
  - Study and tool for civil response and evacuation of affected areas due to a NEO threat of low impact
  - Preliminary studies on less known NEO mitigation options (lasers, solar sails, solar reflectors, etc.)

- These activities could be synergistic with ESA's General Studies Programme (GSP) and with some of the activities carried out within NEOShield

Concepts for Consideration
Simulators

- Possible activities:
  - GNC simulator for hipervelocity impacts
  - GNC simulator for IBS operation
  - GNC simulator for gravity tractor
  - GNC simulator for orbiter operations
  - etc.



- These activities could be synergistic with ESA's Technology Research Programme (TRP) and with some of the activities carried out within NEOShield

Concepts for Consideration
Ground Experiments

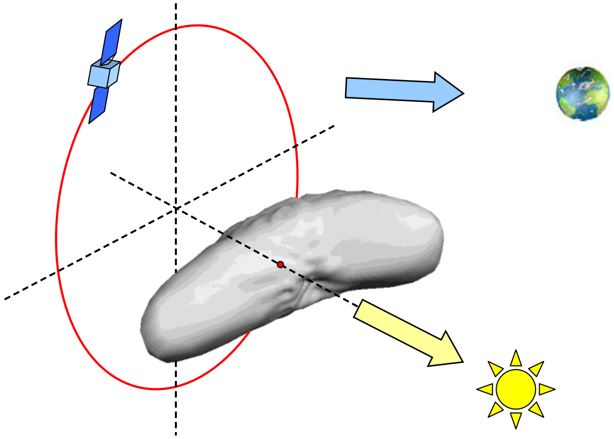
- Activities to increase the level of knowledge of the possible response of a NEO to an impact or to a nearby explosion:
  - Impact testing at hypervelocity test facilities
  - Determination of beta for different materials and internal morphology

- Increase the confidence in the actuation of S/C subsystems related to mitigation
  - Low-thrust engine testing: thrust divergence, backsputtering

- These activities could be synergistic with national plans and with some of the activities carried out within NEOShield or other FP7 activities

Concepts for Consideration
Mission experiments and techniques

- Possible activities:
  - Support a PGSO experiment in Marco Polo-R
  - Support an RSE experiment in Marco Polo-R for accurate orbit determination
  - Participate in the mission concept AIDA

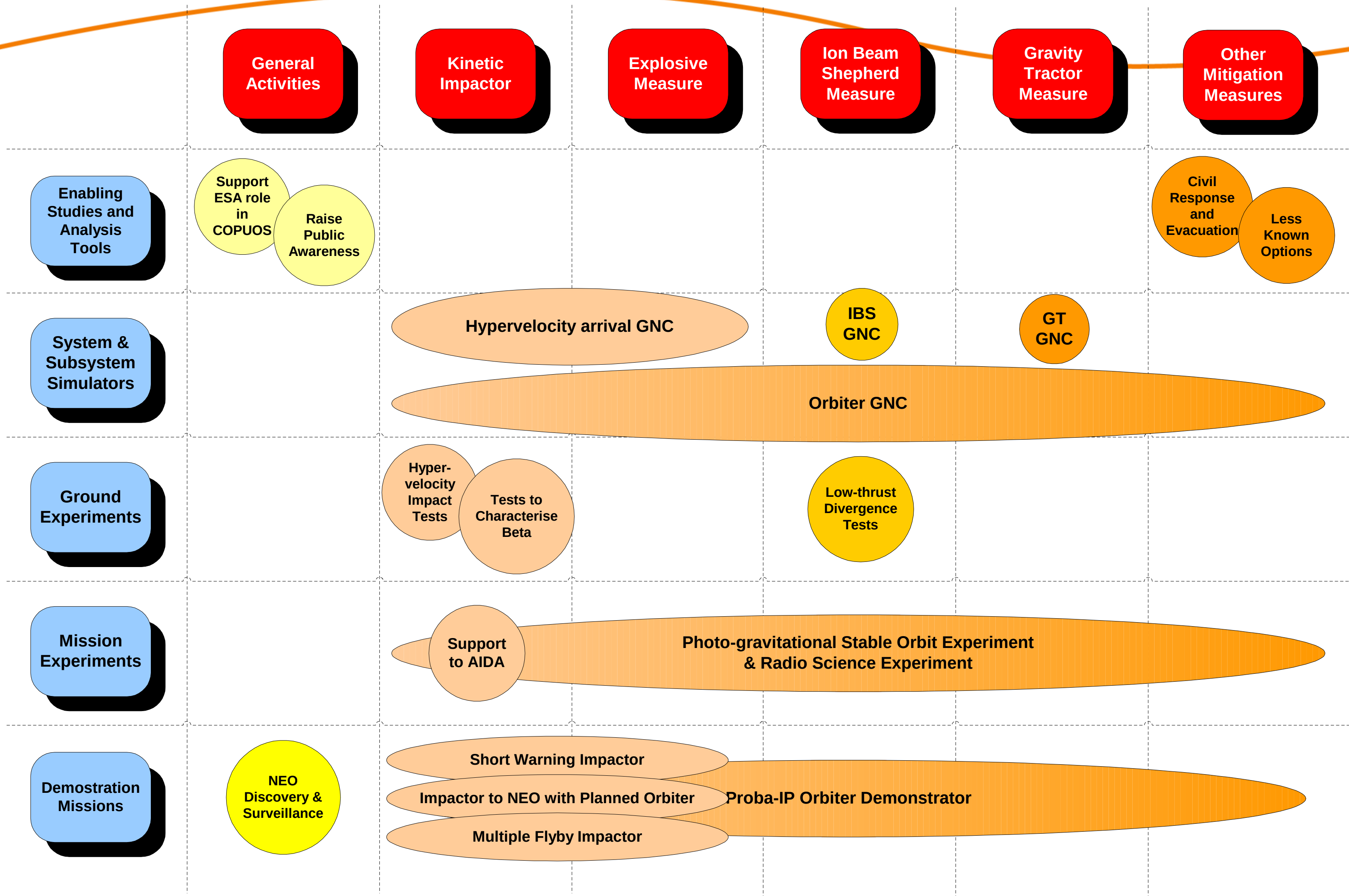


- These activities could be synergistic with ESA's GSP, Cosmic Vision and others

Concepts for Consideration Missions

- Possible activities:
  - NEO discovery and surveillance mission
  - Impactor demonstration mission for short term mitigation
  - Kinetic impactor mission for already existing orbiter missions (Hayabusa 2, OSIRIS-REX)
  - Multiple flyby impactor mission
  - Beacon mission for potential impactor
  - Proba-IP like orbiter for GNC demonstration
- These activities could be synergistic with ESA's GSP, GSTP and with some of the activities carried out within NEOShield and other EC activities in the future (possibly the SRC on NEO)

Summary of Actions vs Mitigation Measures



Final Recommendations
Preparatory activities for NEO mitigation missions

1. Take measures to increase the public awareness of the impact risk and potential civil protection measures

2. GNC simulations for different mitigation options

3. Investigate what aspects of the mitigation measures could be tested on ground or in Earth orbit within a reasonable amount of resources. The following could be considered:
   - Demonstration of the IBS concept by impinging a plasma beam on a target with realistic NEO properties. This would allow demonstrating plasma momentum transfer and interaction effects
   - Demonstration of the laser-beam concept, including consideration of consequences of material release from the target
   - Study the possibility to perform tests of advanced GNC technologies and other mitigation aspects on opportunity missions in Earth orbit

4. Study the possibility to perform kinetic impactor missions for small targets (50 m -150 m) and on short notice

Final Recommendations
Preparatory activities for NEO mitigation missions

5. Study the possibility to test mitigation concepts on very accessible NEOs as for example 2006 RH120 which is recurrently passing close by the Earth

6. Study the feasibility of different mitigation mission concepts

7. Assess and propose the inclusion of demonstration concepts within the Marco Polo-R yellow book

8. Pursue the realisation of the AIDA mission by:
   - Coordinate related activities and funding requests within ESA for the AIM part of AIDA
   - Develop technologies required for the AIDA NEO mission concept (which will also be relevant for other missions
   - Seek international cooperation
   - Develop and procure the AIM spacecraft

5 SUMMARY AND CONCLUSIONS

SN-VII Summary and Conclusions
NEO Impact Effects

- A detailed assessment of the NEO impact effects on Earth has been performed and documented
- Impact effect models have been reviewed in detail
- A number of tools have been reviewed and demonstrated in a set of representative test cases (iSALE, SAGE, SOVA, NEOSim, NEOImpactor, NEOMiSS, CFD tool, DEBRIS)
- A roadmap of actions has been proposed for discussion
- A workshop has been organised to discuss the state of the art in impact modelling and discuss and conclude on the proposed roadmap
- A number of institutions have been brought to the ESA community, particularly in the research side (UiO, MfN)

SN-VII Summary and Conclusions
NEO Threat Mitigation Measures

- A detailed assessment of the NEO threat mitigation measures has been performed
- The maturity and scientific soundness of each method has been assessed
- Current proposed mitigation missions have been reviewed and analysed
- A roadmap of actions has been proposed for discussion
- A workshop has been organised to discuss the state of the art in mitigation measures and discuss and conclude on the proposed roadmap

Thank you