2017 IAA Planetary Defense Conference

Conference Summary and Recommendations

1.0 Introduction

The 2017 International Academy of Astronautics (IAA) Planetary Defense Conference was held on May 15-19, 2017 in Tokyo, Japan. This was the seventh in a series of conferences that began in 2004 in Anaheim, California, with subsequent conferences in Washington, D.C. in 2007, Granada, Spain in 2009, Bucharest Romania in 2011, Flagstaff, Arizona in 2013, and Frascati, Italy in 2015. The conference became associated with the IAA in 2009.

In addition to the IAA, the conference had six major sponsors, ten additional sponsors, and eight partnering organizations. Sponsors and major sponsors provided funds that helped cover major conference expenses. Names of sponsoring organizations are given in Attachment A.

Members of the Organizing Committee, listed in Attachment B, held monthly telecoms to organize the conference and develop the program given in Attachment C and summarized in Section 3. A total of 192 individuals representing 24 different countries attended the 2017 conference. Attendees included 16 members of the press. Figure 1 shows conference attendees, and names and nations represented are given in Attachment D.

Figure 1. Conference attendees.

In general, the conference followed a format like that for the previous conferences: the conference was single track, meaning that sessions were sequential, and participants were able to attend all of the sessions offered, including an evening poster session. This feature was seen by many as a very positive characteristic of the meeting in that it gave each participant the opportunity to become familiar with virtually all aspects of planetary defense, including what we know about asteroids, how we characterize these objects, how we might deflect a threatening object, the effects of an asteroid impact, and response to an asteroid impact disaster.

The conference included a total of 85 oral presentations. A total of approximately 80 poster papers were accepted and posted at the conference, and posters were highlighted at an end-of-the day reception on Tuesday. Each session was organized by the chairs of that session. Chairs were free to set time limits for presentations and to dedicate time slots for short presentations highlighting poster papers. Presentations were generally limited to 12 minutes, with three additional minutes allocated for questions. Oral poster presentations were limited to three minutes each. A meeting timer was used to assure that speakers stayed within allocated time limits.

Each presenter provided both briefing charts and a paper, which could be either a full-length paper or an extended abstract. Papers, presentation charts, and videos of presentations are available at the conference website, **http://pdc.iaaweb.org.**

The highlight of the conference was a tabletop exercise that included updates on the progress of a hypothetical ten-year asteroid threat where participants developed possible responses to the threat. More details on the tabletop exercise are given in Section 3.

At the end of the conference, attendees were asked for their input for findings and recommendations that should be carried forward in this summary report. This material is included in Section 4 of this document.

2.0 Summary of Sessions

As previously noted, the conference was a single-track conference and all attendees were able to attend all presentations. A brief summary of topics covered in each session is given below.

2.1 Session 1: Key International & Political Developments

Presenters in this session summarized projects and programs that are currently funded or are being seriously considered for funding by space agencies or governments. These included projects supported by the European Space Agency (ESA) as part of their space situational awareness (SSA) program, a status report on the NEOShield project funded by the European Commission, a proposal for a Russian effort to build a system for detecting and monitoring hazardous asteroids and comets, recent enhancements of NASA's Near Earth Object Observations program and the establishment of its Planetary Defense Coordination Office, and results of initial steps to establish an Asia-Pacific asteroid observation program.

International:

Speakers described the progress of the International Asteroid Warning Network (IAWN) and the Space Mission Planning Advisory Group (SMPAG), two groups endorsed by the United Nations in December 2013. IAWN links existing NEO discovery teams, NEO observers, orbit computation centers, and communication experts to assist governments in understanding asteroid impacts, their frequency, consequences, and possible responses.

NASA, being the sponsor of the most assets participating, is the current lead agency for IAWN, which will alert the international community in the event of an imminent impact, and SMPAG if an object is discovered that meets threshold criteria established in recent joint meetings. SMPAG brings together space agencies to prepare for an international response to the NEO threat through the exchange of information, development of options for collaborative research and mission opportunities, and to conduct NEO threat mitigation planning activities. The European Space Agency (ESA) currently chairs SMPAG.

In 2016, the Space Mission Planning Advisory Group (SMPAG) endorsed by the United Nations, established a working group to investigate the legal issues relating to planetary defense deflection missions. The group is a mix of experts in the fields of public international law, space law, and scientists/engineers from Austria, Belgium, ESA, Germany, Italy, Mexico, United Kingdom, and United States.

NASA:

NASA Headquarters recently established the Planetary Defense Coordination Office (PDCO) to manage the Agency's planetary defense-related projects and coordinate activities across multiple U.S. agencies as well as with international efforts to plan appropriate responses to the potential asteroid impact hazard. PDCO leads national and international efforts to:

- Detect any potential for significant impact of the Earth by natural objects,
- Appraise the range of potential effects by any possible object, and
- Develop strategies to mitigate impact effects on human welfare.

Since commencing an active NEO discovery program in 1998, NASA has provided funding to upgrade and operate existing 1-meter class telescopes to conduct the search for NEOs. Today, NASA funds three primary ground-based survey capabilities--the Lincoln Near-Earth Asteroid Research (LINEAR) project, the Catalina Sky Survey (CSS), and the Panoramic Survey Telescope and Rapid Reporting System (Pan-STARRS), and one space-based asset--the NEO Widefield Infrared Survey Explorer (NEOWISE). Recent enhancements to NASA's Near-Earth Object (NEO) Observations Program have led to ~83% increase in the discovery rate of near-Earth asteroids (NEAs) over the past three years, mainly in the medium to small size range. NASA also supports research to determine the effects of asteroid impacts within various scenarios, both on land and ocean, and is also pursuing the development of projects to demonstrate asteroid deflection techniques such as the Double Asteroid Redirection Test (DART).

Russia:

The Russian Academy of Sciences (RAS) summarized developments related to coordination of various organizations internal to Russia on instrumentation and collision consequences. The NEO problem seems to be recognized at the federal level as a problem which should be funded. As a result, construction of special NEO detection instruments and techniques has been included in the Federal Space Program (FSP) for the period of 2016-2025. The main goal of this special program is to construct an efficient system for detection of dangerous asteroids and comets.

In 2016, a new 1.6 m wide field telescope saw first light. The instrument is installed at the observatory of the Institute of Solar-Terrestrial Physics of the Siberian Branch of the Russian Academy of Sciences. It is to be used for search of NEOs in a long-distance detection mode—to find objects well before they might impact. A team from the Institute of Astronomy of the RAS proposes to build a dedicated network of robotic telescopes to detect

10-m class NEOs entering into near-Earth space. Projects with larger space instruments (NEBOSVOD-2 and SODA) are under design.

The planned System of Observation of Day-time Asteroids (SODA) project will detect decameter (larger than 10 m) bodies coming toward near-Earth space from the direction of the Sun (Chelyabinsk-type meteoroids). The project includes medium-size (30 cm) wide field telescopes that will be put into vicinity of the L1 (Earth-Sun) point.

Experts of the three institutes of the RAS (Institute of Dynamics of Geospheres, Institute of Oceanology, and Institute of Astronomy) have proposed to construct a world databank of impact consequences.

ESA:

The European Space Agency (ESA) has been building an activity called the Near-Earth Object (NEO) Segment as part of its Space Situational Awareness program (SSA-NEO) since 2008. Major progress in establishing the initially envisaged services was reported. Specifically:

- A technical web portal has been established at http://neo.ssa.esa.int/. This portal federates existing European assets to perform orbit computations and impact warnings. These include the NEODyS system (University of Pisa), a physical properties database (DLR, Berlin), and a priority list for observations (INAF, Rome). Additional tools have been developed and are available; e.g., an orbit visualization tool and an overview of NEO statistics.
- A NEO Coordination Centre has been established at ESA's ESRIN facility in Frascati, Italy.
- Excellent connections have been established to different European and international observatories. These include the Klet observatory in Czech Republic, the Calar Alto Observatory in Spain, telescopes in Brazil and South Korea, the Large Binocular Telescope in Arizona, and the European Southern Observatory's Very Large Telescope.
- ESA is commissioning additional small telescopes for both NEO and space debris observations. Furthermore, ESA has started construction of a NEO survey telescope called Fly-Eye, which has a 1-m effective aperture and 6.7 x 6.7 deg field of view. The site selection for this telescope is ongoing.
- Relevant ESA member countries have agreed on a procedure for disseminating information in case a real asteroid impact threat is discovered. This interface is in process of being established.
- ESA is active in the UN-endorsed International Asteroid Warning Network (IAWN) and is chairing the Space Mission Planning Advisory Group (SMPAG). ESA is actively supporting expansion to include more international participation and collaboration.

At the ESA Council Meeting on Ministerial Level in Dec 2016, new funding for the next period of the SSA program (called Period 3) was approved. Work will focus on starting operations of the first Fly-Eye telescope, starting the development of a second fly-eye telescope, migrating the NEODyS system completely to the NEO Coordination Centre, finalizing interfaces to the emergency response agencies within Europe, and expanding international collaboration.

Japan

The Bisei Spaceguard Center operates both 1-m and 0.5-m aperture telescopes, which perform follow-up exercises for asteroids and observe space debris. These telescopes are operated by the members of the Japan Spaceguard Association (JSGA).

Providing support to space missions is another important activity in Japan. In 2003 Hayabusa, world's first asteroid sample return mission, was launched. In 2014, Hayabusa2, the follow-on mission of Hayabusa, was launched, and it is now on the way to its target asteroid. The main purposes of these missions are to develop new technologies for space missions and to study the origin and evolution of the solar system. However, they are also important from the point of the planetary defense, because the target asteroids of both missions, Itokawa and Ryugu, are near-Earth asteroids, which actually approach the Earth closely. The Hayabusa mission helped us understand the nature of a small, S-type near-Earth asteroid; Hayabusa2 will help us understand the nature of a small C-type asteroid.

JAXA initiated formation of the Asia-Pacific Asteroid Observation Network (APAON), a voluntary network to promote the discovery and observations of asteroids by nations in the Asia-Pacific region. Currently, observatories in eleven countries are members of APAON, including China, Indonesia, Korea, Mongolia, and Thailand.

2.2 Session 2: Advancements & Progress in NEO Discovery

Nine presentations were given in Session 2, with the following topics:

- Estimates of the **population of large (>1 km) NEOs** have been revised to correct a round-off error, reducing the estimated population from ~990 to ~934 and bringing the estimated survey completion of these objects up from ~88% to ~93%.
- Pan-STARRS and the Catalina Sky Survey currently find the most **new asteroids**; however, discovering new objects often requires the follow-up capabilities of other telescopes, especially for NEOs. When an object is not followed-up, its astrometry is relegated to the Minor Planet Center's (MPC) Isolated Tracklet File (ITF), which contains 13.5+ million detections of unlinked tracklets--a rich source for data mining purposes. A new method has been developed for linking observations that have not previously been linked. Work is ongoing.
- JPL has developed a **Short-Arc Orbit Analysis and Hazard Assessment for Newly Discovered Asteroids tool**, or SCOUT, that provides early detection of potential asteroid impacts, close approaches, and mission accessible asteroids. The system includes systematic ranging for orbit determination and is quick, fully automated, and provides email and text alerts.
- A **new star catalog** promises to improve the accuracy of asteroid impact probabilities. A full catalog is available for download from the Gaia web site (https://www.cosmos.esa.int/web/gaia).
- More than 90% of the observing time on **Pan-STARRS1** since April 2014 has been dedicated to searching for NEOs. Pan_STARRS1 has made 3236 NEOs discoveries to date, including 267 Potentially Hazardous Asteroids, and when the weather is good, Pan-STARRS1 discovers 60–100 NEOs per month. Pan-STARRS is good at finding larger, undiscovered NEOs that are distant and faint, but is less efficient at finding smaller fast-moving nearby NEOs. Pan-STARRS has discovered more than half of the new comets since 2014. **Pan-STARRS2** expects to be back on-line in June 2017.
- **ATLAS** is a NASA-funded effort to find dangerous asteroids, with a ~2-day warning time for Chelyabinsk-sized asteroids and ~1-week warning time for a Tunguska-sized object. ATLAS uses two 0.5-meter telescopes to perform all-sky monitoring, except near the Sun.
- The operation of the US National Science Foundation's **Large Synoptic Survey Telescope (LSST)** for discovery of NEOs is expected to start in 2022.
- The NASA-funded **Catalina Sky Survey** for near-Earth objects, a 100% NEO-dedicated survey program that has been operational since 1998, is currently using

three telescopes located in Southern Arizona, where data are acquired, processed, visually validated, reported and followed up in near real time. Real-time operations enable discovery of imminent impactors. Catalina Sky Survey is currently discovering 900+ NEOs per year, with 350+ discovered through May 2017.

- **DEEP-South**, the deep ecliptic patrol of the southern sky, carries out discovery monitoring and physical characterization of NEOs. DEEP-South seeks to enhance discovery and self-follow-up capabilities for NEOs using the Korean Microlensing Telescope Network (KMTNet) in the southern hemisphere. DEEP South is looking for partners for coordinated use of existing telescopes for astrometric and photometric follow-up of its targets to bridge the gaps in global sky coverage. KMTNet facilities include Cerro Tololo Interamerican Observatory in Chile, the South African Astronomical Observatory, and Siding Spring Observatory in Australia.

2.3 Session 3: NEO Characterization Results

Fifteen papers were presented in this session. Key points from these presentations were:

- As part of the **Italian contribution to the NEOShield-2** EU project, it is estimated that the project will acquire new data for ~200 NEOs. This large sample of data will minimize several bias effects present in data available in the literature, and will allow an in-depth statistical study of the small NEO population. The project has identified a few carbonaceous targets with high inclination that require a detailed investigation.
- **Arecibo and Goldstone radars** have conducted ground-based radar observations of Potentially Hazardous Asteroids (PHAs). The presentation noted that Radar is a unique and powerful tool for post-discovery dynamical and physical characterization of NEOs, and that radar is invaluable for mission planning and validation of technical demonstrations of mitigation techniques. Arecibo and Goldstone detect ~100 asteroids per year and are capable of more.
- Arecibo radar will begin **characterization of 138971 (2001 CB21)**, a flyby target for the DART Spacecraft, in mid-Feb 2022. Radar imaging with resolution ~15 m will be available in the first week of March 2022. Position uncertainty of ±12 km (3σ) prior to DART flyby will be possible with Feb 2022 observations only.
- Observations of NEOs using 32m radio telescopes of Quasar VLBI network as receivers confirm the capability and effectiveness of **bistatic radar observations** of NEOs.
- Physical characterization of **NEA 2012 TC4** has found the object to be a highly elongated ~10-meter diameter, possibly basaltic, object of non-negligible strength.
- An examination of the relevance of asteroid thermal inertia to planetary defense has found that, for a spin period > 10 h, knowledge of the rotation rate of an asteroid is crucial to choosing an appropriate value of thermal conductivity for calculation of the Yarkovsky effect. These results are also relevant to modelers concerned with the mass and velocity distributions of ejecta expelled by a kinetic impactor spacecraft, and the corresponding ejecta-related momentum enhancement factor.
- The **Hayabusa** mission revealed the nature of asteroid Itokawa, which was found to be a small, S-type NEO. In June-July 2018, **Hayabusa2** will visit asteroid Ryugu, which is a small, 850-880 meter, C-Type asteroid.
- A study investigated plausible **properties of the Didymos** (asteroid 65803, the primary target of the proposed Asteroid Impact and Deflection Assessment (AIDA) mission) and found that failure initiation and behavior are sensitive to the structural

cohesive strength. For Didymos Primary, when cohesion is not included, the bulk density of the primary would be higher than 2.4 gram per cc. Otherwise, if the nominal bulk density is real, there must be some cohesion as high as 6.5 Pa in the primary's material. In the future, the method will be extended to study the cohesive strength for different configurations and derive its relation to the bulk density.

- Another study assessed **asteroid shapes produced by impact disruption** to learn if shapes of an asteroid can lead insights on the physical properties of top-shaped asteroids such as Didymos. The study found that Didymos could be the product of impact disruption, especially if the parent object was porous with cohesive aggregates following a low obliquity impact.
- New observations of **asteroid 3200 Phaethon**, which has a very small perihelion (~0.14 AU) and a dust tail near its perihelion, were described. The observations were used to refine the pole of Phaethon and the variation of the spectra over the body.
- A new database, https://neoproperties.arc.nasa.gov/, aggregates **physical properties of NEOs and meteorites into a searchable database** with an emphasis on properties of interest to the planetary defense community. These include taxonomic class, diameters and albedos for asteroids and density and porosity, compressive and tensile strength, elastic and shear moduli, and heat capacity and thermal conductivity for meteorites.
- A study described the size and orbital distributions of **interplanetary dust** associated with NEOs obtained by Kyoto University's RISH middle and upper atmosphere monostatic coherent pulse Doppler radar meteor head echo observations.

2.4 Session 4: Deflection & Disruption Models & Testing

Speakers in Session 4 discussed missions related to planetary defense that are planned or in the design stage. Specifically:

- A study provided characteristics of **stand-off nuclear explosions**, which could be used to deflect kilometer-sized asteroids. The stand-off distance can be used to "dial-a-push," or to tune the amount of delta-V delivered. Models are available to assess high-resolution blow-off and large-scale breakup of a target object after a nearby nuclear explosion.
- An overview of work related to planetary defense being conducted at **Los Alamos National Laboratory** was presented. The work includes examination of a stand-off burst of a nuclear explosive using a radiation-hydrodynamics code with full x-ray transport.
- Characterization of a **high-power ion beam deflection** system found that ion beam deflection (IBD) using high-power solar electric power is well suited for the deflection of asteroids in the 50-m to 150-m size. The force applied by IBD is almost entirely in the control of engineers and is nearly independent of the target asteroid's characteristics. A 160-kW IBD vehicle could successfully deflect the PDC exercise scenario asteroid 2017 PDC within the available time if the asteroid size was less than 140-m diameter with a density of ≤ 2 g/cm^3.
- A **solar sail** with reflectivity control devices, if attached to an asteroid, could be used to de-spin or deflect that asteroid. A 30-meter sail could be used to deflect a 50-meter asteroid; a 100-meter sail would be required for a 100-meter asteroid.
- **Dispersive pulverization** of small asteroids (< 150 m) by a 5,000 – 10,000 kg, multiple non-nuclear kinetic energy impactors launched from a single Delta IV

Heavy or Falcon Heavy, might to be a technically/economically/politically viable option for short warning time scenario.
- **Impact simulations** provide one of the best means for interpreting and extrapolating results of asteroid impact experiments such as DART for future missions, and different methods of calculating beta lead to similar results, providing confidence when comparing between code types. Simulations suggest that the composition of a target asteroid does not have significant effect on β; that porosity of the object affects crater formation, shape, ejecta angle and velocity, and that β (momentum enhancement factor) decreases with porosity and ΔV increases due to lower target density/mass for a fixed object size.
- Laboratory and numerical experiments of **impact-generated waves in agglomerated asteroids** suggest that β will be in the range 1.5-3.5 for kilometer-size bodies of this type.
- 2-D modeling of the **effect of kinetic impactors on rubble-pile asteroids** gives preliminary results showing that crater size is fairly consistent (craters on boulders are a bit shallower and wider, but matrix impacts are deeper), damage propagation within the body is different (which may imply disruption behavior is different), and that β will vary in the presence of boulders.
- 3-D models of **kinetic impactors** for asteroid deflection show that damage morphology of the target is sensitive to both the material parameters selected in the pressure-dependent strength model and sensitive to the distribution of flaws in the target material. Fragment velocity distribution is sensitive to the strength model, and target material properties selected in the pressure-dependent strength model changes the damage morphology.

2.5 Session 5: Mission & Campaign Designs

Eighteen speakers in Session 5 discussed a variety of topics on mitigation missions and campaigns.

- A **directed energy system** would focus a beam on a target object, and use material ejected from the target object to impart a deflection delta-V. Results show that a 200-m diameter asteroid could be deflected by two Earth radii in ~1 year after rendezvous using a 500 kw-class laser. A two-Earth-radii miss of an Apophis class asteroid (325m) could be achieved with ~6 years of exposure of a modest 100-200kW laser. Short-time response to a Tunguska class 40-m object would be days after rendezvous. The directed energy method is well suited for deflection of comets due to its rapid response, which is necessary for short warning. Modest laser time can mitigate large comets.
- **Hayabusa2** is the Japanese sample return and kinetic impact mission to near-Earth asteroid Ryugu. The system is powered by an ion engine for continuous-thrust trajectory control. Hayabusa2 is currently in transit, is flying normally, and will perform a 1.5-year proximity operation at Ryugu starting in mid-2018. It will return to Earth with samples in late 2020. The system contains several scientific instruments including a spectrometer, sampler, small impactor, rover, and lander. The small impactor will attempt to form a crater. Hayabusa2 will contribute to future planetary defense technology by pushing forward the boundaries in areas of small body surface access, roving, sampling and impacting.
- NASA's **Double Asteroid Redirection Test (DART)** is one component of the AIDA dual mission NASA/ESA collaborative project. It will be the first kinetic impact test at realistic scale for planetary defense, and will: improve impact models by measuring the momentum enhancement due to ejecta from an impact; refine

concepts of operations for deflection missions; inform planning for the planetary defense decision process and policy definition, and will be the first flight of NEXT, NASA's Evolutionary Xenon Thruster. Secondary objectives (in collaboration with ESA's AIM observer mission) are to better understand the internal structure and evolution of NEOs and validate performance models by in-situ measurements of the target NEO pre- and post-impact. Additionally, DART will be the first mission to study a binary asteroid system and measure asteroid deflection by measuring the ejecta momentum amplification factor β. The deflection performance metric used in this project is the diameter of a NEO that can be deflected the full width of the Earth, driven by mass of the impactor, relative velocity at impact, and time from impact to close approach.

- ESA's **Asteroid Impact Mission (AIM)** is the European component of AIDA. AIM had not yet reached full budget approval prior to PDC 17. At present, there is no small body mission planned in Europe before at least 2030. AIM's launch opportunity is currently delayed; the launch of DART is scheduled in January 2021 on a commercial rideshare. Impact of Didymoon, the moon of asteroid Didymos, would occur in Oct 2022.
- The **Enhanced Gravity Tractor** was derived from the Asteroid Redirect Mission (ARM) for deflecting the hypothetical 2017 PDC asteroid. The system collects in-situ mass to augment the spacecraft's mass and maximize the gravity tractor effect to reduce deflection time relative to the traditional gravity tractor. Several Earth departure dates and asteroid arrival dates were possible depending on system power and mass characteristics. This class of rendezvous mission provides the best orbit determination (pre- and post-deflection) and physical characterization of the asteroid. Planetary defense and asteroid mining applications are closely linked in this concept.
- **Solar Electric Propulsion (SEP)** is technology that has been demonstrated in deep space. SEP would enable much higher impact/arrival mass than chemical propulsion, and would allow an extended launch period (months, vs. weeks for chemical propulsion). Both flyby and rendezvous mission options to the 2017 PDC object are possible with this method, and the rendezvous mission could stand-off to observe the outcome of kinetic deflection attempts. Key findings indicate that 250m asteroids will likely require multiple launches; for objects ~170 m or less, single launches with existing SEP technology could be used.
- NASA uses several mission analysis tools for designing **missions to deflect the exercise scenario 2017 PDC asteroid**. These include a custom grid search tool for linked ballistic campaign trajectories, the Evolutionary Mission Trajectory Generator (EMTG), and the NEO Deflection App (NDA). Possible trajectory types are chemical and Solar Electric Propulsion (SEP). Asteroid 2017 PDC's orbit makes rendezvous difficult, but more opportunities exist for missions to fly by the object with various flyby relative speeds and phase angles). Arming a rendezvous spacecraft with a nuclear device accomplishes pre-deflection characterization, deflection, deflection monitoring, and post-deflection monitoring with a single, relatively low mass spacecraft. Two spacecraft could be built and launched for redundancy. SEP offers several weeks of flexibility in terms launch and arrival dates. SEP is very enabling for rendezvous, and can serve to improve an intercept mission as well. For this scenario, delivering a nuclear explosive via rendezvous achieves deflection with fewer launches and less spacecraft mass than kinetic impactors.
- The **NEOShield-2** consortium consists of 11 European partners and consists of three reference space missions: NEOTωIST, a small impactor spacecraft, and a sample return mission. Physical characterization of "small" NEOs is achieved by

statistical analysis of correlations between infrared data, radar albedo and spin period. The NEO properties portal contains mission targets, observation and characterization results, and observational support tools in a dynamical web interface. The consortium environment enables testing and verification of key technologies for kinetic impact, proximity operations, and landing on small NEOs, and provides a method to derive mineralogy, metal content, and surface structure from IR observations.

- **NEOTωIST**, or Near-Earth Object Transfer of angular momentum, is a relatively inexpensive kinetic impactor demonstration mission and feasibility study conducted within the NEOShield-2 framework. It is characterized by a low-cost, single-launch kinetic impactor targeting a well-characterized (previously visited) NEO a few hundred meters in diameter (e.g., Itokawa). The mission's objective is to quantify the momentum transfer due to impact using the change in the object's spin period as measured from Earth. Possible mission architectures are impactor; impactor plus flyby vehicle; and impactor plus flyby vehicle plus nano-spacecraft chasers. The concept involves one impactor spacecraft also functioning as an interplanetary carrier, and one flyby sub-spacecraft ejected prior to impact. High quality imaging of the ejecta cloud during the high velocity pass is a design driver.
- **Recognizing that NEO deflection campaign must be as reliable as possible**, estimates of launch and mission reliability were developed using actual launch and deep-space mission success history. The total number of launches for variable level of mission success rate and desired level of campaign reliability were estimated. The 2015 and 2017 PDC hypothetical impact scenarios were used as case studies, demonstrating that mission reliability should be taken into account when planning for a mitigation campaign.
- **Concurrent engineering methodology (CEM) for a NEO impactor mission** was developed for design of the subsystems for a spacecraft that will intercept 2017 PDC. CEM, a high-level conceptual design and analysis tool that draws from parts databases and historical trends, allows for a group of subsystem experts to work on a single mission concurrently and create several possible mission configurations in a short amount of time. Subsystems modeled in the CEM include propulsion, structures, communications, astrodynamics, guidance, navigation and control, command and data handling, electrical power subsystems, reliability, and launch vehicles. CEM was utilized to create two configurations for the 2017 PDC deflection system based on the mass needed to deflect the object and launch times. The first configuration delivered about eight tons on a Delta IV Heavy launch vehicle 5.1 years before Earth impact. The second configuration delivered about 5 tons on an Atlas V 7.7 years before impact.
- A study compared **Ion Beam and Kinetic Impactor** deflection of hypothetical asteroid 2017 PDC. The ion beam spacecraft hovers at safe distance from the asteroid's surface and points a primary ion engine at the surface to implant ions below the asteroid surface and transmit momentum; kinetic impact deflection involves a spacecraft hitting the asteroid at high velocity to transfer momentum. Two options were considered: full or partial ion beam deflection, or one of more kinetic spacecraft. In general, kinetic impact has higher deflection capability (by a factor of 2-3 in the 2017 PDC case). A relatively small ion beam spacecraft can be accommodated on a rendezvous reconnaissance mission and can be used to deflect the asteroid alone or in cooperation with a follow-up KI mission.
- A parameter study of **kinetic-impactor mission design** examined feasibility of sending kinetic impactors to all PHAs and generated preliminary mission designs for the whole parameter space. The method is suitable for studying strict impacts,

useful to highlight properties and symmetries without loss of generality, and enables analytical studies of optimal kinetic-impactor mission classes.

- **A solar sail** concept was examined for in-situ characterization of a NEO's spectral information, shape and topography, and orbital dynamics. A three-step DLR-ESTEC Gossamer roadmap to solar sailing was established in 2009 to develop key technologies for these types of science missions. The concept is not suitable for the 2017 PDC scenario due to late launch and arrival at the asteroid; however, a fully optimized launch in 2025 could be diverted to rendezvous with 2011 AG5.

2.6 Session 6: Impact Consequences

Presenters in Session 6 considered the consequences of an asteroid's impact.

- For considerations of when it might be possible to **"take the hit,"** a study examined airburst and impact effects of 100 to 250-meter asteroids on land and in deep or shallow water. The asteroids were assumed to enter vertically at 17 km/sec and would deliver kinetic energy equivalent to 1 GT of TNT. The study concluded that the Gobi Desert might be an acceptable location to allow a 1-GT impact, and that deep ocean may also be acceptable if far enough away from shore and there is a low likelihood of triggering an undersea landslide. Impacts in shallow water are not advised. Future work will look at different ground properties, intermediate water depth (2-4 km), entry of a rubble pile asteroid, and non-vertical entry.
- A **fragment cloud model** (FCM) was developed to model breakup and energy deposition of different asteroid structures. The model produces a realistic variety of energy deposition features that enable very good matches to observed meteors, demonstrate how we can use those matches to make inferences about asteroid characteristics, and highlights potential parameter refinements for modeling debris clouds. For risk assessment applications, the analytic approach is efficient enough to run the large numbers of cases needed for probabilistic risk assessments, yet variable enough to represent a wide range of potential asteroid structures. It also provides a way to move beyond the typical point-source estimates and incorporate the different energy deposition rates into ground damage estimates. Several updates are planned.
- Presentations at the NASA-NOAA workshop held in Seattle in August 2016 examined **contributions of asteroid-generated tsunami** to the impact hazard from impacts by small (<250m diameter) asteroids. Results found that most damage to coastal populations is limited to surface strikes close to the shore, in which case the direct blast damage may be more important than the wave generated. The risk from near-shore impacts can be important for considering individual cases, but they do not contribute significantly to the ensemble hazard. Current estimates are that the ensemble hazard from ocean impacts is at least an order of magnitude less than from land impacts.
- **Recent results show that large airbursts may produce significant water gravity waves,** leading to regional coastal threat. The rarefaction "suction phase" appears to be to be much more strongly coupled to water wave than compressional air blast; coastal inundation does not depend strongly on source distance over studied range; water depth increases amplitude but decreases wavelength; and air-driven impact and airburst tsunamis may be significant contributors to overall risk and need to be quantified. The researchers noted that smaller airburst coupling mechanisms such as plume ejection, steam explosion, and toroidal vortices have not been eliminated.
- **Simulations of the water impact of 2017 PDC** in the Sea of Japan and in the Pacific Ocean found that the maximum wave heights would be in the range of 4m and 3.5m, respectively. The research also found that only 15 to 25% of the energy delivered is

"impact" energy; the rest is mainly used to a) vaporize the asteroid and ocean, and b) create wind and shear waves. Salt water vapor dissociates into chlorine, which reacts with oxygen and bromine and destroys stratospheric ozone. One case considered the effects of a 250m impactor over a deep-water section in the Gulf of Mexico, which found that ~$6x10^{10}$kg of sea water would be vaporized, with $1.2x10^{8}$kg of HCL, $1,8x10^{5}$kg of HBr, and $6x10^{7}$kg of NO. These quantities were projected to have no significant long-term effect on the global climate, while impact of a 400m asteroid in the same region would have "sizeable" effects, increasing the background concentration of Cl by a factor of ~2, increasing the stratospheric water vapor by 5 to 10%, decreasing stratospheric ozone by 10-15%, and decreasing the temperature in the stratosphere by 1-3^{o}K.

- Research on the **immediate effects of asteroid impact on the human population** found that for asteroid sizes in the range of 15 to 400 m, aerothermal effects were most severe, ground effects were least severe, that tsunamis account for 20% in a global scenario, and that land impact is ten times more severe on population than water impacts. The research provided charts showing the average loss per impactor as a function of impactor size for both water and land impacts.
- Another researcher used a Monte Carlo risk model to assess risk on a scenario-by-scenario basis, and estimated that the **total nominal risk from impacts** of potentially hazardous objects (PHOs) is 2500 casualties/year, which is dominated by global effects of large object impacts. The risk associated with undiscovered PHOs (2023) is about 180 casualties/year, with 170 casualties/year from global effects, 10 casualties/year from land impacts, and <1 casualty/year for water impacts.

2.7 Session 7: Disaster Response

Four papers were presented in the disaster response session.

- The first considered whether and when **shelter-in-place** might be effective as a strategy for protecting the public in case of an asteroid entry. Using an ensemble of impact and airburst simulations, the study shows that shelter-in-place would save lives and that the number depends on the assumptions. The author recommends development of an online tool for use in policy analyses.
- The second described a **NEO Information Plan** developed by the European Space Agency. The plan defines the interface between ESA and its member countries in the case of an imminent asteroid impact threat for impact warning in case of a credible impact threat, and information release in case of an event which may get public attention (close flyby, bright asteroid, large fireballs). The plan specifies criteria for when to distribute information, what information will be distributed, and who the recipients should be. The content of the plan is based on workshops with European emergency response agencies. The plan is now in place, and all ESA countries will be added by 2020.
- The third discussed the **NEO impact tabletop exercise** developed by NASA and the U.S. Federal Emergence Management Agency (FEMA) and presented in 2016 in California. The exercise emphasized interactions with FEMA's California staff and state and local emergency management officials. Lessons learned were used to inform the national strategy for NEO impact threat preparedness. A full report on the exercise and its findings will be published. More information on the exercise is presented in Session 9.

2.8 Session 8: Impact Risk Assessment & Decision to Act

The eight oral presentations of this session covered a range of topics.

- **Impact risk assessments** were addressed by a presentation on a new tool initiated by ESA for the calculation and visualization of impact corridors on Earth. A comparison of test cases showed very good agreement of this tool with a similar tool from NASA which uses a different method. A paper on the performance of impact monitoring pointed out that present **impact predictions** should be able to calculate impact probabilities down to a probability level of 10^{-7}. Smaller impact probabilities could be overlooked by present methods.
- Several papers addressed the **policies and processes of the decision to act** in case of a potential impact threat. Presentations addressed the distribution of required deflection impulses as function of time before impact, policies and processes of planetary defense and mitigation decision steps and triggers. NASA´s activities to define **thresholds for government actions** were presented in detail. Another presentation considered **political aspects of international cooperation** in the field of planetary defense. The need for a coordinated approach was emphasized. Apathy or distraction by nations which do not feel concerned from a specific impact threat must be avoided.
- One presentation addressed the **risk from comets** (surprisingly, this was the only presentation during the PDC 2017 that addressed comets). There are far more near-Earth asteroids than near-Earth comets. However, comets are on average much larger (several kilometers in size) and faster than asteroids, so any impact from a comet could have catastrophic consequences. In addition, most comets come from the outer solar system and will typically only be detected between the orbits of Saturn and Jupiter, which gives only several months to a couple of years of warning time. Furthermore, non-gravitational disturbances like outgassing makes their orbit more difficult to predict than asteroid orbits. The discussion showed a general consensus of the audience that comets should receive more attention in the future.
-

2.9 Session 9: Public Education & Communication

Presentations in this session discussed

- A recent **asteroid impact tabletop exercise** was used to acquaint NASA and U.S. Federal Emergency Management Agency (FEMA) public affairs experts on how an actual asteroid threat might evolve and the potential consequences of such an impact. The exercise used an asteroid threat scenario that began with the October 2016 discovery of asteroid 2016 TTX (a fictional 100-300-meter asteroid) that had a 2% chance of impact in September 2020. As Figure 2 shows, the uncertainty region at discovery crossed both the United States and Africa. As the scenario progressed, the probability of impact increased in November 2017 to 100%, and in March 2020, NASA confirmed that impact would occur in six months in the northern Los Angeles area, with major disruptions expected. As the scenario evolved, participants discussed a number of issues that included coordinated messaging across other federal, state and local agencies, and with our international partners. Important considerations are applicability of existing disaster response planning, addressing critical infrastructure concerns, implementing evacuation orders, and staying on message and ensuring that messaging to the public is accurate, timely, and understandable. Actions that should be taken now are: similar exercises should be conducted involving other stakeholders; public affairs staff from space and emergency management agencies should be involved in exercise coordination meetings so communication challenges can be considered and addressed; templates for notification messages, press releases and other updates should be drafted; and an asteroid hazard communication plan should be created that includes messaging that is proactive and creative, especially on social media.

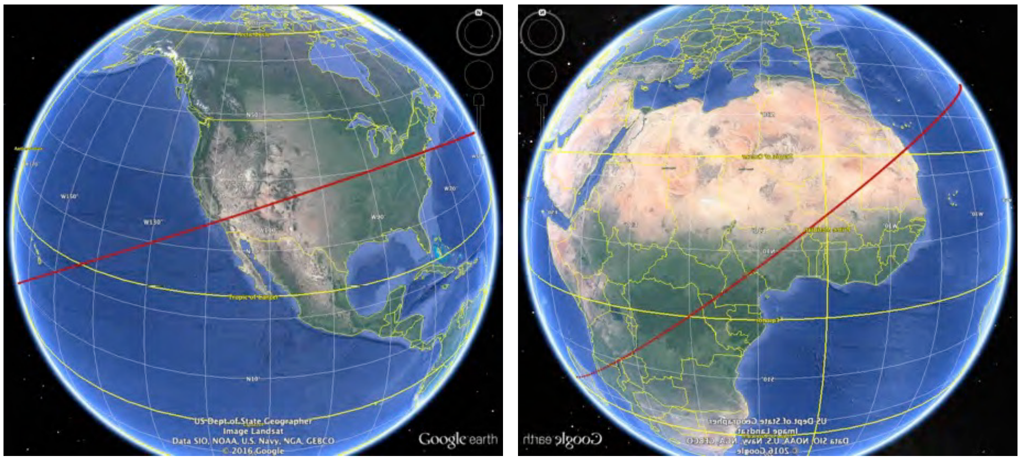

Figure 2. Threat corridor at discovery of the fictional asteroid threat used for the NASA/FEMA tabletop exercise.

- A study by 12 young researchers during a summer session at NASA's Frontier Development Lab was presented that matched "doctoral-level talent from the planetary sciences with peers from the machine learning community" to "develop and demonstrate material breakthroughs of exceptional value, specifically in the field of planetary defense and machine learning." Participants developed: an **automatic meteorite detection system**, all driven by a user-friendly app that could be used in the field to help find meteor fragments after a known entry event; an approach that could enable a more rapid understanding of the shape of an asteroid while it is being tracked by radar; and a machine-learning decision tree to select the **most effective deflection technology for a given hazardous object**. This final tool found that the nuclear explosive device is the most effective given its ability t impart high delta-V and instantaneous effect.
- The Planetary Society recommended using a **"scalable" public communication strategy for planetary defense**, where information for the public is clear, succinct, and memorable and is organized into a small number of steps/points. The same structure could be used for a one-minute video or a one-hour talk. A 5-Step Plan to Prevent Asteroid Impact was presented as an example. The steps are: Find, Track, Characterize, Deflect, and Internationally Coordinate and Educate. The Planetary Society has begun implementing this strategy and presented a short video clip as one example (see planetary.org/defense).
- A knowledge gateway for **smart management and discovery of planetary defense information** was described. The gateway is designed to find planetary defense related information quickly and provide discovery and easy access to the knowledge and expert opinion within a project team. The approach strengthens "the linkage between different organizations, scientists, engineers, decision makers, and citizens."

3.0 Threat Response Exercise

The primary goal of the exercise for the 2017 conference was to explore the decision-making process that might be followed in the event of a real threat. To do this, the exercise development team (see Attachment E) injected information on the threat posed by hypothetical asteroid 2017 PDC prior to the conference. The information provided prior to the conference was to encourage individuals to use that information to conduct their own research into the threat and its possible outcome. As noted in the preceding sections, several attendees used the hypothetical asteroid threat as the basis for papers and presentations at the conference.

Seven focus groups were established to examine, discuss, and provide recommendations to a group of individuals who volunteered to be "world leaders" who would make decisions on actions to be taken as the threat progressed. The seven focus groups, and the questions posed to each, were:

Group 1: International Asteroid Warning Group (IAWN)[1]—What is known about the threatening object? What are its probability and time of impact, and size, mass, shape, etc.?

Group 2: Impact Effects—What would happen were the object to enter Earth's atmosphere and impact? How big would the area affected be?

Group 3: Deflection and Disruption—What techniques are available and suitable to deflect or disrupt the threatening object away from Earth or move it to a different impact location should either be necessary?

Group 4: Space Mission Planning Advisory Group (SMPAG)[2]—What would a mission or campaign to send one or more deflection/disruption payloads to the threatening object look like (e.g., how long would it take to build, launch, and get the payload to the object)?

Group 5: Decision to Act—What considerations will affect the decision to do something (e.g., is the risk level high enough to take action)?

Group 6: Communication to and from the Public—What is the public saying about the risk and actions that might be taken?

Group 7: Disaster Planning and Management—What preparations should be made to prepare for an impact?

As noted, the final group represented **World Leaders**, individuals whose role was to make decisions as to what actions should be taken given the information presented at each phase in the evolution of the threat. Decisions of the World Leaders guided the evolution of the threat, so the outcome was not known until after Friday's considerations and decisions.

Updates on the threat were provide in the afternoon of the first three days of the conference. The final updates and discussions were held on Friday, which was dedicated to completing the exercise.

A special procedure was established that allowed individuals not at the conference to register their names and organizations and to participate by providing their comments via the Internet. At least two groups in Europe remotely participated: the Swiss "Nationale Alarmzentrale," and the German "Weltraumlagezentrum" (Space Situational Awareness

[1] The International Asteroid Warning Network (IAWN) is a United Nations-endorsed organization. See discussion in notes for Session 1.

[2] The Space Mission Planning Advisory Group (SMPAG) is a United Nations-endorced organization. See discussion in notes for Session 1.

center). While both groups sent no direct communications during the conference, after the conference they reported that the exercise was well received and triggered a number of internal discussions on how to react to the scenario and the asteroid threat in general. It was recommended that we continue to

A quick summary of the observations and comments from the exercise groups as the scenario developed is included in Attachment E.

4.0 Recommendations

4.1 Strengthen international cooperation

Since the threat of asteroid impact is global and not man-made, planetary defense is a good area for international cooperation and coordination. The need for surveys and potential mitigation measures is not controversial. NEO data are usually openly available and shared worldwide. During PDC 2017, presentations were given by the International Asteroid Warning Network (IAWN) and the Space Mission Planning Advisory Group (SMPAG), two entities that were endorsed by the United Nations. The main purpose of both groups is the enhancement of the exchange of information and international coordination of NEO-related activities. In the field of NEO observations, paths for worldwide cooperation has have been established for using of suitable sensors in case a NEO requires special attention. Specific recommendations are that:

- International cooperation on NEOs and planetary defense should continue and should be enhanced.
- International awareness of existing networks and groups like IAWN and SMPAG should be fostered.
- Coordination among civil protection agencies and disaster response organizations should be increased, possibly by establishing a UN-endorsed group to collaborate with disaster response agencies on impact threats.
- NEO-related disasters should be added to discussion topics at international conferences of disaster response agencies.
- Nations should include NEO impact into their disaster planning and documentation.

4.2 Increase NEO surveys

At the time of PDC 2017, more than 16000 NEOs were known, and the detection rate now exceeds 1500 per year. With the arrival of Pan-STARRS-2, ESA´s wide angle fly-eye telescopes, the LSST and several other new telescopes, worldwide detection rate will go up. The total number of NEOs larger than 20 m (Chelyabinsk-sized and larger, smaller ones should normally do no major damage on impact) is estimated to be in the range of 10 to 20 million. Discovery of threatening asteroids coming from the direction of the sun (similar to Chelyabinsk) remains a challenge. Infrared (IR) telescopes provide much better information on an asteroid’s size than sensors utilizing reflected light for observations.

- Continued and systematic efforts to search for NEOs should continue and be augmented with dedicated space-based sensors.
- Space-based systems utilizing IR sensors for asteroid discovery should be stationed in locations where early discovery of objects approaching from sunward directions is possible.

4.3 Increase support for physical characterization assets

Good progress has been made on the physical characterization of NEOs. Radar observations of NEOs are now undertaken for all objects within range. In addition to very precise orbital information, radar data also provide the shape of asteroids, and several hundred images of asteroids are now available that show a surprising variety of characteristics and shapes. Observed objects include binaries and contact binaries and illustrate rotational shape effects and even one object with sharp edges. New statistical methods provide new information on metallic objects and the distribution of albedos. Physical characterization, particularly the size of an asteroid, is important for minimizing the overall uncertainty (and cost) associated with a deflection campaign.

- Given the importance of radar and infrared sensors to refining NEO characteristics, funding of the detection and characterization infrastructure should be increased.
- Research on how physical characteristics affect the efficiency of kinetic impact, nuclear explosive, and other deflection techniques should be emphasized.

4.4 Plan and perform NEO reconnaissance missions

A reconnaissance mission to a threatening NEO would provide valuable information for a deflection campaign. Such a mission, either a rendezvous or flyby mission, could be relatively small, cheap and quick to launch, particularly if significant pre-planning is put into place. It could provide essential new information on the physical properties of an object, and help refine estimates of impact probability and reduce deflection uncertainties and the overall time and resources required for deflection.

- Options and required technologies for reconnaissance missions should be studied in more detail.

4.5 Test and verify deflection technologies

The need for a NEO deflection demonstration mission has been emphasized in previous conferences. The SMPAG has issued a recommendation to perform a NEO deflection demonstration mission, and considerable progress has been made on technologies required for such a mission. Development of the AIDA mission with an impactor (DART) from NASA and an observer spacecraft (AIM) from ESA has been initiated, but full realization of the mission is uncertain because of funding issues.

- NEO deflection demonstration missions should be conducted to gain confidence that deflection techniques will work as predicted.

4.6 Pay more attention to comets

At present, most efforts are spent on mitigating the risk from asteroids. Recent research suggests that the population of comets is higher than predicted earlier. Comets are typically bigger and faster than asteroids, and any comet impact could be truly catastrophic and with global consequences. Comets from the Kuiper Belt or the Oort Cloud on a collision course with Earth will only be detected a few months to a couple of years before impact.

- Develop tools for accurate orbit predictions and impact monitoring of comets.
- Conduct research on mission designs and potential deflection methods for use against comets.

4.7 Associate probability of success with cost

A reliable deflection campaign will require early decisions to expend resources for flyby and deflection missions, even when impact probability is relatively low. Given that launch and space systems do not have 100% probability of success, multiple launches will be required to assure critical payloads are delivered and function correctly. Decision makers will ask questions on the necessity of spending large sums on planetary defense campaigns. The rationale and background materials should be developed before a serious threat is discovered.

- Make the linkage between deflection probability and the cost of success more prominent in educational materials.

4.8 Provide more information on deflection options

Members of the public and national leaders will need to have general knowledge of the types of deflection tools our planet has available in the event of an actual threat. The conference's tabletop exercise provided dramatic evidence that decisions to use nuclear explosions for deflection, even if they are a last resort, can be very difficult to make. Information should be developed and made available to the public on the possible necessity of and possible safety issues with using such high-energy explosives (or Atomic Deflection Devices, as suggested by exercise participants) for planetary defense.

4.9 Increase research on the long-term consequences of NEO impacts

We have direct evidence of the long-term consequences of impacts of very large objects, but the current focus in the community are consequences of small objects where "take the hit" might be an option. Decision makers will need information on the long-term consequence to the weather, economy, etc., should "take the hit" be proposed as an option for an actual impact threat.

- Need more discussion of the effects of material lofted into and above the atmosphere
- Need to see more modeling on what happens after the impact on a longer time scale

Attachment A. Sponsors & Supporters

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The 2017 IAA Planetary Defense Conference was also supported by the United Nations Office for Outer Space Affairs (www.unoosa.org), which is the permanent secretariat to the Committee on Peaceful Uses of Outer Space (COPUOS), secretariat for the Space Mission Planning Advisory Group (SMPAG), and works with the International Asteroid Warning Network (IAWN) on planetary defense issues.

Attachment B. Conference Organizers

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V Ashok	Indian Space Research Organization	
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Bruce Betts	The Planetary Society	
Mark B Boslough	Sandia National Laboratories	
Juan Cano	Deimos Space	
Ian Carnelli	European Space Agency	
Clark Chapman	Southwest Research Institute	
Paul Chodas	JPL	
Jean-Michel Contant	International Academy of Astronautics	
Richard Crowther	United Kingdom Space Agency	
Fabrice Dennemont	International Academy of Astronautics	
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Karel A. van der Hucht	International Astronomical Union	
Frans von der Dunk	University of Nebraska-Lincoln	
Bong Wie	Iowa State University	
Makoto Yoshikawa	JAXA	

Attachment C. Program

DAY 1		**Monday May 15**	
0800		**REGISTRATION**	
0850		**OPENING REMARKS: Conference Organizers**	
0900		**OPENING REMARKS: Hiroki Matsuo**, IAA Vice-President	
0910		**WELCOME**: **Hajime Funada**, Member, House of Representatives of Japan	
0920	IAA-PDC-17-00-01	**KEYNOTE: Saku Tsuneta**, Director of Institute of Space and Astronautical Science, Japan	
0940	IAA-PDC-17-00-02	**KEYNOTE: Johann-Dietrich Woerner**, Director General, European Space Agency	
1000		**BREAK**	
		SESSION 1: KEY INTERNATIONAL AND POLITICAL DEVELOPMENTS **120 minutes** **Session Organizers: Hajime Yano (Japan), Romana Kofler (UNOOSA)**	
1020	IAA-PDC-17-01-01	An Overview of Developments related to NEOs within the Framework of the United Nations & the Committee on the Peaceful of Outer Space	Romana Kofler
1030	IAA-PDC-17-01-02	The International Asteroid Warning Network: History, -Background, and Current Status	Timothy Spahr
1045	IAA-PDC-17-01-03	The Space Mission Planning Advisory Group	Gerhard Drolshagen
1100	IAA-PDC-17-01-04	SMPAG Working Group on Legal Issues in Planetary Defense	Line Drube
1115	IAA-PDC-17-01-05	Advancement of Planetary Defense in the United States	Lindley Johnson
1130	IAA-PDC-17-01-06	Activities in Russia On NEO: Progress in Instrumentation, Study of Consequences and Coordination	Boris Shustov
1145	IAA-PDC-17-01-07	The Near-Earth Object Segment of ESA's Space Situational Awareness Programme - Achievements and Outlook for Period 3	Detlef Koschny
1200	IAA-PDC-17-01-08	Planetary Defense Activity in Japan	Makoto Yoshikawa
1215		**LUNCH**	
		SESSION 2: ADVANCEMENTS AND PROGRESS IN NEO DISCOVERY **135 Minutes** **Session Organizers: Alan Harris (U.S.), Giovanni Valsecchi**	
1315	IAA-PDC-17-02-01	NEA Population and Current Survey Status	Alan Harris
1330	IAA-PDC-17-02-02	Linking the Isolated Tracklet Astrometry	Robert Weryk
1345	IAA-PDC-17-02-03	SCOUT: Short-Arc Orbit Analysis and Hazard Assessment for Newly Discovered Asteroids	Davide Farnocchia
1400	IAA-PDC-17-02-04	Improved NEO Astrometry with the GAIA CATALOG: Application to Apophis	David Tholen
1415	IAA-PDC-17-02-05	The PAN-STARRS Search for Near Earth Objects	Richard J. Wainscoat
1430	IAA-PDC-17-02-06	ATLAS	John Tonry
1445	IAA-PDC-17-03-02	Deep Ecliptic Patrol of the Southern Sky: Round-the-Clock Census and Survey of Near Earth Asteroids in the Southern Hemisphere	Hong-Kyu Moon

1500	IAA-PDC-17-02-08	Projected Near-Earth Object Discovery Performance of LSST	Steven Chesley
1515	IAA-PDC-17-02-09	Contributions to Observations of Near-Earth Objects by a Wide-Field CMOS Camera Tomo-e Gozen	Ryou Ohsawa
1530		BREAK	
1545		**INJECT & DISCUSSION: Press Release #1**	
1715		**Presentation of recommendations**	
1800		**ADJOURN DAY 1**	
		WELCOME RECEPTION (6 to 8 PM, accompanying persons invited)	

DAY 2		**Tuesday May 16**	
0850		**INTRODUCTORY REMARKS**	
		SESSION 3: NEO CHARACTERIZATION RESULTS **240 minutes** **Session Organizers: Line Drube, Alan Harris (DLR)**	
0900	IAA-PDC-17-03-01	The Italian contribution to the NEOShield-2 EU project: Results of the first year of activity	Simone Ieva
0915	IAA-PDC-17-02-07	Status of the Catalina Sky Survey for Near-Earth Objects	Eric Christensen
0930	IAA-PDC-17-03-03	Ground-based radar observations of potentially hazardous asteroids	Patrick Taylor
0945	IAA-PDC-17-03-04	Goldstone and Arecibo radar observations of (99942) Apophis in 2012-2013	Marina Brozovic
1000	IAA-PDC-17-03-05	Radar Observations of NEO by Quasar VLBI Network	Yuri Medvedev
1015	IAA-PDC-17-03-06	Arecibo Radar Characterization of 138971 (2001 CB21), a Flyby Target for the DART Spacecraft	Michael W. Busch
1030		**BREAK**	
1100	IAA-PDC-17-03-07	Physical characterization of NEA 2012 TC4	William Ryan
1115	IAA-PDC-17-03-08	Relevance of Thermal Inertia to Planetary Defense	Alan Harris
1130	IAA-PDC-17-03-09	Results of Hayabusa and Hayabusa 2	Makoto Yoshikawa
1145	IAA-PDC-17-03-10	Cohesive strength of 65803 Didymos, the target of the AIDA Mission	Yun Zhang
1200	IAA-PDC-17-03-11	Assessment of asteroid shapes produced after catastrophic disruption	Oliver Barnouin
1215	IAA-PDC-17-03-12	The ESA SSA-NEO System evolution	Ettore Perozzi
1230		**LUNCH**	
1330	IAA-PDC-17-03-13	New observations for (3200) Phaethon and analysis results	Xiaobin Wang
1345	IAA-PDC-17-03-14	Near Earth Asteroid Characterization for Threat Assessment	Jessie Dotson
1400	IAA-PDC-17-03-15	Size and orbital distribution of interplanetary dusts associated with near-earth asteroids by mu radar meteor head echo observation	Shinsuke Abe
1415		**BREAK**	

		SESSION 4: DEFLECTION AND DISRUPTION MODELS & TESTING 135 minutes Session Organizers: Brent Barbee, Patrick Michel	
1445	IAA-PDC-17-04-01	Integrated Blowoff and Breakup Calculations for Asteroid Deflection by Nuclear Ablation	Megan Bruck-Syal
1500	IAA-PDC-17-04-02	An Overview of the Los Alamos Project Supporting Planetary Defense Studies	Robert P. Weaver
1515	IAA-PDC-17-04-03	Characteristics of a High-Power Ion Beam Deflection System Necessary to Deflect the Hypothetical Asteroid 2017 PDC	John R. Brophy
1530	IAA-PDC-17-04-04	Asteroid De-Spin and Deflection Strategy using a Solar-Sail Spacecraft with Reflectivity Control Devices	Shota Kikushi
1545	IAA-PDC-17-04-05	New Multiple Kinetic-Energy Impactor Vehicle (MKIV) Mission Concept for Disrupting/Pulverizing Small Asteroids	Bong Wie
1600		**BREAK**	
1630		**INJECT & DISCUSSION: PRESS RELEASE #2**	
1730		**Presentation of recommendations**	
1800		**ADJOURN DAY 2**	
1800		**POSTER RECEPTION (6 to 8 PM)**	

DAY 3		**Wednesday May 17**	
0850		**INTRODUCTORY REMARKS**	
		Session 4: Continued	
0900	IAA-PDC-17-04-06	Impact Simulations in support of the Double Asteroid Redirection Test (DART) and the Asteroid Impact and Deflection Assessment (AIDA)	Angela M. Stickle
0915	IAA-PDC-17-04-07	Laboratory and Numerical Experiments of Impact Generated Waves in Agglomerated Asteroids	Gonzalo Tancredi
0930	IAA-PDC-17-04-08	Modeling Kinetic Impactors on a Rubble Pile Asteroid	J. Michael Owen
0945	IAA-PDC-17-04-09	Benchmarking Asteroid-Deflection Experiments	Tane P. Remington
1000		**BREAK**	
		SESSION 5: MISSION & CAMPAIGN DESIGNS (240 minutes) Session Organizers: Nahum Melamed, Marco Tantardini, Makoto Yoshikawa	
1030	IAA-PDC-17-05-17	Directed Energy for Planetary Defense	Philip M. Lubin
1043	IAA-PDC-17-05-01	Hayabusa2 – Sample Return and Kinetic Impact Mission to Near-Earth Asteroid Ryugu	Yuichi Tsuda
1056	IAA-PDC-17-05-02	Asteroid Impact And Deflection Assessment (AIDA): The Double Asteroid Redirection Test (DART) Mission Overview	Cheryl Reed
1109	IAA-PDC-17-05-03	Asteroid Impact and Deflection Assessment (AIDA): The Double Asteroid Redirection Test (DART) Mission Technical Update	Andrew F. Cheng

1122	IAA-PDC-17-05-04	Extension of the DART Mission to Kinetic Deflection	Brian L. Kantsiper
1135	IAA-PDC-17-05-05	Asteroid Impact Mission: Minimum System Design to Support Planetary Defense Demonstration	Ian Carnelli
1148	IAA-PDC-17-05-06	Asteroid Impact Mission: Performing Binary Asteroid Investigation and Supporting Planetary Defense	Patrick Michel
1201	IAA-PDC-17-05-08	Enhanced Gravity Tractor Derived from the Asteroid Redirect Mission for Deflecting Hypothetical Asteroid 2017PDC	Daniel D. Mazanek
1214	IAA-PDC-17-05-09	Asteroid Deflection Campaign Design for Scenarios with Decade-Long Warning Times	Anastassios Petropoulos
1227		**LUNCH**	
1330	IAA-PDC-17-05-10	Spacecraft Mission Design for the Mitigation of the 2017PDC Hypothetical Asteroid Threat	Brent W. Barbee
1343	IAA-PDC-17-05-11	NEOShield-2: Overview and Results So Far	Albert Falke
1356	IAA-PDC-17-05-12	NEOTωIST: A Relatively Inexpensive Kinetic Impactor Demonstration Mission Concept	Line Drube
1409	IAA-PDC-17-05-13	NEOTωIST – Design Study of a Kinetic Impactor Demonstration Mission Featuring NEO Spin Change and Observer Sub-Spacecraft	Killian Engel
1422	IAA-PDC-17-05-14	NEO Mitigation Mission Assurance	Curtis Iwata
1435	IAA-PDC-17-05-15	Concurrent Engineering Methodology for a Near Earth Object Impactor Mission	Nate Byerly
1448	IAA-PDC-17-05-16	Deflection of Fictitious Asteroid 2017PDC: Ion Beam vs. Kinetic Impactor	Claudio Bombardelli
1501	IAA-PDC-17-05-18	Parameter-Space Study of Kinetic-Impactor Mission Design	Alexandre Payez
1514	IAA-PDC-17-05-19	Soil to Sail – Asteroid Landers on Near-Term Sailcraft as an Evolution of the Gossamer Small Spacecraft Solar Sail Concept for In-Situ Characterization	Jan Thimo Grundmann
1527			2-min Posters
1540		**BREAK**	
1555		**INJECT & DISCUSSION: Press release #3**	
1725		**Presentations of recommendations**	
1800		**ADJOURN DAY 3**	

DAY 4		**Thursday May 18**	
0830		**INTRODUCTORY REMARKS**	
		SESSION 6: IMPACT CONSEQUENCES (135 minutes) **Session Organizers: Mark Boslough, David Morrison**	
0845	IAA-PDC-17-06-01	Comparison of Damage from Hydrocode Simulations of an Asteroid Airburst or Impact on Land, in Deep, or in Shallow Water	Darrel Robertson
0900	IAA-PDC-17-06-02	Ablation and Heating During Atmospheric Entry and its Effect on Airburst and Impact Risk	Eric C. Stern
0915	IAA-PDC-17-06-03	Modeling the Atmospheric Breakup of Varied Asteroid Structures: Inferences for the Chelyabinsk Meteor and Risk Assessment Applications	Lorien Wheeler
0930	IAA-PDC-17-06-04	Contribution of Asteroid Generated Tsunami to the Impact Hazard	David Morrison
0945	IAA-PDC-17-06-05	Airburst-Generated Tsunami by Various Coupling Mechanisms	Mark Boslough
1000	IAA-PDC-17-06-06	Three-Dimensional Simulations of Oblique Asteroid Impacts into Water	Galen R. Gisler
1015	IAA-PDC-17-06-07	Simulation of PDC2017 Asteroid Entry, Water Impact, Hazard and Consequences on Japan's East and West Coasts	Souheil Ezzedine
1030	IAA-PDC-17-06-08	Immediate Effects of Asteroid Impacts on the Human Population	Clemens Rumpf
1045	IAA-PDC-17-06-09	Ensemble Risk Assessment in Support of the 2016 NEO Science Definition Team	Donovan Mathias
1100		**BREAK**	
		SESSION 7: DISASTER RESPONSE (60 minutes) **Session Organizers: Lindley Johnson, Barbara Jennings**	
1130	IAA-PDC-17-07-01	Shelter-In-Place as an Effective Means of Civil Protection	Mark Boslough
1145	IAA-PDC-17-07-02	Community level Emergency Preparedness for Disasters – A model to supplement Remote Sensing	Venkataramaiah Jagannatha
1200	IAA-PDC-17-07-03	Impact threat exercises - Interfacing with emergency response agencies	Detlef Koschny
1215	IAA-PDC-17-07-04	The Third FEMA/NASA Near-Earth Object Impact Tabletop Exercise	Paul W. Chodas
1230		**LUNCH**	
		SESSION 8: IMPACT RISK ASSESSMENT & DECISION TO ACT (105 minutes) **Session Organizers: Victoria Friedensen, Gerhard Drolshagen**	
1330	IAA-PDC-17-08-01	The Politics and Process of Planetary Defense	Avishai Melamed
1345	IAA-PDC-17-08-02	NEO Impact Mitigation Decision Steps and Triggers	Nahum Melamed
1400	IAA-PDC-17-08-03	Short Term Threat Response Requires Long Term Preparation	Joseph A. Nuth
1415	IAA-PDC-17-08-04	The Distribution of Required Deflection Impulses as a Function of Time Before Impact for Earth Impacting Asteroids	Edward Lu
1430	IAA-PDC-17-08-05	Impact Corridor Visualizer Tool for ESA	Fabrizio Bernardi
1445	IAA-PDC-17-08-06	Deciding to Act: Summary of NASA's Planetary Defense Coordination Office Activities to Define Thresholds for Government Decisions to Aid in Emergency Preparedness and Response	Victoria Friedensen

1500	IAA-PDC-17-08-07	Measuring the Performance of Impact Monitoring	Andrea Milani
1515	IAA-PDC-17-08-08	Strengthening Global Collaboration and REDUCING the Risk of Defection of a Cooperating Nation in Planetary Defense	Nikola Schmidt
1530		**BREAK**	
		SESSION 9: PUBLIC EDUCATION & COMMUNICATION (60 minutes) **Session Organizers: Alex Karl, Ian Carnelli**	
1600	IAA-PDC-17-09-01	Considering All Stakeholders: Communicating with Various 'Publics' About the Asteroid Hazard and an Impact Event	Melissa Wiehenstroer
1615	IAA-PDC-17-09-02	Application of Machine Learning for Planetary Defense – Three Case Studies	James Parr
1630	IAA-PDC-17-09-03	Public Communication Using 5 Steps to Prevent Asteroid Impact	Bruce Betts
1645	IAA-PDC-17-09-04	A Knowledge Framework for Smart Discovery of Planetary Defense Resources	Myra Bambacus
1700		**INJECT: Press Release #4**	
1715		**ADJOURN DAY 4**	
		CONFERENCE BANQUET	

DAY 5		**Friday May 19**
0850		**INTRODUCTORY REMARKS**
		SESSION 10: THREAT RESPONSE EXERCISE
0900		**INJECT & DISCUSSION (Press Release #4)**
1000		**Presentations from Focus Group**
1030		**BREAK**
1100		**INJECT & DISCUSSION: Press Release #5**
1120		**Focus Group Discussion**
1230		**LUNCH**
1345		**FEEDBACK FROM FOCUS GROUPS**
1430		**DISCUSSION: LESSONS LEARNED AND RECOMMENDATIONS**
1530		**CONFERENCE ENDS**

	POSTERS	
	Posters SESSION 2: ADVANCEMENTS AND PROGRESS IN NEO DISCOVERY **Session Organizers: Alan Harris (U.S.), Giovanni Valsecchi**	
IAA-PDC-17-02-P01	Observational Activities at ESA's SSA-NEO Coordination Centre	Marco Micheli
IAA-PDC-17-02-P02	System of Observation of Day-time Asteroids (SODA)	Boris Shustov
IAA-PDC-17-02-P03	INASAN NEO finder (INF) project	Sergey Naroenkov
IAA-PDC-17-02-P04	TLS Participation in MPC's NEO Confirmation Program	Bringfried Stecklum
IAA-PDC-17-02-P05	Optical Wide-field patroL Network (OWL-Net): Characterization of Earth Close Approaching PHAs	Myung-Jin Kim
IAA-PDC-17-02-P06	Klenot Project in the Framework of ESA-SSA NEO Programme	Jana Ticha
IAA-PDC-17-02-P07	NEO Mineral Sources Usage for Electrical Power Production	Ankita Vashishtha
IAA-PDC-17-02-P08	Prioritisation of Near-Earth Asteroid Follow-Up Observations	Dora Fohring
IAA-PDC-17-02-P09	Organization and Promotion of Asia-Pacific Asteroid Observation Network (APAON)	Shin-Ishiro Okumura
IAA-PDC-17-02-P10	High-Precision Follow-Up Observations of Near-Earth Objects	Yudish Ramanjooloo
IAA-PDC-17-02-P11	Modeling the Joined Performance of the PAN-STARRS1 and PAN-STARRS2 Telescopes	Eva Lilly Schunova
IAA-PDC-17-02-P13	The PAN-STARRS2 System and the PS1 Referecence Catalog: Implications for NEO Discovery and Characterization	Kenneth Chambers
IAA-PDC-17-02-P14	Current Activities and the Future Plan of BISEI Spaceguard Center	Tomoko Fujiwara
IAA-PDC-17-02-P15	Exploiting GAIA Asteroid Alerts	Daniel Hestroffer
IAA-PDC-17-02-P16	Shoemaker NEO Grants: Upgrading NEO Observational Capability	Bruce Betts
IAA-PDC-17-02-P17	Effects of the First Gaia Data Release on Orbit Determination and Impact Monitoring of Near-Earth Asteroids	Federica Spoto
IAA-PDC-17-02-P18	Using the GAIA Astrometric Grid to Refine NEO Orbits	Martin Elvis
IAA-PDC-17-02-P19	Towards a Network of Amateur Astronomers Relying on an Innovative Telescope	Jean-Yves Prado
	Posters SESSION 3: NEO CHARACTERIZATION RESULTS **Session Organizers: Line Drube, Alan Harris (DLR)**	
IAA-PDC-17-03-P02	NEOSHIELD-2 European Project: Compositional Characterization of Small NE0s	Maria Antonietta Barucci
IAA-PDC-17-03-P03	Analysis of Natural Landing Trajectories for Passive Landers in Binary Asteroids: A Case Study for (65803) 1996 GT DIDYMOS	Onur Celik
IAA-PDC-17-03-P04	A Possible Signature of Split Event on (3200) Phaethon	Daisuke Kinoshita
IAA-PDC-17-03-P05	Meteoroid Bulk Density and Ceplecha Types	Rhiannon Blaauw
IAA-PDC-17-03-P06	Possible Collisions of Asteroids with the Earth	Maria A. Borukha
IAA-PDC-17-03-P07	Observation of Near-Earth Object (1566) Icarus and the Split Candidate 2007 MK6	Seitaro Urakawa
IAA-PDC-17-03-P08	New Observations for (3200) Phaethon and Analysis Results	Xiaobin Wang
IAA-PDC-17-03-P09	DynAstVO: The Europlanet Orbital Near-Earth Asteroid Database	Josselin Desmars
IAA-PDC-17-03-P10	Distant Composition Detection: Determining NEO Makeup Remotely	Jonathan Madajian

IAA-PDC-17-03-P11	Observation of Possible Breakup Near-Earth Asteroids	Ryou Umehara
IAA-PDC-17-03-P12	Modified Dust Trail Model for Forecasting Earth Impactors	Masashi Imamura
IAA-PDC-17-03-P13	Asteroid Shapes and Rotational Properties Based on Lightcurve Analysis	Maria Gritsevich
IAA-PDC-17-03-P15	The Effects of Non-Gravitational Perturbations on Potentially Hazardous Objects' Trajectories and Earth Approach Parameters	Adam H. Greenberg
IAA-PDC-17-03-P16	Ground-Based Radar Observations of Human Space Flight Accessible Targets	Anne K. Virkki
IAA-PDC-17-03-P17	Integration and Validation of NEO systems within the ESA SSA Preparatory Programme	Arturo Vinue Visus
IAA-PDC-17-03-P18	In-Site Determination of Asteroid Thermal Inertia using the MASCOT Radiometer	Jan Thimo Grundmann
IAA-PDC-17-03-P19	Directed Energy Deflection Laboratory Measurements of Common Space Based Targets	Travis Brashears
IAA-PDC-17-03-P20	A Simple Method for Probing the Strength of an Asteroid	Daniel J. Scheeres
IAA-PDC-17-03-P21	Uncertainty Propagation in the N-body Problem using Dromo Elements	Javier Hernando-Ayuso
IAA-PDC-17-03-P22	CROWN: Constellation of Heterogeneous Wide-Field NEO Surveyors	Zhuoxi Huo
	Posters SESSION 4: DEFLECTION AND DISRUPTION MODELS & TESTING **Session Organizers: Brent Barbee, Patrick Michel**	
IAA-PDC-17-04-P01	Measuring Ejecta Characteristics and Momentum Transfer in Experimental Simulation of Kinetic Impact	Martin Schimmerohn
IAA-PDC-17-04-P02	Hypervelocity Spacecraft Guidance Control Analysis to Intercept Small Diameter Objects	Melak Zebenay
IAA-PDC-17-04-P03	Asteroid Deflection via Neutral Beam Emitting Spacecraft	Anthony J. DeCicco
IAA-PDC-17-04-P04	Magnetic Tractor	William Brown
IAA-PDC-17-04-P05	Earth and Moon Based Directed Energy Systems for Planetary Defense	Nikola Schmidt
IAA-PDC-17-04-P06	The Projectile Shape and Material Effect on the Momentum Transfer for Asteroid Orbit Change	Daisuke Yokoo
IAA-PDC-17-04-P07	Systematic Planning Method of Disruption of Rubble Pile Asteroids by Natural Vibration Mode Analysis	Toshihiro Chujo
IAA-PDC-17-04-P08	Calculating the Momentum Enhancement Factor for Simulations of Kinetic-Impacts in Asteroid Deflection	Tamra Heberling
IAA-PDC-17-04-P09	The Directed Energy Comet Deflection Process	Qicheng Zhang
IAA-PDC-17-04-P10	Modeling Potential Outcomes of the Dart Impact Using CTH	Emma S. G. Rainey
IAA-PDC-17-04-P11	The Deflector Selector: A Machine Learning Framework for Prioritizing Deflection Technology Development	Adam H. Greenberg

	Posters SESSION 5: MISSION & CAMPAIGN DESIGNS **Session Organizers: Nahum Melamed, Marco Tantardini, Makoto Yoshikawa**	
IAA-PDC-17-05-P01	Studies of Short Time Response Options for Potentially Hazardous Objects: Current and Forthcoming Results	Brent W. Barbee
IAA-PDC-17-05-P03	Near Earth Asteroids Deflection Mission Using Electric Solar Wind Sail Kinetic Impactor	Kohei Yamaguchi
IAA-PDC-17-05-P04	The DART Terminal Guidance Phase	Brian L. Kantsiper
IAA-PDC-17-05-P05	THE HIGH-FIDELITY ASTEROID DEFLECTION EVALUATION SOFTWARE (HADES): ASSESSING THE IMPACT OF ENVIRONMENTAL AND SYSTEM UNCERTAINTIES ON THE ASTEROID'S THREAT MITIGATION OF 2017 PDC THROUGH SLOW PUSH METHODS	Massimo Vetrisano
IAA-PDC-17-05-P06	Proximity Operations by the Asteroid Impact and Deflection Assessment (AIDA) mission	Olivier S. Barnouin
IAA-PDC-17-05-P07	The Third FEMA/NASA Near-Earth Object Impact Tabletop Exercise	Paul W. Chodas
IAA-PDC-17-05-P08	Asteroid Impact Mission: Minimum System Design to Support Planetary Defense Demonstration	Ian Carnelli
IAA-PDC-17-05-P09	Kinetic Impactor GNC System Design and End-to-End Validation	Marc Chapuy
IAA-PDC-17-05-P10	NEOSHIELD-2: Overview and Results So Far	Albert Falke
IAA-PDC-17-05-P11	Moon-Based Planetary Defense Operations	Thomas Miyano
IAA-PDC-17-05-P12	Design of Trajectories for Asteroid Impact in the Earth-Moon System Using the Pseudostate Theory	Hongwei Yang
IAA-PDC-17-05-P13	New Smoothing Optimization Technique for Continuous Low-Thrust Mission to Capture the Outer Planet	Mohammadreza Saghamanesh
IAA-PDC-17-05-P14	MASCOT2, a Lander to Characterize the Target of an Asteroid Kinetic Impactor Deflection Test Mission	Jens Biele
IAA-PDC-17-05-P15	Orbital Dependencies of Ejecta from the Dart Impact on the Secondary of 65803 DIDYMOS	Yu Yang
IAA-PDC-17-05-P16	Keyhole Maps for Post Deflection Impact Risk Assessment	Siegfried Eggl
IAA-PDC-17-05-P17	NEOT!IST: Determining the Momentum Enhancement	Siegfried Eggl
IAA-PDC-17-05-P18	Radar Package for a Direct Observation the Asteroid's Structure from Deep Interior to Regolith	Alain Herique
IAA-PDC-17-05-P19	Trajectory Design for Observing NEA with Different Mineralogies	Zhemin Chi
IAA-PDC-17-05-P20	NEOSHIELD-2: Optical Navigation for Near-Inertial Hovering at Close Proximity of Very Small Asteroids	Simon Delchambre
IAA-PDC-17-05-P21	Nano-Landers for the Geophysical Exploration of Near Earth Objects	Ozgur Karatekin
IAA-PDC-17-05-P22	Responsive Development of Optimized Small Spacecraft through Balanced Ad-hoc and Strategic Re-Use with Model-Based System Engineering for Planetary Defence, Science and Emerging Applications	Jan Thimo Grundmann
IAA-PDC-17-05-P23	Qualification Tested Technologies of the Gossamer-1 Solar Sail Deployment Demonstrator for Planetary Defence and Small Solar System Body Science and Applications	Jan Thimo Grundmann

IAA-PDC-17-05-P24	GoSolAr: Large-scale Deployable Photovoltaics for Planetary Defence and Small Solar System Body Applications using Gossamer Deployment Technologies	Jan Thimo Grundmann
IAA-PDC-17-05-P25	Experimental Studies of Space Weathering Effects on Thin Membranes in Planetary Defence Applications and Asteroid Surface Materials by a Complex Irradiation Facility	Jan Thimo Grundmann
IAA-PDC-17-05-P26	ASPECT (Asteroid Spectral Imaging Mission)	Tomas Kohout
IAA-PDC-17-05-P27	OpGrav - Implications for Planetary Defense	Ryan H. Mitch
IAA-PDC-17-05-P28	Laser Retroreflectors as NEO Tracking and Geodetic Targets	Simone DellAgnello
IAA-PDC-17-05-P31	NEOSHIELD-2: Technology Readiness Level Assessment for Visual Based Guidance, Navigation and Control Algorithms Applicable to Small Solar System Body Spacecraft Missions	Tobias Ziegler
IAA-PDC-17-05-P32	SCORPION: A Low-Cost Multi-Phase and Multi-Objective Asteroid Mission	Mariella Graziano
IAA-PDC-17-05-P33	AIM Autonomous GNC for Close Proximity Operations	Andrea Pellacani
IAA-PDC-17-05-P34	Numerical Modeling of Interactions of a Lander with Low-Gravity Asteroid Regolith Surfaces	Florian Thuillet
IAA-PDC-17-05-P35	Observations of Lunar Impact Flashes and NEOs from Earth-Moon L2 HALO Orbit	Ryota Fuse
IAA-PDC-17-05-P36	Integrated Air and Missile Defence under Spatial Grasp Technology	Peter Sapaty
IAA-PDC-17-05-P37	Last-Minute Semi-Analytical Asteroid Deflection by Nuclear Explosion	Javier Hernando-Ayuso
IAA-PDC-17-05-P38	An Exploration of the Technical Challenges of Deploying a Nuclear Explosive Device Against a Potentially Hazardous Object	Catherine S. Plesko
	Posters SESSION 6: IMPACT CONSEQUENCES **Session Organizers: Mark Boslough, David Morrison**	
IAA-PDC-17-06-P01	Kinetic Damage from Meteorites	William J. Cooke
IAA-PDC-17-06-P02	Sea-Water Tsunami Hazard and Risk Against Life-Planet Earth by Asteroid Impact on Ocean Water	Yasunori Miura
IAA-PDC-17-06-P03	Atmospheric Trajectory and Recovery of the Osceola Meteorite (January 24, 2016)	Tomas Kohout
IAA-PDC-17-06-P04	HAYABUSA2 Impact Experiment: Fate of the Asteroid Ryugu Ejecta	Stefania Soldini
IAA-PDC-17-06-P05	In Pursuit of Improving Airburst and Ground Damage Predictions: Recent Advances in Multi-Body Aerodynamic Testing and Computational Modeling Validation	Ethiraj Venkatapathy
IAA-PDC-17-06-P06	Simulation-Based Height of Burst Map for Asteroid Airburst Damage Prediction	Michael J. Aftosmis
IAA-PDC-17-06-P07	Best-Case Appraisals of Impact Damage to Planet Earth by Natural Objects Enabled by Rendezvous Missions	James O. Arnold
IAA-PDC-17-06-P08	A Concept of Hazardous NEO Detection and Impact Warning System	Toshinori Ikenaga

	Posters SESSION 7: DISASTER RESPONSE **Session Organizers: Mariella Graziano, L.A. Lewis**	
IAA-PDC-17-07-P01	The U.S. Geological Survey's Capabilities Related to Planetary Defense	Laszlo Kestay
IAA-PDC-17-07-P02	Integrated International Strategy for Mitigating Effects of Minor Asteroid Impacts Through a Collaborative and Effective Early Warning and Disaster Response System	Mina Takla
IAA-PDC-17-07-P03	Southampton Asteroid Impact Hazard Scale	Clemens M. Rumpf
	Posters SESSION 8: IMPACT RISK ASSESSMENT & DECISION TO ACT **Session Organizers: Victoria Friedensen, Gerhard Drolshagen**	
IAA-PDC-17-08-P01	Big Data Used as a Tool for International Cooperation in International Policies Against NEO	Jairo Becerra
IAA-PDC-17-08-P02	Potential US Department of Defense Organizational Responses to 2017 PDC	Brent Ziarnick
	Posters SESSION 9: PUBLIC EDUCATION & COMMUNICATION **Session Organizers: Alex Karl, Ian Carnelli**	
IAA-PDC-17-09-P01	Findings and Recommendations of the The READI Project: The 3rd International Space University Planetary Defense Project 2015	Nikola Schmidt
IAA-PDC-17-09-P02	Klet Observatory : 25 Years of Experience in NEO Public Education and Communication	Jana Ticha
IAA-PDC-17-09-P03	Meteor Observations as Big Data Citizen Science	Dejan Vinkovic

Attachment D. Attendees

Shinsuke Abe	Japan	Line Drube	Denmark
Paul Abell	USA	Siegfried Eggl	Austria
Michael J. Aftosmis	USA	Joshua Eggleston	USA
William Ailor	USA	Kilian Engel	Germany
Yasuhiro Akahoshi	Japan	Souheil Ezzedine	USA
James O. Arnold	USA	Laura Faggioli	Italy
Jacques Arnould	France	Albert Falke	Germany
Myra J.Bambacus	USA	Davide Farnocchia	Italy
Brent W.Barbee	USA	Kelly Fast	USA
Olivier S.Barnouin	USA	William Fogleman	USA
Jim Bell	USA	Dora Fohring	Hungary
Fabrizio Bernardi	Italy	Victoria P Friedensen	USA
Bruce Betts	USA	Tomoko Fujiwara	Japan
Jens Biele	Germany	Kazuhiro Funabashi	Japan
Rhiannon C. Blaauw	USA	Ryota Fuse	Japan
Ralf Boden	Germany	Galen R. Gisler	USA
Bryce Bolin	USA	Adam H. Greenberg	USA
Claudio Bombardelli	Italy	Jan Thimo Grundmann	Germany
Maria Borukha	Russian	Alissa Haddaji	France
Mark Boslough	USA	Alan Harris	UK
Kristi Bradford	USA	Allan Harris	USA
Travis Brashears	USA	Alain Herique	France
Nicole Bressaw		Daniel Hestroffer	France
John R. Brophy	USA	Brandon Hing	USA
William Brown	USA	Akira Hirota	Japan
Marina Brozovic	USA	Jeong Yoo Hong	South Korea
Megan Bruck Syal	USA	Hiroki Horanai	Japan
Michael W Busch	USA	Yasushi Horikawa	Japan
Ian Carnelli	Italy	Simone Ieva	Italy
Marco Castronuovo	Italy	Toshinori Ikenaga	Japan
Marta Ceccaroni	Italy	Masashi Imamura	Japan
Onur Celik	Turkey	Curtis Iwata	USA
Kenneth C. Chambers	USA	Becerra Jairo	Colombia
Clark Chapman	USA	Hernando-Ayuso Javier	Spain
Marc Chapuy	France	Barbara Jennings	USA
Andrew Cheng	USA	Jung Hyun Jo	South Korea
Steven Chesley	USA	Lindley Johnson	USA
Zhemin Chi	China	Abraham Kaligambe	Japan
Sungki Cho	South Korea	Brian L. Kantsiper	USA
Paul Chodas	USA	Ozgur Karatekin	Belgium
Eric J. Christensen	USA	Goutham Karthikeyan	Japan
Toshihiro Chujo	Japan	Kanpatom Kasonsuwan	Thailand
William J. Cooke	USA	Ryo Kato	Japan
Yokoo Daisuke	Japan	Michael Kelley	USA
Anthony J. DeCicco	USA	Laszlo Kestay	USA
Danielle DeLatte	Japan	Greenaugh Kevin	USA
Simon Delchambre	Belgium	Shota Kikuchi	Japan
Jessie Dotson	USA	MyungJin Kim	South Korea
Gerhard Drolshagen	Germany	Thagoon Kirdkao	Thailand

Romana Kofler	Slovenia
Tomas Kohout	Czech Republic
Detlef Koschny	Germany
Kenichi Kumagai	Japan
Rob Landis	USA
Chatchai Leaosrisuk	
Eva Lilly	Slovak Republic
Edward Lu	USA
Philip M. Lubin	USA
Jonathan Madajian	USA
Franck Marchis	France
Peter Marquez	USA
Donovan Mathias	USA
Daniel D. Mazanek	USA
Yuri Medvedev	Russia
Avishai Melamed	USA
Nahum Melamed	USA
Patrick Michel	France
Marco Micheli	Italy
Andrea Milani Comparetti	Italy
Paul Miller	USA
Thomas Miyano	USA
Joachim Moeyens	Belgium
Hong-Kyu Moon	South Korea
David Morrison	USA
Raffaele Mugnuolo	Italy
Atsushi Nakajima	Japan
Soichi Noguchi	Japan
Joseph A. Nuth	USA
Ryou Ohsawa	Japan
Shinichiro Okumura	Japan
Mike Owen	USA
Alexandre Payez	Belgium
Ettore Perozzi	Italy
Anastassios Petropoulos	USA
Catherine S. Plesko	USA
Jean-Yves Prado	France
Budhaditya Pyne	Japan
Emma S.G. Rainey	USA
Yudish Ramanjooloo	UK
Aaron Reaves	USA
Cheryl Reed	USA
David Reeves	USA
Tané Remington	USA
James Reuter	USA
Matt Richardson	Japan
Andy Rivkin	USA
Darrel K. Robertson	USA
Josh Rodenbaugh	USA
Clemens Rumpf	Germany
William H. Ryan	USA
Eileen Ryan	USA
Park Ryan	USA
Ryo Sakagami	Japan
Diane Salim	Japan
Kyosuke Sawai	Japan
Daniel J. Scheeres	USA
Martin Schimmerohn	Germany
Nikola Schmidt	Czech Republic
Boris Shustov	Russia
Stefania Soldini	Italy
Timothy Spahr	USA
Bringfried Stecklum	Germany
Eric C. Stern	USA
Angela M. Stickle	USA
Yohei Sugimoto	Japan
Gonzalo Tancredi	Uruguay
Marco Tantardini	Italy
Patrick A. Taylor	USA
David J. Tholen	USA
Florian Thuillet	France
Jana Ticha	Czech Republic
Milos Tichy	Czech Republic
John Tonry	USA
Yuichi Tsuda	Japan
Stephan Ulamec	Austrian
Ryou Umehara	Japan
Seitaro Urakawa	Japan
Anne K. Virkki	Finland
Richard J. Wainscoat	USA
Xiaobin Wang	Chinese
Robert Weaver	USA
Robert Weryk	Canada
Lorien Wheeler	USA
Earl White	USA
Bong Wie	USA
Sheene Winder	USA
Kohei Yamaguchi	Japan
Koshiro Yamaguchi	Japan
Chaowei Yang	USA
Liu Yisi	China
Makoto Yoshikawa	Japan
Qicheng Zhang	USA
Yun Zhang	China

Attachment E. Threat Exercise

PDC 2017 Asteroid Threat Response Exercise

Threat Development

The asteroid threat response exercise for the 2017 IAA Planetary Defense Conference was developed by the individuals below:

William Ailor, The Aerospace Corporation, Exercise Coordinator
Brent Barbee, NASA Goddard Spaceflight Center
Mark Boslough, Sandia National Laboratories
Paul Chodas, NASA Jet Propulsion Laboratory
Barbara Jennings, Sandia National Laboratories
Nahum Melamed, The Aerospace Corporation

It should be noted that Dr. Paul Chodas of JPL was the "Threat Master" and developed details of the threat for the first and subsequent press releases. Dr. Chodas also spent evenings of each conference day incorporating the decisions made by the World Leader team into the threat's evolution and press release for the following day.

Exercise Process

At the conference, attendees were invited to join one of eight focus groups that would consider information on the threat and make recommendations and decisions about what actions should be taken as the threat evolved. The groups were:

Group 1: International Asteroid Warning Network (IAWN)[1]-- What is known about the threatening object? What's its size, mass, shape, etc.?

Group 2: Impact Effects—What would happen were the object to enter Earth's atmosphere and impact? How big would the area affected be?

Group 3: Deflection and Disruption—What techniques are available and suitable to deflect or disrupt the threatening object away from Earth or move it to a different impact location should either be necessary?

Group 4: Space Mission Planning Advisory Group (SMPAG)[1]—What would a mission or campaign to send one or more deflection/disruption payloads to the threatening object look like (e.g., how long would it take to build, launch, and get the payload to the object)?

Group 5: Decision to Act—What considerations will affect the decision to do something (e.g., is the risk level high enough to take action)?

Group 6: Communications to and from the Public—What is the public saying about the risk and actions that might be taken?

Group 7: Disaster Planning and Management—What preparations should be made to prepare for an impact?

Group 8: World Leaders—Receive recommendations from Groups 1 through 7 and make decisions.

[1] The International Asteroid Warning Network (IAWN) and Space Mission Planning Advisory Group (SMPAG) are United Nations-endorsed organizations. See discussion in notes for Session 1.

In addition to the conference attendees, individuals not at the conference were invited to participate by reading the press releases, viewing videos of each day's presentations by the focus groups and the discussion among the World Leaders, and sending short text messages for consideration in the next day's discussion. External participants could target their suggestions to one of the focus groups, and comments were delivered to each group during its discussion.

Threat Exercise

The asteroid threat response exercise for the 2017 IAA Planetary Defense Conference began with publication of the first press release, Attachment D-1, before the conference began. That release and related material was briefed to all conference attendees at the end of the first day. Each attendee then selected and joined an exercise group, where the threat information was considered. After discussion, a representative of each group presented recommended actions to the World Leaders. World Leaders discussed the recommendations and authorized actions to be taken (e.g., launch of an observation mission). The exercise development team used this information to generate a new press release, which was the starting point for exercise group discussions the next day. This process continued for the second and third day of the conference and was concluded on the last day.

Early publication of the first press release enabled individuals not in attendance to comment before the conference started. Subsequent releases, generally before midnight Japan time, enabled these individuals to analyze the threat and submit their thoughts to the exercise groups for their consideration at the next opportunity.

Press Releases and Decisions

First Press Release

EXERCISE ***EXERCISE*** ***EXERCISE***

NOT A REAL-WORLD EVENT *This is part of a hypothetical asteroid threat exercise conducted at the 2017 IAA Planetary Defense Conference*

DAY 1

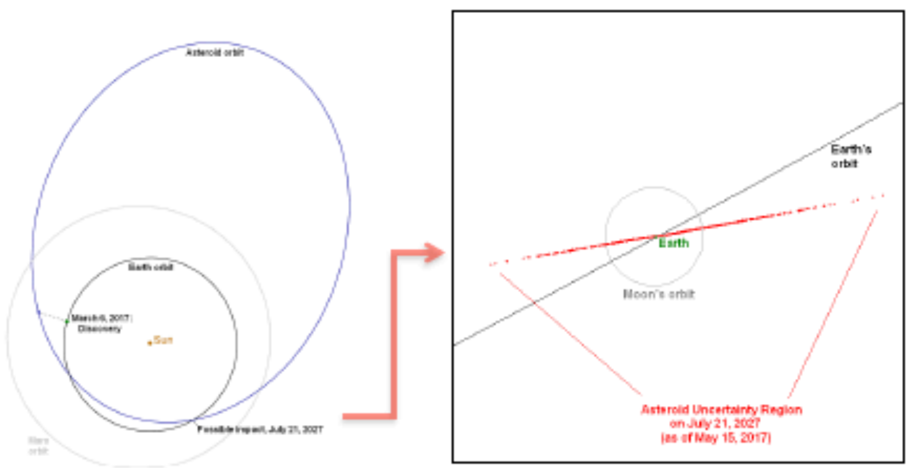
PRESS RELEASE: MAY 15, 2017

NEWLY DISCOVERED ASTEROID POSES SMALL THREAT OF EARTH IMPACT

A recently discovered near-Earth asteroid could pass very close to the Earth 10 years from now, on July 21, 2027, and there is a small chance that it could impact our planet. The asteroid, designated 2017 PDC, was discovered two months ago, on March 6, 2017, and it has been tracked extensively since then by observatories around the world. The observations indicate that the likelihood of impact is only about 1%, or 1 chance in 100, according to the International Asteroid Warning Network (IAWN), a worldwide collaborative network of agencies and institutions that detect, track and characterize potentially hazardous asteroids.

2017 PDC's encounter should not be a cause for public concern, since an actual collision is very unlikely: chances are 99 out of 100 that the asteroid will safely pass by our planet. As the asteroid is tracked by astronomers through the rest of 2017, its orbit will become better refined, and in all likelihood the possibility that it could impact will be eliminated.

The brightness of 2017 PDC suggests that it is roughly 100 to 250 meters (330 to 800 feet) in size, but it is too distant at this time for astronomers to make a more accurate estimate. The asteroid approached to about 0.13 au (19 million kilometers or 12 million miles) of Earth on April 27, but it is now receding from the Earth and will not approach our planet again until the encounter in 2027. The image below on the left shows the orbits of 2017 PDC and the Earth, along with their positions when the asteroid was discovered. The image on the right shows a zoomed-in view of the intersection point of the two orbits, along with the current uncertainty in the asteroid's predicted position at the time when the Earth crosses the asteroid's orbit in 2027; the Moon's orbit is shown for scale.



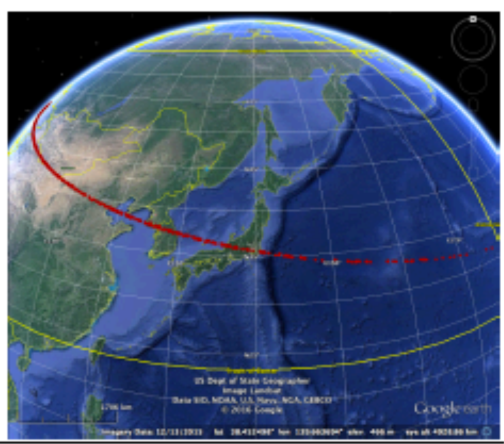
EXERCISE ***EXERCISE*** ***EXERCISE***

The current best estimate for the actual close approach distance in 2027 is about 120,000 km (77,000 miles).

Asteroid 2017 PDC has now reached a rating of 4 (Yellow) on the 0-to-10 Torino Scale, indicating that it merits special attention by astronomers. Only one other asteroid has ever been rated level 4 on the Torino Scale: (99942) Apophis reached that level in late 2004 before additional observations collected from sky-image archives eliminated the possibility of impact in 2029. IAWN astronomers are now actively searching archives for similar serendipitous pre-discovery images of 2017 PDC, but none have been found to date. The asteroid has not approached close to Earth for the last 20 years, during the time that extensive and systematic asteroid searches have been in operation.

IAWN[1], established with the endorsement of the United Nations in 2013, links together institutions that discover, monitor, and characterize potentially hazardous Near-Earth Objects (NEOs). In addition to observatories around the world, IAWN members include NASA's Planetary Defense Coordination Office (PDCO)[2], the Minor Planet Center (MPC)[3], JPL's Center for NEO Studies (CNEOS)[4], and the European Space Agency's NEO Coordination Centre (NEOCC) with its NEO Dynamics Site (NEODyS)[5]. CNEOS and NEODyS specialize in high precision orbit calculation for NEOs and computation of impact probabilities.

The IAWN partners have published details on the parts of the Earth that might be directly impacted in the unlikely event asteroid 2017 PDC actually collides with Earth. The images below depict the corridor of possible impact locations, traced by red dots that begin in the northern Pacific Ocean, pass through Japan, China, Kazakhstan, Russia, northern Europe, and the British Isles, extending all the way to the north Atlantic Ocean.



For more information, visit: http://neo.jpl.nasa.gov/pdc17. IAWN will publish weekly updates of the impact probability as this asteroid is tracked throughout 2017.

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1 http://www.iawn.net/
2 http://www.nasa.gov/planetarydefense
3 http://neo.jpl.nasa.gov
4 http://minorplanetcenter.net
5 http://newton.dm.inipi/neodys/

Recommendations

After hearing a presentation of the details on the threat described by the press release, groups met to develop and provide comments and recommendations for the leadership group. This process was followed for all subsequent releases. Comments for Press Release #1 are below.

International Asteroid Warning Network (IAWN)

- The taxonomy of this object (therefore, approximate density) is likely known if routine monitoring programs will have already yielded a spectral classification and a good light curve
- Hubble Space Telescope and 8-10 m class facilities on the ground should be used next year, when the object will reach magnitude 27, to get additional astrometric follow-up
- Plan to use JWST, which should be available by the end of 2018, for astrometric observations
- Check WISE data to see if the object has been seen during the current apparition, when it crossed 90° elongation, to possibly estimate the diameter and albedo (which may also solve any ambiguities of spectral class)
- Explore the possibility that ground-based NIR facilities may see thermal signatures slightly above 2 microns, which would allow for a determination of the diameter
- Explore whether Gaia can provide high-precision astrometry on this object at V~20.5 (peak for the current apparition). This is too faint for the routine mode of operation of Gaia, but it may be within reach if the spacecraft is used to its limiting magnitude.

Impact Effects Working Group

- Wide range from 0 to 29 million people could be affected
- 1 in 10 chance for more than 10 million people affected if it impacts
- Better information on possible impact location is needed

Deflection and Disruption Working Group

- Information is needed on mass, orbit, rotation rate and subsurface structure
- Begin the development of a slow push mechanism (e.g., gravity tractor)
- Carry a small nuclear device and use it if necessary
- If kinetic devices can be used, then a fleet of them would be necessary

Space Mission Planning Advisory Group (SMPAG)

- Kick off half a dozen phase A studies (flyby, reconnaissance, kinetic impactor, etc.), which will also put teams in place
- Prepare for the fast flyby mission with objectives to get shape and diameter and to determine if the impact probability is 0 or 100%
- Support deflection mission launches in 2022-2023
- Enact policies for using the nuclear deflection option in advance
- Track flight spares and off-the-shelf instruments (communication equipment, high-quality imaging camera, and a spectrometer)
- Look for options for the launch vehicle

Decision to Act Working Group

- At 1% level, it is not recommended to start building or launching
- Request all possible observations using existing infrastructure and request political backing to get these resources
- Follow recommendations of IAWN and SMPAG

- Start planning now so that action can be taken if probability of impact goes up

Communication to and from the Public Working Group

- UNCOPUOS informs all the member states as soon as practical, which then decide how to inform their own citizens
- Consistent messaging is critical - all nations/leaders should be quoting the same information
- Our experience to date is that these probabilities will reduce; i.e., more data will show there is no threat
- Don’t show the impact analyses. Do show the observation opportunities
- Develop standard explanations for the jargon and terminology
- Demonstrate that we are doing everything we can to get more data

Disaster Planning & Management Working Group

- Educate the people who may be impacted
- Reach out to the respective disaster agencies and governments
- Let the local disaster agencies make the plans for evacuations

Decisions by World Leaders

- Proceed with Hubble Space Telescope observations
- Planning for a flyby mission will proceed, either by diverting a spacecraft already in space or launching a dedicated mission
- Begin investigation of a rendezvous mission
- Begin Phase A planning for redirect mission
- Use the recommended communications strategy for informing the public
- Invest in the modeling of the impact and in developing evacuation plans

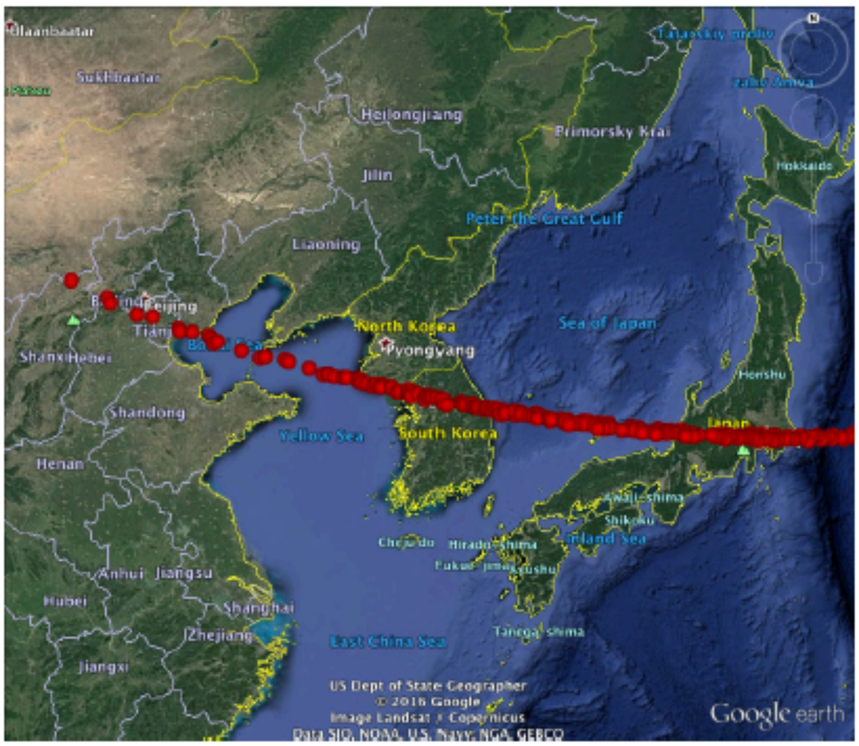
Second Press Release

DAY 2

PRESS RELEASE: NOVEMBER 30, 2018

ASTEROID'S CHANCE OF EARTH IMPACT IN 2027 NOW 96%

Based on new tracking measurements taken this week, the International Asteroid Warning Network (IAWN) has confirmed that asteroid 2017 PDC is on a course that will almost certainly impact Earth on July 21, 2027, less than nine years from now. IAWN estimates that the chance of impact is 96%, and the possible locations of impact are confined to a long narrow region outlined by the red dots on the image below.



Nations most at risk from the effects of a land impact or an airburst are: China, North and South Korea, and Japan. The impact footprint extends into the North Pacific Ocean, but does not intersect any other land mass. Many nations bordering the Pacific could be affected if the impact generates a tsunami.

The critical new measurements of 2017 PDC taken this week came from NASA's Hubble Space Telescope and the National Astronomical Observatory of Japan's 8-meter Subaru Telescope on Maunakea, Hawaii. The new data did not eliminate the possibility of impact, as had been hoped, but instead revealed that the asteroid is almost certainly on a trajectory that will impact on July 21, 2027. Prior to this week, the asteroid had been unobservable from Earth for almost a full year as it travelled through the glare of the Sun, and IAWN's estimate of its impact probability remained fixed at 26%. No further ground-based observations are possible for the next 11 months, as 2017 PDC has become too faint once again to be observed from Earth.

IAWN has refined its estimate of the size of 2017 PDC, based on data from the NEOWISE spacecraft. The asteroid is now estimated to be between roughly 200 and 280 meters (650 to 900 feet) in size. Spectral measurements taken last year suggest that 2017 PDC is a C-class asteroid, which typically implies that it has a low albedo (reflectivity), which is now believed to be in the range of 4% to 8%. Further refinements to that taxonomic classification will be available soon from the recently launched James Webb Space Telescope (JWST). A size larger than 300 meters (1000 feet) was ruled out by a radar non-detection in 2017; radar astronomers are confident they would have detected the object if it were larger than 300 meters. Photometric light curves taken in 2017 are ambiguous, and a definitive rotation period has not been established. Scientists stress that the more that is known about the asteroid, the better the chances of successful deflection.

Over the last eighteen months the UN Space Missions Planning Advisory Group (SMPAG) has been very active in advising for and coordinating an international response to the impact threat posed by 2017 PDC. Spacefaring member states have begun development of several types of space missions that could be launched towards the asteroid. SMPAG plans call for a fast flyby characterization mission to be launched 11 months from now (October 2019) to fly by the asteroid in May 2020. This spacecraft will provide data on the asteroid's size, shape and composition, and establish the asteroid's precise trajectory, which pinpoints the impact location. The data from this mission will aid in the design of the deflection campaign. To rendezvous with the asteroid, a pair of missions with a would launch 18 months from now (May 2020). Those spacecraft require 3 years to get to their target, but will then remain in place to observe the deflection attempts and assess the results. SMPAG, the UN, and the space agencies are considering the option of adding a deployable nuclear explosive device on the rendezvous spacecraft.

SMPAG is considering two different kinetic impactor (KI) deflection campaigns, both designed to deflect the asteroid near its perihelion point in early 2024. One campaign would deflect the asteroid so that the impact location moves westwards along the risk corridor, across Asia and Europe. The kinetic impactor missions in this campaign are simpler and have shorter flight times, but a series of 4 individual spacecraft working in tandem would still be required to prevent the impact. The missions could launch as late as mid-2023. The alternate campaign would change the asteroid trajectory in the other direction, moving the impact location eastwards across Japan and into the Pacific Ocean. That is a more difficult direction for KI deflections, because the missions would require a more difficult-to-obtain orbit and a longer flight time. To succeed, this campaign would have to launch its spacecraft only 16 months from now, in March 2020, and a minimum of 3 deflections would be required in combination to prevent the impact.

For more information, visit: https://cneos.jpl.nasa.gov/pd/cs/pdc17/day2.html.

Recommendations

International Asteroid Warning Network (IAWN)

- Use all available and necessary ground-based and existing space-based observation methods, including JWST, to get the best physical characterization possible
- Strongly recommend a flyby or rendezvous mission to reduce impact uncertainty, to determine whether the asteroid is a binary (or contact binary), to investigate possible outgassing, and to get shape information for properly targeting a potential kinetic impactor.
- The flyby/rendezvous will improve the mass determination, fix the size of the deflection effort, and constrain the impact point on Earth to a few km.
- Design the rendezvous mission to last past 2027 and have redundancy to make an accurate mass determination. Include radar on the spacecraft to study the interior and to monitor the deflection.

Impact Effects Working Group

- Land impacts are more severe than impacts over water (tsunamis present a lower risk)
- Each kinetic impactor will move the risk corridor 460 km east: 2-3 hits could move the entire risk corridor into the Pacific Ocean
- The mean blast radius is likely to be 50-150 km, with a worst case of 250km, so the impact point needs to be at least this far offshore
- Tightening up the uncertainty in the impact ellipse will help

Deflection and Disruption Working Group

- Given COST and RELIABILITY consideration, two deflection mission options are proposed: The first option includes two “active” rendezvous ships carrying nuclear devices to launch in June 2020 at a cost of $3 billion; the second option includes two “passive” rendezvous missions with no nuclear devices, followed by six kinetic impactors. Rendezvous missions would launch in June 2020 at a cost of $8 billion ($2 billion for the rendezvous spacecraft + $6 billion for the kinetic impactors)
- For the second option, start with an eastward (into the Pacific) deflection plan. Attempt to make March 2020 launch date. The impactors would arrive before the rendezvous mission. A total of 6 interceptors provides redundancy because, based on current estimates of the asteroid properties, 3 impactors are required to deflect the asteroid. The eastward deflection plan uses solar electric propulsion (SEP).
- If the eastward launch date is not possible, continue spacecraft construction efforts and go for a westward deflection launch date, which is in July 2023. The westward deflection will benefit from 7 weeks of data from the rendezvous ship(s). The westward deflection plan uses chemical propulsion.
- Consider 50% failure per mission because of the non-standard circumstances and high stakes

Space Mission Planning Advisory Group (SMPAG)

- Eastward deflection is recommended
- A precision drop on central Asia (westward deflection) is very difficult
- Nuclear devices on rendezvous missions are recommended
- A nuclear deflection will require only 1 successful mission, but a kinetic impactor deflection will require 3 successful missions

Decision to Act Working Group

- Six eastward deflection missions are recommended for launch
- Nuclear warheads are recommended for launching on the rendezvous missions
- Keep all deflection options open (eastward, westward, nuclear)
- Formation of formal decision-making body is recommended since political coordination at the highest level is required given the complex nature of this problem (4 countries in risk corridor, other countries with space agencies will launch missions)

Communication Working Group

- Clear, concise, and consistent information must be publicly available
- Prepare to answer the big questions from the public, including details about the Kinetic Impactor missions. The justification of the east versus west deflection and the decision process for building and launching will need to be made clear.
- Communication will occur through established processes with the UN to understand, monitor, and plan. Publicly recognizable organizations such as the Red Cross could be asked to lend their support in disseminating information.
- Instill hope for the future: The nations are working together, we have the technology to solve this problem, and we are doing everything we can to prevent this disaster and to preserve lives and livelihoods.
- Be ready for challenging questions: How do we know that decision makers are right? Are we using nuclear weapons? Who is going to pay for all of these missions? What if the missions are not successful? What is the Plan B?

Disaster Planning & Management Working Group

- 2024 is the key date
- The goal is to plan so that nobody dies from the impact
- Mitigate economic issues, insurance
- International agreements between countries in impact zone within 6 months
- Incentivize other countries to participate due to uncertainty and refugees within 6 months
- The tsunami threat needs to be considered
- Slogan: “No fatalities,” “Nobody dies”

Decisions *by World Leaders*

- All Possible Earth/Space based observations are funded
- Number of Flyby Spacecraft – 2 as recommended by scientists (investigate AIDA-like inclusion)
- Number of Rendezvous Spacecraft – 2 for June 2020 (include nuclear device in each for use only if all other efforts fail)
- Number of Impactor Spacecraft – 8 of multiple designs to increase probability of success
- Impactor missions will be for eastward deflection (westward if failure to meet launch window)
- No action taken yet to address economic issues
- The possibility for a unilateral launch of a hypervelocity nuclear mission remains open

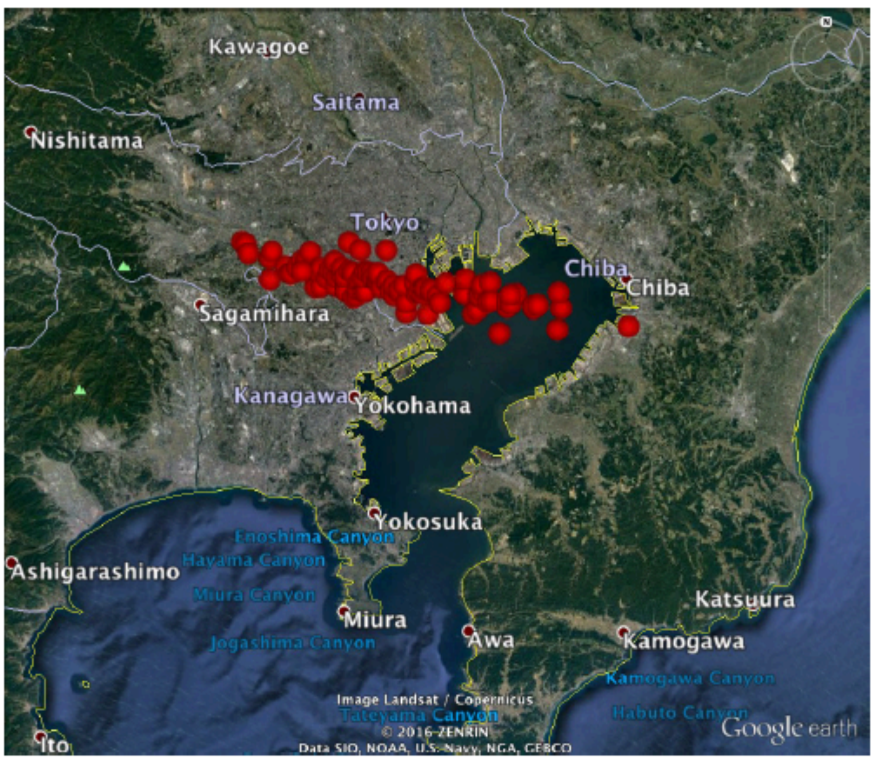
Third Press Release

DAY 3

PRESS RELEASE: MAY 15, 2020

ASTEROID 2017 PDC DISCOVERED TO BE BINARY AND CONFIRMED TO BE HEADED FOR IMPACT NEAR TOKYO, SIX SPACECRAFT ON THE WAY TO DEFLECT IT

The first of a series of space missions flew by the threatening asteroid 2017 PDC today, and took up-close images that revealed the asteroid to be a binary: a primary body about 270 meters (900 feet) in size with a roughly 100-meter (330-foot) moon orbiting around it. The images also provided key data on the asteroid's trajectory, and the International Asteroid Warning Network (IAWN) has concluded that 2017 PDC is headed for impact near Tokyo, Japan, on July 21, 2027. Unless it is deflected, IAWN predicts that the asteroid will impact somewhere within the region outlined by the red dots below.



Over the last two years, the Space Missions Planning Advisory Group (SMPAG) has been very active in coordinating an international response to the impact threat posed by 2017 PDC. The fast flyby spacecraft that just arrived at the asteroid was only the first of an armada of spacecraft launched towards this object. Attempts were made to construct eight Kinetic Impactor (KI) spacecraft, but only six of them are ready for launch. The six

KI spacecraft were launched over a 3-week period beginning two months ago on trajectories to intercept the asteroid in February 2024, around the time that it will be closest to the Sun. One of the launches failed, leaving a total of five spacecraft headed towards the asteroid. The KI spacecraft will crash into the asteroid at high velocity, one at a time, and separated by several days. Each KI impact will impart a small velocity change to the asteroid. The cumulative effect of multiple KI impacts is designed to deflect the asteroid off of its collision course by boosting the asteroid's speed around the Sun, thereby moving the asteroid's trajectory eastwards in 2027. An additional set of Kinetic Impactors was under development for moving the asteroid trajectory westwards, but the change to the asteroid's orbit necessary to prevent impact altogether was much larger in that direction and could have inadvertently moved the impact point to one of several other countries; the westwards deflection plan was therefore abandoned.

The fact that 2017 PDC is binary has added an unanticipated complication to the deflection campaign. The orbital radius of 2017 PDC's moon (the "secondary") is 1 to 2 kilometers, considerably larger than expected for asteroid binaries in this size range. The implication is that the secondary is only loosely bound gravitationally to the primary. While any deflection applied to the primary component will certainly affect the orbit of the secondary through their mutual gravitational attraction, there is a chance that the secondary could escape the system and continue on its own trajectory.

The sequence of approach images from the flyby spacecraft has provided enough data for IAWN to estimate an approximate orbital period for the secondary, which is on the order of a few days. This result allows scientists to obtain an approximate estimate of the mass of the primary body, an unexpected benefit from the flyby mission. The mass of the primary is a key determinant of the amount of deflection each of the KI spacecraft will produce. Together with an approximate shape model produced from the flyby images, and a resulting volume estimate, scientists have concluded that the density of 2017 PDC is about 20% higher than assumed previously. The important result from this analysis is that, in the worst case, a successful deflection is required from all five kinetic impactors in order to divert 2017 PDC from colliding with tour planet.

Two spacecraft have been prepared for launch next month on a mission to rendezvous with 2017 PDC in May, 2023, three years from now. Decision-makers discussed whether to install nuclear devices on the rendezvous spacecraft and decided not to do so. However, the rendezvous spacecraft were still designed and built to be capable of carrying nuclear devices. Those spacecraft will arrive in time to observe the series of kinetic impactor deflections scheduled for February 2024, and the data sent back will be invaluable in assessing the results of the deflection and establishing new trajectories for both components of the binary asteroid.

For more information, visit: https://cneos.jpl.nasa.gov/pd/cs/pdc17/day3.html.

Recommendations

International Asteroid Warning Network (IAWN) Working Group

- The current rendezvous missions should have enough instruments on the spacecraft to fully characterize the size, shape, orbit and rotational state of the system with wide and small field imagers, and thermal cameras to determine size and shapes
- The radar on the spacecraft will allow the determination of the internal structure: a solid body or a rubble pile composed of large components
- Both rendezvous spacecraft must survive the collisions intact, since after the impacts, the number of massive bodies could range from two (the original bodies) to many, and the instrumentation is needed to rapidly establish which ones are still on impact trajectories
- When the two largest impacting components are located, they will need to be followed by the two rendezvous spacecraft to be fully characterized

Impact Effects Working Group

- Consider two separate situations: primary and secondary both impact, or only the secondary impacts (assuming the primary is fully deflected).
- If both impact (assuming binary system remains intact), only the impacts from the primary need to be considered, as the secondary will impact in the same general location and cannot cause more damage than the primary
- If only the secondary impacts, uncertainty in the impact location is introduced, therefore the risk corridor widens significantly
- The best solution is to time the Kinetic Impactors to collapse the binary orbit, keeping the system together, while simultaneously shifting the impact point into the Pacific Ocean
- Two Kinetic Impactors (out of 5) are required to move the impact point ~800km into Pacific Ocean, where tsunami hazards are relatively small

Space Mission Planning Advisory Group (SMPAG) and Campaign Design Working Group

- Primary recommendation - Carry nuclear devices on the two rendezvous missions. A single nuclear device, deployed from either of the spacecraft, can effectively remove the impact threat from both the primary and the secondary. The primary would be deflected and the secondary would be destroyed.
- If the primary recommendation above is not implemented or successful, then we recommend proceeding to strike the primary with all 5 kinetic impactors for East-ward deflection in a controlled manner such that the secondary does not depart the binary system in an uncontrolled manner that could pose an Earth impact hazard.
- If the above efforts do not succeed, we suggest continuing to build and launch two more kinetic impactor spacecraft, possibly armed with nuclear devices, in 2022 or 2023 or 2024. Those spacecraft could be used to deflect or destroy the secondary body if necessary.

Decision to Act Working Group

- Propose installing nuclear devices on both rendezvous missions
- Use two or more Kinetic Impactors on the binary companion
- Prepare two additional flyby missions with nuclear devices to be used later
- Prepare two additional KI missions to deflect binary companion

- Recommend developing six possible plans/scenarios. It is not possible decide which now. We want missions that can be used in any combination depending on which scenario is realized.
- Prepare massive education and evacuation plans for Tokyo

Communication Working Group

- Convey the options and the information clearly, concisely, and consistently: Despite the difficult challenges, the flyby was successful, and the five KIs can make a difference. Then, scientists have made progress thanks to your generous support. We have the information necessary to mitigate the new risk. We strongly recommend continuing to support the trusted public information channels put in place that are working and should nevertheless be expanded.
- 75% of the public was opposed to the use of nuclear devices at the last inject. With this new information that the danger is greater, the opposition is weakened somewhat but the majority is still opposed. Discussion on the pros and cons on the use of nuclear devices needs to be included and properly described so the public can grasp the importance of the use of this technology.
- Even with the cooperative measures in place to aid the populations at risk, the individual nations potentially involved in the impacts are facing great fear. The decision by the leaders to not announce the evacuations prior to assessing the success of the KI missions is increasing the anxiety. The people need to know now what their options will be even while they hope for the success of the missions. This includes timelines and how infrastructure and services, as well as businesses will be moved. Need to welcome public comment on the plans.
- What nation is launching the rendezvous mission and is that nation willing to add the atomic deflection device? And what is the risk if there’s a launch failure? We advocate for openness and transparency in the decision. There must be very clear messages on the risks as well as the benefits.
- We advocate naming the asteroids.
- Clear up your language and don’t say “nukes” or “nuclear weapons.” -We propose Atomic Deflection Device (ADD) as an alternative.

Disaster Planning & Management Working Group

- Continue planning for relocation in threatened region
- Need to plan for secondary impact in Russia along the uncertainty corridor presented on Day 1 (represents potential impact locations following deflection if not deflected off the Earth) - “This is a planned relocation. Even with this new uncertainty, no one dies.”
- Work with various groups in terms of economic fallout and to guarantee livelihood and property values (e.g., World Bank)
- This group gives input to the communication working group, so verify communication channels
- Provide a timeline of what to expect – countries along the uncertainty corridor should create plans, but NOT implement them. They can be successful if organized well ahead of time (global crisis).

Decisions by World Leaders

- Voted Yes to put ADD (Atomic Deflection Device) on current rendezvous missions

- Voted Yes to use a KI (Kinetic Impactor) on the asteroid binary companion
- Voted Yes on 2 additional KI missions
- Voted Yes on 2 additional flyby missions carrying ADD
- Voted Yes on plan of action for things to do for people who will be affected
- Voted Yes on plan of action for people not directly affected

Fourth Press Release

DAY 4

PRESS RELEASE: JUNE 15, 2023

RENDEZVOUS SPACECRAFT REACHES ASTEROID 2017 PDC; DECISION MAKERS DELIBERATE ON USE OF NUCLEAR DEVICE; KINETIC IMPACTORS STILL ENROUTE

One of two rendezvous observer spacecraft has reached asteroid 2017 PDC and has been surveying and characterizing the binary asteroid for the past month. A second rendezvous observer spacecraft was launched on a similar mission, but it experienced an unrecoverable reaction-wheel malfunction a year after launch, and its mission was abandoned. Before the two spacecraft were launched, there was much debate about whether or not the spacecraft should carry nuclear explosive devices (NEDs) to be used to deflect the asteroid away from Earth impact. Just a month before launch, the collaborating nations reached an agreement to install one such device on each spacecraft.

The rendezvous observer now has approximately eight months to survey and characterize the asteroid before the arrival of the five kinetic impactors, which are still enroute to the asteroid and cruising normally, on target to deflect the asteroid starting on February 24, 2024.

Decision makers must now decide whether to utilize the nuclear device onboard the rendezvous observer to deflect the asteroid away from Earth impact, or to wait for the series of kinetic impactors to strike the asteroid in early 2024. They must also decide whether or not to deliberately detonate the nuclear device onboard the other spacecraft to safely dispose of the device. That spacecraft can still be commanded, but it cannot rendezvous with the asteroid.

For more information, visit: **https://cneos.jpl.nasa.gov/pd/cs/pdc17/day4.html**.

Discussion

Discussion of the Fourth Press Release centered on using the five incoming kinetic impactors as the primary method of deflecting the asteroid and its moon, or activating the nuclear explosive on the spacecraft currently orbiting the asteroid first, with the kinetic impactors as backup. During the discussion, it was noted that:

- The use of the nuclear explosive was felt to have the highest probability of success given that all five of the kinetic impactors would need to successfully hit their target, but that the target object (the primary) was small, would present targeting challenges for the incoming vehicles, and each impact would likely create a debris cloud that could also affect targeting. It was noted that the impact velocity would be 8 km/sec, below the 10 km/sec impact velocity for Deep Impact mission, but the target for that mission was about 20 times larger.
- A nuclear explosive has not been used in deep space, and it has had a long resident time there, so that raised some uncertainty.
- A successful impact of one kinetic impactor would move the asteroid's impact point into the Pacific Ocean, yielding a tsunami as a near-immediate threat. Consensus from experts was that the tsunami would be of a size that nations bordering the Pacific prepare for already, and given the warning, damage would be sustainable.
- Given the public's concern about using nuclear explosives, there was strong support for making that option a last resort if all else failed. There was no discussion of possible longer-term effects on the atmosphere, weather, etc.
- Public was concerned about the nuclear explosive device following the asteroid into the atmosphere and adding a "dirty bomb" incident to the consequences, so they felt that all devices left in orbit should be activated to eliminate the threat.

Factors Affecting Leadership's Decision

- Activating the nuclear explosive between the primary and secondary objects would provide sufficient delta-V to deflect the primary and destroy the secondary.
- The existence of the threat is affecting the world economy badly
- Strong public opinion supports eliminating the threat as soon as possible
- The disaster response community has plans ready to deal with any potential outcome
- Great concern in some communities about using a "nuclear weapon" in space. It was suggested that the planetary defense community should use another description (e.g., nuclear explosive or Atomic Deflection Device). In preparation for a real threat, there should be a strong effort to educate the public on risks associated nuclear devices for this application.

Decisions by World Leaders

- Use the nuclear explosive currently orbiting the primary to deflect the primary and destroy the secondary.
- Use the incoming kinetic impactors to provide any additional delta-V required.

Post-Exercise Discussion of Possible Outcomes

- The nuclear explosive would do the job, even if activated a couple of months before or after the target's perihelion.

- Impacts by one or more kinetic impactor would move the object away from Tokyo and into the Pacific.

Key Lessons

- Different nations will have different opinions on what should be done and when it should be done, and more work should be done on the decision-making process and factors that will affect that process. A good example was discussion of the use of nuclear explosives as a deflection technique. In a real scenario, how would decisions be made as to the deflection option? Who would be authorized to make the decision? What information should be provided to increase the acceptability of using atomic deflection devices?
- The cost and economic implications and consequences of an asteroid threat, even a threat that is determined to be a false alarm, must be considered. The area that might be affected should an object impact will likely be public information shortly after the object is discovered, and work should be done to assess the response and provide appropriate, authoritative information to the public, nations, and decision makers along the threat corridor as the threat evolves.

For the next conference

Comments on the exercise and suggestions for what might be improved or included in the next exercise were:

- While there was some skepticism that the exercise would use up too much time of the conference, the response from attendees and external participants showed that it was well received and one of the highlights of the conference.
- An impact exercise is a valuable part of the PDC conference.
- Improved efforts should be made to involve real decision makers, including those deciding on the finances. It is unrealistic to expect their active involvement over several days. Perhaps, some of them could be briefed before and they could give some milestone decisions as input to be made public during the exercise.
- We should continue to offer the option to have the 'real players' involved via external communications. We should consider a special setup (e.g., contact them in person before the conference, set up date/times to brief them and ask for their opinion).
- A future scenario could perhaps concentrate on a smaller object 30 - 50 m in size with just a few weeks warning time and no option for deflection. That would concentrate on the civil protection aspect (and it is much more likely to happen).
- Use a comet for future scenarios
- Have small groups working on different scenarios and report back at the end to present what they decided
- Thought the outcome of the exercise was highly unrealistic. Sending a fleet of spacecraft isn’t realistic.

- Consider scenario so that disaster management people have something to do
  - Planning team did consider that but wanted the scenario to "win"
  - Find a way engage disaster management in different ways
  - Wanted to provide a way for decision makers to win
- Have non-technical people as playing the "Leaders" role. Felt the leaders were biased to using NED
- Maybe do the scenario backwards
- The effect of a threat on the world market and economics was a new element to this scenario; We should have economists involved in this type of scenario
- We discussed whether to deflect east or west, and the economic implications are there but unknown to us now
- Economists are accustomed to this (PDC-like) risk analysis all the time
- We haven't considered the value of a small flyby to reduce the uncertainty for economic benefit
- Maybe seek input from legal team that advises SMPAG
- Need to capture the recovery aspect after deflection or impact
- We need to change nature of exercise in the future because we'll be able to detect smaller and smaller asteroids. Then, the problem is to avoid impact of something 100 years out or small asteroid impacts.
- Recommend exploring the post-impact consequences
- Improve the public participation aspect, add a poll? It would be interesting to know how the public vote
- If the groups are too large, split them up into sub-groups so that discussions can happen
- The discussion of the nuclear option brought forward the discussion points
- Maybe reorganize the way how decisions are made
- Need to make the roles more explicit and explanation
  - The "Decision to Act" group struggled to find its place
  - It was good to see the groups converged into what is now existing (i.e., IAWN, SMPAG)
  - The explanation of IAWN and SMPAG not good enough for this group to grasp their roles
- It is important to stress that this exercise is chosen to be complex with many options and long time before impact
- This conference was different in that it was ad hoc, and it evolved over the course of the conference
  - It made it exciting and interesting
  - However, was frustrated that a lot of the information that was generated was not used
- As future detection systems come online, we have a different problem in our hands. Maybe we may have multiple Apophis type asteroids
- Take a page from "Defense"
  - The military will not allow themselves to use untested weapons
  - As a community, we need to advocate to test our techniques
- For 1% probability, it appeared the leadership seemed apt to use resources

    - Maybe we start with two asteroids with 1% with fixed budget
    - Planning team – agree that the budgetary element was not captured well
- Commend the international nature and first time in Asia
- Maybe allow the asteroid to miss...
- Third time in a row, this asteroid snuck up from the south
    - Provide recommendation to improve radar capabilities
- Suggest engaging graduate students and in other forums