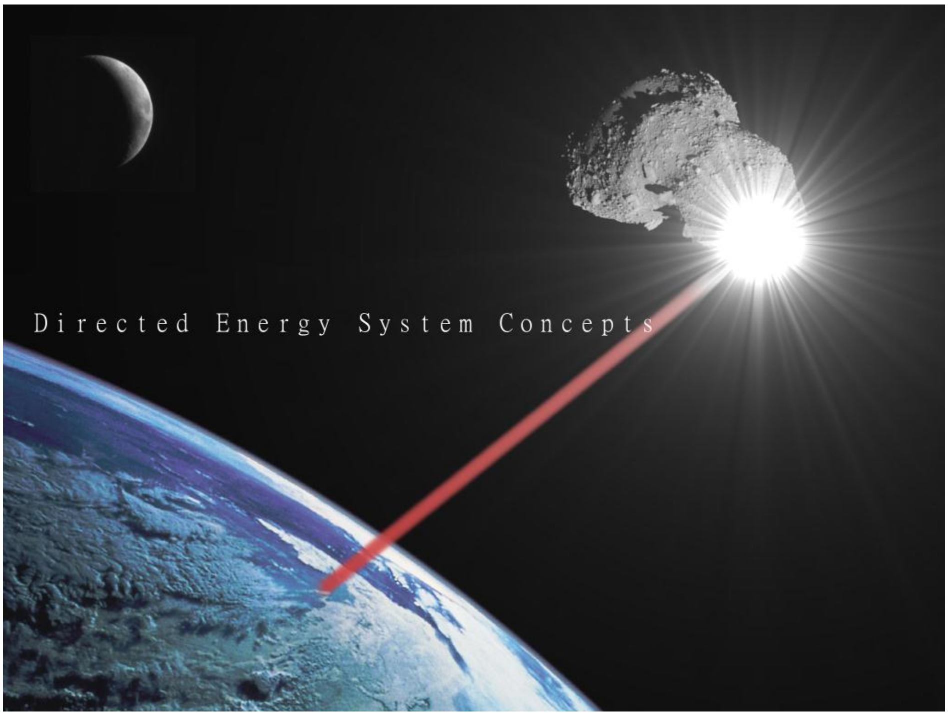
4th IAA Planetary Defense Conference – PDC 2015
13-17 April 2015, Frascati, Roma, Italy

IAA-PDC-15-03-11

QBOLT - Directed Energy System Concepts for Asteroid Threat Mitigation

M.Thangavelu[1], J.M McVicker[2]
[(1)]Conductor, Graduate Space Concepts Studio, Dept. of Astronautical Engineering, Viterbi School of Engineering, Los Angeles, California 90089-1191,
[(2)]Graduate student, Dept. of Astronautical Engineering, Viterbi School of Engineering, Los Angeles, California 90089-1191



Abstract

Asteroids and other extraterrestrial impactor threats to Earth occur naturally in our solar system. Larger, more massive bodies including cometary fragments in high energy trajectories will be able to pierce the Earth's atmosphere and cause cataclysmic destruction if they are not stopped well enough in advance. Modern Directed Energy Systems are an emerging feasible concept for mitigating the threat of Near-Earth Objects (NEOs). Directed Energy Systems are versatile, scalable, reusable architectures that focus intense coherent beams of energy on a target's surface through the use of phased array lasers. The energy is typically used for the purpose of ablating the surface of the target, or generating substantial ablative thrust to alter the trajectory of the bolide to a new innocuous path. Technologies are fast maturing that allow the integration, test and commissioning of such directed energy systems for use at astronomical distances. This concept architecture study explored innovative strategies for directed energy system application to potentially hazardous asteroid threat.

Introduction

Asteroids and other extraterrestrial impactor threats to Earth occur naturally in the Solar System – ranging from solid monolithic and metallic bodies, to large conglomerates of Solar System rubble, loosely held together by Van der Waals binding forces or weak gravity. Larger, more massive bodies including cometary fragments in high energy trajectories will be able to pierce the Earth's atmosphere and cause cataclysmic destruction if they are not stopped well enough in advance. Fortunately, the majority of such bodies within the inner confines of our Solar System have a few unique properties that can be exploited by Directed Energy Systems, a concept with a long lineage in war fighting strategies dating from the siege of Syracuse(212-214BC).[Figure 1] An MIT class exercise proved the principle feasibility.[Mythbusters 2006]

Figure 1. Historians attribute Archimedes as the architect of the directed energy weapon that was employed to scuttle enemy ships in the 3rd century BC during the siege of Syracuse using the sun as the source of energy.[picture credit Wikipedia]

Modern Directed Energy Systems are being readied for advanced ground, air and naval weapon systems[Bagnell 2013, CNET 2013, Boeing 2010, ONR 2011] and appears to be an emerging feasible concept for mitigating the threat of Near-Earth Objects (NEOs)[Lubin 2013].

Directed Energy Systems are versatile, scalable, reusable architectures that focus intense coherent beams of energy on a target's surface through the use of phased array lasers or other maturing technologies. The energy is typically used for the purpose of ablating the surface of the target, or generating substantial ablative thrust to alter the trajectory of the bolide to a new and innocuous path. Technologies are fast maturing that allow the integration, test and commissioning of such directed energy systems for use at astronomical distances.

Forced Vibrations, Natural Frequency and Resonance

All systems possess natural or fundamental frequencies. If external forces are applied, tuned to these natural frequencies or their harmonics, systems will exhibit resonant behavior. The system will oscillate, absorbing the incident energy, gaining amplitude, and if unchecked or undamped, will lead to runaway oscillations that will quickly peak and destroy it. Such forced vibrations have caused the collapse of large structures on Earth. The Tacoma Narrows bridge collapse of 1940 was caused by forced, resonant vibrations imparted by steady, continuous wind forces. Tall buildings oscillate due to the same phenomenon, and active damping systems are employed to curtail dangerous, runaway, excessive oscillations that can lead to structural collapse. Space launch vehicles are designed to damp such oscillations caused by acoustics, and sploshing within fuel tanks are also associated with forced vibrations. Active damping is employed routinely to negate the forced vibration energy buildup and to stabilize dynamic structures.

QBOLT Concept Architecture

This programmatic concept architecture study explored innovative strategies for directed energy system application to potentially hazardous asteroid threat.

At least two alternative methods to pure vaporization and trajectory alteration need further investigation because of the intense physical reactionary forces associated with the large ablative thrust produced by the focused energy on the surface of the target.

QBOLT is a concept that proposes employing forced vibrations via the directed energy beam, tapping into the natural resonant frequency of a dense monolithic asteroid, in order to fracture it into harmless fragments. The concept derives its name from the dimensionless Q-factor or amplification factor, used in fundamental resonance.

In principle, QBOLT is potentially most effective against the larger monolithic asteroid fragments that populate the main asteroid belt as well as NEOs of similar morphology.[Figure 2]

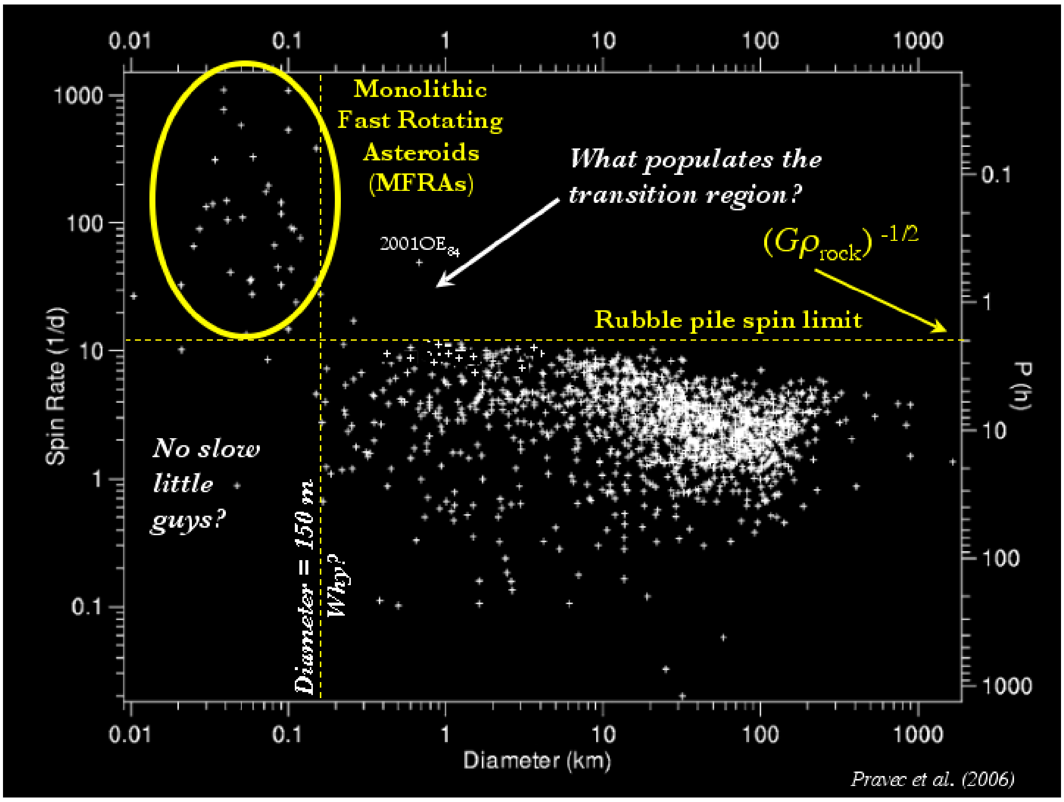


Figure 2. The QBOLT architecture may be more suitable to disintegrating monolithic asteroids though it can also be effective to scatter and disintegrate rubble pile bolides among the asteroid population.[Table credit Pravec 2006]

Additionally, large rubble piles could be spin-destabilized by applying a torque and overcoming the weak Van Der Waals's force or gravity through the resultant effects of centrifugal forces. Both methods attempt to produce a field of much smaller debris fragments that could further be diverted or vaporized by the directed energy system, or allowed to burn up in the Earth's atmosphere.

State-of-the-Art Technologies Employed

Advances and state of the art technologies in optics include optical phased arrays [Vorontsov 2009] that allow several low power lasers to converge energy at extreme distances in directed energy systems such as the DESTAR concept[Figure 3], and beam combining that allow multiple lasers to form an intense beam.[Figure 4]

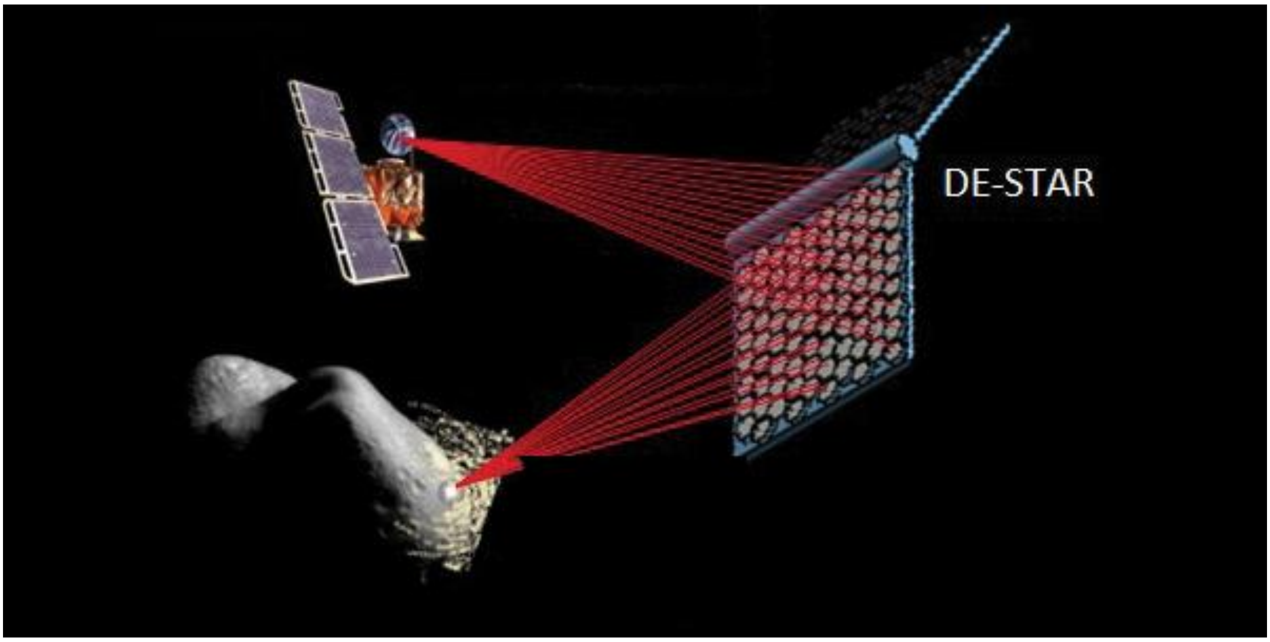


Figure 3. DE-STAR (Directed Energy Solar Targeting of Asteroids and exploRation) concept proposes a space based phased array of lasers to target and ablate rogue asteroids.[Lubin 2013]

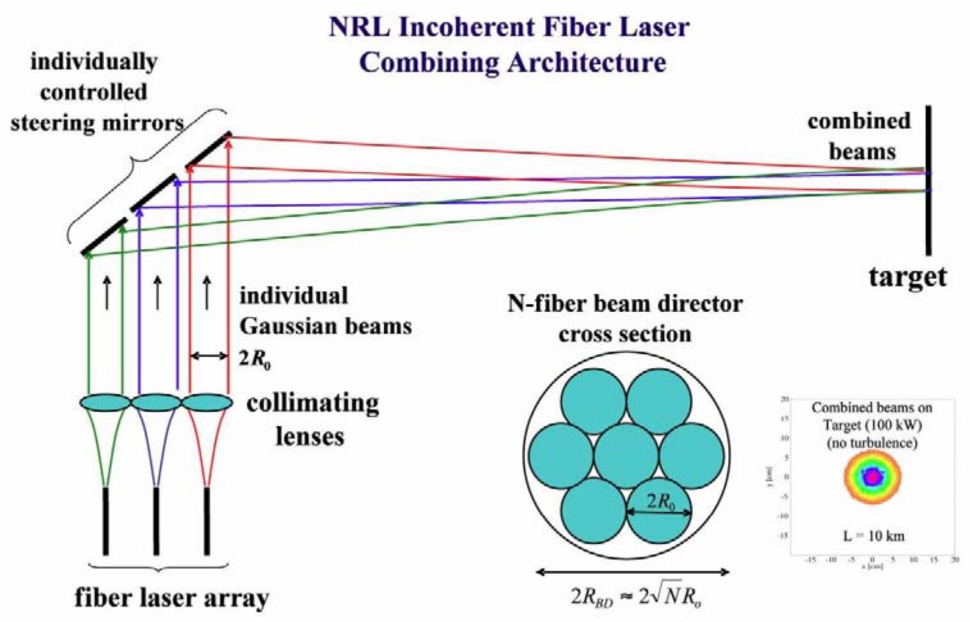


Figure 4. Schematic diagram of incoherently combined fiber lasers. Laser beams are expanded and directed to the target by individually controlled steering mirrors. Spot size of the individual beams at the source is made large enough to limit diffractive spreading.[Parry NRL 2013]

Advances in optics include thin disc lasers that currently allow systems to deliver 1KW/ 5kg system mass and fast approaching 1KW/kg[Figure 5]. Current techniques used in synthetic aperture astronomy include beam conjugation and atmospheric disturbance correction employing adaptive optics. These technologies may be brought to bear on precise target acquisition at 1-2 AU distances, as far out as Mars orbit and sub milli arc second optical tracking and pointing are being designed in astrometry to resolve objects in deep space.[Jankov 2014, Skinner 2007]

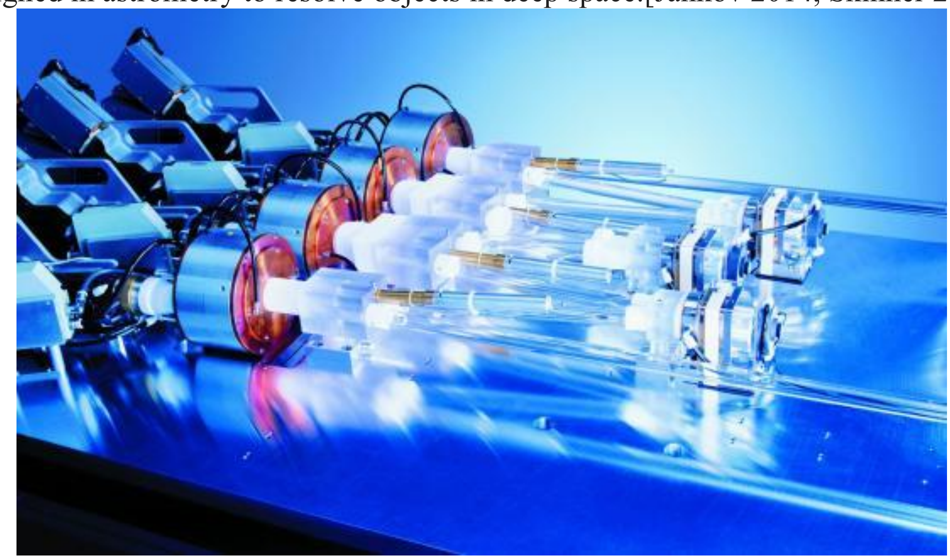


Figure 5. An 8kW thin disc laser setup. Each of 4 thin disc lasers emits 2kW of power that is combined to produce the output of the system. Such systems can be scaled up to desired power levels without the need for extensive heat management system that would be necessary otherwise.[Image credit TRUMPF Laser-und Systemtechnik GmbH]

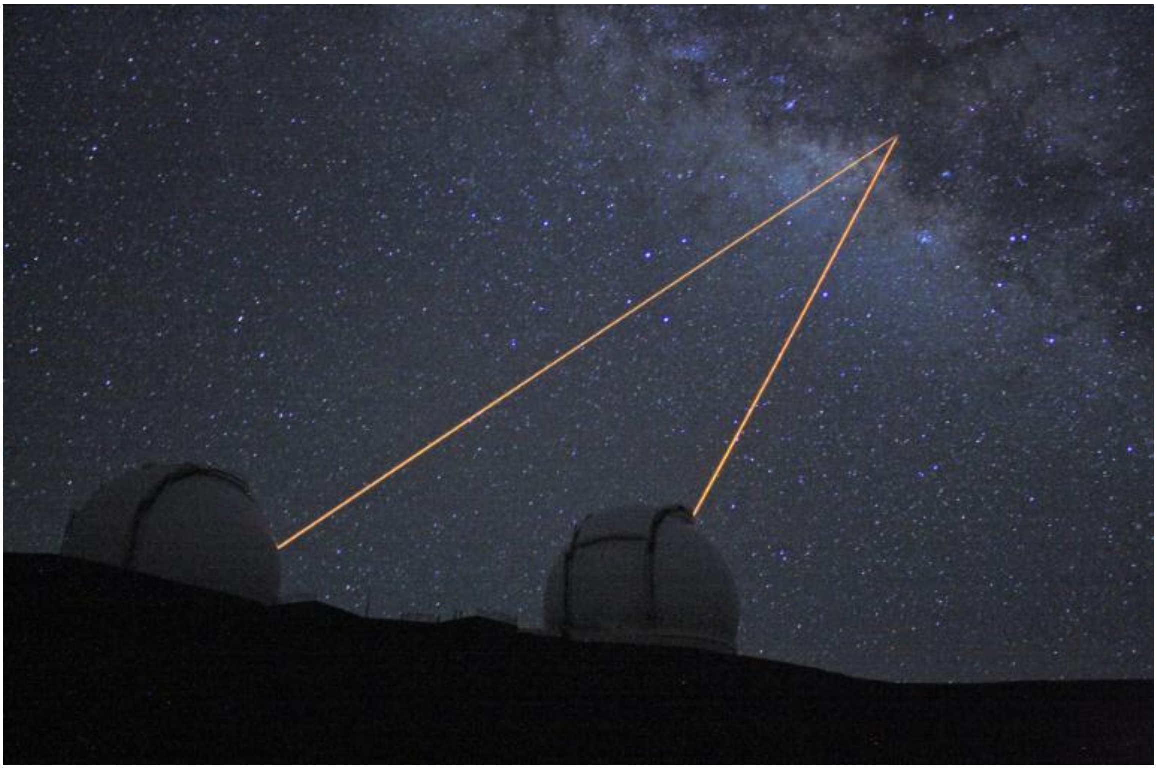


Figure 6. Adaptive optics is routinely employed in high resolution astronomy. The Keck telescopes at Mauna Kea uses adaptive optics to resolve the Sagittarius stars in the Milky Way galactic center. Reference beams such as these can be used to compensate for atmospheric disturbances while QBOLT system targets asteroids at 1-2 AU distances.[pic credit UCLA GCG]

QBOLT Mode of Engagement

The suggested QBOLT Concept mode of engagement is as follows. Using powerful lasers it is possible to paint asteroids and fragments that are too dim and hence difficult to observe since their natural albedo is very poor[Lubin 2013]. Once such objects are located and identified as potentially hazardous, it is possible to quickly ascertain their precise trajectories. A typical QBOLT engagement is proposed for those 10-100m monolithic bolides on a direct Earth impact trajectory, identified during terminal approach phase. By terminal approach phase is meant a period of weeks to days before impact(1-2AU). Such targets have very little apparent motion and are easier to target. Once acquired, a return signal from a “first ping” beam from the QBOLT system will reveal characteristics including the bolide’s fundamental resonance frequency. The QBOLT system then would tune the laser beam to this characteristic resonance frequency in order to efficiently pump energy into the target, amplifying and breaking up the target bolide. Pulsed or amplitude modulated directed energy lasers may be used to impart resonant energy to the bolide.

As global population expands and establishes in new regions, the threat of loss of life, assets and damage to property due to asteroid strikes is bound to increase.[Figure7a,b] Ground Infrastructure Evolution includes the need to place several QBOLT systems around the globe in order to be able to locate and engage rogue bolides on a collision course with Earth that may appear from any part of the celestial sphere. The ability to power such systems using the expanding and evolving transcontinental power grid makes it an attractive option to have it operate from the Earth's surface, and from population centers as opposed to building and operating it in space. However trades are needed to ascertain factors like continuous seeing time, interference with other existing and proposed high value assets in the space and various orbital segments, as well as environmental impacts that are not yet fully understood.

Figure 7a. NASA night-time satellite imagery shows human population spread across the globe. Projections suggest 9 billion by 2050 with growth occurring mostly in so-called "high-fertility countries" in sub-Saharan Africa, Asia, Oceania and Latin America. Coastal cities are also more vulnerable to tsunamis caused by asteroid impacts close to landforms.[Image credit NASA]

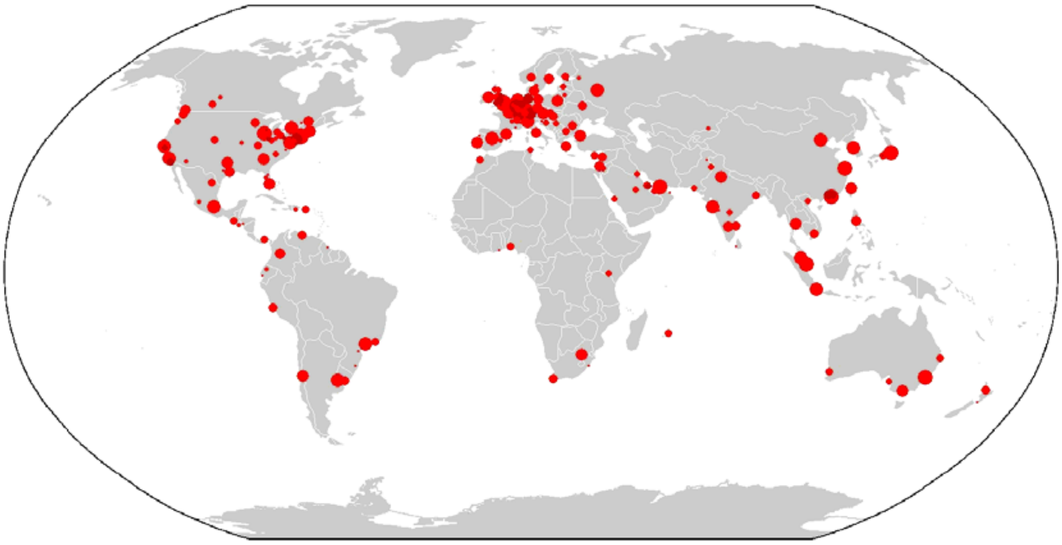


Figure 7b. Population centers of the world today clearly show that a global network of QBOLT systems could be located strategically across several metropolises, and powered by the existing and evolving transcontinental power grids that balance power needs across nations. This infrastructure allows round the clock targeting opportunities of rogue asteroids or cometary fragments employing ground based directed energy systems.[pic credit Global Cities, Wikipedia]

Collimation and Calibration of the QBOLT system

Collimation and calibration tests of the QBOLT system may be done by guiding the beam from Earth to very precise locations on the Moon or on those small objects or asteroid fragments passing by Earth, or even some of those near Earth Asteroids that are in temporary captured orbits around the Earth or Moon system.

QBOLT Ablative Thrust

As the QBOLT beam strikes the target, the intense energy causes surface material to ablate rapidly. The reactive thrusting forces due to this effect is comparable to exhaust ejecta from rocket engines The rate of ablation is dependent on a variety of factors including the power of the QBOLT beam, the characteristics of the material of the target as well as the dwell time. [Figure 8]. The reactive thrust will force vibrations on the body. The forced vibration may be tuned to the natural frequency of the asteroid or cometary fragment. As the energy accumulates in the body, with no path to vent, the amplitude will spike, causing the monolithic structure to fragment and shatter. The energy distribution on the rotation of the target asteroid needs to be taken into consideration.

Figure 8. The sheer intensity of the beam causing a high velocity plume of vaporized material that is comparable to rocket exhaust is sufficient to alter the trajectory of the bolide if the target is engaged far enough from Earth.[Picture credit Smithsonian Air and Space, P.Lubin]

Other Applications for QBOLT system

While the QBOLT system concept is proposed to mitigate the threat of rogue asteroid impacts on Earth’s population centers, it would clearly serve the dual purpose of deterrent, capable of neutralizing missiles and weapons of mass destruction during Earth entry phase as well. The QBOLT system may also be used to spectroscopically sample and characterize deep space objects.

Orbital debris is fast becoming a threat to high value assets in the Earth orbital regime and may pose moderate to severe risk for both outbound and incoming crewed vehicles if proactive steps to curb man made debris pollution are not initiated soon. Lasers have been suggested for ablating debris.[Bekey 1997, Vasile 2014] The QBOLT system could be used to remove debris from vital orbital regimes, preserving a precious regime from a cascade calamity known as the Kessler Syndrome.

Conclusion

Asteroidal bombardment is a natural phenomenon associated with solar system genesis and evolution. The Earth continues to be a target and a recent plot show the random distribution of events.[Figure 9.] Much literature to date on asteroid threat mitigation presents long term concepts for thwarting impact. The QBOLT concept proposes a benign architecture using existing technologies, while pushing the envelope, with no space segment elements involved but the target extraterrestrial bolide during its terminal Earth impact approach phase.

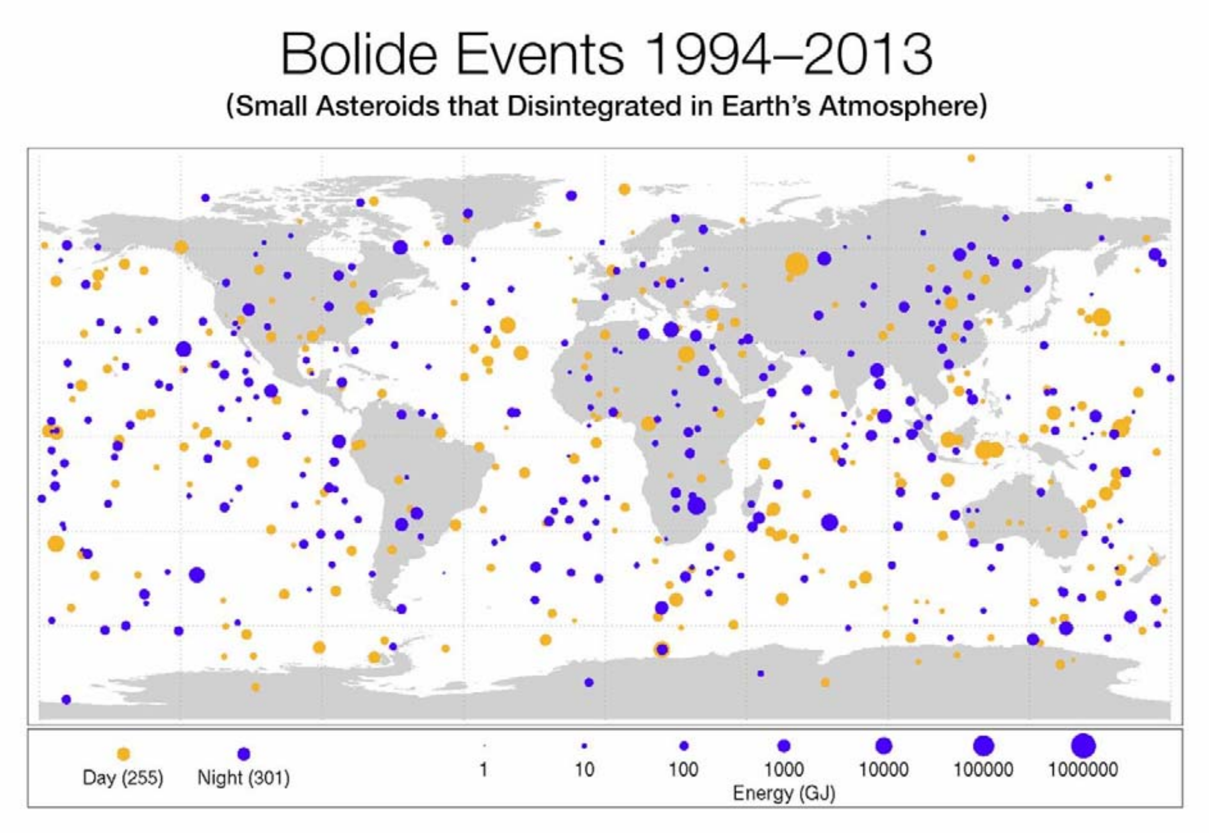


Figure 9. Asteroidal bombardment is a natural phenomenon associated with solar system genesis and evolution. The Earth continues to be a target. A recent plot shows the random distribution of events and imparted energies.[Credit NASA JPL Near Earth Object Program 2014]

Whether the scalable Directed Energy System is built in orbit or commissioned here on the ground or on another extraterrestrial surface like the Moon, it will provide strategic options for protecting humanity as well as an effective means for orbital debris mitigation. Of course, an Earth surface-based QBOLT global system network will utilize the power grid and may also be used as an effective deterrent against rogue actors wielding nuclear weapons of mass destruction such as ICBMs targeting population centers. As the energy density of laser directed energy systems scale up, and system equipment footprint shrink, it is possible to imagine very high power, highly mobile, directed energy systems that may be rapidly deployed to engage the threat, with little or short notice.

Further modeling is needed to identify the correct option for the specified threat. If we are able to mature and commission such a system, and if we detect the threat early enough, a QBolt system could be an effective and promising option to thwart a rogue asteroid impact by deflection or ablative methods. Operational issues and global policies need to be examined and verified to ascertain the merits, limitations and value of such a system.

Acknowledgments

This concept architecture was developed in the ASTE527 Space Architecting Studio in the Department of Astronautical Engineering within the Viterbi School of Engineering at USC in the Fall of 2013. This 3-unit elective is open to masters and doctoral candidates as well as professionals from the space industry seeking to advance skills in rapid alternative complex system concept creation.

The studio participants met once a week for 15 weeks in three-hour meetings. In the fall of 2013, the team project focused on Planetary Defense concepts. The entire slide set of the team project entitled "Eden Shield: Strategies and Concepts for Planetary Defense may be found at : http://denecs.usc.edu/hosted/ASTE/527_20111/06%20-%20Eden%20Shield%20-%20Concept%20and%20Strategies%20for%20Planetary%20Defense/

The authors would like to thank all the guest lecturers and reviewers who brought us up to speed in planetary defense and allied topics and provided insight into the latest strategies being pondered and implemented and to all those who made this a most productive exercise during this term.

References

AIAA Aerospace Design Engineers Guide. American Institute of Aeronautics and Astronautics, Washington DC.

"Asteroid Fast Facts." (2011). Asteroid and Comet Watch (blog) http://www.nasa.gov/mission_pages/asteroids/overview/fastfacts.html

Bagnell, R.(2013) High Energy Liquid Laser Area Defense System, Program Manager, DARPA Strategic Technology Office.

Bekey, I.,(1997) Project Orion: Orbital Debris Removal Using Ground-Based Sensors and Lasers, Second European Conference on Space Debris, Organized by ESA, held 17-19 March, 1997, ESOC, Darmstadt, Germany (1997), ESA-SP 393., p. 699

Boeing Company(2010)YAL-1 Airborne Laser(ABL)http://www.airforce-technology.com/projects/abl/

Boeing Company, Airborne Laser(2007) [[Web Photo].]. Retrieved from http://en.wikipedia.org/wiki/File:Airbornelaserturret.jpg

Britt, D.T., Yeomans, D., Housen, K., and Consolmagno, G.,(2002) Asteroid Densities. EAR-A-5-DDR-ASTEROID-DENSITIES-V1.1. NASA Planetary Data System

Carnelli, I., Ailor, W.,Tremayne-Smith, R., Editors.,(2013)Acta Astronautica, Volume 90, Issue 1, Pages 1-180 (September 2013), NEO Planetary Defense: From Threat to Action - Selected Papers from the 2011 IAA Planetary Defense Conference, http://www.sciencedirect.com/science/journal/00945765/90/1

Choi, C. (2013) Asteroids: Formation, discovery and exploration. Retrieved from http://www.space.com/51-asteroids-formation-discovery-and-exploration.html

CNET (2013) Laser Weapons at Sea, http://news.cnet.com/2300-11386_3-10012168.html

Ghez, A etal.,(2014) http://www.galacticcenter.astro.ucla.edu/

Gustafson G.(2008) Resonance. Retrieved from Dept Math, Utah University http://www.math.utah.edu/~gustafso/2250resonance.pdf pp 231-237

S. Jankov, Z. Cvetkovi´c and R. Pavlovi´c(2014) Binary Star Astrometry With Milli And Sub-Milli Arcsecond Precision, Astronomical Observatory, Volgina 7, 11060 Belgrade 38, Serbia

Lubin, P.M, etal.,(2013); Directed energy planetary defense. Proc. SPIE 8876, Nanophotonics and Macrophotonics for Space Environments VII, 887602 (September 24, 2013); doi:10.1117/12.2030228.

Lubin, P.M(2013) DE-STAR: A Planetary Defense and Exploration System & Beamed Power for Relativistic Propulsion, ICARUS Proceedings.

Mythbusters(2006), http://en.wikipedia.org/wiki/MythBusters_(2006_season)#Episode_46_.E2.80.93_.22Archimedes_Death_Ray.22

NASA(2013) "Impact Risk." Near Earth Object Program(blog), December 8, 2013. http://neo.jpl.nasa.gov/risk/

NASA Capability Road Map (CRM) 4. Advanced Telescope and Observatory (ATO). Chair: Lee Feinberg, Report (2007).

National Ignition Facility(2012) Seven Wonders of NIF, Lawrence Livermore National Laboratory, https://lasers.llnl.gov/about/nif/seven_wonders.php

Newport Corporation(2013) http://www.newport.com/About-Optical-Table-Performance-Specifications/168086/1033/content.aspx

ONR Office of Naval Research Maritme Laser Demonstrator(MLD), http://www.onr.navy.mil/

ONR-Office of Naval Research(2011) MLD Test Moves Navy a Step Closer to Lasers for Ship Self-Defense, Arlington, VA.

Parry, D.,(2013) Incoherent Combining of Fiber Lasers Developed for Directed Energy Applications http://www.nrl.navy.mil/media/news-releases/2013/incoherent-combining-of-fiber-lasers-developed-for-directed-energy-applications#sthash.cnCL4nrt.dpuf

Pravec, P., and Harris A.W.,(2007), VII Workshop on Catastrophic Disruptions in the Solar System, Alicante, Spain.

Sánchez P., Scheeres The D. J.,(2013) Strength of Regolith and Rubble Pile Asteroids, http://arxiv.org/abs/1306.1622, Cornell University Library.

Skinner G.K.etal(MASSIM Milli-Arc-Second Structure Imager Proposal (2007), NASA GSFC

Statler, T. Rotation of Near-Earth Asteroids, http://www.phy.ohiou.edu/~tss/NEA_Rotation.html
Vorontsov, M.A.,(2009)"Adaptive Array of Phase-Locked Fiber Collimators: Analysis and Experimental Demonstration,"Selected Topics in Quantum Electronics, IEEE Journal of , vol.15, no.2, pp.269,280,

The Seige of Syracuse, Archimedes Death Ray, http://www.ancientgreece.com/s/People/Archimedes/

Townes, C.H.,(1964) Nobel Lecture: Production of Coherent Radiation by Atoms and Molecules". Nobelprize.org. Nobel Media AB 2013. Web. 22 Jan 2014. http://www.nobelprize.org/nobel_prizes/physics/laureates/1964/townes-lecture.html

Vasile, M., Gibbings, A., Watson, I., Hopkins, J-M.,(2014) Improved Laser Ablation Model for Asteroid Deflection, Acta Astronautica, 103, 382-394, doi:10.1016/j.actaastro.2014.01.033

Yeomans, D.,etal., NASA Near Earth Object Program, http://neo.jpl.nasa.gov/ca/