Remote Manoeuvre of Space Debris using Photon Pressure for Active Collision Avoidance

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ABSTRACT

The Cooperative Research Centre for Space Environment Management and its participants, is developing a system to demonstrate remote manoeuvre of space debris using photon pressure for active collision avoidance. The Cooperative Research Centre operated by the Space Environment Research Centre (SERC) is comprised of participants from Industry (EOS Space Systems, Lockheed Martin Australia, Optus satellite Systems), Academia (Australian National University, RMIT University) and Government (National Institute of Information and Communications Research Institute, Japan and the Department of Industry, Commonwealth of Australia) Debris on debris collisions in orbital space are now a significant contributor to the growth of the space debris population. Left unchecked there is the possible (probable) runaway cascade (Kessler Syndrome caused by such collisions in popular orbits, possibly rendering these valuable orbital slots unusable in the future.

To reduce the collision risk there have been a number of proposals for removal of large debris objects, mostly involving rendezvous with and capture of large debris objects. However, none of the debris removal capture plans are particularly affordable and none reduce the current collision risk, only future population growth.

Rather than remove debris from orbit we will demonstrate the ability to avoid collisions by making small orbit changes to one or both objects in a predicted collision so that the intersection in time and space does not occur. The objects remain in orbit but do not crash and generate more collision debris.

As the ability to effect orbit change with a ground based laser is likely to be small it is necessary to start with very accurate predictions of the orbit conjunction. These will be made using laser ranging systems to provide high accuracy tracking of the intersecting objects and advanced orbit propagation and conjunction models. When a collision prediction is confirmed it is proposed to make small changes to the debris object's orbit (1mm/s change in along track velocity) using photon pressure from a ground based laser. Over time (24 hours) the small velocity change grows to a significant displacement and essentially de-phases the two orbits so that the two objects do not occupy the same space at the same time even though they remain in similar orbit geometry.

To effect an orbit change using photon pressure delivered from a ground based laser system, SERC and participants have augmented the EOS 1.8m SSA telescope with a high power (up to 18kW) CW laser and high order adaptive optics system including a sodium laser guide star module. These hardware components are coupled with developments in obit predictions, propagation, and atmospheric density modelling and conjunctions analysis. The laser and AO systems are now entering advanced stages on integration and alignment. The photon pressure remote manoeuvre system is scheduled to commence operations within the second half of 2019.

1. INTRODUCTION

The use of orbital space over the past 50 years has led to a growing hazard to navigation due to the risk of collision with space debris. NASA [1] and ESA [2] studies estimate that there are between 200,000-600,000 uncontrolled objects of 1cm diameter or greater in Low Earth Orbits (LEO). Each of these debris objects is capable of causing catastrophic damage should a collision occur with an active satellite.

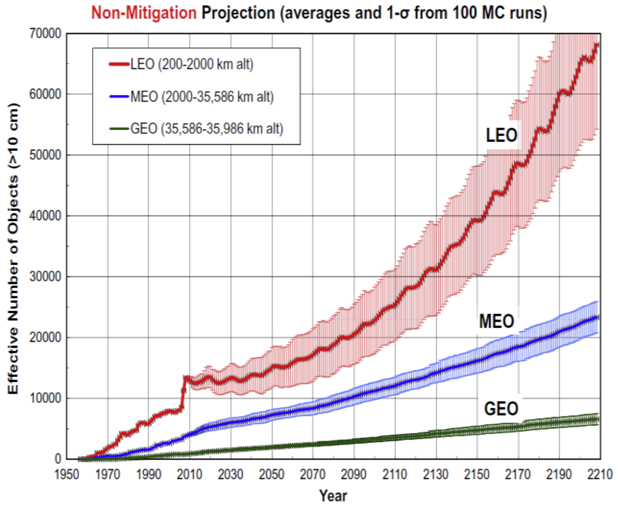

Fig 1. *Number of space objects (debris and active satellites) tracked over time. Tracking data until 2010, projection of future object populations thereafter. [3].*

For orbits below 400-500km altitude the lifetime of an uncontrolled object in orbit is ~10 years, limited by atmospheric drag which slows the object, thereby reducing its altitude. Eventually the drag is sufficient to cause re-entry into the Earth's atmosphere where it burns up. Above 400-500km band the lifetime of debris objects is typically hundreds to thousands of years as the atmosphere becomes more tenuous.

The space debris population is most dense in low earth orbits (LEO) around 800-1000km with near polar inclinations (sun-synchronous orbits SSO). In those regions, it is possible [4,5] that the spatial density has reached a point where the creation of debris due to debris-on-debris "feedback" collisions exceeds the removal of debris due to atmospheric drag which can lead to a runaway, known as the "Kessler cascade" [6]. If no corrective measures are taken, this cascade will decrease the average life-time of satellites and impose rising costs and increased risks on space operations.

Mitigation

The dominant source of new LEO debris is collision fragmentation. The obvious solution to prevent a cascading effect is to remove a sufficient number of debris objects to decrease the collision probability and stabilize the rate of fragment generation. A number of active debris removal (ADR) concepts have been proposed (see e.g. NASA/DARPA International Debris Removal Conference 2009). They fit into broad sub-categories:

1) **Active Satellite "tug" missions** with mechanisms to remove debris, usually through rendezvous, grappling mechanisms and a propulsion system.
2) **High Energy Pulsed laser systems** on 5-10m class telescopes that ablate (partially vaporize) debris to generate a recoil ΔV, which causes the debris to re-enter the Earth atmosphere (*e.g.,* the Orion project)
3) **Passive drag devices** which may include liquid/gas/particulate clouds, and so called sweepers that capture debris fragments.

To date, none of those approaches have been demonstrated and all imply additional risks:

Crash Avoidance

When an active satellite is predicted to have a "close" conjunction with a debris object, they generally have the option to maneuver (using on-board thrusters) into a new orbit, thereby avoiding a possible collision.

However, knowing that a crash is coming does nothing when two in-active debris objects are on collision course. While a collision of in active debris has few immediate consequences for satellite owners, all users of orbital space suffer when such an even occurs, and of course the probability of debris on debris collisions (with 20,000 tracked objects) is much larger than for active satellites (of which there are around one thousand).

A solution is needed to stop (or at least slow) the on-going cascade of debris collisions that threatens our use of some orbital slots. Launch mitigations strategies have been shown to reduce the rate of debris growth but not resolve the problem. De-orbiting some of the debris could solve the problem but is 10 or more years away and probably billions of dollars in cost to implement.

Mason et al [7] have proposed a very different approach to mitigation of collision risk and collision cascade by using photon pressure for remote maneuver of space debris. They proposed to use photon pressure to make very small changes to a space object's orbit to create a "near-miss" rather than a "hit" in cases where a collision is predicted.

2. SPACE ENVIRONEMTN RESEARCH CENTRE (SERC)

The Cooperative Research Centre for Space Environment Management and its participants, is developing a system to demonstrate remote manoeuvre of space debris using photon pressure for active collision avoidance. The Cooperative Research Centre operated by the Space Environment Research Centre (SERC) is comprised of participants from Industry (EOS Space Systems, Lockheed Martin Australia, Optus satellite Systems), Academia (Australian National University, RMIT University) and Government (National Institute of Information and Communications Research Institute, Japan and the Department of Industry, Commonwealth of Australia).

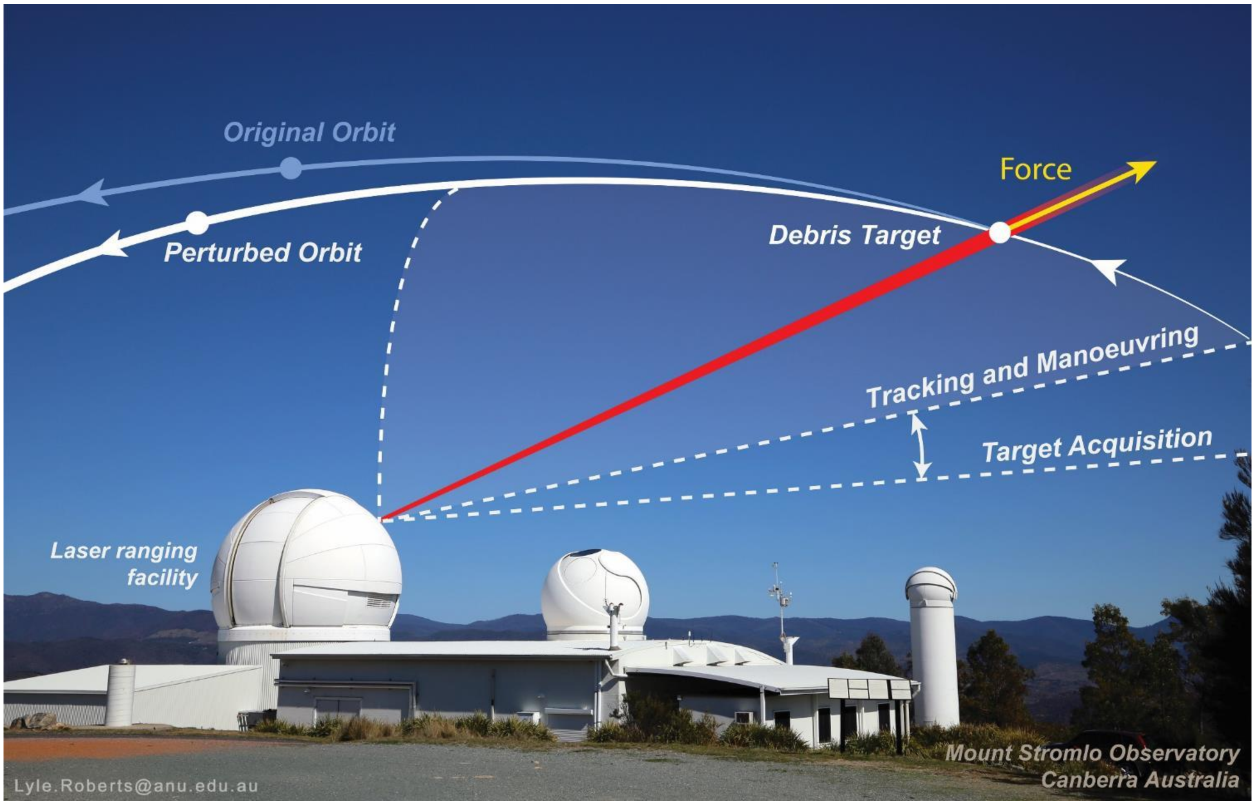

Fig 2: Planned laser engagement scenario from the EOS Space Research Centre, at Mt Stromlo near Canberra, Australia.

3. PHOTON PRESSURE FOR COLLISION AVOIDANCE

3.1 Photon Pressure

Basic physics tells us that photons of light carry both energy and momentum and photon momentum can be transferred from a source of light to solid object, by absorption of the light, called radiation pressure and discovered by Maxwell in 1871. This is the principle of the Nichols radiometer and solar sails.

The momentum that a single photon can deliver is small ($\sim 6.2 \times 10^{-28}$ kg.m.s^{-1} at 1064nm) but not insignificant. It can drive the vanes in a radiometer and in astrodynamics solar radiation pressure is one of the dominant sources for orbit perturbation. So clearly, if an illumination source of similar order of magnitude to the solar radiation pressure can be applied to an object, and controlled in the direction of application, then it is possible to affect the orbital parameters of an object, even a large space craft.

Photon Pressure operates on a different fundamental principle to previously conceived debris removal schemes which aim to de-orbit the debris. It addresses the debris problem by actively preventing imminent collisions, instead of bringing objects down to Earth.

The total work needed to perform debris collision avoidance is orders of magnitude less than active debris removal. Deorbiting an object using available radiation pressure would take centuries, but to retard an object slightly in its orbit using photon pressure need only take days, depending on object mass, illumination power and orbit parameters.

3.2 Tracking and Orbit Prediction Accuracy

To be useful for collision avoidance, the orbital modifications have to be larger than the uncertainties in orbital predictions.

The EOS Space Systems space debris tracking systems at Mt Stromlo have demonstrated [8, 9] high accuracy in orbit measurement and prediction. The Mt Stromlo tracking system provides ~1-2m rms accuracy in three dimensions and taking high accuracy observations it is then possible to make high accuracy predictions. The figure below shows the orbit error between predicted and measured location in space some 24 hours after the last measurement for a satellite at 850km.

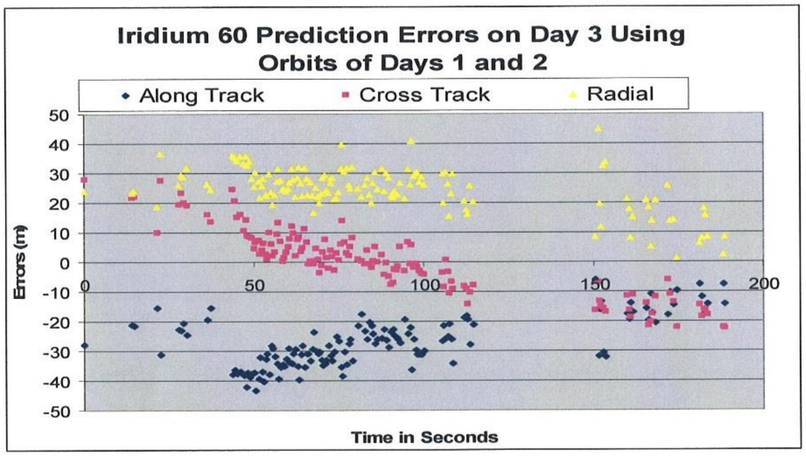

Fig 3. Orbit prediction error (compared with measured position) 24 hours after last prediction.

From this we can see that we can propagate and orbit out 24 hours with an along track error of ~ 40 m. This indicates that an orbit change of ~100m should be a measureable amount if pre and post laser tracking are employed.

3.3 Requited Velocity Change

Conjunction analysis based on high accuracy orbits derived from laser tracking can be performed up to a week in advance. This allows us to schedule a laser engagement with an object to be manoeuvred at least one day prior to the time of a predicted collision. This then allows 24 hours for any achieved along-track velocity change to create a 100m change in the orbit location.

As an example: for an object at 500km altitude the orbital velocity is over 7000 m/s. Over a 24 hour period this requires a change in orbital velocity of approximately 1 mm/s to open up a 100m change in position (along track) along the orbit.

3.4 Radiation Pressure Budget

SERC is currently developing a scaled (affordable) demonstration of remote manoeuvre in space. To minimize costs while we demonstrate feasibility of the photon pressure concept we will adopt a high-area-to-mass-ratio (HAMR) object in orbit (of which there are numerous examples) then we can scale the demonstration to attempt to retard an object that is ~20cm in optical cross section and 0.5kg in mass. (e.g. an Al plate that is 5mm thick and typical of much rocket booster debris).

The required momentum change ($\Delta p = \Delta v * m$) to obtain 1mm/s velocity change on a 0.5kg is 5×10^{-4} kg.m.s^{-1}. Detailed modelling shows that this momentum change can be effected using a 18kW CW laser (λ=1064nm) if concentrated into a half meter spot for several minutes, a time scale commensurate with satellite overhead passes. To concentrate the energy into a spot of this size the minimum requirement is a 2m class telescope/beam director, near diffraction limited laser and an Adaptive Optics system capable of compensating for the distortion caused by atmospheric turbulence (calculation is based on delivery of a Strehl ratio ~0.2-0.3).

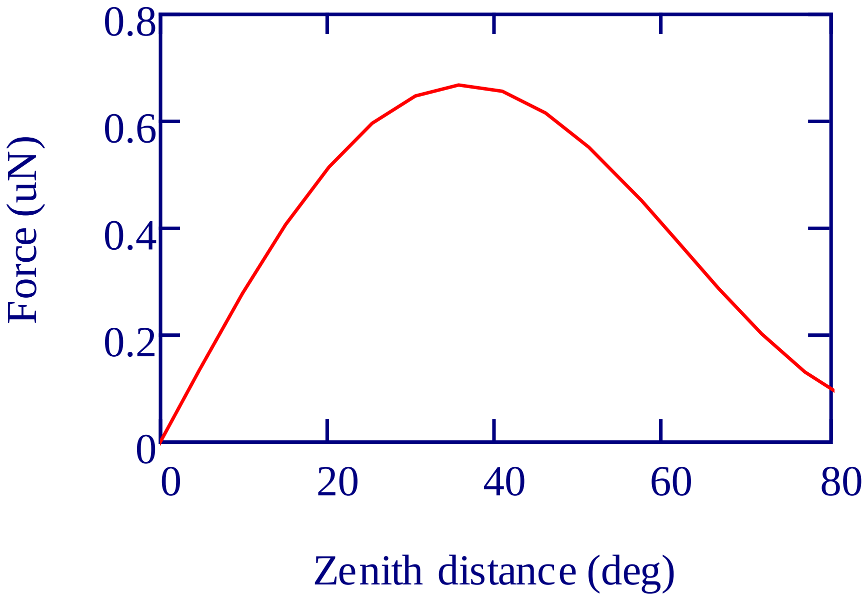

Fig 4: Plot showing predicted force vs zenith distance applied to an object at 600km altitude.

4. MT STROMLO DEVELOPMENTS

To provide an on-orbit demonstration of remote manoeuvre of a space object by radiation pressure the SERC and partners are upgrading the existing EOS Space Debris Tracking System located at Mt Stromlo, near Canberra Australia with a high order adaptive optics system including a sodium laser guide star, complete with point ahead capability as well as 18kW of CW laser power to be delivered at near diffraction limited beam quality and compensated for atmospheric distortions.

Table 1: Remote Manoeuvre System Parameters

Parameter	**Value**
Orbit Altitude	500 km
Target Diameter	20 cm
Target Mass	0.2 kg
Beam Director Diameter	1.8 m
Laser Power	18 kW
Laser Beam Quality (M^2)	1.2
Delivered Strehl	0.3

The project is now deep into the integration phase of the developments with the sodium laser recently moved from lab and installed on the 1.8m telescope. The AO system has been in place for some time and has demonstrated closing the loop on passive tracking (stars and satellites). The active tracking system must include a point ahead capability for the sodium laser as the light travel time from laser to target means that the target itself cannot be used as a reference beacon for the wave front sensors.

With the arrival of the sodium laser the active tracking AO loop can now be integrated and tested.

To effect the actual radiation pressure EOS and LMC have developed 18kW of CW laser power that is propagated through the adaptive optics system to the target object.

The coating for the deformable mirror has itself been a significant challenge. The coating has to survive the high average power of the CW laser (at 1064nm) but also provide high reflectivity at the sodium (589nm) wavelengths and tip-tilt reference ((600-800nm). This has led to a challenging coating with more than 32 layers but has finally be completed and provided more than 99.99% reflectivity at 1064nm as well as good (>85%) reflectivity at sodium tip-tilt reference wavelengths.

As noted, final integration and commissioning of the system is underway now and we hope to have measurable results on the sky before the end of 2019.

5. REFERENCES

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