“Catcher’s Mitt” as an Alternative to laser Space Debris Mitigation

Claude Phipps

Photonic Associates, LLC
200A Ojo de la Vaca Road
Santa Fe, NM 87508

Abstract. Other papers in this conference discuss the ORION concept for laser space debris mitigation. An alternative approach to removing space debris nicknamed “Catcher’s Mitt” has been proposed. In this concept, a block of low density solid material is placed in a precessing, elliptical, near-equatorial orbit to sweep out near-Earth space between about 400km and 1100km altitude where the hazardous debris objects reside. The concept could work by vaporizing or trapping the objects, or slowing them enough for re-entry on passing through the “mitt.” To compete with ORION, an alternative must intercept 300k objects in two years. We demonstrate two difficulties with the “mitt” idea. The first of these is that even if it is made of aerogel with 1mg/cm^3 density, the required mass is about 2MT. The second problem is that an elliptical mitt orbit covering the 400 – 1100 km debris altitude range would suffer ram pressure that would have to be compensated by a 10kN-thrust engine operating continuously for the mission duration, which is assumed to be two years.

Keywords: Catcher’s mitt, space debris, ORION
PACS: 07.87.+v, 95.40.+s, 94.05.Hk, 42.62.-b

THE NEAR-EARTH SPACE DEBRIS PROBLEM

One result of 35 years of space activity is that there are now several hundred thousand pieces of space debris larger than 1cm in near-Earth orbit. Debris in the 1-10-cm size range are especially hazardous to near-Earth space assets because they are not tracked, but can cause fatal damage. Larger objects can usually be tracked and avoided (although this is becoming more difficult with time), while spacecraft shielding is practical for smaller objects. The 1 – 10-cm debris were created from explosions or mutual collisions and, because of the range of launch latitudes and inclinations of the source objects, their typical velocity in the reference frame of an orbiting spacecraft is 12km/s. Their density maximizes in the 400- to 1100 km altitude range.

The debris problem has become more urgent recently. In February 2009, an American communications satellite collided with a Russian Kosmos satellite, spreading debris around the Earth and prompting concerns about the safety of the final Hubble service mission. In March, 2009, the International Space Station crew spent the morning taking cover in a Soyuz capsule to reduce their cross-section in the event of collision with a space debris object whose track might have intercepted the Space

Station. Mutual collisions will continue to increase the debris density until the problem is dealt with.

The concept of removing the debris with a high-power, pulsed, ground-based laser system was first presented in 1993 [1]. Laser space debris removal uses a high-intensity pulsed laser beam to ablate (not pulverize) a fraction of the debris itself in an orientation such that the debris is slowed sufficiently to re-enter the atmosphere and burn up. Pulsed lasers are much more effective for this purpose than CW lasers, because the latter tend to melt the target and create more debris.

The concept was later named ORION by NASA headquarters staff, who authorized a concept validation study in 1995 [2, 3] . The study concluded that the capability to remove essentially all dangerous orbital debris in the 1 – 10-cm range between 400 and 1100 km altitude was feasible within two years, and that its cost would be modest relative to the likely costs to shield, repair, or replace high-value spacecraft that could otherwise be lost to debris impacts.

CATCHER'S MITT

An alternative concept nicknamed "Catcher's Mitt" has been discussed [4]. In this concept, a block of low density material is placed in a precessing, elliptical, near-equatorial orbit to sweep out near-Earth space between about 400km and 1100km altitude where the hazardous debris objects reside. The concept could work by vaporizing or trapping the objects, or slowing them enough for re-entry on passing through the "mitt." There are two problems with the concept.

First Problem: Mass

To compete with ORION, an alternative must intercept N = 300k objects in two years time. Given the above altitude range, the mean debris number density is

$$n = N/V = 2.7\text{ E-6 km}^{-3}. \tag{1}$$

where volume

$$V = 4\pi\left[R_E + (h_1 + h_2)/2\right]^2 (h_1 - h_2) \quad , \tag{2}$$

h_1 = 400km, h_2 = 1100km and R_E = 6378 km is Earth's radius. To remove N objects in two years, the reaction rate must be

$$R = 4.7\text{E-3/s} = n\,\sigma\,v, \tag{3}$$

and, taking a conservative figure of 10 km/s for relative velocity v between mitt and debris, the mitt cross-section σ must be 174 km^2.

For the mitt material, we take aerogel with a density ρ = 1 mg/cm^3 = 1E9 kg/km^3. If the mitt is Δx cm thick, its mass is

$$m = \rho\sigma\Delta x = 1740\ \Delta x \text{ tonne.} \tag{4}$$

Now the problem is to determine the required thickness Δx to just slow the debris particle by Δv = 150m/s, which is adequate to de-orbit typical low Earth orbit debris. For a debris particle with effective thickness dimension and density ρ_p intersecting gel with density ρ_gel, we have

$$-\rho_\mathrm{p}\dot{v}\,d = p = C\rho_\mathrm{gel}v^2 \tag{5}$$

where constant C is a factor proportional to $\rho_\mathrm{p}^{2/3}$ which will be developed later to correct for the additional effective area being swept out of the gel target due to the shock front developed by the supersonic particle.

Eq. (5) is a Riccati equation of form

$$\dot{y} + y^2/a = 0 \tag{6}$$

and the solution appropriate to our case is

$$v(t) = \frac{\rho_\mathrm{p}d}{C\rho_\mathrm{gel}(t+k)} \tag{7}$$

where

$$k = \frac{\rho_\mathrm{p}d}{C\rho_\mathrm{gel}v_\mathrm{o}} \tag{8}$$

and v_o is the particle's initial velocity relative to the mitt and k is determined by requiring the particle to slow by Δv at the end of travel time T,

$$T + k = \frac{\rho_\mathrm{p}d}{C\rho_\mathrm{gel}(v_\mathrm{o} - \Delta v)} \quad . \tag{9}$$

The distance traveled by the particle while slowing is equal to the required mitt thickness:

$$\Delta x = \int_0^T v(t)\mathrm{d}t = \frac{\rho_\mathrm{p}d}{C\rho_\mathrm{gel}}\ln\left(\frac{T+k}{k}\right) = \frac{\rho_\mathrm{p}d}{C\rho_\mathrm{gel}}\ln\left(\frac{v_\mathrm{o}}{v_\mathrm{o} - \Delta v}\right) \quad . \tag{10}$$

In order to determine C, we ask what gel thickness is predicted by Eq. (10) with $C = 1$ to slow the particles to the local speed of sound, $v_\mathrm{o} - \Delta v = c$ = 200m/s in the gel material. The results are shown in Table 1.

TABLE 1. Mitt Thickness Δx (cm) with $C = 1$ Required to Slow Particles to Speed c

Particle Density ρ_p (g/cm^3)	**Particle Diameter *d* (cm)** 1	 10
1	3900	3.9E4
9	3.5E4	3.5E5

We then anchor this calculation to a different one in which we compute the distance traveled by the incident particle if it stops after creating a void of melted material with volume equal to that of the Mach cone with half angle c/v_o. Using T = 1473K for SiO_2 and $C_v = 0.84\ Jg^{-1}K^{-1}$, the deposited energy density is $1.24 J/cm^3$ melted, and the cone volume

$$V = \frac{\pi}{12}\frac{c^2(\Delta x)^3}{v_o^2} = \frac{\pi}{12}\frac{\rho_p d^3 v_o^2}{\rho_g C_v T} \tag{11}$$

gives

$$\Delta x = \left[\frac{\rho_p d^3 v_o^4}{\rho_g C_v T c^2}\right]^{1/3} \tag{12}$$

There results:

TABLE 2. Mitt Thickness Δx (cm) from Gel Melt Calculation

	Particle Diameter *d* (cm)	
Particle Density ρ_p (g/cm^3)	1	10
1	580	5800
9	12100	1.21E4

TABLE 3. Correction Factor *C* to Slowing Calculation

	Particle Diameter *d* (cm)	
Particle Density ρ_p (g/cm^3)	1	10
1	6.71	6.71
9	29.0	29.0

From which:

TABLE 4. Mitt Thickness Δx (cm) From Eq. (10), with C from Table 3, Required to Slow Particles by Just 150m/s

	Particle diameter *d* (cm)	
Particle Density ρ_p (g/cm^3)	1	10
1	2.25	22.5
9	4.68	46.8

Table 4 shows the results for particles of size 1 and 10 cm and densities 1 (representing polymers) and 9 g/cm^3 (steel). To slow all these particles, the Table shows that the mitt thickness must be 47 cm, so mitt mass from Eq. (4) must be m = 81 kT on orbit. With current launch technology, m/M = 4.8% [5], so launch vehicle mass M would be 1.7 MT, and would require a thruster capable of 3.8 billion pounds thrust at liftoff, 500 times larger than any thruster ever built. Even if the object were divided into 500 payloads, the cost would be prohibitive.

Problem 2: Orbit Maintenance

Even though atmospheric density at altitude h_1 is just 3.7E-15 g/cm^3 [6], ram pressure at orbital velocity is $p = \rho v^2$, which works out to 438N/km^2. For our aerogel block with cross-sectional area 174 km^2, the thrust required to oppose orbital decay at h_1 is 74kN. This thrust is dramatically reduced at higher altitudes, so the approximate average thrust required to maintain orbit, averaged over an orbit, is 12kN. In other words, a rocket developing approximately 2,500 pounds thrust is required to operate continuously for the life of the mission (two years). This would require a fuel mass of 1.54E8 kg, twice the mass of the mitt. The associated costs (at least 3E12$ at current costs of 20k$ per kg lifted to low Earth orbit [5]) would be unacceptable. If mitt perigee is raised until this thrust becomes reasonable (e.g., 4.4N at 1000km), the mitt fails to address the debris problem except for the small subset of very elliptical or very high altitude debris orbits.

SPACECRAFT PROTECTION: WHERE A MITT WOULD WORK

To protect an individual spacecraft, a “cocoon” of aerogel would work, providing it is thick enough to nearly stop 10-cm objects. Table 4 shows it would need to be 47 cm thick. Apertures would need to be provided to permit the spacecraft to see anything, but their collective cross-section would be orders of magnitude less than that of the spacecraft, not to mention the smaller acceptance solid angle of a port through the gel. If a reasonable goal would be to increase the spacecraft lifetime by just one order of magnitude, a great deal of protection could be provided without limiting the spacecraft functionality in a major way. Because air at 1 atmosphere has about the same density as the aerogel considered here, gas-filled balloons or similar transparent containers 50 cm in diameter could provide protection to an individual spacecraft while giving improved visibility compared to what aerogel would offer. These could be easily redeployed when punctured.

DISCUSSION

We have shown that a passive solid absorber “mitt” is ineffective as a method of re-entering near-Earth space debris. However, a low density material surrounding an individual spacecraft would provide local protection.

ACKNOWLEDGMENTS

This work was supported by Photonic Associates, LLC’s internal research and development fund.

REFERENCES

1. C. R. Phipps, *AIP Conference Proceedings* **318**, Laser Interaction and Related Plasma Phenomena, 11th International Workshop, Monterey, CA October, 1993, George Miley, ed. American Institute of Physics, New York (1994)pp. 466-8
2. C. R. Phipps, H. Friedman, D. Gavel, J. Murray, G. Albrecht, E. V. George, C. Ho, W. Priedhorsky, M. M. Michaelis and J. P. Reilly, *Laser and Particle Beams*, **14** (1) (1996) pp. 1-44
3. C. R. Phipps in *Project ORION: Orbital Debris Removal Using Ground-Based Sensors and Lasers*, J. W. Campbell, ed. NASA Marshall Spaceflight Center Technical Memorandum 108522 October 1996
4. See http://ceramics.org/ceramictechtoday/materials-innovations/aerogel-worlds-universes-largest-catchers-mitt/
5. C. R. Phipps, J. P. Reilly and J. W. Campbell, “Optimum Parameters for Laser-launching Objects into Low Earth Orbit”, J. Laser and Particle Beams, **18** no. 4 pp. 661-695 (2000)
6. C. R. Phipps in *Project ORION: Orbital Debris Removal Using Ground-Based Sensors and Lasers*, J. W. Campbell, ed. NASA Marshall Spaceflight Center Technical Memorandum 108522 October 1996