Nonlinear-optical approach to problem of space debris tracking and removal

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Space debris threats and application of phase conjugation methods for concentrating the debris illumination

- Nearly 90% of orbital debris has dimensions ~ 1-5 cm. This debris is not tracked.
- Debris removal demands a high density in illumination laser energy, though it is restricted by the atmospheric turbulence.
- Space debris illumination concentration by laser point narrowing can be achieved by means of phase conjugation of the debris scattered illumination.
- When phase conjugation compensates for turbulent distortions, the conjugated signal will be concentrated on the debris to an accuracy that is determined not by the turbulent scattering angle (~10^{-5} \; \text{rad}), but instead by the receiving aperture of laser amplifier (e.g., ~ 5 \cdot 10^{-7} \; \text{rad} for the primary mirror of 200 cm).
What is phase conjugation and four wave mixing?

Brillouin enhanced four wave mixing

Phase conjugation mirror
Nonlinear optical (BEFWM) laser image amplifier

- The sensitivity is limited by quantum noise and is near $4.8 \cdot 10^{-19}$ J (approximately two photons) per pixel;
- Extremely narrow frequency band corresponds to two frequency-temporal modes (input spectral band $\sim 0.001$ nm and response time of $\sim 30$ nsec);
- Comparatively wide field of view (350 X 350 pixels in image);
- High coefficient of amplification (amplifies weak signal by $\sim 10^{12}$).

A two-step concentration of laser illumination of orbital debris is sufficient for small-scale debris tracked by the nonlinear optical system at distances from 600 to 800 km even for a moderate level of illumination pulse energy (~ 10 J).
The scheme for concentrating illumination

Laser facility for model experiments at open-air test field with turbulence scaling
Creation of artificial turbulence

Desired $r_0 \sim 1-2 \text{ см}$

$r_0 \approx (k^2 C_n^2 L)^{-3/5}$

$C_n^2 \approx 10^{-12} C_T^2$

$C_n^2 = [cm^{-2/3}] \quad C_T^2 = [\text{deg}^2/cm^{2/3}]$

$C_T^2 |z_1-z_2|^{2/3} = (dT/dz)^2 |z_1-z_2|^2$

Three heating-fans (MASTER B15) provide the required 50 kW
Measurements of turbulent strength along the path

With heating $C_n^2 = (4-20-170) \times 10^{-14} m^{-2/3}$

Without heating $C_n^2 = (2-5-7) \times 10^{-14} m^{-2/3}$
Detection of illumination concentration on remote target
Active impact on space debris using intense lasers

Physical mechanisms of recoil impulse generation:

• Developed surface evaporation of the debris

The maximum efficiency of recoil impulse at laser intensity of $I \sim 10^6 \text{ W/cm}^2$

• Optical breakdown in the vapor. Laser-plasma absorption

For near IR lasers ($\lambda = 1.06$ $\mu$m): $I > 5 \times 10^8 \text{ W/cm}^2$
Propulsion of SD object to elliptical low-perigee orbit

$$E = \frac{mv^2}{2} - \frac{G \cdot M \cdot m}{r}$$

Total energy of SD object

$$v = v_r + v_\varphi \quad \overrightarrow{L} = [\overrightarrow{r}, \overrightarrow{p}] = m \cdot v_\varphi \cdot r$$

$$r_{\text{min}} = \frac{-GMm}{2E} \left(1 - \sqrt{1 + \frac{2LE}{(GM)^2 m^3}}\right)$$

$$v_r = 0$$

Round orbit: $E_0, v_0, L_0, p_0$

Recoil change of energy and angular momentum:

$$\Delta E = E_1 - E_0 = \frac{m}{2} (v_1^2 - v_0^2) = \frac{p^2}{2m} - \frac{p \cdot v_0}{\sqrt{2}}$$

$$\Delta L = L_1 - L_0 = -\frac{p \cdot r_0}{\sqrt{2}}$$

Elliptical orbit: $E_1, v_1, L_1, p_1$

SD object: $m = 1$ kg; $v_0 = 7.62$ km/c

at $r_0 = R_\text{s} + h_0 = 6371$ km + 500 km

this SD object shifts to desirable $r_{\text{min}} = 200$ km

if recoil momentum is provided $p = 114$ kg·m/c

taking into consideration a mass defect $\Delta m$ caused by evaporation we have $p = 106.7$ kg·m/c
Laser energy evaluation for SD object propulsion

It is assumed for SD \( m = 1 \) kg, velocity \( v_0 = 7.62 \) km/c
a rebound velocity of vapoured part \( - v_{Al} \)
(in the movable frame of reference)
we have got \( v_{Al} \) from relation:
\[
\frac{m_{Al} v_{Al}}{2} = \frac{3}{2} kT
\]
For Aluminium atom \( m_{Al} = 4.484 \cdot 10^{-26} \) kg
And temperature \( T = 2770 \) K \( v_{Al} = 1.60 \) km/c and \( \Delta m = 6.7\% \ m \)

We have got a desirable energy of laser pulse by using Aluminium parameters

- Melting heat \( \lambda = 3.9 \cdot 10^5 \) J/kg
- Evaporation heat \( L = 9.22 \cdot 10^6 \) J/kg
- Heat capacity \( c = 930 \) J/(kg·K)

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W = \Delta m(\lambda + L + c\Delta T) = \Delta m(3.9 \cdot 10^5 + 9.22 \cdot 10^6 + 930 \cdot 2770) = 807 \) kJ
\]
As a conclusion, a laser pulse energy of 1 kJ (at repetition rate of 100 Hz and efficiency of conversion into the recoil pulse \~10\%) is acceptable to provide desirable propulsion during one pass of SD object by orbit

Hence, a laser output \~ 1kJ x 10 \) ns x 100 Hz looks sufficient for small LEO orbital debris removal using non-linear optical laser energy concentration.
Possible full-scale experiment of model SD object control by laser amplifier with BEFWM

**Purposes:**
- Measurements of recoil pulse;
- Investigation of SD movement dynamics (rotation, oscillations, etc.);
- Influence of SD material and laser parameters

- The poor quality primary mirror is acceptable because of using phase conjugation technique.
- Laser parameter combination of 30 J x 10 ns x 30 Hz is enough to shift a model LEO object by ~100 m of orbit height due to the laser recoil impact during one orbital pass