P04

High-precision Trajectory Calculation of Small/medium Sized Orbital Objects Realizing Laser Active Debris Removal

レーザーを用いた小型/中型デブリの除去を実現するための高精度軌道計算

〇SHIBATA Kazunori (Osaka University), UCHIDA Shigeaki (Coherent Systems Co., Ltd.)
〇柴田一範（大阪大学），内田成明（(株)コヒーレントシステムズ）

In low Earth orbit(LEO), over a million of small/medium space debris objects are estimated to exist. A laser-based active debris removal for such objects has been proposed. One challenging problem of this method is to focus a high power laser on the debris surface. If the laser is irradiated from the ground, the target is 400 km above and flies at 8 km/s. To solve this problem, highly accurate orbit prediction is necessary. In addition, it must also be ensured that the debris will fall to Earth certainly within a short period of time after deorbiting. In the presentation, we will describe analytical methods for trajectory calculations to answer these questions and show some specific results. Our analysis method guarantees that the laser will always be able to focus on the debris surface. For example, a computational method is realized which confines the orbital prediction error can be less than 1 cm within 10 seconds after finding the debris.

低軌道(LEO)には、10cm 未満の小型/中型のデブリ(lethal non-trackable, LNT)が数 100 万個あると推定されている。地上もしくは軌道上に配置したレーザーを用いて、LNT を除去する方法が提案されている。これを実現するための大きな問題は、十分な強度のレーザーをデブリの表面に集光することである。仮に地上からレーザーを照射する場合、高度 400km を秒速 8km で飛行する、直径 10cm の対象に集光する必要がある。これを可能にするために cm オーダーでの軌道予測が要求される。しかし、大気の影響や太陽の光圧など、定量化が困難な摂動の影響も考慮する必要がある。また、軌道変更後のデブリが、短時間のうちに確実に地球に落下することも保証せねばならない。本講演では、これらの問題に答えるための軌道計算の解析手法を述べ、具体的な計算例を示す。我々の解析手法はレーザーがデブリ表面に必ず集光できることを保証する。例えば、デブリ発見から 10 秒後の軌道予測の誤差を 1cm に抑える計算手法を構築した。

レーザーを用いた小型/中型デブリの除去を実現するための高精度軌道計算 (Laser ADR for LNT)

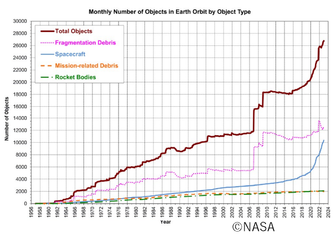
柴田　一範 (Kazunori Shibata)
大阪大学レーザー科学研究所 (Osaka Univ.)

Background

Space debris is increasing at an accelerating rate.
In low earth orbit (LEO),"medium-sized" debris in the 1 cm to 10 cm size range is called lethal-nontrackable (LNT).
LNT is a very troublesome debris with the following characteristics

- Extremely difficult to find and track
- Relative velocity at impact can reach 15 km/s
- Estimated to be over 1 million in existence

Active debris removal (ADR) of LNT is already a challenge for sustainable space development.



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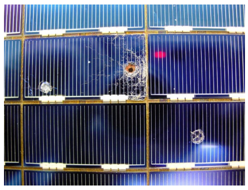
Impact mark on a solar panel of the Hubble Telescope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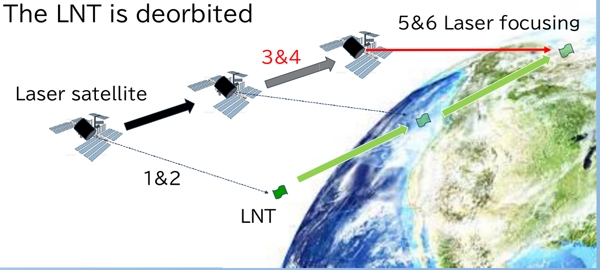
Laser-driven ADR

1. A LNT is detected by chance
2. Estimate the position and velocity at a certain time (t=0) by multiple measurements
3. **Predict the trajectory(below $s(t)$)**
4. **Prepare an intense laser for deorbiting**
5. Irradiate the laser and cause ablation
6. The LNT is deorbited



Real vs numerical trajectories

The real trajectory $\boldsymbol{r}(t)$ is determined by the force $\boldsymbol{F}$.

$$\boldsymbol{r}'' = \boldsymbol{F}(\boldsymbol{r}, \boldsymbol{r}', t)$$

It is impossible to know $\boldsymbol{F}$ exactly (e.g. the atmospheric drag and solar pressure). The force is divided in two parts.

$$\boldsymbol{F} = \boldsymbol{F}_{\mathrm{NC}} + \boldsymbol{F}_{\mathrm{dis}}$$

$\boldsymbol{F}_{\mathrm{NC}}$ represents the forces whose function forms are specified with sufficient precision.
The numerical trajectory is calculated by this force.

$$\boldsymbol{s}'' = \boldsymbol{F}_{\mathrm{NC}}(\boldsymbol{s}, \boldsymbol{s}', t)$$

Question: How large is the error between the real and numerical trajectories ?

$$|\boldsymbol{r}(t) - \boldsymbol{s}(t)| < ?$$

Three constants L,M,A

From $\boldsymbol{F}_{\mathrm{NC}}$, two constants are introduced in the form of Lipschitz condition.

$$|\boldsymbol{F}_{\mathrm{NC}}(\boldsymbol{a}, \boldsymbol{a}', t) - \boldsymbol{F}_{\mathrm{NC}}(\boldsymbol{b}, \boldsymbol{b}', t)| \leq L|\boldsymbol{a} - \boldsymbol{b}| + M|\boldsymbol{a}' - \boldsymbol{b}'|$$

Unknown part $\boldsymbol{F}_{\mathrm{dis}}$ is estimated by models.

$$|\boldsymbol{F}_{\mathrm{dis}}| \leq A$$

Definitive error evaluation

Observation errors (at step 2) turn into the initial value errors.

$$r_{err} = |\boldsymbol{r}(0) - \boldsymbol{s}(0)|, \quad v_{err} = |\boldsymbol{r}'(0) - \boldsymbol{s}'(0)|$$

We gave an upper bound on the orbit prediction.

$$|\boldsymbol{r}(t) - \boldsymbol{s}(t)| \leq \frac{A}{L}\left(-\frac{\lambda_-}{\sqrt{M^2+4L}}e^{\lambda_+ t} + \frac{\lambda_+}{\sqrt{M^2+4L}}e^{\lambda_- t} - 1\right) + \frac{r_{err}}{\sqrt{M^2+4L}}\left(-\lambda_- e^{\lambda_+ t} + \lambda_+ e^{\lambda_- t}\right) + \frac{v_{err}}{\sqrt{M^2+4L}}\left(e^{\lambda_+ t} - e^{\lambda_- t}\right)$$

where

$$\lambda_{\pm} = \frac{M \pm \sqrt{M^2+4L}}{2}$$

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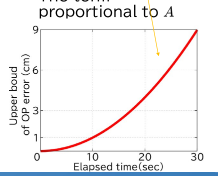
Example

L=4.49×10^{-6} (1/s^2)
M=1.46×10^{-4} (1/s)
A=1.99×10^{-4} (m/s^2)

Altitude is 400～500km.
The EGM2008 model is used for the Earth's gravity.

The term proportional to A



Conclusions & next assignments

- We show that a precise orbit prediction is possible
  - Within 10 seconds, the error can be less than 1cm
  - An intense laser can be focused on the LNT with relative speed of 10km/s
- We are going to treat the rest problems to realize the laser ADR for LNT [collaboration with Power laser co. ltd.]

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