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デブリの軌道・回転運動把握のための SLR 反射器(Mt. FUJI)の開発

Development of SLR Reflector (Mt.FUJI) for Grasping Orbital and Rotational Motion of Debris

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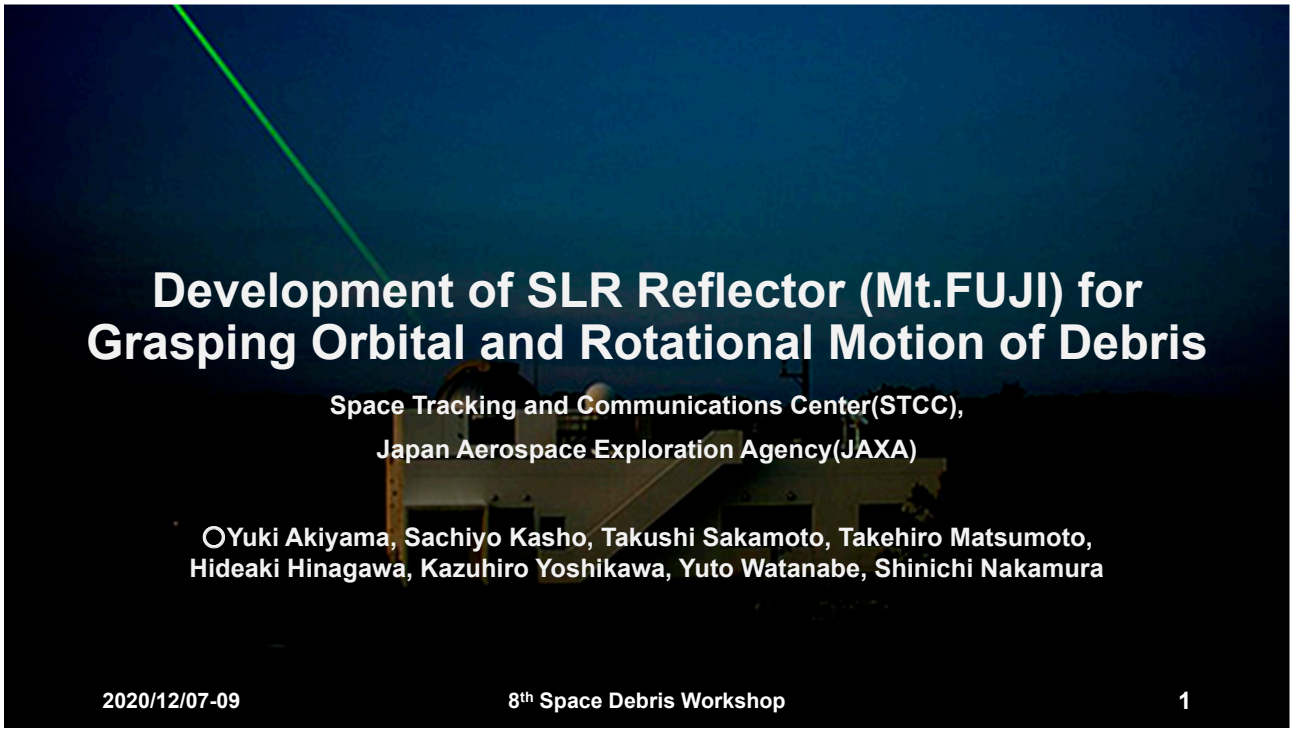
近年, 宇宙環境の急激な混雑化が進んでおり, 宇宙状況把握(SSA)が国際的な課題となっている. 通常宇宙ゴミ(デブリ)は, レーダ観測や光学観測により軌道把握がなされるが, 地上からの視認性の悪さや機器的制約などにより, 位置決定精度はせいぜい数十 m オーダである. 近年ではデブリへのランデブー・捕獲を行う能動的デブリ除去(ADR)も盛んに検討されている. ADR では予めデブリの軌道・回転運動を把握している必要がある一方で, 地上からデブリの回転運動を把握する技術は未確立である. 飛翔体が反射器を搭載していれば, 衛星レーザ測距(SLR)により数 cm オーダで軌道決定, さらに軌道決定残さから回転運動の推定が可能である. 従来, 反射器は特注品であり大型・高価であった. しかし, 反射器が安価な市販品となれば, 将来デブリとなる物体に搭載でき, 軌道・回転運動の把握の一助となる. そこで, JAXA では小型・軽量・安価をコンセプトに汎用的な反射器(Mt.FUJI)の開発を 2018 年度より開始した. 本発表では Mt.FUJI の概要について報告する.

The dawn of space engineering development brought the rapid pollution and congestion of the space environment due to orbital debris. Therefore, space situational awareness (SSA) has become an international issue. Conventionally, orbital debris can be tracked by radar and/or optical observations. However due to poorness of their visibility from the ground and constraints of observation systems, their positioning accuracy is on the order of tens of meters at most. In recent years, active debris removal (ADR), which performs rendezvous and capture of debris, has been actively studied. Although it is necessary to grasp the orbital and rotational motion of orbital debris in advance, the techniques for grasping the rotational motion of orbital debris from the ground has not been fully established yet. If the space vehicle is equipped with one or more reflectors, it is possible to determine its orbit on the order of several cm by satellite laser ranging (SLR), and to estimate the rotational motion from the orbit determination residuals. The reflectors developed and installed in Japan and overseas were custom-made, large, and expensive. If reflectors become inexpensive commercial products, they can be mounted on objects that will become orbital debris, it will help to grasp the orbital/rotational motion. Therefore, JAXA started development of a general-purpose reflector (called Mt.FUJI) in 2018 with the concept of small size, light weight, and low cost. In this presentation, we report the overview of Mt.FUJI.



Development of SLR Reflector (Mt.FUJI) for Grasping Orbital and Rotational Motion of Debris

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Contents

1. Introduction

- SSA(Space Situational Awareness) is an international issue. Debris can be tracked by radar and/or optical observations, however due to poorness of its visibility from the ground, its positioning accuracy is on the order of tens of meters at most.
- In ADR(Active Debris Removal), it is necessary to grasp the orbital and rotational motion of debris in advance. However, the techniques for grasping the rotational motion of debris from the ground has not been established yet.

Break through these issues by SLR (Satellite Laser Ranging) and LRA(Laser Reflector Array) !

Development purpose:
Development of compact, lightweight, inexpensive general-purpose LRA(Mt. FUJI)

Research purpose:
Demonstration of Mt.FUJI performance and evaluation of rotational motion estimation method by SLR

- Small space objects cannot mount LRAs
- Little benefit to universities and businesses at expense of increased weight and development costs.
- Poor visibility after becoming debris

Large, and Heavy / Custom -made / Expensive → former LRA

former LRA → OD / Rotation Estimation?

- Key device for high precision orbit determination
- Although attracted attention as a means of estimating rotational motion, not yet evaluated estimation accuracy since true rotational motion of target object is unknown,

Mt.FUJI: MulTiple reFlector Unit from Jaxa Investigation

- More space objects can mount LRAs
- Rich visibility after becoming debris.
- Possible to grasp the orbit with high accuracy.
- Contributes to SSA

Small and Light / general-purpose / Inexpensive → JAXA Developed LRA Mt.FUJI

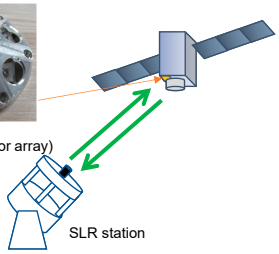
JAXA Developed LRA Mt.FUJI → OD / Rotation Estimation

- Performance demonstration of Mt.FUJI can be performed by using HTV-X.
- The world's-first evaluation of rotation estimation accuracy by SLR and LRAs since true value of HTV-X's rotational motion are known.
- Contributes to ADR

2. What is SLR?

SLR : Satellite Laser Ranging
High precision ranging system that measures the distance between a SLR station and a target object by measuring time from shooting laser pulse from SLR station toward a target mounting LRA to detection the reflected pulse.

LRA
(laser reflector array)



SLR

- High accuracy
- Verification of other orbit determination methods
- No electrical I/F for space object

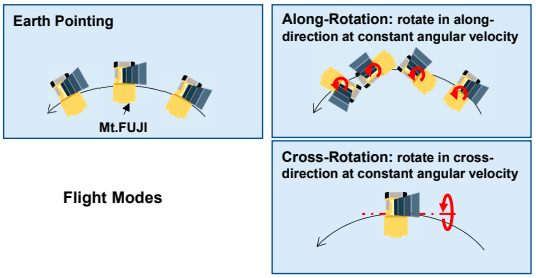
- Sensitive to weather
- Interference with sensors mounted on space object

- About 40 SLR stations in the world (3 domestic stations)
- Laser ranging activities are organized under the International Laser Ranging Service (ILRS)
- Prediction data (CPF) and acquired SLR data (FR / NP) are uploaded to the public server which anyone can freely download and use it
- FR is a correction of raw observation data
- NP is a compressed version of FR in a specific period
- New SLR station is under construction in Tsukuba Space Center (operation starts in 2021).

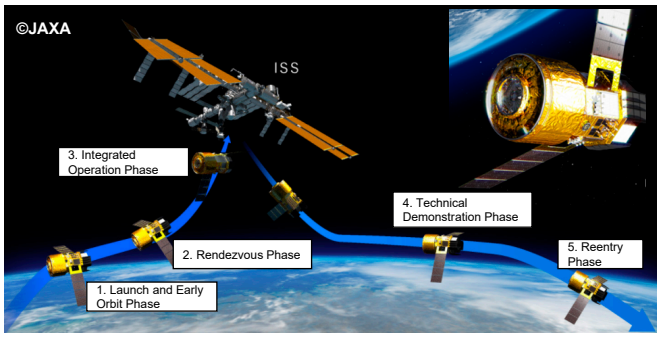
SLR stations

3. HTV-X and Technology Demonstration Mission

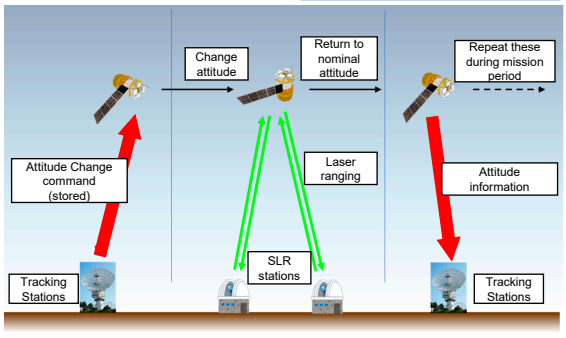
- HTV-X is the successor to HTV (Launch in FY2022 (planned))
- 3 Mt.FUJIs are mounted onto the back side of HTV-X
- HTV-X changes its attitude when SLR
- The period, duration(at least one week), and flight mode are currently being adjusted
- 3 different types of flight modes are under consideration
- Purpose of the SLR Technology Demonstration Mission
  - ① Performance demonstration of LRA (Mt.FUJI)
  - ② Evaluation of rotational motion (angular velocity) estimation method by SLR



Flight Modes



HTV-X



Operation overview

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4. What is Mt.FUJI?

Mt.FUJI : MulTiple reFlector Unit from Jaxa Investigation

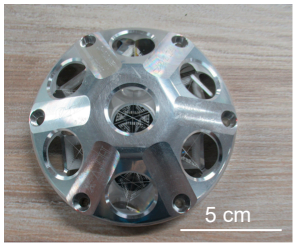
✓ Small, light, and inexpensive LRA for LEO space objects developed by JAXA from 2018

✓ Smaller and lighter LRA, Mini-Mt.FUJI, is also under development

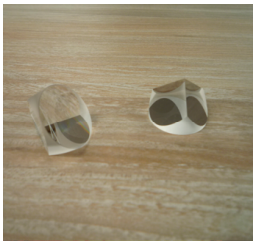
- Equipped with 7 CCRs (Corner Cube Reflector; reflecting waves directly towards the source)
- 45 degrees half-cone angle of FOV(Field Of View)
- Palm size
- Less than 800 km for Mt.FUJI and 400 km for Mini-Mt.FUJI are target altitudes
- 3 Mt.FUJIs are mounted on the cone bumper panel of HTV-X at 120 degrees intervals, along with a pedestal for adjusting the angle so that each FOVs do not overlap

Specifications

Item	Mt.FUJI	Mini-Mt.FUJI
Altitude	< 800 km	< 400 km
Diameter	112 mm	70 mm (TBD)
Height	32 mm	20 mm (TBD)
Mass	< 280 g	<120 g (TBD)
CCR size	1 inch	0.5 inch
Number of CCRs	7	
FOV	45 deg/Mt.FUJI (approx. 15deg/CCR)	
Material	Body: Aluminum CCR: Fused silica Cushion: PTFE, PFA	

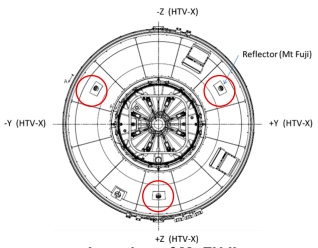


Mt.FUJI



CCR

Mt.FUJI with pedestal



Location of Mt.FUJIs

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5. How to estimate attitude motion by SLR?

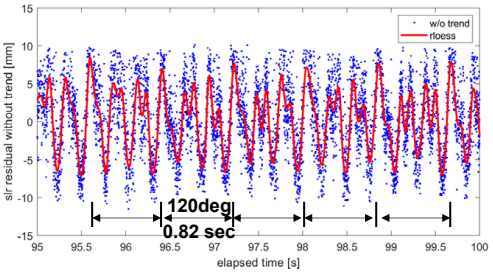
Basic idea: When a target object is in rotational motion, the CCRs that contributes to the laser reflection is switched to another by the rotational motion. Therefore SLR data should contain information on the CCR switching. If so, by analyzing the data somehow, we can grasp the rotational motion of the target?

Step1: Orbit determination — Orbit determination by SLR data or other sources (ex.GPS, RAAN, …)

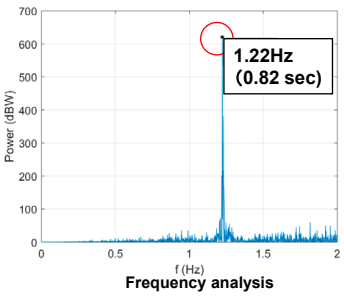
Strep2: O-C(SLR residual) — Calculation of SLR residual (O-C) by using OD ephemeris and SLR data

Step3: angular velocity estimation — Estimate angular velocity by reading angular velocity directly from the waveform of SLR residual or by performing frequency analysis

Flow of estimation



SLR residual



Frequency analysis

Example

- Using AJISAI SLR data, SLR residual is calculated. Blue dot is SLR residual, and red is smoothing of SLR residual
- <Direct reading>: 1 peak→ 2 peaks → 2 peaks are repeated at intervals of about 0.82 seconds. Since AJISAI has a 120 degrees symmetric structure, it rotates 120 degrees in 0.82 seconds.
- <Frequency analysis>: When the intensity of the signal contained in the SLR data is calculated for each frequency, a sharp peak is at 1.22 Hz corresponding to 0.82 seconds.
- With either method, the angular velocity is estimated to be approximately 146 degrees / sec.

Although such high-speed rotation is impossible for HTV-X mission, is this method effective for attitude estimation of HTV-X?

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6. Validation of Method for HTV-X Mission

Purpose of this survey

- Check if angular velocity can be estimated from SLR residual with flight modes and angular velocities under consideration

Survey method

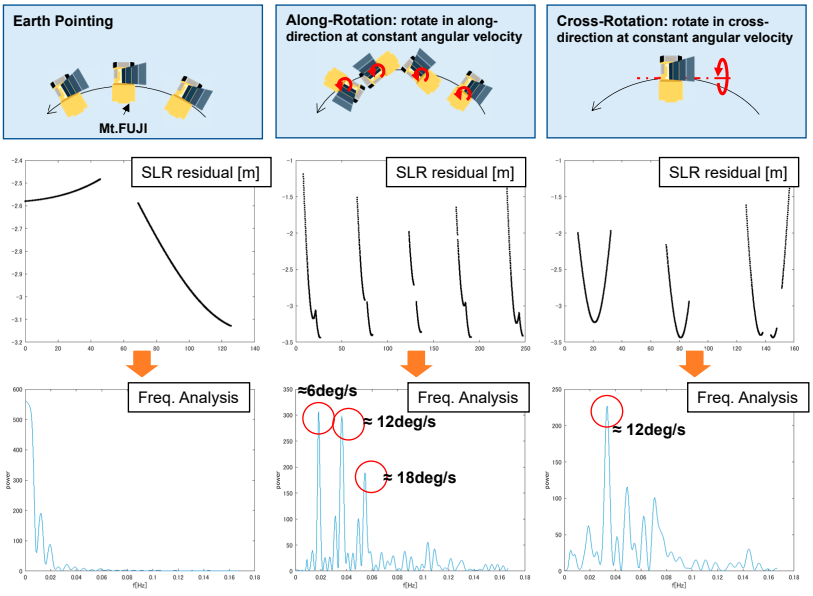
SLR residual(t) = d(t)- r(t)
d(t): dist. b/w SLR station and CCR
r(t): dist. b/w SLR station and HTV-X center of gravity

- d(t) is NaN when SLR station is out of FOV of CCR
- Attitude motion is considered for orbit propagation
- Investigate whether angular velocity can be estimated from SLR residual

Result

- SLR station is CHAL, minimum elevation angle of SLR station 20 degrees, and the rotational angular velocity is 6 deg/s (which is higher than the actual experiment)
- The SLR residuals and frequency analysis results differ greatly depending on the flight modes

- Although more detailed examination is required, considered possible to estimate flight mode and angular velocity of HTV-X from the SLR residual



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7. Summary

- **Introduction**
  - Development of compact, lightweight, and inexpensive general-purpose SLR reflector (Mt.FUJI) → Contributes to SSA
  - Demonstration of Mt.FUJI performance and evaluation of rotational motion estimation method by SLR → Contributes to ADR
- **SLR**
  - High-precision ranging system using laser
  - On-board component is only a reflector that do not required electrical I/F
- **Mt.FUJI**
  - Compact, lightweight, and inexpensive SLR reflector being developed by JAXA
- **HTV-X and Technology Demonstration Mission**
  - Platform for technology demonstration
  - Performance demonstration of Mt.FUJI and the world's-first evaluation of rotation estimation accuracy by SLR and LRAs
- **Angular velocity estimation method based on SLR residual**
  - SLR residual contains information on CCR switching (equivalent to attitude motion information)
  - Angular velocity can be estimated by reading directly from the waveform of SLR residual or detecting peaks by frequency analysis
  - Confirmed applicability of the method to HTV-X technology demonstration mission
- **Future works**
  - Statistical evaluation of estimation method by pseudo data analysis and construction of estimation model by machine learning
  - Higher accuracy of estimation method (correction considering geometry for stations at the time of observation, construction of attitude estimation model, etc.)