F3

軌道上光学センサによるLEOデブリ観測

Low Earth orbit debris observation using space-based optical sensors

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スペースデブリの存在は持続的な宇宙開発利用に対する大きな脅威である．特に地球低軌道（LEO）には追跡されている宇宙機のおよそ 7 割が集中しており，衝突による破砕リスクが高いため早急な対策が必要である．衝突による破砕を防止するために有効な手段の一つが，軌道上物体の高精度な追跡情報に基づく衝突回避運用である．現状で，LEO において定常的に追跡されている物体サイズの下限はおよそ 10cm である．本研究では，LEO に配置した光学センサによって観測能力を向上させることを提案する．効果的なシステム提案を行うためには，LEO 同士の観測における能力評価を適切に行う必要がある．著者らは能力評価のツールとして軌道上観測シミュレータの開発を進めている．また軌道上観測結果に対する初期軌道推定手法やフィルタの検討も行なっている．それらツール開発や検討結果の現状とあわせて技術的課題などについて報告を行う．

Space-debris related issues are major threats for sustainable space development and utilization. Urgent countermeasure for satellite breakup due to collision is required especially for Low Earth Region because approximately 70 percent of tracked objects are concentrated to the region. Collision avoidance maneuver based on precise tracking information is one of effective measure to prevent collision. Current size limitation of steady tracking operation for LEO region is about 10 cm in diameter. We propose space-based optical sensor for debris placed in LEO region as a tracking capability improvement method. Proper capability assessment for LEO to LEO observation geometry is required to propose effective system. We develop space-based observation simulator as an assessment tool and consider suitable algorithms of initial orbit determination, correlation and filter. Current status of the simulator and algorithms consideration results, and technical problems are reported.

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Objectives

- Track small debris in Low Earth Orbit (LEO)
  - Smaller than 10 cm
  - We propose a “space-based” optical system for this mission
    - All-day observation, No atmospheric disturbances, Close to LEO objects (i.e. brighter)
- Clarify capabilities and technical problems through feasibility studies

Our approaches (1)

- Space-based observatory simulator
  - Input
    - Observatory orbit
    - Optical system specifications
    - Small LEO debris catalog
    - Mission duration
  - Output
    - Density distribution of observation points
    - Target's motion in Field Of View (FOV)
    - Detected objects number and their observation interval
    - Target's apparent magnitude

Our approaches (2)

- Orbit Determination (OD)
  - Angles only
    - Typical optical observation only provides angles and their time derivatives ($\alpha, \dot{\alpha}, \delta, \dot{\delta}$)
    - Initial Orbit Determination (IOD) and correlation
    - Gaussian, Admissible region, Circular assumed IOD
  - Ranging
    - Range measurement by two optical observatories
      - Triangulation
  - Batch least square
- Collaborative observation with ground telescope

Optical system

- Specification assumptions
  - 2k2k cooled CCD camera
  - F2 f=135mm single focus lens
- $N_t = \sqrt{N_{sys}^2 + N_{dc}^2 + N_{shot}^2 + N_{sky}^2}$
  - Assumed noise component
- Signal to Noise Ratio requirement
  → 5

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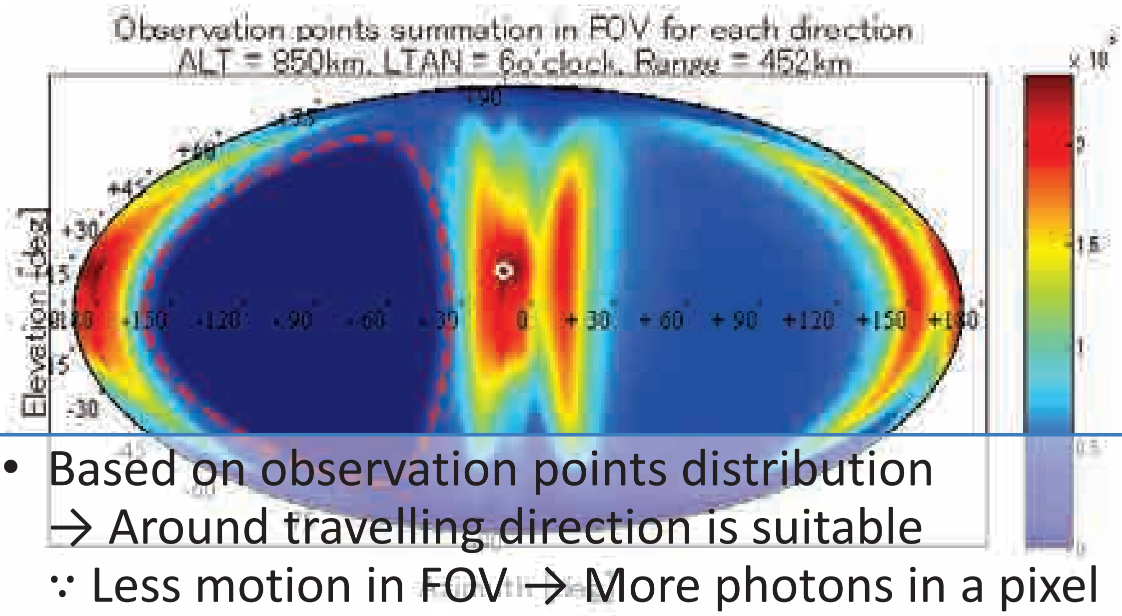
Space-based observatory simulator: Observation points distribution



- Based on observation points distribution
  → Around travelling direction is suitable
  ∵ Less motion in FOV → More photons in a pixel

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Space-based observatory simulator: Observed objects number

- Small debris (1 ~ 10 cm in diameter)
  - Observed 0.2 % in a year
    - Travelling direction observation
    - Observed objects in almost same altitude of observatory
    - Observable orbit period and drift rate (RAAN) is limited
      - RAAN: Right ascension of the ascending node
  - Needs improvement

Correlation:
Test case (Angles only, Travelling direction)

- Tracklets in different epochs
  - Object identification
- FOV is assumed as travelling direction
  - Virtual observation data (Error 0.01[deg]:1σ)
  - Correlation based on degree of similarity in orbital elements (Admissible Region method)
- Failed
  - Different objects are correlated
  - Same object’s tracklets are not correlated

Causes for correlation failure

- Angles only observation
  - Range cannot be determined
    - Far and fast, close and slow → same apparent motion
  - Travelling direction observation
    - Less motion in FOV → less information
    - Unable to identify different objects
- Brief summary
  - Travelling direction FOV is suitable from a view point of sensitivity
  - However, less information in FOV causes negative effect in correlation

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Solutions

- Sweep observation for higher or lower altitude
  - Tilt FOV from travelling direction
- Ranging

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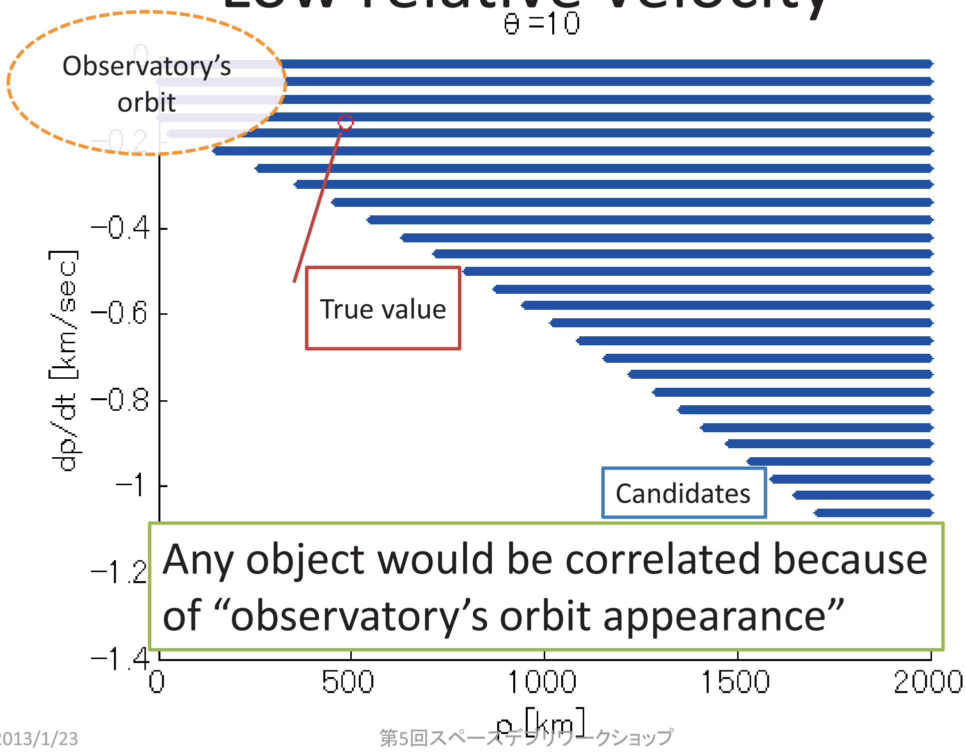
Sweep observation, Tilt FOV from travelling direction

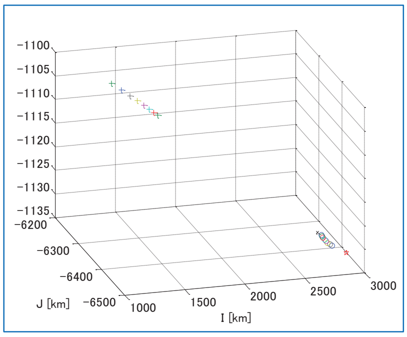
- Put observatory into lower (or higher) orbit than observation target region (e.g. 800 - 900 km)
  - Difference in orbital period, RAAN drift rate
  - Whole target region (shell like shape) can be observed
  - For example, 4.3% (approx. 12000) of LEO small debris can be swept
- Tilt optical axis from travelling direction
  - High relative velocity → cannot be observed
  - Low relative velocity → can be observed
    - However, problem in correlation remains (AR method)

Low relative velocity



Typical OD, (Angles only)

- Low relative velocity gives longer duration of observations
- IOD by Gaussian and circular orbit assumption
  - Gaussian : Poor accuracy
  - Circular : Better but still poor
- Refine by batch least square
  - Does not converge
  - Extremely short arc



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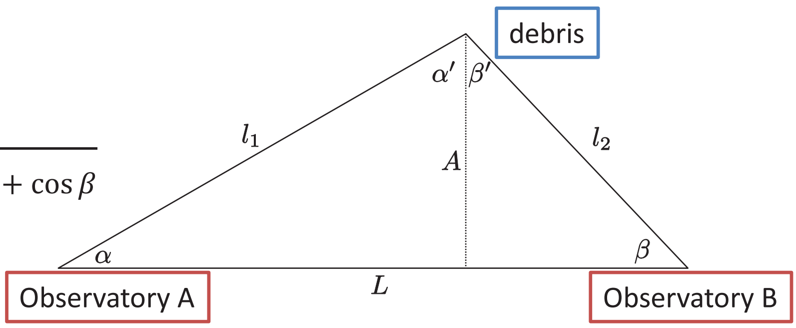
Ranging

- Range information determines unique position vectors from angles data
- Triangulation

$$l_2 = \frac{L}{\frac{\sin\beta}{\sin\alpha}\cos\alpha + \cos\beta}$$



- Proper configuration provides 10m accuracy
  - 0.01[deg] angles error

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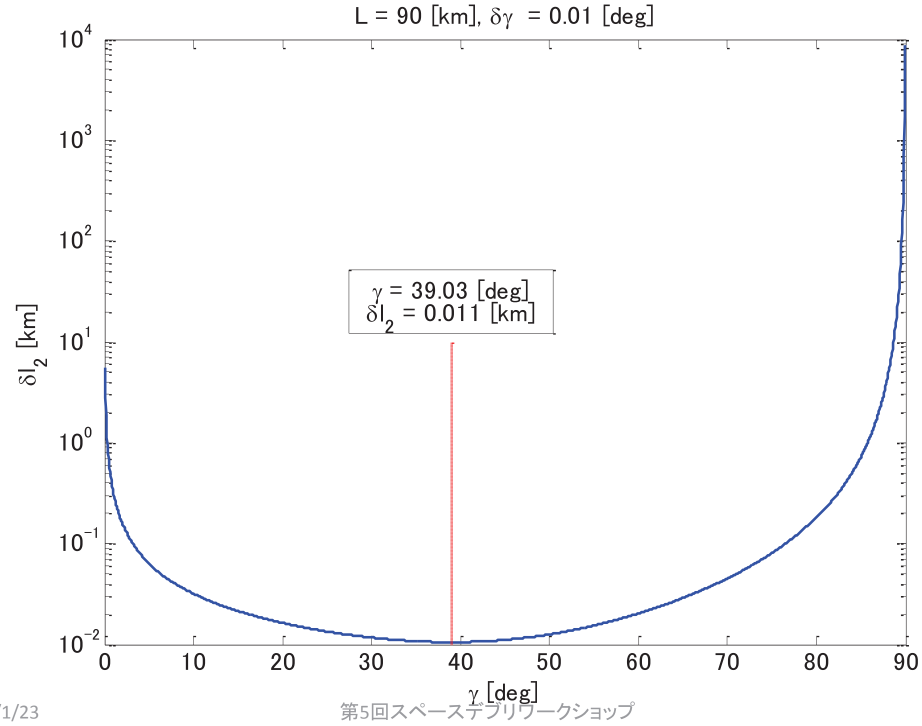
FOV tilt angle and range accuracy



OD using triangulation: Test case

- Observe object in 800km altitude
- From observatory in 700km altitude
- Angles error 0.01[deg] (1σ)
- OD result accuracy
  - Position ~100m
  - Velocity ~4m/s
- High accuracy estimation is available
  - However, sweep observation is not suitable for periodic data update

Collaborative observation concept

- Space-based observatory
  - Sweep, Triangulation
  - Less than 100m accuracy
  - Not suitable for frequent observation
- Ground-based observatory
  - Small debris are too dark to detect
  - OD result provided by space-based system enables target motion estimation
  - Then TDI (Time Delayed Integration) or image stacking method are available
  - Periodic data update

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Summary

- Travelling direction is suitable for observation in terms of photon criteria
- However, this direction has negative effects in correlation and observation efficiency
- Tilted FOV enables sweep observation
  - 4.3 % of LEO debris
    → potentially observable (800 – 900km)
- It is hard to determine target's orbit from space-based angles only observation
- Triangulation by two satellites provides precise range information
- Target's orbit can be determined less than 100m accuracy with triangulation

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Future tasks

- Improvement of space-based observatory simulator
- Detailed study of collaborative observation between space-based and ground telescope
- Review optical system (CCD, CMOS, EMCCD)
- Feasibility study of triangulation ranging
  - Object identification

IOD