B6

非協力的ターゲットへの接近ストラテジ

Approach Strategy to a Non-Cooperative Target

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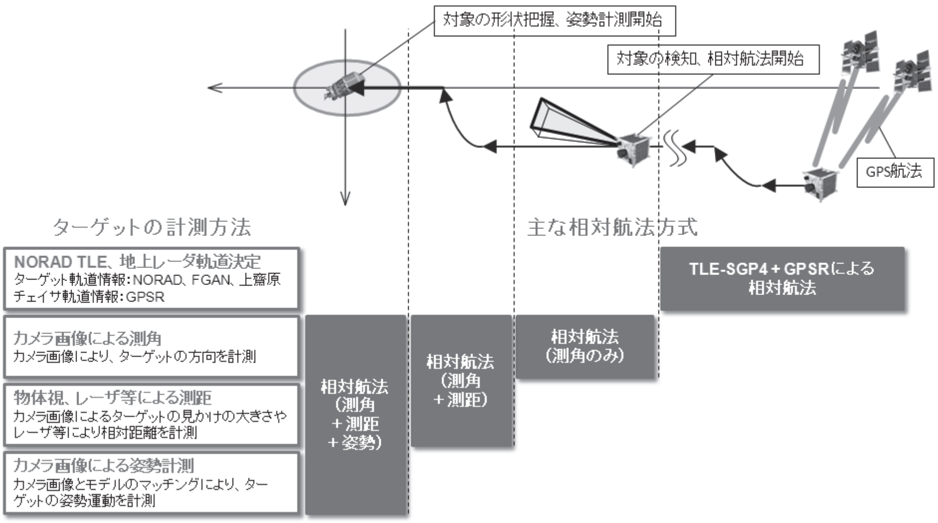
デブリの積極的除去のために、接近し何らかの推進系を取り付ける必要がある。デブリのような非協力的ターゲットへの接近には、ISS のような協力的ターゲットと比較して、事前の軌道情報（NORAD TLE）の精度が低い、相対航法の継続性・安定性の確保が困難、といった技術的課題がある。これらの技術的課題を考慮した接近ストラテジの検討状況について紹介する。まず、非協力的ターゲット接近シナリオの全体像と必要技術を概観する。また、事前の軌道情報の精度の調査結果を示すとともに、相対航法センサシステムの概念的検討を示す。さらに、カメラによる相対航法においてキー技術となる、Angles-only navigation の簡易的検討結果を示し、可観測性と衝突安全を考慮した接近軌道設計の考え方を示す。最後に、今後の課題と技術開発プランについて述べる。



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Space debris workshop

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Outline

- Introduction
  - What is a "non-cooperative target" ?
  - Why approach to a non-cooperative target is challenging ?
- Structure of approach operation and necessary technologies
- Key technical issues
  - Orbit prediction accuracy of LEO space debris
  - Relative navigation sensors for space debris
  - Angles-only navigation
  - Trajectory design to avoid a collision with a target
- Approach case study by numerical simulations
- Conclusions

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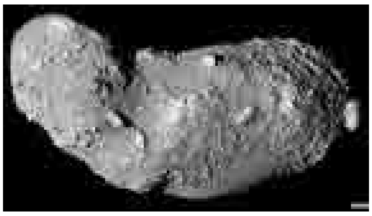
1. Introduction

What is a "non-cooperative target" ?

- Non-cooperative target is
  - A rendezvous target which does not have any cooperative functionalities to support approach guidance, navigation and control
- Features of non-cooperative targets
  - Orbit determination by R&RR, GPSR is not available
  - No target markers or laser retroreflecters for vision/laser sensors are available
  - Knowledge about optical property (specular/diffuse reflectance, etc.) is limited
  - Attitude is not known and it is not controlled but in natural motion

"cooperative" target

"non-cooperative" targets



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1. Introduction

Why approach to a non-cooperative target is challenging ?

- Approach to a non-cooperative target is mandatory for active debris removal (ADR), but it is NOT EASY
- Poor knowledge of a target orbit
  - Accurate orbit data by R&RR, GPSR is not available
  - Orbit data by radar tracking (TLE, etc.) is available but poor
- Poor knowledge to design S/N of relative navigation
  - Poor knowledge of optical property of surface and attitude
  - Wide range of lighting condition (Solar illumination, Earth albedo)
  - Difficult to confirm stable relative navigation
- Poor knowledge of location of target center of mass
  - Location of target center of mass should be known to establish stable relative orbit keeping
  - Estimation of target center of mass in the target body is not easy

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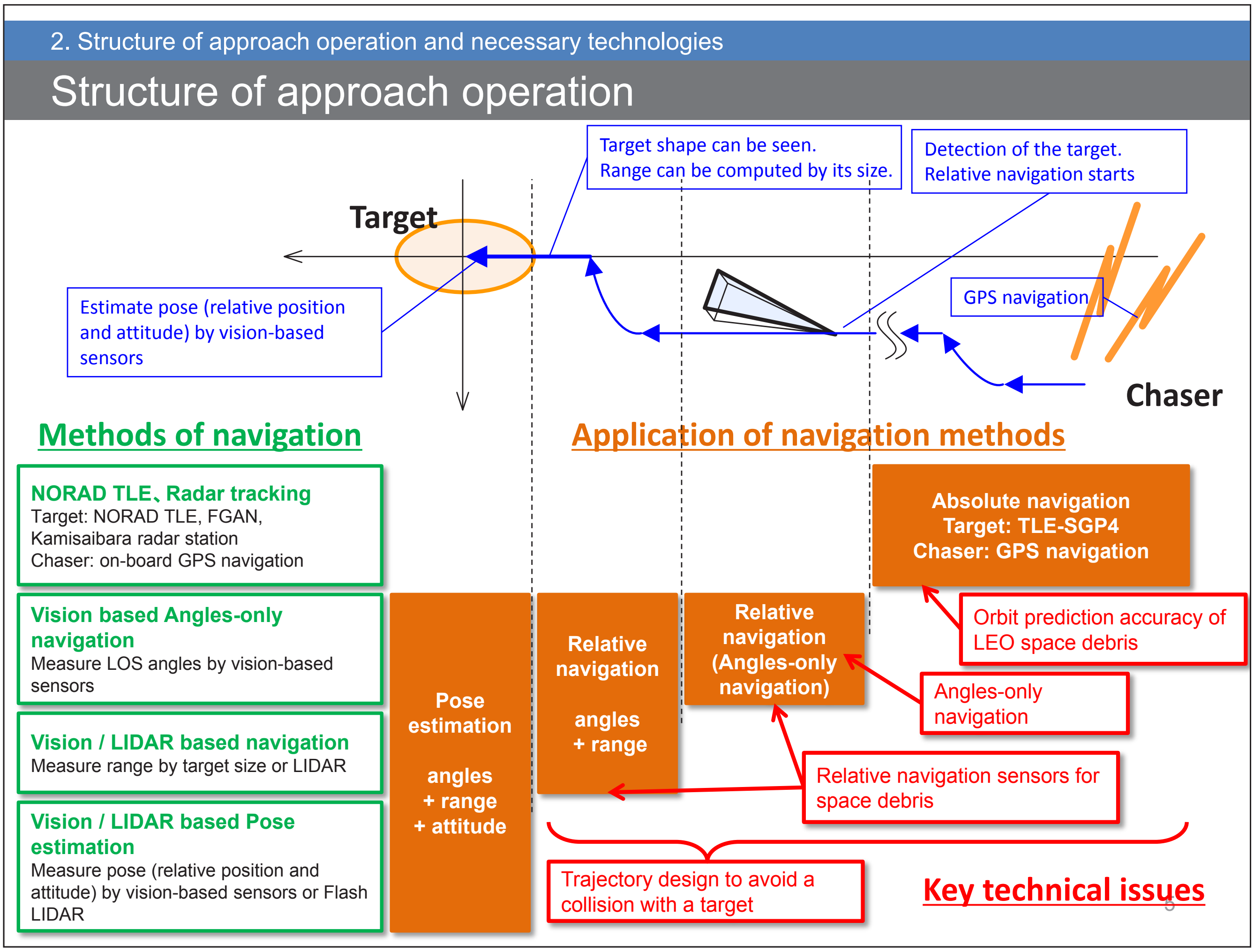
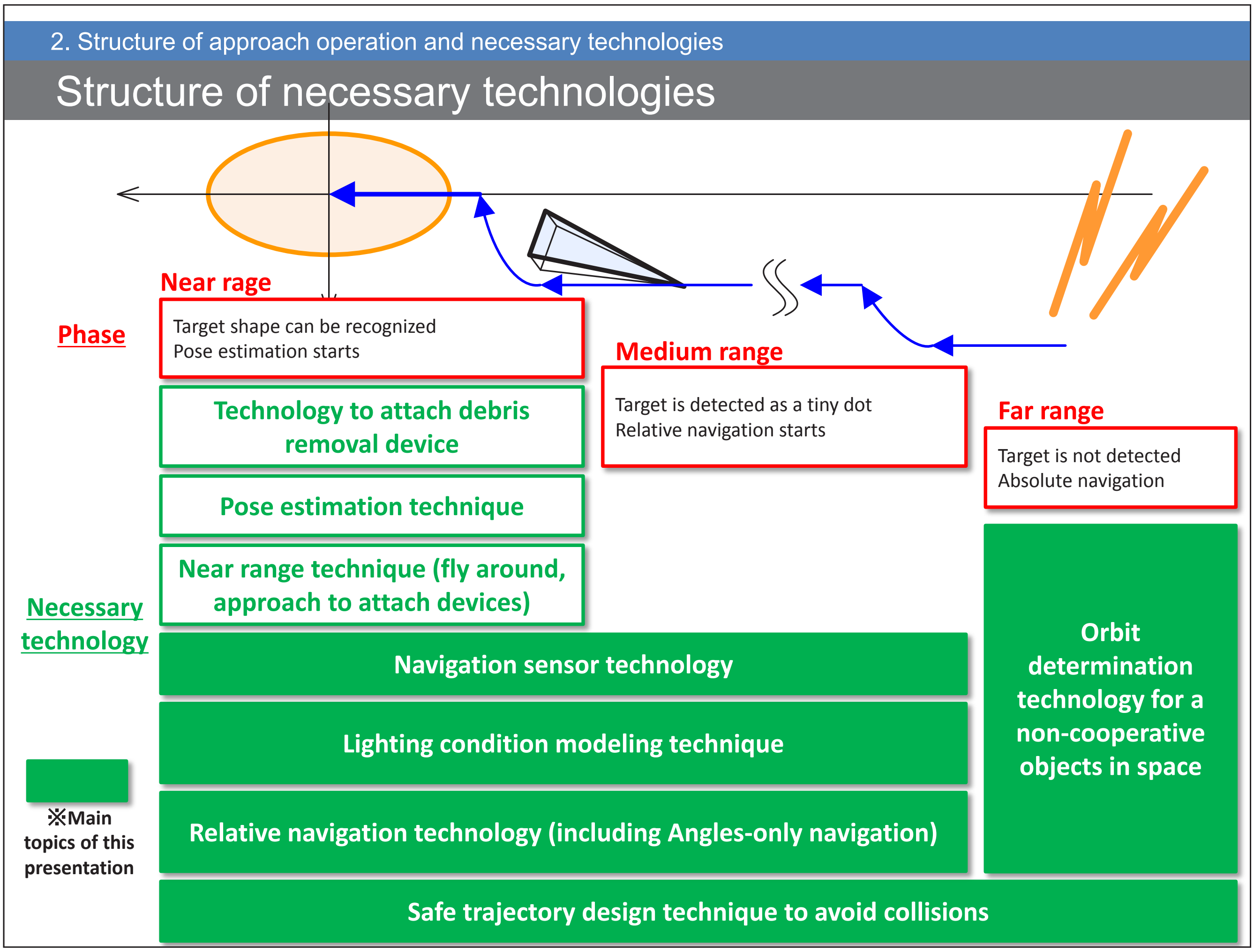

2. Structure of approach operation and necessary technologies
Structure of approach operation
Target shape can be seen.
Range can be computed by its size.
Detection of the target.
Relative navigation starts
Target
GPS navigation
Estimate pose (relative position and attitude) by vision-based sensors
Chaser
Methods of navigation
Application of navigation methods
NORAD TLE、Radar tracking
Target: NORAD TLE, FGAN, Kamisaibara radar station
Chaser: on-board GPS navigation
Vision based Angles-only navigation
Measure LOS angles by vision-based sensors
Vision / LIDAR based navigation
Measure range by target size or LIDAR
Vision / LIDAR based Pose estimation
Measure pose (relative position and attitude) by vision-based sensors or Flash LIDAR
Pose estimation
angles + range + attitude
Relative navigation
angles + range
Relative navigation (Angles-only navigation)
Absolute navigation
Target: TLE-SGP4
Chaser: GPS navigation
Orbit prediction accuracy of LEO space debris
Angles-only navigation
Relative navigation sensors for space debris
Trajectory design to avoid a collision with a target
Key technical issues


2. Structure of approach operation and necessary technologies
Structure of necessary technologies
Phase
Near rage
Target shape can be recognized
Pose estimation starts
Medium range
Target is detected as a tiny dot
Relative navigation starts
Far range
Target is not detected
Absolute navigation
Necessary technology
Technology to attach debris removal device
Pose estimation technique
Near range technique (fly around, approach to attach devices)
Navigation sensor technology
Lighting condition modeling technique
Relative navigation technology (including Angles-only navigation)
Safe trajectory design technique to avoid collisions
Orbit determination technology for a non-cooperative objects in space
※Main topics of this presentation

3.1 Key technical issues - Orbit prediction accuracy of LEO space debris

Orbit prediction accuracy of LEO space debris

- TLE is important apriori knowledge of target orbit
- Orbit prediction accuracy of TLE/SGP4 is investigated by several authors
  - Aida S., Kirschner M., “Collision Risk Assessment and Operational Experiences for LEO Satellites at GSOC”, 22nd ISSFD, 28 Feb. - 4 March 2011, Sao Jose dos Campos, Brazil (2011)
  - 倉田育枝, 足立学, 矢里秀作, 亀山雅也, 松田郁未, 廣瀬史子, 工藤伸夫, “スペースデブリ軌道精度評価”, 第54回宇宙科学技術連合講演会, 17 Nov., 静岡県コンベンションアーツセンター (2010)
- Typical TLE/SGP4 performance of LEO debris:

	1 day propagation		7day propagation	
	Radial Cross-Track	Tangential	Radial Cross-Track	Tangential
High solar activity	0.5 - 1 km	2 - 10 km	0.5 - 2 km	15 - 50 km
Low solar activity	0.5 - 1 km	1 - 2 km	0.5 - 2 km	2 - 8 km

  - During high solar activity period tangential errors after long propagation become large
  - Low altitude debris tend to have larger tangential errors after long propagation
  - Radar Cross Section (RCS) has sensitivity to accuracy of TLE
- Other radar tracking stations (ex. FGAN, Kamisaibara) have great functionalities to provide target orbit data timely

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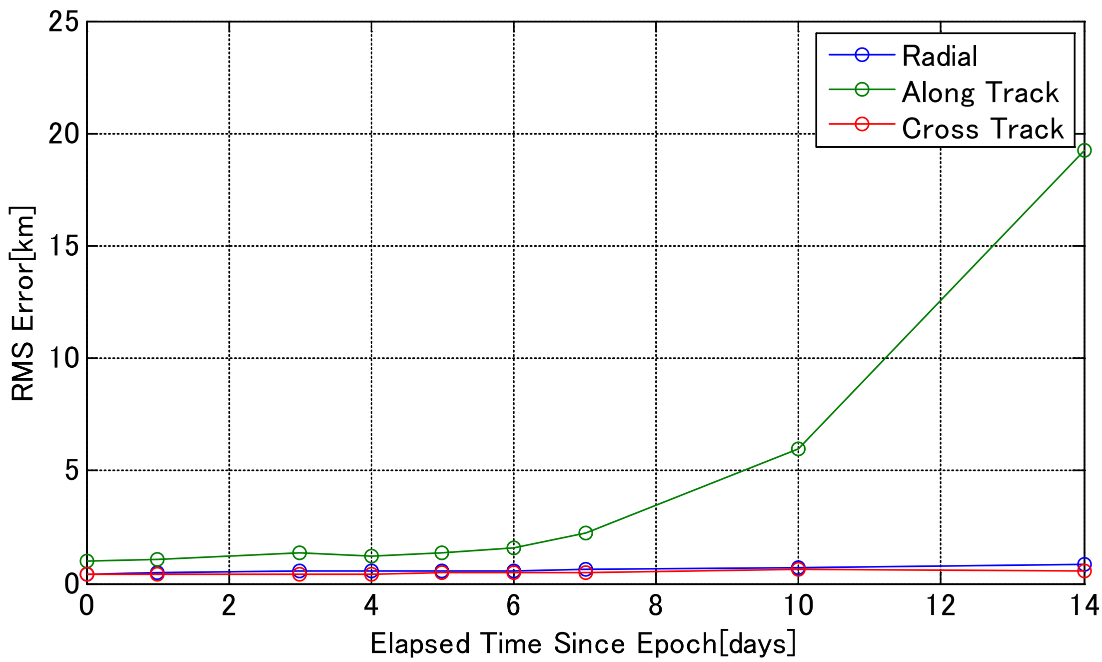
3.1 Key technical issues - Orbit prediction accuracy of LEO space debris

Example: TLE/SGP4 prediction accuracy of ADEOS-II

- ADEOS-2(803km), 2003/5/20, F10.7 flux = 117.1
- GPS orbit determination data is used as reference



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3.2 Key technical issues - Relative navigation sensors for space debris

Relative navigation sensors for space debris

- Visible Camera is low cost and available in long distance, but not available at night and sensitive to lighting conditions
- Infrared Camera is available at night and not sensitive to lighting conditions, but available distance is medium
- Laser sensors are available at night and stable, but need high power and high cost

		Attitude	Range		LOS Angles	Night	Pros	Cons	Examples
			Far	Near					
Visible Camera		○	×	○	○	×	Low cost Long distance High resolution	Not available at night Sensitive to lighting conditions Poor range accuracy	So many on-board visible cameras are flying in space
Infrared Camera		○	×	○	○	○	Available at night Robust to lighting conditions	Low resolution Available distance is medium Poor range accuracy	Planet-C, ALOS-2, Hayabusa-2, Orbital Express, Space-X Dragon
Laser Sensor	Laser Range Finder	×	○	○	×	○	Available at night Long distance Accurate	LOS angles NOT measured High power consumption High cost (?)	Hayabusa-1/2, SELENE, Orbital Express
	SCAN LIDAR	△	○	○	○	○	Available at night Long distance Accurate	High power consumption High cost (?)	XSS-11
	FLASH LIDAR	○	×	○	○	○	Available at night Attitude can be measured	Short distance only High power consumption High cost (?)	Space-X DRAGON

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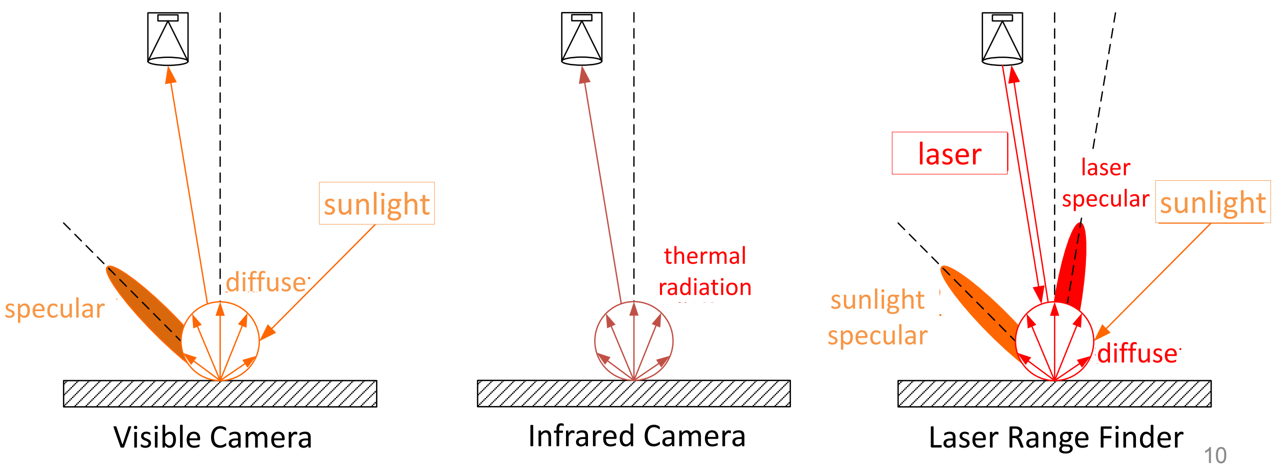
3.2 Key technical issues - Relative navigation sensors for space debris

Mathematical modeling of relative navigation sensors

- Visible camera detects reflection (both specular and diffuse) of sunlight from target surface
- Infrared camera detects thermal radiation from target surface
- Laser range finder detects reflection (both specular and diffuse) of transmitted laser pulses from target surface
- "Modified Phong model" is used as reflection model



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3.2 Key technical issues - Relative navigation sensors for space debris

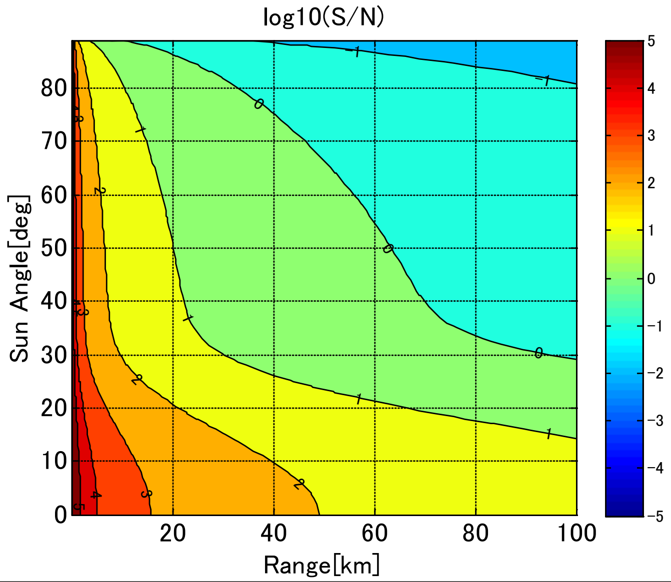
Case study: Visible camera detectability

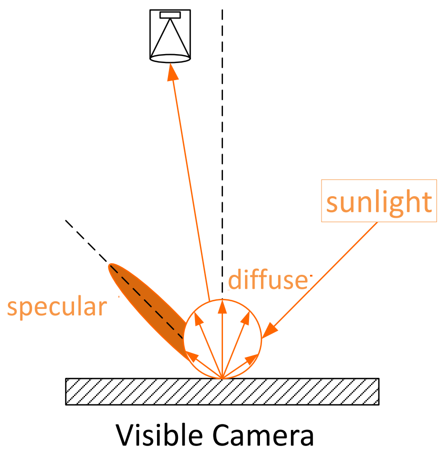
- Detectability strongly depends on optical property of target

⇒ This is just a case study!

- Visible camera may detect target
  - from 65km@20deg sun angle
  - from 30km@30deg sun angle
  - from 15km@80deg sun angle

```
Kd = 0.2;           % diffuse property
Ks = 0.5;           % specular property
D = 5.8e-3;         % diameter of optics[m]
A = pi*2*2;         % target size[m^2]
```





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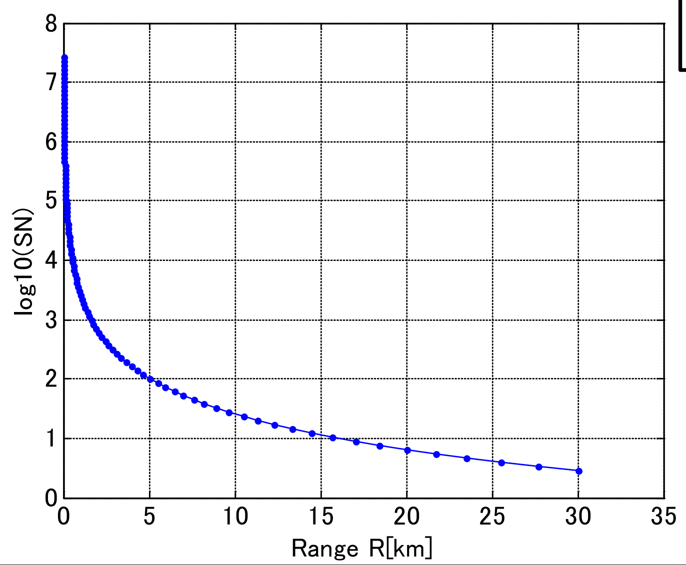
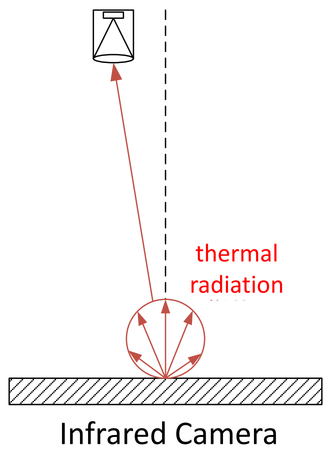
3.2 Key technical issues - Relative navigation sensors for space debris

Case study: Infrared camera detectability

- Detectability strongly depends on temprature and infrared emissivity of target ⇒ This is just a case study!
- Infrared camera may detect target from 15km
- Infrared camera is rather stable against solar lighting conditions

```
epsilon = 0.57;      % Emissivity of surface
A = pi*2^2;          % target size[m^2]
D = 47e-3;           % diameter of optics[m]
D_star = 2.00E+06;   % Specific detectivity[m Hz^1/2 W^-1]
```





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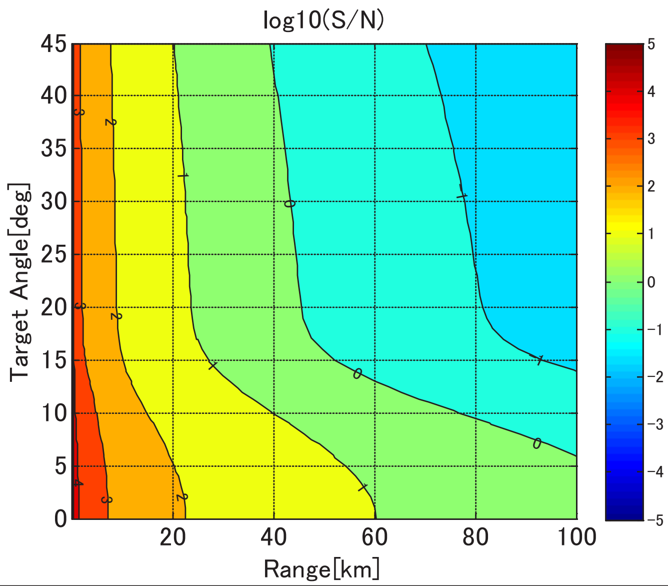
3.2 Key technical issues - Relative navigation sensors for space debris

Case study: Laser range finder detectability

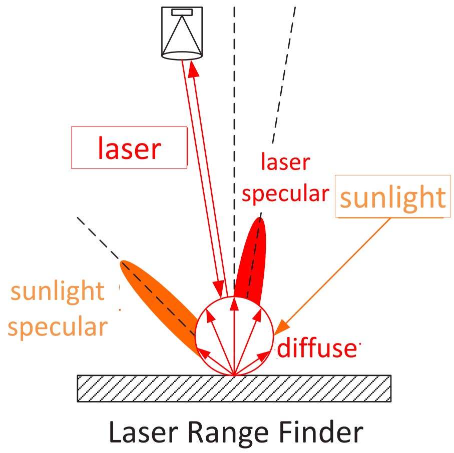
- Detectability strongly depends on optical property of target

⇒ This is just a case study!

- Laser range finder may detect target from 20 - 60km



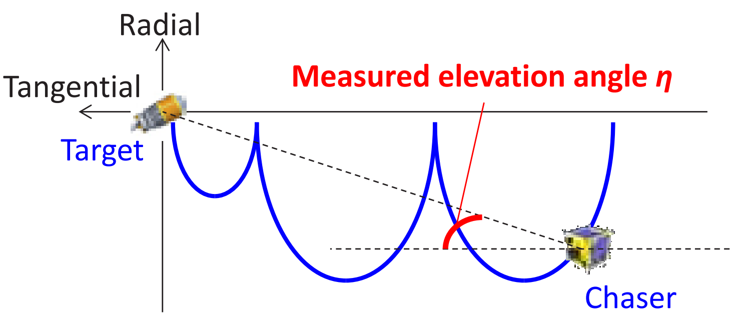

```
Kd = 0.2;          % diffuse property
Ks = 0.5;          % specular property
Po = 1.00E+06;     % laser peak power[W]
D = 0.1;           % diameter of optics[m]
SA = 0.4;          % sensitivity[A/W]
A = pi*2*2;        % target size[m^2]
```

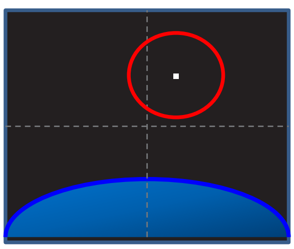


3.3 Key technical issues - Angles only navigation

Angles-only navigation

- What is Angles-only navigation ?
  - Navigation method to estimate relative position and velocity by only target direction (Azimuth/Elevation) from cameras
- Why angles-only navigation is necessary ?
  - A target is seen as a tiny point from long distance
  - If laser sensors are not available, a chaser must approach to a target using only direction information until target shape can be seen on a camera image
- Features of angles-only navigation
  - No direct 3D position information
  - Trajectory should ensure visibility and observability
  - Proper maneuver execution stimulates observability in tangential direction





3.3 Key technical issues - Angles only navigation

Navigation filter for Angles-only navigation

- Extended kalman filter is formulated for angles-only navigation of LEO rendezvous
  - Estimated states

$$\boldsymbol{x} = [\delta a, a\delta e_x, a\delta e_y, a\delta i_x, a\delta i_y a\delta u]^T$$

Relative orbital elements

  - Measurement model

$$\boldsymbol{z} = [\eta, \phi]^T = h(\boldsymbol{x}) \quad \eta = a\tan(u_x^{CAM} / u_z^{CAM})$$
$$\phi = a\sin(u_y^{CAM})$$

Elevation η and Azimuth ϕ are measurements from cameras

$$\boldsymbol{z} = [r]^T = h(\boldsymbol{x}) \quad r = norm(\boldsymbol{r}^{CAM})$$

Range is measurement from laser range finder

$$\boldsymbol{r}^{CAM} = C_{RTN}^{CAM} C_{CVL}^{RTN} C_{REL}^{CVL} \boldsymbol{x}, \quad \boldsymbol{u}^{CAM} = \boldsymbol{r}^{CAM} / r$$

  - Dynamics model

$$\boldsymbol{x}_{k+1} = \Phi(t_{k+1}, t_k)\boldsymbol{x}_k$$

Simple state transition matrix

CAM: camera coordinates
RTN: cartesian orbital coordinates
CVL: curvilinear orbital coordinates
REL: relative orbital elements

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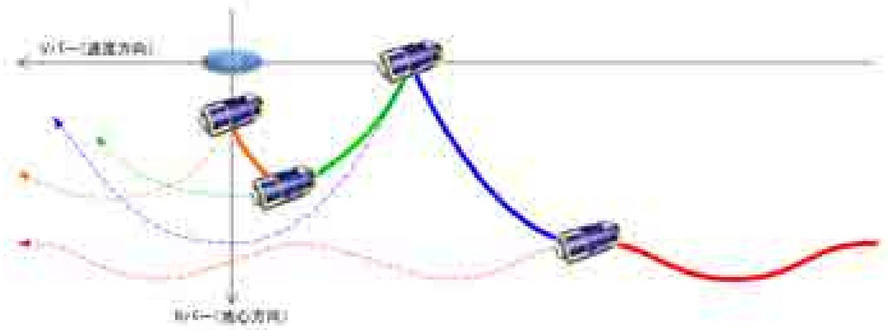
3.4 Key technical issues - Trajectory design to avoid a collision with a target

Trajectory design to avoid a collision with a target

- Tangential (Along-track) direction of a target is dangerous zone
  - Relative navigation to a non-cooperative target is unstable
  - Knowledge of tangential relative distance by angles-only navigation is poor
- Three basic principles to design safe trajectory
  - 1: Propagated trajectory should be safe even if a maneuver is cancelled
  - 2: Propagated trajectory should be safe even if navigation errors are considered
  - 3: Opportunities to be at the same height with a target should be minimized



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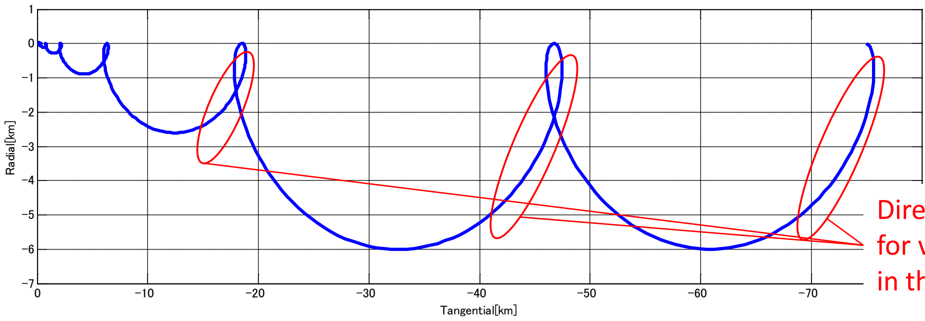
4 Approach case study by numerical simulations

Approach case study by numerical simulations

- A sample approach scenario has been designed
- Navigation simulation from far-range to medium-range phase
- Main interest is investigation of Angles-only navigation performance

Target true orbit	Actual GRACE-A orbit by precise GPS orbit determination.
Target TLE/SGP4 orbit	Actual GRACE-A TLE.
Chaser true orbit	Simulation data. 21x21 geopotential, Jacchia-Roberts atmospheric drag, SUN, MOON, Solar radiation pressure.
Chaser delta-V estimation error	5% (3σ) error.
Sensor measurements	Camera:0.1deg(1σ), Laser range finder:6m(1σ) random errors. Detectability computation based on mathematical model described above.

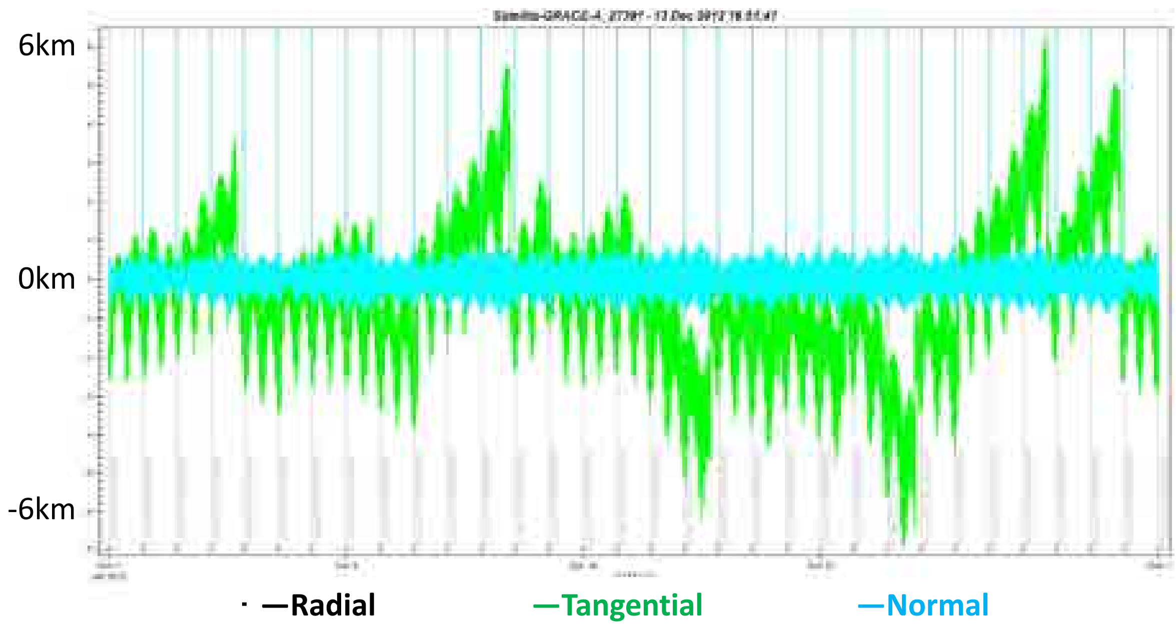


Approach trajectory is similar to "stable orbit rendezvous" used for space shuttle missions

4 Approach case study by numerical simulations

GRACE-A TLE/SGP4 accuracy

- Error of GRACE-A TLE/SGP4 is:
  - less than 7km in Tangential direction
  - less than 1km in Radial/Cross-track direction



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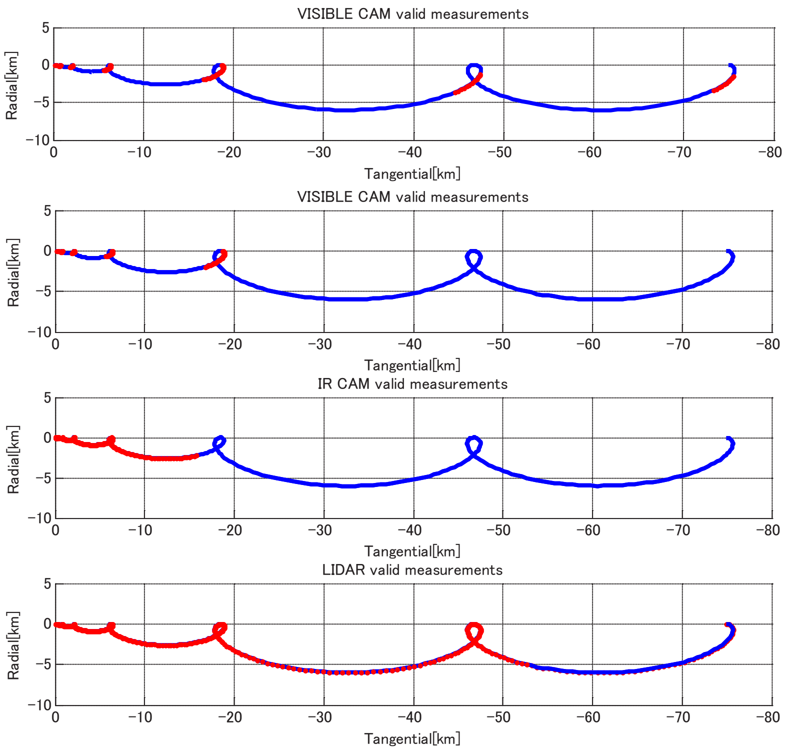
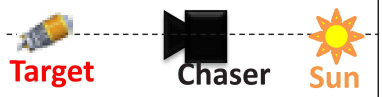
4 Approach case study by numerical simulations

Detectability of sensors

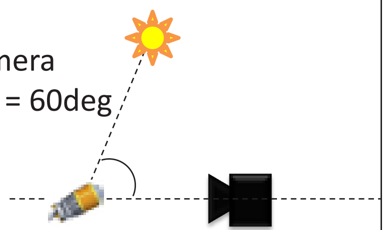
RED LINE ー : valid measurements



Visible Camera
beta angle = 0deg



Visible Camera
beta angle = 60deg



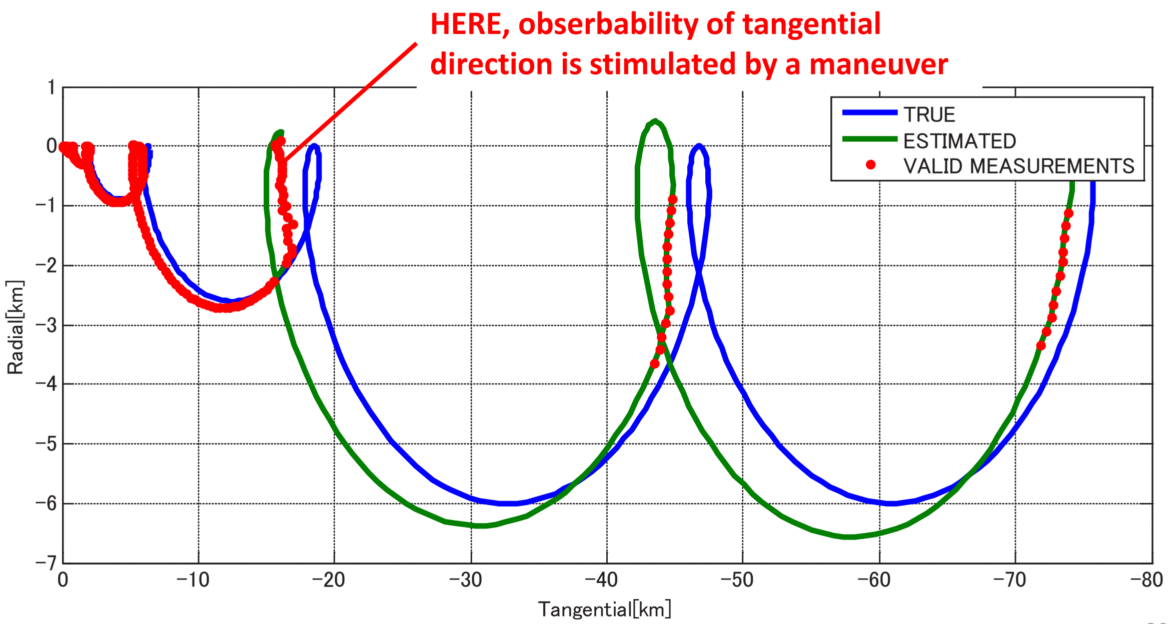
Infrared Camera

Laser Range Finder

4 Approach case study by numerical simulations

Estimated trajectory by Angles-only navigation

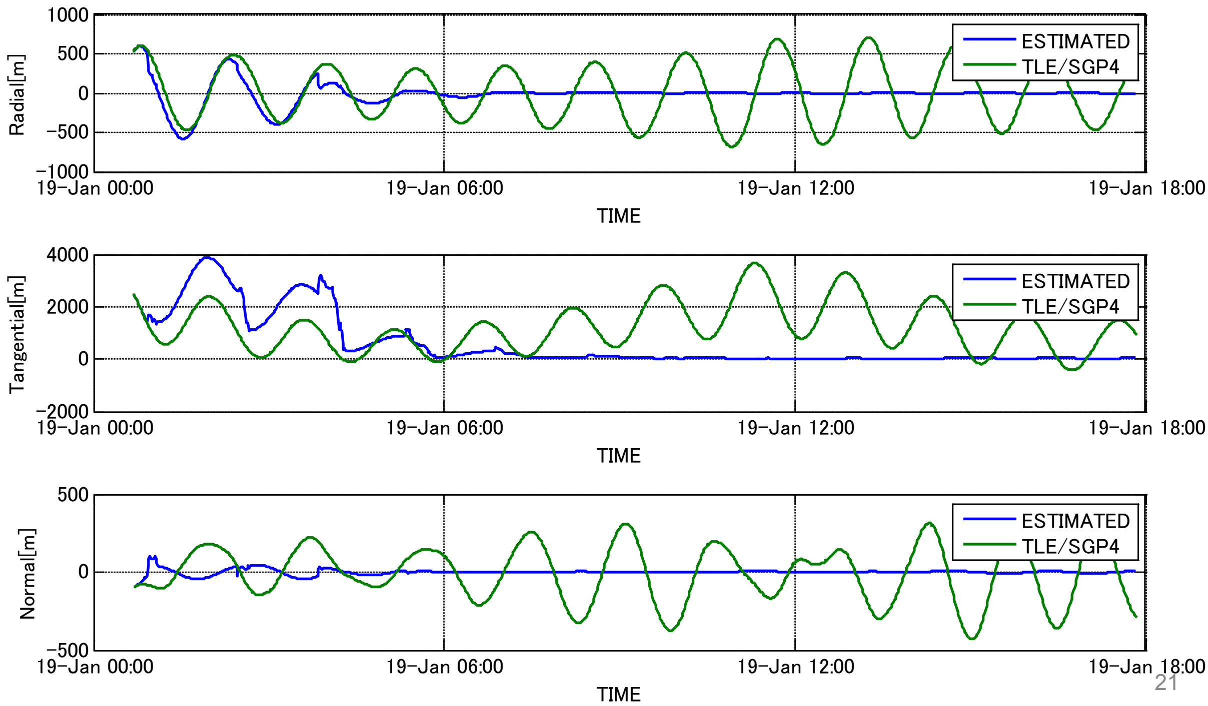
- True and estimated trajectory by angles-only navigation
- Visible camera only, beta angle = 0deg



4 Approach case study by numerical simulations

Performance of Angles-only navigation V.S. TLE/SGP4

Navigation error in Radial, Tangential, and Cross-track direction
Visible camera only, beta angle = 0deg



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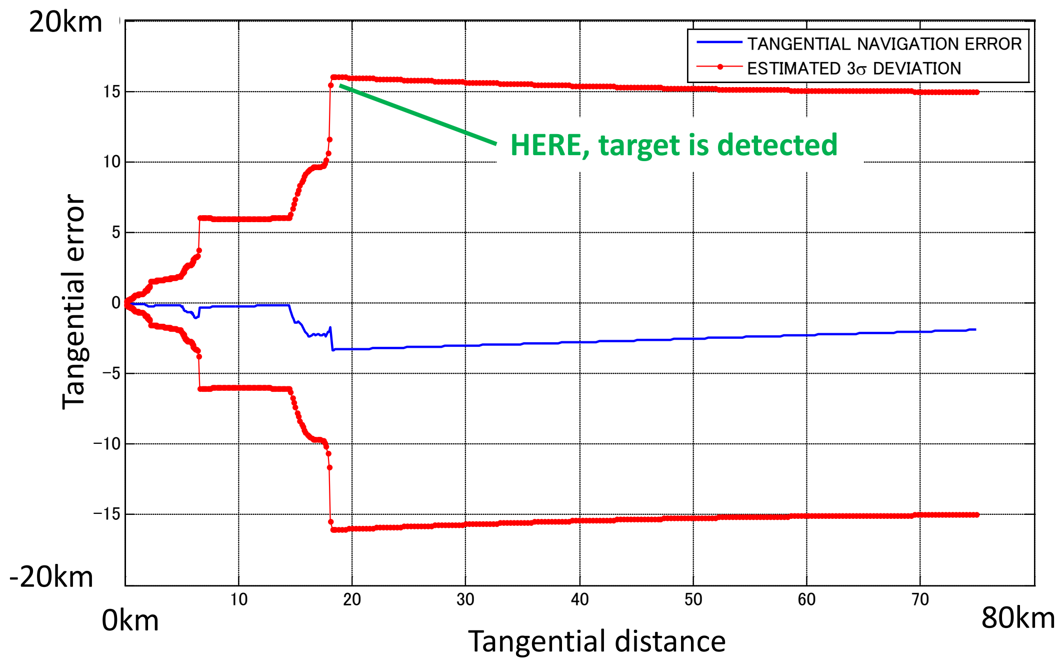
4 Approach case study by numerical simulations

Performance of Angles-only navigation in tangential direction

- Error in tangential direction
- Visible Camera only, beta angle = 60deg



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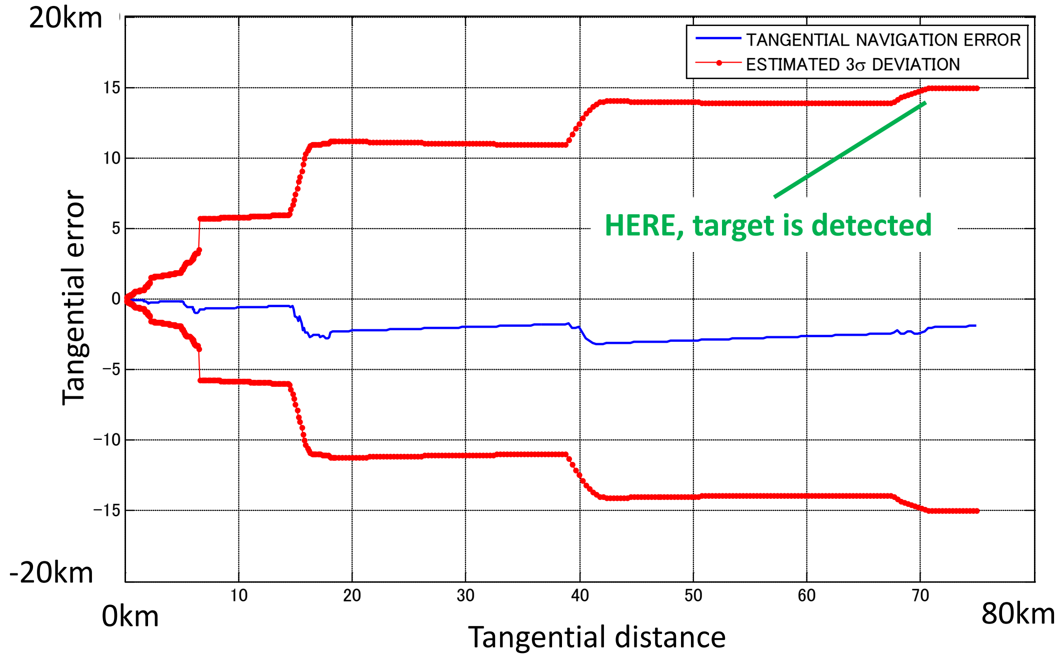
4 Approach case study by numerical simulations

Performance of Angles-only navigation in tangential direction

- Error in tangential direction
- Visible Camera only, beta angle = 0deg



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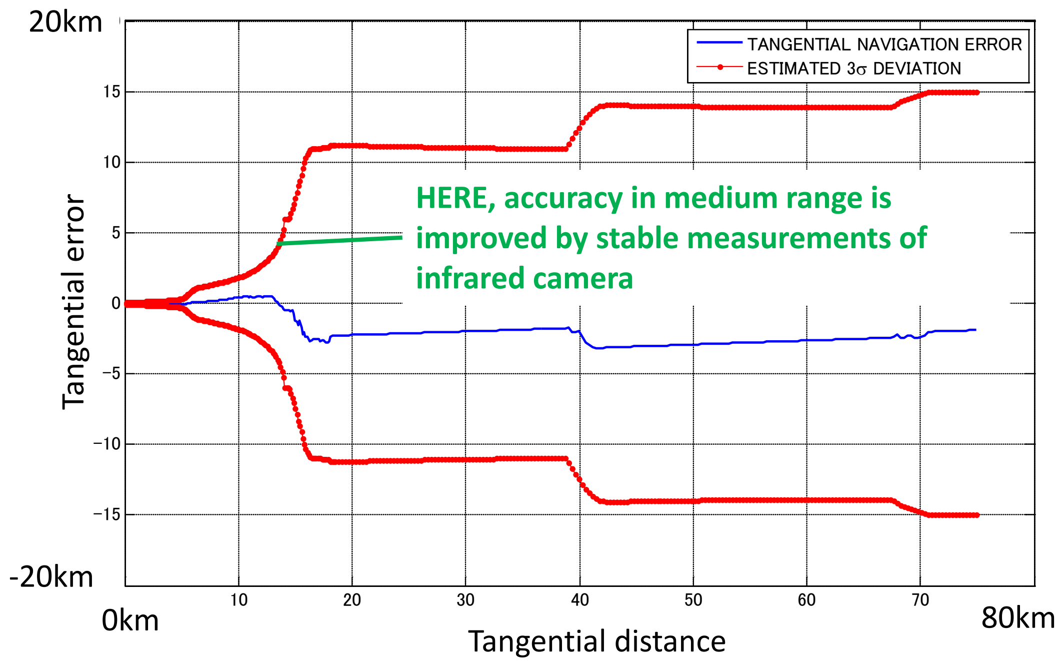
4 Approach case study by numerical simulations

Performance of Angles-only navigation in tangential direction

- Error in tangential direction
- Visible and infrared, beta angle = 0deg



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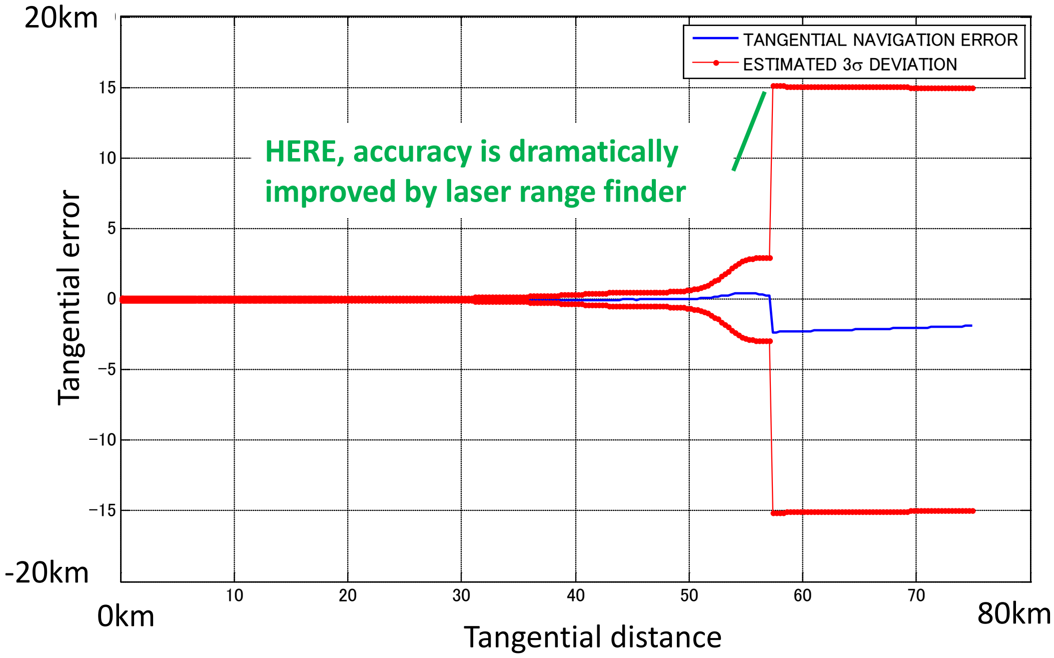
4 Approach case study by numerical simulations

Performance of Angles-only navigation in tangential direction

- Error in tangential direction
- Visible, infrared and laser range finder



4 Approach case study by numerical simulations

Summary of navigation case study simulation

- Angles-only navigation may provide navigation data with sufficient accuracy to connect from TLE/SGP4 navigation to vision-based navigation using size of the target.
- Detectability of visible camera depends on beta angle.
- Detectability of visible camera strongly depends on sunlight direction. Measurements of visible camera are available in a limited portion of an orbital revolution.
- Infrared camera can be great stable navigation source in medium range.
- Direct range information from laser range finder dramatically improve navigation accuracy in tangential direction.
- Optical property of the target is the key factor of detectability and this case study strongly depends on it.

Conclusions

- Approach to a non-cooperative target is not a easy task
- Poor knowledge of target optical property and motion is the key factor of the difficulty
- Rendezvous system for active debris removal should be able to absorb wide dynamic range of these uncertainties
- High fidelity modeling of target optical property, motion, and sensor hardware is important, but it may be challenging to be precise enough on ground
- The most important point is flexibility of rendezvous system and operation plan to be able to absorb remaining uncertainties during actual flight

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