D5

軌道上デブリへのランデブシナリオ

Rendezvous strategy for the active debris removal missions

○村上尚美, 山元透 (JAXA 研究開発部門 第一研究ユニット)
○Naomi Murakami, Toru Yamamoto
(JAXA Research and Development Directorate, Research Unit I)

デブリの積極的除去にあたり、デブリ除去衛星はターゲットとなるデブリに安全に接近する必要がある。ISSのような協力的ターゲットと異なり、デブリのような非協力的ターゲットへの接近には、事前の軌道情報（TLE）の精度が低い、相対航法の継続性・安定性の確保が困難、といった航法の観点での技術的課題が存在する。これまでの研究の結果、航法手段として可視光/赤外センサを活用した航法が有効であることがわかっているが、それらの航法センサに求められる精度や観測更新頻度などの要求は現時点で明確になっていない。著者らは、本課題を解決すべく、デブリへのランデブ軌道、および、航法系の運用シナリオを設計し、共分散解析を用いた手法によって、安全なランデブに必要な航法系への要求を検討している。本発表では、その検討状況について紹介する。

In the Active Debris Removal (ADR) mission, the chaser satellite should approach to and rendezvous with the non-cooperative space debris. Since non-cooperative target does not have precise orbit information nor any navigation aids such as laser reflectors or markers, it is difficult for the chaser to perform reliable relative navigation against the debris. image sensors, such as visible cameras and infrared cameras, are considered effective navigation sensors which can be used in wide ranges. However, functions and performances required to these sensors have not been clarified. In this study, authors suggest a practical rendezvous scenario which secures the trajectory safety and clarifies the requirements regarding relative navigation.

軌道上デブリへのランデブシナリオ

Rendezvous Strategy for the Active Debris Removal Missions

村上尚美、山元透 (JAXA)
Naomi Murakami and Toru Yamamoto (JAXA)

19 Oct. 2016

7th Space Debris Workshop

OUTLINE

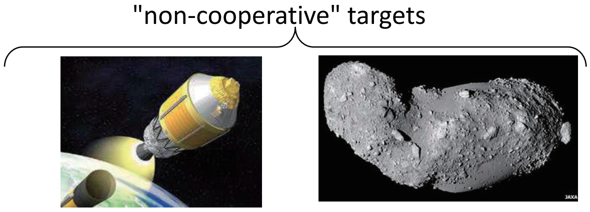
- Background and Motivation
- Relative Navigation System
- Rendezvous Scenario
- Approach to clarify the requirement for navigaton sensors
  -> Linear Covariance Analysis
- LCA result (example)
- Summary & Future Work

Background and Motivations

- Space debris are non-cooperative targets

"cooperative" target

"non-cooperative" targets



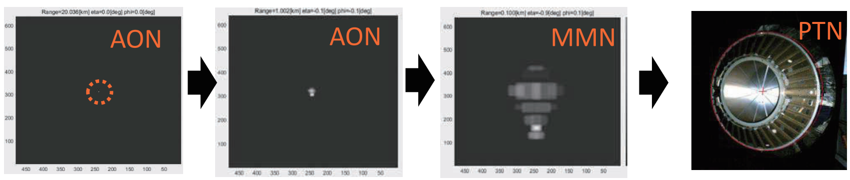
- Trajectory information contains large error and is less frequently updated
  - High precision orbit determination such as R&RR and GPSR is not available
- Relative navigation is less reliable
  - No “active” aids for relative navigation: GPSR, transponder, retro-reflector
  - Limited information on the target surface characteristic and posture
  - Sensitive to lighting condition (geometry of the target, chaser, and the sun)

Relative navigation feasibility is the key to rendezvous with debris

→ Clarify the requirement for the relative navigation system to approach to the debris

Relative Navigation Method

- Vision-based navigation using cameras (visible and IR) has the 1st priority
  - Relatively low cost, small size and mass
  - Valid in wide range   ** Visible >100km, IR ～20 km*
    - Far: Angles-Only Navigation (AON) -> bearing angles (⇒ relative position)
    - Middle: Model Matching Navigation (MMN) -> bearing angles + range
    - Near: PAF-Tracking Navigation (PTN) -> 6-DOF

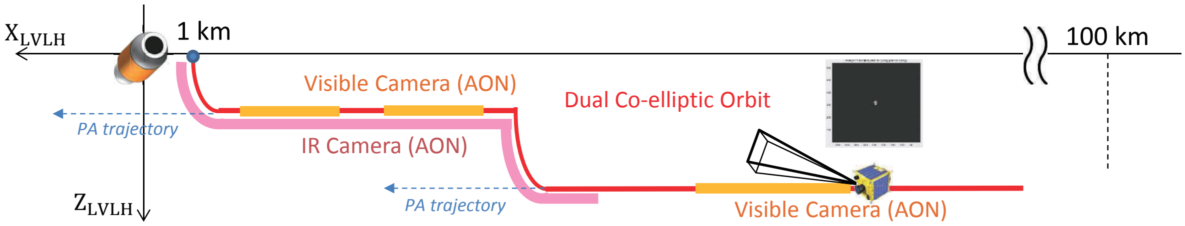


  - IR camera is robust to lighting conditions, but lower resolution than visible camera

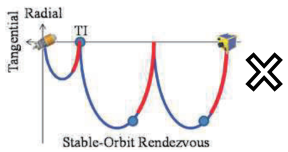
- Laser sensors are options. Stable, but need high power and high cost

Rendezvous Scenario (1/3)

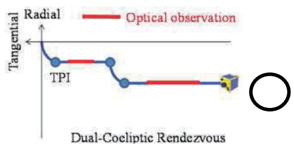
1. Rendezvous Phase (distance ≈ 100 km – 1 km)



- Dual co-elliptic orbit
  - Passive Abort (PA) safety would be prioritized considering the navigation uncertainty



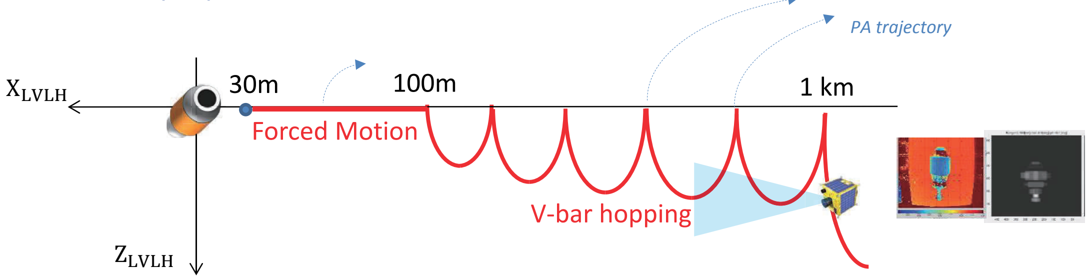
- Vision-based Angles-Only Navigation (AON)
  - Beyond the AON available range, TLE/SGP4 navigation is used
  - AON starts from about 100 km with visible camera
  - From about 20 km, IR camera is available



5

Rendezvous Scenario (2/3)

2. Proximity Operation Phase (distance ≈ 1 km – 30 m)



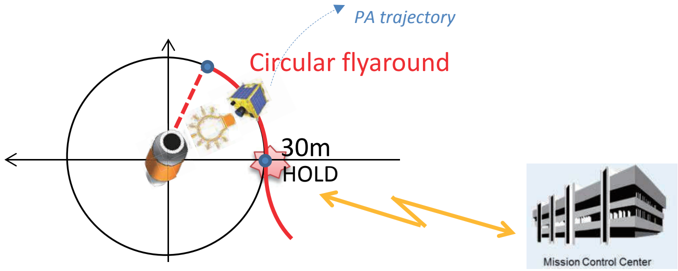
- V-bar Hopping -> Forced Motion
  - Keep Passive Abort (PA) safety
  - V-bar hopping requires lower ΔV compared to forced motion

- Model Matching Navigation (MMN)
  - From about 1.2 km, the shapes of the debris imaging becomes clear and MMN starts.
  - Range and bearing angle data obtained from MMN.
  - Optional laser sensor provides range measurement with higher accuracy.

6

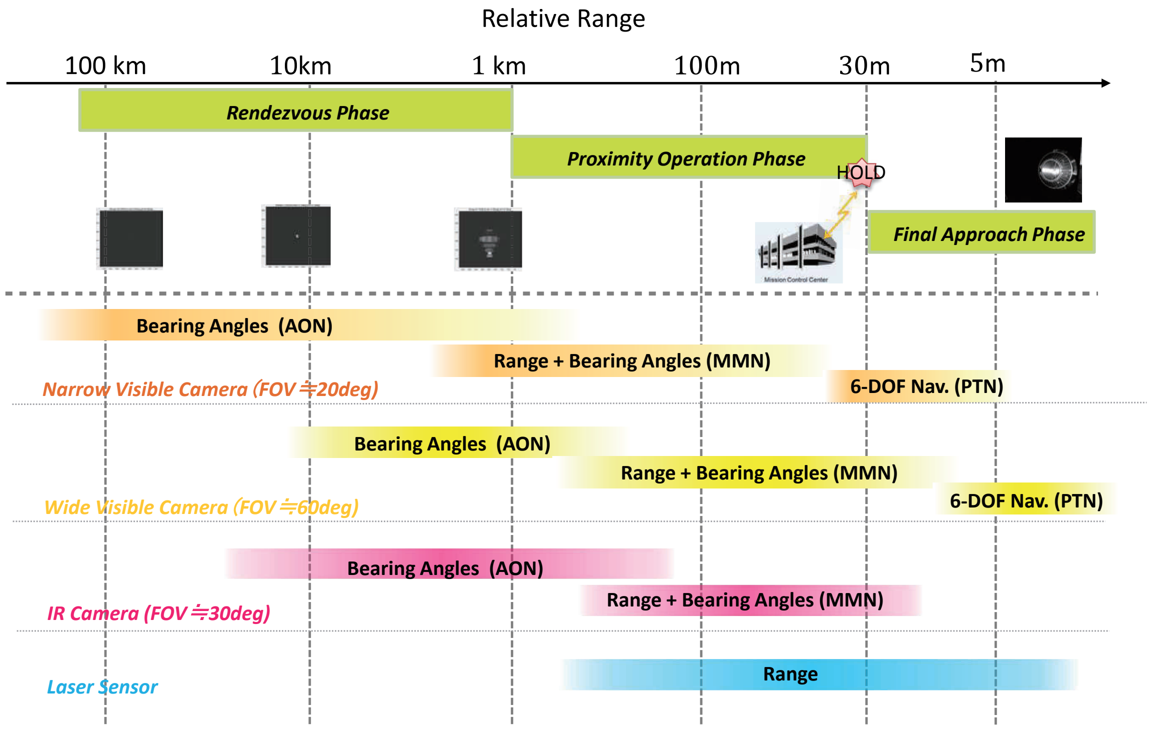
Rendezvous Scenario (3/3)

3. Final Approach Phase (distance ≈ 30 m -)



- 30m Hold -> Circular Flyaround
  - Keep Passive Abort (PA) safety
  - Proper final approach trajectory generated with reference to the predicted motion
- Motion estimation on ground -> PAF Tracking Navigation (PTN)
  - Ground operator performs precise pose estimation and prediction by collected images
  - Onboard PTN starts in the middle of circular flyaround

Navigation Sensor Mapping



Question

- What are the requirements for Visible /IR camera?
  - Bearing measurement accuracy
  - MMN range accuracy
  - operational range
  - Measurement frequency
- Hand-over from AON-> MMN at 1km distance feasible ?
- Laser sensors inevitable ?

→ Clarify the requirement for relative navigation sensors

[APPROACH]

- Perform Linear Covariance Analysis (LCA) for various simulation cases with different combinations of sensor specifications
  – accuracy, frequency, operational range…
- Investigate the trajectory dispersions and find out the simplest combination which achieves safety approach.

9

Linear Covariance Analysis (LCA)

- Method to evaluate dispersions of rendezvous navigation/control errors
  - Monte Carlo method
  - Linear Covariance Analysis
    - Produce the same statistical results as the Monte Carlo simulation with shorter period of time
    - Powerful tool especially in the early study phase
- Inertial state based LCA formulation with event trigger, proposed by Geller.

$$\mathbf{x} \triangleq [\mathbf{r}_{debris} \quad \mathbf{v}_{debris} \quad \mathbf{r}_{chaser} \quad \mathbf{v}_{chaser}]$$

$\delta \mathbf{x} = \mathbf{x} - \bar{\mathbf{x}}$: true state error

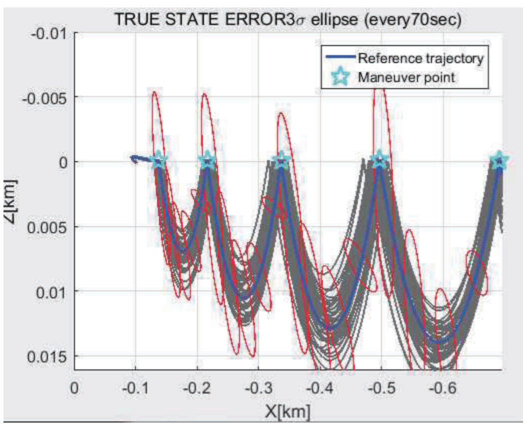
$\delta \hat{\mathbf{x}} = \hat{x} - \bar{x}$: navigation state error

$$\delta \mathbf{X}^T = [\delta \mathbf{x}^T \ \delta \hat{\mathbf{x}}^T] \Rightarrow \mathbf{C}_A = E[\delta \mathbf{X} \delta \mathbf{X}^T]$$

Propagation $\dot{\mathbf{C}}_A = \mathcal{F}\mathbf{C}_A + \mathbf{C}_A\mathcal{F}^T + \mathcal{W}\mathbf{S}_w\mathcal{W}^T$

Measurement Update $\mathbf{C}_A(t_k^+) = \mathcal{A}_k\mathbf{C}_A(t_k^-)\mathcal{A}_k^T + \mathcal{B}_k\mathbf{R}_\nu(t_k)\mathcal{B}_k^T$

Maneuver Correction $\mathbf{C}_A(t_j^{+c}) = \mathcal{D}_j\mathbf{C}_A(t_j^{-c})\mathcal{D}_j^T + \mathcal{N}_j S_{\Delta w_j}(t_j)\mathcal{N}_j^T$



Linear Covariance Analysis (LCA)

- Method to evaluate dispersions of rendezvous navigation/control errors
  - Monte Carlo method
  - Linear Covariance Analysis
    - Produce the same statistical results as the Monte Carlo simulation with shorter period of time
    - Powerful tool especially in the early study phase

- Inertial state based LCA formulation with event trigger, proposed by Geller.

$$\mathbf{x} \triangleq [\mathbf{r}_{debris} \quad \mathbf{v}_{debris} \quad \mathbf{r}_{chaser} \quad \mathbf{v}_{chaser}]$$

$\delta \mathbf{x} = \mathbf{x} - \bar{\mathbf{x}}$: true state error

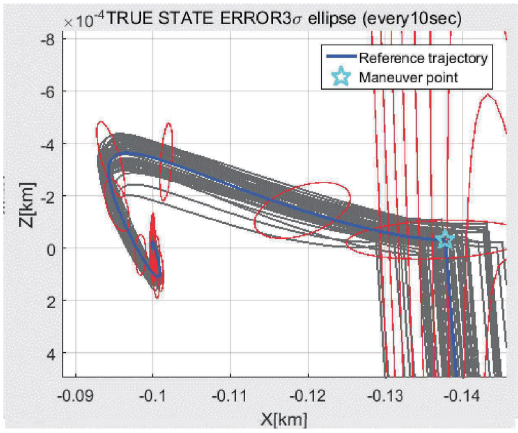
$\delta \hat{\mathbf{x}} = \hat{\mathbf{x}} - \bar{\mathbf{x}}$: navigation state error

$$\delta \mathbf{X}^T = [\delta \mathbf{x}^T \ \delta \hat{\mathbf{x}}^T] \Rightarrow \mathbf{C}_A = E[\delta \mathbf{X} \delta \mathbf{X}^T]$$

Propagation $\dot{\mathbf{C}}_A = \mathscr{F}\mathbf{C}_A + \mathbf{C}_A \mathscr{F}^T + \mathscr{W}\mathbf{S}_w \mathscr{W}^T$

Measurement Update $\mathbf{C}_A(t_k^+) = \mathscr{A}_k \mathbf{C}_A(t_k^-)\mathscr{A}_k^T + \mathscr{B}_k \mathbf{R}_\nu(t_k)\mathscr{B}_k^T$

Maneuver Correction $\mathbf{C}_A(t_j^{+c}) = \mathscr{D}_j \mathbf{C}_A(t_j^{-c})\mathscr{D}_j^T + \mathscr{N}_j \mathbf{S}_{\Delta w_j}(t_j)\mathscr{N}_j^T$



Linear Covariance Analysis (LCA)

- Method to evaluate dispersions of rendezvous navigation/control errors
  - Monte Carlo method
  - Linear Covariance Analysis
    - Produce the same statistical results as the Monte Carlo simulation with shorter period of time
    - Powerful tool especially in the early study phase

- Inertial state based LCA formulation with event trigger, proposed by Geller.

$$\mathbf{x} \triangleq [\mathbf{r}_{debris} \quad \mathbf{v}_{debris} \quad \mathbf{r}_{chaser} \quad \mathbf{v}_{chaser}]$$

$\delta \mathbf{x} = \mathbf{x} - \bar{\mathbf{x}}$: true state error

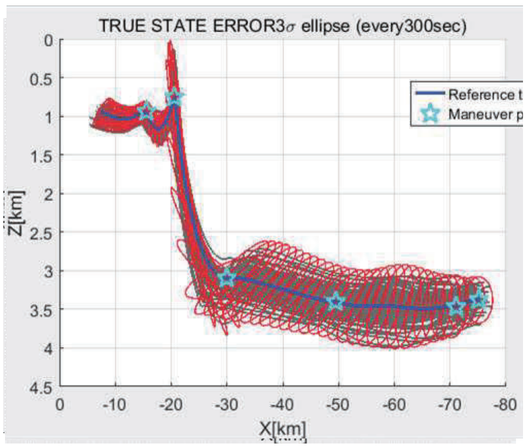
$\delta \hat{\mathbf{x}} = \hat{\mathbf{x}} - \bar{\mathbf{x}}$: navigation state error

$$\delta \mathbf{X}^T = [\delta \mathbf{x}^T \ \delta \hat{\mathbf{x}}^T] \Rightarrow \mathbf{C}_A = E[\delta \mathbf{X} \delta \mathbf{X}^T]$$

Propagation $\dot{\mathbf{C}}_A = \mathscr{F}\mathbf{C}_A + \mathbf{C}_A \mathscr{F}^T + \mathscr{W}\mathbf{S}_w \mathscr{W}^T$

Measurement Update $\mathbf{C}_A(t_k^+) = \mathscr{A}_k \mathbf{C}_A(t_k^-)\mathscr{A}_k^T + \mathscr{B}_k \mathbf{R}_\nu(t_k)\mathscr{B}_k^T$

Maneuver Correction $\mathbf{C}_A(t_j^{+c}) = \mathscr{D}_j \mathbf{C}_A(t_j^{-c})\mathscr{D}_j^T + \mathscr{N}_j \mathbf{S}_{\Delta w_j}(t_j)\mathscr{N}_j^T$



Linear Covariance Analysis (LCA)

- **Method to evaluate dispersions of rendezvous navigation/control errors**
  - Monte Carlo method
  - Linear Covariance Analysis
    - Produce the same statistical results as the Monte Carlo simulation with shorter period of time
    - Powerful tool especially in the early study phase

- **Inertial state based LCA formulation with event trigger, proposed by Geller.**

$$\mathbf{x} \triangleq [\mathbf{r}_{debris}\quad \mathbf{v}_{debris}\quad \mathbf{r}_{chaser}\quad \mathbf{v}_{chaser}]$$

$\delta\mathbf{x} = \mathbf{x} - \bar{\mathbf{x}}$: true state error

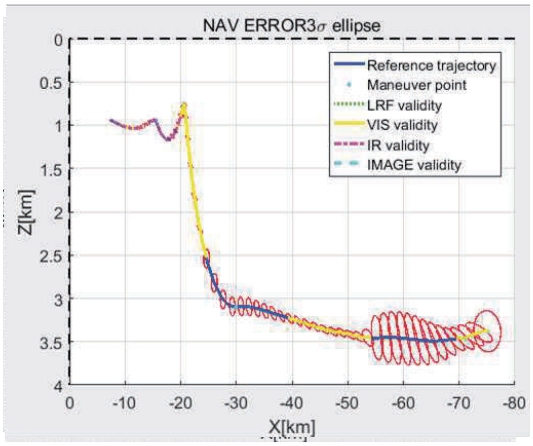
$\delta\hat{\mathbf{x}} = \hat{\mathbf{x}} - \bar{\mathbf{x}}$: navigation state error

$$\delta\mathbf{X}^T = [\delta\mathbf{x}^T\ \delta\hat{\mathbf{x}}^T] \Rightarrow \mathbf{C}_A = E[\delta\mathbf{X}\delta\mathbf{X}^T]$$

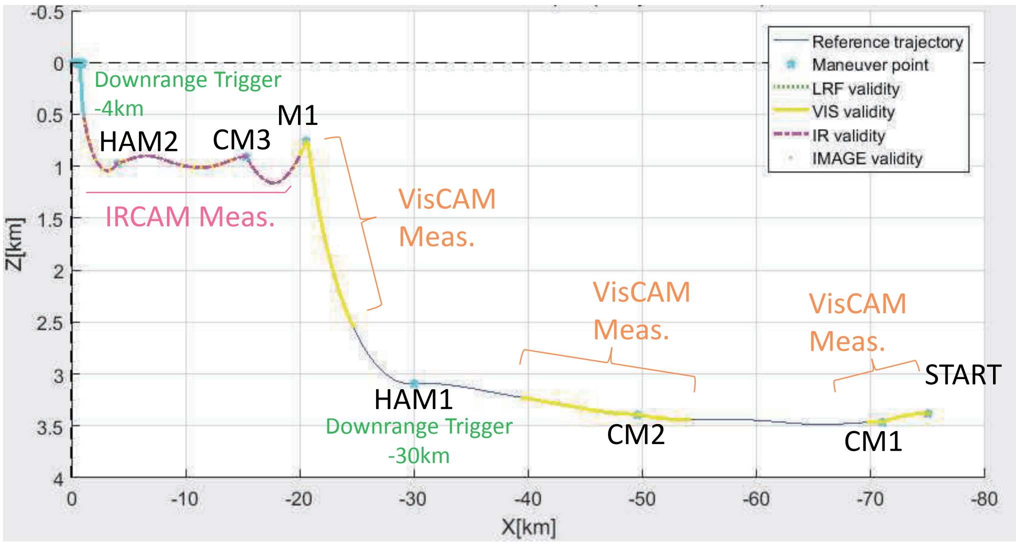
Propagation $\dot{\mathbf{C}}_A = \mathcal{F}\mathbf{C}_A + \mathbf{C}_A\mathcal{F}^T + \mathcal{W}\mathbf{S}_w\mathcal{W}^T$

Measurement Update $\mathbf{C}_A(t_k^+) = \mathcal{A}_k\mathbf{C}_A(t_k^-)\mathcal{A}_k^T + \mathcal{B}_k\mathbf{R}_\nu(t_k)\mathcal{B}_k^T$

Maneuver Correction $\mathbf{C}_A(t_j^{+c}) = \mathcal{D}_j\mathbf{C}_A(t_j^{-c})\mathcal{D}_j^T + \mathcal{N}_j\mathbf{S}_{\Delta w_j}(t_j)\mathcal{N}_j^T$



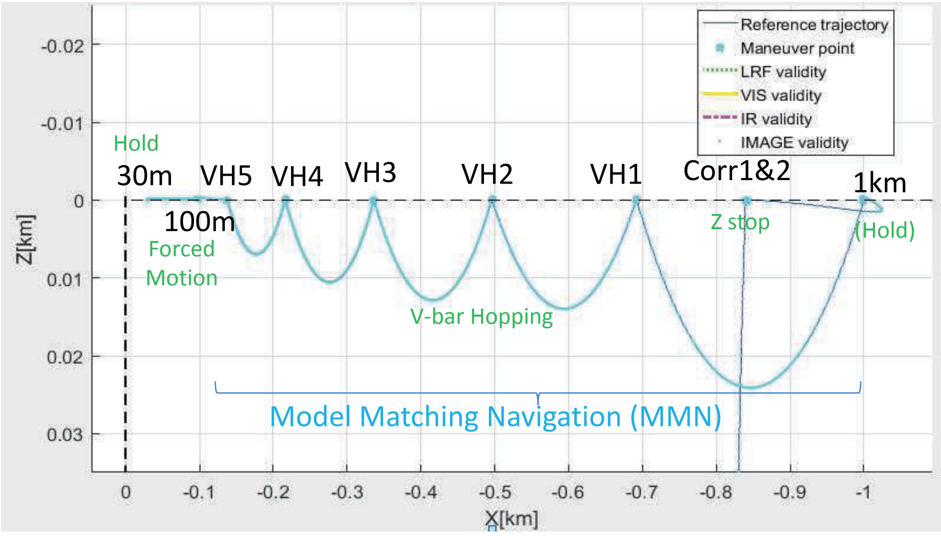
Baseline Trajectory (1/2)



Point	Time [sec]	Trigger	Maneuver	ΔV[m/s]
CM1	830	Δt	Coelliptic	0.087
CM2	5010	Δt	Coelliptic	0.18
HAM1	(8898)	X=-30km	CW targeting	0.67
M1	11868	Δt	CW targeting	0.66
CM3	14959	Δt	Coelliptic	0.31

Point	Time [sec]	Trigger	Maneuver	ΔV[m/s]
HAM2	22381	X = -4 km	CW targeting	0.41
Corr1	24806	Z = 0 km	Z stop	0.60
Corr2	24818	Z = 0 km	Z stop	0.20
1 km	24819	Δt	1km VbarHold	

Baseline Trajectory (2/2)



Point	Time [sec]	Trigger	Maneuver	ΔV[m/s]
1km	0	-	Vbar Hopping	0.001
VH1	297	Z = 0	Vbar Hopping	0.60
VH2	570	Z = 0	Vbar Hopping	0.42
VH3	878	Z = 0	Vbar Hopping	0.33
VH4	1216	Z = 0	Vbar Hopping	0.24

Point	Time [sec]	Trigger	Maneuver	ΔV[m/s]
VH5	1557	Z = 0	Z stop/ Hold	0.23
100m	2557	Δt	Forced Motion	0.23
30m	4357		Hold	

Total: 6.4 m/s (excluding 1km/100m Hold)

Simulation Parameter (1/2)

Item		Spec./ value
Debris Orbit		Altitude 620 km Sun synchronous Orbit (LST 18)
Propagator		1 Hz Geopotential: JGM3 20 × 20 Drag, Solar radiation, Luni-Solar perturbations: not applied
Navigation Filter		1Hz EKF to estimate inertial position and velocity of debris/chaser Geopotential: J2
Initial Error Random(3σ)	Truth	Tangential : 2.5 km, Ragial: 300 m, Normal:300 m (TLE/SGP4 estimated navigation accuracy)
	Navigation	Save as above
Maneuver Error	Noise(3σ)	5% of magnitude
	Misalignment	Not Applicable

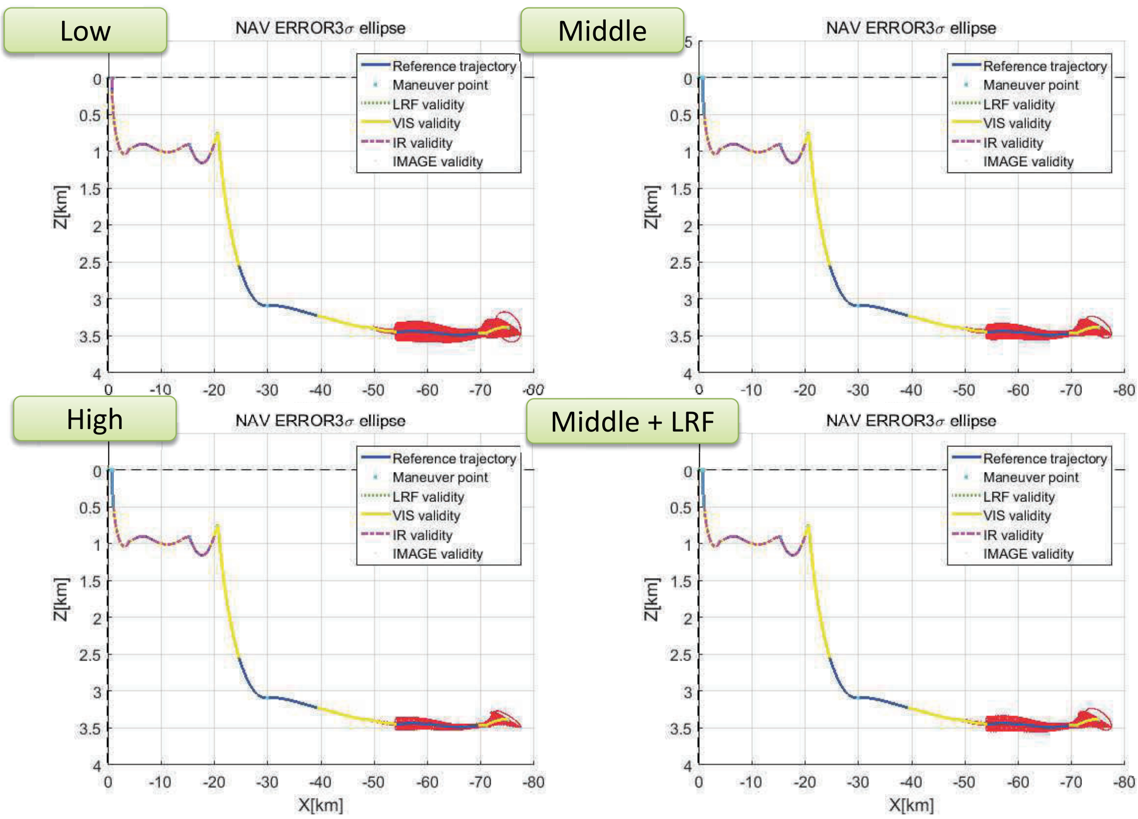
LCA Simulation Parameter (2/2)

		Low	Medium	Medium+LRF	High
Visible Camera (AON)	Update frequency	1 Hz			
	Operational Range	MMN Start ～ 100 km			
	Random Error (3σ) Bearing angles	0.1953 deg (10 pix)	0.0977 deg (5 pix)		0.0391 deg (2 pix)
		Assuming ±10 deg FOV, 1024pix Resolution			
IR Camera (AON)	Update frequency	1 Hz			
	Operational Range	MMN Start ～ 20 km			
	Random Error (3σ) Bearing angles	0.2344 deg (10 pix)	0.1172 deg (5 pix)		0.0469 deg (2pix)
		Assuming ±15 deg FOV, 640pix Resolution			
Vis/IR Camera (MMN)	Update frequency	0.5 Hz	0.5 Hz		1 Hz
	Operational Range	< 600 m	< 1.2 km		< 1.2 km
	Random Error (3σ) Bearing angles	0.2344 deg (10 pix)	0.1172 deg (5 pix)		0.0469 deg (2pix)
	Random Error (3σ) Range	10 % of range	5 % of range		3 % of range
Laser Range Finder	Update frequency			1 Hz	
	Operational Range			< 600 m	
	Random Error (3σ) Range			1 m	

＊ Bias errors are excluded in this simulation

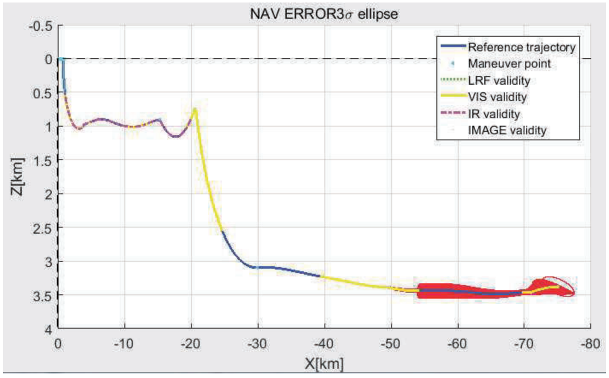
17

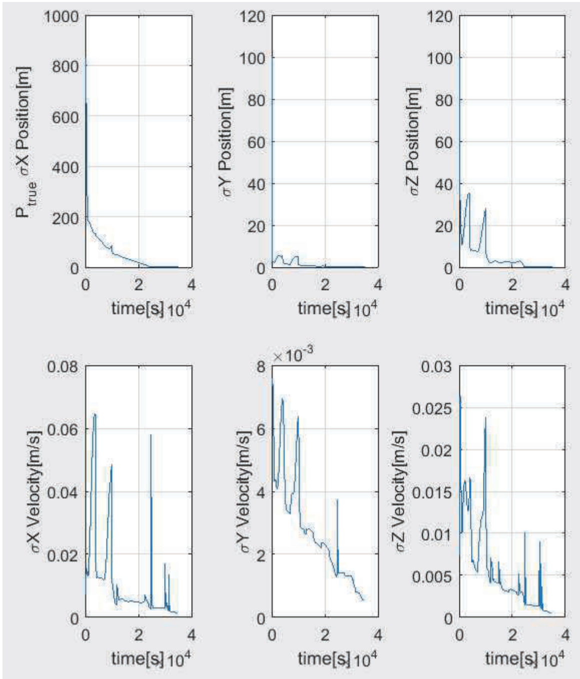
Result – Navigation Dispersion (1/2)



Result – Navigation Dispersion (2/2)

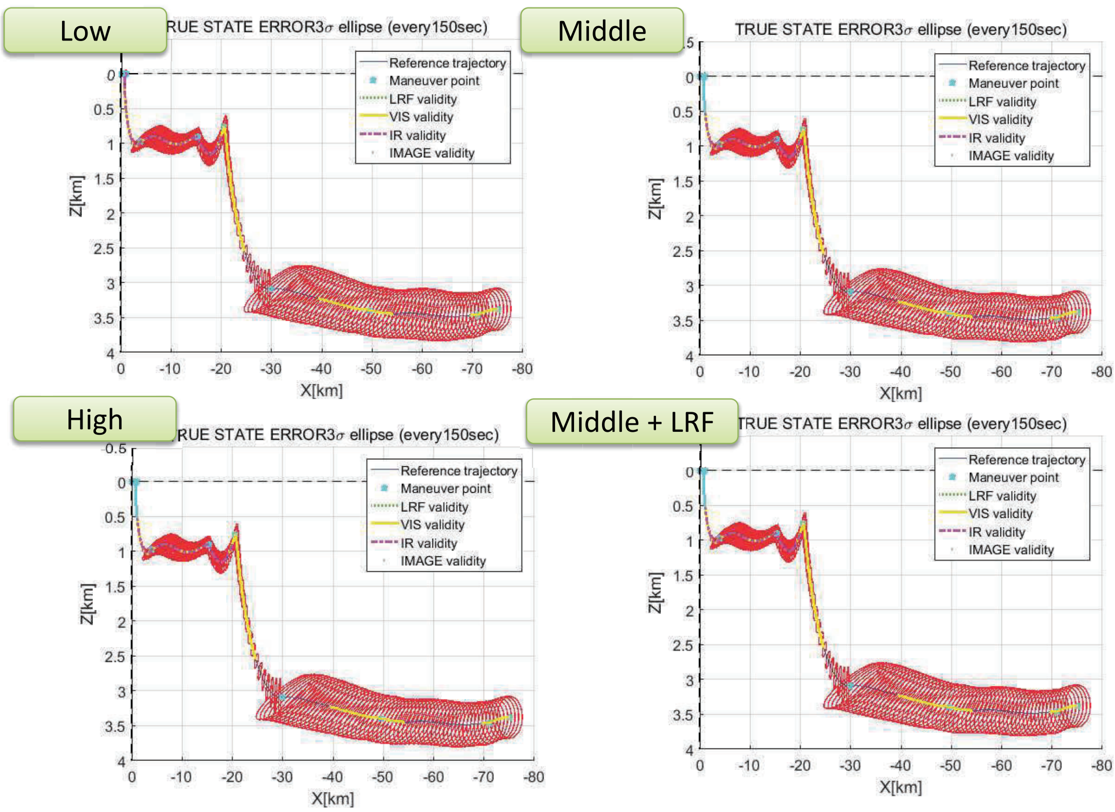
Navigation Dispersion (Medium Case)





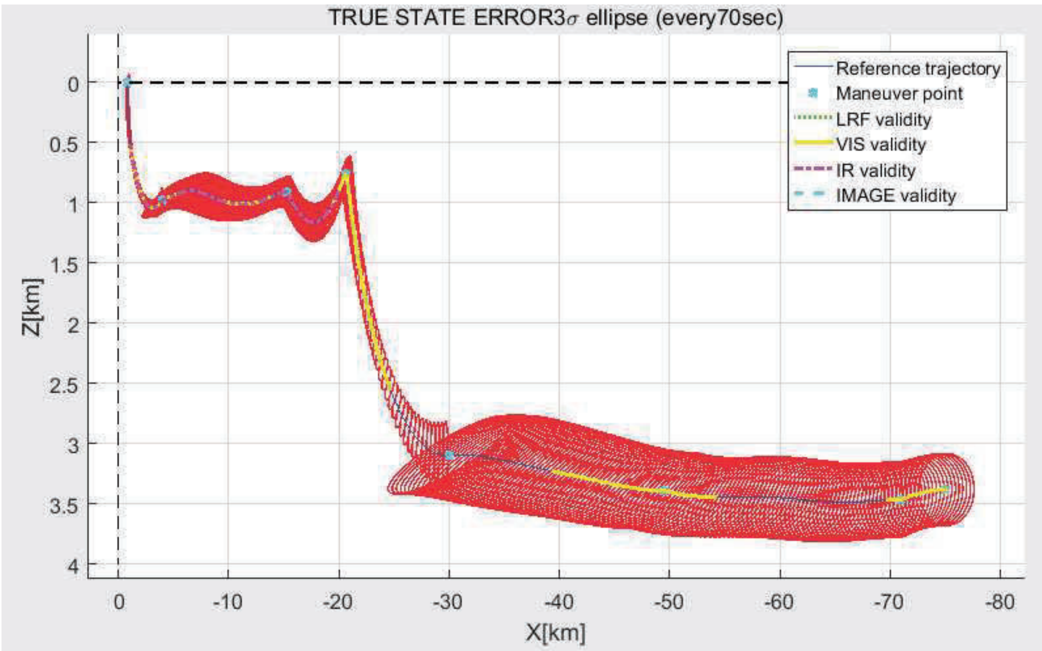
At 30m Hold point,
σx = 9.9 cm, σy = 6.0 mm
σz = 6.0 mm

Result – True State Dispersion (1/2)



Result - True State Dispersion (2/2)

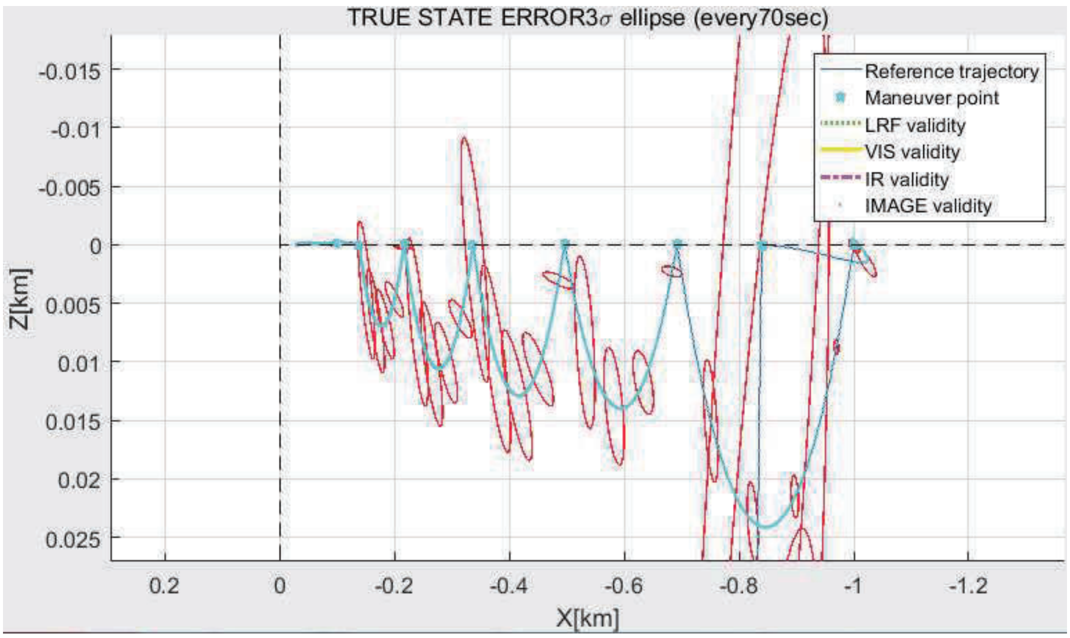
- True State Dispersion (Medium Case)



21

Result - True State Dispersion (2/2)

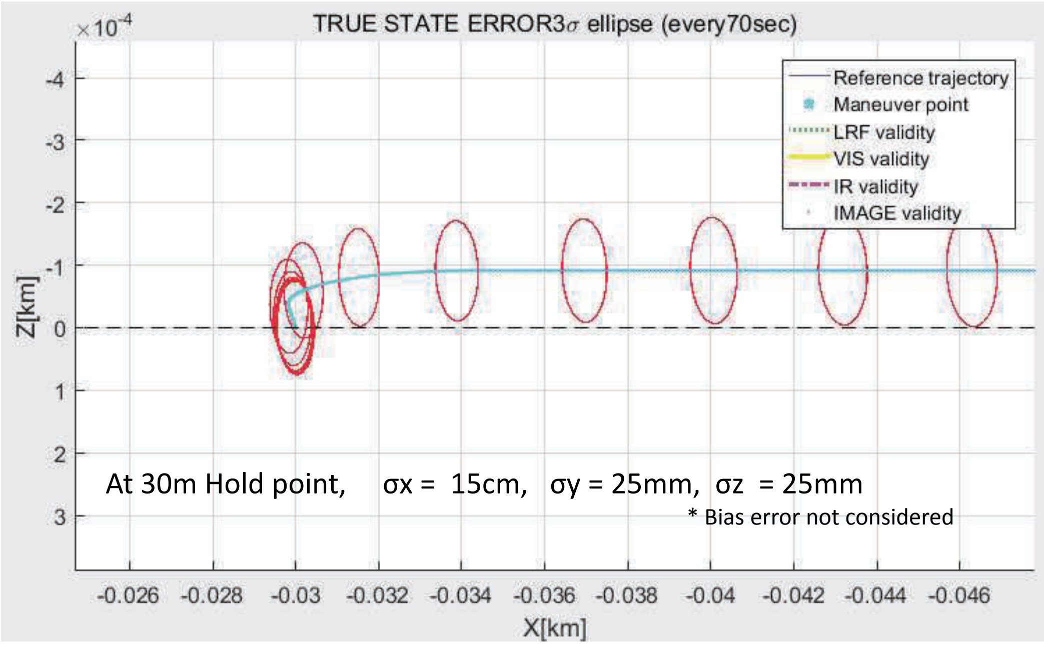
- True State Dispersion (Medium Case)



22

Result – True State Dispersion (2/2)

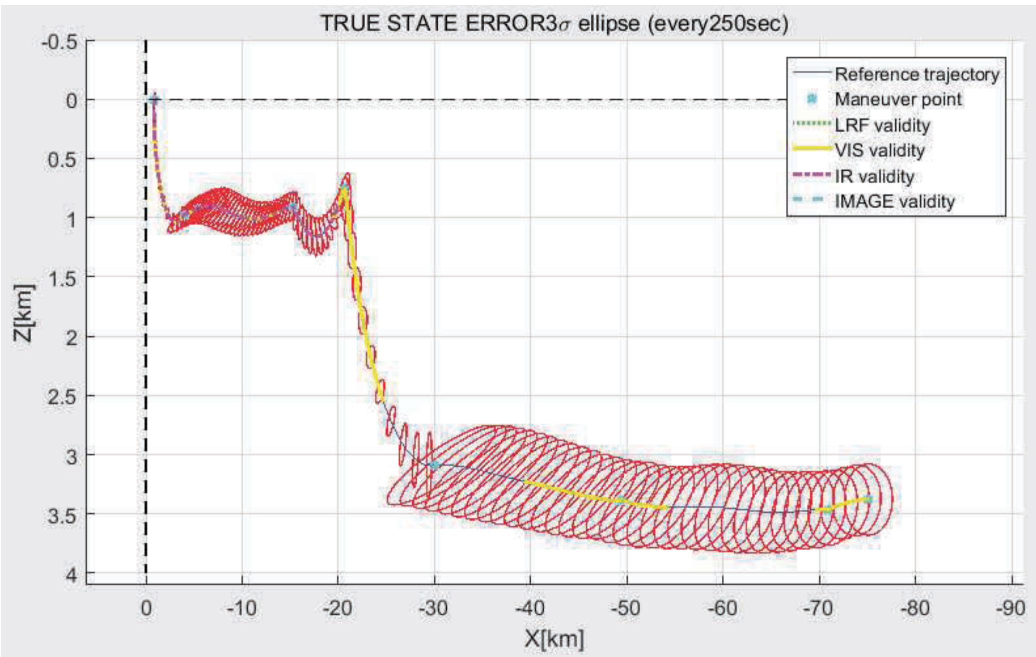
- True State Dispersion (Medium Case)



Without bias errors, the dispersion is small enough

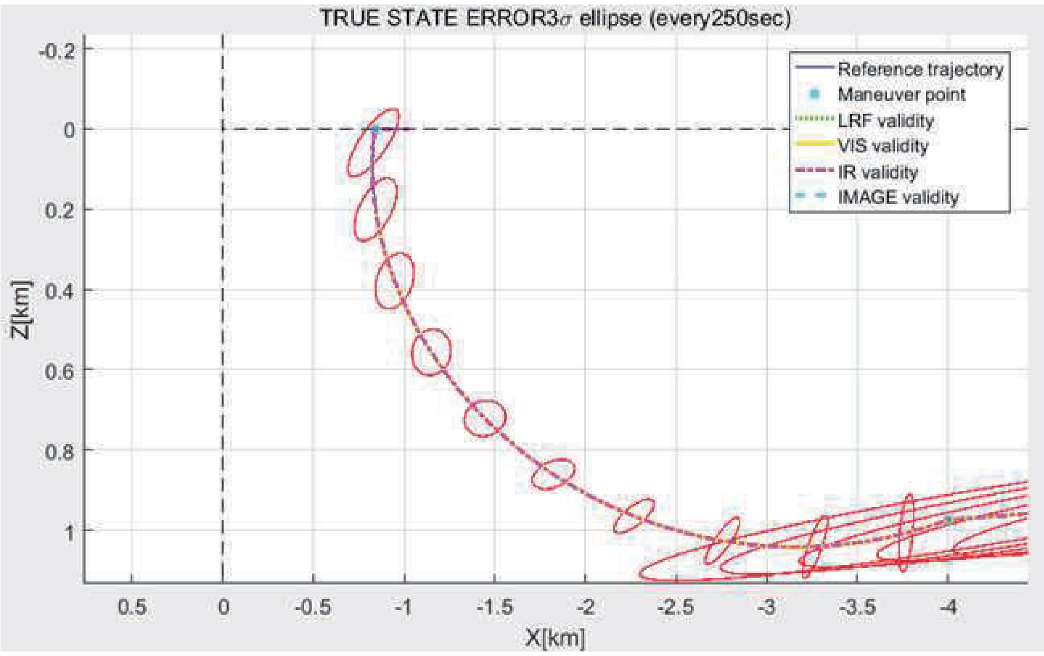
Vbar 1km Insertion with AON only

- True State Dispersion (Low Case)



Vbar 1km Insertion with AON only

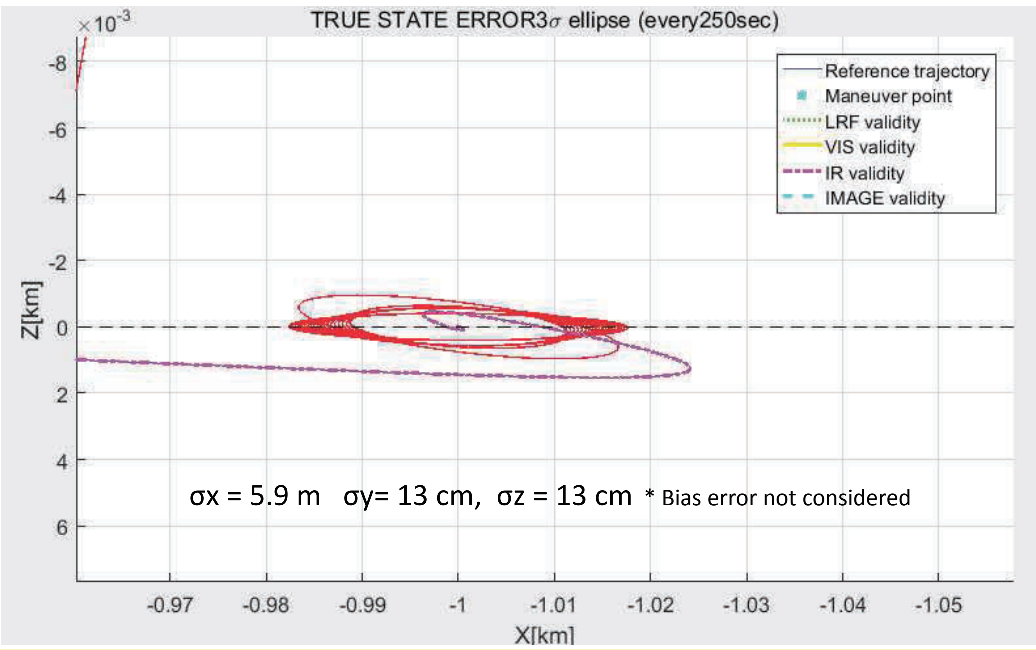
- True State Dispersion (Low Case)



25

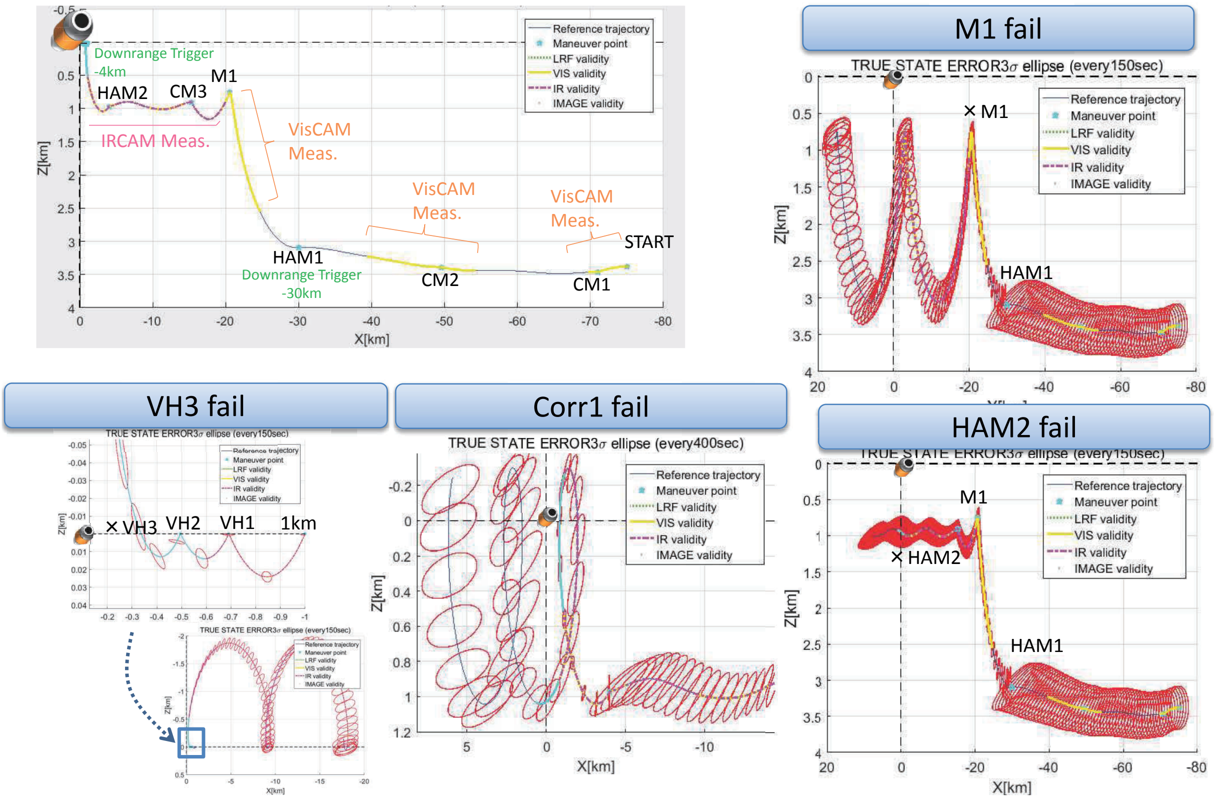
Vbar 1km Insertion with AON only

- True State Dispersion (Low Case)



LCA with bias error considered will clarify the actual requirement → Next Step

Passive Abort Safety



Summary and Future Work

- A practical navigation system and rendezvous trajectory which secures the trajectory safety was proposed.

- Linear Covariance Analysis (LCA) were performed against various simulation cases with different combinations of sensor specifications (only random errors considered).

→ It is shown that investigating of the trajectory dispersions from LCA would clarify the requirements for relative navigation sensors/system.

- Current result shows that the dispersions at 1 km/ 30 m would be small enough to keep the safe approach. However, potential bias errors such as thruster/sensor misalignment and measurement biases, which are not considered in the current work, will widen the dispersions.

→ LCA with bias error considered will clarify the actual requirement