Navigation Satellite Fault Detection and Failure Cause Identification Methods Using Inter-satellite Links and Trigonometry Law

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- Comparison of ground measurement method and proposed method
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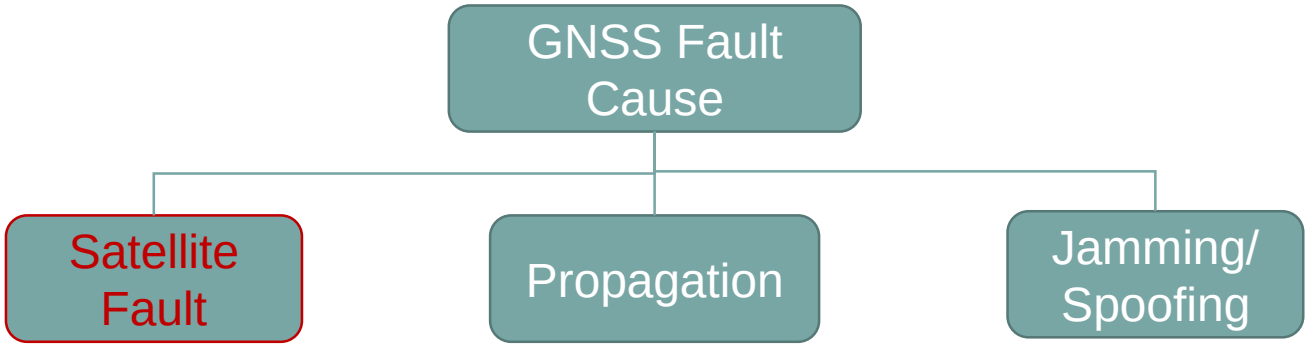
Introduction

- **GNSS Fault Cause**

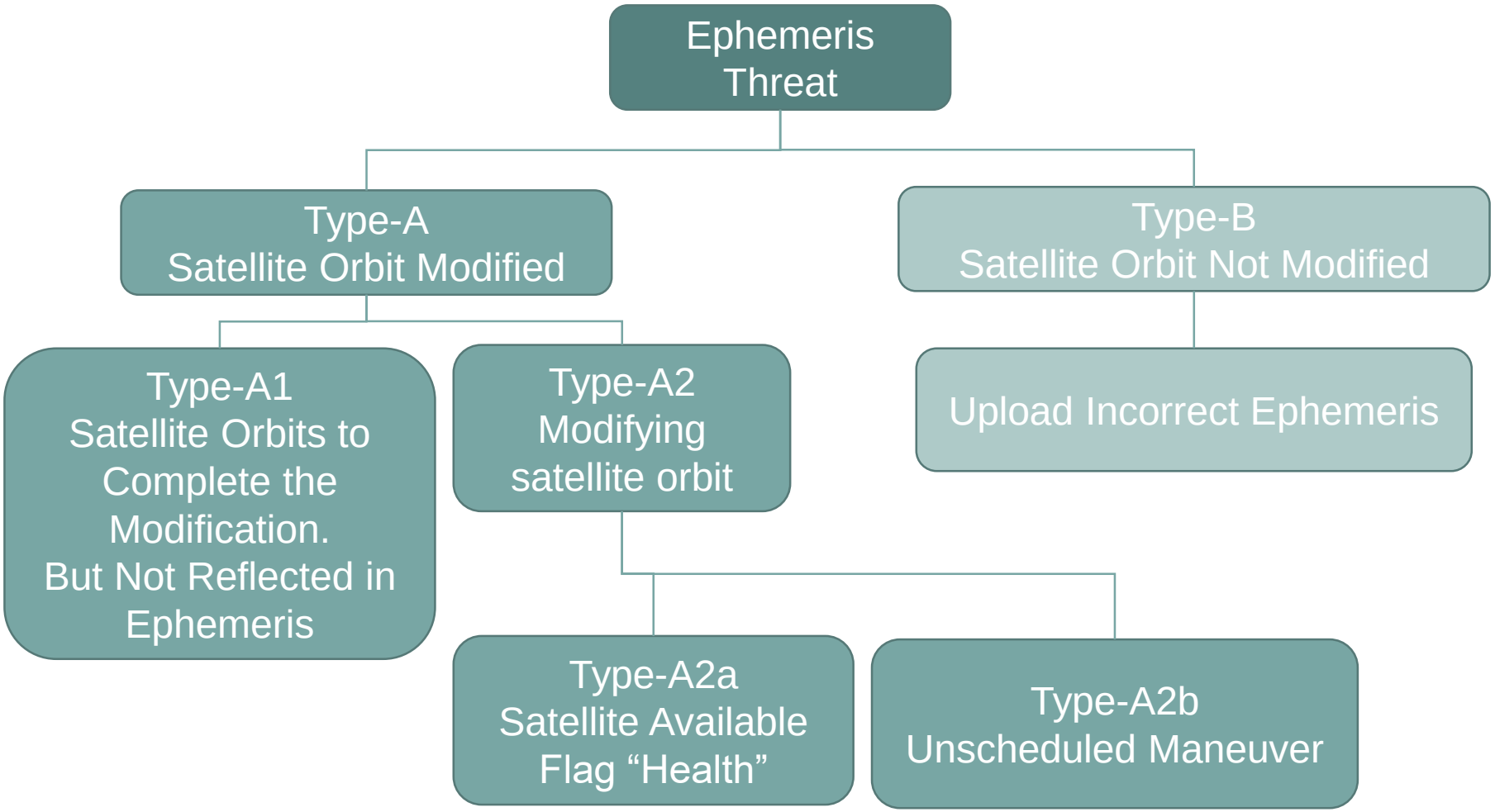


- **Fault Case**

Fault Cause	Phenomenon	PRN	Note
Digital and Analogue Circuit error	Flat, distorted multiple peak in correlator	19	1993. 10
Clock Anomaly	Discontinuity of satellite broadcast signal	27	1998. 3
Erratic Clock	Discontinuity of satellite broadcast signal	20	
Mis-modeling by master control station	Satellite ephemeris error SA-like	21	
Vehicle instability	Satellite ephemeris error SA-like	16	2004. 1
Clock Anomaly	Instability in carrier frequency range and range rate error	23	2009
Hardware Interference	Demonstrating larger than expect pseudorange errors that appear to be elevation-dependent	49	

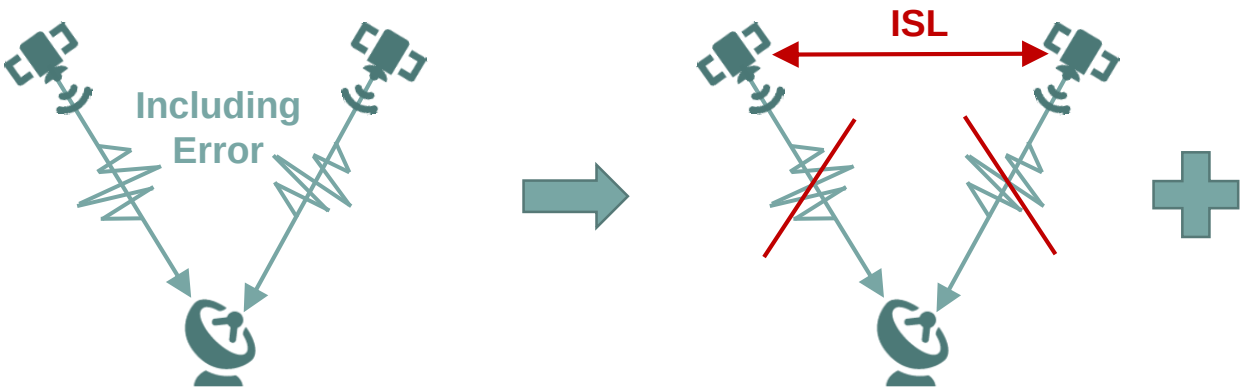
Introduction

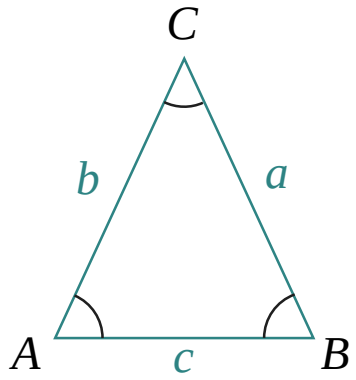
- **GPS Satellite Ephemeris Threat Class**



Introduction

- **Conventional Satellite Fault Detection Methods**
  - Measure-based techniques obtained from ground-based stations in GBAS and SBAS
    → As the **error factors** included in the ground measurements, the estimation process is required and the failure detection performance degradation
- **Propose Method**
  - Methods using **Inter-satellite link (ISL)** measurement
    → Ground measurement error factors remove
  - Satellite fault monitoring using **trigonometric law** in triangular condition
    → Improved detection performance
  - **Difference of measured value** according to cause of failure
    → The failure cause identification method





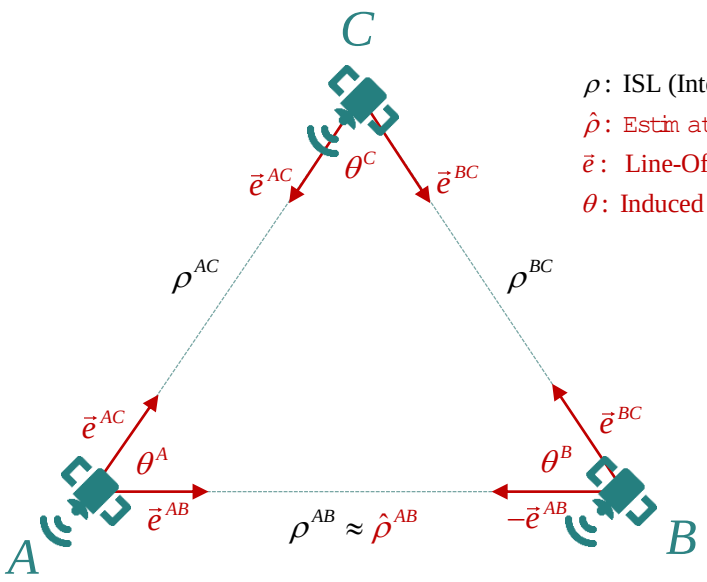
First Law of Cosines

$$c = a\cos B + b\cos A$$

Algorithm Concept

- **Concept of fault monitoring algorithm using trigonometric law**

[Normal-state]



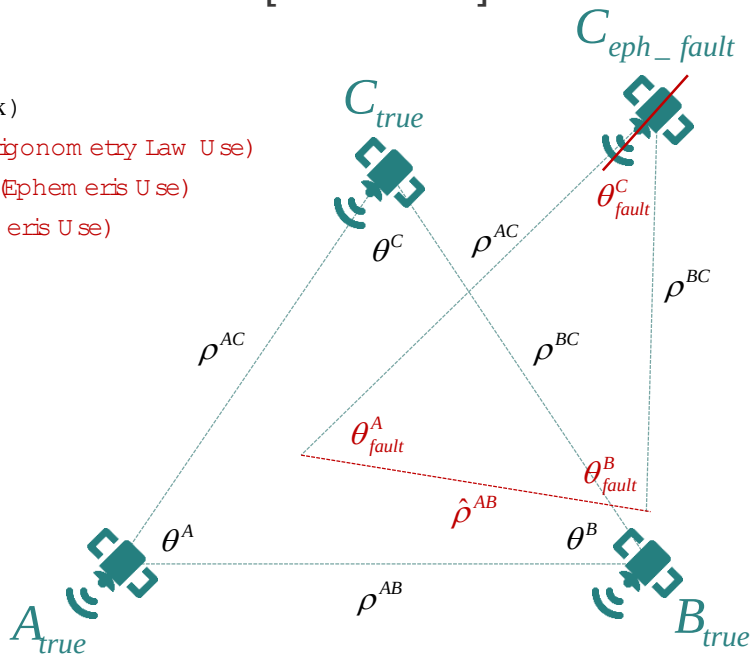
ρ : ISL (Inter Satellite Link)

$\hat{\rho}$: Estimated Range (Trigonometry Law Use)

$\vec{e}$: Line-Of-Sight Vector (Ephemeris Use)

θ : Induced Angle (Ephemeris Use)

[Fault-state]



[Test Statistic]

$$TS^C = \rho_{AB} - \hat{\rho}_{AB}$$

[Trigonometry Law]

The Law of Cosines #1: $\hat{\rho}^{AB} = \rho^{AC}\cos\theta_A + \rho^{BC}\cos\theta_B$

The Law of Cosines #2: $\left(\hat{\rho}^{AB}\right)^2 = \left(\rho^{AC}\right)^2 + \left(\rho^{BC}\right)^2 - 2\rho^{AC}\rho^{BC}\cos\theta_C$

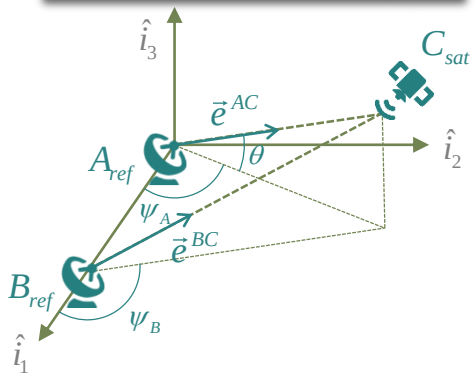
[Assumption]

1 Satellite Fault

Comparison of ground measurement method and proposed method

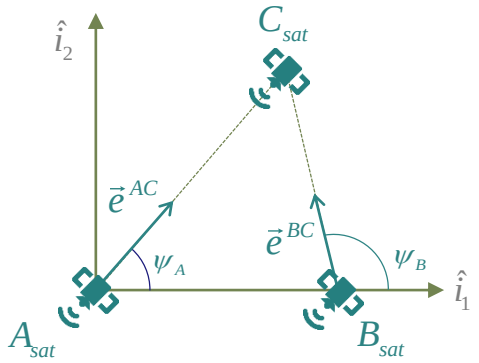
- **Situation according to triangle component**

2 Reference Station + 1 Fault-state Satellite



VS

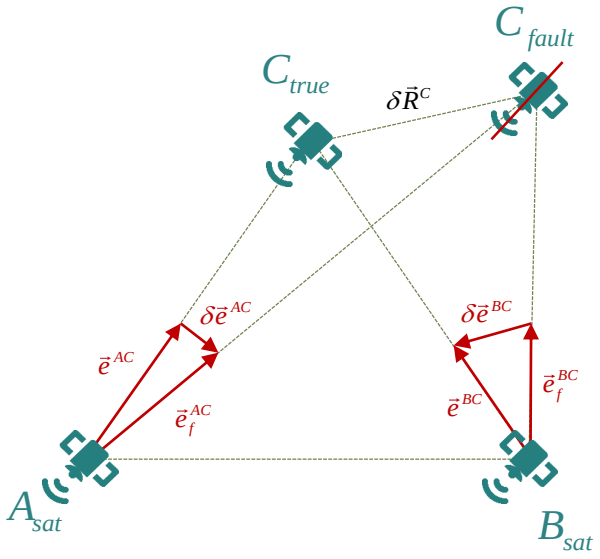
2 Normal-state Satellite + 1 Fault-state Satellite



2 Reference Station	**Normal-state**	2 Normal-state Satellite
Baseline Distance	**Measure distance between normal-states**	ISL
Pseudorange	**Measure distance between satellite and normal-states**	ISL
3D	**Local coordinate**	2D
O	**Presence or absence of elevation angle**	X
O	**Presence or absence of requirement reference station**	X (Satellite Self-monitoring)
Pseudorange	**Error-containing Parts**	Broadcast Ephemeris of Normal-state Satellite

Sensitivity Analysis

- **Sensitivity**
  - Factors that determine the **detectable fault size**
  - Used as **performance indicator** of fault detection algorithm



$$\delta\vec{e} = \frac{\left(I - \vec{e}^T \cdot \vec{e}\right)\delta\vec{R}}{\rho}$$

$$\vec{e}_f^{AC} = \vec{e}^{AC} + \delta\vec{e}^{AC} \qquad \vec{e}_f^{BC} = \vec{e}^{BC} + \delta\vec{e}^{BC}$$

$$TS^C = \left|\rho_{AB} - \hat{\rho}_{AB}\right|$$
$$= \delta\vec{R}^T \cdot \left[\left(\vec{e}^{AC}\right)^T \cdot \left(\vec{e}^{AC}\right) - \left(\vec{e}^{AB}\right)^T \cdot \left(\vec{e}^{AB}\right)\right]^T \cdot \vec{e}^{AB}$$
$$= \delta\vec{R}^T \cdot \left[E^C\right]^T \cdot \vec{e}^{AB}$$

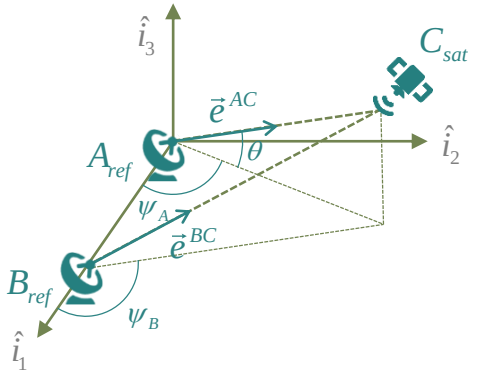
$$\vec{e}^{AB} = \begin{bmatrix}1 & 0 & 0\end{bmatrix}^T$$
$$TS^C = \left[E^C\right]_L^T \cdot \delta\vec{R}^T$$
$$\left[E^C\right]_L = \left[E^C\right]^T \cdot \vec{e}^{AB}$$

Sensitivity

Sensitivity Analysis

- **Sensitivity**
  - Derive sensitivity according to local coordinate system setting

2 Reference Station + 1 Fault-state Satellite

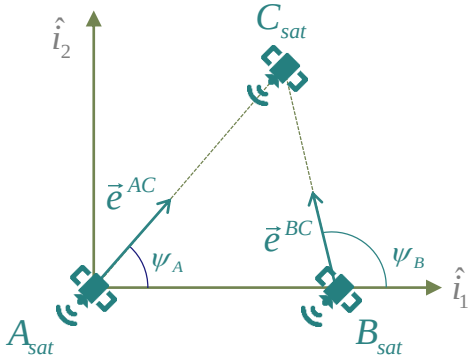


$$\vec{e}^{AC} = \cos\theta\cos\psi_A\hat{i}_1 + \cos\theta\sin\psi_A\hat{i}_2 + \sin\theta\hat{i}_3$$
$$\vec{e}^{BC} = \cos\theta\cos\psi_B\hat{i}_1 + \cos\theta\sin\psi_B\hat{i}_2 + \sin\theta\hat{i}_3$$

$$\left[E^C\right]_L^T = \left[E^C\right]^T \cdot \vec{e}^{AB}$$
$$= \begin{bmatrix} \cos^2\theta\left(\cos^2\psi_A - \cos^2\psi_B\right) \\ \cos^2\theta\left(\cos\psi_A\sin\psi_A - \cos\psi_B\sin\psi_B\right) \\ \cos\theta\sin\theta\left(\cos\psi_A - \cos\psi_B\right) \end{bmatrix}^T$$

Elevation Angle X
↓
Simplification of formulas

2 Normal-state Satellite + 1 Fault-state Satellite



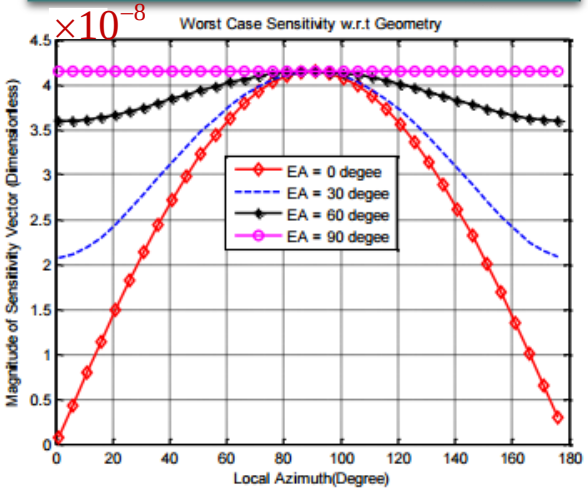
$$\vec{e}^{AC} = \cos\psi_A\hat{i}_1 + \sin\psi_A\hat{i}_2$$
$$\vec{e}^{BC} = \cos\psi_B\hat{i}_1 + \sin\psi_B\hat{i}_2$$

$$\left[E^C\right]_L^T = \left[E^C\right]^T \cdot \vec{e}^{AB}$$
$$= \begin{bmatrix} \cos^2\psi_A - \cos^2\psi_B \\ \cos\psi_A\sin\psi_A - \cos\psi_B\sin\psi_B \end{bmatrix}^T$$

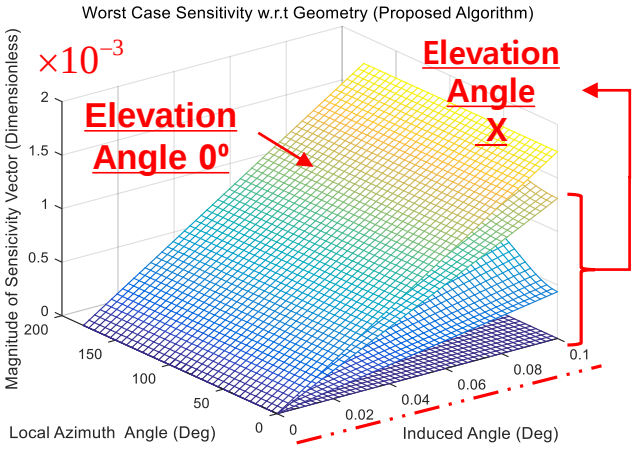
Sensitivity Analysis

- **Sensitivity comparison through simulation**
  - Algorithm performance prediction based on triangle component change

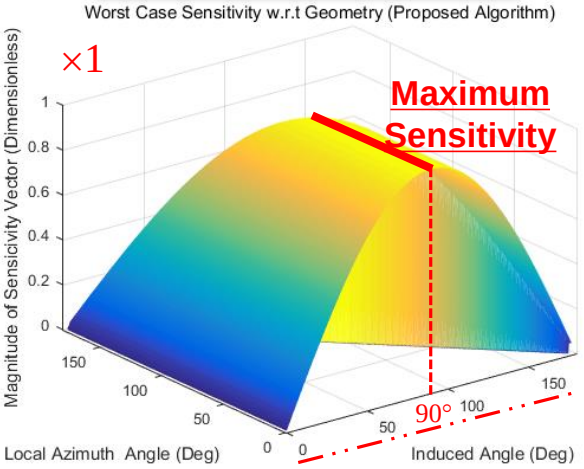
GBAS phase based satellite fault detection method



2 Reference Station + 1 Fault-state Satellite



2 Normal-state Satellite + 1 Fault-state Satellite



- No triangle configuration
- Relatively low sensitivity

→

- Distance limit is generated by using reference station
- Geometric restriction of the angle of induced

→

- Geometric constraints X
- No condition of included angle

Sensitivity increase

↓

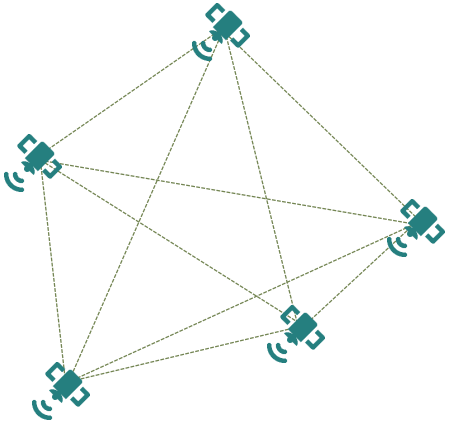
Reduced detectable fault size

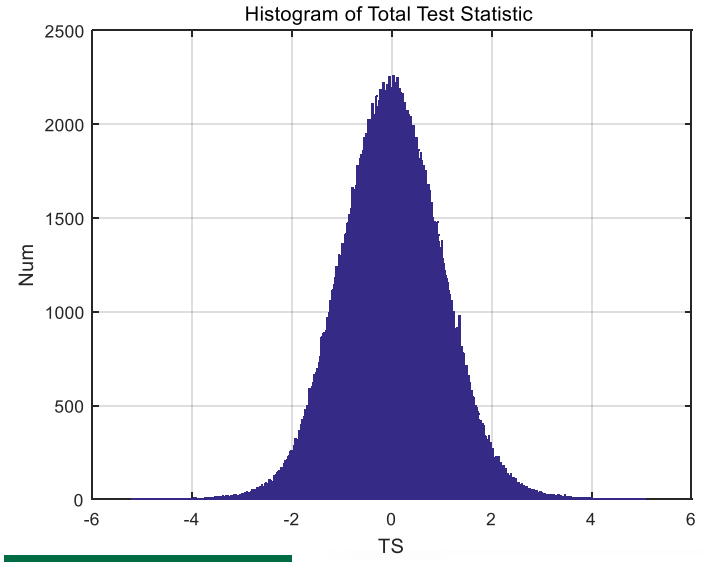
Fault Simulation

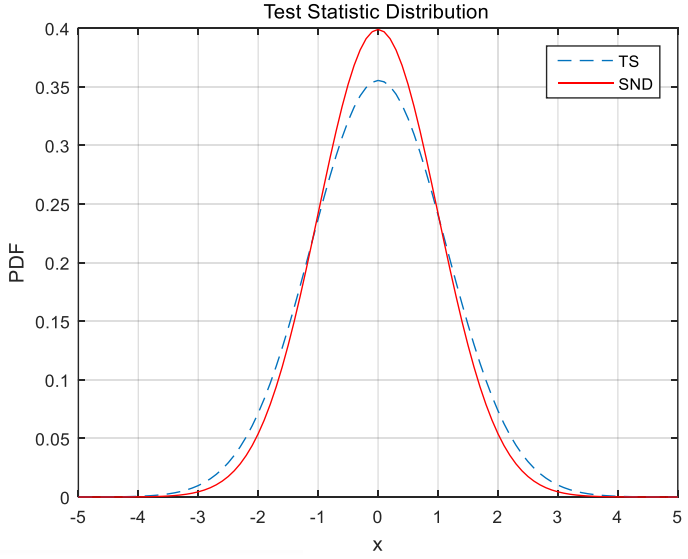
- **Normal-state test statistic analysis**
  - Procedure for calculation of threshold

Analysis Data		
Data	Date	2011. 2. 13 ~ 2.19 (1 Week)
	ISL	Calculated using IGS (ISL is not measurable)
	Ephemeris	Suwon International GNSS Service (IGS) in South Korea
	Period	15 minute

Analysis of all triangular configurations of visible satellites







Normal-state test statistic

↓

The trend of standard normal distribution

↓

Threshold

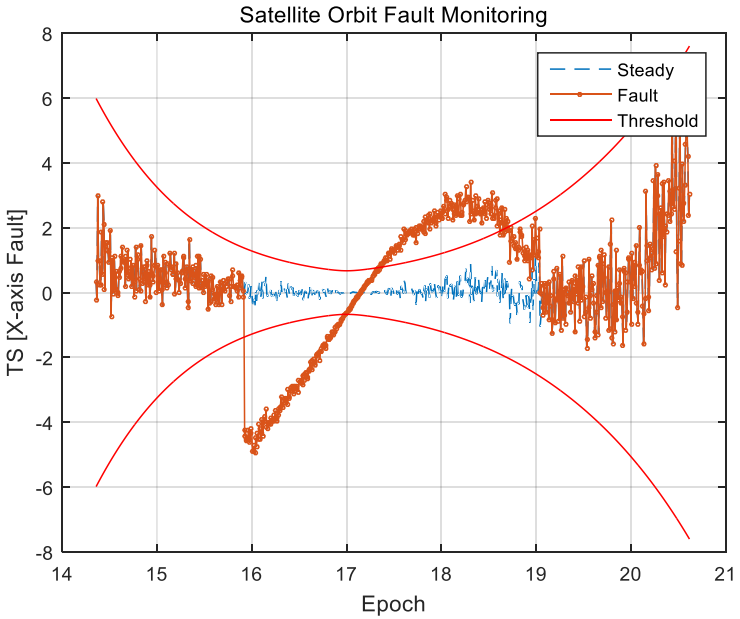
Normal-state Data 3σ

Fault Simulation

- **Comparison of Detectable Fault Size According to Triangle Configuration**
  - Both configurations result in the implementation of this algorithm
  - All fault detection possible
  - Possible difference in detectable fault size

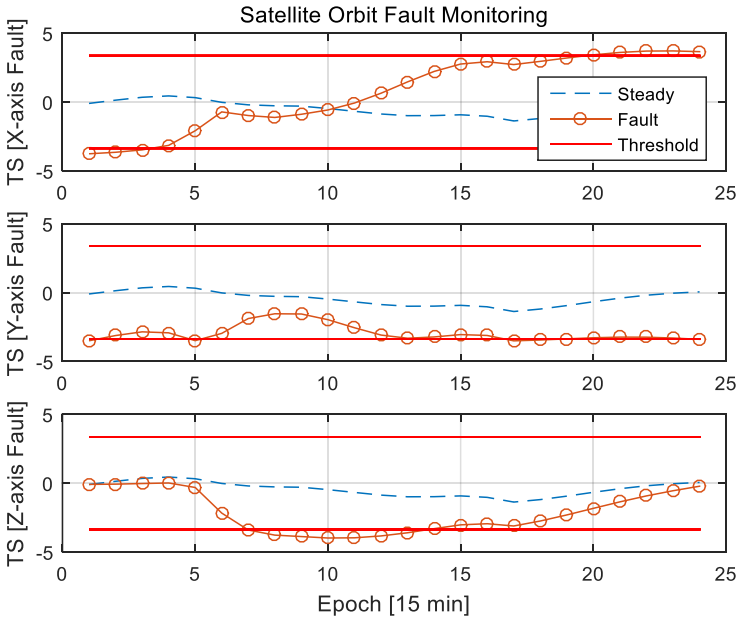
2 Reference Station + 1 Fault-state Satellite

Insertion satellite Orbital failure size : 1 km



2 Normal-state Satellite + 1 Fault-state Satellite

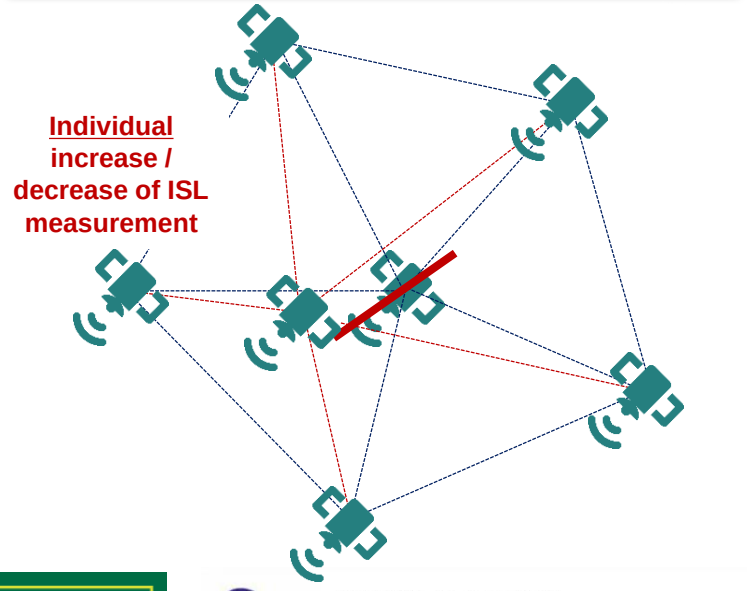
Insertion satellite Orbital failure size : 5 m



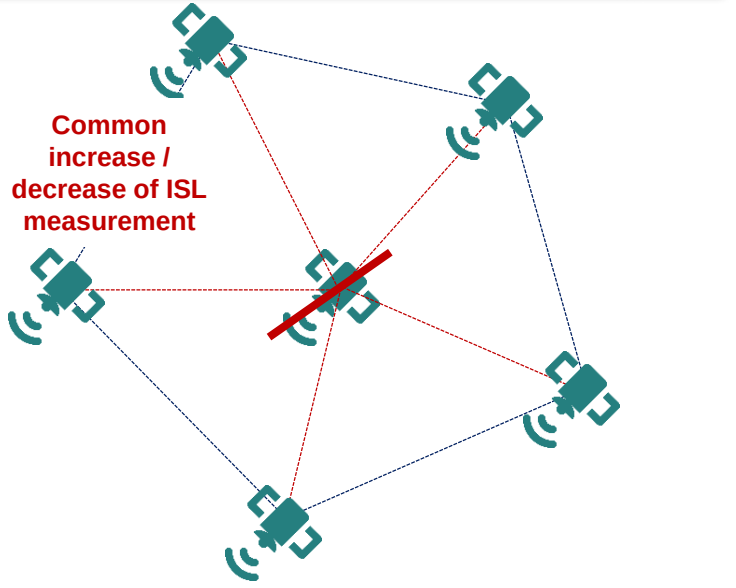
Satellite Failure Cause Identification Method

- **ISL measurement trends due to satellite failure**
  - Assumption: ISL measurements are synchronized with satellite time
  - There is a difference in ISL measurement failure due to the cause of failure and the geometry of the satellite
  - Orbit fault: Fault effect difference for each ISL measurement according to orbital failure direction
  - Clock fault: Same size fault for both ISL measurements connected to faulty satellites

Satellite Orbit Fault



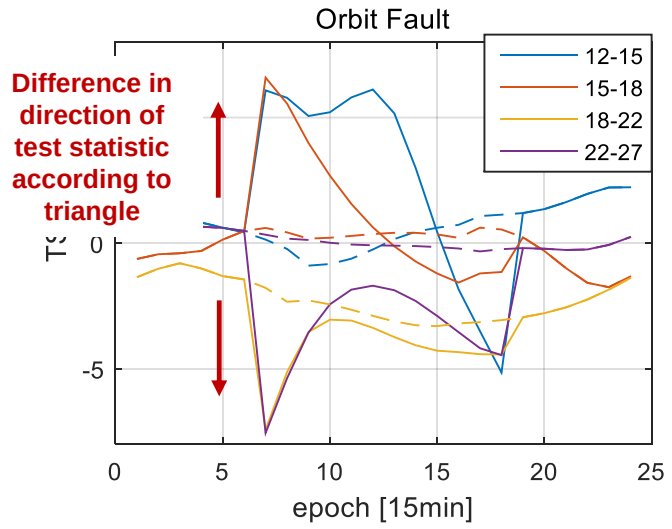
Satellite Clock Fault



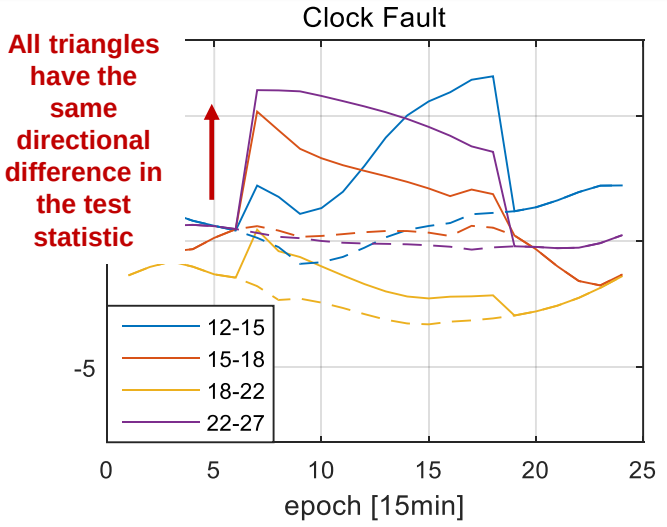
Satellite Failure Cause Identification Method

- **Confirmation test statistic trend through failure simulation**
  - Failure simulation for checking the predicted test statistic tendency according to the cause of failure
  - Comparison of test statistic after orbital / clock fault insertion
  - Orbit fault: Change in test statistic is positive / negative
  - Clock fault: Change in test statistic occurs in positive or negative direction

Satellite Orbit Fault

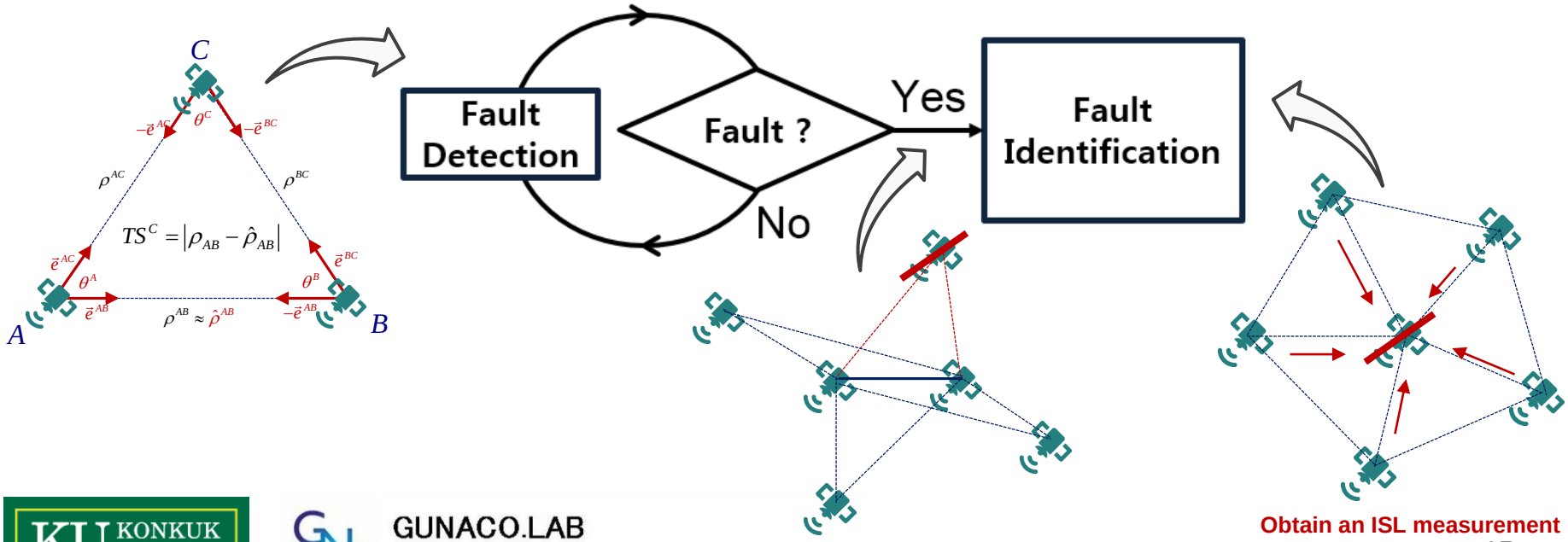


Satellite Clock Fault



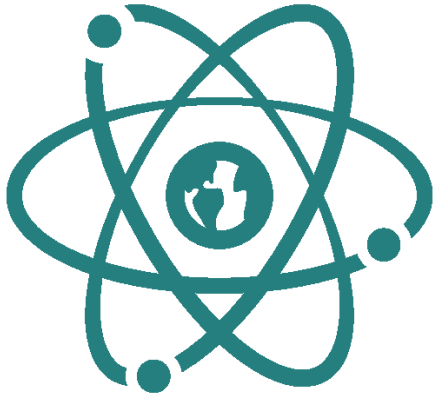
Operational Concept of Methods

- **Operational Concept of the Satellite Fault Detection and Satellite Failure Cause Identification Methods**
  - If ISL measurements can be received on the ground, the methods can be employed on the ground. Otherwise, satellite on-board processing is necessary
  - First, the satellite fault detection algorithm is run continuously
  - Once a fault is detected, the satellite involved is declared out of service
  - All satellites near the fault-state satellite are then configured to provide their ISL measurements. And perform fault identification



Conclusion

- Explain **satellite fault detection method** using ISL measurement, instead of ground measurements, coupled with a trigonometry law
- **Sensitivity comparison analysis** was performed
- Setting the **threshold** and performing fault simulation
- Explain **satellite failure cause identification method** using ISL and trigonometry law
- Cause-dependent tendency of measurements was predicted, simulation was performed to verify **the predicted changes in the test statistic**
- Finally, an overview of the **operational concept** of the satellite fault detection and satellite failure cause identification



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