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

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GUNACO

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Introduction

- GNSS Fault Cause

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Satellite Fault

- GNSS Fault Cause
  - Propagation
  - Jamming/Spoofing

- Fault Case

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

- GPS Satellite Ephemeris Threat Class

  Ephemeris Threat

  - Type-A
    - Satellite Orbit Modified
      - Type-A1
        - Satellite Orbits to Complete the Modification. But Not Reflected in Ephemeris
      - Type-A2
        - Modifying satellite orbit
        - Type-A2a
          - Satellite Available Flag “Health”
        - Type-A2b
          - Unscheduled Maneuver
  - Type-B
    - Satellite Orbit Not Modified
      - Upload Incorrect Ephemeris
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

\[ c = a \cos B + b \cos A \]
Concept of fault monitoring algorithm using trigonometric law

[Normal-state]

\[ \rho : ISL \ (Inter \ Satellite \ Link) \]
\[ \hat{\rho} : Estimated \ Range \ (Trigonometric\ Law \ Use) \]
\[ \bar{e} : \ \text{Line-Of-Sight} \ \text{Vector} \ \ (Ephemeris\ Use) \]
\[ \theta : \ \text{Induced} \ \text{Angle} \ \ (Ephemeris\ Use) \]

[Fault-state]

\[ \rho^A \approx \hat{\rho}^A \]

[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: 
\[ (\hat{\rho}^{AB})^2 = (\rho^{AC})^2 + (\rho^{BC})^2 - 2\rho^{AC}\rho^{BC}\cos \theta_C \]

[Assumption]

1 Satellite Fault
### Comparison of ground measurement method and proposed method

- **Situation according to triangle component**

<table>
<thead>
<tr>
<th>2 Reference Station</th>
<th>Normal-state</th>
<th>2 Normal-state Satellite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Distance</td>
<td>Measure distance between normal-states</td>
<td>ISL</td>
</tr>
<tr>
<td>Pseudorange</td>
<td>Measure distance between satellite and normal-states</td>
<td>ISL</td>
</tr>
<tr>
<td>3D</td>
<td>Local coordinate</td>
<td>2D</td>
</tr>
<tr>
<td>O</td>
<td>Presence or absence of elevation angle</td>
<td>X</td>
</tr>
<tr>
<td>O</td>
<td>Presence or absence of requirement reference station</td>
<td>X (Satellite Self-monitoring)</td>
</tr>
<tr>
<td>Pseudorange</td>
<td>Error-containing Parts</td>
<td>Broadcast Ephemeris of Normal-state Satellite</td>
</tr>
</tbody>
</table>
Sensitivity Analysis

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

\[
\delta \tilde{e} = \frac{(I - \tilde{e}^T \cdot \tilde{e}) \delta \tilde{R}}{\rho}
\]

\[
\tilde{e}_f^{AC} = \tilde{e}^{AC} + \delta \tilde{e}^{AC} \\
\tilde{e}_f^{BC} = \tilde{e}^{BC} + \delta \tilde{e}^{BC}
\]

\[
TS^C = |\rho_{AB} - \hat{\rho}_{AB}|
\]

\[
= \delta \tilde{R}^T \cdot \left[ \left( \tilde{e}^{AC} \right)^T \cdot \left( \tilde{e}^{AC} \right) - \left( \tilde{e}^{AB} \right)^T \cdot \tilde{e}^{AB} \right]^T \cdot \tilde{e}^{AB}
\]

\[
\tilde{e}^{AB} = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}^T
\]

\[
TS^C = \left[ E^C \right]_L \delta \tilde{R}^T
\]

\[
\left[ E^C \right]_L = \left[ E^C \right]^T \cdot \tilde{e}^{AB}
\]
### Sensitivity Analysis

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

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**2 Reference Station + 1 Fault-state Satellite**

\[
\varepsilon^{AC} = \cos \theta \cos \psi_A \hat{i}_1 + \cos \theta \sin \psi_B \hat{i}_2 + \sin \theta \hat{i}_3
\]

\[
\varepsilon^{BC} = \cos \theta \cos \psi_B \hat{i}_1 + \cos \theta \sin \psi_B \hat{i}_2 + \sin \theta \hat{i}_3
\]

\[
\left[ E^C \right]^T_L = \left[ E^C \right]^T \cdot \varepsilon^{AB}
\]

\[
= \begin{bmatrix}
\cos^2 \theta (\cos^2 \psi_A - \cos^2 \psi_B) \\
\cos^2 \theta (\cos \psi_A \sin \psi_A - \cos \psi_B \sin \psi_B) \\
\cos \theta \sin \theta (\cos \psi_A - \cos \psi_B)
\end{bmatrix}^T
\]

---

**2 Normal-state Satellite + 1 Fault-state Satellite**

\[
\varepsilon^{AC} = \cos \psi_A \hat{i}_1 + \sin \psi_A \hat{i}_2
\]

\[
\varepsilon^{BC} = \cos \psi_B \hat{i}_1 + \sin \psi_B \hat{i}_2
\]

\[
\left[ E^C \right]^T_L = \left[ E^C \right]^T \cdot \varepsilon^{AB}
\]

\[
= \begin{bmatrix}
\cos^2 \psi_A - \cos^2 \psi_B \\
\cos \psi_A \sin \psi_A - \cos \psi_B \sin \psi_B
\end{bmatrix}^T
\]

---

**Elevation Angle X**

\[
\downarrow \text{Simplification of formulas}
\]
Sensitivity Analysis

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

GBAS phase based satellite fault detection method

- No triangle configuration
- Relatively low sensitivity

2 Reference Station + 1 Fault-state Satellite

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

2 Normal-state Satellite + 1 Fault-state Satellite

- 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

<table>
<thead>
<tr>
<th>Date</th>
<th>2011. 2. 13 ~ 2.19 (1 Week)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>Calculated using IGS (ISL is not measurable)</td>
</tr>
<tr>
<td>Ephemeris</td>
<td>Suwon International GNSS Service (IGS) in South Korea</td>
</tr>
<tr>
<td>Period</td>
<td>15 minute</td>
</tr>
</tbody>
</table>

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**Analysis of all triangular configurations of visible satellites**

- Normal-state test statistic
- The trend of standard normal distribution
- Threshold
- Normal-state Data $3\sigma$
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

**Insertion satellite Orbital failure size:**
- 1 km
- 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 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

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**Satellite Orbit Fault**

**Satellite Clock Fault**

- Difference in direction of test statistic according to triangle
- All triangles have the same directional difference in the test statistic
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.

\[ TS^C = |\rho_{AB} - \hat{\rho}_{AB}| \]
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