Preliminary Results and Findings
Limited Deployment – Cooperative Airspace Project

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Background

- Bottom Line Up Front
- Background
  - Goals and Objective
  - Integrated Test Capability
  - Initial Use Case: Evaluating Cooperative Automatic Sense-and-Avoid
- FY2012 Flight Evaluations
- Simulation and Flight Comparisons
- Observations and Lessons Learned
- Summary and Next Steps
NASA Langley Research Center (LaRC) and MITRE developed an integrated simulation and flight test capability for testing prototype sense-and-avoid (SAA) system elements. \(^1\)

In FY2012, the integrated test capability was used to evaluate the viability of cooperative automatic SAA alternatives for unmanned aircraft systems in basic encounter scenarios.

- Two prototype cooperative automatic SAA algorithms \(^2\) were subjected to millions of simulated 1-on-1 encounters and ~150 live-flight encounters.
- Using ADS-B messages \(^3\), both algorithms under test identified conflicts, issued maneuver commands, and routinely maintained the desired separation between ownship and the intruder aircraft.
- Results to date suggest reasonable congruence between the simulated and flight environments for the encounter scenarios examined.
- Data generated may help inform development of performance standards.

In FY2013, the integrated test capability will be used to evaluate the viability of cooperative automatic SAA alternatives for unmanned aircraft systems in more complex encounter scenarios.

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1: SAA system elements include hardware & software (e.g., real/simulated ADS-B transceiver, real/simulated research autopilot control capability, SAA system software), data-collection capability, personnel, and data communications (e.g., command and control data-links).
2: One developed by University of North Dakota (UND) and the other developed by MITRE.
3: ADS-B refers to Automatic Dependent Surveillance-Broadcast. Aircraft equipped with ADS-B IN and OUT capabilities transmit their location and receive aircraft information for proximate traffic equipped with ADS-B avionics.
Background: **Goals and Objectives**

- Develop an effective simulation and flight test capability for evaluating prototype SAA system elements
  - Support ongoing validation efforts for analysis tools and infrastructure
  - Promote interoperability between both test beds (i.e., simulation and flight test) via the use of standards and interface requirements

- Use integrated test capability to evaluate prototype cooperative automatic SAA alternatives
  - Perform iterative studies to support development of performance standards
  - Generate data for standards development and SAA alternatives analysis

Inform analysis of sense & avoid alternatives with data
Background: Integrated Test Capability

Simulation Testbed

- Fast-time computer simulation
- Evaluates the performance of SAA algorithms across a wide array of flight encounters and conditions
- Initial operating capability focused on simulating cooperative aircraft operating under visual flight rules (VFR) in low altitude airspace
- *Capable of millions of encounters*

Flight-Test Platform and Testbed

- Surrogate unmanned aircraft system (UAS)
- Supports hardware and software in-the-loop evaluation of SAA system elements in a mixed airspace environment
- Operates with NASA Safety Pilot/Pilot in Command onboard; however, can be controlled remotely via generic Ground Station uplink or automatically via onboard systems
- *Capable of scores of encounters*
Background:

Integrated Test Capability: Flight-Test Platform and Testbed

Diagram:

- General Purpose Computer GPC-1
  - SAA Algorithm
  - Connected to Ethernet Switch
  - Receives VHF Data Link 1 (9600 baud)
  - Receives VHF Data Link 2 (9600 baud)

- Operator Work Station
  - Connected to RS-232
  - Provides Keyboard Mouse Video inputs

- Servo Amplifier
  - Drives Auto-Throttle

- Digital-to-Analog
  - Connects to UAT (ADS-B)
  - Provides RS-422 and RS-232 interfaces

- Avidyne Multi Function Display

- Athena ADAHRS (state data)

- S-TEC 55X Autopilot (modified)

- Data Flow:
  - Discrete A-429
  - Video
  - RS-232
  - RS-422

- Other Components:
  - Cabin Event Markers
  - Engine Indication System
  - Video & Data
  - Fuel Gage
  - Master Surface CPT
  - Air Data, Attitude, Tach
  - Acceleration, Heading, Position
  - A/T Sensors
  - Pedal & Elevator Surface RTU

- System Overview:
  - Integrated Test Capability
  - Flight-Test Platform
  - Testbed

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Background:

Initial Use Case: Cooperative Automatic SAA (1 of 4)

- **WHAT?**
  - Evaluate the viability of (onboard) cooperative automatic SAA alternatives for UAS

- **WHY ONBOARD and AUTOMATIC?**
  - No onboard pilot to perform “see and avoid” duties
  - Command and control (C2) link—between the unmanned aircraft and its pilot—is susceptible to vulnerabilities and latencies

- **WHY COOPERATIVE?**
  - Available, proven technology with known accuracy and integrity
  - FAA has mandated the use of ADS-B transmitters (i.e., ADS-B OUT) by 2020 on all aircraft that operate in airspace that today requires operation of Mode C or Mode S transponders\(^1\)
  - Accurate sensor \(\rightarrow\) bounds solution space

\(^{1}\) 14 CFR §92.225 and §91.227

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HOW?

- Adopt four key focus areas:
  - Algorithms
  - Dev, Test & Eval Environments
  - Platforms & Flight Plans
  - Data Collection & Analysis
Background:
Initial Use Case: Cooperative Automatic SAA (3 of 4)

**HOW?**

- Employ an integrated test concept
Background:
Initial Use Case: Cooperative Automatic SAA (4 of 4)

WHO?

Langley Research Center

* Deihim Hashemi, Jonathan Schwartz, Ganghuai Wang, and Pierre Chaloux not pictured.
FY2012 flight evaluations demonstrated that prototype SAA algorithms could identify potential conflicts, issue an ICD compliant maneuver, and routinely maintain the desired separation between ownship and the intruder aircraft without direct pilot action.

Results to date suggest reasonable congruence between the two environments (simulation and flight) for the encounter scenarios examined.
FY2012 Flight Evaluations

Safety Considerations

- VFR flights with PIC (See & Avoid Procedures)
- Features of surrogate UAS
- Flight test procedures

For safety and test coordination purposes, the research aircraft displays actual target location and altitude for ALL aircraft on traffic display.

PILOT ALWAYS SEES ACTUAL ADS-B DATA FOR TARGET AIRCRAFT

Separation achieved with time, track/fix, and altitude-based controls

Algorithm framework adjusts target aircraft altitude for use within the sense-and-avoid algorithm to create conflict WITHOUT risk to test aircraft

Reviewed and Approved by NASA LaRC Airworthiness and Safety Review Board (ASRB)
FY2012 Flight Evaluations
Overview of Encounters Flown

- 2 prototype cooperative automatic SAA algorithms
- 147 1v1 encounters flown using NASA LaRC Surrogate UAS (Cirrus SR22) and UND piloted Cessna 172

Speed Profiles (knots)
- 147 → 112
- 96 → 96
- 90 → 115

Initial Headings (degrees)
- 135 → 180 → 225
- 90 → 270
- 45 → 30 → 15 → 0 → 345 → 330 → 315 → 0

- Surrogate UAS
- Intruder Aircraft

Photo: University of North Dakota Aerospace Network

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FY2012 Flight Evaluations
Example Encounters
FY2012 Flight Evaluations
ND10 30L Example

algorithmEvaluator
DTE Environment Demonstration

Surrogate UAS
Intruder Aircraft

Relative to Intruder Position & Initial Heading

Converging to CPA

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**FY2012 Flight Evaluations**

**ND10 OrthoR Example**

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**OrthoR**

- **Surrogate UAS**
- **Intruder Aircraft**

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**algorithmEvaluator**

**DTE Environment Demonstration**

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**Relative to Intruder Position & Initial Heading**

- 7,200' 92 kts 188°
- 6,550' 114 kts 95°

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**Converging to CPA**

- nautical miles (nmi)
- time

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FY2012 Flight Evaluations
ND10 Overtake Example

Surrogate UAS
Intruder Aircraft

algorithmEvaluator
DTE Environment Demonstration

Converging to CPA

Relative to Intruder Position & Initial Heading

6,000’
141 kts
207°

6,575’
115 kts
183°
Comparisons
ND10 30L Example

NACp 9 Cases
- Separated vertical
- Separated (co-alt)
- Violation
- Violation (≥ 45° vertical)
- Selected Tracks

NACp 10 Cases
- Separated vertical
- Separated (co-alt)
- Violation
- Violation (≥ 45° vertical)
- Selected Tracks

Surrogate UAS
Intruder Aircraft
Comparisons
ND10 OrthoR Example

Preliminary

OrthoR

Surrogate UAS

Intruder Aircraft

NACp 9 Cases

- Separated vertical
- Separated (co-alt)

Violation
- Violation (> 45° vertical)

Selected Tracks

NACp 10 Cases

- Separated vertical
- Separated (co-alt)

Violation
- Violation (> 45° vertical)

Selected Tracks

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Comparisons
ND10 Overtake Example

NACp 9 Cases

NACp 10 Cases
Simulation to Flight Comparisons

Behavioral Differences Between Algorithms

Enc0 – State 2
Algorithm A.2
ND10

Enc1 – State 8
Algorithm B.2
ND12

Enc7 – State 4
Algorithm A.2
ND10

Enc7 – State 4 & 15
Algorithm B.2
ND12

NACp 9 Cases

NACp 10 Cases

NACp 9 Cases

NACp 10 Cases

NACp 9 Cases

NACp 10 Cases

NACp 9 Cases

NACp 10 Cases

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Observations and Lessons Learned

- A single hour of flight test may require dozens of hours of effort by programmers, maintainers, and flight crews
- Engineering an intentional midair (even a virtual one) is difficult
  - Tests are conducted under *actual* flight conditions (e.g., uncooperative weather; delays; maintenance glitches; non-participating traffic in test area)
  - Communication is key

Flight test time is a limited resource. Testing every case is not feasible.
Observations and Lessons Learned

- On-site team with procedures in place to adjust/tweak system and algorithm software key to flying every day - problems identified in flight/post-flight were addressed overnight - ‘next day’ release for revised software was the norm
- Integrated on-site team with leads for each functional area (flight operations; maintenance/aircraft systems; aircraft systems software; algorithm software) prevents time-wasting disconnects
- Timely access data-collection and monitoring tools is critical
Observations and Lessons Learned

- Risk burn-down requires frequent focused flight tests prior to deployment
  - Fly early - fly often; wring out all systems before deployment
  - A little data early (i.e., early enough to tweak algorithms, procedures, scenarios) is worth more than a lot of data later (i.e., too late to do much about identified issues)
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Next Steps

- Capability enhancements are underway
- Simulation-to-Flight evaluations are planned for mid-2013 in eastern North Dakota to explore:
  - More complex encounter geometries
    - Maneuvering conflict aircraft (e.g., climb/descend into conflict)
  - Additional conflict aircraft
    - Alternative surveillance sources (e.g., ADS-R, TIS-B)
    - Measurement implications of algorithmic enhancements
Backup Slides
FY2012 Flight Evaluations
Additional ND10 Examples

Converging to CPA

nautical miles (nmi)

nmi  cnt
1.985  2.8
2.018  2.7
2.033  2.6
2.038  2.5
2.135  2.4
2.252  2.3
2.679  2.2

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algorithmEvaluator DTE Environment
Quick Reference
FY2012 Flight Evaluations
Additional ND10 Examples

Converging to CPA
0 - 500'
- 1000'
nautical miles (nmi)

Preliminary

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Horizontal Tau Perspective

Preliminary
Horizontal Tau Perspective
Horizontal Tau Perspective

Range Rate

\[ \dot{R} = \frac{S}{\sqrt{1 + \frac{x^2}{Y^2}}} = \frac{SY}{R} \]

\[ \tau = T_{cpa} \left( 1 + \frac{x^2}{Y^2} \right) \]

\( \tau \) is at minima when \( Y = x \) or \( R = \sqrt{2} x \)

\[ \tau_{min} = \frac{2x}{S} \]

\[ S_a = \frac{2x}{\tau_a} \quad \text{the lowest speed that would be triggered by tau} \]

\[ S_a = \frac{1.185x}{\tau_a} \quad \text{when x in feet} \]

\[ S_a = \frac{2700x}{\tau_a} \quad \text{when x in nmi} \]

the probability that an encounter would fail to alert for 2 aircraft with fixed speeds

\[ a \cos \left( \frac{S_{us}^2 + S_{them}^2 - S_a^2}{2 S_{us} S_{them}} \right) / \pi \]
# Triggers & Metrics

**“What we measure and When”**

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Definition</th>
<th>Metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLOSS Alert</td>
<td>Algorithm declares an impending loss of the specified separation threshold</td>
<td>• Distance to PLOSS;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Time to PLOSS;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Predicted Miss Distance;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Alignment (right of, left of, overtake, head on)</td>
</tr>
<tr>
<td>PLOSS Action</td>
<td>Algorithm issues maneuver command</td>
<td>• Distance to PLOSS;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Time to PLOSS;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Predicted Miss Distance;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Alignment (right of, left of, overtake, head on)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Maneuver Type</td>
</tr>
<tr>
<td>PLOSS Release</td>
<td>Algorithm declares maneuver finished</td>
<td>• Maneuver Effect</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Maneuver Strength</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Maneuver Delay</td>
</tr>
<tr>
<td>Test End</td>
<td>End of the test event</td>
<td>• Summary Metrics</td>
</tr>
</tbody>
</table>

PLOSS = Predicted Loss of Specified Separation
# Metrics

<table>
<thead>
<tr>
<th>Metric</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maneuver Effect</td>
<td>Net change in separation distance</td>
</tr>
<tr>
<td>Maneuver Type</td>
<td>Description of the issued maneuver command (i.e., Heading Change, Altitude Change, Speed Change, Combo(<em>{H/A^*}), Combo(</em>{A/S}), Combo(_{H/A/S}))</td>
</tr>
<tr>
<td>Maneuver Strength</td>
<td>Description of the maneuver command’s aggressiveness in terms of the maximum allowable turn rate and angle, and climb/descend rate.</td>
</tr>
<tr>
<td>Maneuver Delay</td>
<td>Time between commanded action and executed action</td>
</tr>
<tr>
<td>Distance to PLOSS</td>
<td>Distance to the point where the specified separation is lost</td>
</tr>
<tr>
<td>Time to PLOSS</td>
<td>Time to the point where the specified separation is lost</td>
</tr>
<tr>
<td>Predicted Miss Distance</td>
<td>Algorithm’s forecast of the distance between own ship and the intruder aircraft at closest point of approach</td>
</tr>
<tr>
<td>Alignment</td>
<td>Relative location to the Intruder Aircraft (e.g., right of, left of, head on, overtake)</td>
</tr>
</tbody>
</table>

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## Summary Metrics

<table>
<thead>
<tr>
<th>Metric</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution Matrix</td>
<td>Exploration of the encounter space:</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Violation Ratio</td>
<td>Compares Loss of Separation (LOS) occurrences with and without the Algorithm engaged:</td>
</tr>
<tr>
<td></td>
<td>(# LOSS with Algorithm) / (# LOSS without Algorithm)</td>
</tr>
<tr>
<td>Violation Severity</td>
<td>Indication of the depth and duration of the violation</td>
</tr>
<tr>
<td>Induced Violation</td>
<td>Number of LOSS occurrences instigated by the Algorithm</td>
</tr>
<tr>
<td>Flight Path Deviation</td>
<td>Maximum deviation from the nominal flight path</td>
</tr>
<tr>
<td>Nuisance Alert</td>
<td>Errant declaration of an impending loss of the specified separation threshold</td>
</tr>
<tr>
<td>Minimum Miss Distance</td>
<td>Minimum distance between own ship and the intruder aircraft*</td>
</tr>
<tr>
<td>(Intruder)</td>
<td></td>
</tr>
<tr>
<td>Minimum Miss Distance</td>
<td>Minimum vertical distance between own ship and the specified ceiling</td>
</tr>
<tr>
<td>(Ceiling)</td>
<td></td>
</tr>
<tr>
<td>Minimum Miss Distance</td>
<td>Minimum vertical distance between own ship and the specified floor</td>
</tr>
<tr>
<td>(Floor)</td>
<td></td>
</tr>
<tr>
<td>Minimum Miss Distance</td>
<td>Minimum distance between own ship and other hazards (e.g., terrain, TRF, restricted airspace, manmade obstacle)</td>
</tr>
<tr>
<td>(Hazard)</td>
<td></td>
</tr>
</tbody>
</table>

*NOTE: Minimum horizontal distance between own ship and the intruder aircraft when not separated vertically. Minimum difference in altitude between own ship and intruder aircraft when not separated horizontally.

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FY2012 Suitability Evaluations

- 2 example ADS-B-based SAA algorithms
- Millions of simulated 1v1 encounters
  - **Key Variables:** Speed; Initial Heading; CPA; Delta Vertical; Positional Accuracy; Velocity Accuracy; Probability of Reception; Latency; Time of Applicability

**Speed Profiles (knots)**
- 147
- 90
- 112
- 90
- 270
- 115

**Initial Headings (degrees)**
- 180
- 90
- 270
- 0
- 5°
- 0

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FY2012 Suitability Evaluations
“Quick Look” Results - As Briefed at SARP Open Day

Algorithm A.2

<table>
<thead>
<tr>
<th>Condition</th>
<th>Resolution Matrix</th>
<th>Violation Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Noise</td>
<td>195/20</td>
<td>20/215 = 9.3%</td>
</tr>
<tr>
<td>ADS-B Variance</td>
<td>5475/330</td>
<td>330/5805 = 5.7%</td>
</tr>
<tr>
<td>COMM Variance</td>
<td>3000/225</td>
<td>225/3225 = 7.0%</td>
</tr>
</tbody>
</table>

Simulation Data
Algorithm A.2 (pLOSS 3min out)
## FY2012 Suitability Evaluations

### “Quick Look” Results - As Briefed at SARP Open Day

<table>
<thead>
<tr>
<th>Resolution Matrix</th>
<th>189</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>26</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Violation Ratio</th>
<th>26</th>
<th>12.1%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>215</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Resolution Matrix</th>
<th>5433</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>372</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Violation Ratio</th>
<th>372</th>
<th>6.4%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5805</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Resolution Matrix</th>
<th>3203</th>
<th>0</th>
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<tbody>
<tr>
<td></td>
<td>23</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Violation Ratio</th>
<th>23</th>
<th>0.7%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3225</td>
<td></td>
</tr>
</tbody>
</table>

Simulation Data
Algorithm B.2 (pLOSS 3min out)

No Noise

ADS-B Variance

COMMs Variance
**FY2012 Suitability Evaluations**

**“Quick Look” Results - As Briefed at SARP Open Day**

<table>
<thead>
<tr>
<th>Speed Profiles</th>
<th>Algorithm A.2</th>
<th>Algorithm B.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>147-112</td>
<td>138 (42%)</td>
<td>198 (53%)</td>
</tr>
<tr>
<td>96-96</td>
<td>90 (27%)</td>
<td>120 (32%)</td>
</tr>
<tr>
<td>90-115</td>
<td>102 (31%)</td>
<td>54 (15%)</td>
</tr>
<tr>
<td>330</td>
<td></td>
<td>372</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Heading Type vs. Speed Profile</th>
<th>NACp</th>
<th>Algorithm A.2</th>
<th>Algorithm B.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>147-112</td>
<td>138</td>
<td>198</td>
<td>372</td>
</tr>
<tr>
<td>96-96</td>
<td>90</td>
<td>120</td>
<td>372</td>
</tr>
<tr>
<td>90-115</td>
<td>102</td>
<td>54</td>
<td>372</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NACp</th>
<th>np12</th>
<th>np11</th>
<th>np10</th>
<th>np9</th>
<th>np8</th>
<th>Algorithm A.2</th>
<th>Algorithm B.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>np12</td>
<td>n/a</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>np11</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>np10</td>
<td>66</td>
<td>62</td>
<td>20%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>np9</td>
<td>120</td>
<td>133</td>
<td>36%</td>
<td></td>
<td></td>
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<td></td>
</tr>
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Simulation Data

LOSS Events (ADS-B Variance; pLOSS 3min out)
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Simulation Data

LOSS Events (ADS-B Variance; pLOSS 3min out)