Automatic Dependent Surveillance Broadcast: \( \mu \)ADS-B Detect-and-Avoid Flight Tests

Ricardo Arteaga
NASA Armstrong Flight Research Center
AIAA, Jan 08-12
Kissimmee FL
Introduction to ADS-B

Automatic Dependent Surveillance Broadcast

• Replacing radar for tracking aircraft worldwide
  – Prevent collisions

• Sharing position, altitude, velocity, etc. with air traffic control and other aircraft
  – ADS-B Out = Transmit
  – ADS-B In = Receive

• FAA-mandate by Jan. 1, 2020
Operational View

LEGEND
- Detect and Avoid (DAA Technologies)
- Air Traffic Services
- ADS-B Ground Stations and Network
- Legacy Command and Control (C2) Links

ACRONYMS
- ADS-B: Automatic Dependent Surveillance—Broadcast
- DAA: Detect and Avoid
- NAS: National Air Space

Detect and Avoid

Communications satellite

Cooperative aircraft

Non cooperative aircraft

Air traffic services (en route)

Unmanned aircraft

Manned aircraft

UAS ground control station

Research ground control station

Human Systems Integration

Small UAS Detect and Avoid

UAS Restricted-Use Certification

Humanitarian Aid

Precision agriculture

Communication satellite

Unmanned aircraft

Manned aircraft

Detect and Avoid

Cooperative aircraft

Non cooperative aircraft

Air traffic services (en route)

Unmanned aircraft

Manned aircraft

Detect and Avoid

Cooperative aircraft

Non cooperative aircraft

Air traffic services (en route)

Unmanned aircraft

Manned aircraft

Detect and Avoid

Cooperative aircraft

Non cooperative aircraft

Air traffic services (en route)
Operational Use Cases

• Urgent need to safely integrate UAS into the National Air Space (NAS)
  – Search-and-rescue missions
  – First responders and firefighters
  – Monitoring and/or fighting forest fires
  – Package delivery (Amazon®, Domino’s®, FedEx®)
  – Surveying farmland, borders, pipelines

• Consumer/Commercial demand for UAS likely to explode in the next decade
  – 442,000 drones operating by 2021 (FAA)¹

• Drone safety incidents are averaging 250 a month, up by more than 50% than last year²

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¹ https://www.faa.gov/data_research/aviation/aerospace_forecasts/media/Unmanned_Aircraft_Systems.pdf accessed on October 20, 2017
Flight Test Goals

- Demonstrate a µADS-B Detect and Avoid system on DJI Phantom 4 platform(s) for BVLOS operations
- Demonstrate DAA Display System for Pilot-in-the-Loop Collision Avoidance
Fig. 2. ADS-B system architecture (US Patent Serial No. 9,405,005).²
Airborne DAA Hardware

- Components Dual ADS-B transceiver (978 and 1090 MHz)
- Meets MOPS DO-282B
  - µADS-B transceiver
    - ADS-B Out
    - ADS-B In
  - GPS NAV Receiver
  - UAT 978 Omni Antenna

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Input Power</td>
<td>6-29V 500mW Ave.</td>
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<tr>
<td></td>
<td>30W Peak (400us)</td>
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<tr>
<td>Size</td>
<td>25x39x12mm</td>
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<tr>
<td>Weight</td>
<td>20grams</td>
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<td>SDA</td>
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<table>
<thead>
<tr>
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<tr>
<td>MTL 1090MHz</td>
<td>-88dBm</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>-79 to 0dBm</td>
</tr>
<tr>
<td>MTL 978MHz</td>
<td>-93dBm</td>
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<tr>
<td>Dynamic Range</td>
<td>-90 to -3dBm</td>
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Supported Interfaces

| Host Serial | 57600bps |
| Nav Serial  | 115200bps|

Transmit

| 1090MHz       | S/W disabled.         |
| 978MHz        | 20W (43dBm)           |

Options
- Nav DO-229D GPS with Barometer
ADS-B Detect and Avoid Display

- FlightHorizon software provides the pilot with situational awareness and detect and avoid capabilities.

ADS-B IN
978/1090 MHz
Stratway+ Conflict Resolution Algorithm

- Stratway – strategies are iterated.
Detect-and-Avoid sub-functions

µADS-B Detect and Avoid system provides an integrated DAA solution for SUAS

- Detect
- Track
- Evaluate
- Prioritize
- Declare
- Determine
- Command
- Execute
NASA ADS-B DAA Display

LEGEND

Target aircraft transmitting ADS-B

Ownship’s resolution advisory

Aircraft’s nominal trajectory

Traffic alert advisory

Traffic threat advisory

NASA Patent (US Patent Serial No. 9,405,005)²
## Detect and Avoid Flight Test Plan

<table>
<thead>
<tr>
<th>Vertical</th>
<th>Scenario</th>
<th>Priority</th>
<th>Speed (Knots)</th>
<th>Aimpoint Offset</th>
<th>Phantom 1</th>
<th>Phantom 2</th>
<th>Objective</th>
<th>Planned</th>
<th>Advisory</th>
<th>Automatic Response to RA</th>
<th>Loss Link Phantom 1</th>
<th>Loss Link Phantom 2</th>
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<td><strong>Profile</strong></td>
<td><strong>Designation</strong></td>
<td><strong>CPA</strong></td>
<td><strong>Altitude AGL</strong></td>
<td><strong>Altitude AGL</strong></td>
<td><strong>Vertical Separation</strong></td>
<td><strong>RA Type</strong></td>
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<td><strong>LL1</strong></td>
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<td>Scenario X11</td>
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<td>20</td>
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<td>250</td>
<td>50</td>
<td>Ensure miss &amp; safety plot fam</td>
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<td>250</td>
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<td>”Climb, Climb” 1000 fpm</td>
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<td>”Climb, Climb” 1000 fpm</td>
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<td>3 (50 ft Vert)</td>
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<td>75</td>
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<td>4 (0 ft Horiz)</td>
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<td>50</td>
<td>180 degree approach, expect “Turn Right”</td>
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<td>”Turn Left, Turn Left”</td>
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</tbody>
</table>
Types of DAA Encounter Scenarios (CA)

- Horizontal & Vertical Encounters
- 200, 100, 50, -50, -100, -200 feet offsets

**Fig. 7. Vertical Profile for Series 10 Encounters**

**Fig. 8. Vertical Profile for Series 20 Encounters**

**Fig. 9. Vertical Profile for Series 30 Encounters**
Types of DAA Encounter Scenarios (CA)

- Horizontal & Vertical Encounters
- Head On, Crossing, 45, 60, 90, 135, 180 degree.

Fig. 10. ADS-B DAA Scenario Geometrics
Unmanned Vehicles

Test Aircraft (Ownship)  SUAS: Phantom 4 Pro  Intruder
- Gross Weight: 4.02 lbs
- Length/Wingspan: 1.9 / 1.9 feet
- Service Ceiling: 500 AGL feet
- Cruise Speed: 22 – 39 knots
- μADS-B DAA System: 1000 fpm
- 18 Fully Charged LiPo Batteries
Flight Operations Area

Flight Volume
• Muroc Model Masters
• All flights below 500’ AGL
• Day VMC

Operating Volume
• BVLOS operations
• FPV flight operations
• Geofenced operations

Personnel Area
• Flight Test Crew
• Visual Observers

Fig. 11. Flight Operations Area
1. PH2 Hover at 150 feet AGL at Initial Point 2
2. PH2 Accelerate Towards CPA Point 2 (@1-3 sec till Test Groundspeed)
3. PH2 Stable at Test Groundspeed (@ 3-12 sec)
4. PH1 Expected Avoidance (turn left and slows to stop)
5. If No Avoidance
6. PH1 Hover at 50 feet AGL at Initial Point 1
2. PH1 Accelerate Towards CPA Point 1 (@1-3 sec till Test Groundspeed)
3. PH1 Stable at Test Groundspeed (@ 3-12 sec)

Fig. 12. Encounters Scenario Geometries
ADS-B Detect and Avoid Performance Simulation

Fig. 13. X33 Simulation with Resolution Advisory
DAA Algorithm Performance

- Computational efficiency and performance of DAA algorithm for Large UAS with a CA Threshold of 1 NM and 400 feet (above)

- Performance of DAA algorithm tailored for SUAS maintains “well clear” with a CA Threshold of 0.1 NM and 200 feet
ADS-B DAA Flight 1 - December 6, 2016: Detect and Track Intruders using ADS-B
ADS-B DAA Flight 2 - December 7, 2016: Determine if intruder is a collision threat
• Replacement of the 9 volt batteries every 1.5 hours and testing the voltage to verify greater than 6 volts.

• Replacement of the μADS-B transponder updating at only 4 seconds and a UAT antenna.

ADS-B DAA Flight 3 - December 8th 2016: Transmission Issues with hardware
ADS-B DAA Flight 4 - December 9th 2016: Commands maneuver to avoid the collision
ADS-B DAA Flight 5 - May 2017: Commands Avoidance maneuver to safely avoid the collision
ADS-B DAA flights July 2017: Commands Avoidance maneuver to safely avoid the collision
Flight Test Lessons Learned

• Fly, Fix, Fly; don’t try to get it totally right the first time, success comes only after overcoming many technical challenges.

• Incrementally integrate the ADS-B hardware and ADS-B DAA software capability.

• Use better ADS-B In receivers and antennas to increase range reception for BVLOS operations at low very altitudes.

• Reset the trajectories when the drone performs a hover (ground speed <3 knots). Halt and hover can be an avoidance maneuver.
Conclusion

- Demonstrated a µADS-B Detect and Avoid system on DJI Phantom 4 platform(s) for collision avoidance and BVLOS UAS operations.
- Vigilant Aerospace Systems, Inc has successfully licensed the NASA ADS-B DAA technology.
- NASA will conduct research on a miniaturized radar for detecting uncooperative targets and/or objects.
- To this end, this NASA patented UAS-DAA technology was deployed for FEMA damage and aid assessment missions to help our fellow American’s in need.

Fig. 19. NASA Armstrong Research Flight Test Team (NASA photo AFRC2016-0365-01)
Hurricane Harvey Humanitarian Aid Video

https://youtu.be/2CdkQJ01OSg
http://humanitariandrones.org/
https://www.nasa.gov/centers/armstrong/features/drones_assist_harvey_recovery_efforts.html
Future Applications and Benefits

ADS-B on Supersonic Vehicles

- Complies with FAA certification for ADS-B Out
- ADS-B represents the backbone technology for NextGen.
- Provides tracking from ground station
- Manned supersonic detect and avoid

Commercial Applications both inside and outside NASA: Commercial supersonic vehicles with ADS-B Systems will likely emerge in the near future.

NASA is a world class leader in cutting edge astronautics technology.
Future Applications and Benefits

ADS-B on Space Craft Vehicles

- Complies with FAA certification for ADS-B Out
- ADS-B represents the backbone technology for NextGen.
- Provides re-entry tracking from ground station/UAS for space vehicle recovery

Commercial Applications both inside and outside NASA: Commercial space vehicles with ADS-B Systems will likely emerge in the next decade.

NASA is a world class leader in cutting edge astronautics technology.
Backup Slides
UNMANNED ADS-B AIRCRAFT SYSTEMS

New Technology
• ADS-B OUT
• ADS-B IN
• ADS-B Sense and Avoid

• ADS-B system coupled to an unmanned aerial vehicle for increased situational awareness and self-separation assurance

C-BAND

LOS Datalink

978 MHz

978 MHz

1090 MHz

GPS

NASA Patent (US Patent Serial No. 9,405,005)²
NASA Results and Benefits

**Results**

ADS-B flight tests on Ikhana UAS

- **ADS-B Out: March 2012**
  - First time a UAS as large as the MQ-9 had flown equipped with ADS-B

- **ADS-B In: May 2012**
  - 2 Flight Tests at Dryden with successful traffic surveillance

**Benefits**

- **Complies with FAA certification for ADS-B Out**
  (5.7 feet position accuracy, FAA independent analysis)

- **Provides backbone technology for NextGen**

- **Increases safety** by ensuring safe separation

- **Increases pilot awareness, situational and traffic**

- **Other technical benefits**
  - Provides 3D synthetic views
  - Loss link of UAS telemetry uses FAA Tech Center ADS-B data for redundancy

NASA Patent (US Patent Serial No. 9,405,005)²
NASA’s Successful Flight Tests

- **Various sizes:** Ikhana, DROID, Phantom 4 Pro
- **Performance:** 5.7 ft. accuracy (304 ft. mandate)
- **Traffic surveillance:** Up to 17 real-time tracks
- **Record-setting:** First time large UAS had flown with ADS-B

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Ikhana M-Q9

Dryden Remotely Operated Integrated Drone (DROID)

Phantom 4 Pro

http://www.nasa.gov/centers/armstrong/Features/armstrong_engineers_honored.html, accessed on October 15, 2104
### μADS-B Detect and Avoid System

<table>
<thead>
<tr>
<th>Sub-Functions</th>
<th>μADS-B Detect and Avoid</th>
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<tbody>
<tr>
<td><strong>Cooperative Surveillance</strong></td>
<td>ADS-B active Air-to-Air Surveillance</td>
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</table>
| **Threat Alert Logic** | Full range of large and small UAS vertical and horizontal vehicle performance  
Collision Avoidance Threshold : Range base scalable |
| **Advisories**         | Traffic Alerts: Traffic & Threats  
Vertical Resolution Advisories  
Horizontal Resolution  
Speed Resolution Advisories  
Automatic RA response |
<table>
<thead>
<tr>
<th>From</th>
<th>To</th>
<th>Wireless/Wired</th>
<th>Type/Protocol</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>µADS-B IN EFB (uavionix)</td>
<td>PC running DAA Software</td>
<td>Wired</td>
<td>USB Serial / raw AVR</td>
<td>A raw ADS-B RX</td>
</tr>
<tr>
<td>PC running DAA Software</td>
<td>Tablet running DAA Autonomous App</td>
<td>Wireless</td>
<td>2.4ghz WIFI / TCP</td>
<td>Communicate conflict avoidance maneuvers to DJI Drone through controller</td>
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<tr>
<td>Tablet running DAA Autonomous App</td>
<td>DJI Controller</td>
<td>Wired</td>
<td>USB Serial / DJI Proprietary</td>
<td>Tablet is allowed to communicate to drone through DJI MOBILE SDK</td>
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<tr>
<td>DJI Controller</td>
<td>DJI Rx on DJI Phantom 4</td>
<td>Wireless</td>
<td>2.4ghz, 5.8ghz/ DJI Proprietary</td>
<td>DJI Controller communicates with drone and allows the pilot to fly the drone</td>
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<td>ADS-B Traffic from other aircraft and ground station</td>
<td>µADS-B IN EFB (uavionix)</td>
<td>Wireless</td>
<td>978 Mhz, 1090 Mhz / ADS-B IN</td>
<td>ADS-B data of aircraft position, speed, and heading</td>
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<td>µADS-B TX</td>
<td>Any ADS-B RX Air-to Air Surveillance</td>
<td>Wireless</td>
<td>978 Mhz / ADS-B OUT</td>
<td>ADS-B data of aircraft position, speed, and heading</td>
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Fig. 14. DAA Verification and Validation Methodology
Detect and Avoid Scenario X33 Flight Test Cards

Scenario X33

1. TC announces COMEX time.
2. Setup Vehicle at IP1, Hover at Target Altitude
3. Accelerate Aircraft On condition at least 20 seconds prior to CPA1
4. Perform Resolution Advisory Maneuver or hover at CPA1
5. TC calls "terminate" when run complete.
6. TC announces next Card Number.

COMEX TIME: N34° 52.16' W118° 04.31'
IP WIND: 75 ° 0.3

WPT | LATITUDE | LONGITUDE | ALT | DIST MC | KGS | LEG TIME
--- | --- | --- | --- | --- | --- | ---
IP1 | N34° 52.16' | W118° 04.31' | 125 | 0.3 | 30 | 0-36
LL1 | N34° 52.16' | W118° 04.31' | 0 | 0.0 | 30 | 0-36
CPA1 | N34° 52.16' | W118° 04.31' | 25 | 0.0 | 30 | 0-36
CPA2 | N34° 52.16' | W118° 04.31' | 125 | 0.3 | 30 | 0-36

NOTES: Ownership maneuver. At CPA Hover for 10 seconds and/or until receive DAA Guidance. Follow DAA Guidance.
RA Maneuver: YES

Scenario X33

1. TC announces COMEX time.
2. Setup Vehicle at IP, Hover at Target Altitude
3. Accelerate Aircraft On condition at least 20 seconds prior to CPA2
4. Hover at CPA2.
5. TC calls "terminate" when run complete.
6. TC announces next Card Number.

COMEX TIME: N34° 52.16' W118° 04.31'
IP WIND: 75 ° 0.3

WPT | LATITUDE | LONGITUDE | ALT | DIST MC | KGS | LEG TIME
--- | --- | --- | --- | --- | --- | ---
IP2 | N34° 52.16' | W118° 04.31' | 75 | 0.3 | 30 | 0-36
LL2 | N34° 52.16' | W118° 04.31' | 0 | 0.0 | 30 | 0-36
CPA1 | N34° 52.16' | W118° 04.31' | 75 | 0.3 | 30 | 0-36
CPA2 | N34° 52.16' | W118° 04.31' | 0 | 0.0 | 30 | 0-36

NOTES: Expect Ownership maneuver.
Litchi® Phantom 4 APP Display


Fig. 4. Litchi® Phantom 4 Pro Application
Alerting Logic
RISK Collision Volumes

- **Collision Avoidance Threshold**
- **Self Separation Threshold**
- **Collision Volume**
- **Near Mid-Air Collision Alert**
- **Traffic Alert**
- **Intruder**
- **ATC Separation Services**

Thresholds:
- 5 nm
- 1000 ft. ±100 ft
- 3 nm ±1000 ft
- 1 nm ±500 ft

Proximity:
- 3 – 5 nm
MANNED AIRCRAFT SYSTEMS

Tablet User Interface

New Technology

Aircraft

- Traffic Conflict Detection
- Integrated 2D/3D Weather
- Integrated 3D Terrain
- NASA Armstrong developed capability
- ADS-B Sense and Avoid

Architecture

ADS-B Out & In

- ADS-B Out Broadcasts Ownship
- ADS-B In reception of air-to-air ADS-B messages from proximate aircraft and ADS-B In traffic information.

Sensors

Displays

Algorithms

Sense and Avoid Self-Separation

- Detects intruding aircraft in terms of increasing threat risk
- Alerts pilots of potential collisions and provides resolution advisories
NASA Armstrong Flight Research Center
Small UAS ADS-B Sense and Avoid System for the DROID and Towed Glider

BACKGROUND
Urgent need to safely integrate UAS into the National Air Space (NAS), as these systems are less expensive alternatives for:
- Search and rescue missions
- Monitoring forest fires
- Package delivery
- Surveying farmland, borders, and pipelines
- Fire Fighting missions

What is ADS-B?
- ADS-B Out is the broadcast of position information to other aircraft and ground stations.
- ADS-B In is the ability to receive ADS-B Out transmissions.

Why use ADS-B?
- By 2020, all aircraft flying in transponder airspaces will be required to have ADS-B.
- Provides more reliable tracking of aerial vehicles and increases safety.

OBJECTIVE
- Evaluate SAA Algorithm performance with small and mid-sized UAVs

SYSTEM
ADS-B Hardware
ADS-B Out transponder
- 3.5 x 1.8 x 0.7 inches
- 100 grams (3.5 ounces)

Sense & Avoid Software and Algorithms
The software package is entirely developed by NASA
- World Wind – 3D Geobrowser
- Stratway - Strategic resolutions for aircraft conflicts
- Sense & Avoid–Alerts pilot of potential collisions to avoid accidents

SYNOPSIS
- Advanced system will be needed to keep drones from colliding with manned aircraft vehicles.
- Validating the software algorithms with flight experiments to improve safety.
- This ADS-B Sense and Avoid product is key to safety.

http://www.nasa.gov/centers/armstrong/Features/armstrong_engineers_honored.html, accessed on October 15, 2104
Flight Heritage

• The ADS-B Display has previously successfully flown in the IKHANA aircraft (right).

• The ADS-B systems has previously successfully flown on other large and small UASs.

• Phantom 4 platforms most popular commercial small UASs.

Dryden Remotely Operated Integrated Drone (DROID)

11/7/2017
ADS-B Equipped DRIOD
ADS-B Detect-and-Avoid algorithm

Stratway – a modular approach to safe conflict resolutions.

NASA Patent Pending 13/785,661
Advanced sense-and-avoid algorithm

- Software uses ADS-B broadcast information to construct aircraft trajectories, and predict future loss of separation.

Collision possible: 33s
Benefits of NASA’s ADS-B Technology

- **Complies with FAA** certification for ADS-B Out
- **Provides backbone** technology for NextGen
  - Tracking UAVs and other aircraft on tablets
- **Increases safety** by ensuring safe separation
  - ADS-B sense-and-avoid capability
- **Increases awareness**, situational and traffic
  - Preeminent attribute for successful UAS operations
- **Other technical benefits**
  - Provides 3D synthetic views of the UAS
  - Loss link of UAS telemetry uses FAA Tech Center ADS-B data for redundancy
ADS-B SAA Display
Traffic Advisory
Flight Tests ADS-B Sense and Avoid (Green Resolution Advisory)
Conflict Detection
Resolution Advisory
NASA Pilot Usability Tests

Human Factors

- Conflict detection
- Resolution advisory

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<tr>
<th>Factor</th>
<th>Conflict detection</th>
<th>Resolution advisory</th>
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<tr>
<td>Usefulness</td>
<td>9.2</td>
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<tr>
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Usefulness, Accuracy, Safety, and Effectiveness are evaluated using two metrics: Conflict detection and Resolution advisory.
ADS-B Situational Display
Traffic Alerting

TRAFFIC THREAT INDICATORS