Automatic Dependent Surveillance Broadcast:
μADS-B Detect-and-Avoid Flight Tests

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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

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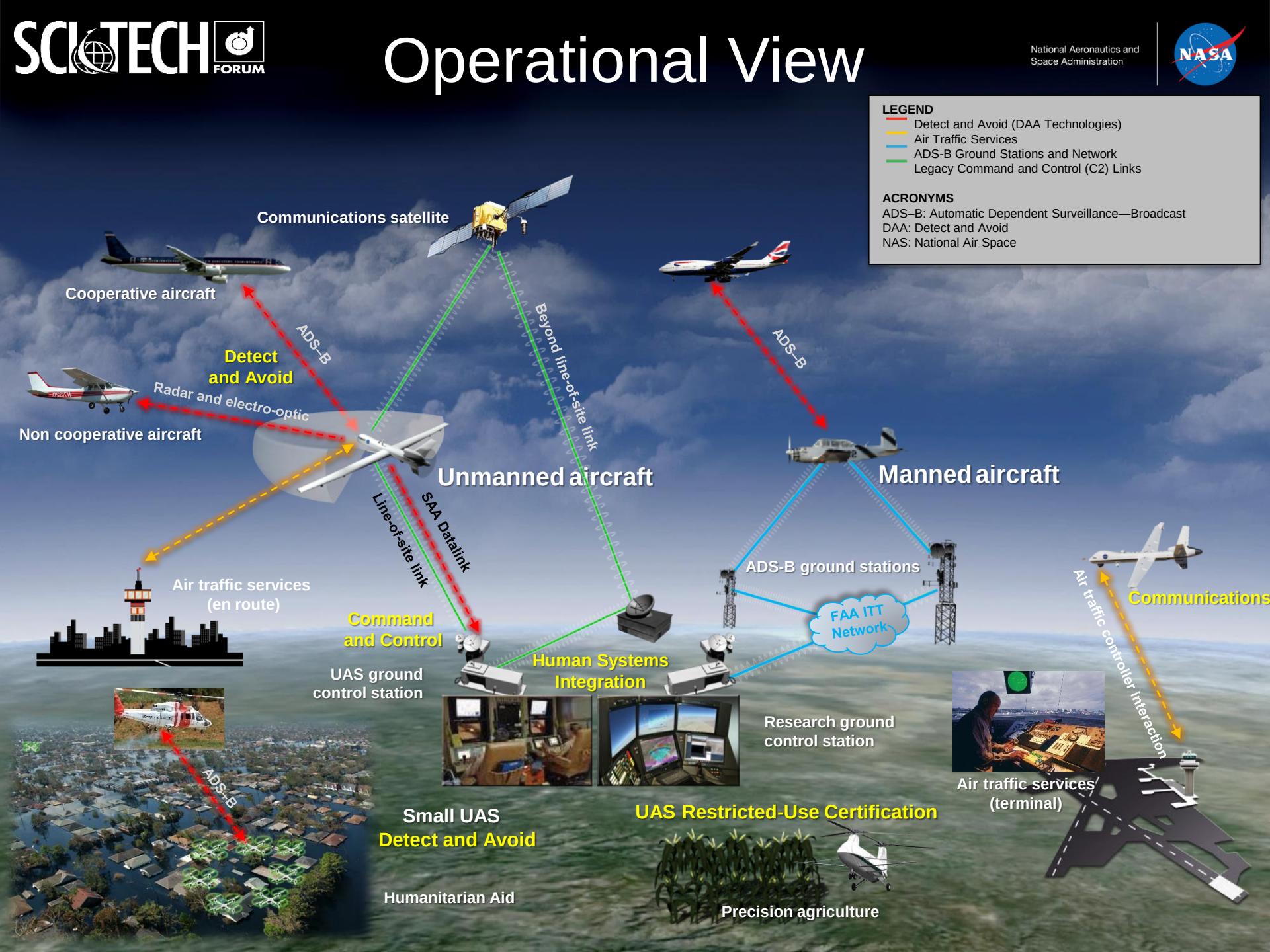
Operational View

National Aeronautics and Space Administration

NASA

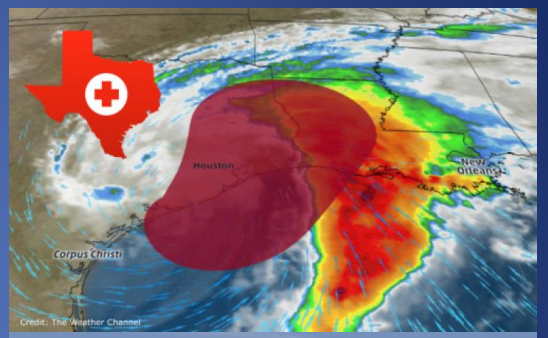
LEGEND
- Detect and Avoid (DAA Technologies)
- Air Traffic Services
- ADS-B Ground Stations and Network
- Legacy Command and Control (C2) Links

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



Operational Use Cases

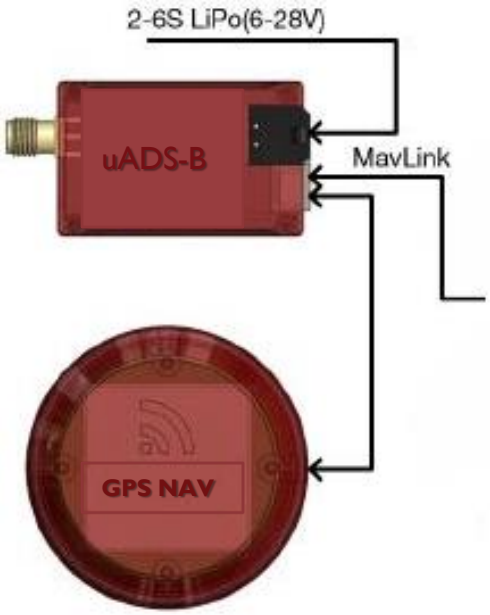
- Urgent need to safely integrate UAS into the National Air Space (NAS)
  - Search-and-rescue missions
  - First responders and firefighters
  - Monitoring and/or fighting forest fires
  - Package delivery (Amazon®, Domino's®, FedEx®)
  - Surveying farmland, borders, pipelines
- Consumer/Commercial demand 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 year** [2]



[1] https://www.faa.gov/data_research/aviation/aerospace_forecasts/media/Unmanned_Aircraft_Systems.pdf accessed on October 20, 2017
[2] https://www.bloomberg.com/news/articles/2017-10-13/surge-in-drone-safety-reports-prompts-emergency-action-at-faa

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**



µADS-B Transceiver

Object detection and collision avoidance

Architecture

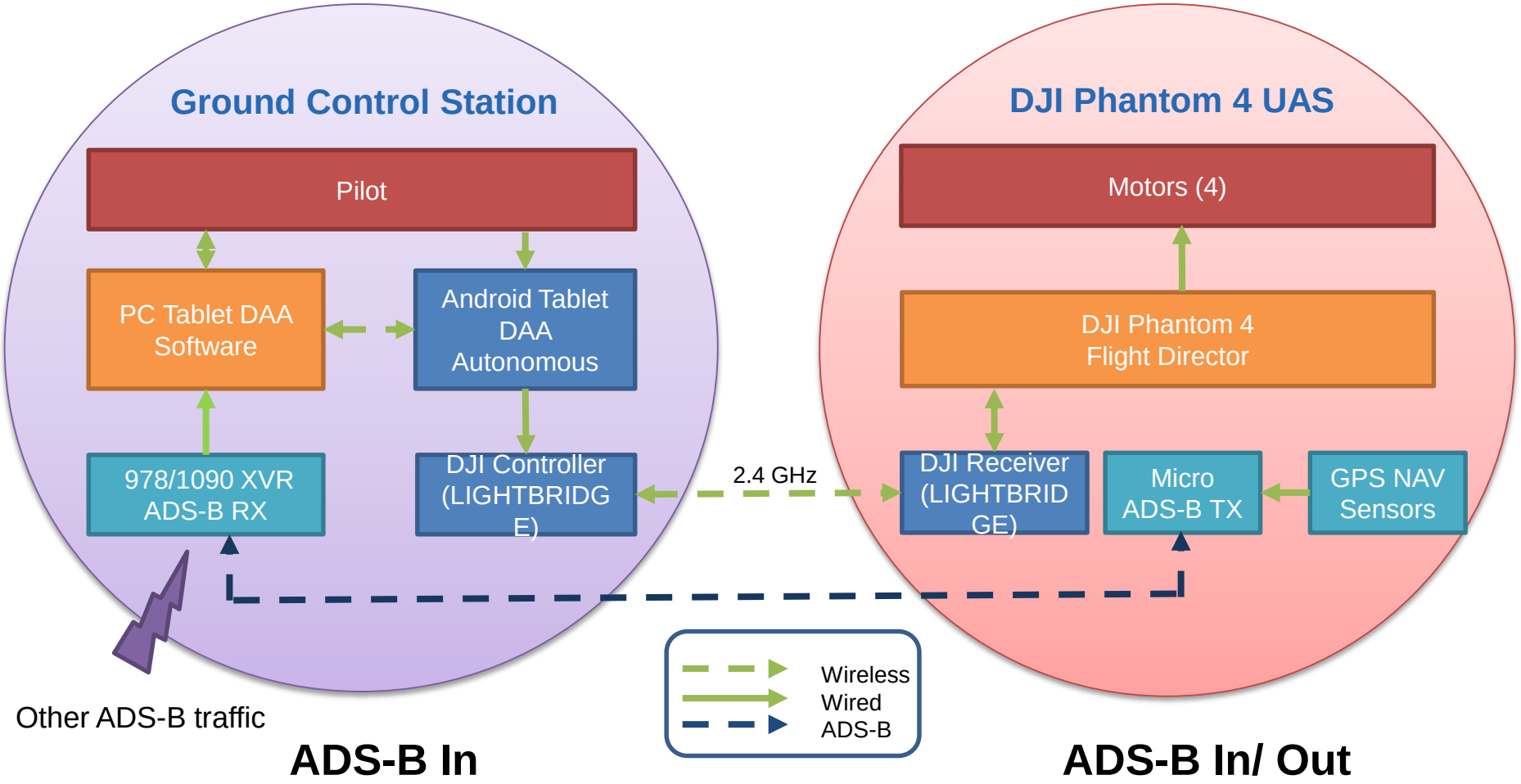


Fig. 2. ADS-B system architecture (US Patent Serial No. 9,405,005).[2]

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

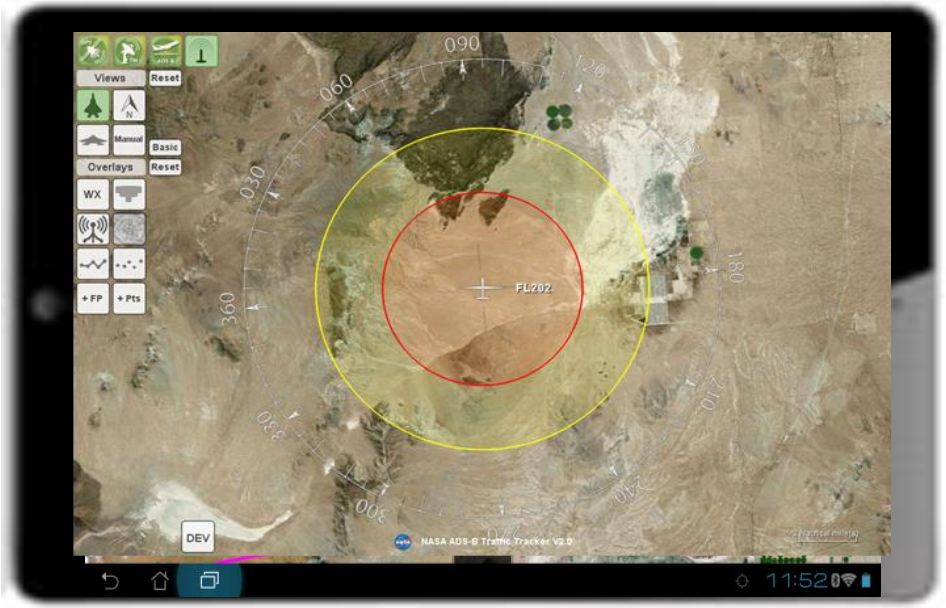
Technical Specifications

Specification	Value
Input Power	6-29V 500mW Ave. 30W Peak (400us)
Size	25x39x12mm
Weight	20grams
SDA	3
Receiver	
MTL 1090MHz	-88dBm
Dynamic Range	-79 to 0dBm
MTL 978MHz	-93dBm
Dynamic Range	-90 to -3dBm
Supported Interfaces	
Host Serial	57600bps
Nav Serial	115200bps
Transmit	
1090MHz	S/W disabled.
978MHz	20W (43dBm)
Options	
•	Nav DO-229D GPS with Barometer

GCS DAA Display / ADS-B In Sensor

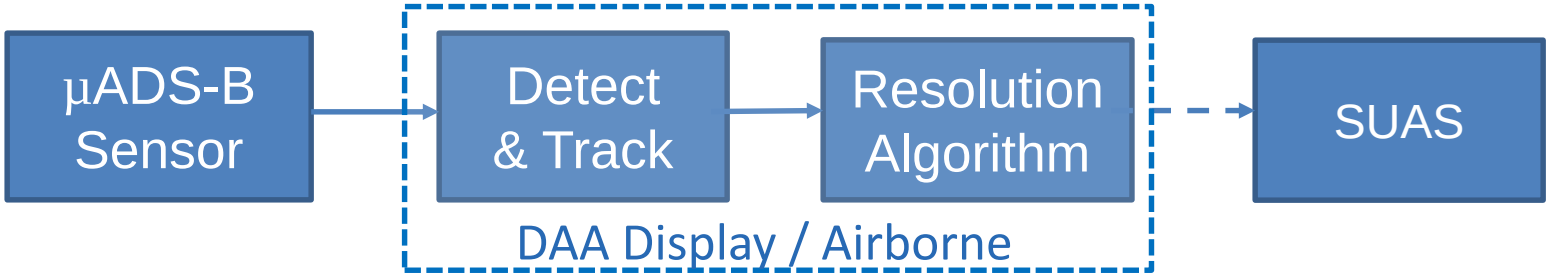
- ADS-B Detect and Avoid Display
  - FlightHorizon software provides the pilot with situational awareness and detect and avoid capabilities.

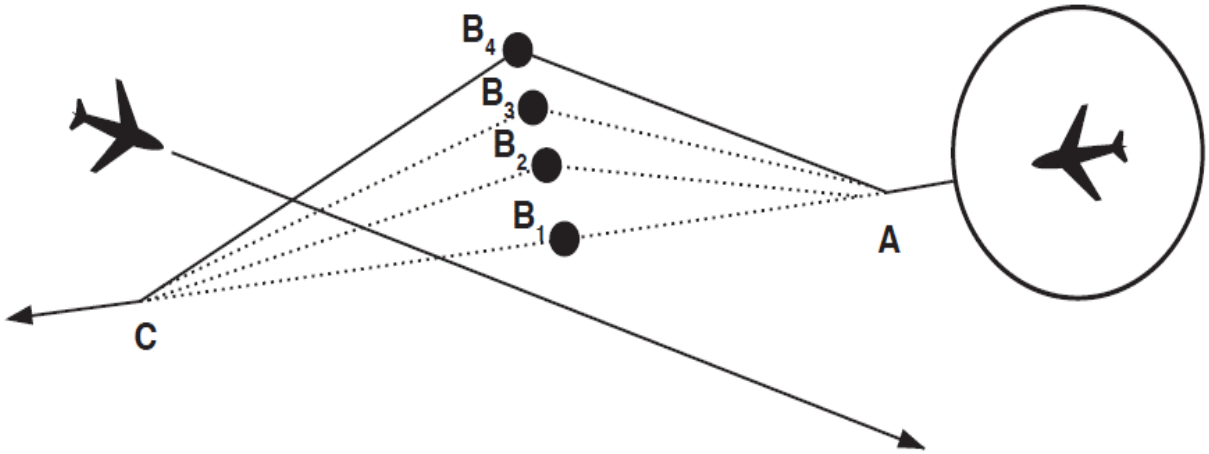
ADS-B IN
978/1090 MHz



R&D 100
55 Years of Invention
Finalist 2017

Stratway+ Conflict Resolution Algorithm



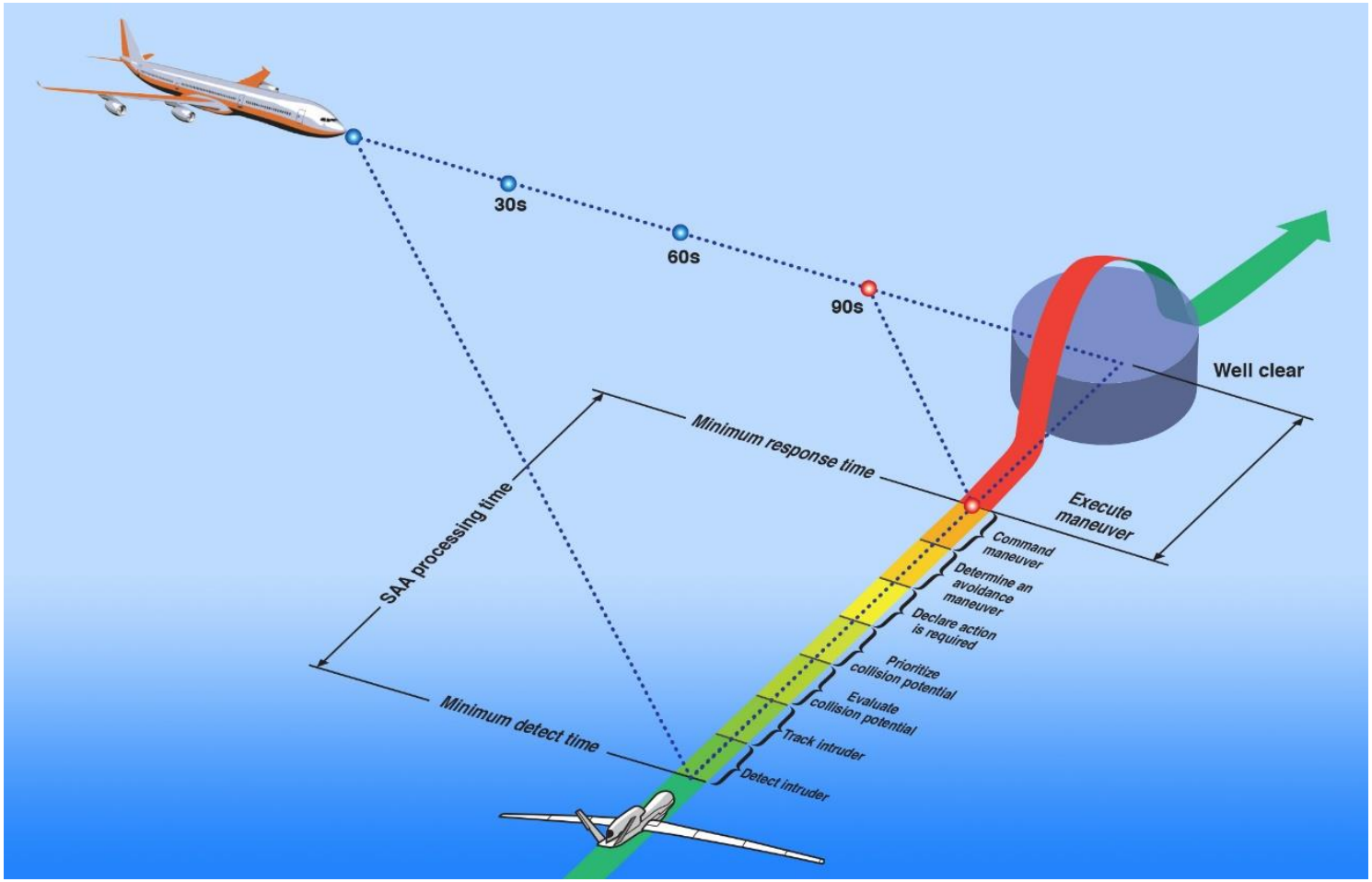


Stratway – strategies are iterated.

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

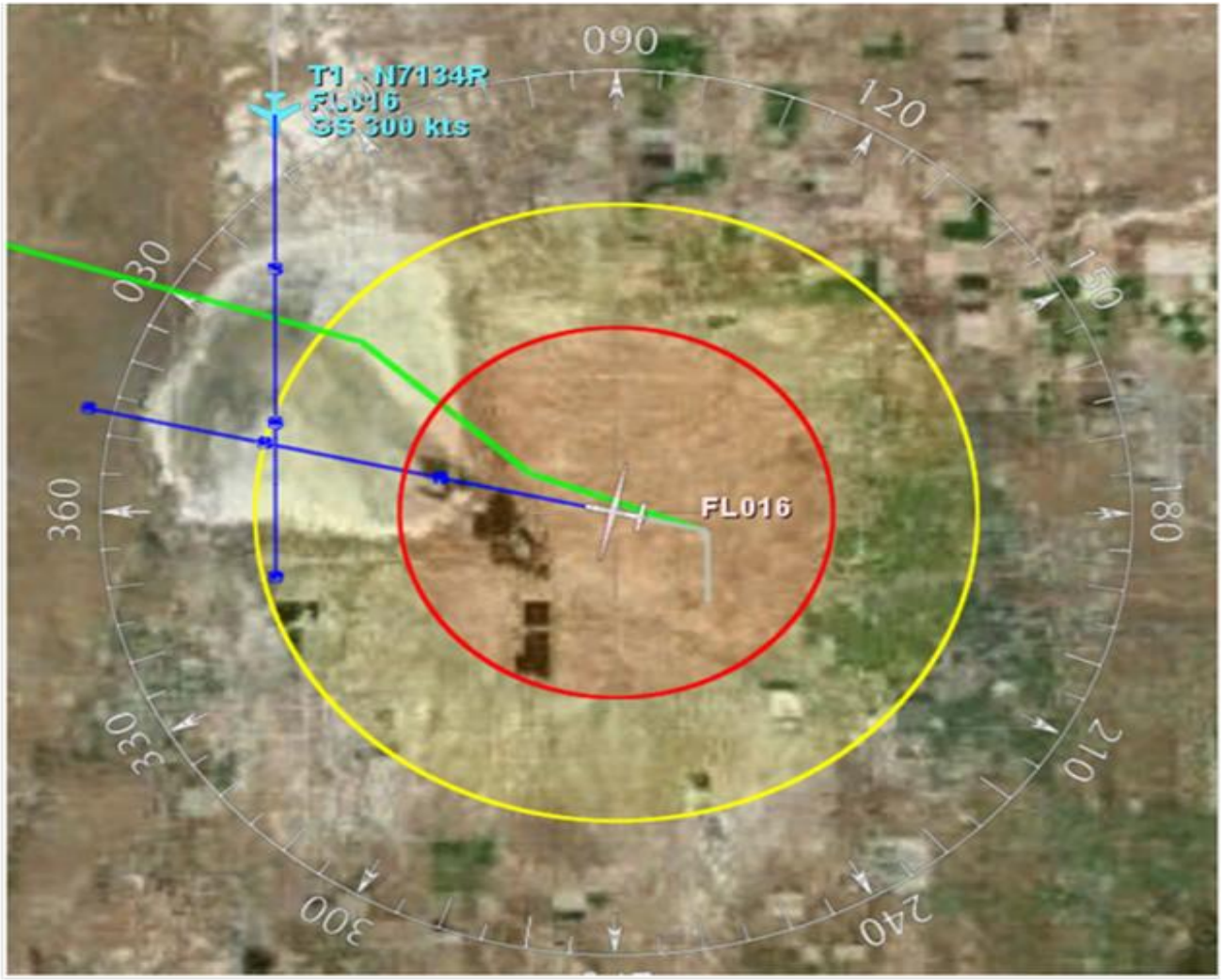
Target aircraft transmitting ADS-B

Ownship's resolution advisory

Aircraft's nominal trajectory

Traffic alert advisory

Traffic threat advisory



NASA Patent (US Patent Serial No. 9,405,005)[2]

SCITECH FORUM

VIGILANT AEROSPACE SYSTEMS

NASA

Detect and Avoid Flight Test Plan

Vertical Profile	Scenario Designation	Priority	Speed Knots	Aimpoint Offset CPA	Phantom 1 Altitude AGL	Phantom 2 Altitude AGL	Objective	Planned Vertical Seperation	Advisory RA Type	Automatic Response to RA	Loss Link Phantom 1	Loss Link Phantom 1
10 Series Scenarios 200 foot Level	Scenario X11	1	20	1 (200 ft Vert)	250	50	Ensure miss & safety pilot fam	200	No Advisory	No	LL1	LL2
	Scenario X12	1	20	1 (200 ft Vert)	250	50	No activation & safety pilot fam: No RA	200	No Advisory	No	LL1	LL2
	Scenario X13	1	30	1 (200 ft Vert)	250	50	No activation & safety pilot fam: No RA	200	No Advisory	No	LL1	LL2
	Scenario X14	1	30	1 (200 ft Vert)	250	50	No activation & safety pilot fam: No RA	200	No Advisory	No	LL1	LL2
20 Series Scenarios 100 foot Level	Scenario X21	1	20	2 (100 ft Vert)	150	50	Approach at head on, expect "Climb"	100	"Climb, Climb" 1000 fpm	Yes	LL1	LL2
	Scenario X22	2	20	2 (100 ft Vert)	150	50	Approach at head on, expect "Climb"	100	"Climb, Climb" 1000 fpm	Yes	LL1	LL2
	Scenario X23	2	30	2 (100 ft Vert)	150	50	Approach at head on, expect "Climb"	100	"Climb, Climb" 1000 fpm	Yes	LL1	LL2
	Scenario X24	2	30	2 (100 ft Vert)	150	50	Approach at head on, expect "Climb"	100	"Climb, Climb" 1000 fpm	Yes	LL1	LL2
30 Series Scenarios 50 foot Level	Scenario X31	2	20	3 (50 ft Vert)	125	75	Approach at head on, expect "Climb"	50	"Climb, Climb" 1000 fpm	No	LL1	LL2
	Scenario X32	1	20	3 (50 ft Vert)	125	75	Approach at head on, expect "Climb"	50	"Climb, Climb" 1000 fpm	No	LL1	LL2
	Scenario X33	1	30	3 (50 ft Vert)	125	75	Approach at head on, expect "Climb"	50	"Climb, Climb" 1000 fpm	No	LL1	LL2
	Scenario X34	1	30	3 (50 ft Vert)	125	75	Approach at head on, expect "Climb"	50	"Climb, Climb" 1000 fpm	No	LL1	LL2
50 Series Scenarios50\ foot Level	Scenario X51	3	20	4 (0 ft Horiz)	100	150	0 degree approach, expect "Turn Left"	50	"Turn Left, Turn Left"	Yes	LL1	LL2
	Scenario X52	3	20	4 (0 ft Horiz)	100	150	45 degree approach, expect "Turn Left"	50	"Turn Left, Turn Left"	Yes	LL1	LL2
	Scenario X53	3	30	4 (0 ft Horiz)	100	50	60 degree approach, expect "Turn Left"	50	"Turn Left, Turn Left"	No	LL1	LL2
	Scenario X54	3	30	4 (0 ft Horiz)	100	50	90 Degree approach, expect "Turn Right"	50	"Turn Right, Turn Right"	Yes	LL1	LL2
	Scenario X55	3	30	4 (0 ft Horiz)	100	50	135 degree approach, expect "Turn Left"	50	"Turn Left, Turn Left"	No	LL1	LL2
	Scenario X56	3	30	4 (0 ft Horiz)	100	50	180 degree approach, expect "Turn Right"	50	"Turn Left, Turn Left"	No	LL1	LL2

Types of DAA Encounter Scenarios (CA)

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

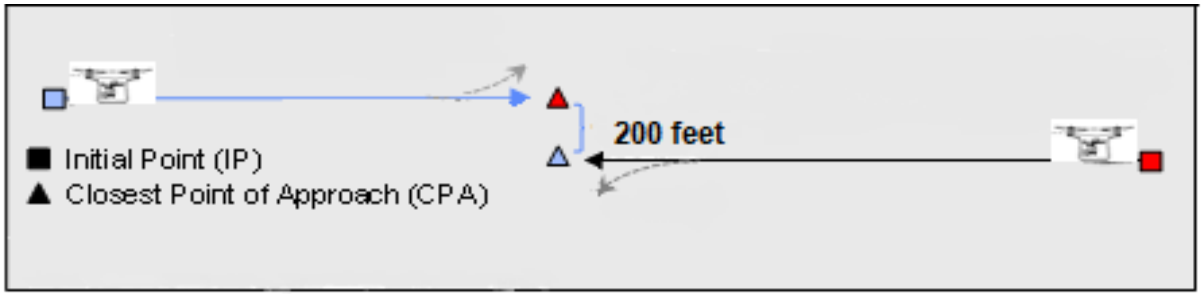


Fig. 7. Vertical Profile for Series 10 Encounters

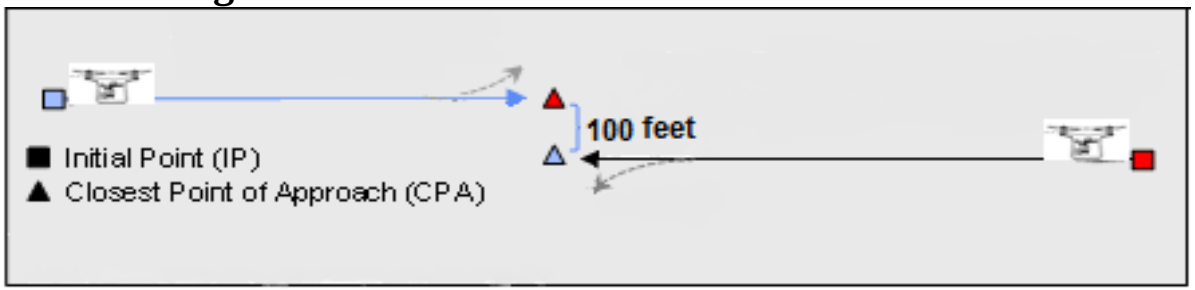


Fig. 8. Vertical Profile for Series 20 Encounters

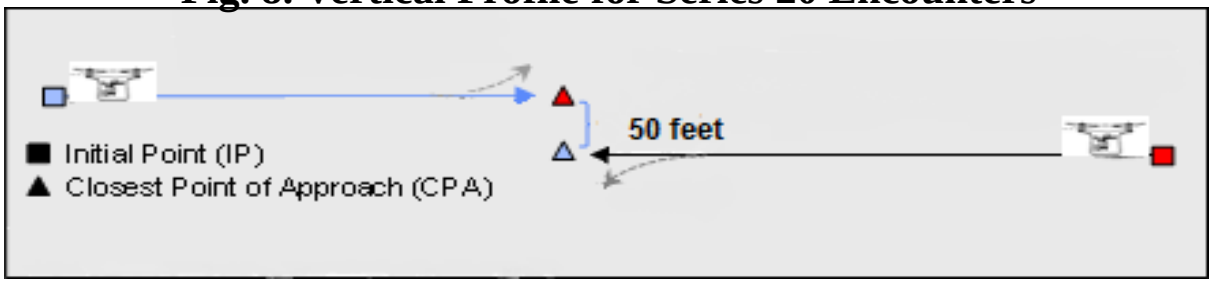


Fig. 9. Vertical Profile for Series 30 Encounters

Types of DAA Encounter Scenarios (CA)

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

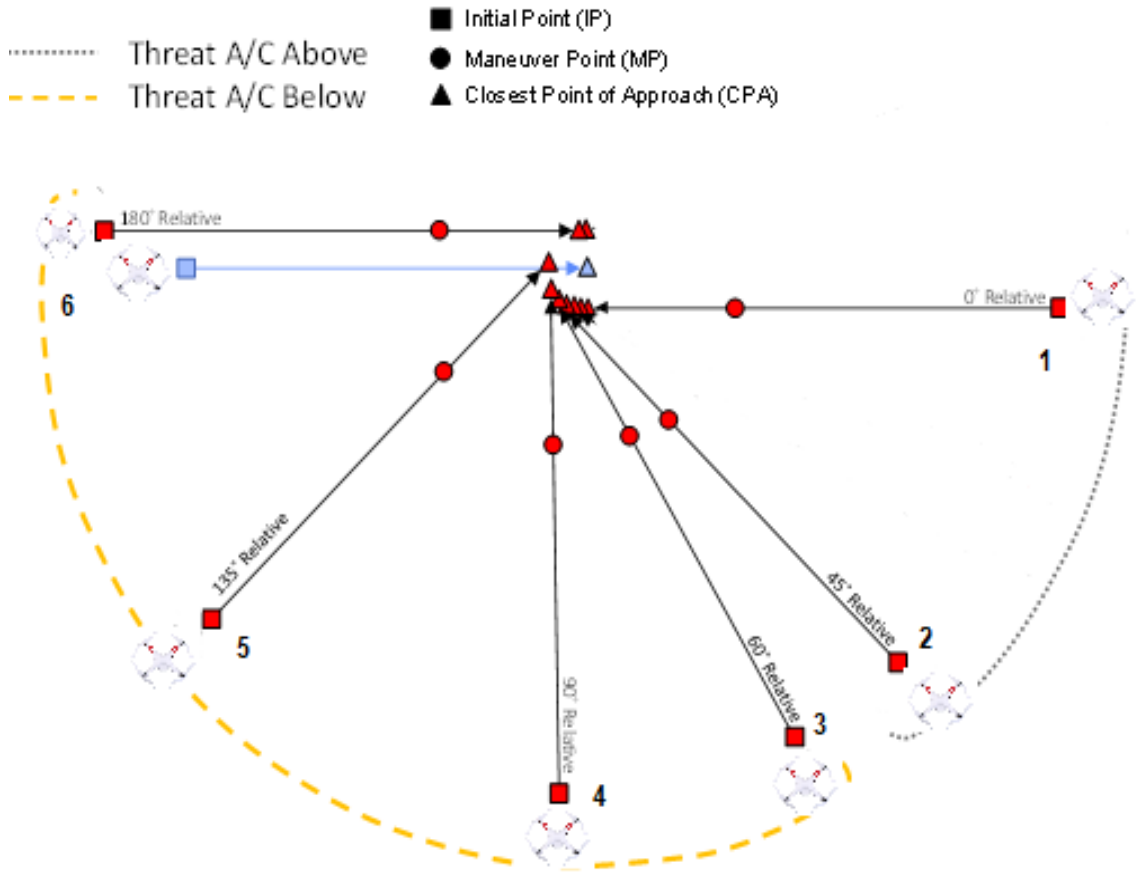
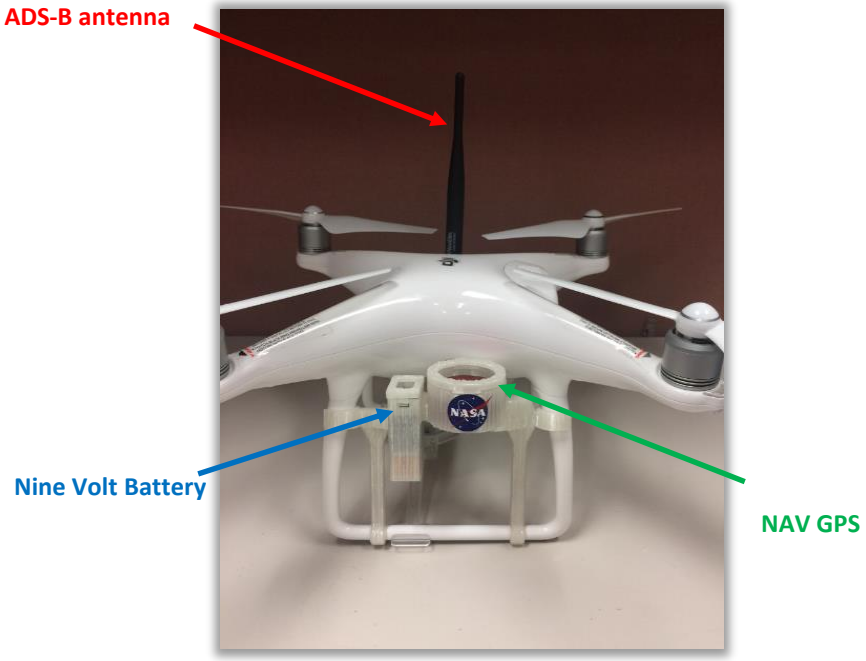


Fig. 10. ADS-B DAA Scenario Geometrics

Unmanned Vehicles



- **Test Aircraft (Ownship)** **SUAS: Phantom 4 Pro**
  - •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
- **Intruder**

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

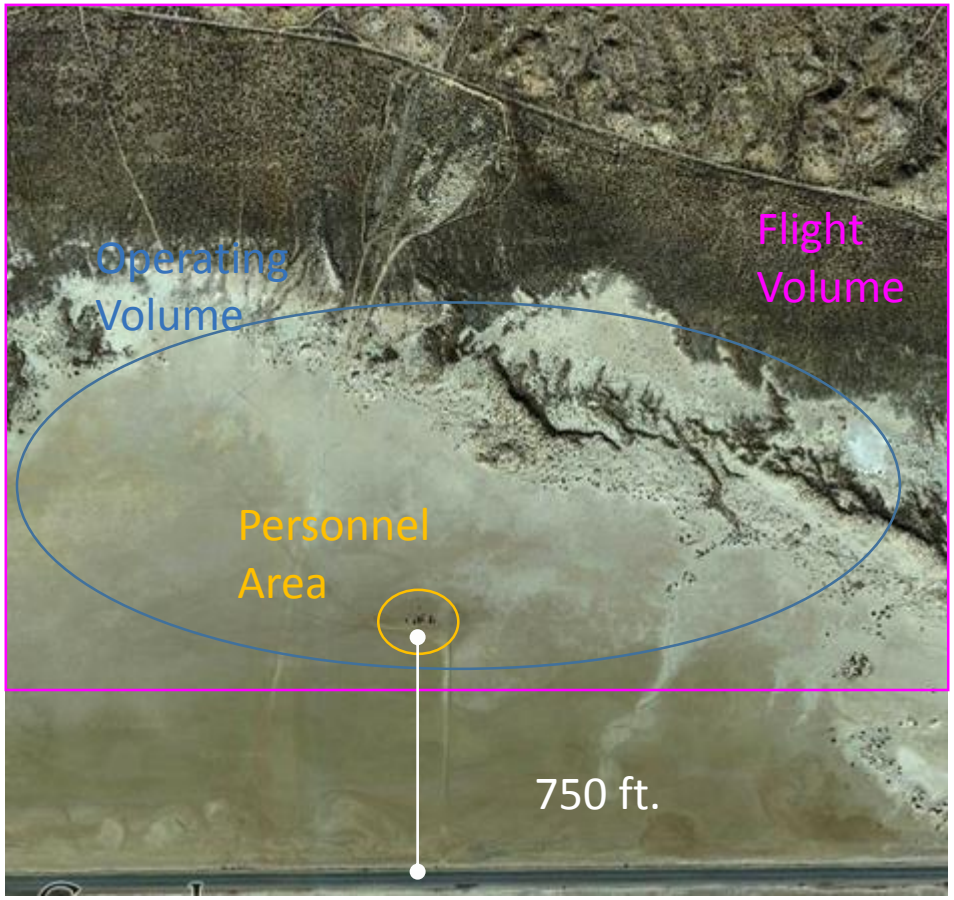


Fig. 11. Flight Operations Area

Vertical Profile for Series 20 Encounters

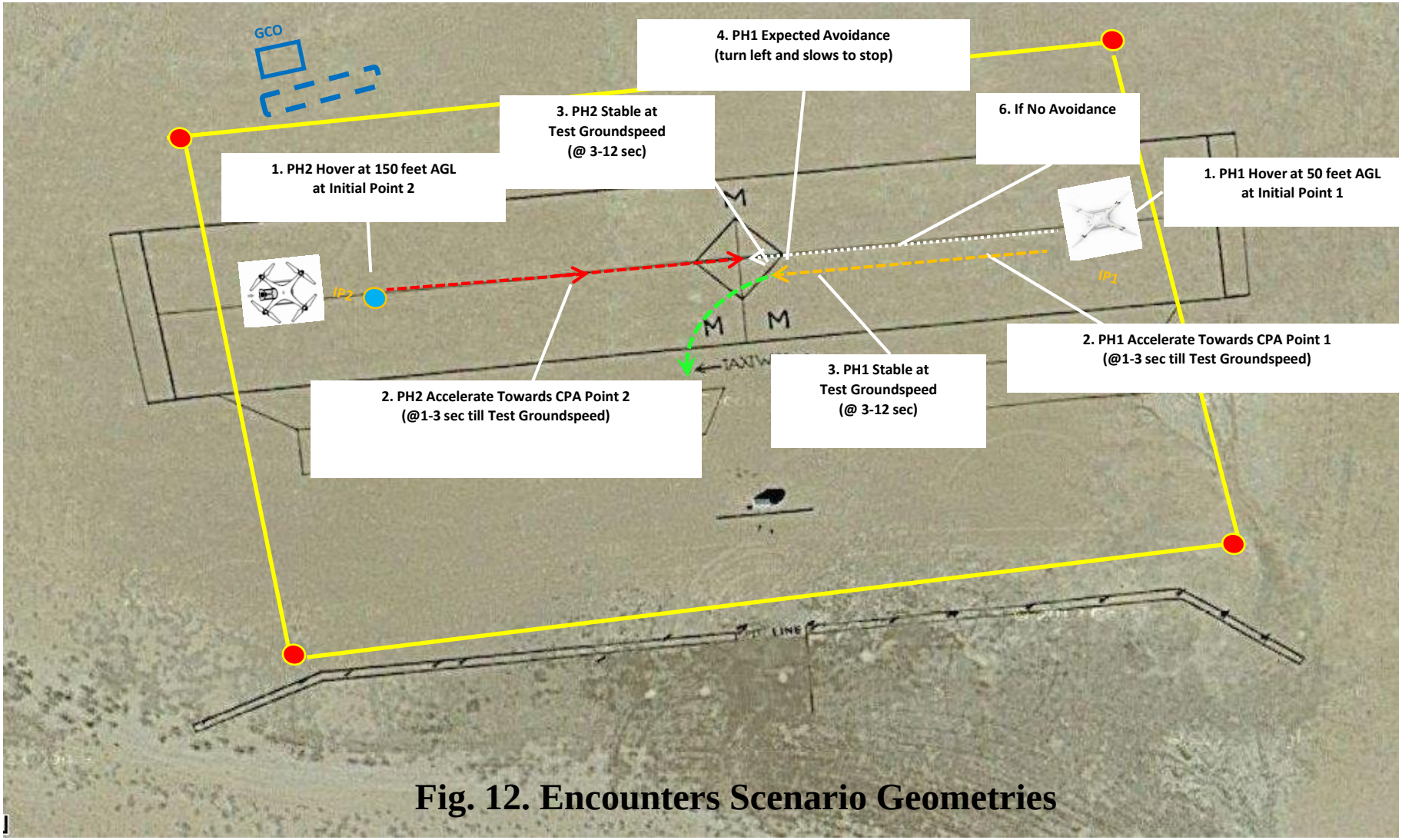


Fig. 12. Encounters Scenario Geometries

ADS-B Detect and Avoid Performance Simulation

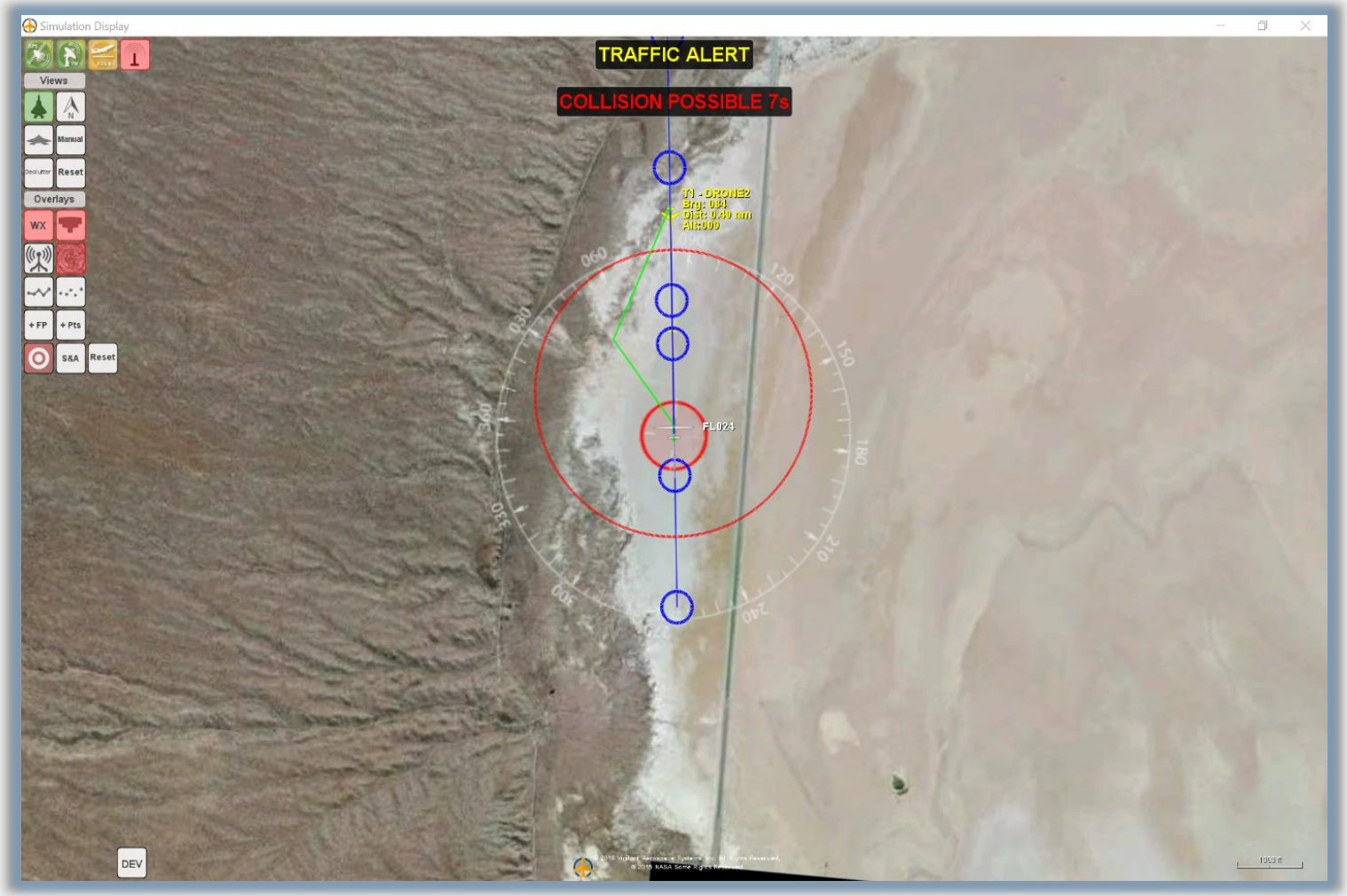
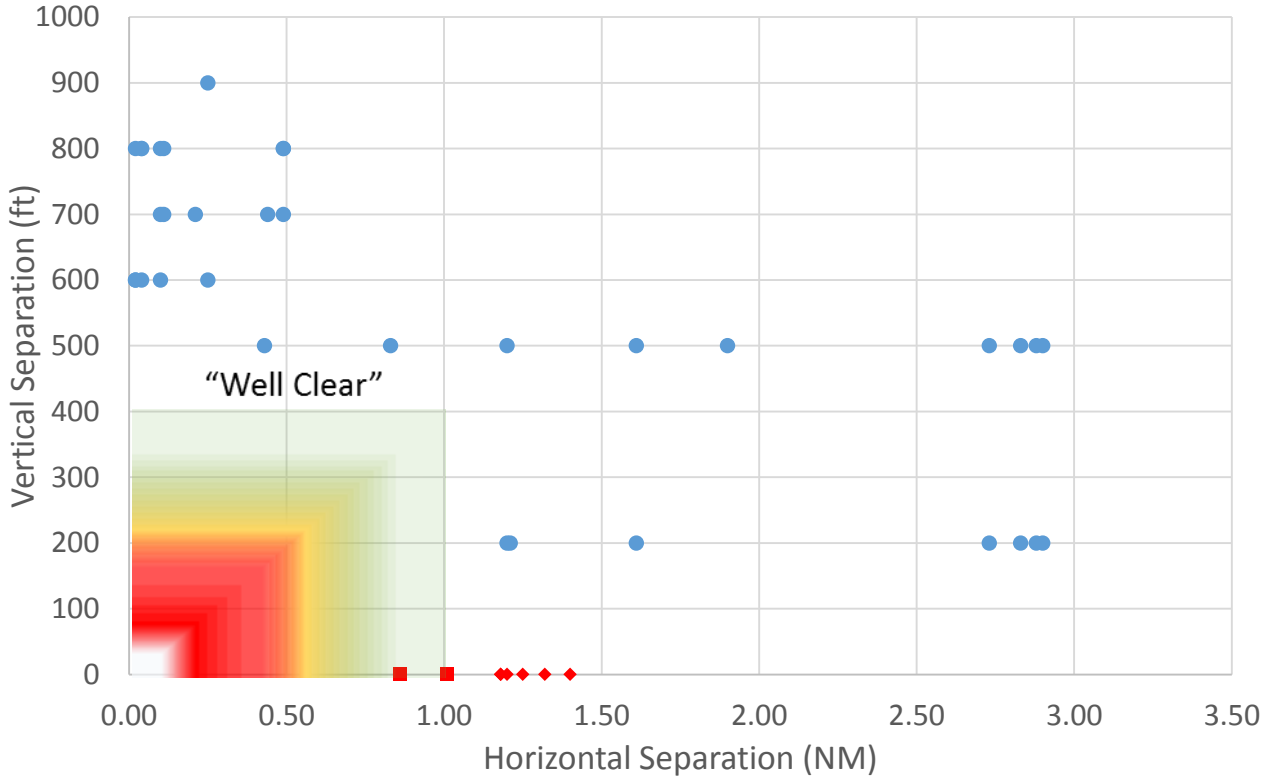


Fig. 13. X33 Simulation with Resolution Advisory

DAA Algorithm Performance

- Vertical Encounters
- Horizontal Encounters
- Multiple Intruders Scenario



- **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 Detect and Avoid Flight #1

ADS-B DAA Flight 1 - December 6, 2016: Detect and Track intruders using ADS-B

ADS-B Detect and Avoid Flight #2

ADS-B DAA Flight 2 - December 7, 2016: Determine if intruder is a collision threat

ADS-B Detect and Avoid Flight #3

- 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

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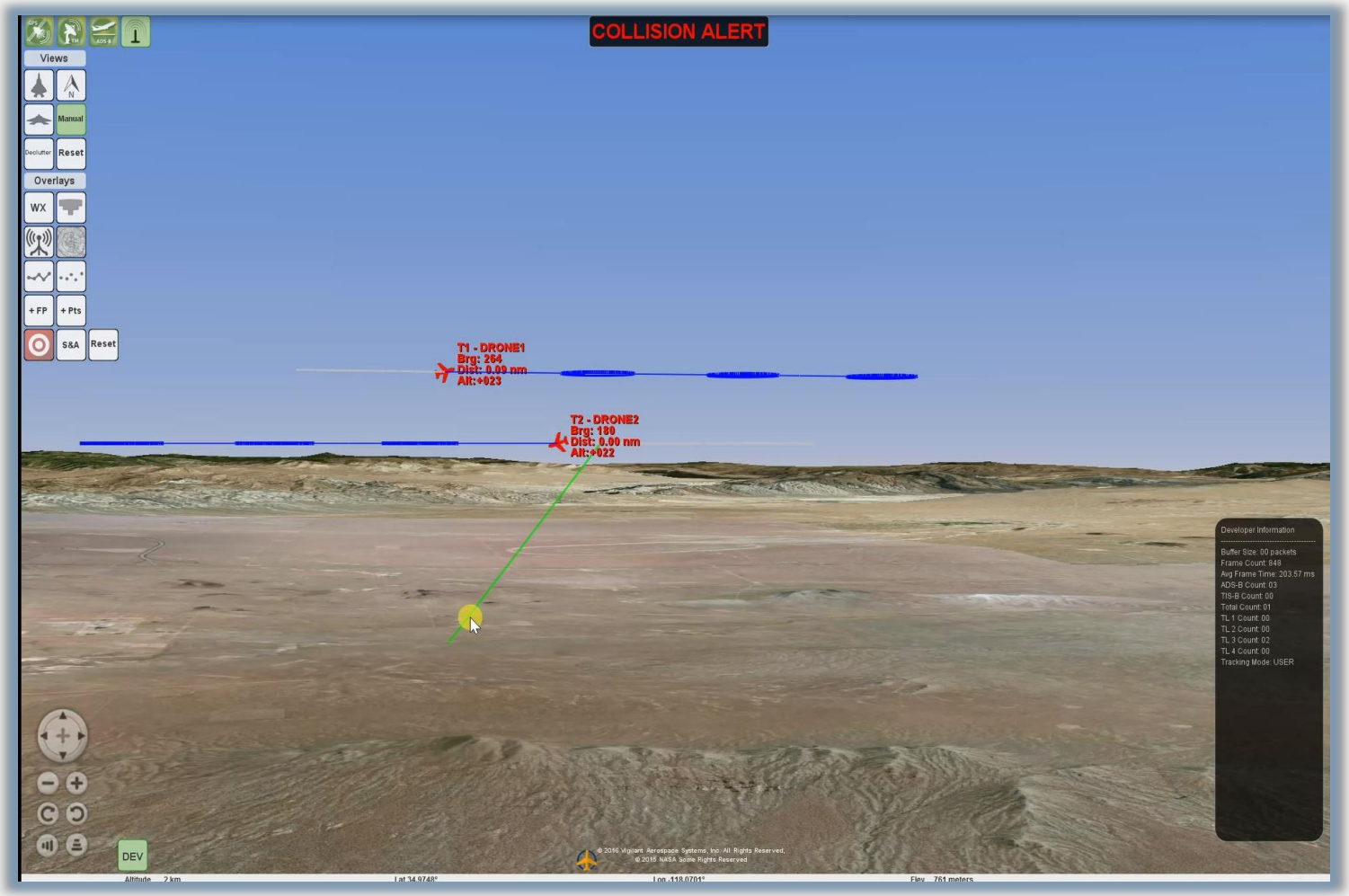
ADS-B Detect and Avoid Flight #4

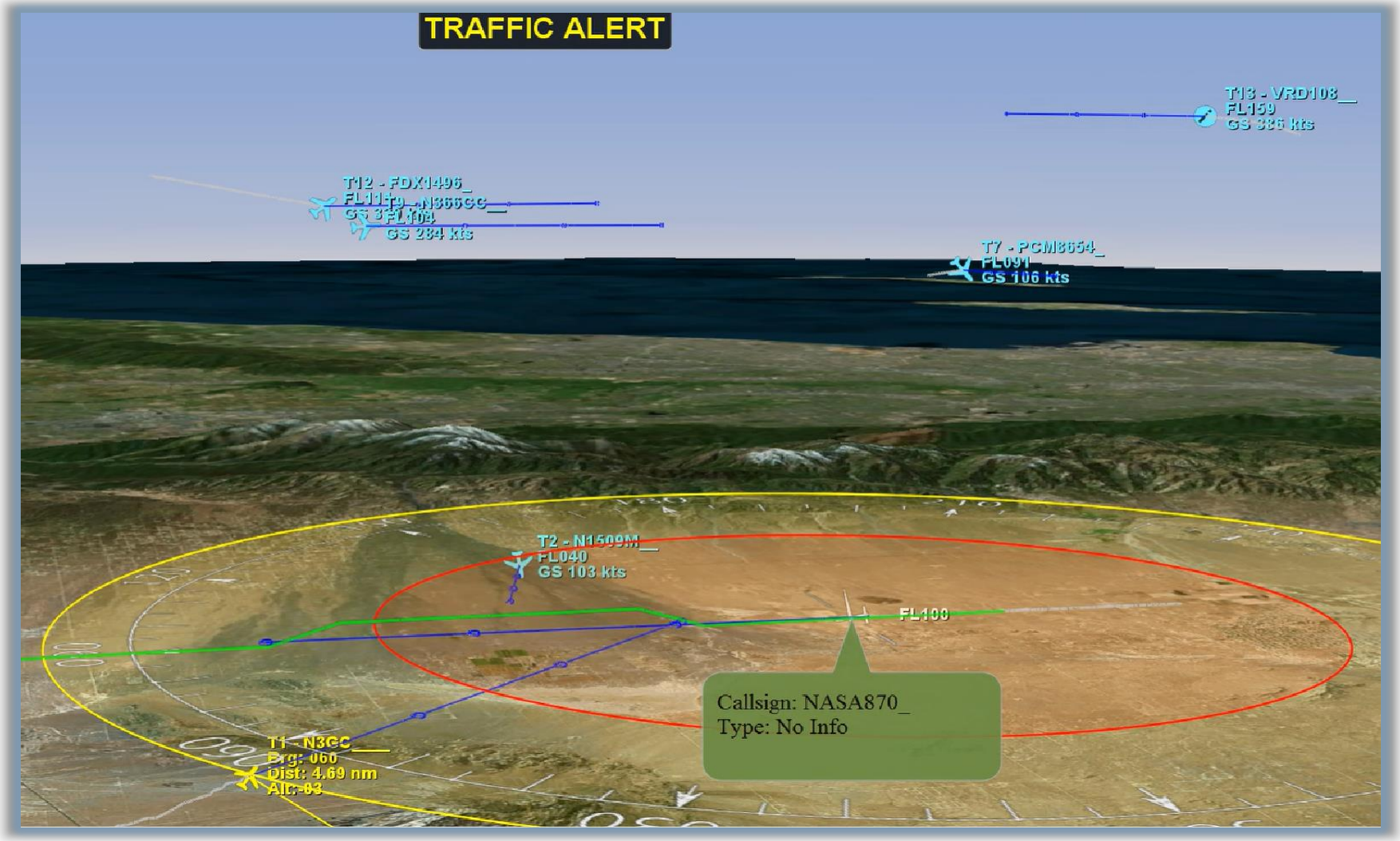


ADS-B DAA Flight 4 - December 9th 2016: Commands maneuver to avoid the collision

ADS-B Detect and Avoid Flight #5

ADS-B DAA Flight 5 - May 2017: Commands Avoidance maneuver to safely avoid the collision

ADS-B Detect and Avoid Flight #6



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.

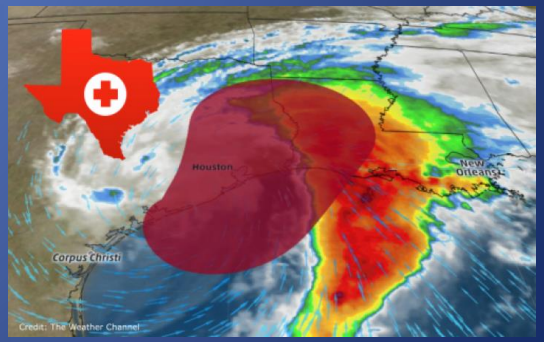


Fig. 19. NASA Armstrong Research Flight Test Team (NASA photo AFRC2016-0365-01)

Hurricane Harvey Humanitarian Aid Video

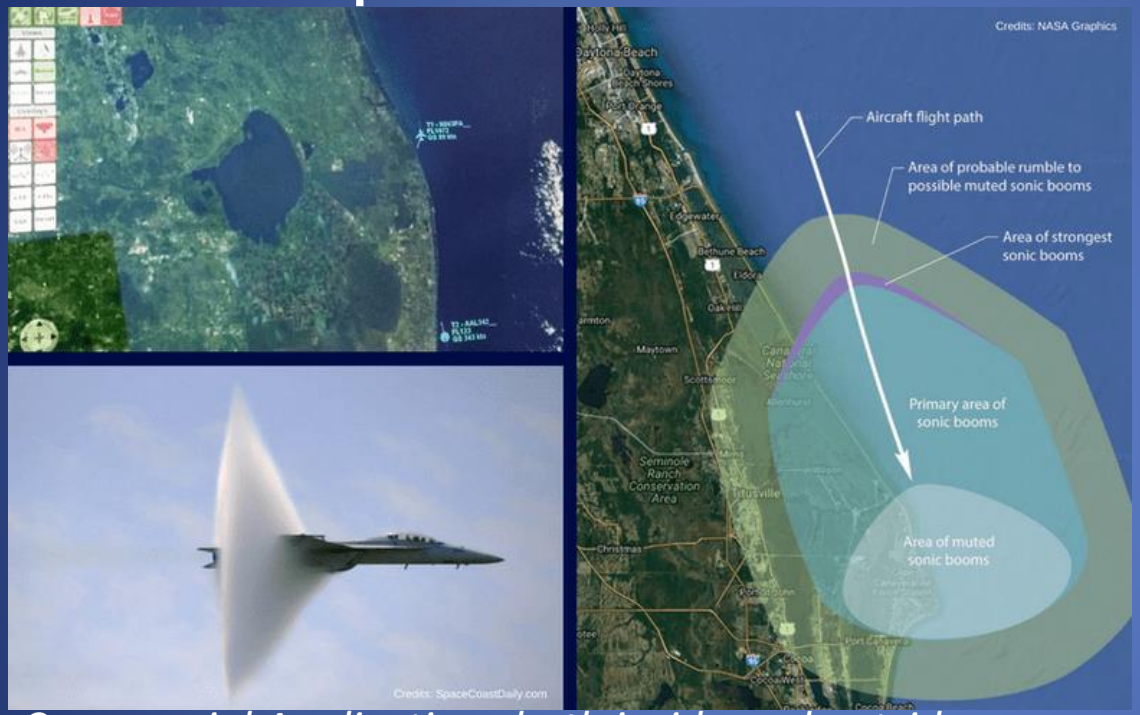
https://youtu.be/2CdkQJ01OSg
http://humanitariandrones.org/
https://www.nasa.gov/centers/armstrong/features/drones_assist_harvey_recovery_efforts.html

Questions?

https://vigilantaerospace.com/new-90-second-video-nasa-beyond-line-sight-detect-avoid-flight-tests-flighthorizon/

Future Applications and Benefits

ADS-B on Supersonic Vehicles



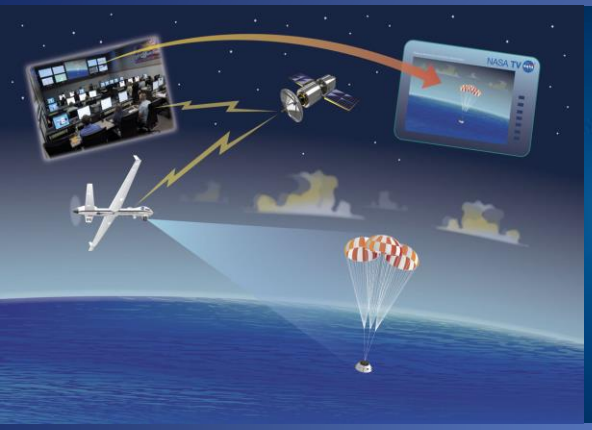
Commercial Applications both inside and outside NASA: Commercial supersonic vehicles with ADS-B Systems will likely emerge in the near future.

NASA is a world class leader in cutting edge astronautics technology.

- 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

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

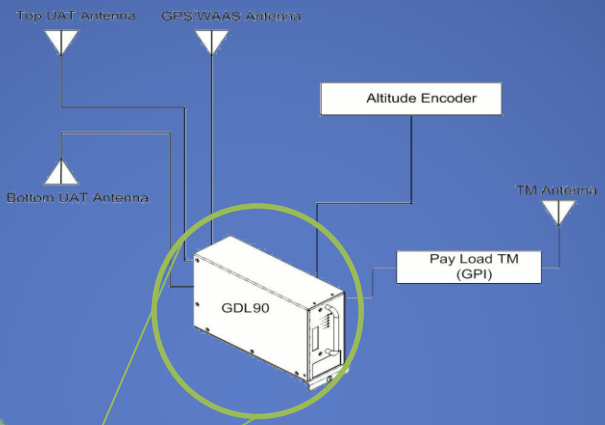
National Aeronautics and Space Administration

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

GPS



C-BAND

LOS Datalink

978 MHz

978 MHz

1090 MHz

GCS

ADS-B Ground Station

NASA Patent (US Patent Serial No. 9,405,005)[2]

NASA Results and Benefits

National Aeronautics and Space Administration

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

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

Sub-Functions	 **µADS-B Detect and Avoid** 
Cooperative Surveillance	ADS-B active Air-to-Air Surveillance
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

Software & Electrical Connection Architecture

From	To	Wireless/Wired	Type/Protocol	Purpose
µADS-B IN EFB (uavionix)	PC running DAA Software	Wired	USB Serial / raw AVR	A raw ADS-B RX
PC running DAA Software	Tablet running DAA Autonomous App	Wireless	2.4ghz WIFI / TCP	Communicate conflict avoidance maneuvers to DJI Drone through controller
Tablet running DAA Autonomous App	DJI Controller	Wired	USB Serial / DJI Proprietary	Tablet is allowed to communicate to drone through DJI MOBILE SDK
DJI Controller	DJI Rx on DJI Phantom 4	Wireless	2.4ghz, 5.8ghz/ DJI Proprietary	DJI Controller communicates with drone and allows the pilot to fly the drone
ADS-B Traffic from other aircraft and ground station	µADS-B IN EFB (uavionix)	Wireless	978 Mhz, 1090 Mhz / ADS-B IN	ADS-B data of aircraft position, speed, and heading
µADS-B TX	Any ADS-B RX Air-to Air Surveillance	Wireless	978 Mhz / ADS-B OUT	ADS-B data of aircraft position, speed, and heading

Model Elements Used To Develop and Validate Requirements

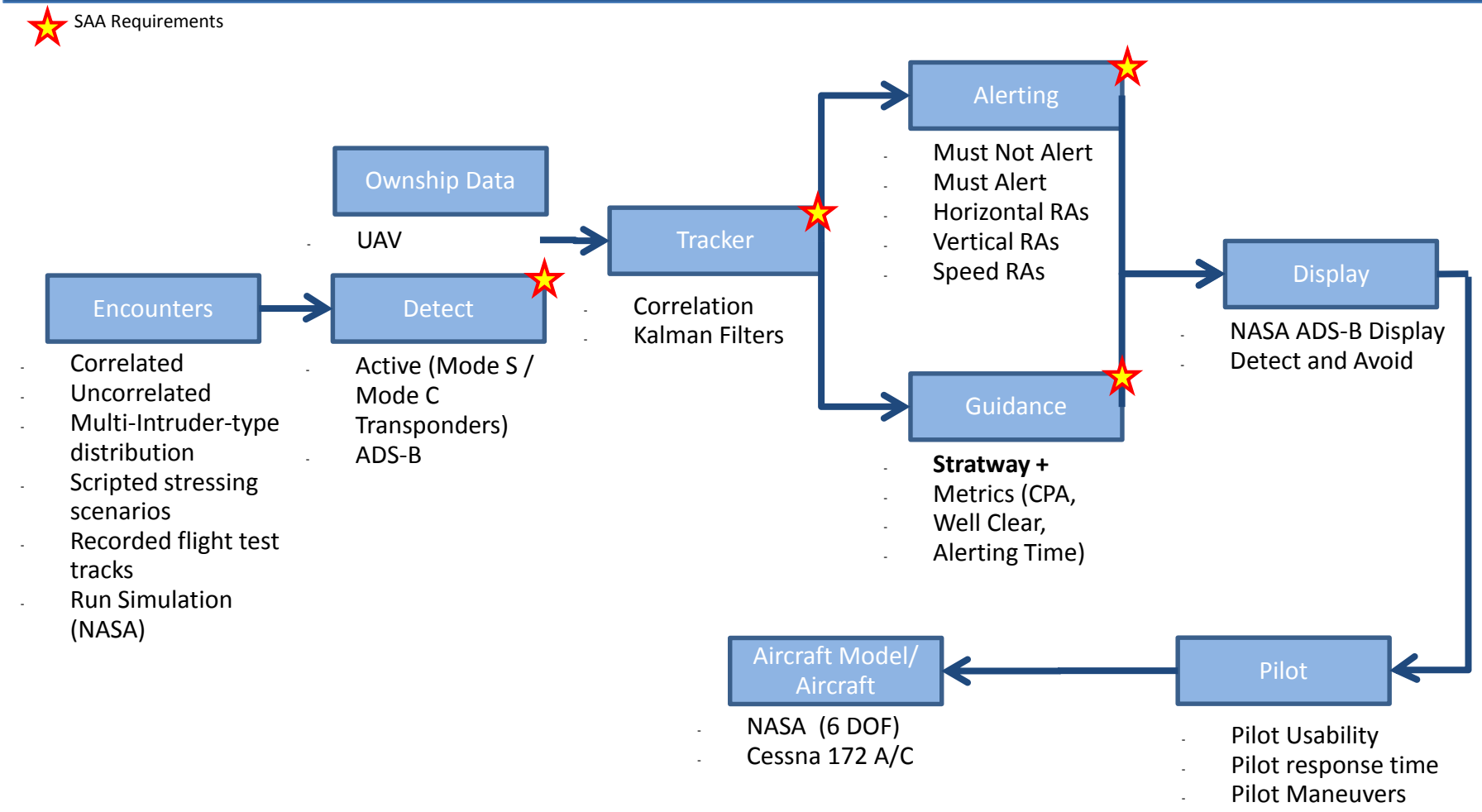
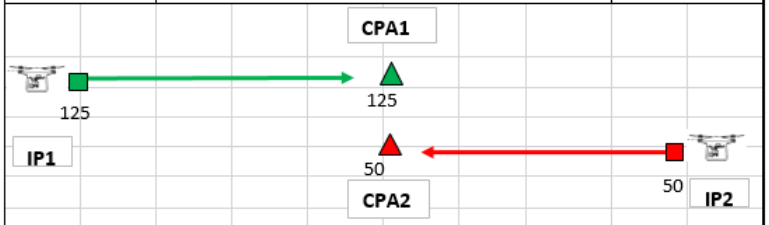


Fig. 14. DAA Verification and Validation Methodology

Detect and Avoid Scenario X33 Flight Test Cards

DAA Scripted	AIRCRAFT: Phantom 1	S/N: 181	VERSION 4
CARD#	**Scenario X33**		OWNSHIP



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

LOST LINK MISSION: 1

DECONFLICTION ALT: 125

ADS-B:	OFF	ON		
DISPLAY:			DAA	
MANEUVER:	OFF	Advisory	AUTO	
SENSOR SELECT:			ADS-B	

ABORT PROCEDURE: 125 — MAINTAIN HEADING

COMEX TIME:

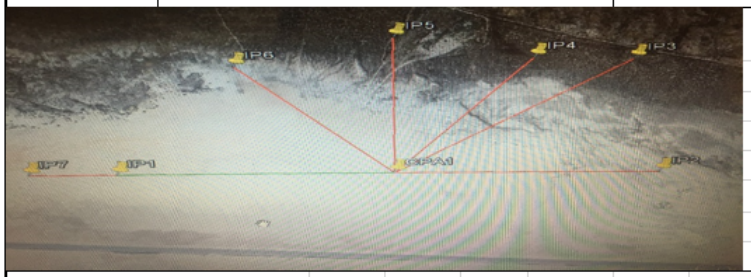
IP WIND:

WPT	LATITUDE	LONGITUDE	ALT V/V	DIST MC	KGS	LEG TIME
IP1	N34° 52.10'	W118° 05.04'	125	0.3	30	0+36
	N34° 52' 05.9"	W118° 05' 02.3"	0	084		
LL1						
	N34° 52 07.78"	W118° 04 40.38"	25			
CPA1	N34° 52.13'	W118° 04.67'	125	0.0	30	
	N34° 52' 07.9"	W118° 04' 40.3"	0	084		

NOTES: Ownship maneuver. At CPA Hover for 10 seconds and/or until receive DAA Guidance. Follow DAA Guidance

RA Maneuver: YES NO ☑ Check

DAA Scripted	A/C: Phantom 2	S/N: 181	VERSION 4
CARD#	**Scenario X33**		INTRUDER 1



1. TC announces COMEX time.
2. Setup Vehicle at IP, Hover at Target Altitude
3. Accelerate Aircaft 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.

DECONFLICTION ALT: 50

ABORT PROCEDURE: 50 — MAINTAIN HEADING

COMEX TIME:

IP WIND:

WPT	LATITUDE	LONGITUDE	ALT V/V	DIST MC	KGS	LEG TIME
IP2	N34° 52.16'	W118° 04.31'	75	0.3	30	0+36
	N34° 52' 09.6"	W118° 04' 18.7"	0	264		
LL2					30	
	N34° 52 07.80"	W118° 04 40.10"	50			
CPA2	N34° 52.13'	W118° 04.67'	75	0.0	30	
	N34° 52' 07.9"	W118° 04' 40.3"	0	264		

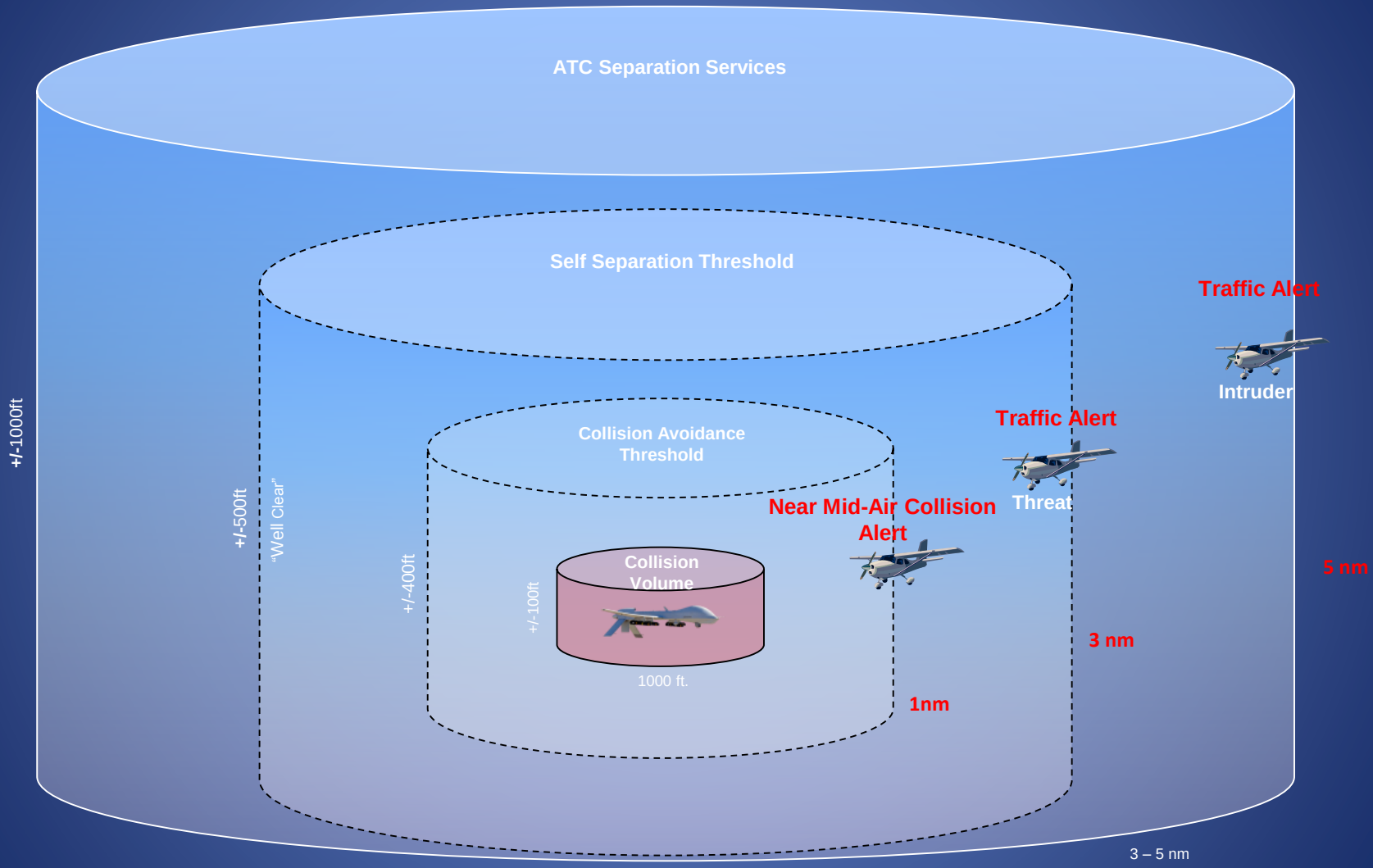
NOTES: Expect Ownship maneuver.

Litchi® Phantom 4 APP Display

https://flylitchi.com/assets/img/doc/p3/p3_gs.jpg?4

Fig. 4. Litchi® Phantom 4 Pro Application

Alerting Logic
RISK Collision Volumes



New Technology

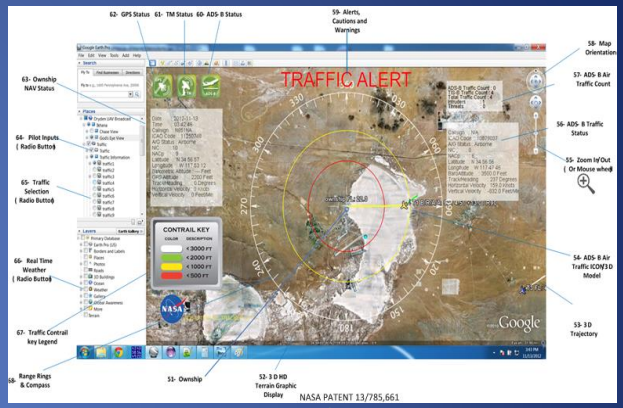
MANNED AIRCRAFT SYSTEMS

National Aeronautics and Space Administration

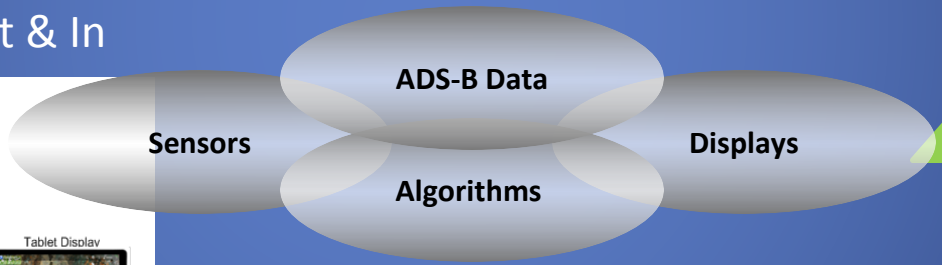
Aircraft

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

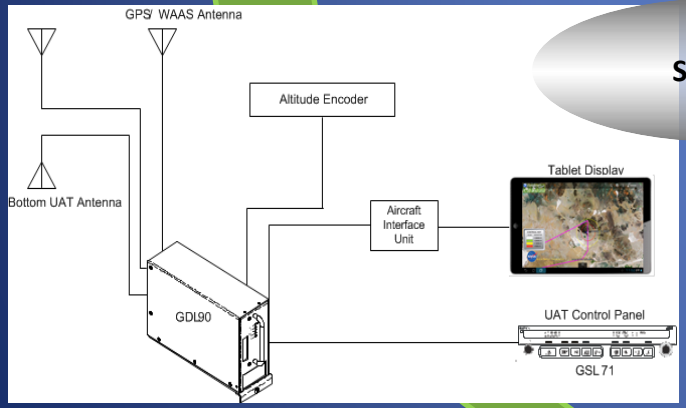
Tablet User Interface



Architecture

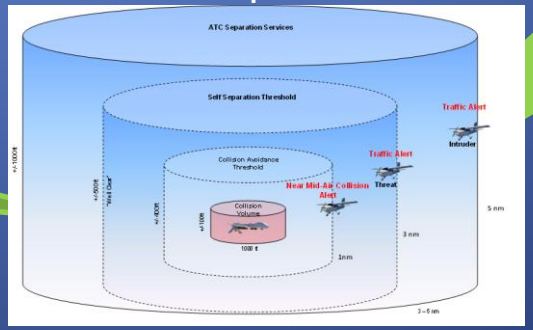


ADS-B Out & In



- 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.

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

Dryden
Remotely
Operated
Integrated
Drone

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

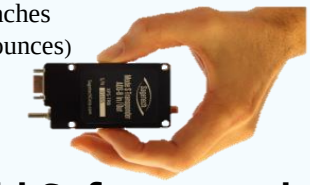
Towed glider

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

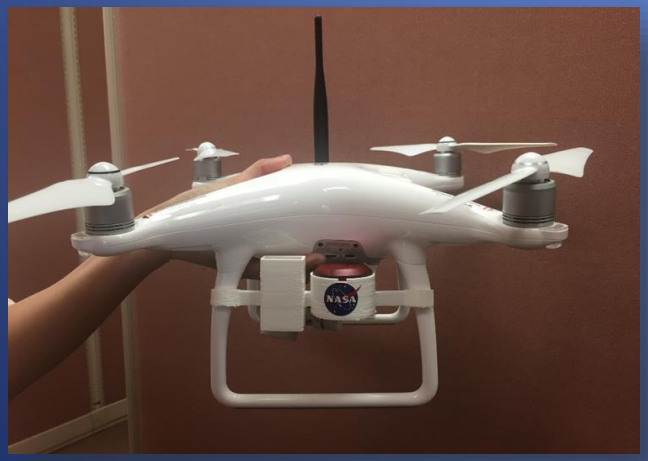
SYNOPSIS

- **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

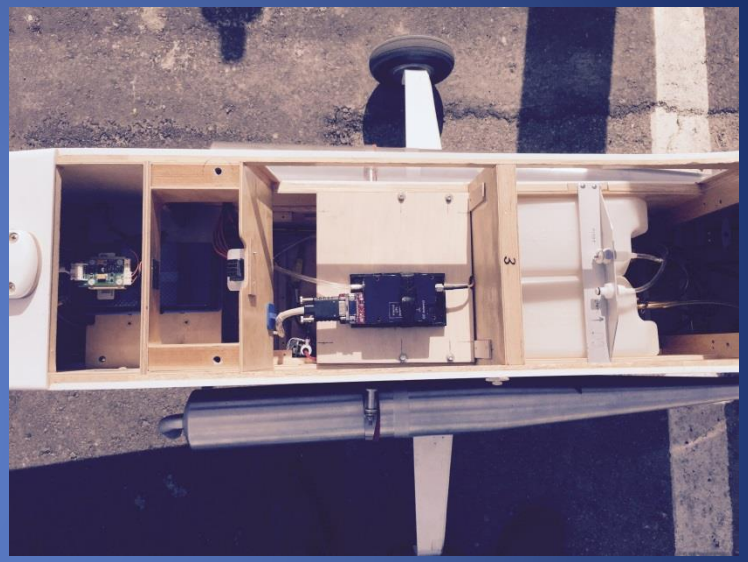
Flight Heritage

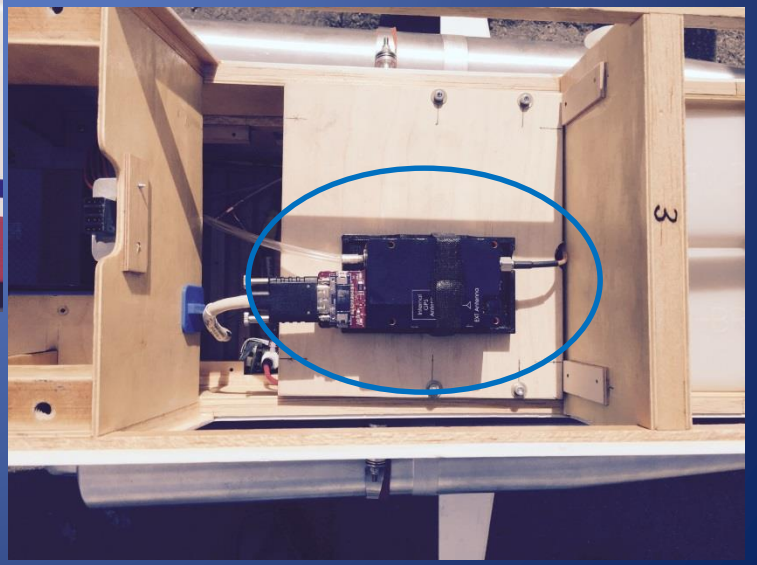
- **The ADS-B Display has previously successfully flown in the IKHANA aircraft (right).**
- **The ADS-B systems has previously successfully flown on other large and small UASs.**
- **Phantom 4 platforms most popular commercial small UASs.**



Dryden Remotely Operated Integrated Drone (DROID)

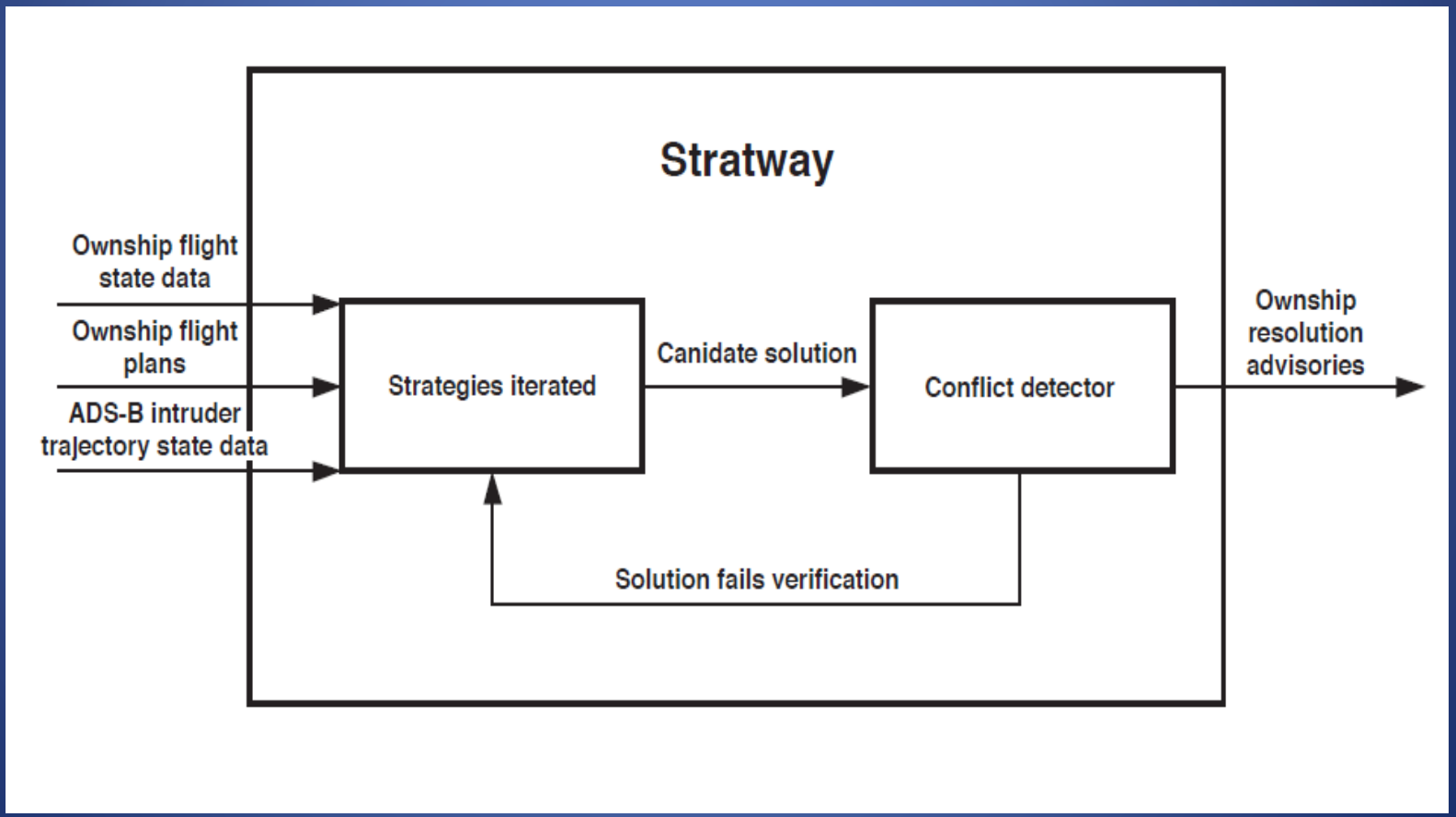
ADS-B Equipped DRIOD





ADS-B Detect-and-Avoid algorithm

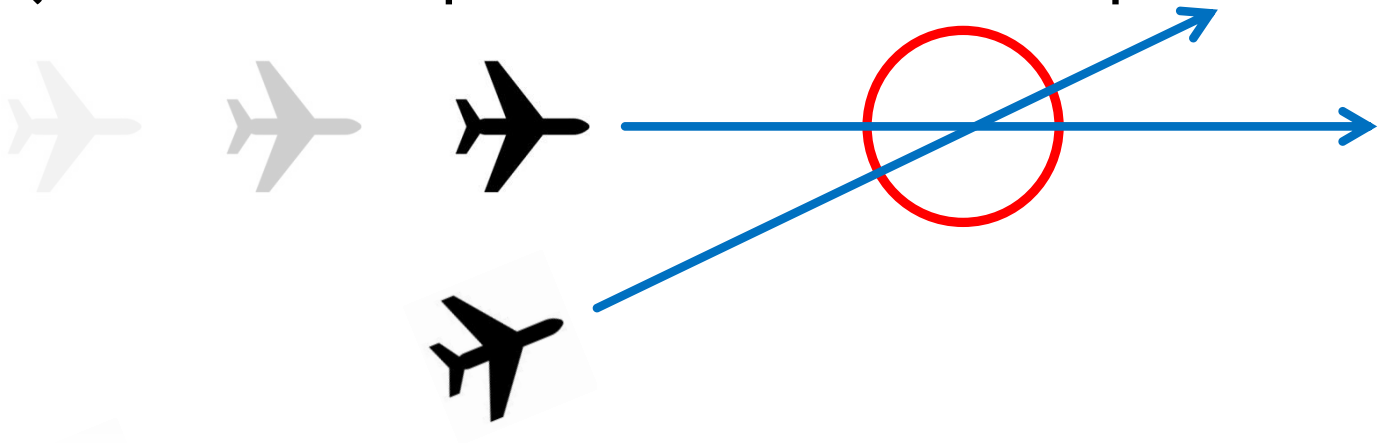
Stratway – a modular approach to safe conflict resolutions.



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.



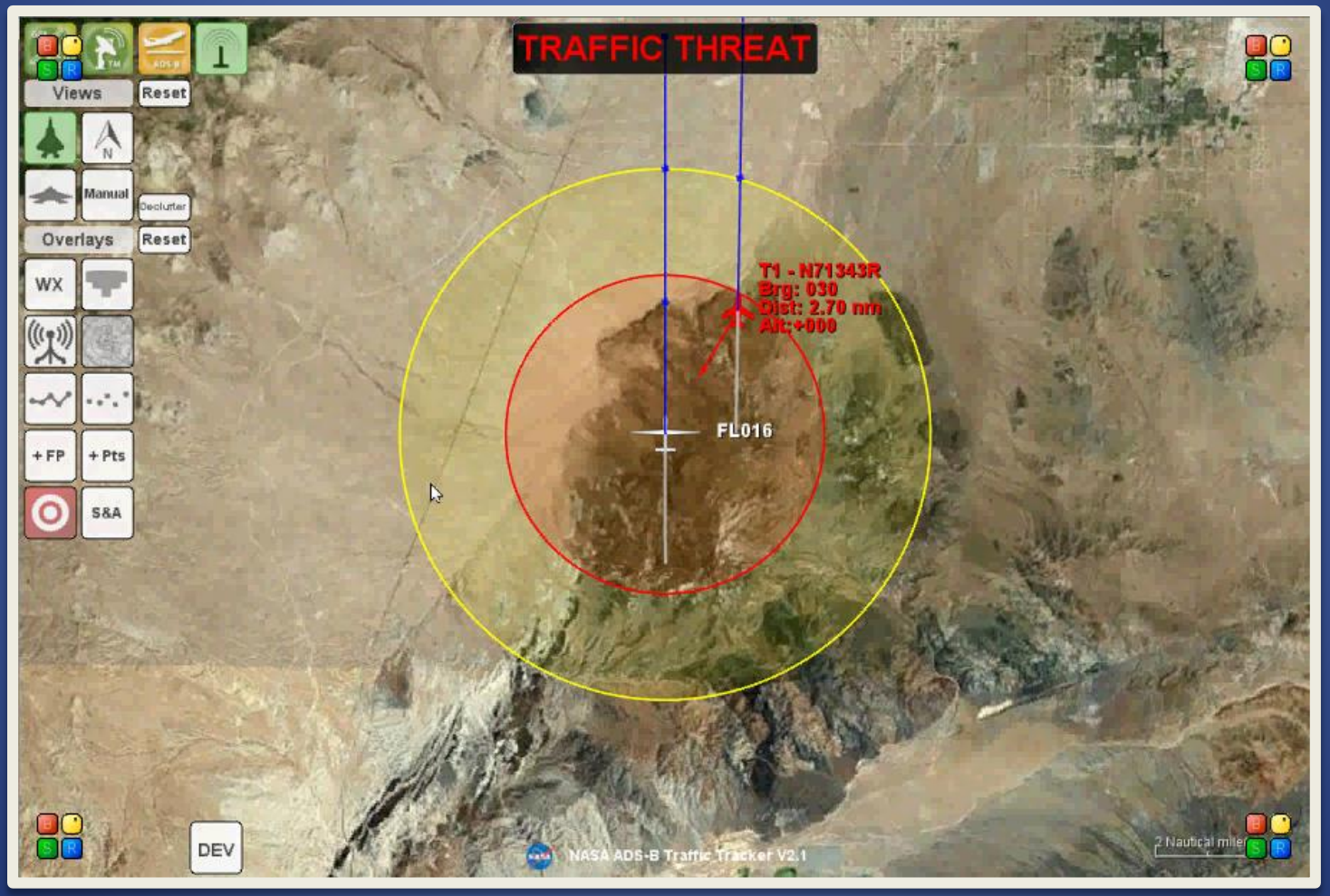
Collision possible: 33s

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

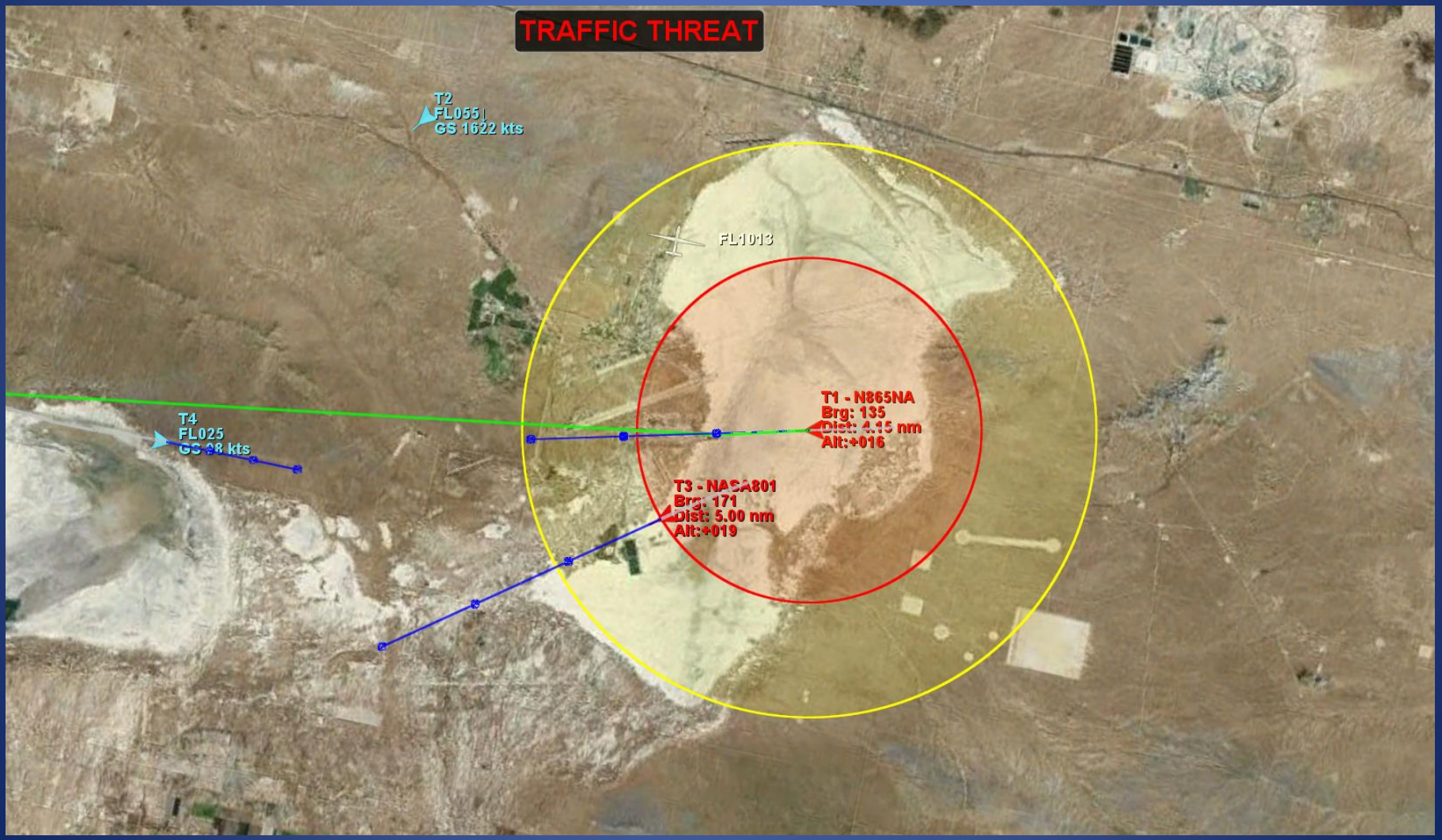
National Aeronautics and Space Administration

ADS-B SAA Display
Traffic Advisory



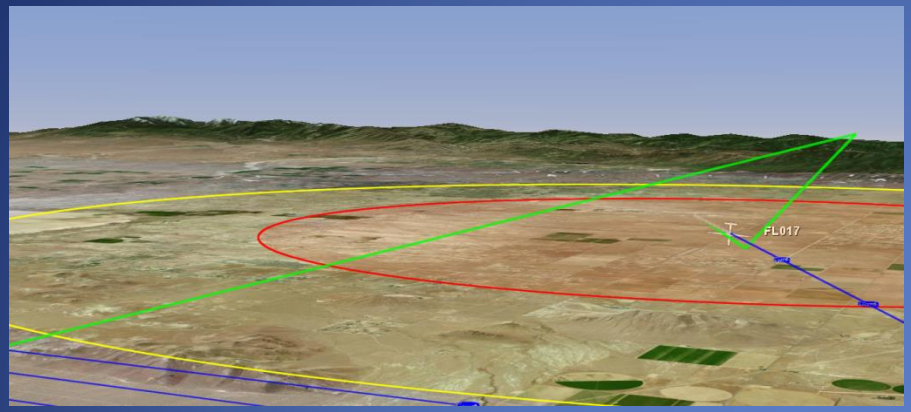
National Aeronautics and Space Administration

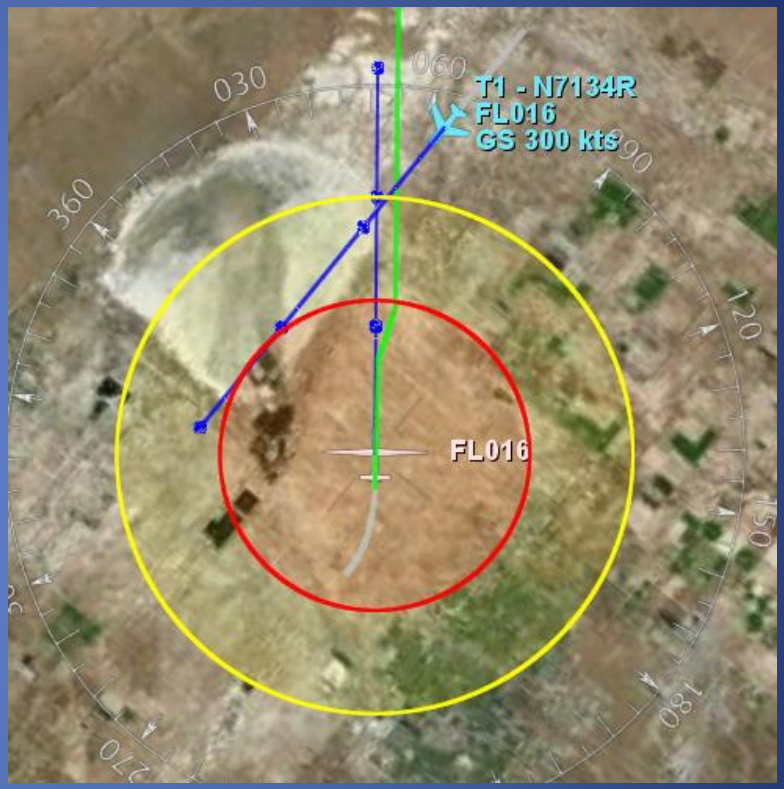
Flight Tests ADS-B Sense and Avoid
(Green Resolution Advisory)

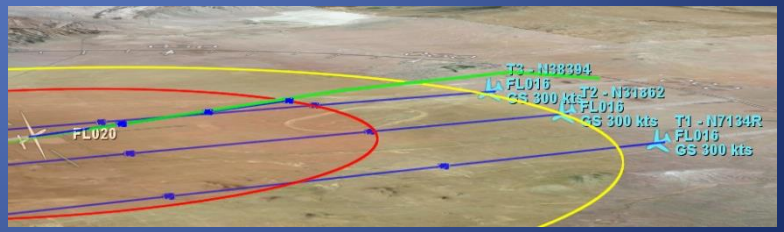


Conflict Detection Resolution Advisory

National Aeronautics and Space Administration

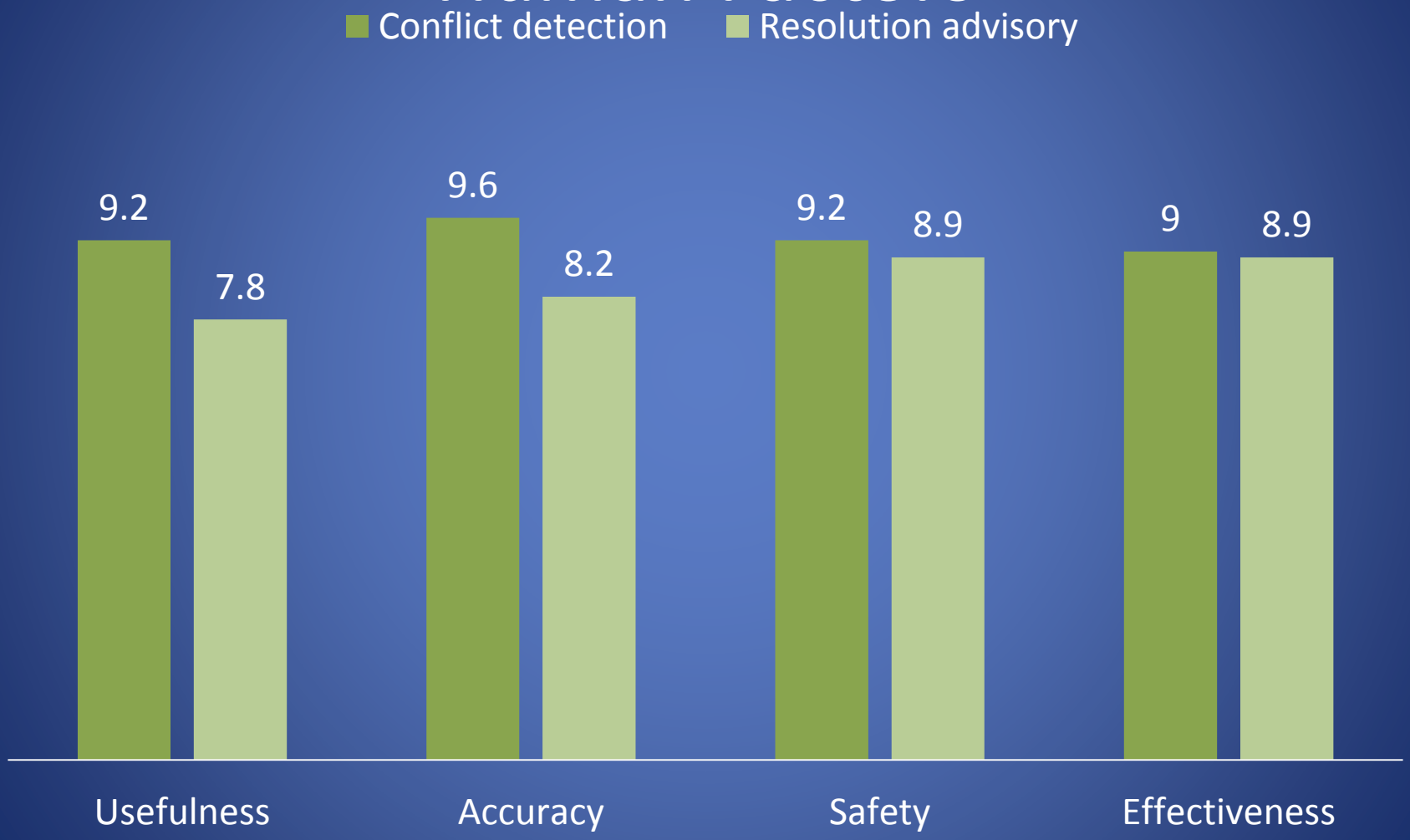






National Aeronautics and Space Administration

NASA Pilot Usability Tests Human Factors



ADS-B Situational Display
Traffic Alerting

TRAFFIC THREAT INDICATORS