Multibeam Monopulse Radar for Airborne Sense and Avoid System

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ABSTRACT

The multibeam monopulse radar for Airborne Based Sense and Avoid (ABSAA) system concept is the next step in the development of passive monopulse direction finder proposed by Stephen E. Lipsky in the 80s. In the proposed system the multibeam monopulse radar with an array of directional antennas is positioned on a small aircaraft or Unmanned Aircraft System (UAS). Radar signals are simultaneously transmitted and received by multiple angle shifted directional antennas with overlapping antenna patterns and the entire sky, 360° for both horizontal and vertical coverage. Digitizing of amplitude and phase of signals in separate directional antennas relative to reference signals provides high-accuracy high-resolution range and azimuth measurement and allows to record real time amplitude and phase of reflected from non-cooperative aircraft signals. High resolution range and azimuth measurement provides minimal tracking errors in both position and velocity of non-cooperative aircraft and determined by sampling frequency of the digitizer. High speed sampling with high-accuracy processor clock provides high resolution phase/time domain measurement even for directional antennas with wide Field of View (FOV). Fourier transform (frequency domain processing) of received radar signals provides signatures and dramatically increases probability of detection for non-cooperative aircraft. Steering of transmitting power and integration, correlation period of received reflected signals for separate antennas (directions) allows dramatically decreased ground clutter for low altitude flights. An open architecture, modular construction allows the combination of a radar sensor with Automatic Dependent Surveillance – Broadcast (ADS-B), electro-optic, acoustic sensors.

Keywords: multibeam, monopulse, airborne, sense and avoid system, direction finder, non-cooperative, high-accuracy, fly eye radar.

1. INTRODUCTION

The **multibeam monopulse** radar for Airborne Based Sense and Avoid (ABSAA) system concept is presented in Figure 1. The multibeam monopulse radar with an array of directional antennas is positioned on an Unmanned Aircraft System (UAS). Radar signals **simultaneously** transmitted and received by multiple angle shifted directional antennas with overlapping antenna patterns the entire sky, **360° for both horizontal and vertical coverage**.

Digitizing of signals in separate directional antennas relative to reference signals provide a high-accuracy high-resolution range and azimuth measurement of signals reflected from non-cooperative aircraft signals. This **high resolution range and azimuth measurement** provides minimal tracking errors in both position and velocity of non-cooperative aircraft and will be determined by sampling the frequency of the digitizer. High speed sampling with high-accuracy processor clock provides high resolution phase/time domain measurement even for wide Field of View (FOV) directional antennas. Fourier transform (**frequency domain processing**) of received radar signals provides signatures and dramatically increases probability of detection for non-cooperative aircraft.

Steering of transmitting power and integration, correlation period of received reflected signals for separate antennas (directions) allows dramatically **decreased ground clutter** for low altitude flights. An **open architecture**, modular construction allows the combination of a radar sensor with Automatic Dependent Surveillance – Broadcast (**ADS-B**), electro-optic, acoustic sensors.

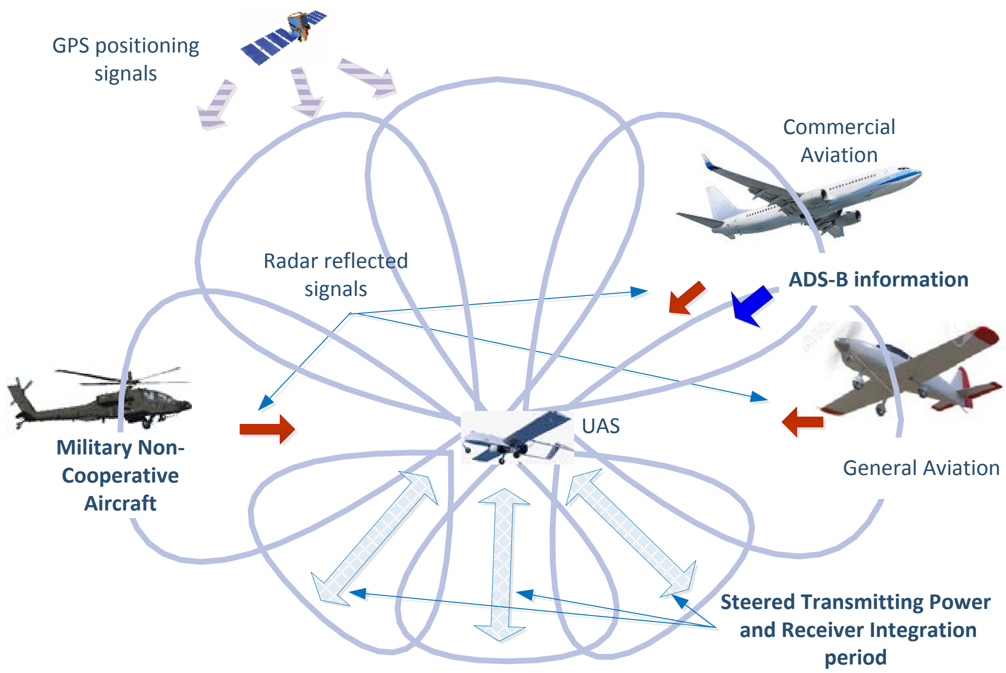


Figure 1. Concept of multibeam monopulse radar for airborne based sense and avoid system.

1.1 State of the Art Ground Based Sense and Avoid System

Ground Based Sense and Avoid (GBSAA) systems provide limited area of observation because of limited radar FOV and shadows, created by ground obstacles, for example mountains and buildings as shown in Figure 2.

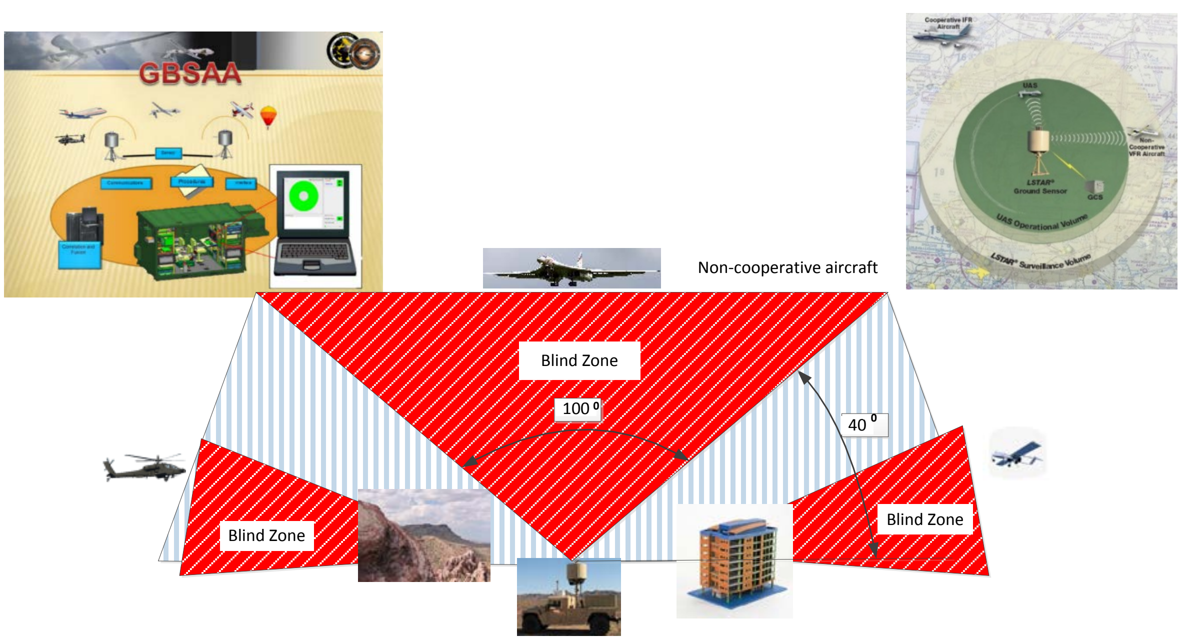


Figure 2. Ground based sense and avoid system with LSTAR (V)3 radar by SRC Inc. providing limited area of observation with large blind zones, where non-cooperative aircraft invisible.

1.2 State of the Art Airborne Based Sense and Avoid System

In Airborne Based Sense and Avoid Systems (ABSAA), radar area of observation is not limited by ground obstacles and the system does not depend on outside sources of air traffic information.

MIT Lincoln Laboratory's propose ABSAA Radar Panel with a stepped-notch antenna array in Ku band, 13–15 GHz operational frequency range [1].

Excelis Inc. designed ABSAA radar positioned behind the nose cone of the aircraft. The radar is a three-panel, thin-tile array operating in the Ku-band. The range will be 8 to 10 nm, with a wide field of view (110° on either side, and 30° up and down). Both systems presented in Figure 3.

Figure 3. ABSAA systems with phased antenna array designed by Excelis Inc. (on left) and MIT LL (on right).

The SkySense-2020MTM innovative sensor solution is adaptable to a wide variety of UAS platforms, including helicopters. Growth options include sensing and displaying weather, fusing data from other sensors (e.g., ADS-B, TCAS, etc.) to provide longer range intruder detection, eventually leading to fully autonomous operation.

But even scanning phase antenna array cannot provide a Field of View (FOV) of more than 120°. Phase array is a frequency dependent system (phase shift is proportional to frequency) and wide band and multiband regimes are connected with complicated system changes.

Even ABSAA **scanning** radar with FOV +/- 20° still will have wide blind zones (Figure 4) and a relatively small tilt of UAS will lead to decreased radar range up to 50% because ground clutter caused ground reflections (Figure 5).

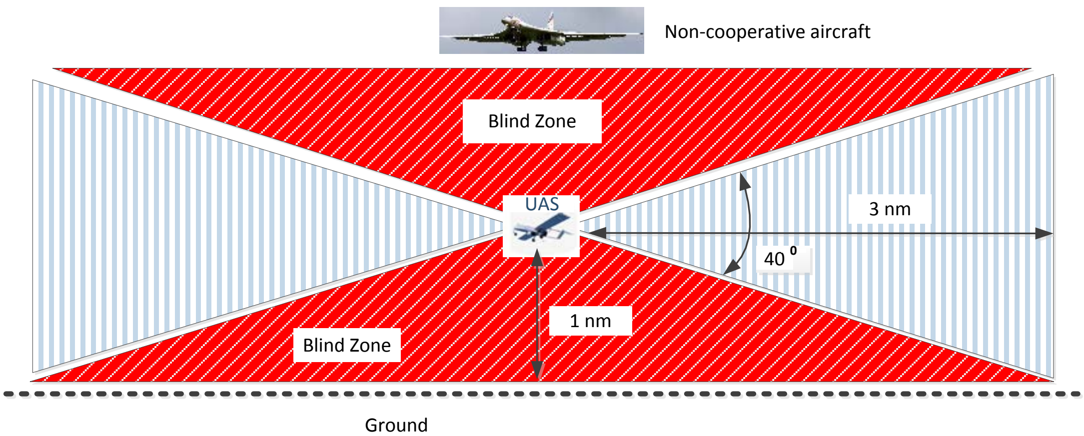


Figure 4. Airborne Based Sense and Avoid System (ABSAA) with **scanning** radar can provide limited area of observation.

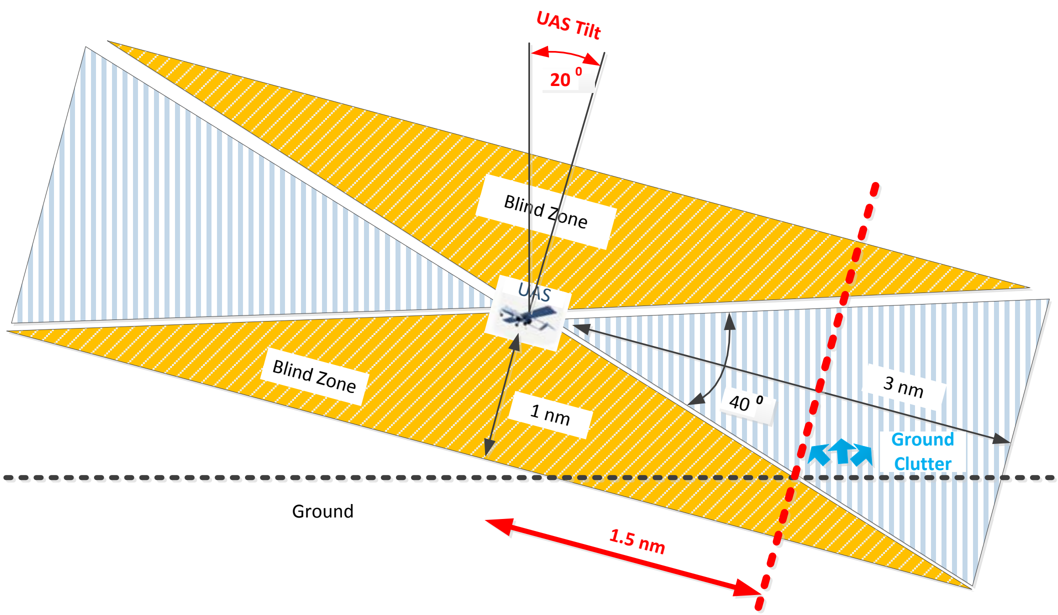


Figure 5. Small (20 degree) tilt of UAS with ABSAA scanning radar will decrease radar range approximately to 50%.

2. MULTIBEAM MONOPULSE SENSE AND AVOID RADAR SYSTEM

Application of Fly Eye radar concept [2] shown in Figure 6 provides high-accuracy amplitude and phase measurement for the entire sky with minimal distance between antennas required for small UAS. To compensate for its eye's inability to point at a target, the fly's eye consists of multiple angularly spaced sensors which give the fly the wide-area visual coverage it needs to detect and avoid the threats around him. Each sensor is coupled with a detector and connected separately to memory. This same concept is used in the multibeam monopulse antenna array presented in Figure 6. Multiple angular spaced directional antennas are coupled with microwave receivers and separately connected to a processor by a digital interface.

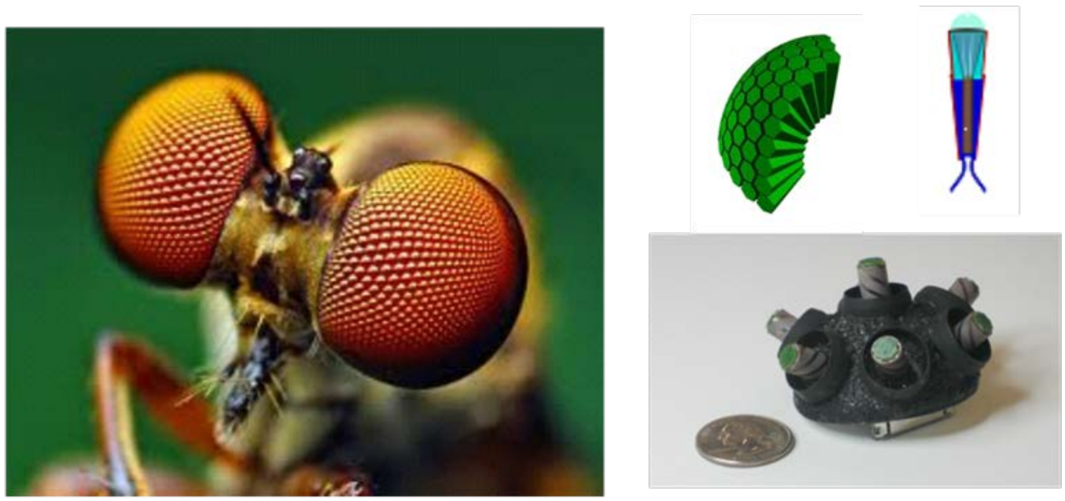
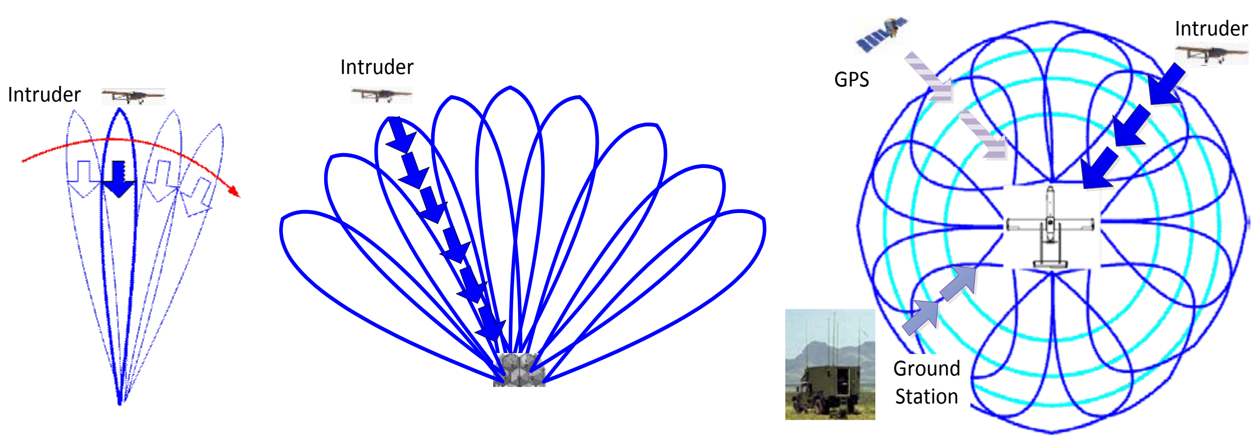


Figure 6. Fly Eye antenna array with angular shifted array of directional antennas.

Any traditional scanning radar receives one reflected signal per scan (per 30-40 sec for mechanical scanner, per 1 sec for phase array). Monopulse radar can transmit and receive more than 100,000 pulses reflected from the target per second. The Fly Eye radar simultaneously transmits and receives by multiple angle shifted directional antennas with overlaping antenna patterns approximately 20,000 pulses per second and cover the entire sky: 360° horizontal and vertical as shown in Figure 7. Fly Eye radar can be multifrequency and multifunctional because of the phase shift in the array of directional antennas provided by antennas angular shift and frequency independent.



(a) (b) (c)

Figure 7. Scanning radar (a), monopulse radar (b) and Fly Eye radar (c).

Fly Eye radar concept:

- An array of angular shifted directional antennas with overlapping antenna patterns covering entire sky;

- Each directional antenna is coupled with a separate front end module consists transmitting/receiving Tx/Rx circuit and Analog to Digital Converter (ADC);
- An array of directional antennas may be loosely distributed over the perimeter of the carrier platform or between separate robotic carriers in swarm;
- Radar front end modules are connected with radar signal processor over digital interface for 3D intelligent processing;
- An array of directional antennas is not phase dependent and can be multi-band or multi-function.

Proposed by PMI multibeam monopulse technique with separate digitizing in each front end module radar signals provides:

- Fast **open architecture radar** with **simple algorithm** of digital processing;
- Proposed radar technique **adaptable to several radar frequency bands**;
- Fly Eye radar will provide not only 3D azimuth and range information, but information about **speed and direction** of targets will be available by application **Kalman Filters**. When state vector information comes in, track updates are generated, filter values are updated, the current track is generated and extrapolated to future predicted tracks;
- Fly Eye radar technique allows **minimized tracking errors** in both position and velocity for non-cooperative aircraft for assessing potential collision threats and determining optimum avoidance maneuvers;
- Modular design allows combination of radar sensor with **ADS-B**, electro-optic, acoustic, other kind of sensors.

The maximum range equation for monostatic radar (one in which the transmitter and receiver are co-located) is given by the following equation [3]:

$$R = [\frac{P_t\, G_t G_r \sigma \lambda^2 F_t^2 F_r^2}{(4\pi)^3 P_r}]^{\frac{1}{4}} \tag{1}$$

Where:

R - radar-to-target distance (range); σ = radar target cross section; λ= wavelength;

Pr - received-signal power being equal to the receiver minimum detectable signal *Smin;*

Pt - transmitted-signal power (at antenna terminals);

Gt - transmitting antenna power gain;

Gr - receiving antenna power gain;

Ft - pattern propagation factor for transmitting-antenna-to-target path;

Fr - pattern propagation factor for target-to-receiving-antenna path.

Regular radar with a scanning antenna can transmit a maximum of 1 target hit pulse every 30-40 seconds. One pulse hits the target per scan. If the distance to the target is **4 miles**, 4 x 5280 ft., time for reflected pulse return is approx. 40 microseconds. Thereby pulse with 1 microsecond width may be transmitted and reflected from the target every 40 microseconds. This means that monopulse radar can transmit to and receive from any target direction **20,000 pulses per second**. Integration of the received 20,000 pulses will radically increase information about target.

The Maximum range equation for monopulse radar must include the number of integrated pulses:

$$R = \left[\frac{(P_t\, I_e M) G_t G_r \sigma \lambda^2 F_t^2 F_r^2}{(4\pi)^3 P_r}\right]^{\frac{1}{4}} \qquad (2)$$

Where:

Ie - integrator efficiency;

M - number of transmitted/received pulses per period of integration

As follows from equation (2), for ***Ie***=1, ***M***=20,000 and *Pt* smaller by 100 times, the maximum **radar range will be increased 500 times**.

Conclusion: Fly Eye radar can transmit smaller power in the target direction, but continuous target observation and integration of the reflected signals provides a 500 fold increase of radar range.

Simultaneous correlation and integration of thousands of signals per second from each point of surveillance area allows not only the detection of low level signals (low profile targets), but helps to recognize and classify signals (targets) by using diversity signals, polarization modulation and intelligent processing.

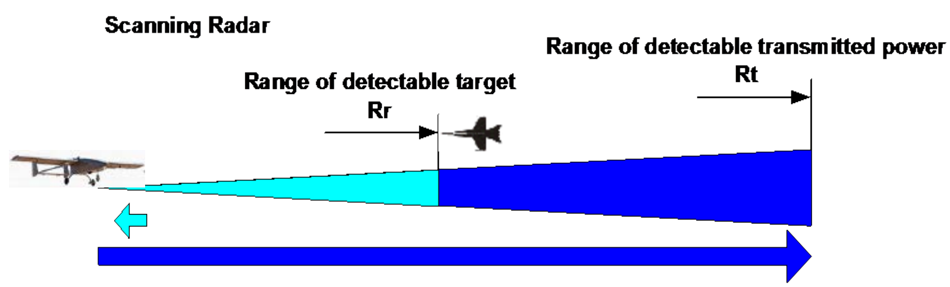
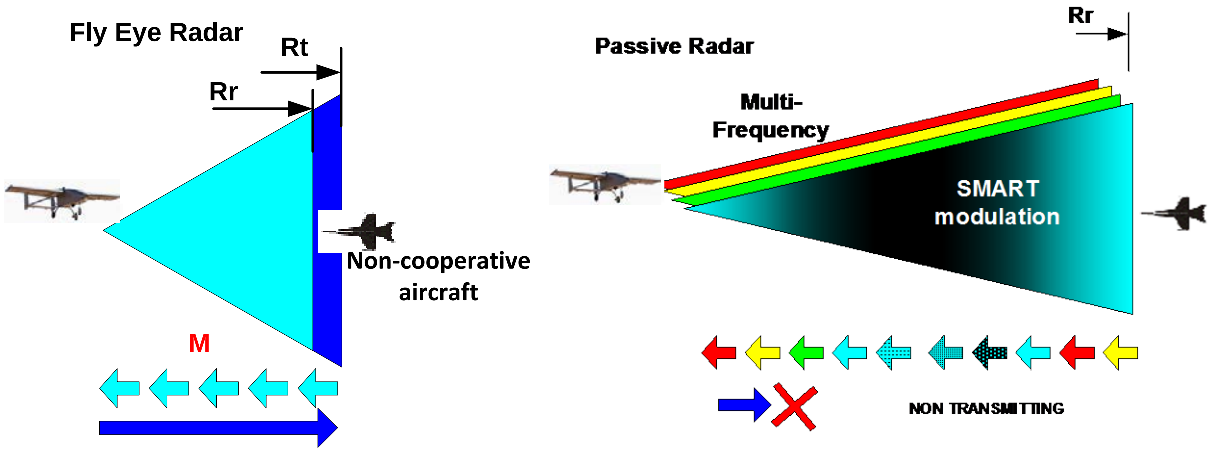


Figure 8. In regular scanning radar the range of detectable transmitted power Rt is larger for larger transmitting power and smaller beamwidth.

For regular scanning radar range of detectable target *Rr* and minimum receivable power -100 dBm will depend from transmitted power, reflected from target and target cross-section (Figure 8). In Fly Eye radar range of detectable target *Rr* will approach to range of detectable transmitted power *Rt* as presented in Figure 9 as result of large number of reflected signals and signals integration.



(a) (b)

Figure 9. Range of detectable target Rr for Fly Eye radar (a), **Passive** regime of Fly Eye radar (b).

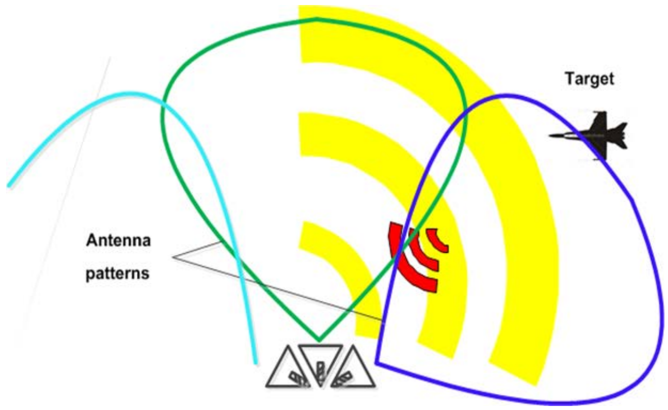
Regular active (transmitting) radars can be easily detected and are not always acceptable for military application. There are lot of ambient RF/microwave sources in battle-space: different kinds of communication, radar, navigation and datalink transmitters, and at the same time a lot of moving with different size and speed objects in battle-space.

Passive regime of Fly Eye radar is proposed for the next generation of sense and avoid systems. Integration, correlation, smart modulation (compression of signals, modulation of signals polarization, step-frequency, multi-frequency processing) allows to increase passive radar range up to a few miles. Measuring and filtering the Doppler frequency shift will allow for creating a **passive sense and avoid radar** with high probability of non-cooperative aircraft detection because of their limited velocity range.

3. RADAR SYSTEM ACCURACY

Monopulse direction finder was designed by Stephen E. Lipsky in the 80s [4]. Direction measuring as ratio of signals in two angle shifted directional antennas with overlapping lobes is presented in Figure 10. Whereas classical conical scan systems generate pointing accuracy on the order of **0.1°**, monopulse radars generally improve this by a factor of 10, and advanced tracking radars like the AN/FPS-16 are accurate to **0.006°** [5].

An array of directional antennas was designed and tested by Principal Investigator in USAF SBIR FA8650-13-M-2373 project. Accuracy for four (two vertical, two horizontal) directional antennas was **smaller than 1°** in both vertical and horizontal dimensions for 3D tracking.



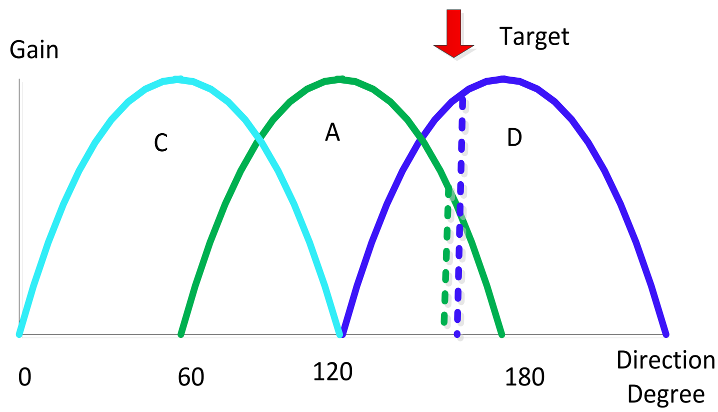


Figure 10. If the lobes of two antennas are overlapped, this signal can produce a high degree of pointing accuracy within the beam, adding to the natural accuracy of the conical scanning system.

4. ABSAA ALGOROTHM AND SOFTWARE

Digital processing of data, received from separate directional antennas will increase dynamic range, tracking accuracy and number of aircraft that can be simultaneously tracked in multiple frequency bands. PMI proposes to use a digital processor and field-programmable gate array (FPGA) technology which will provide most progressive tracking modes, algorithms, required bandwidth and number of tracking non-cooperative aircraft and obstacles.

PMI has extensive experience in design and manufacturing of miniature integrated satellite navigation and tracking systems. The Principal Investigator took part with R Cubed Inc. and APPAREO Systems Inc. in design the multifunctional All Weather Sense and Avoid System (AWSAS) for UAS and small aircraft, which contained UAT, FPGA processor, satellite navigation and multi-band transmitting and receiving antennas and receiver [6-14]. This **open architecture** algorithm can be applied with proposed ABSAA system without significant hardware modifications (Figure 11).

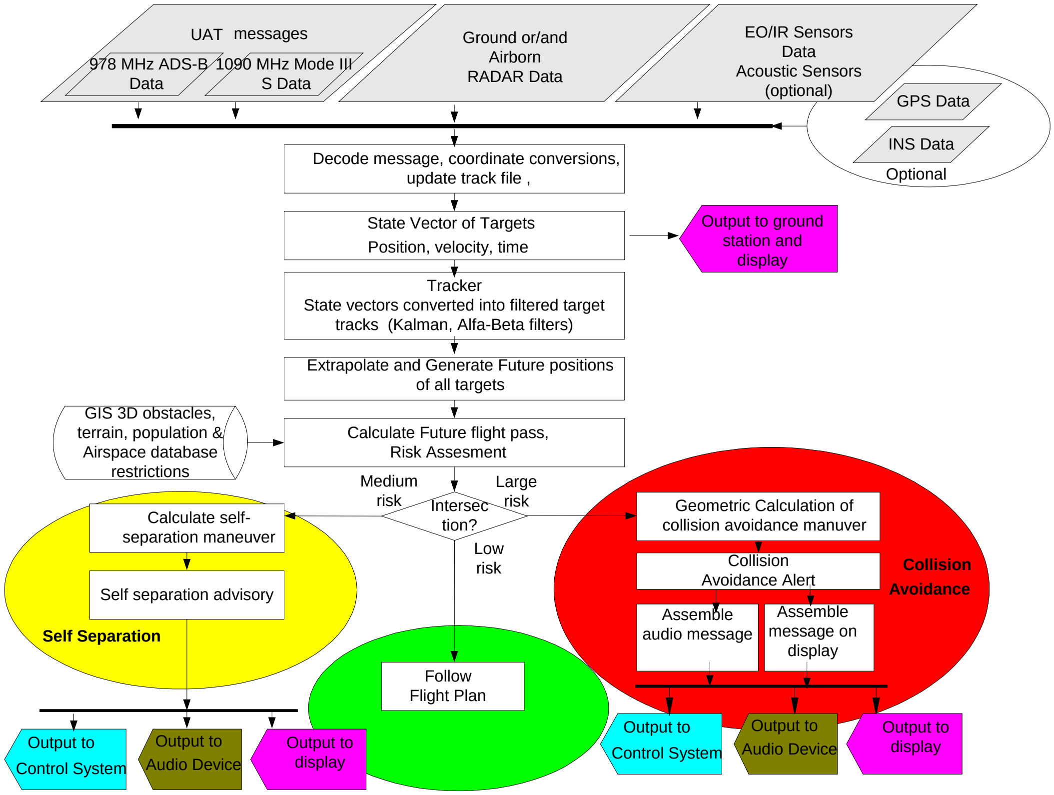


Figure 11. Open architecture ABSAA algorithm consists of three main parts including self-separation and collision avoidance.

Algorithm and software was tested with Software Defined Radio (SDR) SDRSharp and USB Stick, SDR RTL2832 W/R820T receiver for receiving ADS-B messages on 978 MHz and 1090 MHz (Figure 12).

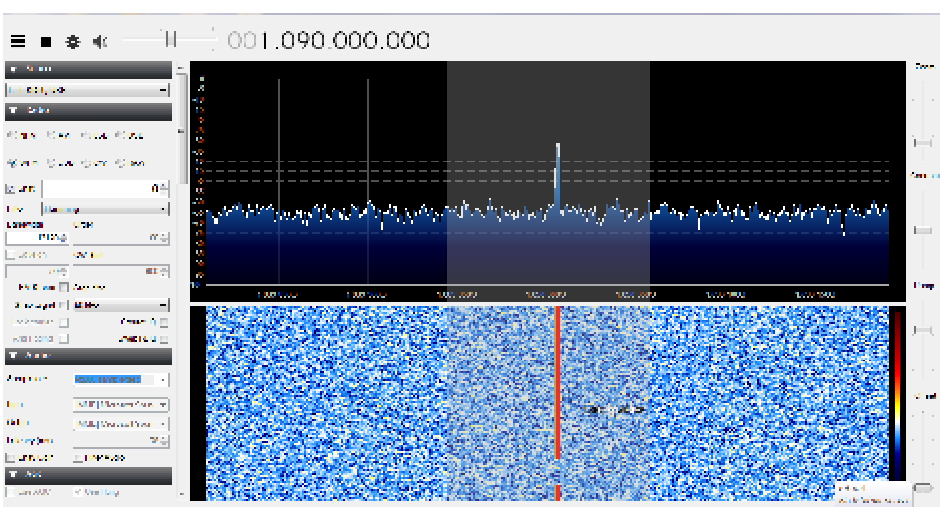


Figure 12. Result of SDR software test with SDRSharp program.

PMI recommends for ABSAA SDR with open source programming provided by Analog Devices Inc. The Analog Devices AD9361 module is a two channel high performance; highly integrated radio frequency (RF) Agile Transceiver™ integrated with 12-bit DACs and ADCs. Its programmability and wideband capability make it ideal for a broad range of transceiver applications. The device combines a RF front end with a flexible mixed-signal baseband section and integrated frequency synthesizers, simplifying design-in by providing a configurable digital interface to a processor. The AD9361 operates in the 70 MHz to 6.0 GHz range, covering most licensed and unlicensed bands. Channel bandwidths from less than 200 kHz to 56 MHz are supported.

5. RADAR TEST

Open architecture, modular design and open source programming provide the possibility to add a radar sensor to AWSAS or XP transponders without hardware change (Figure 13). Test result for radar receiver presented in Figure 14.

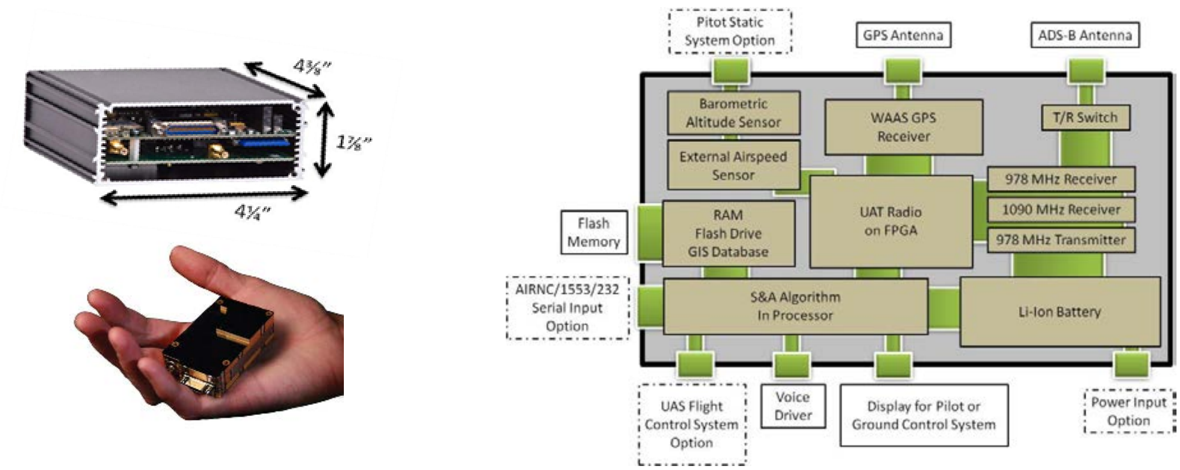


Figure 13. AWSAS (R Cubed Inc.) sense and avoid system consists 978 MHz 1090 MHz receivers and 978 MHz transmitter, Sagatech Inc. XP transponder for 1030 MHz, 1090 MHz.

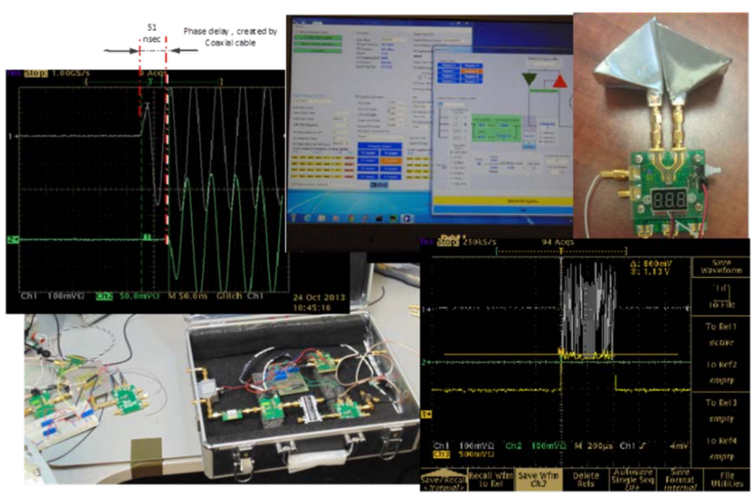


Figure 14. Test of radar receiver designed by Dr. Pavlo Molchanov as PI in Air force FA8650-13-M-2373 project. Measurement of time delay between ADS-B messages. The frequency of radar signals (multi-frequency or special shape signals optional) can be synthesized with a Phase Locked Loop (PLL) or optionally ADS-B messages can be used as radar signals.

6. TEST OF UAS BASED ABSAA

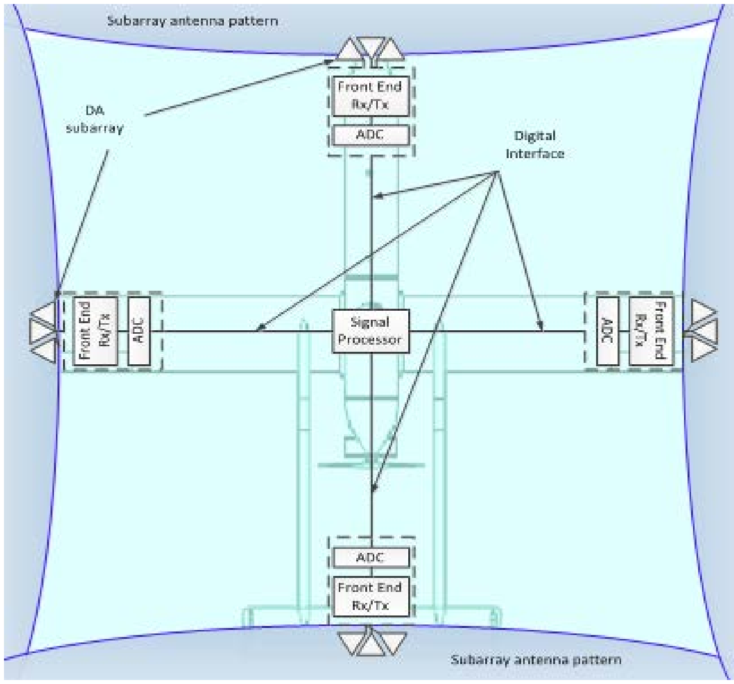


Figure 15. Sub-arrays of directional antennas coupled with Tx/Rx modules can be loosely distributed over UAS perimeter and connected with radar signal processor by digital interface.

Application of fiber optic cables for connection of Tx/Rx modules as shown in Figure 15, allows for no interference inside aircraft and creates a green zone.

In Figure 16 presented installation of ADS-B sense and avoid system inside TS-60 UAS for test of avoidance maneuver between two UAS. AWSAS unit with RF cable (coiled three times) connected to antenna inside nose cone of UAS. Cable leading to GPS antenna mounted on top of TS-60. Wiring harness PN: 31912643 Rev X1 W643 connecting the Piccolo autopilot to the AWSAS. PC connection harness used when downloading data.

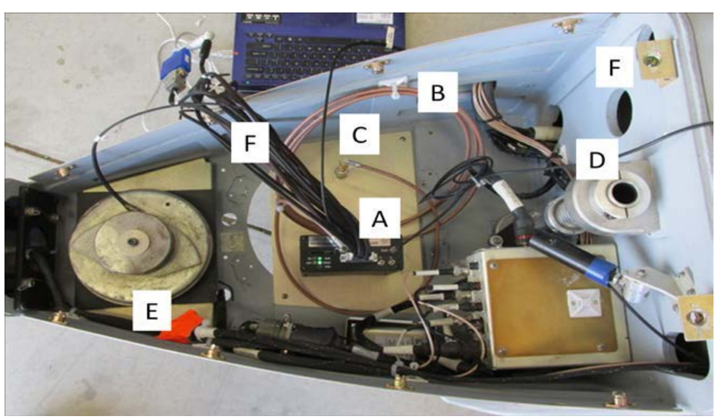


Figure 16. Installation of the AWSAS (A) in the TS-60 UAS.

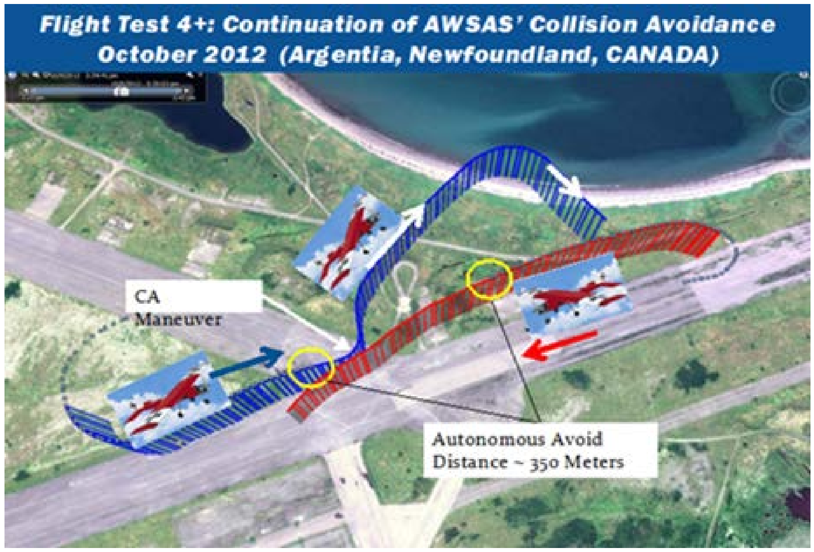


Figure 17. Collision avoidance test results with group 2 UAS. Newfoundland, Canada.

In Figure 17 TS-63 (blue track) heading 180; TS-60 (red) heading 150, merging tracks intersecting at "C". A 360° LEFT circling maneuver was initiated at "A" when the aircraft were 8,907 feet apart, approximately 97 seconds before "C". CPA was 8,487 feet at 13 seconds after the autonomous maneuver started. TS-63 crossed "C" 2 min 44 sec after TS-60 [6].

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