Fly Eye Radar Concept

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Abstract: *Presented Fly Eye Radar is nature inspired new radar concept, based on application of monopulse direction finding method to multi-beam, wide area of observation RF radar system for wide area simultaneous non scanning detection, tracking and recognition of multiple targets.*

1. Introduction

To compensate for its eye's inability to point at a target, the fly's eye consists of multiple angularly shifted sensors which gives the fly the wide-area visual coverage it needs to detect and avoid the threats around it (Figure1). Each sensor is coupled with a detector and connected separately to memory. Application of fly eye antenna array with space shifted multiple directional antennas provides simultaneous high-accuracy amplitude and phase measurement for multiple targets with minimal distance between antennas [1-3]. Fly Eye antenna array is the next step in development of passive monopulse direction finder proposed by Stephen E. Lipsky in 70th [4].

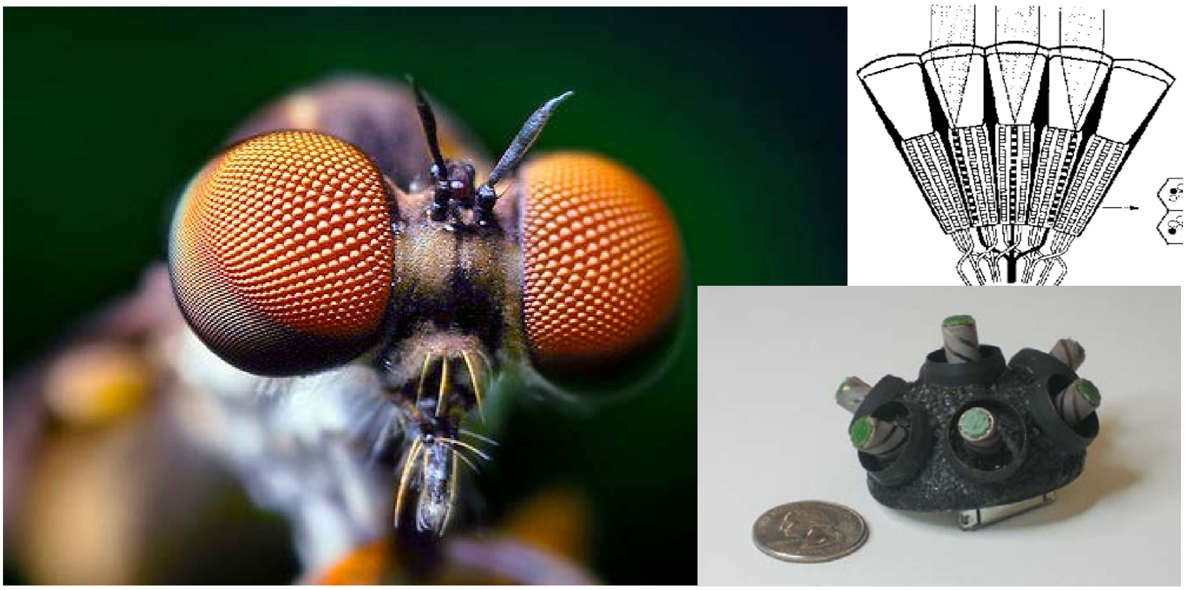

Figure 1. The fly's eye consists multiple directional optical sensors coupled with detectors. Each sensor connected to memory by separate nerve. Fly Eye antenna array concept: multiple directional antennas coupled with front end circuits and analog-digital converters in each antenna modules. Digital interface connecting all antenna modules to processor.

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2. Radar Range Estimation

Regular radar with a scanning antenna can transmit and receive a maximum of 1 target hit pulse every 30-40 seconds. One pulse hits the target per scan as presented in Figure 2(a). If the distance to the target is 1 miles, 1 x 5280 ft., time for reflected pulse return is approx. <1 microsecond. Thereby pulse with 1 microseconds width may be transmitted and reflected from the target every 10 microseconds for monopulse radar. This means that monopulse radar can transmit to and receive from any target direction 100,000 pulses per second and dramatically increase radar sensitivity (Figure 2b). Integration of the received 100,000 pulses will radically increase information about target. Fly eye radar presented in Figure 2 (c).

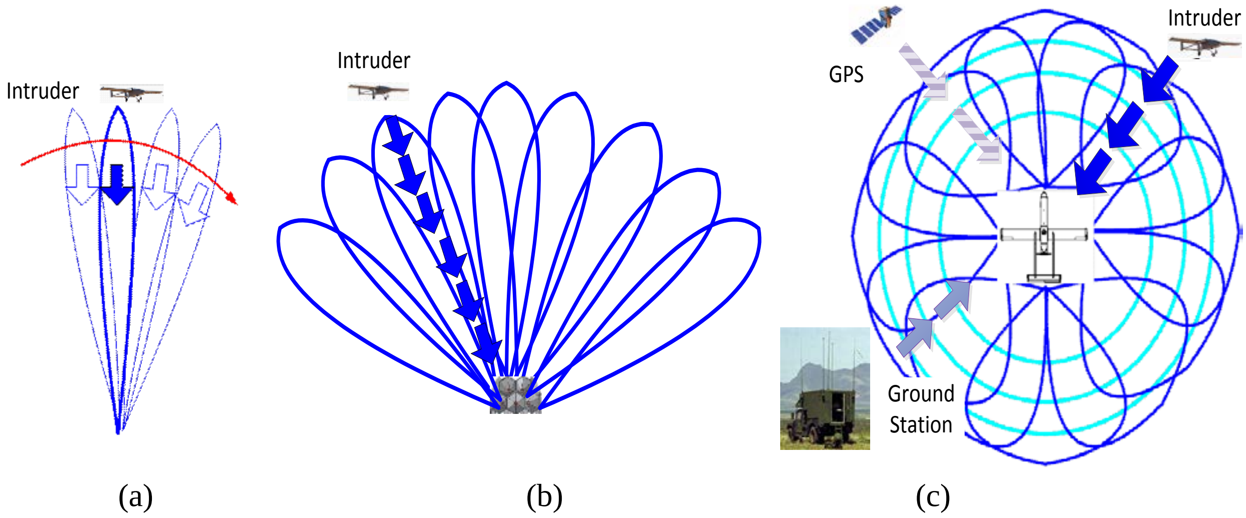

Figure 2. Scanning radar (a), monopulse radar (b) and Fly Eye radar (c).

The maximum range equation for monostatic radar (one in which the transmitter and receiver are co-located) is given by the following equation [5]:

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

Where:

R - radar-to-target distance (range); σ - radar target cross section; λ - wavelength; P_r - received-signal power being equal to the receiver minimum detectable signal S_{min}; P_t - transmitted-signal power (at antenna terminals); G_t - transmitting antenna power gain; G_r - receiving antenna power gain; F_t - pattern propagation factor for transmitting-antenna-to-target path; F_r - pattern propagation factor for target-to-receiving-antenna path.

The maximum range equation for monopulse radar must include the number of integrated pulses and integration efficiency:

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

Where:
I_e - integrator efficiency;
M - number of transmitted/received pulses per period of integration

As follows from equation (2), for I_e=1, M=100,000 and P_t smaller by 100 times, the maximum radar range will be increased approx. 20 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 2 times increase of radar range. Simultaneous correlation and integration of thousands of signals per second from each point of surveillance area allows not only detecting of low level signals (low profile targets), but help to recognize and classify signals (targets) by using diversity signals, polarization modulation and intelligent processing.

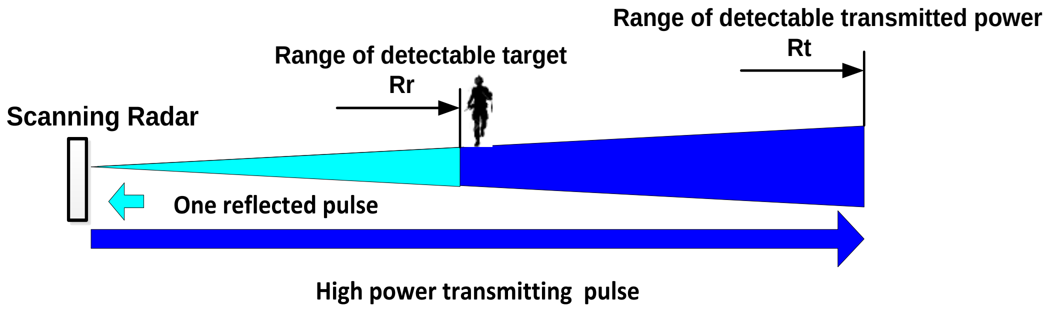

Figure 3. In regular scanning radar the range of detectable transmitted power Rt is larger for larger transmitting power and smaller beamwidth.

For regular scanning radar range of detectable target R_r and minimum receivable power -100 dBm will depend from transmitted power, reflected from target and target cross-section (Figure 3). In Fly Eye radar range of detectable target R_r will approach to range of detectable transmitted power R_t as presented in Figure 4 as result of large number (M) of reflected signals and signals integration (Figure 4).

Regular active (transmitting) radars can be easily detected and not always acceptable for military application. There are lot of ambient RF/microwave sources in battlespace: 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 battlespace. Passive regime of Fly Eye radar proposed for next generation of radar 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 few miles.

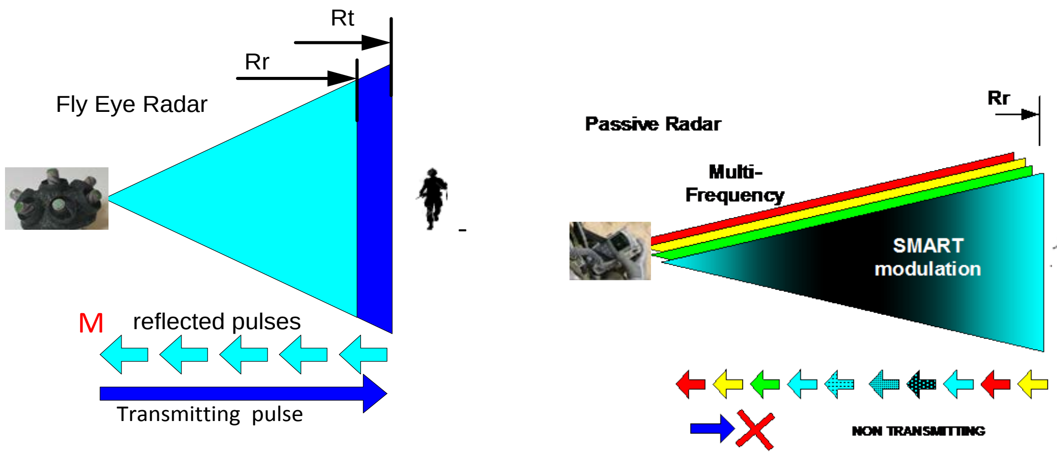

Figure 4. Range of detectable target Rr for Fly Eye radar. Passive regime of Fly Eye radar. Multi-frequency receiver with integration and smart modulation in each channel. Spectrum signatures provides possibility of automatic detection and recognition of different objects: human, small drones, weapon, explosives and different chemicals.

3. Fly Eye Radar System Accuracy

Monopulse direction finder designed by Stephen E. Lipsky in 70's [4]. In monopulse direction finder direction to target measured as ratio of signals in two angle shifted directional antennas with overlap lobes. The difference in the phase angle as measured in each antenna of and arriving phase front of a signal is ψ. Difference in path length of $S = D \sin \varphi$ due to the antenna aperture displacement (angle shift in space) *D*. Letting φ be the phase lag due to the difference in the time of arrival of the two signals gives [6]:

$$\psi = -2\pi \frac{S}{\lambda} = -2\pi \frac{D \sin \varphi}{\lambda} \quad (1)$$

Where:
φ = the angle of arrival measured from bore sight;
λ = the wavelength;
If *A* and *B* are the RF voltages at each antenna, then

$$A = M \sin(\omega t) \quad (2)$$

and

$$B = M \sin(\omega t + \psi) = M \sin(\omega t - \frac{2\pi D}{\lambda} \sin \varphi), \quad (3)$$

where *M* is a common constant. This shows that the angle of arrival φ is contained in the RF argument or phase difference of the two beams for all signals off the boresight axis.
Amplitude comparison direction finding can provide Root Mean Square (RMS) accuracy smaller than 2 degrees in 100 ns after direct wave arrives.
Array of directional antennas was designed and tested in USAF SBIR project. Accuracy for four (two vertical, two horizontal) directional antennas was smaller than 1 degree in both vertical and horizontal dimensions for 3D tracking.

Fly Eye antenna array architecture provides:

- Array of angular shifted directional antennas with overlap antenna patterns covering wide area of observation or entire sky and provides muli-beam non-scanning simultaneous detection and tracking multiple targets;
- Monopulse method applied to multiple overlap directional antennas provides high accuracy direction and range measurement even for long wavelength RF signals. Accuracy of direction measurement 2-3 orders better than in scanning radars because not determined by beam width, but ratio of signals in overlap antennas;
- Digitizing of signals directly in antenna modules provides high accuracy apmplitude and phase measurement in each antenna. Accuracy in Fly Eye radar determined by accuracy of processor time and processor sampling frequency;
- Array of angular shifted directional antennas is not phase/frequency dependent because phase, amplitude measurement related to processor time. Fly Eye antenna array can be ultra-wideband or multi-band. Wide frequency band will provide spectrum analysis of target, including material analysis and targets discrimination by spectrum signatures;
- Integration of ultra-wideband antennas with front end circuits allows to exclude waveguides, which limiting frequency bandwidth and creating additional phase/frequency dependence;
- Directional antennas may be installed closely or loosely distributed over the perimeter of the carrier platform or between separate robotic carriers in swarm because amplitude/phase measurement related to processor time.

4. Sense and Avoid Radar for UAS

Multibeam monopulse radar for Airborne Based Sense and Avoid (ABSAA) system concept [8-14] (Figure 5):

- Multibeam monopulse radar with array of directional antennas is positioned on Unmanned Aircraft System (UAS). Radar signals simultaneously transmitted and received by multiple angle shifted directional antennas with overlap antenna patterns the entire sky, 360 degrees for both horizontal and vertical coverage.
- 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 frequency of 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.
- Open architecture, modular construction allows combination of radar sensor with Automatic Dependent Surveillance – Broadcast (ADS-B), electro-optic, acoustic sensors.

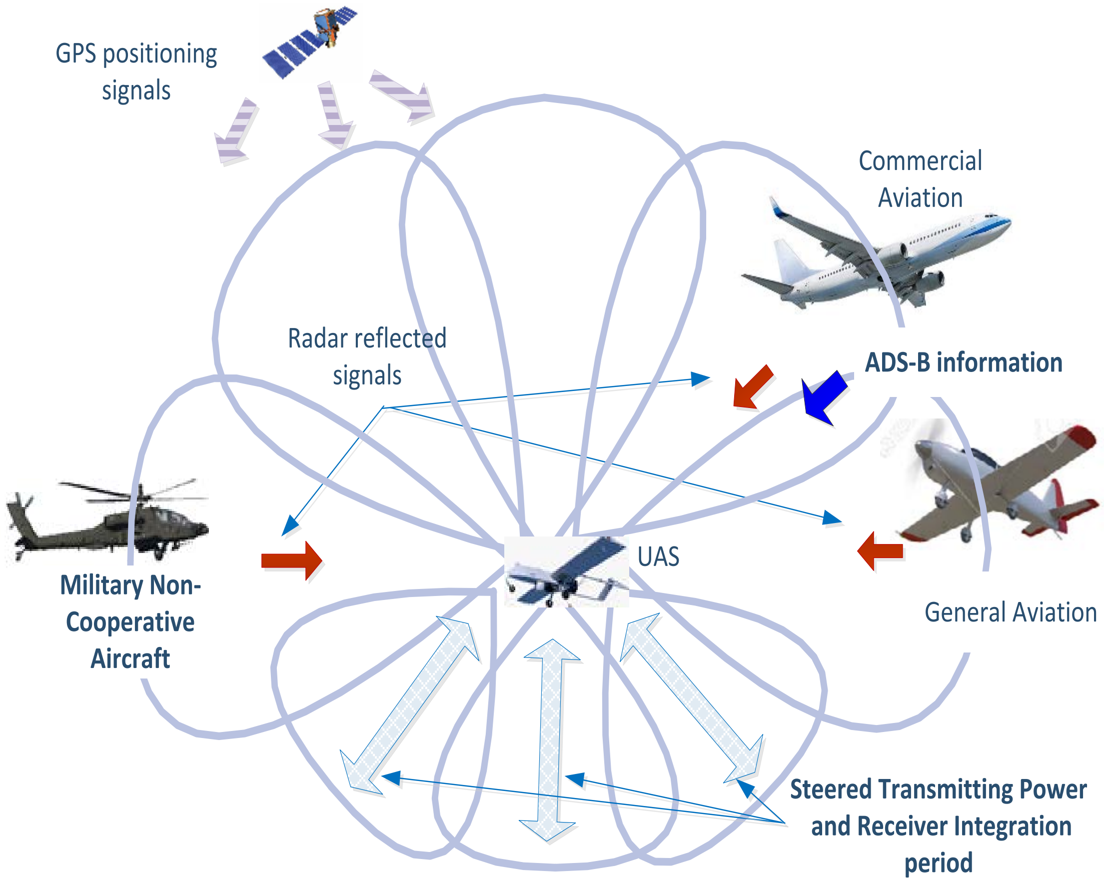

Figure 5. Ground clutter can be automatically suppresed in multibeam monopulse sense and avoid system by steering of transmitting power and receiver integration period in separate beams. System can be multi-function and combined with ADS-B system.

5. Distributed Radar for Drone Detection

The concept of distributed (multi-static) radar (Figure 6) is based on the application of multiple illuminating (transmitting) devices distributed along the perimeter of protected zone or surveillance area [8-14]. Ultra-wide multibeam monopulse radar receiver with an array of the angle shifted directional antennas positioned at a safe distance. Radar signals simultaneously received by two or a few directional antennas are used for high-accuracy high-resolution azimuth and range measurement. Digitizing of signals in separate directional antennas relative to processor reference signals allows for high-accuracy real time amplitude and phase measurement and as a result, high resolution tagets tracking. Fourier transform (frequency domain processing) of received radar signals provides signatures and information not only about shape, but about material of detected targets.

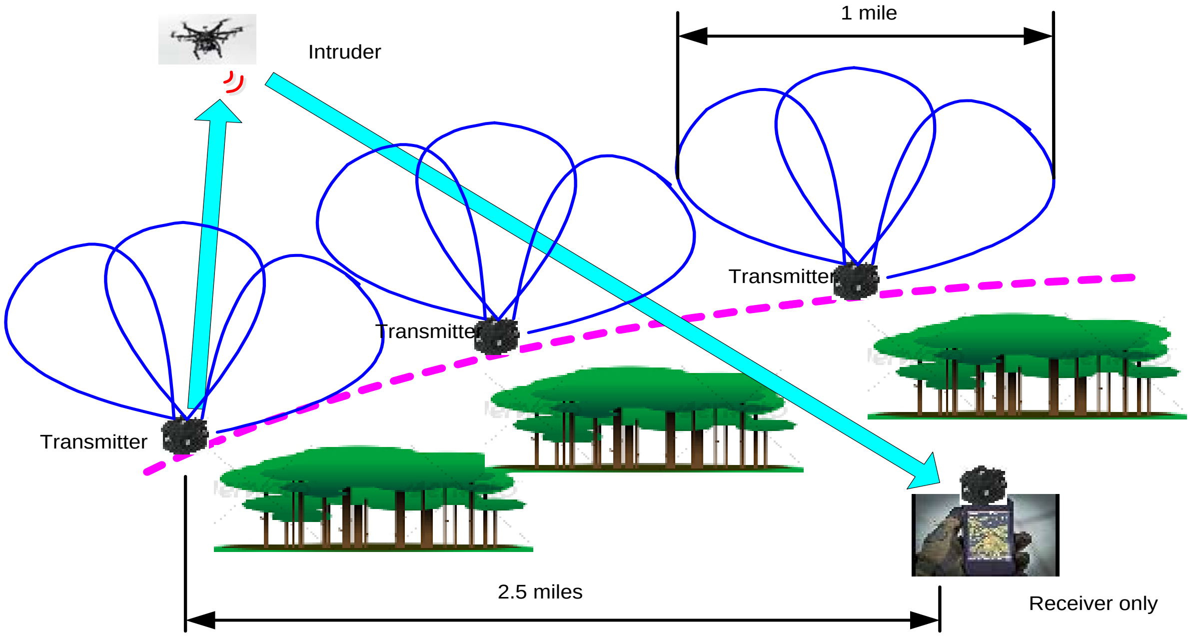

Figure 6. Transmitting modules can be distributed around perimeter of protected zone in bi-static drone detection system.

6. Mine Detection with Tethered Drone

Bi-static ground penetrating radar concept with presented in Figure 7. Low frequency waves with good ground penetration allows decrease transmitter power up to hundred milliwatt for one meter depth of exploration. As result low frequency low transmitting power GPR transmitter can be positioned on small tethered drone and provide maximum targets cross-section. Ultra-wide band multibeam monopulse radar receiver with array of angle shifted directional antennas provides high-accuracy high-resolution measurement by application of reference beam (Figure 10). Digitizing of signals in separate directional antennas relative to processor reference signals allows to record real time digital hologram with amplitude and phase information about underground targets. Resolution of digital hologram and corresponding image resolution will be determined by sampling frequency of digitizer and not depends from radar beamwidth. High speed sampling with high-accuracy processor clock will provide high resolution of images even for low frequency radar waves. Holographic digital phase/time domain processing of received signals allows to restore images of detected objects. Fourier transform (frequency domain processing) of received radar signals provides signatures and information not only about shape, but about material of buried objects.

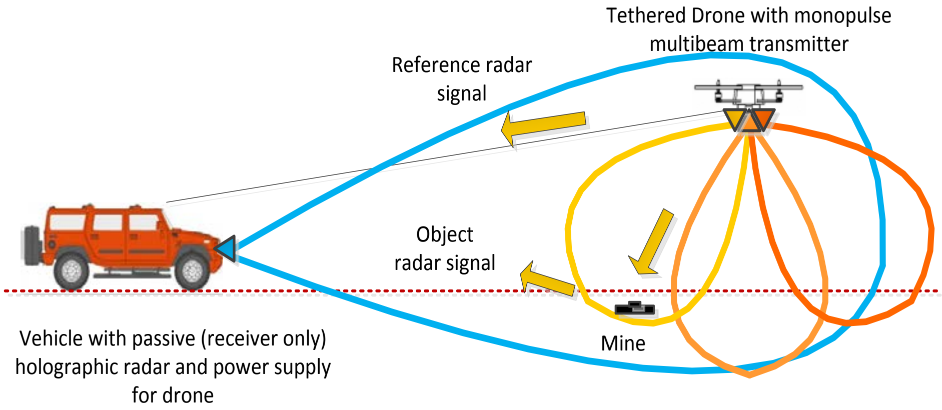

Figure 7. Mine detection from tethered drone provided possibility to detect mines 8-12 hours. Radar position optimal for mine detection.

To extend high frequency limit and provide high sensitivity over the broadband of frequencies, Stephen E. Lipsky proposed to integrate detector and mixing elements with antenna [4]. Multiple angularly spaced directional antennas in proposed micro-radar are coupled with front end circuits and separately connected to a direction finder processor by a digital interface. If the lobes are overlap or closely spaced, micro-radar can produce a high degree of pointing accuracy within the beam, adding to the natural accuracy of the conical scanning system. Whereas classical conical scan systems generate pointing accuracy on the order of 0.1 degree, monopulse radars generally improve this by a factor of 10, and advanced tracking radars like the AN/FPS-16 are accurate to 0.006 degrees [7].

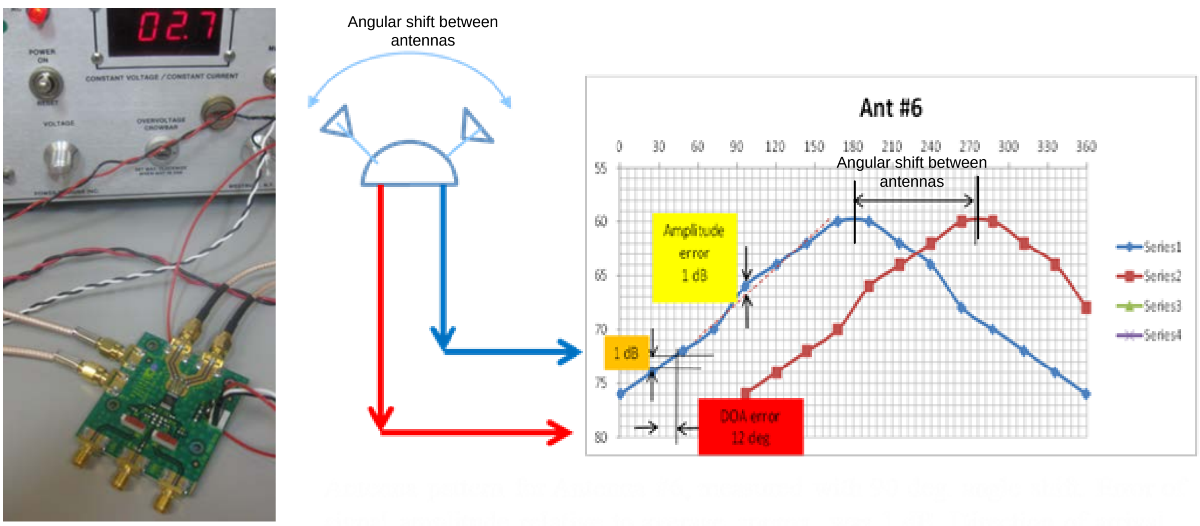

Figure 8. Test and accuracy estimation for direction finder with two directional antennas.

Digitizing of received signals proximate to antennas allows dramatically decrease phase errors connected with waveguides. Accuracy of direction finding in proposed micro-radar in this case will be determined by time accuracy of digital processor and sampling frequency.
. Phase detector for measurement range and azimuth presented in Figure 8. Azimuth of signal source was measured on laboratory bench. High accuracy direction measurement made in noisy laboratory environment, no shielding or screening was applied.
Array of dual polarization directional antennas are small enough and can fit small 2’ x 2" aperture opening and installation to aircraft. In Figure 9 presented antenna arrays with helical antennas with circular polarization manufactured by Sarantel Inc. UK, Pulse Electronics Inc. Finland, Cobham Inc.

Figure 9. Fly Eye antenna array designed by PMI Inc. and antenna arrays designed by Cobham Inc.

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