Phase-conjugating retrodirective cross-eye jamming

W.P. du Plessis✉

A cross-eye jammer based on a phase-conjugating (PC) retrodirective array is proposed. Such PC cross-eye jammers eliminate the delay inherent in traditional Van-Atta (VA) cross-eye jammers and induce errors in radars that use the same antenna beam for transmission and reception, while VA cross-eye jammers do not. Validated simulations are provided to confirm the effectiveness and retrodirective properties of the PC cross-eye jammer.

Introduction: Glint is a naturally-occurring phenomenon that affects all radar systems and can cause large angular errors [1–5]. Cross-eye jamming is an electronic attack (EA) technique that seeks to artificially recreate the conditions under which glint causes large angular errors [6–13]. The primary benefits of cross-eye jamming are that it is one of only a small number of countermeasures capable of generating an angular error and its origin in glint means that it should affect all radar systems.

The two main challenges to implementing cross-eye jamming are the high jammer-to-signal ratio (JSR) required as a result of the signal cancellation that arises from the conditions corresponding to a large angular error, and the extremely fine tolerances required [8–15]. The tolerance requirements arise because a radar needs to in a narrow angular region to experience a significant angular error. This narrow angular region means that a retrodirective implementation is required to direct the region of large angular error towards an incoming radar signal.

Retrodirective cross-eye jamming is traditionally based on a two-antenna Van-Atta (VA) retrodirective array [16]. However, this implementation has a number of additional drawbacks with the jammer return appearing some distance behind the jammer antennas, and radars that use the same antenna beam for transmission and reception experiencing no angular error [7, 11, 17].

Basing a cross-eye jammer on a phase-conjugating (PC) retrodirective array [18, 19] offers the possibility of overcoming both of these drawbacks [20]. This approach is considered below and compared to the traditional VA retrodirective cross-eye jammer to demonstrate its potential.

Retrodirective arrays: A retrodirective array automatically transmits a signal in the direction of an incoming signal, thereby removing the need to explicitly steer the transmitted signal. This retrodirective property is achieved by ensuring that the signals transmitted by an array of antennas add in phase in the direction of the incoming signal. The two approaches to achieving this phase coherence in the direction of an incoming signal are described below.

An example of a VA retrodirective array is shown in Figs. 1*a* and *b* [16]. The antennas in a VA array are connected in pairs so that the signal received by one antenna is retransmitted by the other antenna in the pair. Additionally, all antenna pairs share the same midpoint as shown in Fig. 1*a*, and the feed networks of all antenna pairs have equal phase shifts shown in Fig. 1*b*.

The significance of the common centre point for all pairs of antennas in a VA array is shown in Fig. 2*a*. When rotated around a point halfway between the antennas ($l_1 = l_2$), the distance that one antenna moves closer to an incoming plane wave is equal to the distance the other antenna in the pair moves further from the incoming plane wave ($l_3 = l_4$). The result is that the total distance the plane wave propagates to and from each pair of antennas is a constant over all rotations because the signal received by one antenna is transmitted by the other.

The return from a VA array appears to originate from the position at the common centre of the antenna pairs, but at a range behind that the position corresponding to half the delay between the antenna pairs. The return is thus behind the physical location of the VA array and may even be in a separate radar range gate to the platform mounting the VA array. This range separation makes it relatively simple to separate the repeater return from the return of the platform it is mounted on – a problem compounded by the fact that electromagnetic (EM) waves propagate slower in cables and waveguides than in air [21].

PC arrays use a common phase reference to compensate the phases at the antennas as shown in Figs. 1*c* and *d*. The transmitted signal phase is the negative of the received phase relative to the reference phase (the conjugate of the signal in phasor representation), thereby compensating for the phase shifts due to the position differences relative to a phase front [18, 19].

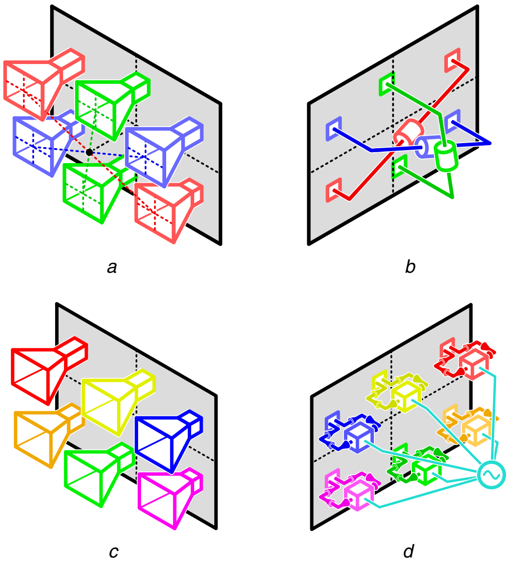

Fig. 1 *Retrodirective array structures*

a VA array front view: note the common centre of all antenna pairs
b VA array back view: note the equal-length feed networks
c Phase-conjugating array front view: note the arbitrary antenna layout
d Phase-conjugating array back view: note the common phase reference

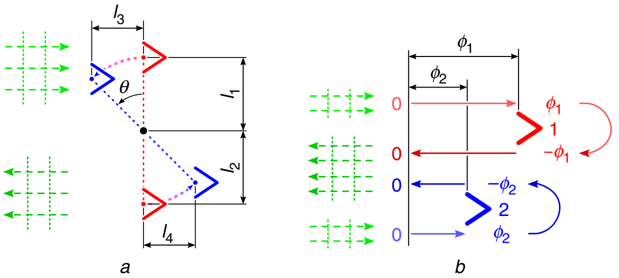

Fig. 2 *Principles underlying retrodirective arrays*

a Rotating a pair of antennas around its centre does not change the total distance a retransmitted wave propagates in a VA array
b Transmitted signals add in phase at the reference plane in a PC array

The operating principle of a PC array is shown in Fig. 2*b*. The phase shifts from a reference point on the incoming plane wave to two antennas are ϕ_1 and ϕ_2 at antennas 1 and 2, respectively. Transmitting signals with the negatives of these phases ($-\phi_1$ and $-\phi_2$) will cause the transmitted signals to be phase at the plane-wave reference point because the phase shift to that plane is compensated by the phases of the transmitted signals ($-\phi_1 + \phi_1 = 0 = -\phi_2 + \phi_2$). The use of a common phase reference for all antennas in a PC array effectively achieves the situation depicted in Fig. 2*b* by substituting a common phase reference for a common reference plane.

Retrodirective cross-eye jamming: Analyses of glint have shown that a large angular error is induced in radar systems that receive two signals which have equal amplitudes and a phase difference of 180° [1–5]. These conditions correspond to signal cancellation and are the reason cross-eye jamming requires high (JSR).

Retrodirective cross-eye jamming is traditionally based on the two-antenna VA retrodirective implementation shown in Fig. 3 (e.g. [6–13]), with two patents describing such systems being filed in 1958 [22, 23]. The only change to a VA array necessary to create a retrodirective cross-eye jammer is to shift the signals in one direction through the jammer by 180° (i.e. $a \to 1$ and $\phi \to 180°$ in Fig. 3).

The major advantage of VA cross-eye jammers is that all shared aspects of the propagation path, including all the components, apart from the portions in the box in Fig. 3, are identical, so their effects cancel. This cancellation simplifies the practical implementation of such systems by avoiding the need to match shared components.

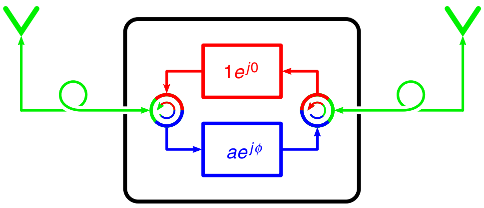

Fig. 3 *VA retrodirective cross-eye jamming implementation*

The main drawback of the use of the VA retrodirective implementation for cross-eye jamming is the delay caused by signals having to travel from one antenna to the other before retransmission as outlined above. Cross-eye jammers create larger angular errors as the spacing between the jammer antennas increases, with typical antenna spacings varying from 10 to 20 m [12]. This delay will mean that the Van-Atta cross-eye jammer return be 5 to 10 m behind its antennas in even the best case. However, transmission lines and waveguides propagate signals slower than the speed of light in air [21], practical considerations increase the required lengths of transmission lines and waveguides, and any processing required by the jammer will further increase the delay, and thus, the apparent range of the jammer return. This apparent range offset is the motivation for using leading-edge tracking as a countermeasure to cross-eye jamming [10], even though leading-edge tracking does not directly influence the angular error caused by a cross-eye jammer.

A further drawback of a VA retrodirective cross-eye jammer is that no angular error is induced in any radar that uses the same antenna beam for transmission and reception, including the sum channel of a monopulse radar [7, 11, 17]. This is clearly a significant consideration as it limits the threats that can be countered using VA cross-eye jamming and suggests that relatively simple countermeasures are possible.

The use of PC arrays to implement retrodirective cross-eye jamming, as shown in Fig. 4, has not previously been proposed. Extending PC arrays to cross-eye jamming can again be achieved by changing the phase of one of the two signals transmitted by a retrodirective array by 180° (i.e. $a_x \to 1$, $\phi_x \to -2\phi_1$, $a_y \to 1$, and $\phi_y \to -2\phi_1 + 180°$ in Fig. 3).

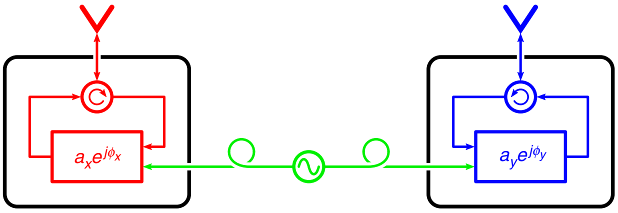

Fig. 4 *Proposed PC retrodirective cross-eye jamming implementation*

The primary benefit of a PC cross-eye jammer is that the delay inherent in a VA cross-eye jammer is eliminated. An additional benefit is that angular errors will also be induced in radars that use the same antenna beam for transmission and reception. This is not true for a VA cross-eye jammer as the signal received by one antenna is transmitted by the other. However, the signal received by each antenna is transmitted by that antenna in a PC cross-eye jammer, and this condition corresponds directly to the conditions that cause glint, which affects all radar systems.

Simulations: Simulations were performed to compare the performance of VA and phase-comparison cross-eye jammers. The parameters used are listed below and are representative of cross-eye jamming against a missile threat to the aircraft or ship (e.g. [7, 11, 24]):

- 10 GHz carrier frequency,
- 1 km engagement range ($r = 1\,000$ m),
- 10 m jammer baseline ($d_c = 10$ m),
- 2.54 wavelength separation of the radar antenna elements ($d_r = 2.54\lambda$) to give a radar sum-channel beamwidth of approximately 10°,
- 30° jammer-rotation angle ($\theta_c = 30°$),
- jammer-amplitude match of 0.5 dB ($a = 0.9441$), and
- jammer phase difference of 175° ($\phi = 175°$).

The geometric parameters are defined in Fig. 5.

The simulations were performed with the `nec2c` version 1.3 implementation of the Numerical Electromagnetics Code (NEC) [25] because the use of a full-wave electromagnetic simulator means that all propagation effects are accounted for. Horizontal dipoles of length 0.4860 wavelengths with 21 segments were used to model both the phase-comparison monopulse antenna elements and the jammer antennas. Horizontal dipoles were used to minimise the coupling in the radar and jammer systems as end-on dipoles have low coupling [26], and their length was chosen to minimise the imaginary component of their input impedance.

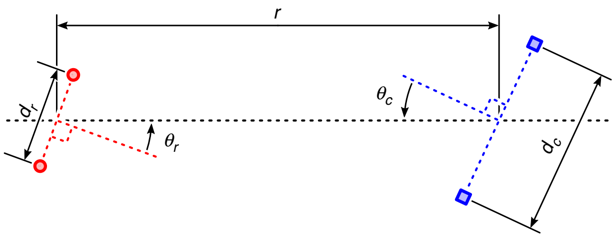

Fig. 5 *Geometry of a cross-eye jamming engagement with the monopulse radar antenna elements on the left denoted by circles and the jammer antennas on the right denoted by blocks*

A first simulation was performed with the two radar dipoles excited with 1-V sources at their centre segments to create a sum-channel transmission. The signals received by the jammer antennas were determined from the resulting voltages at centre segments of the jammer dipoles. These received jammer signals were then used to determine the signals that would be transmitted by the jammer. The voltages at the centre segments of the jammer antennas were then set to these jammer transmission signals, and a second simulation was performed. The resulting voltages at the two radar dipoles were then combined to form the sum- and difference-pattern returns, after which monopulse processing was performed [4]. This two-step approach mimics a pulsed radar and allows the small voltages at the jammer due to transmission from the radar to be determined without needing to separate small received signals from large transmitted jammer signals and vice versa.

The first task was to validate the accuracy this approach to simulating retrodirective targets. The results for both VA and PC retrodirective beacons were considered, and as shown in Fig. 6, the results correspond to a target at a radar rotation of zero ($\theta_r = 0°$) as expected. A simulated VA cross-eye jammer was then compared to theoretical results that have been experimentally validated [7, 11, 17]. The monopulse indicated angles for the theoretical and simulated results are seen to agree extremely well in Fig. 6. The proposed simulation approach is thus shown to be accurate.

The next task is to demonstrate that a PC cross-eye jammer induces large angular errors in the threat radar. The indicated angle due to the PC cross-eye jammer is seen to be large in Fig. 6*a*, with the indicated angles at zero radar rotation being 2.86° and 1.88° in the VA and PC cases respectively, while the jammer antennas are positioned at ±0.25°.

Now that the PC cross-eye jammer has been shown to induce large angular errors, the final task is to show that the jammer is retrodirective by rotating the jammer and confirming that the induced indicated angle remains high. This is done in Fig. 6*b*, where the indicated angle due to the phase-comparison cross-eye jammer is shown to be high over a wide range of jammer rotations.

The major differences between the VA and PC cross-eye jammers in Fig. 6 are the non-monotonic variations with radar rotation and asymmetry with jammer rotation in the PC case. These effects are believed to be due to the differing ranges to each of the jammer antennas leading to different path losses. The previously-noted sensitivity of cross-eye jamming to parameters such as amplitude matching, coupled to the r^{-4} amplitude variation of radar systems with range means that even small range differences can be significant. Additional study is necessary to resolve this question. A similar effect cannot occur in a VA cross-eye jammer as both signals travel along identical paths, just in different directions, so the path losses are equal.

The final point to confirm is that a PC cross-eye jammer will induce an angular error in a radar that uses the same antenna beam for transmission and reception. This is shown in Fig. 7, where the sum-channel returns for all cases except the PC cross-eye jammer have their peaks at a radar rotation of zero. The condition corresponds to accurate tracking of the retrodirective system (the absence of an angular error), as expected [7, 11, 17]. By comparison, the maximum return from the PC cross-eye jammer is not at a radar rotation of zero, but rather at −3.22°, which is the same angle where the indicated angle is zero in Fig. 6*a*. As an aside, it is noted that this agreement with experimentally-validated results provides further validation of the simulation approach used.

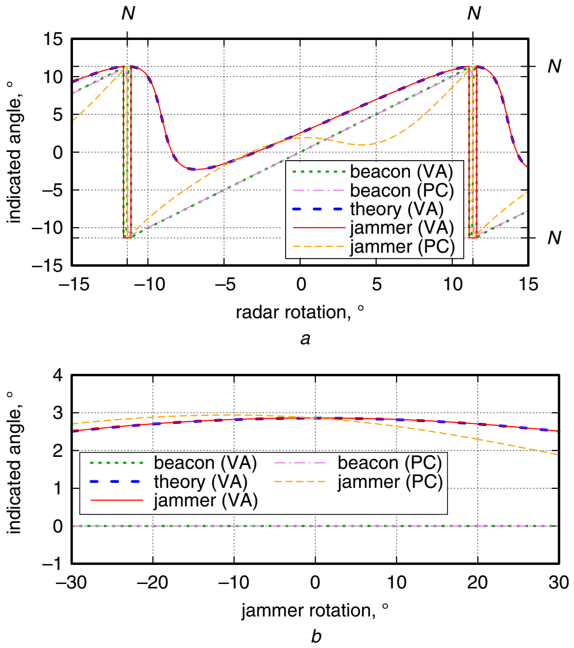

Fig. 6 *Indicated angle induced in a monopulse radar by VA and phase-conjugating (PC) beacons and cross-eye jammers. The letters 'N' on the top and the right axes indicate the positions of the first sum-channel nulls. The two beacon cases are indistinguishable*

a Radar is rotated with the jammer at a 30° angle ($\theta_c = 30°$)
b Jammer is rotated with the radar pointing towards the jammer ($\theta_r = 0°$)

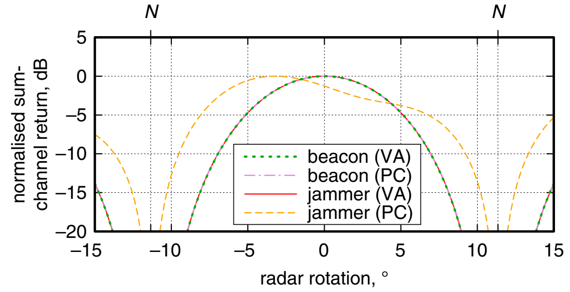

Fig. 7 *Normalised sum-channel returns for VA and PC beacons and cross-eye jammers. The letters 'N' on the top axis indicate the positions of the first sum-channel nulls. All cases apart from the phase-conjugating cross-eye jammer case are indistinguishable and show no angular error*

Conclusion: Retrodirective cross-eye jammers based on PC retrodirective arrays are proposed. Traditional retrodirective cross-eye jammers are based on the VA arrays leading to disadvantages related to the delay inherent in such systems and their inability to induce angular errors in radars that use the same antenna beam for transmission and reception. Both of these drawbacks are shown to be overcome by PC cross-eye jamming, with validated simulations confirming this.

Submitted: *19 June 2020* E-first: *10 August 2020*
doi: 10.1049/el.2020.1818
One or more of the Figures in this Letter are available in colour online.

W.P. du Plessis (*University of Pretoria, Pretoria 0002, South Africa*)

✉ E-mail: wduplessis@ieee.org

References

1 Howard, D.D.: 'Radar target angular scintillation in tracking and guidance systems based on echo signal phase front distortion'. Proc. Nat. Eng. Conf., vol. 15, 1959. reprinted in Radars, Vol. 4, Radar Resolution & Multipath Effects, David K. Barton, Ed., Artech House, Chicago, IL, USA, 1975
2 Dunn, J.H., and Howard, D.D.: 'Radar target amplitude, angle, and Doppler scintillation from analysis of the echo signal propagating in space', *IEEE Trans. Microw. Theory Tech.*, 1968, **9**, (9), pp. 715–728
3 Lindsay, J.E.: 'Angular glint and the moving, rotating, complex radar target', *IEEE Trans. Aerosp. Electron. Syst.*, 1968, **4**, (2), pp. 164–173
4 Sherman, S.M., and Barton, D.K.: 'Monopulse principles and techniques' (Artech House, USA, 2011, 2nd edn.)
5 Wright, J.W.: 'Radar glint – a survey', *Electromagnetics*, 1984, **4**, (2), pp. 205–227
6 Golden, A.: 'Radar electronic warfare' (AIAA Inc., USA, 1987)
7 du Plessis, W.P., Odendaal, J.W., and Joubert, J.: 'Extended analysis of retrodirective cross-eye jamming', *IEEE Trans. Antennas Propag.*, 2009, **57**, (9), pp. 2803–2806
8 Vakin, S.A., and Shustov, L.N.: 'Principles of jamming and electronic reconnaissance', vol. I (U.S. Air Force, USA, 1969). FTD-MT-24-115-69, AD692642
9 Van Brunt, L.B.: 'Applied ECM', vol. 1 (EW Engineering, Inc., USA, 1978)
10 Schleher, D.C.: 'Electronic warfare in the information age' (Artech House, USA, 1999)
11 du Plessis, W.P.: 'A comprehensive investigation of retrodirective cross-eye jamming' (University of Pretoria, Pretoria, South Africa, 2010)
12 Falk, L.: 'Cross-eye jamming of monopulse radar'. IEEE Waveform Divers. Des. Conf., Pisa, Italy, 2007, pp. 209–213
13 Neri, F.: 'Introduction to electronic defense systems' (SciTech Publishing, Rayleigh, USA, 2006, 2nd edn.)
14 du Plessis, W.P., Odendaal, J.W., and Joubert, J.: 'Tolerance analysis of cross-eye jamming systems', *IEEE Trans. Aerosp. Electron. Syst.*, 2011, **47**, (1), pp. 740–745
15 du Plessis, W.P.: 'Statistical skin-return results for retrodirective cross-eye jamming', *IEEE Trans. Aerosp. Electron. Syst.*, 2019, **55**, (5), pp. 2581–2591
16 'Electromagnetic reflector'. 2908002, 1959
17 du Plessis, W.P., Odendaal, J.W., and Joubert, J.: 'Experimental simulation of retrodirective cross-eye jamming', *IEEE Trans. Aerosp. Electron. Syst.*, 2011, **47**, (1), pp. 734–740
18 Cutler, C.C., Kompfner, R., and Tillotson, L.C.: 'A self-steering array repeater', *Bell Syst. Tech. J.*, 1963, **42**, (5), pp. 2013–2032
19 Pon, C.Y.: 'Retrodirective array using the heterodyne technique', *IEEE Trans. Aerosp. Electron. Syst.*, 1964, **12**, (2), pp. 176–180
20 'Phase-conjugating retrodirective cross-eye radar jamming'. P85977ZP00, provisional patent submitted on 5 June 2020
21 Pozar, D.M.: 'Microwave engineering' (John Wiley & Sons, Inc., USA, 1998, 2nd edn.)
22 'Angular deception countermeasure system'. 4117484, 1978
23 'Security device'. 4006478, 1977
24 du Plessis, W.P.: 'Path-length effects in multiloop retrodirective cross-eye jamming', *IEEE Antennas Wirel. Propag. Lett.*, 2016, **15**, pp. 626–629
25 Kyriazis, N.: 'Ham radio station 5B4AZ', 2020. Available from: http://www.5b4az.org/
26 Stutzman, W.L., and Thiele, G.A.: 'Antenna theory and design' (John Wiley & Sons Inc., USA, 1998, 2nd edn.)