Defence Science Journal, Vol. 68, No. 1, January 2018, pp. 70-75, DOI : 10.14429/dsj.68.10993

Networking of Tracking Radars of Two Different SAM Weapons to Protect the Missile in Intensive Jamming Environment

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ABSTRACT

Many countries including India use the Russian made SAM-3 (Pechora) surface-to-air missile (SAM) weapon systems to protect their strategic and tactical infrastructure. The mathematical computations done in this paper, conclusively proves that SA-125 low-blow tracking radar of Pechora is vulnerable to jamming. A project was undertaken to overcome the jamming vulnerability of Pechora aiming to design and develop an electronic counter counter measure system. This system networked the Pechora tracking radar with a western tracking radar, Flycatcher, developed by HSA Holland. The latter radar works in a MMW band. When jamming (x band) is employed by enemy aircraft the Low blow radar failed to provide target coordinates. But the flycatcher tracking radar which is tracking in Ka band provided the tracking coordinates (after parallax correction) to the command guidance computer. This way the missile guidance is protected until missile warhead in missile blasts near the target. Extensive trials carried out with a number of aircraft sorties proved the success of this developed system against jamming.

Keywords: Surface-to-air missile; Networking; Tracking radar; Electronic counter measure; Command line of sight guidance

1. INTRODUCTION

In every air war, the military and industrial infrastructure like atomic power plants, arms depots, airports, seaports, rail links, bridges etc. will be attacked. Slow moving bombers or attacking aircrafts are employed to drop bombs. These infrastructures need to be protected by deploying surface-to-air-missiles (SAMs), and anti-aircraft artillery (AAA) guns. But the attacking aircraft carry jammers to deny tracking by SAM radars. India has more than 3 million mt^2 of airspace. This requires to be protected at all costs from troublesome neighbours. Indian Air Force is entrusted with this formidable job. Many countries including India possess SAM-3 (Pechora) weapon systems (Russian origin) to protect the fixed infrastructure from being strafed. This paper aims to show analytically it is possible to jam the tracking radar of SA-125, SA-3 Goa with the present day jammers.

Operational squads have reported the vulnerability of jamming of Pechora system. The task of designing and developing an electronic counter counter measure (ECCM) system was undertaken. A western tracking radar (Flycatcher) used by Indian Army is chosen for networking with SAM-3 weapon system. The two tracking radars work in different widely separate frequency bands. After developing the system, it was extensively tested by carrying out aircraft sorties in one of the Air bases on the western front. It was practically demonstrated that in the event of intense jamming, the missile can be continued to be guided to the target by employing the tracking coordinates from the Western Flycatcher Radar by networking the two tracking radars. The Flycatcher provides the tracking coordinate data of attacking aircraft to low blow radar in times of its being jammed. This ensures accurate guidance of the missile onto the target and the proper functioning of proximity fuze which triggers the explosion of warhead. The effort that went into design and development of a counter counter measure is explained in the succeeding paragraphs.

2. TECHNICAL DETAILS OF PECHORA MISSILE[1]

The S-125 Neva/Pechora is Soviet surface-to-air-missile system with SA-3 Goa as its NATO designation. The S-125 Neva-M was developed by Lavochkin and Grushkin OKB and produced by Fakel MKB. It has shorter range and lower engagement altitude than its predecessor SAM-2 (S-75).It can also engage low flying targets with a missile speed reach of 3.5 Mach in flight. It is effective against more manoeuvring targets than SAM-2. Pechora system radar is shown in Fig. 1.

The Pechora system has an engagement altitude of 0.02 to 25 km and a maximum cross range of 25 km. It has a maximum target speed engagement of 900 m/s and the kill probability with one missile is 0.85. The system includes by P-15 M-Squat eye-search radar, PRV-II radar altimeter and low blow guidance

Received : 20 December 2016, Revised : 06 October 2017
Accepted : 06 October 2017, Online published : 18 December 2017

(tracking) radar. A built-in TV camera with 25 km range increases its EW resistance in clear weather. It is an effective proven weapon against low flying and small size targets. Most of middle east countries and India possess SAM-3 batteries in large numbers. It uses the command guidance throughout the missile flight like its predecessor SAM-2. The system can engage and destroy fighter aircraft and cruise missiles, travelling at speeds of up to 1500 km/hr and altitudes 100 m to 5000 m, at ranges up to 12 km. The RSN/SNR-75 Fan Song radar used for SA-2 (6 GHz) was replaced by a 9 GHz radar with narrower antenna main lobes[1].

3. TECHNICAL DETAILS OF FLYCATCHER[2-3]

Flycatcher is a dual band I/K-band short range tracking radar manufactured by Hollandse Signal Apparaten BV, in The Netherlands. It is used for controlling AAA guns in air defence and short range SAMs. The tracking radar is mounted on a transportable container. Flycatcher has

(a) X-band surveillance radar,
(b) X-band target tracking radar, and
(c) Ka-band tracking radar.

The search radar has a fan beam 1.1^0 x 20^0. The search radar antenna is a slotted waveguide and has a gain of 33 dB. Its detection range is 20 km for a 1 m^2 target. It uses dual band tracking. Monopulse technique is used to track the target. It uses a pseudo random PRF with a pulse width of 0.2 microseconds. It also employs split range gate tracking with a tracking range of 19 km. The radar uses an alternating tracking system working in X and Ka-band. It has a beam width of 0.6^0 X 0.6^0 with a tracking range of around 20 kms for 1 m^2 targets. When jamming in X-band is detected, the radar automatically switches to MMW band from X-band tracking. Picture of the Flycatcher radar is shown at Fig. 1.

4. TECHNICAL SPECIFICATIONS OF S-125 LOW BLOW TRACKING RADAR

The various technical specifications of the S-125 radar are as follows:

- Peak power (Pε) = 250 kW (250 x 10^3)
- Antenna gain (Gt) = 33 dB (1995.3)
- Radiated frequency (I-band) = 9 GHz (9 X 10^9 Hz)
- Wavelength (λ) = $\frac{C}{f} = \frac{3\times10^8}{9\times10^9} = 0.033\ mt$
- Pulse width (PW) = 0.25 micro s. (0.25 × 10^{-6} s.)
- Matched filter bandwidth

$$= \frac{1}{\text{Pulse width}} = \frac{1}{0.25\times10^{-6}} = 4\times10^6\ Hz$$

- Pulse repetition frequency (PRF) = 1750 – 3500 assume 1750 pps
- Beam width 1.5^0
- Scanning zone = 12^0
- Scan rate= 16 Hz
- Number of pulses available for integration = n

$$\frac{Beamwidth}{Scan\,rate \times Scan\,Zone} \times PRF = \frac{1.5}{16\times12} \times 1750 = 13.67 = 14$$

- Integration efficiency [$E_{i(n)}$] = 1
- Pulse compression ratio (PCR) = 1
- Probability of detection (PD) = 0.9
- Probability of false alarm (Pfa) = 10^{-6}
- From reference (4) for above PD & Pfa S/N = 12.8 dB (19) (Non fluctuating Swerling target 0)
- Noise figure (NF) = 9 dB (7,94)
- Target cross section = 1 m^2
- Total losses = 8 dB (Typical) (6.3)
- Boltzman constant 1.38 X 10^{-23}
- Temperature = 290 ^{0}K
- $(4π)^3$ = 1981.39
- Maximum detection dange = R_{max}
- $$R_{max}^4 = \frac{P_t G_t^2\ \lambda^2\ \sigma\ n\ E_{i(n)}\ PCR}{(4\pi)^3 \left(\frac{S}{N}\right) K\,T\,B\,F\,L}$$
- $$R_{max}^4 = \frac{250\times10^3 \times (1995.3)^2 \times (0.033)^2 \times 1\times14\times1\times1}{1981.39\times19\times1.38\times10^{-23}\times290\times4\times10^6\times7.94\times6.3}$$
- R_{max} = 26.637 Kms

So the maximum range of low blow radar for 1 m^2 target is 26.637 km and 47.4 km for a 10 m^2 target. This matches with the manufacturer's specification.

Figure 1. S-125 Neva / Pechora weapon and Flycatcher systems.

Source: Technical Report APA-TR- 2009-0602 Air Power Austarlia Almaz 5V24/5V27/S-125 Neva/Pechora AirDefence System SA-3 Goa www.ausairpower.net/APA-S-125-Neva.html and Flycatcher Radar detects enemy aircraft Jan 25, 2004 www.defencetalk.com/pictures/indian-army-command-and-support/p2051-flycatcher-radar.html.

5. VULNERABILITY OF PECHORA TRACKING RADAR TO JAMMING

Specifications of the jammer:

- Jammer power = 200 watts
- Frequency (f) = 9 GHz
- Wavelength (λ) = C / F = 0.033 mt
- Jammer bandwidth (B_j) = 10 MHz (10 x 10^6)
- Antenna gain = 7 dB (5)
- S / J = 21.2 dB (fluctuating swerling target 1)
- Side lobe Gs = 20 dB (100)
- S/J = 21.2 dB (131)
- F = 9 dB (7.9)
- Bn = 4 x 10^6 HZ
- λ = 0.0333 Mt.
- σ = 1 mt^2
- Combined loss $Lt + LR$ = 3 dB (6.3)
- No. of pulses integrated = N = 50

5.1 Stand of Jammer Main Lobe

Stand of jammer (SOJ) is assumed to be airborne and orbiting at a safe range of 30 km.

Range of SOJ = 30 x 10^3 m

Target detection range = R_{tm}

$$R_{tm}{}^4 = \frac{N}{4\pi} \times \frac{P_t}{P_j} \times \frac{B_j}{B_n} \times \frac{G_t}{G_j} \times \frac{\sigma}{S/J} \frac{(RSOJ)^2}{L_t}$$

$$= \frac{50}{4\times 3.14} \times \frac{250\times 10^3}{200} \times \frac{10\times 10^6}{4\times 10^6} \times \frac{1995}{5} \times \frac{1}{131} \times \frac{(30\times 10^3)^2}{6.3}$$

R_{tm} = 1524 Mt = 1.524 km

5.2 Stand of Jammer Side Lobe

SOJ is assumed to be airborne and orbiting at a safe range of 30 kms.

$$R_{ts}{}^4 = \frac{N}{4\pi} \times \frac{P_t}{P_j} \times \frac{B_j}{B_n} \times \frac{G_t \times G_S}{G_j} \times \frac{\sigma}{S/J} \times \frac{(RSOJ)^2}{L_t}$$

where G_s = 20 dB (100).

R_{ts} = 1.524 x $(100)^{1/4}$ = 4.82 km

5.3 Self Screening Jammer

The jammer is being carried by the attacking aircraft

$$R_{tss}{}^2 = \frac{N}{4\pi} \times \frac{P_t}{P_j} \times \frac{B_j}{B_n} \times \frac{G_t}{G_j} \times \frac{\sigma}{S/J} \times \frac{I}{L_t}$$

$$= \frac{50}{4\times 3.14} \times \frac{250\times 10^3}{200} \times \frac{10\times 10^6}{4\times 10^6} \times \frac{1995}{5} \times \frac{1}{131} \times \frac{1}{6.3} = 0.078\ km$$

6. PERFORMANCE EVALUATION OF LOW BLOW RADAR UNDER REPEATER JAMMING CONDITIONS

- S = Power received at input of radar R_x due to target echo

$$S = \frac{P_t\, G_t\, G_r\, \sigma\, \lambda^2}{(4\pi)^3\, (R_j)^4}$$ where R_j is range of repeater jammer.

- Power received at jammer from radar = P_{Rj}

$$P_{RJ} = \frac{P_t\, G_t\, \lambda^2\, G_{jr}}{(4\pi)^2\, (R_j)^2}$$ where G_{jr} is jammer receiving antenna gain

- Power generated by jammer= P_j

$$P_J = \frac{P_t\, G_t\, \lambda^2\, G_{jt}}{(4\pi)^2\, (R_j)^2} \times \frac{G_e}{L_p}$$ where G_e is repeater gain and G_{jt} is jammer transmitted antenna gain

- Jammer power received at radar R_x input

$$J = \frac{P_t\, G_t\, \lambda^2}{(4\pi)^2\, (R_j)^2} \times \frac{G_{jt} G_e}{L_p} \times \frac{1}{4\pi\, R_j^2} \times \frac{\lambda^2}{4\pi} \times G_r \times \frac{1}{L_p}$$

$$\frac{J}{S} = \frac{G_{jr}\, G_{jt}\, G_e\, \lambda^2}{4\pi\, \sigma\, L_p^2}$$

Gain of repeater $G_e = \dfrac{4\pi\, \sigma\, J/S\ L_p^2}{G_{jt}\, G_{jr}\, \lambda^2}$

6.1 Power Requirement of Repeater for Different *J/S* Ratios

- $G_{jt} = G_{jr}$ = 10 dB (10)
- σ = 1 mt^2
- R_j = 10, 20, 30 km (10×10^3, 20×10^3, 30×10^3 m)
- J/S = 10, 20, 30 dB (100, 200, 300)
- L_p = Polarisation loss = 3 dB = 2

For J/S = 10 dB (10) and $Rj = 10 \times 10^3$ mt

$$G_e = \frac{4\times 3.14\times 1\times 10\times 2\times 2}{10\times 10\times (0.033)^2} = 4613.4$$

- Repeater output power, $P_{jr} = \dfrac{P_t\, G_t\, \lambda^2\, G_{jr}}{(4\pi\, R_j)^2} \times \dfrac{G_e}{L_p}$

$$= \frac{250\times 10^3 \times 1995\times (.033)^2 \times 10\times 4613.4}{(4\times 3.14)^2 \times (10\times 10^3)^2 \times 2} = 0.79\quad watts$$

The Repeater power requirements for various ranges and J/S ratios are given in Table 1. The above computations show that the low blow radar of Pechora is vulnerable to jamming even with low/ moderate power levels of jammer.

Table 1. Repeater power requirement

J/S	R_j = 10 km	R_j = 20 km	R_j = 30 km
10 dB	0.79 W	0.198 W	0.09 W
20 dB	7.9 W	1.975 W	0.88 W
30 dB	79 W	19.75 W	8.8 W

6.2 Principle of Radar Networking

Radar networking is needed to ensure reliable uninterrupted data on hostile targets under conditions of ECM. Networking also extends the capability of detection range. Interlinking two tracking radars lowers the vulnerability to natural or man-made interferences (ECM) and anti-radiation missile attacks. The approach will continue to provide the coordinates of attacking aircraft for purpose of missile guidance under conditions of disruption due to many reasons viz.

(a) EW jamming (ECM),
(b) EMI/EMC effects on weapon control systems,
(c) Malfunctioning of one of the radars, and
(d) redundancy purpose.

Table 2 gives the miss distances between the missile and target for various angular errors.

Table 2. Miss distance versus angular error and range

Range (km)	Angular error degree 0.05	Angular error degree 0.1	Angular error degree 0.2	Angular error degree 0.4	Angular error degree 0.8
3	2.6 Mt	5.23 Mt	10.47 Mt	20.93 Mt	41.86 Mt
5	4.36 Mt	8.72 Mt	17.44 Mt	34.89 Mt	69.78 Mt
10	8.72 Mt	17.44 Mt	34.88 Mt	69.78 Mt	139.6 Mt

7. BRIEF DESCRIPTION OF THE SYSTEM

Radar A is low blow tracking radar and Radar B is Flycatcher Radar (the block diagram for interlinking of the track radars is given in Fig. 2). When the target uses the ECM, Radar A looses the track and it cannot generate azimuth, elevation and range coordinates. These are required for computation of guidance commands of the missile. However Radar B (Flycatcher) which is working in Ka-band frequency continues to track the hostile target enabling availability of angle and range coordinates at Radar B. The Flycatcher provides the tracking coordinate data of attacking aircraft to Low Blow Radar when jamming is encountered. This ensures that the missile is accurately guided onto the target and the proper functioning of proximity fuze which triggers the explosion of warhead. Flycatcher is chosen since it uses MMW frequency and MMW jammers with high power are not available due to technological constraints. Secondly the attacking aircraft cannot carry two jammers at a time. It increases the pay load and drastically reduces the manoeuvrability of the aircraft.

The data convertor shown in the Fig. 3 converts the target coordinates which are in digital parallel form into serial format. Parallax data convertor block is located at Radar A site. It receives the serial data bits and reconverts into parallel data. This subsystem transforms the coordinates of target, as seen by Radar B to coordinate as seen by Radar A. Suitable parallax correction algorithms are used to compute the coordinates.

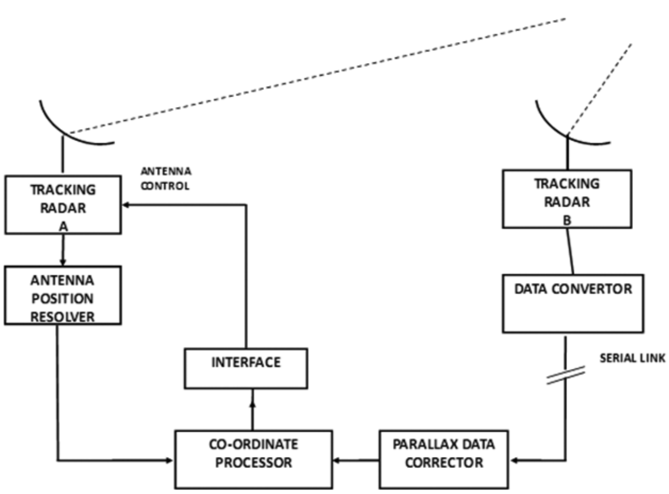

Figure 2. Block diagram of interlinking of two radars.

The present position of Radar A is obtained by tapping two speed synchro system of azimuth and elevation servo system. Antenna position resolver block converts the analog synchro voltages to parallel digital information. These are passed onto the block coordinate processor. Under non jamming conditions the coordinate values coming from antenna position resolver exactly matches. When Low Blow Radar (I-band) is jammed, the coordinates of target from Radar A and B differ. Comparison is made between the Parallax corrected data and Radar A coordinates. The errors thus obtained between the two values are made to drive the antenna null seeking servos of Radar A. In the case of range gate tracking, a synthetic range pulse is generated based on the range information obtained from Radar B. This synthetic range pulse is tracked by Radar A.

7.1 Software Computational Modules

All the functions required are achieved by a high speed processor which is supported by a numeric processor. The following software modules are developed:

- Two-speed synchro processor module
- Offset correction module
- Parallax correction module
- Error generation module
- Extrapolation module
- Input/output module
- Post mortem dump for recording
- Built in test, and
- Target simulator

7.2 Parallax Correction

Among all the above programs, parallax correction software module is the most important one as shown in Fig. 3. In the figure, Υ = range, β = Azimuth angle, ε = elevation angle, X, Y, Z = Cartesian coordinates of target, $\Upsilon\rho/x$, $\beta\rho/x$, $\varepsilon\rho/x$ are the values determined at the time of alignment of Radars A and B with respect to North.

$h = \Upsilon\rho/x \,Cos\,(\beta\,\rho/x)\,Cos\,(\varepsilon\,\rho/x)$

$k = \Upsilon\rho/x \,Sin\,(\beta\,\rho/x)\,Cos\,(\varepsilon\,\rho/x)$

$l = \Upsilon\rho/x \,Sin\,(\varepsilon\,\rho/x)$

$\Upsilon = Sqrt\,(X^2+Y^2+Z^2)$

$\beta = A_{rc}\,Tan\,(Y / X)$

$\varepsilon = A_{rc}\,Tan\,(Z / S_{qrt}\,(X^2+Y^2)$

The computational details are shown in Fig. 3.

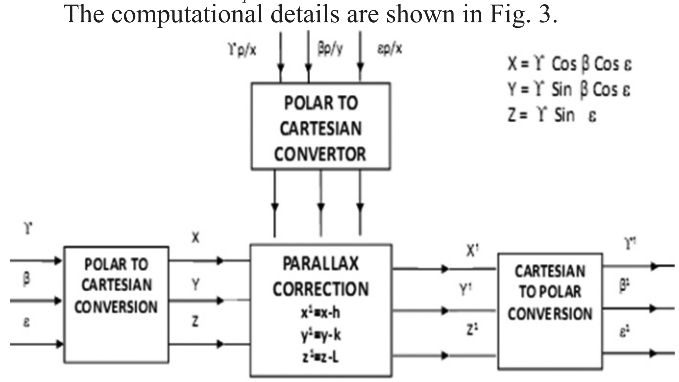

Figure 3. Parallax correction.

8. MODES OF OPERATION

The networking of coordinates is successfully demonstrated in three modes of operation viz. manual mode of tracking, semi automatic mode of tracking, and automatic mode of tracking.

8.1 Manual Mode of Tracking

Figure 4 shows the diagram of manual mode. Radar B (Flycatcher) is tracking the hostile aircraft whereas Radar A (Low Blow radar of Pechora) is not able to track due to jamming. By tapping the synchros mounted on the Radar A, one can obtain the Azimuth and Elevation angles of Radar A. Coarse and fine synchro information is converted to digital format. Synchro to digital converter processes the coarse, fine and digital information, and brings out a single parallel digital 16-bit information in Azimuth and Elevation separately. Radar B, which is not jammed, tracks the target and gives the Azimuth, Elevation and range information to Parallax processor block. This information is passed through the serial link. Parallax corrected data is compared with the servo coordinates of Radar A. The differences in Azimuth, Elevation and range are given to a digital/analog meters. The operations will rotate the speed wheels of the Radar A looking at the meters, such that the meters indicate zero errors. The rotation of wheels makes the antennas of Radar A tracks the target. This feeds the proper information into guidance computer of Radar A. In case of range, a synthetic range pulse is positioned at correct position. The range tracking circuits track the synthetic range pulse. All the three coordinates now depicts the true position of hostile targets. Thus the break in tracking is avoided and missile continues to get correct guidance commands.

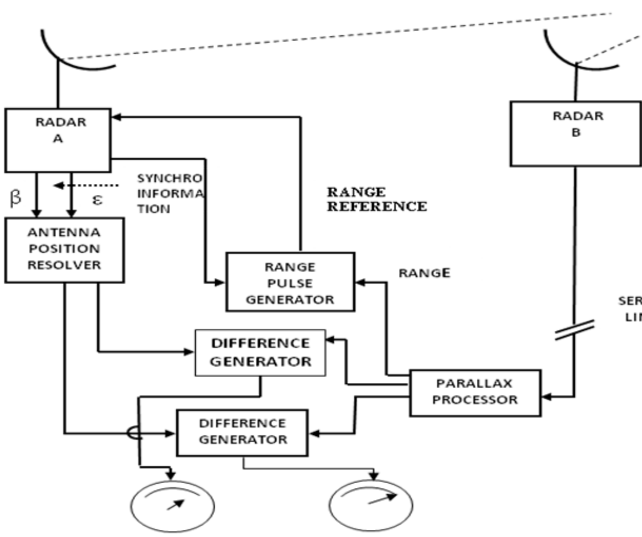

Figure 4. Manual mode of operation.

8.2 Semi Automatic Mode of Tracking

Figure 5 depicts the block diagram of semi automatic mode of networking. In manual mode the manual trackers bring down the error shown in displays by moving the hand wheels. In the semi automatic method the error in angles are fed to the servo amplifiers of the antenna control system of Radar A by breaking the existing servo loop. At all times this

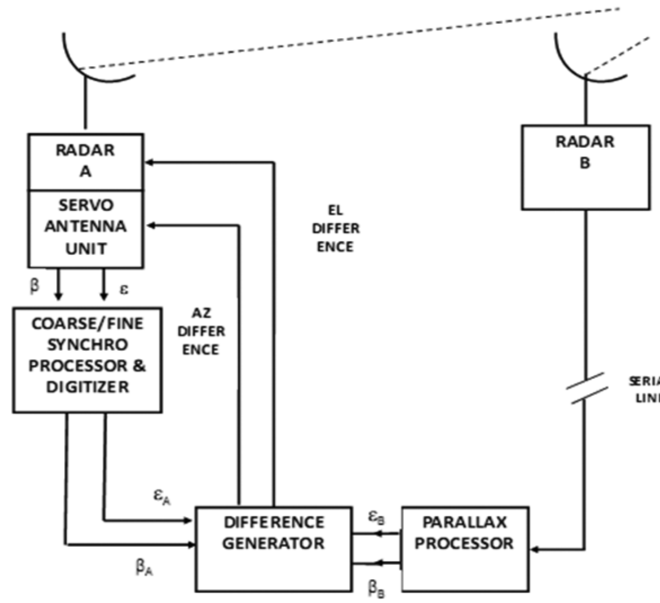

Figure 5. Semi automatic mode of operation.

ensures that the servo antennas move as per the coordinates given by the Parallax processor block.

8.3 Automatic Mode of Tracking

The errors in angles are used to generate a synthetic video packet signals in azimuth, elevation and range. The tracking loop of Radar A is broken at the appropriate place. The synthetic video is introduced at this circuit point. The position of the synthetic video from the start of the scan gets modified as per the amplitude of the error. The radar A starts tracking the synthetic video packet as if they are received from the IF channels of its own radar. This method of tracking is found to be more realistic to the operators using the Pechora SAM-3 system.

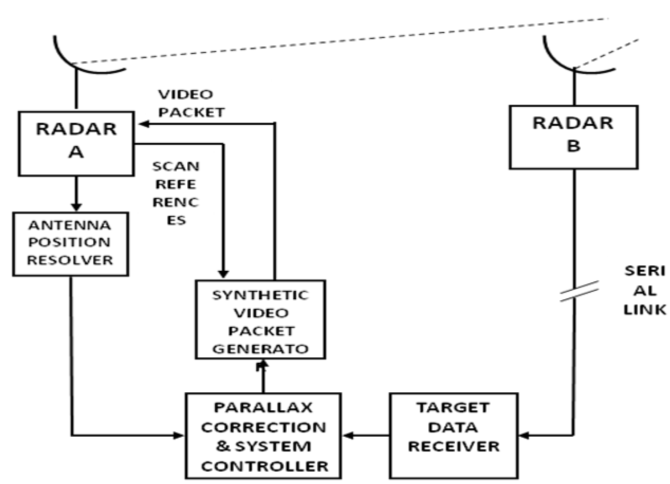

Figure 6. Automatic mode of operation.

9. FLIGHT TRIALS CARRIED OUT

The practical trials carried using an airborne aircraft are as follows.

For any effective missile guidance, we need (a) target aircraft coordinates, (b) missile coordinates, (c) a guidance law (in this case CLOS), and (d) a computer. Our own aircraft is flown with different trajectories and manoeuvres. In this case, the flown aircraft is assumed as enemy's target. Slow Blow Radar of SAM-3 weapon system starts tracking. Since we cannot launch our missile on to our own aircraft, the following is done. We know the aerodynamic parameters and kinematics of our own missile. The mathematical model of the missile is already stored in the Missile generator subsystem (supplied by the manufacturer). Now the missile is launched as per the normal procedure. The weapon system is provided with provision to insert variety of jammer signals into the target tracking channels. (A separate jammer vehicle is available for training the operators). The jammer signals disrupt the target channel tracking which means the target coordinates are lost However the Flycatcher which is put at 500 m from the SAM-3 weapon continue to track the target in Ka band, The coordinates from Fly catcher tracking system are fed into the command guidance computer. This generates K1, K2 and K3 commands. These commands provide the necessary yaw, pitch motion to the missile (roll is not stabilised) until the missile meets the target. The graphs of K1, K2 which are the guidance command and K3 the warhead explosion command is available in the form of graphs from the 'KaZa' System of Pechora. From the analysis of these commands one can determine whether the missile has hit the target if so with what accuracy. This is how all over the world the aircraft engagements trials with weapon systems are carried out. It is impracticable to launch a Rs 3 crore missile on to a 400 crores aircraft and destroy it.

10. FUTURE WORK

(i) This has proven the concept of networking various weapon sensor systems.
(ii) Each system can act as a backup or redundant to achieve 100 per cent kill probability against an airborne intruder.
(iii) Complex EW jamming attacks by enemy can be defeated.
(iv) Our Indian developed Akash missile system can be networked with available Russian missile systems
(v) An effective air defence shield can be realised by networking the available weapon guidance systems of both Indian, Western and Russian systems, so that no aircraft or missile can intrude into our air space.

11. CONCLUSIONS

The Project has successfully linked up to two tracking radars using different philosophies and technologies. It was possible to transfer online tracking coordinates of a target obtained from Flycatcher radar to another tracking radar S-125 Low Blow radar of Soviet origin. Under conditions of jamming, manual, semi automatic and automatic modes were developed and successfully demonstrated with live aircraft sorties with the cooperation of Indian Air Force units across one of the western border. Necessary hardware interfaces and software required for these exercises were developed by DRDO. The modern trend in air defence systems is to use multi-sensor fusion of data. The software packages developed in this project can be used for interfacing any two tracking radar systems.

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ACKNOWLEDGEMENTS

The authors profusely thank the IAF for its full cooperation and the help it rendered in developing the Kiran system and testing it at one of its western airbase. The authors also thank Dr A.L. Moorthy, Chief Consultant, BrahMos Aerospace, Hyderabad for his editorial assistance and suggestions to improve the paper.

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In the current study, he is instrumental in formulating the concept (based on the requirement of IAF), developing the system and carrying the field trials.

Dr R. Sreehari Rao obtained BE from Andhra University, MTech from IIT Kharagpur and PhD from IIT Madras. Presently working as Director (R&D) at Bharat Institute of Engineering & Technology, Hyderabad. He retired as Distinguished Scientist and Chief Controller R&D, DRDO, Delhi. He has guided the activities of number of defence labs. of DRDO.
In the current study, he has reviewed the design of this system critically, and provided the inputs for necessary modifications so that the full fledged system is practically realised.

Dr Subir Kumar Chaudhuri, FNAE obtained B.E.E. from Jadavpur University. MTech from IIT Madras and PhD from Cranfield Institute of Technology, United Kingdom. Presently working as Director BIET. He retired as Scientist 'H' and Director, Research Centre Imarat, Hyderabad. He established Hardware-In-loop Simulation Lab at RCI. He was responsible for design and development onboard mission software for Inertial Guided Missiles. He developed advanced simulation center with high fidility motion simulations for Agni, Prithvi, Akash and Trishul weapon systems.
In the current study, he is involved in designing the interfaces between the SAM - 3 weapon and the developed system.