THE EVOLUTION OF RADAR GUIDANCE

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Since World War 2, radar has been applied to weapon guidance to replace barrages of shells and bombs by precision missiles capable of operating out to long range in all weather conditions. The task of meeting size and weight limitations, severe environmental conditions and long storage life without maintenance has been difficult, and until recently the price and size of radar guided missiles has limited their use to high value targets such as aircraft and ships. However, recent advances in electronics allow much smaller and cheaper guided munitions for use against smaller targets such as radars or armoured vehicles. This paper discusses the principles of radar guidance, and illustrates its evolution by reference to succeeding generations of Marconi systems.

1. THE ORIGINS OF RADAR GUIDANCE

The first application of radar to missile guidance took place in the early 1940's. Aircraft tracking radars were used for gun laying anti-aircraft artillery. Fig. 1 shows a typical mobile anti-aircraft gun laying radar tracker. The 6 ft diameter parabolic reflecting dish produced a narrow radar beam (about 4° beamwidth) which automatically tracked the aircraft in angle. The form of angle tracking which was (and still is) used, termed 'conscan', is illustrated in fig. 2: (a) and (c) show how the narrow beam of the radar is conically scanned around the mechanical boresight of the antenna dish: (b) indicates how the variation in the target signal as the beam scans gives a measure of the angular error in the pointing of the dish. This angular error is fed back to drive the antenna servo mechanism and thus keeps the dish axis on target.

Also in the early 1940's, airborne radar equipments were developed which scanned the ground with a narrow radar beam to produce a radar map (see fig. 30 and 31 relating to modern systems) which was used by bombing aircraft both to navigate to the target in all weather conditions and also to determine the position for the release of bombs.

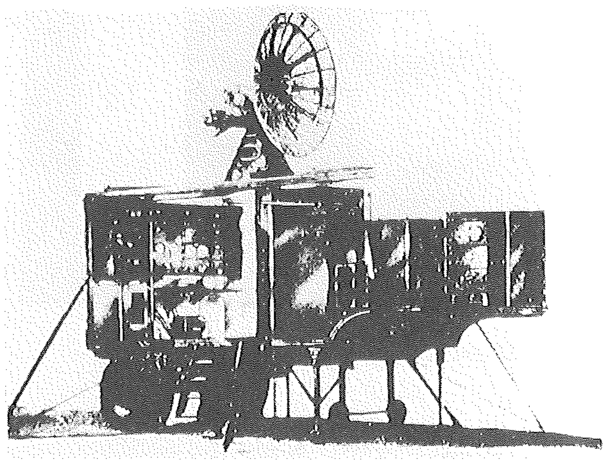

Fig. 1. Gun laying radar tracker for anti-aircraft artillery, 1943

2. FIRST APPLICATIONS OF RADAR TO GUIDING MISSILES DURING FLIGHT

The first application of radar to give guidance during the flight of a missile (and not just – as above – aiming it at launch) started in the late 1940's when there were initial developments of two basic forms of missile guidance: 'beamriding' and 'semi-active homing'. The type of radar initially used was incoherent pulse conscan which was highly developed by the end of World War 2.

2.1. Beamriding

Fig. 3 illustrates the basic principles of radar beamriding. A radar tracker is locked on to the target by the time it is at T_0, at which instant the missile is launched from M_0 into the radar beam. T_1 and M_1 are target and missile positions at a subsequent instant. An antenna in the rear of the missile receives pulses from the radar transmitter and from these pulses a receiver in the missile derives the displacement errors from the centre of the radar beam. These errors are fed into the missile autopilot to keep the missile in the centre of the beam. Thus, riding the beam, the missile must intercept the target at the point I.

Beamriding has the advantages of a very strong received signal and relatively simple missile-borne radar guidance equipment. However, beamriding calls for very high angular accuracy in maintaining the centre of the target tracker beam on target. Also, because the missile is contrained to lie on the line of sight (LOS) from the tracker to the target it has a non-optimum curved trajectory.

Seaslug 1, one of the original guided missiles against aircraft whose development in the UK started in 1950, was a beamrider. The GEC Stanmore Laboratories (now Marconi Defence Systems) were set up to develop its radar guidance system. It was a large ship-to-air missile (over 40 cm in diameter) for area defence of the Royal Navy. Its beamriding receiver was about 30″ × 10″ × 6″ in size and contained about 100 thermionic valves. The large, shipborne, target and missile beamriding radar was an incoherent pulse conscan system.

2.2. Semi-active Homing

The other initial UK anti-aircraft radar guided

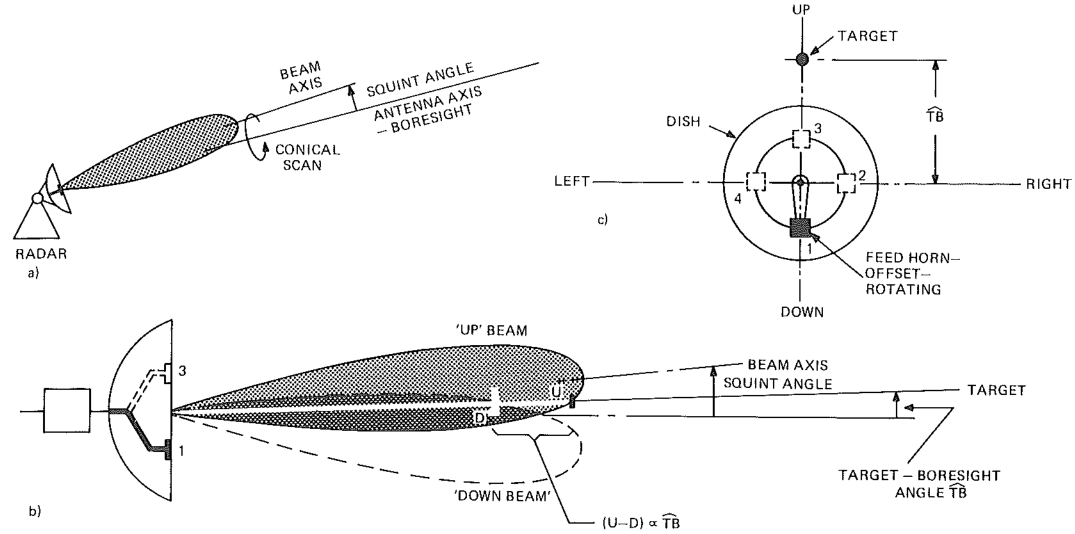

Fig. 2. The 'conscan' form of radar angle tracking

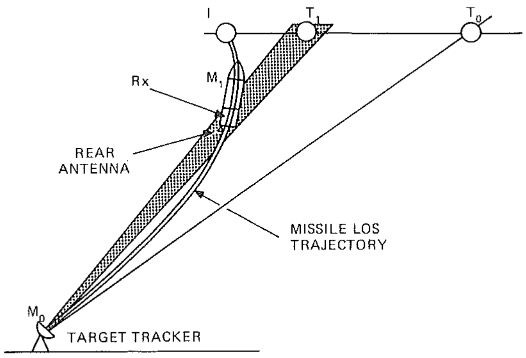

Fig. 3. 'Beamriding' form of radar guidance

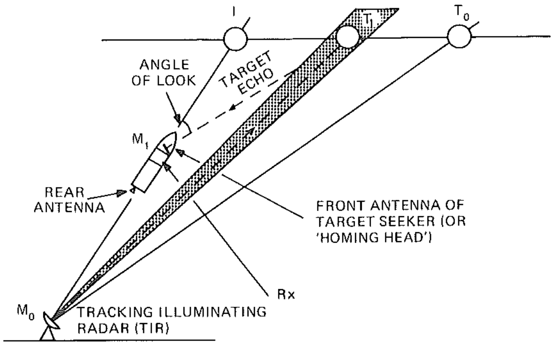

Fig. 4. 'Semi-active homing' form of radar guidance

missiles, Thunderbird and Bloodhound, also started in 1950, used the semi-active homing form of radar guidance whose principles are illustrated in fig. 4.

The tracking illuminating radar (TIR) is locked on to the target before it reaches T_0, at which instant the missile is launched from M_0 into a direct collision course to intercept the target at I. The target is 'illuminated' by the TIR throughout missile flight. The reflection from the target is received by a radar 'target seeker' or 'homing head' in the front of the missile. This semi-active seeker, which is an angle tracking radar minus the transmitter, gives the direction of the target in space throughout missile flight. From this seeker information, control signals are derived which continuously steer the missile to 'home' on to the target.

Semi-active homing offers the advantages of relaxed target tracking accuracy in the radar at the launcher (it need only keep the target within its beam), the possibility of very low miss distance independent of target range (since homing is essentially a closed loop system) and an optimum missile trajectory. On the other hand the missile equipment is complex, and until relatively recently, missile seekers were limited to fairly simple forms of radar.

Fig. 5. Lynx helicopter carrying four Sea Skua missiles

A recent example of a pulsed, semi-active radar homing system is the anti-ship missile Sea Skua, currently in service with the Royal Navy. Fig. 5 shows four Sea Skua missiles on a Lynx helicopter, whose radar tracks and illuminates the ship target prior to the launch of the missile. Fig. 6 shows the semi-active

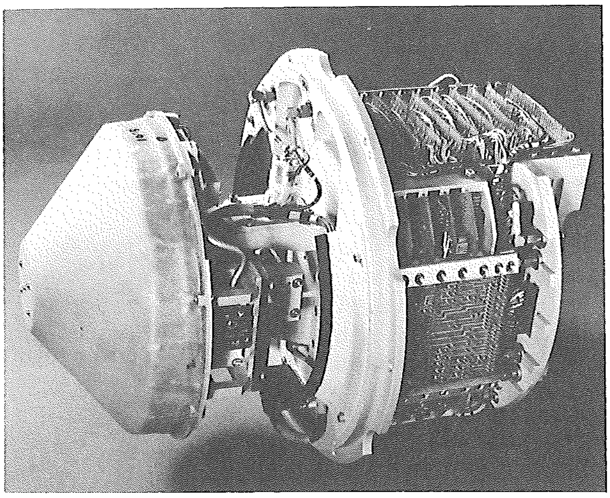

Fig. 6. Semi-active radar seeker in Sea Skua, 25 cm diameter

radar seeker detached from the missile: its bulkhead is about 10 inches (25 cm) in diameter.

3. THE PROBLEM OF CLUTTER

3.1. Incoherent Pulse Radar

Fig. 7 deals with the problem of 'clutter' in relation to the form of radar so far considered – incoherent pulse radar. Clutter is the term for unwanted signals caused by reflection from objects other than the target – from ground, sea, precipitation or chaff. Fig. 7 brings out the fact that clutter signals in an incoherent pulse radar can seriously constrain performance against low level air targets. Reducing the width of the range gate is helpful in increasing the signal to clutter ratio but cannot alone solve the problem.

The pulse length in range ΔR of a pulsed radar is related to the duration Δt of the transmitted pulse as follows, with ΔR in metres and Δt in seconds,

$$\Delta R = 1.5 \times 10^8 \, \Delta t \qquad (1)$$

Also the signal processing bandwidth required is B Hz, where

$$B \approx 1/\Delta t \qquad (2)$$

Up to the early 1950's a pulse duration of 1 μs was typical for radar trackers, corresponding to 150 m range resolution and requiring a 1 MHz bandwidth. Currently, range resolution down to a fraction of a metre (approaching 1 ns pulse duration and 1 GHz bandwidth) is practicable (and especially important for anti-armour munitions – see later).

3.2. Coherent Doppler Radar

Fig. 8 displays the elements of a form of radar which very greatly improves low level performance against moving targets – coherent Doppler radar. In the simplest form of such radar a continuous wave is transmitted at the constant radar frequency f_c. If the echo is reflected from a target which is moving relative to the radar, then the target signal will be at a frequency $(f_c + f_D)$, which is different in frequency from that of the transmitter by the 'Dopper shift' f_D. A narrow band filter – the 'speedgate' (analogous to the 'range gate' in a pulsed radar) – can then extract the target signal from clutter. Doppler, or speed, discrimination can still be achieved even if the transmitter is pulsed, provided the radar carrier wave is coherent. Thus 'pulse Doppler' (ie coherent pulsed) radar can directly measure both range and speed.

The Doppler shift f_D is related to the radial speed V_T of the target relative to the radar by

$$f_D = 2V_T/\lambda \qquad (3)$$

A wavelength of around 2 to 3 cm is typical of semi-active radar seekers now in service, with a speedgate filter of around 700 Hz at maximum acquistion range, which corresponds to 10 metres/second speed resolution (20 knots). However, speed resolution down to a fraction of a metre per second is practicable.

4. THE PROBLEM OF ANGLE TRACKING

4.1. Conscan

Conscan angle tracking, previously described, is an ingenious and simple method. However, it is vulnerable to simple jamming and its measurement of angle is narrow bandwidth: moreover, it modulates the target signal at the antenna, thus reducing the information available on the target.

4.2. Monopulse

Fig. 9 illustrates another form of radar angle tracking in which there are four simultaneous fixed radar beams rather than the one scanning beam of conscan. The angular errors are present instantaneously – or 'in a single pulse' – hence this form is termed 'monopulse angle tracking' – and the limitations of conscan are overcome, because there is no modulation of the target (or 'sum') signal and the error channels can be wide band.

However, there is considerably increased complexity, from a single feed to a four feed antenna and from a single target signal channel to three channels for the simultaneous sum and two difference signals.

One of the earliest missiles (developed in the 1960's) successfully to utilize the more advanced radar forms of coherent doppler and monopulse angle tracking, is the Sea Dart missile. Fig. 10 shows a launching from a Guided Missile Destroyer, while fig. 11 shows the forebody (about 40 cm in diameter) of the coaxial ram jet missile which contains the semi-active radar seeker. Sea Dart is both an anti-air and anti-ship missile.

The much smaller (20 cm in diameter) Sky Flash air-to-air missile (two are shown – white, with 4 delta wings and fins – on the Swedish Viggen in fig. 12) came later (developled in the 1970's), and was a more demanding application for these better but more complex radar forms. Its semi-active radar seeker is shown in fig. 13 (about 18 cm in diameter). Sky Flash realized major improvements in missile performance

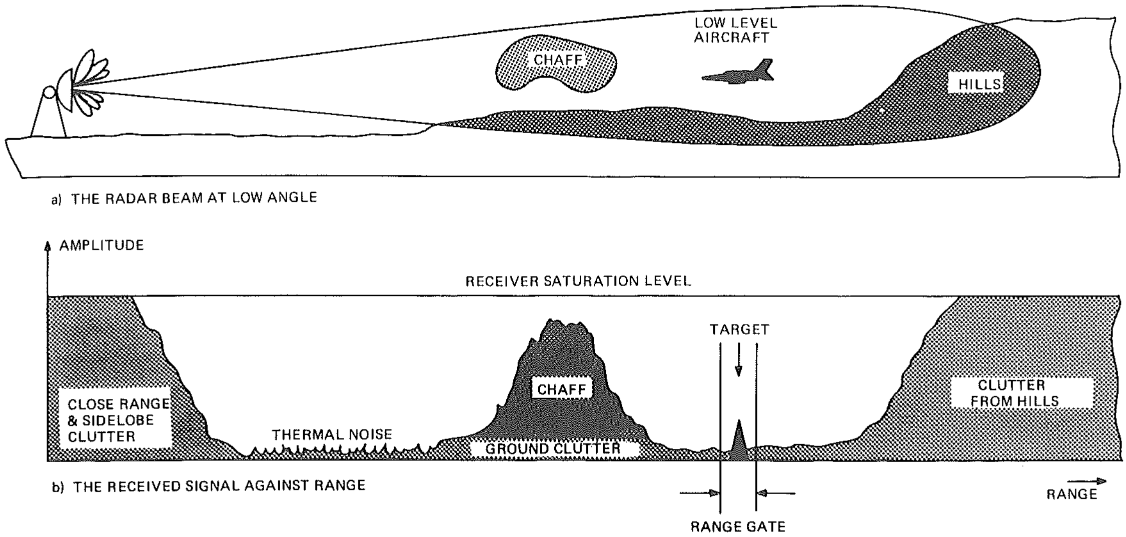

Fig. 7. Clutter – incoherent pulse radar

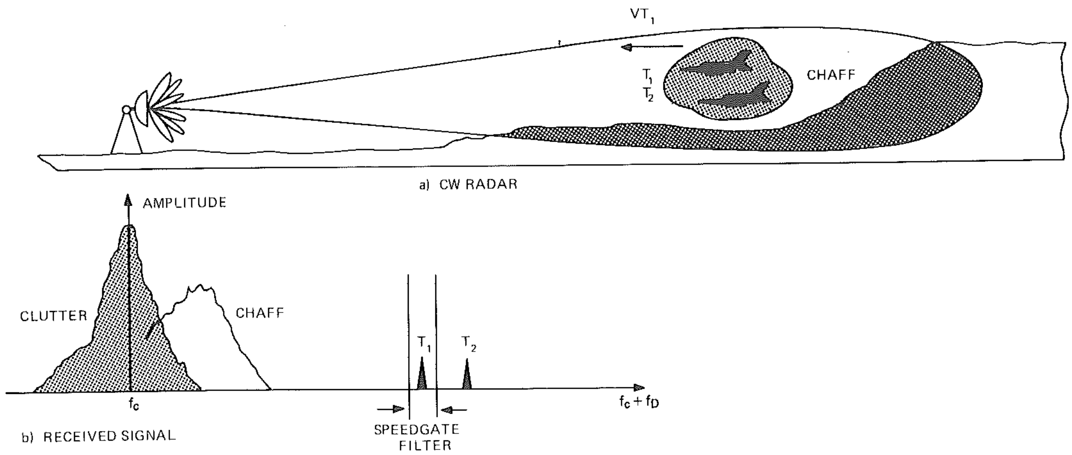

Fig. 8. Clutter – coherent Dopplar radar

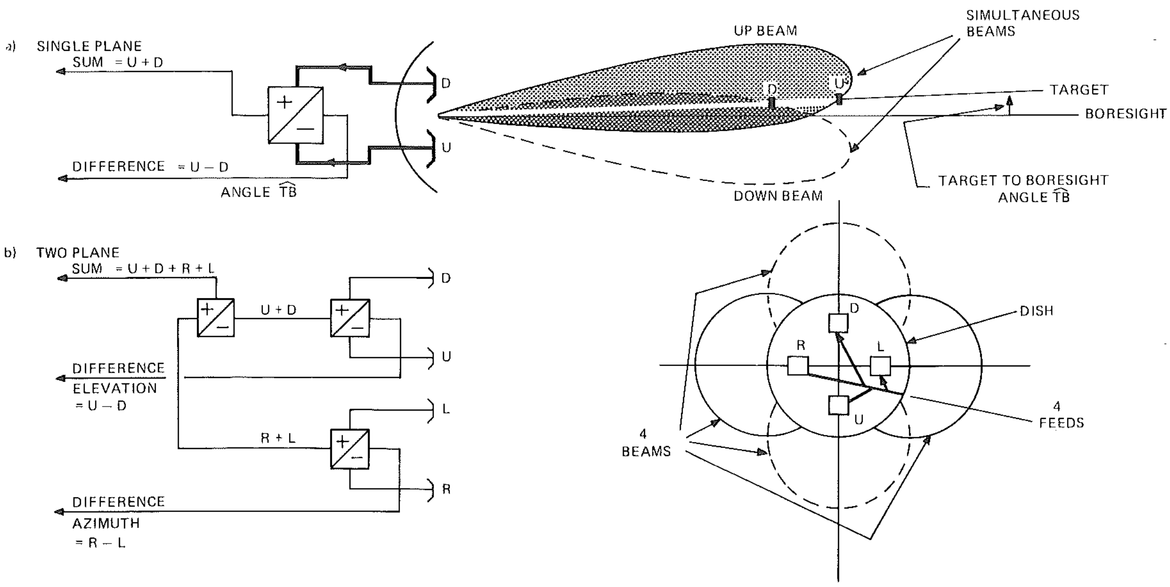

Fig. 9. The 'monopulse' form of radar angle tracking

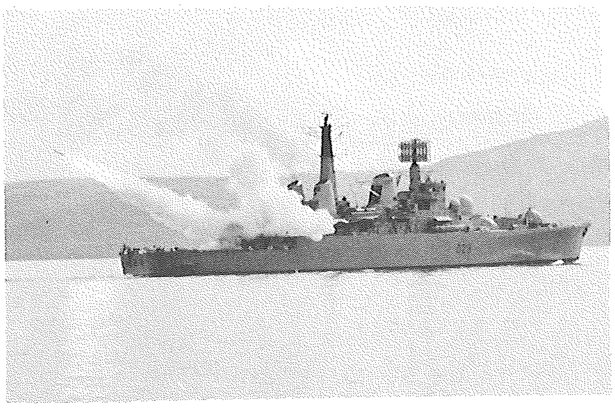

Fig. 10. Sea Dart missile launched from a Guided Missile Destroyer

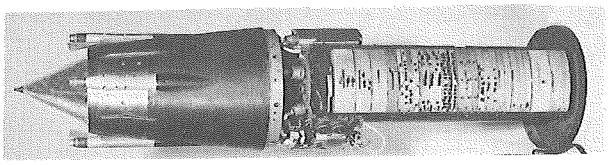

Fig. 11. Sea Dart semi-active radar seeker installed in the forebody of the missile, 40 cm diameter

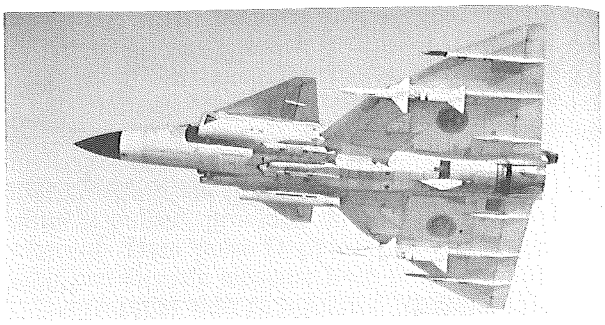

Fig. 12. Sky Flash missiles (two – one at each mid-wing) on a Swedish Viggen

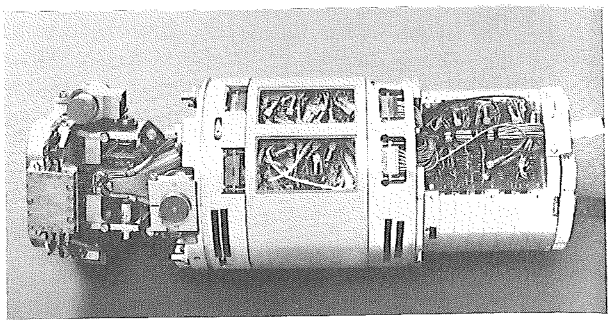

Fig. 13. Sky Flash semi-active radar seeker, 18 cm diameter

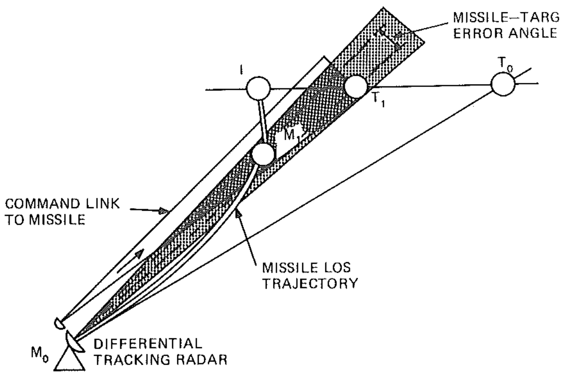

Fig. 14. 'Radar Command to Line of Sight – RCLOS' form of radar guidance

Fig. 15. 'RCLOS' target and missile tracker for RAPIER system

and characteristics in respect of guidance range, miss distance, low level performance – especially in 'look-down shoot-down' engagements – multiple target discrimination, ECCM and interoperability.

5. RADAR COMMAND TO LINE OF SIGHT GUIDANCE (RCLOS)

The elements of RCLOS radar guidance are illustrated in fig. 14. The differential tracking radar is locked on to the target when the target is at T_0 at which instant the missile is launched into the beam at M_0. The tracker thereafter continues to measure the angle between the missile and the target. Commands are then sent to the missile which steers to reduce this angle to zero, i.e., to keep the missile on the target line of sight so that it must intercept at I.

RCLOS has advantages over beamriding. Since the tracker differentially measures the missile-target angle, the accuracy with which the centre of the beam needs to follow the target can be relaxed. Also, of all forms of radar guidance it is the least demanding in terms of missile borne equipment, requiring only a simple command link receiver. RCLOS was developed for relatively short range missiles, too small to contain the sort of semi-active radar seeker then available (1970's). However, very high accuracy is needed in the measurement of the missile to target angle, so the tracker is still complex. RCLOS, like beamriding, has a non-optimum curved trajectory, because again the missile is constrained to lie on the line of sight (LOS) from the tracker to the target.

The Rapier ground to air command to line of sight Army missile system has an RCLOS version, fig. 15. The differential tracking radar (designated DN 181) is in the centre of the photo. Although small and highly mobile (the main antenna – 4 feet vertical aperture – folds down) this tracker has exceptionally high performance. There is also a ship-to-air naval RCLOS system, Sea Wolf, for the radars and radar guidance of which Marconi is again responsible.

6. ACTIVE HOMING MISSILE RADAR GUIDANCE

In 'semi-active' homing, the target is illuminated by a transmitter outside the missile – in the Tracking Illuminating Radar. In 'active homing' the transmitter is included in the missile. The radar seeker in active homing is thus a complete tracking radar, and, once locked on to the target, the missile is autonomous. However, because of the radar range to the fourth power law and the limited antenna size, the maximum range of an active seeker is likely to be appreciably less than that of the aerodynamic range of the missile and an initial mid-course guidance (MCG) phase may be used. This scheme, illustrated in fig. 16, is the form of radar guidance which requires the most complex missile borne equipment. On the other hand it is the form which offers most independence to the missile and hence greatest fire power and interoperability. Advances in technology make it increasingly practicable (see later).

Radar active homing systems now in service are mostly large anti-ship missiles. An example is Sea Eagle. Fig. 17 shows four Sea Eagle missiles on a Buccaneer, and fig. 18 shows a large (about 35 cm in diameter) anti-ship active radar seeker. It is a completely autonomous surveillance and tracking radar. Its engineering development started in the mid 1970's and gave particularly valuable experience in the full utilization of a programmable digital computer integrated into a radar seeker.

7. ADVANCES IN TECHNOLOGY

Anti-aircraft and anti-ship radar guided missile systems developed and brought into service over the period 1950 to around 1980 have been outlined. The technology underlying these systems has been continually advancing and in the case of electronic technology at a dramatic and accelerating pace, so that succeeding generations of these long established families of anti-aircraft and anti-ship weapons have greatly improved.

A further consequence has been a vigorous development over the past decade of radar guidance beyond anti-air and anti-ship applications to a variety of munitions (missiles, shells, drones and other unmanned flying vehicles) against a variety of battlefield targets (radars, armoured vehicles and fixed targets such as bridges).

The requirements of these extensions of radar guidance to the battlefield are much more demanding than ever before. For example, to distinguish the radar reflection signal of a tank from 'clutter', is a very much more difficult problem than picking out an aircraft or ship target from their 'clutter' backgrounds. Another example is the complexity of the problems of guiding a munition against a battlefield radar. The first requirement here is to pick out only the train of pulses from the target radar despite the presence of the 'clutter', which in this case takes the form of millions of pulses per second from other radars. Both these very different examples of tank and radar targets call for more complex signal processing, possibly including pattern recognition capabilities in real time.

Despite requiring such unprecedented capabilities, many of these future battlefield radar guidance equipments must also be of much smaller size and cost, since battlefield targets such as tanks and radars

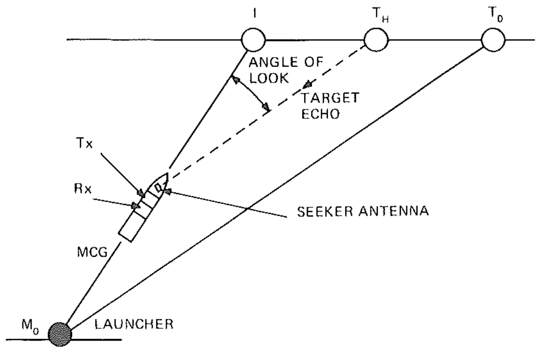

Fig. 16. 'Active Homing' form of radar guidance

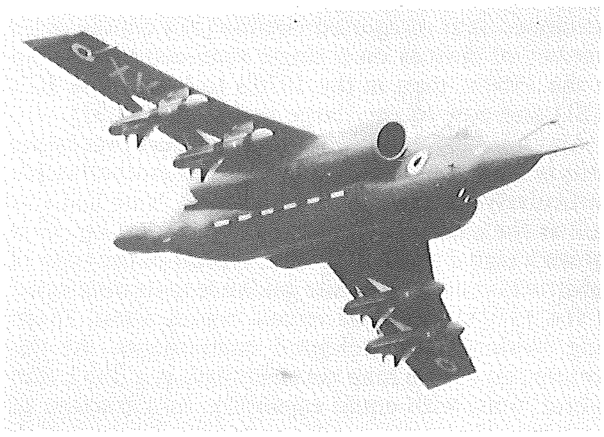

Fig. 17. Four Sea Eagle missiles on a Buccaneer

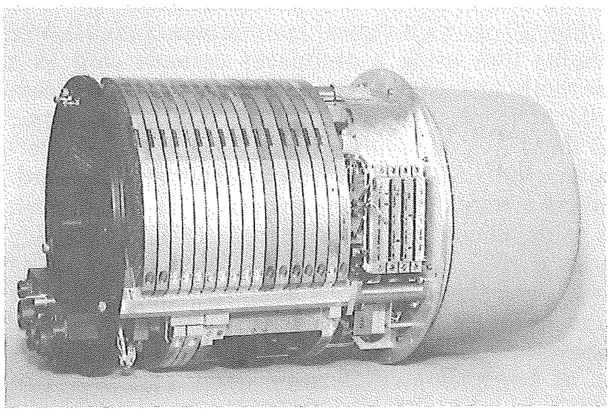

Fig. 18. Anti-ship active radar seeker, about 35 cm diameter

are much more numerous, and individually of much lower military value, than aircraft and ships. Appropriate munitions against such targets are relatively small and low cost (guided shells, submunitions and drones), calling for advances in technology which will now be considered.

7.1. Signal Processing

The dominant factor in the advancement of radar guidance within the past decade and into the foreseeable future (as for all data handling and communication systems) is the extraordinary and continuing development of semiconductor monolithic integrated circuit technology. The original discrete, encapsulated diodes and transistor of the 1950's developed into integrated circuits (IC) containing a number of devices on a single semi-conductor chip in the 1960's, then in the 1970's to large scale IC's (LSI) and now to very large scale IC's (VLSI).

Another fundamental advance in signal processing units is the use of thick film hybrids as motherboards particularly for circuits using many IC's or LSI's as well as for analogue circuits. At the top of fig. 19 is shown a signal processing unit, typical of the type of construction used in missile guidance units developed in the 1970's: a printed circuit board, about 18 cm long, with discrete soldered components. At the bottom, on a 4 cm long ceramic card, is a 'thick film hybrid' unit, with equal capability, in a fraction of the size. The pattern of conducting tracks which interconnect active and passive circuit elements of the thick film hybrid, is similar to that of the printed circuit board, but much reduced in scale.

Fig. 20 shows a typical contemporary signal processing unit using a multilayer ceramic card as a motherboard. Mounted on its surface are 14 encapsulated 'leadless component carriers' (LCC's). Some of these LCC's comprise simply a number of interconnected LSI mounted on a small ceramic card, others are small thick film hybrids. This sort of unit, if using silicon integrated circuits (SIC's) available around 1980, could be equivalent in digital memory and processing capability to about half a million transistors. With present SIC's, this figure could become about two million and by 1987 there is likely to be a further multiplication by at least two. This unit exemplifies the type of signal processor, now well established, of unprecedented power yet of much lower size and cost, which can meet the battlefield munition requirements described in the preamble to this section.

7.2. Microwave Circuits and Antennas

As well as the developments in signal processing just described, advances in microwave technology also have been essential for improved and miniaturised radar guidance systems.

'Stripline' transmission for microwave signals is generally very much smaller and lower in cost than waveguide and various forms for antennas and microwave circuits continue to be developed: it comprises thin metal film conducting tracks on an insulating substrate. One form of stripline, termed 'triplate', can be sandwiched together in layers. Fig. 21 shows a monopulse dipole array antenna with its associated feed and sum and difference microwave circuits as a thin sandwich about 10 cm in diameter and a few millimetres thick (it is shown mounted on top of the unit of fig. 22).

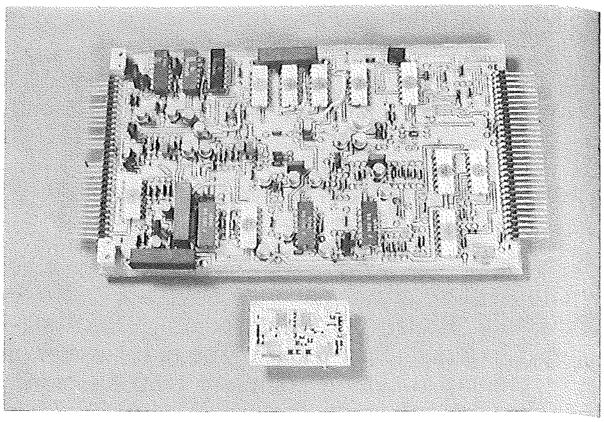

Fig. 19. Signal processing units: top – discrete components on PCB motherboard, 18 cm long: bottom – thick film hybrid, 4 cm long

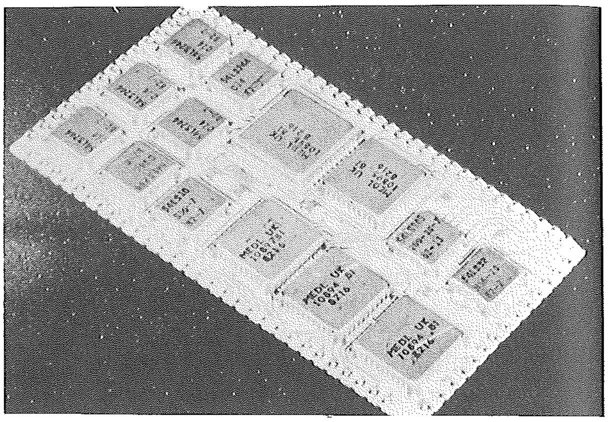

Fig. 20. Multi-layer ceramic card with surface mounted LCC's, 10 cm long

Another form of stripline is 'microstrip' where the conducting tracks are deposited on a rigid substrate of alumina or quartz. Microwave integrated circuits, MIC's, are stripline circuits which have active and passive components (diodes, switches, circulators) bonded into them. Fig. 22 is a microstrip MIC for mounting on the back of the gimballed monopulse antenna of a 12.5 cm diameter missile system.

The monolithic form of MIC has been emerging over the last few years and offers a remarkable potential for miniaturisation (of the order of 1/500 reduction in area compared with hybrid MIC's) and low cost in high volume production. In the monolithic form of MIC both the thin film tracks and the semiconductor devices are formed on a common semiconductor substrate. Fig. 23 shows the surface of the circuit, about 1 mm long, of a 10 GHz GaAs FET amplifier.

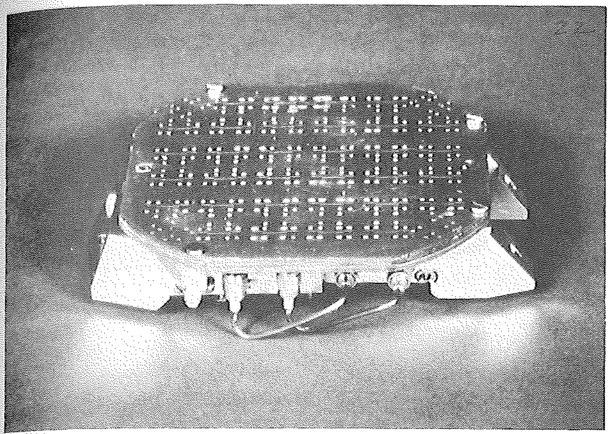

Fig. 21. Triplate antenna and microwave circuits, 10 cm diameter mounted on MIC of fig. 22

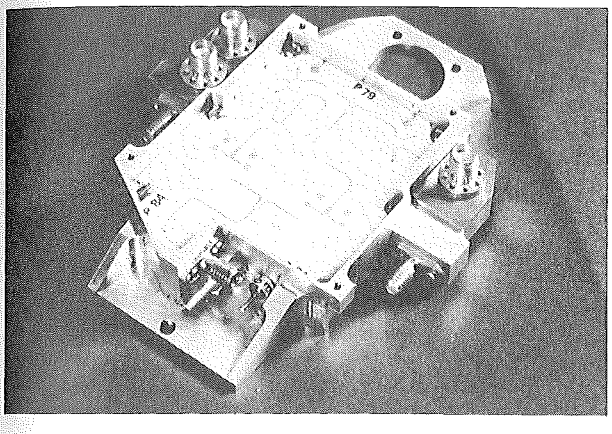

Fig. 22. Hybrid microwave integrated circuit (part of a gimballed antenna system for a 12.5 cm diameter missile)

7.3. Miniature Transmitters

A variety of forms of miniature microwave transmitters, particularly vital for future anti-air and anti-armour munitions to give them 'active', self-contained homing guidance, are now well advanced in development for missile diameters from 18 cm down to 10 cm.

7.4. Millimeter Wave Radar

Increasing attention has been given over the past decade to millimetre wave radar systems. Anti-air and anti-ship radar seekers presently in service operate around 2 to 3 cm in radar wavelength (15 to 10 GHz in frequency): this is a consequence of these systems operating out to seeker ranges of 30 km or more. Because of atmospheric and rain absorption, such ranges are only practicable at wavelengths at or above 2 cm. As is shown in fig. 24, as the radar frequency increases from 15 GHz (2 cm) atmospheric attenuation rises rapidly. There is, however, a 'window' at 8 mm wavelength (35 GHz) which allows a maximum range of say 10 to 15 km and another at 3 mm wavelength (95 GHz) for radar ranges less than 10 km. These millimetric radar ranges are adequate for most battlefield radar seekers and sensors. The

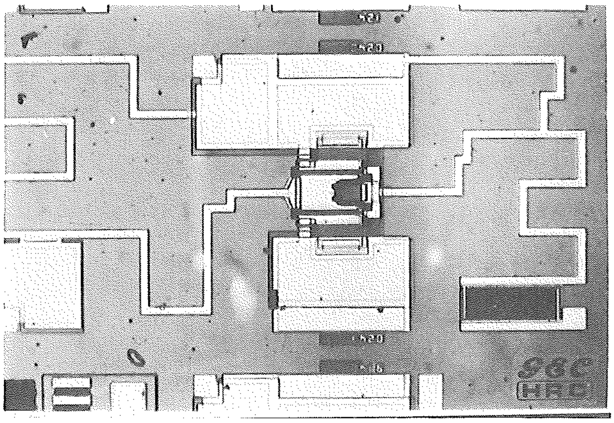

Fig. 23. Monolithic microwave integrated circuit, 1 mm long

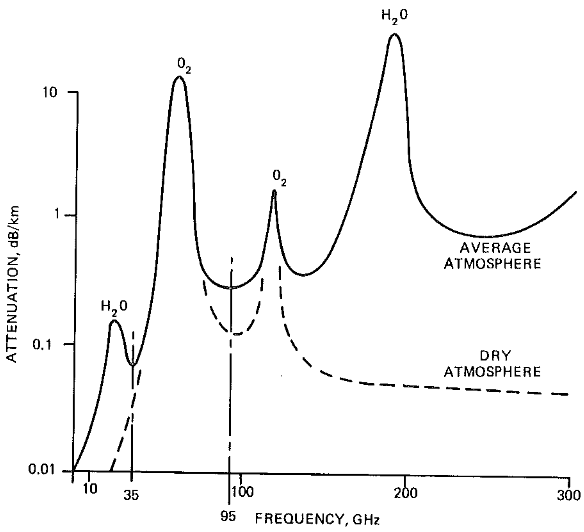

Fig. 24. Radio frequency attenuation in clear atmosphere

great attraction of millimetre wave radar is that both the beamwidth of antennas and the linear size of microwave circuits reduce in proportion to the wavelength. Thus, if D is the diameter of the antenna, the beamwidth in degrees is given by

$$\text{Beamwidth} \simeq 70\,\lambda/D \qquad (4)$$

For example, a 10 cm diameter antenna at $\lambda = 3$ mm (95 GHz) has a beamwidth of only 2°, the same as a 1 metre diameter antenna at 3 cm (10 GHz).

For many years now a very wide range of millimetre radar components have been designed, developed and manufactured by Marconi supported by the GEC Research Laboratories. These components are available now for application to future millimetre wave radar seekers. A striking example is shown in fig. 25. This is a complete 95 GHz active radar, apart from the antenna, whose maximum dimension is only 9 cm. It is in development for all weather terminally guided anti-tank submunitions down to 10 cm in diameter. It has two sum channels so that the two components of polarization can be

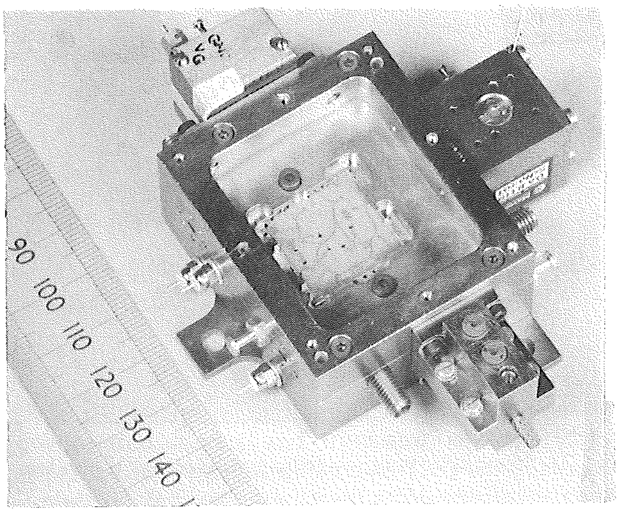

Fig. 25. 95 GHz active dual polarization radar: complete except for antenna (9 cm long. Hybrid MIC in centre 2 cm square)

processed to assist the discrimination of a tank from other objects (see later).

It includes a solid state coherent transmitter and local oscillator. At its centre can be seen a 2 cm square hybrid MIC, taking inputs from the transmitter and local oscillator and connecting to two antenna feeds. This small MIC comprises the complete microwave system incorporating switches, circulators and balanced mixers. Fig. 26 shows the layout of a typical possible design of a 95 GHz active radar seeker.

7.5. Inertial Reference Systems

Inertial reference units (IRU) are now available, small enough in size and cost for even quite small missiles, whose outputs can be processed by the sort of digital processor described earlier to form a missile inertial navigation system (INS). Such INS can now provide a mid-course guidance system preceding terminal homing by either an active radar or an anti-radiation seeker.

8. FUTURE ANTI-AIR MISSILES

Fig. 27 shows a proposed guidance section for a 15 cm diameter anti-air missile. Its radar seeker for terminal active homing includes a transmitter as shown. There is a digital signal processor which, as well as being part of the radar seeker, also provides an inertial navigation system for mid-course guidance, using inputs from the inertial reference unit shown.

An outstanding further feature of this design is the use of a fixed fed, moving reflector, cassegrain antenna system. This is a very much simpler and lower cost antenna system than in any previous anti-air seeker. It is now feasible because, firstly, the IRU can be used as the reference for stabilising the antenna beam in space; secondly, the digital processor can carry out the axes transformations necessary for this stabilization and thirdly, the aberration of this antenna can be corrected by the digital

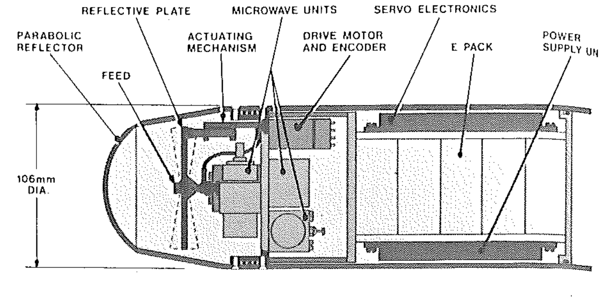

Fig. 26. 95 GHz active seeker, 10 cm diameter

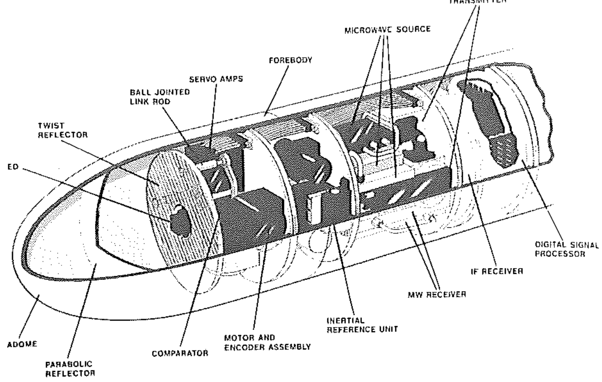

Fig. 27. Future anti-air radar seeker, 15 cm diameter

processor. This type of guidance unit will give future systems an altogether higher order of capability than current systems.

9. ANTI-RADIATION MUNITIONS

Radars are critical elements of the threat posed by an enemy, particularly on the battlefield where there will be dense ground to air defences, in the way of anti-aircraft artillery and missiles, which depend on associated surveillance and tracking radars. Anti-radiation munitions in the forms of missiles, drones and shells are being developed. An anti-radiation seeker in such a munition picks out and locks on to the radiation from a particular source and then steers the munition so as to home on to and destroy that source.

A large variety of radars must be dealt with, covering a very wide RF bandwidth (say 20 octaves) with a great variety of waveforms, one of which must be exactly picked out by the signal processor of the seeker. These requirements pose complex problems in the design of the antennas, microwave systems and signal processors of anti-radiation seekers. However, the advances in electronic technology just described, together with extensive experience in applying them in the fields of electronic warfare and electronic support measures, have greatly expanded the potential for anti-radiation seekers.

A major current programme is ALARM (Air Launched Anti-Radar Missile), now in advanced engineering development. Fig. 28 shows seven of

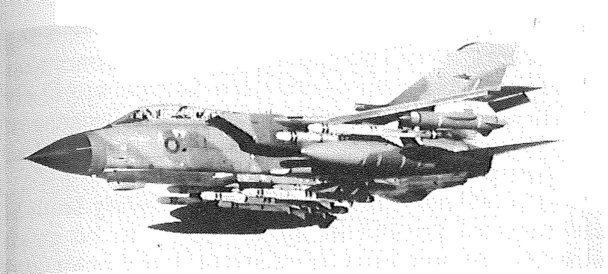

Fig. 28. ALARM (Air Launched Anti-Radar Missile) on Tornado (7 missiles – 2 black rings on nose)

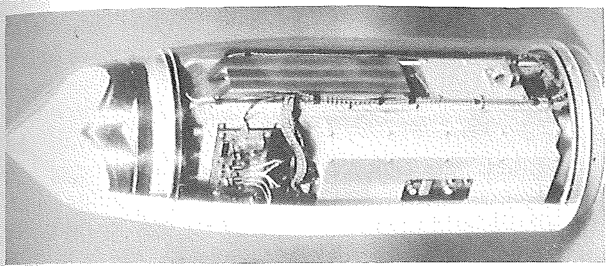

Fig. 29. Anti-radar seeker in ALARM, 22 cm diameter

these missiles on a Tornado. In the nose, behind a radome, is the Marconi anti-radar seeker, shown in fig. 29.

10. MEDIUM AND LONG RANGE STAND-OFF MISSILES (SOM)

At present, precision attacks on specific ground targets behind the enemy front line would be carried out by strike aircraft. Within the past decade there has been work within NATO (including international collaborative studies) on unmanned vehicles for such missions, in particular medium and long range missiles, launched within friendly zones from ground or air. Targets include both fixed objects (airfields, bridges, depots, air defence sites, etc) and mobile armoured vehicles.

Guiding these stand-off missiles beyond a certain range requires sensors for navigation over the terrain to the region of the targets, possibly followed by the operation of a target seeker for terminal guidance. Firstly, a navigation sensor is needed, certainly by the long range missile, which can produce an image of the features of the terrain over which the missile is flying to allow navigation by 'map-matching' or 'feature matching'. Then a terminal seeker might form an image of the target (e.g. a bridge, a group of tanks) from which the final aim point of the missile could be derived. Thus for these probably quite large missiles (say 40 to 50 cm in diameter) there is a need for both navigation sensors and target seekers using imaging techniques.

The use in World War 2 of mapping radar for navigation and for target seeking has already been referred to. What is needed now of course must be, and can be, better by many orders.

The angular resolution of an airborne radar can be improved by advanced forms of radar: 'synthetic aperture radar (SAR)' or 'Doppler beam sharpening'. Fig. 30 illustrates the idea of how a 'Doppler

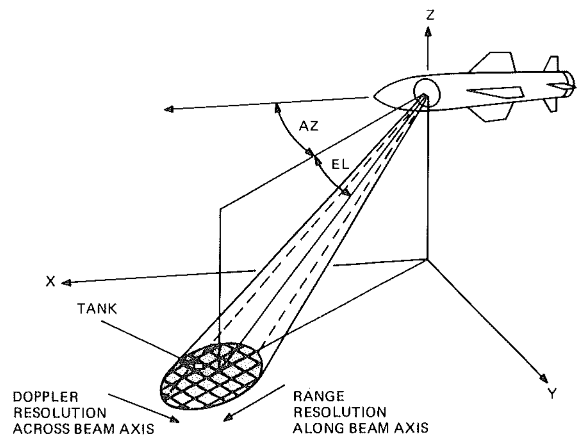

Fig. 30. Airborne radar with 'Doppler beam sharpening'

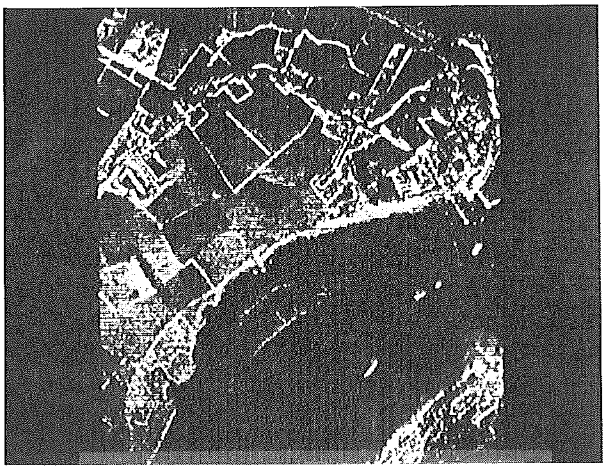

Fig. 31. Map by airborne synthetic aperture radar (SAR)

sharpened' airborne radar beam can produce an image of the ground using range resolution along the beam and Doppler resolution across the beam.

Fig. 31 is an example of a map (supplied by Marconi Research Labs) of a river estuary, from a modern SAR airborne radar. Roads and hedges are clearly defined with an image resolution down to a few metres.

The image resolution depends on Doppler resolution and range resolution. The Doppler shift across beam increases with radar frequency – the Doppler shift at 95 GHz is about ten times that at 10 GHz. Range resolution down to a fraction of a metre can now be achieved but this demands a signal processing bandwidth approaching 1 GHz, which is also easier at 95 GHz than 10 GHz. Thus a millimetre wave SAR might provide the best guidance for these missiles: its range is likely to be adequate.

11. THE PROBLEM OF DETECTING ARMOURED VEHICLES

As already mentioned (Section 7), distinguishing the radar signal of a target from clutter is much more difficult when the target is a tank than when the target is an aircraft or ship.

The reflected electromagnetic wave from an object illuminated by a radar has the following distinct parameters which are functions of the size, shape and surface reflectivity characteristics of the object: they can all be measured by a suitably equipped radar:

amplitude of the wave
angle of the normal to the wavefront, i.e., the instantaneous apparent direction of the target
range from radar
motion relative to the radar (Doppler shift)
polarization
phase

The first four of these parameters are commonly used in radar. In a radar designed to detect and track tanks, special features relating to these four parameters could be: high range resolution (fraction of a metre) to improve signal-to-clutter and to give the size of the tank along the beam: narrow beamwidth, possibly with Doppler beam sharpening, again to improve signal-to-clutter and to give the size of the tank cross beam. Millimetre wave radar can offer advantages in all these respects.

Polarization is not commonly used in radar with the notable exception of rain clutter suppression by filtering out the circularly polarized reflection from rain. However the scattering of polarisation by an object is a direct function of its shape and surface reflection characteristics. If a radar can receive, in two sum channels, (see fig. 25) the two orthogonal components of polarization of a reflected signal, then the detailed polarization 'signature' of the object can be derived.

The last 'discriminant' listed above – 'phase' – again has not commonly been utilized in radar but anti-armour radar seekers can be equipped to derive 'phase signatures' which are characteristic of different types of objects. Its potential value relates to diffraction of an incident wave by an object, since a complete knowledge of the diffraction pattern, i.e. of the amplitude and phase of the wave reflected from an illuminated object, allows the deduction of its exact size and shape, down to a wavelength in magnitude, from Fraunhofer and Fresnel theory (cf. x-ray diffraction in molecular physics). A radar seeker, observing the object only from constrained viewpoints and with limited bandwidth, can only get partial, but nevertheless potentially valuable, knowledge of the object's diffraction pattern. Although complex phenomena underly this problem of distinguishing armoured vehicles from other objects, continuing work is towards demonstrating and validating adequate solutions of minimum complexity.

12. ANTI-ARMOUR MISSILES AND SUBMUNITIONS

The first anti-armour missiles were developed in the 1950's. They were ground launched and guided by an operator using optical command to line of sight via a wire. Later and currently, semi-active laser IR guidance has been used with launch from aircraft as well as from the ground. Most recently, imaging IR seekers have been used to allow autonomous operation. Millimetre wave active seekers are likely also to be used in the future particularly because of their better performance in bad weather, smoke, dust and battle debris.

Individual anti-armour missiles separately launched from the ground or air are likely to be small missiles, say not more than 16 cm in diameter and 1.5 metres in length with a maximum range of at most 10 km. If about that range, they will have inertial midcourse guidance (similar in principle to the midcourse guidance for future anti-air missiles described above in Section 8) followed by terminal active homing by a 35 GHz or 95 GHz radar seeker.

Anti-armour submunitions, dispensed in the vicinity of a group of tanks from the sort of medium and long range stand-off missile already described, will be appreciably smaller and of shorter range than the above individual missiles. A typical terminally guided submunition (TGSM) might be 10 cm in diameter and say 0.6 metres long. A 95 GHz active radar seeker could be less than 30 cm long. Behind it would be a shaped charge warhead and then the aerodynamic control system. A TGSM is unlikely to have a motor, relying instead on its kinetic energy from the carrier missile.

12.1. The Multiple Launch Rocket System – Terminally Guided Warhead (MLRS-TGW)

The MLRS is a ground-launched unguided rocket for NATO forces, 23 cm in diameter with sufficient range to allow attack of second echelon enemy forces. At present it has only unguided warheads. A terminally guided warhead (TGW) has been under international development to allow the attack of a group of tanks. Thus MLRS-TGW is an example of a medium range stand-off missile for the attack of a group of armour, as already referred to in Section 10.

Marconi Defence Systems was a member of the ARMMR team (AEG-Telefunken, Rheinmetall, Marconi, Matra and Raytheon) which for over three years worked on the TGW to be carried by the MLRS. ARMMR's proposed TGW is illustrated in fig. 32. The proposed TGW comprised a set of six TGSM, 10 cm in diameter, with a 95 GHz active radar seeker, which are ejected from the rocket (as shown in the top of the figure). They then disperse and descend to fly horizontally (bottom of figure), each scanning for tank targets. Each TGSM then locks on to its own target and homes on to it.

13. THE WAY AHEAD

Fig. 33 shows an evolution of radar seekers. The three on the left are anti-air target radar seekers which in general terms do a similar job. The large one on the left is Sea Dart – technology vintage 1962 – the next is Sky Flash – vintage 1972 – the next on the right is a 125 mm diameter seeker – technology vintage 1976. The fourth seeker, last on the right, is an active, 100 mm diameter, anti-armour seeker. The

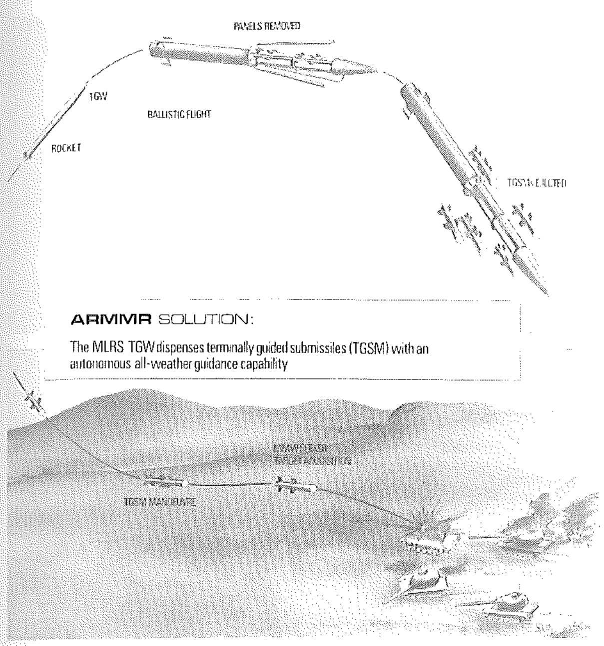

Fig. 32. The MLRS/TGW dispensing terminally guided submunitions (TGSM's) with autonomous all weather guidance by active MMW radar

dramatic reduction in size mainly reflects the advances in electronics which have been outlined in this paper, but experience and improvements in system design have contributed. As well as the great reduction in size, the later seekers also have greatly increased signal processing capability with consequent improvements in performance.

The following summarizes the way ahead for radar guidance in the light of its evolution to date.

(1) Advances in electronics will continue to allow:
- reduction in size and cost
- increased reliability, standardization and interoperability
- improvements in performance
- shorter radar wavelengths
- wider fields of application of radar precision guidance

(2) Digital processors with software control will allow:
- improved use of data from sensors and pre-launch information
- pattern recognition and artificial intelligence
- flexibility

(3) Modernisation of guidance systems during the lifetime of weapon systems will become increasingly practicable as a consequence of (1) and (2).

(4) Multi-sensor seekers incorporating active radar/anti-radiation/infra red sensors all in the same seeker, with a common signal processor, will give improved discrimination, classification, identification and resistance to counter measures

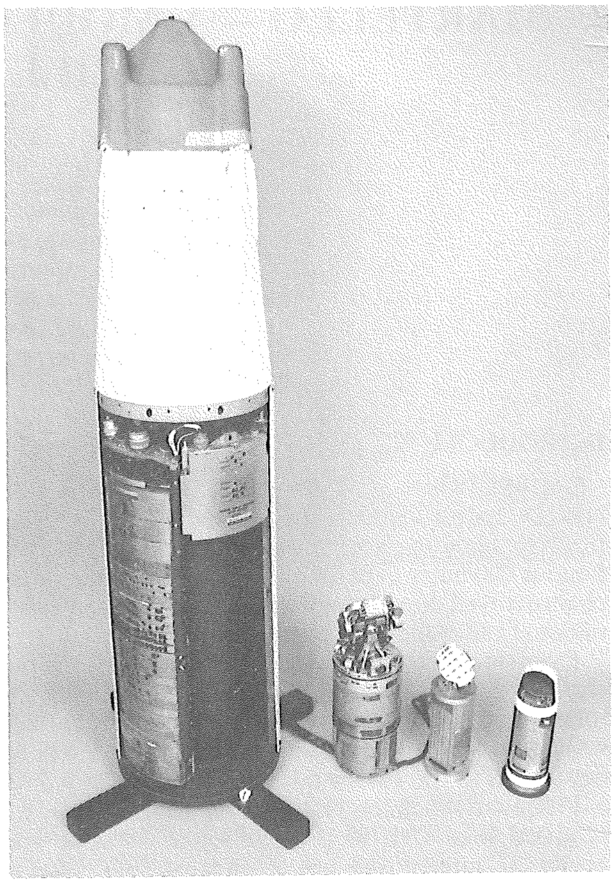

Fig. 33. Evolution of radar seekers: Sea Dart, semi-active, 40 cm diameter; Sky Flash, semi-active, 20 cm diameter; semi-active, 12.5 cm diameter and active, 10 cm diameter

ACKNOWLEDGEMENT

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