The early history of Australia's Radar - 1

The history and development of radar in other countries is well documented, but the Australian effort during World War 2, which proved to be of vital importance in the Pacific campaign, has received very little acknowledgement. Apart from two or three technical papers in the immediate post-war professional engineering literature and three articles by John Moyle in *Radio and Hobbies* in 1946, very little has been written about the development and manufacture of Australian-designed radar. In 1992, we commemorated the 50th anniversary of the introduction of Australian radar and the first bombing raid on Darwin in February 1942, so it is an appropriate time to present the technical history of our own radar undertakings.

by COLIN MACKINNON, VK2DYM

It is now generally accepted that radar was invented by a German engineer, Christian Hülsmeyer, in Düsseldorf, Germany in 1904 with the safety of passing ships in mind. His 'Telemobiloscope' detected ships up to 3000 metres away, but neither the Navy nor marine authorities showed any interest and he did not receive proper recognition for his invention until 1955.

Various radar-like systems were invented and promoted by others, including Marconi, over the period from 1905 to 1935 but none really showed commercial promise. However, in the early 1930's experimenters in a number of countries independently developed workable radar systems for military purposes. Numbered among those countries which by 1939 had significant radar developments were the United Kingdom, USA, Germany, Russia, Japan, France, Italy, Holland and Hungary. Because of the defence connotations much of the research was done in secret and isolation, but surprisingly the concepts and the resultant equipment in each country were quite similar.

One significant omission from this list of countries with radar capacity is Australia — despite the fact that it had a strong radio/electronics research group, under the auspices of the Radio Research Board (RRB). With the introduction of commercial broadcasting to Australia in 1923, it was found that radio waves acted in strange and unknown ways and so the RRB was established in 1926 as a unit of the Council for Scientific & Industrial Research (CSIR), to investigate radio propagation and other matters arising from the application of radio. Members of the RRB included the Universities of Sydney and Melbourne,

Fig.4: A rare photo of an ShD antenna mounted on a concrete building. The hydraulic rotation apparatus is in the steel clad frame supporting the array. The massive construction was necessary to withstand coastal storms.

How did World War II radar work?

The radar set of WW2 consisted of a powerful radio transmitter which sent out short pulses of radio waves via a directional antenna. When these radio waves struck any metal objects in their path, some of the energy was reflected back to the antenna. This minute echo or 'return signal' was amplified in a sensitive receiver and then displayed on a cathode-ray tube, as a vertical 'blip' on a trace moving from left to right.

As in an oscilloscope, the horizontal scanning of the CRT trace was arranged to be linear with time. Since radio waves travel at around 186,000 miles per second (300km/s), the time taken before the return signal pulse was received gave a direct indication of the distance to the target. A scale graduated in terms of distance could therefore be placed over the CRT, allowing the target distance to be read off directly from the horizontal position of the received 'blip'.

It all sounds very simple in theory, but the engineering problems back in the 1930's and early 1940's were daunting. A great deal of research and testing was required before a workable system was achieved.

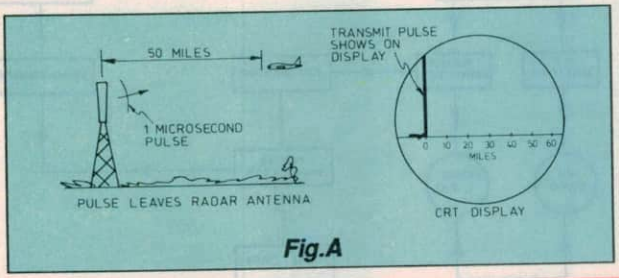

Fig.A

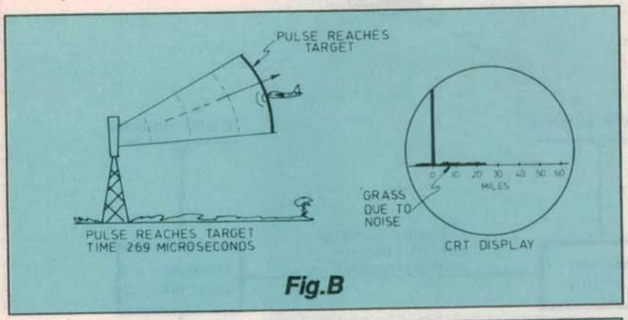

Fig.B

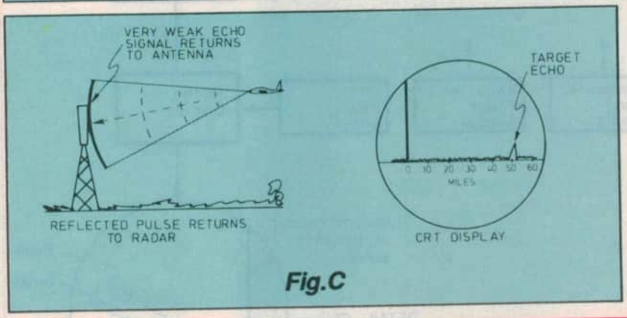

Fig.C

the PMG's Department and the Department of Defence.

By 1936, the universities had well established laboratories and field stations and were carrying out ionospheric sounding using continuous wave and pulse transmitters to probe the atmosphere and record the returning echoes. An ionospheric sounder comprises a transmitter which sends out a radio wave via an antenna, vertically into the atmosphere. An accompanying receiver measures the echo, and the time delay between transmission and reception is an indication of the height of any reflecting layer in the ionosphere.

Had they but realised, the ionospheric researchers had within their grasp the building blocks of a practical radar set; but it appears that no-one in Australia even considered the possibility of obtaining echoes from target objects.

One might well have expected the defence forces to ask about the possibility of using radio echoes for locating enemy ships, but it seems that there was no such vision. The perception of radar only became evident to Australian scientists when one or two visited the UK in the mid-1930's, and became aware of secret research being carried out by their colleagues, using radio pulses for locating targets.

Even when this was communicated back to the RRB in late 1938 by Dr John Piddington, an Australian scientist who had been studying in England and working on aircraft location by radio direction finding, no interest was shown. The significance of this total lack of radar research in Australia will become evident as we follow the story of Australian radar.

Early research

In February 1939 Australia, along with other Commonwealth countries — namely Canada, New Zealand and South Africa — was invited to England to learn 'of a matter of the utmost secrecy involving radio': the secrets of British radar, or as then known, Radio Location. It was logical that the CSIR should be involved because of its expertise in radio research, and when the importance of the British revelations became clear it was decided to establish a Radiophysics Laboratory (RPL) within the CSIR, to carry out research and development of radar under British guidance. The name 'Radiophysics' was chosen to minimise suspicion as to the true purpose of the laboratory, which was set up in the National Standards Laboratory building at Sydney University.

Following consultation between the UK and Australian representatives, the first projects for the new research laboratory were to be:

1. 'ShD' or Shore Defence radar (sometimes also called 'CD', for Coastal Defence);
2. 'GL' or Gun Laying radar (i.e., to assist anti-aircraft gunnery); and
3. 'ASV' or Air to Surface Vessel radar.

Government and defence thinking at the time was that Australia had little to fear from air attack and therefore could concentrate on ShD equipment to safeguard its shores from warships, with ASV radar to permit our aircraft to find enemy ships. GL equipment would be used with anti-aircraft guns to counter the slight possibility of nuisance air attacks.

The emphasis for the RPL was on research, to assist the UK by developing and testing new radar equipment and deriving a better understanding of the techniques involved. The initial intention was for Australia's few radar equipment needs to be supplied from the UK, with some local design and assembly.

While Australian scientists were in England in 1939 to learn about the UK radars, they did order samples of UK radar equipment. By this time the UK radar warning system, the 'CH' or Chain Home system was in operation on frequencies around 25MHz, and development was proceeding on smaller and transportable sets that could fill the gaps in the CH system. These included the CHL, for Chain Home Low, a 200MHz fixed radar with a rotating antenna array suitable for long range detection of low flying aircraft, and the MB2 or Mobile Base Mark 2, a 40MHz semi-portable version of the CH radar using two tall wooden towers with fixed dipoles and capable of long range warning of high flying aircraft. Australia ordered samples of each of these, as well as some ASV and GL radar sets, but Britain was only able to supply a few of them due to the onset of the war in Europe.

The Radiophysics GL and ASV projects proceeded as far as the prototype stage, but were failures because they of-

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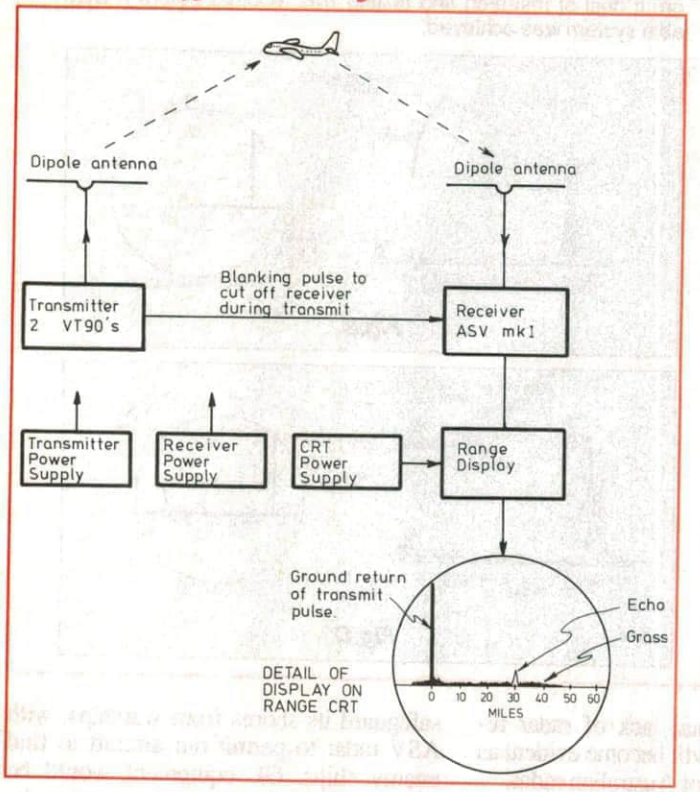

Fig.1: A block diagram of the first radar set developed in Australia by the RPL team, in May 1940. Called the J2, it used two separate antennas and was based on the British ASV.

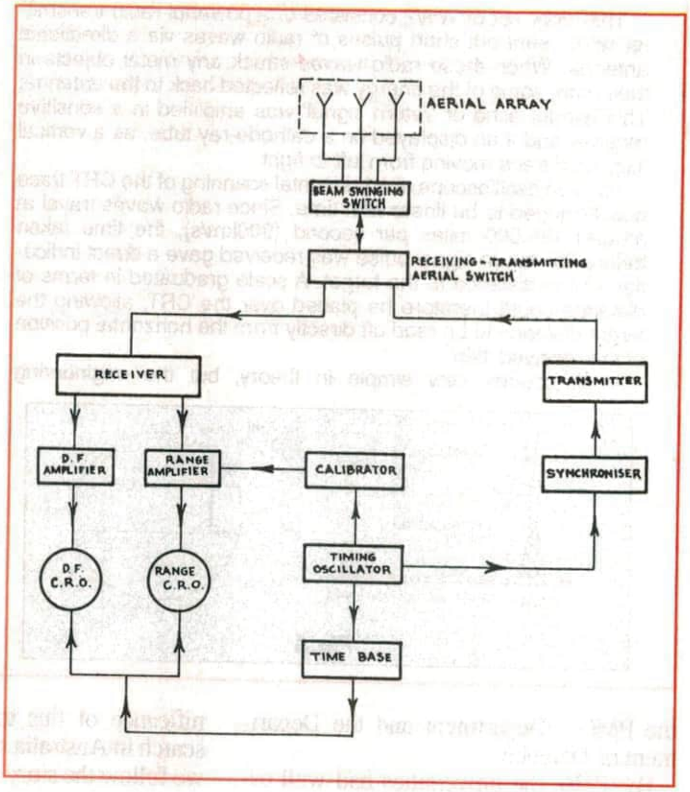

Fig.2: For comparison, here is the block diagram of the complete 'ShD' or Shore Defence radar. This was based on the J3 prototype, which evolved in early 1941.

fered no better performance than the original UK models and were eventually abandoned in favour of improved UK equipment. Local manufacture of a copy of the UK ASV MK II did commence later in 1941, but was contracted out to the Gramophone Company, part of EMI.

The ShD project proceeded satisfactorily, although very slowly. The RPL did not seem to have a sense of urgency — no doubt influenced by the prevailing notion that Australia was safe due to its isolation. The military advisers and the government were happily telling the population that Australia was under no threat. Despite the fact that the military establishment was represented on the Radio Advisory Board, a body which had been set up to guide the RPL, the defence forces showed little enthusiasm and at higher levels there was a great lack of technical understanding of radar.

The actual work was in the hands of young scientists, some with very little electrical knowledge and more used to unhurried experiments using one-off test equipment in a cloistered environment. We should also keep in mind that the entire scheme had the highest security classification ('Most Secret'), and this stress on total secrecy bordered almost on paranoia.

It meant that only Government departments could be trusted with the manufacture of radar components. Therefore the PMG's Department and the NSW Government Railways carried out the bulk of the manufacture at this stage.

First steps

Because no-one in Australia had any practical experience with the operation of radar, the initial RPL effort centred on construction of a working set to gain experience in the techniques and operation of radar. RPL technicians built and tested several simple transmitter and receiver circuits, which essentially repeated previous experiments by an English research team working on airborne radar back in 1937-38 under the leadership of Dr E.G. 'Taffy' Bowen.

This early work by RPL from late 1939 to mid-1940 provided them with much needed experience in electronics and RF circuitry. Frequent reference was made to the ARRL amateur radio handbook, as RPL staff struggled to become RF designers.

By May 1940 a radar set designated the J2, based on a sample of the UK ASV Mark I, was installed in a research station at Dover Heights on Sydney's coastline. It incorporated a push-pull oscillator with two newly-developed valves called the VT90 or 'micropup', giving a pulse output of about 4kW. The receiver was an ASV model imported from England, and it was initially housed in a separate hut.

The transmitter and receiver each had a single dipole aerial. A timebase, an oscilloscope display and other ancillary units were built by RPL to form a rudimentary radar set. This first full working set was able to detect ships and low-flying aircraft at a distance of up to six kilometres, but was obviously inadequate for practical use.

In July 1940, a complete ASV MkII transmitter also using VT90 valves, and a production version of the UK Pye ASV receiver was received from the UK and installed in the second hut at Dover Heights, to gain more operating experience in ship and aircraft detection. This ASV MkII radar operated on a revised frequency of 176MHz, whilst other UK and Australian ground radars were designed for 200MHz.

Trials of the J2 and the ASV continued until about September 1941. See Fig.1 for a diagram of the basic system.

The RPL scientists spent much time and effort improving the timebase of their radar, and it is important to understand the reasons. The ASV transmitter used what is known as a 'squegging' oscillator circuit, wherein a small capacitor in the plate circuit is discharged until the grid bias voltage reduces to a point where the circuit breaks into oscillation. The resulting current flow re-charges the capacitor until it cuts off the grids and stops the oscillation. By adjusting the component values, the period of oscillation could be reduced to a few microseconds, with a pulse recurrent frequency or 'PRF' of about 500 pulses per second.

It is a simple system, and importantly for aircraft use, provides a lightweight design. However, circuit and valve tolerances caused random fluctuations in the output frequency, timing and PRF. This did not matter so much in the ASV role, where an aircraft picks up a return echo and then 'homes in' on the signal until the target is visible; an initial range error of a mile or two does not affect the result.

However in the proposed ShD role, the distance to the target had to be measured precisely — within just a few yards — to allow accurate gun laying. Consequently RPL changed their circuit to a more conventional RF oscillator driven by a modulator, with a very accurate timebase, so that the controlled pulse width and PRF guaranteed accurate range reading.

A working prototype

In January 1941, following on from the work with the J2 and the ASV MkII, an improved radar set design was installed at a second field station at Brookvale, north of Sydney. This set, called the J3, was again based on the UK ASV MkII design but included a locally designed synchroniser with the improved timebase, and other ancillary electronics.

The receiver was modelled on the ASV MkI, after trials with alternate receiver designs showed no advantages. The antenna was a 16-element phased array and RPL had by now developed a method of using one antenna for both transmit and receive.

This radar was operated under field trial conditions by RPL and Army technicians through to September 1941. At this stage the emphasis was still on Shore Defence and Gun Laying, both of which required very accurate range finding but with a maximum range of only 40km. The J3 performed satisfactorily, despite a number of annoying failures due to the poor quality of locally made components, and formed the basis for the ShD and other radars that followed.

The J3 transmitter employed two VT90 'micropup' valves in a grid tuned, push-pull oscillator circuit with Lecher line tuning. Another Lecher line was loose-

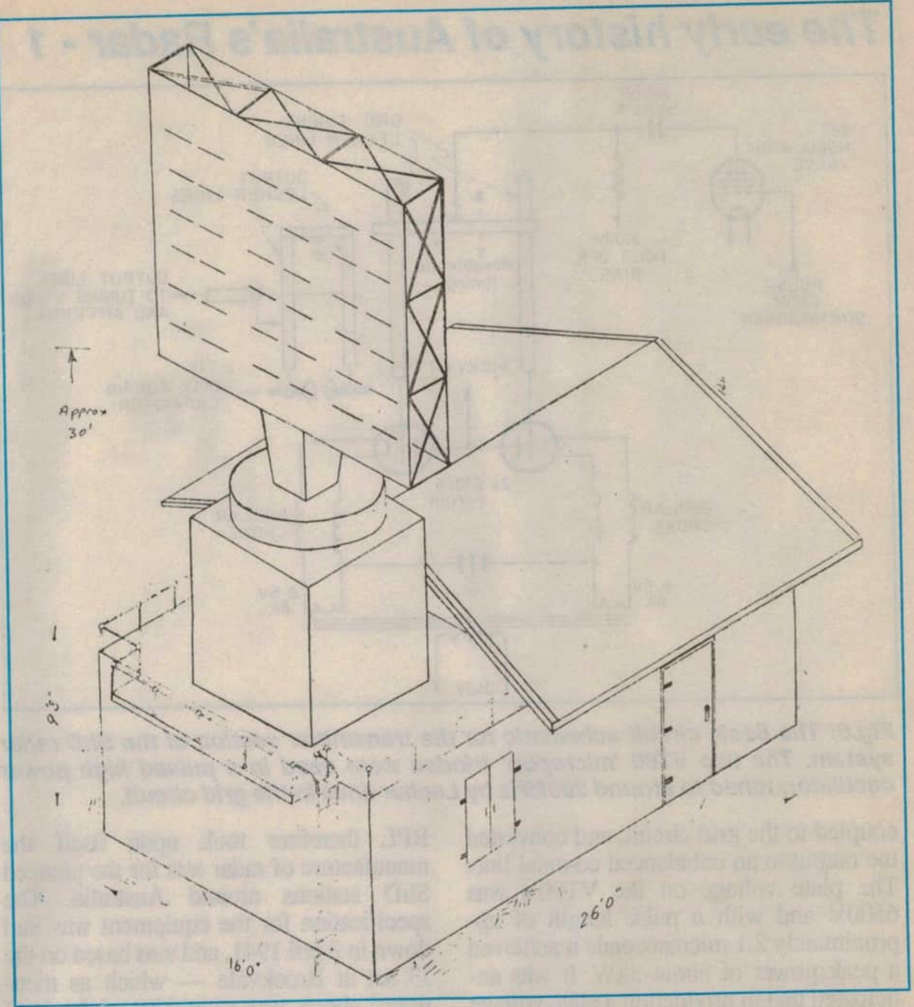

Fig.3: An original design sketch for an ShD installation based on a two room hut with the rotating antenna mounted on top. Compare this with the photo of Fig.4.

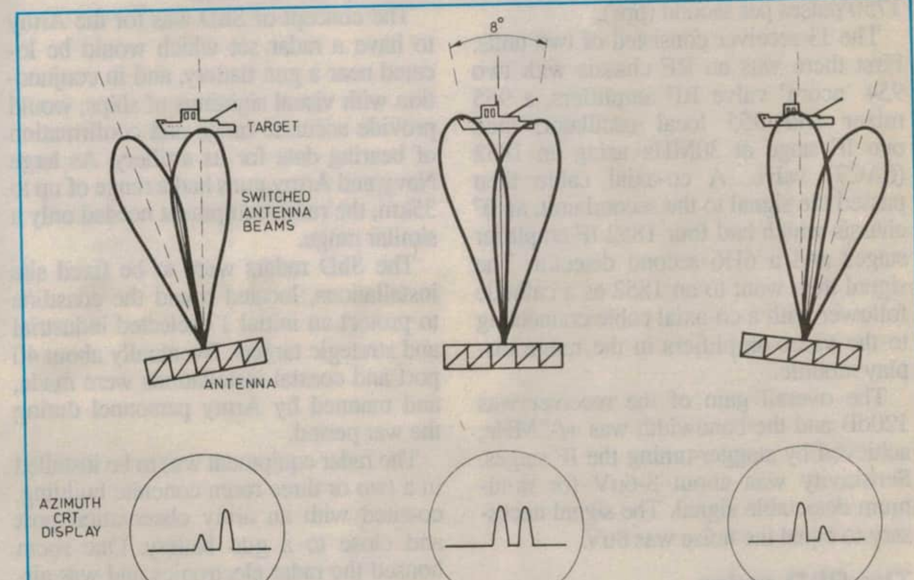

Fig.5: A diagram which illustrates the concept of 'beam swinging', which was used to provide greater accuracy in determining the azimuth bearing of a target. The correct setting was achieved when the two blips were of equal height.

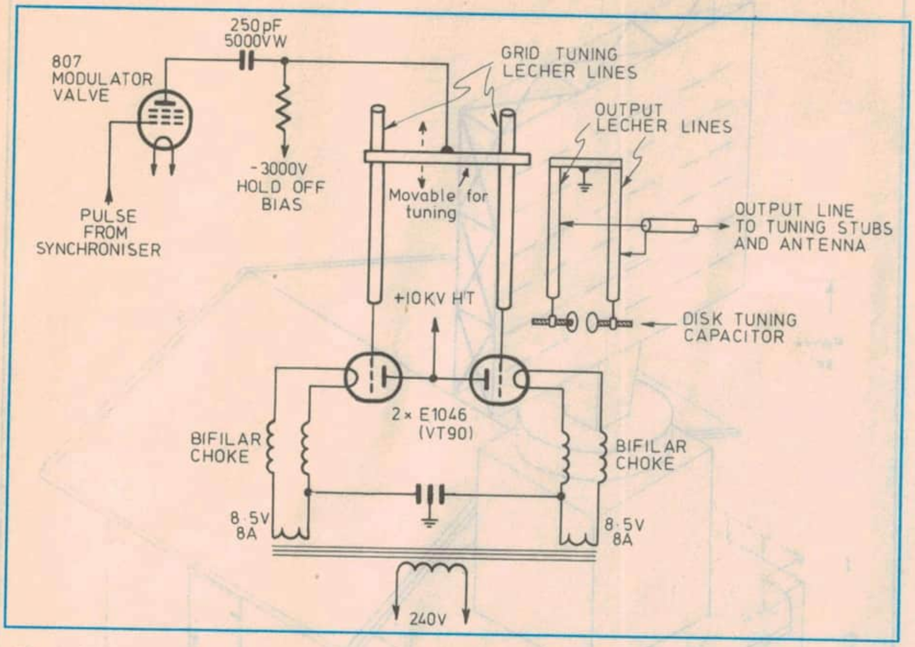

Fig.6: The basic circuit schematic for the transmitter section of the ShD radar system. The two VT90 'micropup' triodes were used in a pulsed high power oscillator, tuned to around 200MHz by Lecher lines in the grid circuit.

coupled to the grid circuit, and converted the output to an unbalanced co-axial line. The plate voltage on the VT90's was 6500V and with a pulse length of approximately 2.1 microseconds it achieved a peak power of about 3kW. It was anticipated that in production a plate voltage of 10,000V would be possible, to give a 10kW pulse.

The pulse repetition frequency was 1750 pulses per second (pps).

The J3 receiver consisted of two units. First there was an RF chassis with two 954 'acorn' valve RF amplifiers, a 955 mixer and 955 local oscillator, then one IF stage at 30MHz using an 1852 (6AC7) valve. A co-axial cable then passed the signal to the second unit, an IF chassis which had four 1852 IF amplifier stages and a 6H6 second detector. The signal then went to an 1852 as a cathode follower with a co-axial cable connecting to the video amplifiers in the range display module.

The overall gain of the receiver was 120dB and the bandwidth was +/-2MHz, achieved by stagger-tuning the IF stages. Sensitivity was about 3-6uV for minimum detectable signal. The signal necessary to equal the noise was 8uV.

The ShD radar

By mid-1940, with the war in Europe going badly and equipment from the UK simply unavailable, it was clear that Australia would have to become virtually self-sufficient in radar production. The RPL therefore took upon itself the manufacture of radar sets for the planned ShD stations around Australia. The specification for the equipment was laid down in April 1941, and was based on the J3 set at Brookvale — which as mentioned above, was a variation of the ASV MkII transmitter and ASV MkI receiver designs. See Fig.2 for a block diagram of the complete ShD radar.

The concept of ShD was for the Army to have a radar set which would be located near a gun battery, and in conjunction with visual sightings of ships, would provide accurate range and confirmation of bearing data for its artillery. As large Navy and Army guns had a range of up to 35km, the radar equipment needed only a similar range.

The ShD radars were to be fixed site installations, located round the coastline to protect an initial 17 selected industrial and strategic targets. Eventually about 40 port and coastal installations were made, and manned by Army personnel during the war period.

The radar equipment was to be installed in a two or three room concrete building, co-sited with an army observation post and close to a gun battery. One room housed the radar electronics and was air-conditioned to maintain the calibration and stability of the electronics; the second was the living quarters, and the third was an observation post, if one was not already available.

The large aerial array had to be about 80-90 metres above sea level, and in most cases a tower around 9m high was mounted on the roof of the building. But for low sites, for example at Darwin, a separate tower was constructed — either 55 or 70m high. The tower base was designed by a young NSW Railways engineer, Mr Ern Bullock, so that even if one leg was destroyed the other three would maintain support.

A separate engine house suitable for a 20kW Ford V8 engine/generator was also constructed, although diesel engine/alternators became the preferred power supply.

A number of these buildings still exist, around Australia's coastline. A typical two-room ShD radar hut is located on Hill 60 at Port Kembla, NSW, whilst about 1km north along the beach there are two gun emplacements for 150mm (6") guns, next to the Army Command Post building — which is now a military museum.

RPL specified and designed the buildings, in collaboration with the Department of the Interior, arranged sub-contracts with other government departments and even assembled the first couple of ShD radar sets.

The PMG made cubicles and electronic assemblies while the Railways made antennas, turning mechanisms and other mechanical components. The PMG was responsible for sub-contracting out the construction of the antenna towers which had been designed by the NSW Government Railways. See Fig.3, a design sketch of the ShD installation, and Fig.4, a photo of an ShD installation.

The first three sets to meet the requirements for ShD were built by the RPL in prototype form and were known as the type CA No.1 MkI. With minor improvements and changes to simplify manufacture, this design became the CA No.1 MkII in full-scale production.

The aerial for the ShD set was a phased array of 36 elements (6 x 6) on an angle iron frame about 5.5m wide by 4m high, covered with a 25mm reflector mesh and weighing several hundred kilograms. It was designed to withstand coastal gales.

Originally the array was fed via 70-ohm co-axial cable, but this was soon replaced by 300-ohm open wire feeders which were easier to adjust for correct phasing. Aerials mounted on the 55m or 70m towers were connected via rigid 50mm diameter co-axial line.

To obtain accurate bearings on the target, a technique known as 'beam-swinging' was used. The aerial elements were connected in three side-by-side sections, and the feeders were arranged so that extra capacitance could be switched into line between the outer two sections at

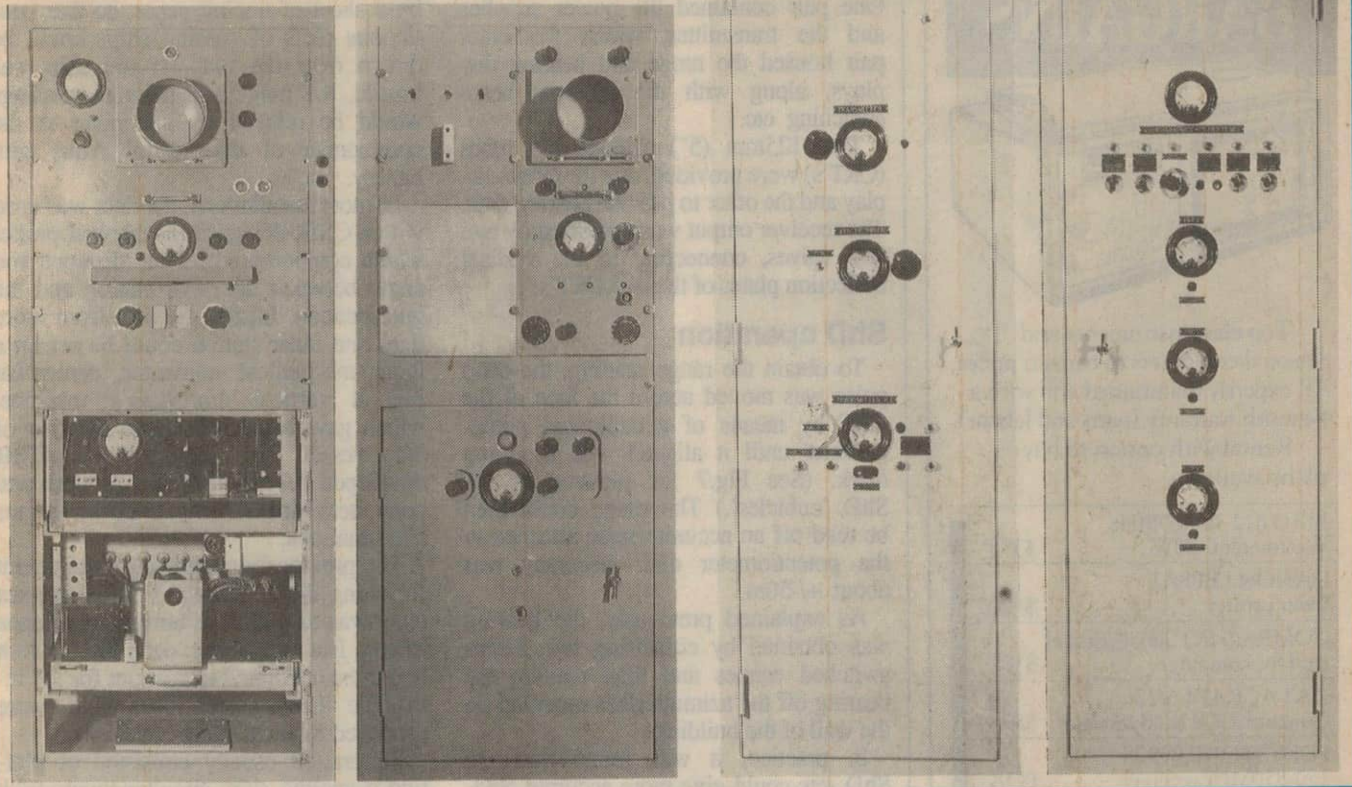

Fig.7:Photos of the original prototype for the ShD radar. From left to right are the range cubicle, with display at the top and time base unit below; next is the bearing cubicle with the bearing display and receiver below it; and finally, the transmitter and power supply cubicles.

about 20 cycles per second. This changed the phasing and caused the polar diagram of the beam to switch back and forth by about 8°.

The display on the oscilloscope was also switched so that two echo pulses appeared, one from each beam. In action the aerial was turned until both pulses appeared of equal height, and this gave a pointing accuracy of around 5' of arc compared to about 2° without beam swinging. See Fig.5 for the concept of beam swinging.

The array could be rotated back and forth through about 270°, driven by a hydraulic motor that was controlled either automatically or manually via servo valves. The bearing, or azimuth, of the array could be read from two dials mounted on the wall of the operating room. These were driven by selsyn servos, one dial showing 5° steps and the other reading to 5' of arc.

The VT90 valve used in the ShD and many other radars had been developed in the UK specially for radar pulse service, and featured an external cylindrical copper finned anode to allow effective cooling. The two VT90's were clamped directly into a circuit comprising two copper tubes as Lecher lines, with a disk type tuning capacitor between the lines as the grid tuned circuit. Output was taken via another close-coupled Lecher line.

The VT90's were held off by a 3000V negative grid bias until the synchroniser, which used an 807 valve, supplied a large positive pulse to the grids at a PRF of 1000 per second. The VT90's broke into strong oscillation with each pulse, for a period of about 1.5us. The operating frequency was around 200MHz. See Fig.6 for a circuit diagram of the ShD transmitter.

Whereas contemporary UK radars produced around 100-150kW, the ShD radar was restricted to only 10kW by the shortage of suitable valves. This was a problem that persisted through the first two or three years of the war, and determined the design of other Australian radar sets.

Although the RPL built and tested a number of different receivers for the ShD, and commissioned others from AWA, the one that was finally used in the ShD and subsequent radars was based on the British ASV MkII receiver and was very similar to that in the J3. It incorporated two RF amplifier stages using the 954 acorn valve, two 955 acorns as mixer and local oscillator, five IF stages at 30MHz with 6AC7 valves and a 6H6 second detector. A 6AC7 was again used as a cathode follower to feed signal to the display units. The bandwidth of the receiver was +/-1MHz. The first RF valve had to withstand a 20V pulse from the ground return echo of the transmitter, and then recover within 2us.

Those who have read of the development of British radar receivers will know that their IF assembly used a 45MHz TRF receiver, made by Pye for the UK television system.

Here in Australia a 30MHz IF was used because the same receiver was to be used with a 76MHz GL radar and it was felt to be a more stable amplifier when tuned to 30MHz.

Later on the receivers for ShD stations were standard ASV MkII sets, also with 30MHz IF, taken from production at the Gramophone Company on Parramatta Road, Sydney, and retuned to 200MHz input.

To house the various electronic sub-assemblies, four standard PMG 19" rack cubicles were bolted together in pairs. One pair contained the power supplies and the transmitter, whilst the other pair housed the range and bearing displays, along with the receiver beam switching etc.

Two 125mm (5") cathode ray tubes (CRT's) were provided, one for range display and the other to provide bearing data. The receiver output was amplified by two 807 valves, connecting to the vertical deflection plates of the two CRT's.

ShD operation

To obtain the range reading, the echo pulse was moved across the face of the CRT by means of a calibrated potentiometer until it aligned with a setting mark. (See Fig.7 for pictures of the ShD 'cubicles'.) The range could then be read off an accurate scale attached to the potentiometer dial. Accuracy was about +/-50m.

As explained previously, the bearing was obtained by equalising two beam-switched echoes and then reading the bearing off the azimuth dials mounted on the wall of the building.

In practice, it was found that the ShD sets could give more accurate readings than the Army's visual split-view range finders, and of course the ShD functioned in poor light and bad weather conditions.

During operation, the antenna array would be rotated automatically via the hydraulic motor through its arc of coverage, whilst an operator watched the range scope. Beam switching would initially be off, as it reduced the maximum range of the set.

When an echo became visible above the background returns and internal circuit noise (called 'grass' because of its appearance along the bottom of the display trace), the array would be switched to manual control and rotated to give the highest echo on the range scope. It would then be switched to beam swinging. Manual control was exercised via a large handwheel which operated hydraulic servo valves so that the array turned to match the rotation of the hand wheel.

After peaking the echo, the operator would turn the range potentiometer knob until the echo was aligned with a calibration mark on the tube. He would then read off the range in yards, from the potentiometer dial. A second operator watching the bearing scope would call out when he had two equal height return pulses, and a third operator would then read the large azimuth servo dials.

The operating room was fitted with a table and a local coastal map overlaid by a sheet of tracing paper, so that continuous plots of passing ships could be drawn over the map. If the ship was hostile, the range and azimuth readings would be relayed by telephone to the commander of the nearby Army gun battery.

In most installations, the data was used with a CSIR-designed mechanical plotter which compensated for the distance and angle between the radar station and the gun location. Ideally the data from more than one radar station could be set on a large mechanical converter, somewhat like a vertical draftsman's machine, which gave a more accurate location of the vessel by triangulation. CSIR developed several different plotters and converters for the Army, to cover various site situations.

The previously mentioned requirement for siting the antenna at 90m above sea level was to minimise unwanted antenna lobing. But before use, each ShD station had to be calibrated to account for the inevitable beam side lobes that were produced by local siting conditions.

Calibration usually consisted of plotting a passing ship, simultaneously with visual sightings to compare the range. Fixed echoes from nearby islands, etc., were also useful for setting compass bearings and for rechecking the performance of the set over a period of time.

Even so, side lobes were a significant problem, and the recent book *Radar Yarns* relates how the crew of the radar station at Port Kembla plotted some suspicious echoes which grew in number and caused considerable consternation within the Navy and RAAF. Eventually the 'invading ships' sailed 30km inland to somewhere round Liverpool, and it was realised that a combination of propagation effects and antenna side lobes had given false readings — much to the embarrassment of all concerned.

Whilst its design role was to track ships, the ShD could also detect aircraft, but was limited in its range and ability to detect high flying aircraft. Nevertheless some ShD stations did plot enemy aircraft successfully during the war. As it happened the threat to Australia's vital ports had passed by the time the ShD sets were installed, and they fulfilled only a watching brief for the duration of hostilities.

In the second of these articles, we will cover the development of the 'AW' or Air Warning radar.

(To be continued) ❖