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Derman Christopherson, E. C. Baughan

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Reminiscences of Operational Research in World War II by Some of its Practitioners: II

DERMAN CHRISTOPHERSON and E. C. BAUGHAN

In *J. Opl Res. Soc.* 40, 115-136, (1989), transcripts were given of four talks by some of the first OR workers describing their experiences during World War II. The present paper supplements these by recording notes, made by the speakers themselves, on two further talks on early OR which were given 'after-dinner' at the 1989 and 1990 International Symposia on Military Operational Research which is arranged annually at the Royal Military College of Science, Shrivenham, UK by Professor R. W. Shephard. By way of introduction to each talk, Professor Shephard has given a brief account of the speakers' careers and the chronology of the organizations of which they formed a part.

Key words: history of OR, World War II

The first work on Air Raid Precautions (ARP) was started by the Home Office in 1935 and was on a very minor scale. Only three officers were employed full-time on studies of shelter design, and protection against fire and gas, and much work was 'contracted out' to other departments. In the last quarter of 1938, however, the menacing political situation gave a considerable impetus to Civil Defence, more funds became available, and the Research and Experiments Branch to which Sir Derman refers was brought into being with much enlarged terms of reference. Further, in order to enable all the expertise that the country could muster to be brought to bear on the formulation and execution of a programme of research, a Civil Defence Research Committee was set up in May 1939 composed of eminent scientists and engineers from many branches of academia, industry, and government, and this played an important role throughout the war years.

The R&E Branch (which later became a Division of the Ministry of Home Security) moved to Princes Risborough from Horseferry House, London, on the outbreak of hostilities and rapidly increased in size. After heavy air-raids on the UK virtually ceased in 1942, the Branch was able to make good use of the knowledge it had acquired about the effects of attacks from the air by providing advice to the Royal Air Force on the best tactics and armaments to use in its raids on Germany.

Sir Derman had graduated in engineering from University College, Oxford, and spent three years as a Fellow at Harvard University before joining the R&E Branch in 1941. He was allowed to join the staff of the Engineering Department of the University of Cambridge very soon after the war finished on condition that he wrote up his wartime work. The report he completed, 'Structural Defence', is still regarded as one of the most authoritative texts on the subject. His career subsequently led him to posts at Leeds University, Imperial College, London, and to the Vice-Chancellorship of Durham. He served on a large number of governmental committees, was a member of the Council of the Royal Society and received many honorary degrees during this time. He retired as Master of Magdalene College, Cambridge, in 1985.

SIR DERMAN CHRISTOPHERSON

The starting point of any account of the situation with regard to air warfare or its consequences for the civilian population, as they appeared in 1939, must be to emphasize the total ignorance at that time of everybody and everything to do with the subject.

The only evidence which existed of what happens when high explosive is dropped on a town was derived from experience in the Spanish Civil War, mainly from one attack on Guernica. The published accounts of this were totally unreliable, in part because they had been written by journalists whose aim was to secure the largest possible headlines, and in part because the attackers (the Falangist Government) were seen as the ally of Hitler, and therefore to be represented as uncivilized as possible.

Almost no research on high explosive weapons or their consequences had been done by the forces in the inter-wars period, and what had been done was mainly about gunnery and armour-piercing shells – the lessons of the battle of Jutland had not been forgotten. For such an entirely new subject, the natural reaction was to create an entirely new Ministry, with a name that suggested a general atmosphere of calmness and peace. Hence the Ministry of Home Security was formed. The scientific arm of this Ministry was required to produce estimates of:

- (a) the nature and scale of the air attacks to be expected;
- (b) the number of civilian casualties expected in (say) the first three months of war;
- (c) the extent to which these numbers could be reduced by building – or finding – air raid shelters for everyone, and particularly for London, which was assumed to be the main target.

The Research and Experiments Division which set to work on these questions was located in Buckinghamshire, and had about 15 scientific and technical officers altogether. It was headed by Sir Reginald Stradling, the pre-war Director of the Building Research Station. The Engineering Division was headed by Professor John Baker, afterwards Head of the Cambridge Engineering Department, and the ‘Operational’ side was led by Professor J. D. Bernal, who disappeared after about a year to become Scientific Advisor to Lord Mountbatten as Head of Combined Operations.

What facilities did we have to do research and development?

- (a) For measuring what happens when a bomb is exploded we had, in the recently invented piezo-electric gauge, a way of observing the pressures generated in the atmosphere round the bomb, and the time they last.
- (b) We had facilities for doing full-scale explosions at Shoeburyness, and small-scale ones (which were, in practice, more informative) at Stewartby, near Peterborough, in a clay-pit, which before the war produced bricks. Also, the staff of the neighbouring Road Research Laboratory did a great deal of experimental work for us.

The Germans very obligingly started in the autumn of 1939 with attacks on a very small scale, so that we were able to observe a manageable number of incidents at any one time. They also conveniently, and perhaps sensibly, in the early months used mainly short-delay fuses, so that most bombs penetrated only a few metres into the earth before exploding, and thus presented us with very easily measurable craters. Within a very few weeks we were able to identify the size and types of the bombs employed simply by looking at the craters, and had a reasonable idea of the magnitude of the resulting earth movements.

By the time I myself joined the department – at the beginning of March 1940 – we had a fair idea of what we were up against, at least in the early stages. We knew that the number of casualties to be taken care of would not be unmanageable. We knew that industrial production, and civilian life in general, would go on much as usual. We had a fair idea that the economic effort which the enemy put into raids on the scale we had so far encountered was probably greater than the loss of production that they had caused us. But naturally we were anxious to shift the balance even more in our favour.

In addition, we knew that there was one hazard, which if skilfully employed, could produce a very different result – that is, if high explosives were replaced by incendiaries. Defence against fire was not part of our terms of reference, quite naturally, since a very well-trained and expert fire service already existed, backed up by an apparently inexhaustible supply of amateur ‘fire-watchers’. Common-sense suggested that we should recommend this line very emphatically to the people planning our own offensive operations; but it also suggested that if we adopted this policy, the enemy would certainly do the same, and since he was in a position to do so on a larger scale than we were, the outcome might be very unfavourable to our side. Accordingly, it was better to concentrate on our own job; in the first instance, the provision of air-raid shelters.

The very first shelters built in the streets of London before the war were unmistakably a failure. They consisted of a brick box with no reinforcement and therefore no ductility, and a flat concrete

slab as a roof. A very moderate impact was capable of collapsing one or more walls and the roof then fell in on the occupants. The citizens of London very quickly observed that this is what would invariably happen, and these shelters were largely unused. Very few of them were in fact built as a consequence.

The next attempt was the Anderson shelter which consisted of a rectangular hole in the ground, covered by an arch made of corrugated iron, which was then covered by the earth excavated from inside. A great many of these were made, and were used extensively in summer; in winter most of them filled with water and were so uncomfortable that most people preferred to stay at home.

The first successful shelters were based on the idea that one should not build shelters from scratch, but should make use of what was already available having been constructed for some other purpose. The most obvious example of this principle was the use of the London Underground Railways. This idea was the first one to which I made a contribution myself. At a very early stage the commonsensical Londoner went into the Underground of his own accord when the alarm sounded, and made his bed on the platform. The Government was somewhat alarmed about this tendency. It would obviously be silly to forbid such a sensible action. On the other hand, if it was officially encouraged and a bomb succeeded in penetrating one of the lines nearer the surface and exploding, there would be a disaster and the Government would be blamed. What was wanted quickly, therefore, was information about how far bombs in fact penetrated in normal circumstances.

The enemy provided this information in two ways:

- (a) by dropping some bombs with fuses timed long enough to ensure that they reached their final position before exploding;
- (b) by dropping a certain number of 'duds'.

The Army had made very efficient provision for coping with the latter, in the form of the 'Bomb Disposal Units' which were made up of very highly trained men whose task it was to dig the duds up and dispose of them. This they did very efficiently, and with far fewer casualties than one would have expected. They also were required to report on the depth at which the bomb was found, the length of the track it had formed in the earth, and various other details. Their reports were all filed in the War Office, though apparently no one had had time to look at them.

For about a week I sat in the War Office, armed with all these reports, a book intended to enlarge my rather limited knowledge of statistics, and a map of the Underground Railway system, and emerged with a figure for the depth at which the odds against a bomb penetrating and exploding in a station was sufficient to be regarded as negligible by the Home Secretary. All tunnels satisfying this requirement were forthwith classified as shelters and, in central London in a blitz period, would probably have hundreds of thousands of people sleeping in them. I believe there were never any casualties in these due to enemy action. The same principle could be used in many other contexts.

For the purpose of determining safety or danger, large buildings can be divided into two categories.

- (a) Multi-storey brick and masonry buildings have very little ductility; they collapse very easily, and bury any occupants beneath a pile of masonry. To be in one of them is probably more dangerous than to be in the open air.
- (b) Steel-framed or reinforced concrete-framed buildings have a great deal of ductility, and virtually never collapse. You probably remember seeing photographs of Hiroshima and Nagasaki after the A-Bomb attack with the high, steel-framed buildings standing undamaged amid the devastation. On the lower floors of such buildings, you have only to shutter the windows and you are practically safe from anything short of an H-Bomb.

Almost all the substantial buildings in London were classified in this way and together provided a very large number of extra safe places. However, ideas of this kind were applicable only to London and other large cities. They could not be applied to the suburbs and small towns, nor to the multitude of small houses in the greater London area. For them a different approach was required.

In about 1943, a new approach was provided by Professor Baker's invention of the Morrison Shelter, in effect a very strong and well-designed steel box which, when put inside the common semi-detached house, replaced the dining table and provided a safe refuge for the family. It was strong enough to ensure that if the house collapsed on top of it, although the top might sag a good deal under the weight, the space inside would still be sufficient for the occupants to be unharmed. More

remarkably, if, in a fairly rare occurrence, a large bomb (say 250 kg) penetrated under the shelter and went off, the whole contraption might be thrown a considerable distance. One might go to bed in the dining room and wake up in the garden of the house next door but one—yet able to get up and go to work as usual!

It could reasonably be argued that, at this stage, the prime purpose of the Ministry of Home Security had been achieved, and the party could be disbanded—certainly there was no more money for developing shelters. But someone somewhere must have decided that the Department's knowledge and experience of explosives could still be useful, and so for the rest of the war we provided an advisory service and some experimental facilities, for primarily offensive operations. Among them were the following:

- (a) to investigate the clearing of minefields on the Normandy beaches by means of hoses filled with explosive charges, rocket-projected across them. This was mainly an exercise in rather sophisticated statistics and was undertaken by Dr Florence David;
- (b) to advise on the behaviour of 'land-mines' (very large charges in relatively very thin cases, usually descending on parachutes); to decide on the targets for which they were most suitable and the height above the target at which they should best be detonated;
- (c) to study the probable effectiveness of the 'V' weapons launched from the pas de Calais—the Flying-Bomb, the V2 Rocket etc, which were being represented in German propaganda as war-winning weapons.

With this last item I had some connection myself. As soon as the Overlord crossing was successful and the battle at Falaise was won, I was sent off to try to discover, from what could be seen on the ground and from what was accessible underground, whether there were any other 'V' weapons so far unseen.

For this purpose I was provided with a Jeep manned by two corporals from the RAF Regiment and an RAF officer's uniform with special badges of rank which were viewed in all quarters with suspicion, but which I was assured were those of an Intelligence Officer. Fortunately, I had in my bag another uniform to which I was entitled and which I had been accustomed to wear when working underground or in very wet environments—that of a sergeant Home Guard. This worked splendidly. Wherever the British Army had a sergeants' mess, everything was available—food and drink, petrol, oil and spares, maps of any locality, and hospitality of all kinds.

The German installations in the pas de Calais turned out to be of two kinds:

- (a) very heavy structures, intended to protect V2 weapons on or near the sites from which they could be fired and thus increase the rate of fire. They were comparable with the celebrated 'Submarine Pens' at Brest;
- (b) the long-range gun at Marquise-Mimoyecques. This weapon was entirely new, at least to me. It could fire projectiles of about 100 kg into central London continuously, perhaps at a rate of one every few seconds. If it had been completed it would certainly have been a great nuisance!

With this information we returned to Paris for new instructions. News had been received that the enemy's intention, if and when the Allies advanced across Germany, was to use the very strong and heavy concrete 'bunkers', originally constructed as large and expensive air-raid shelters, as fortresses from which sorties could be made from time to time, doubtless causing a good deal of trouble to our forces. Information was therefore needed as to how, and with what weapons, the bunkers themselves could be attacked.

The first town containing bunkers to be occupied by the Allies was Aachen, but the Ardennes offensive made it impossible to get there for several weeks. As soon as the way was clear, we set off for Aachen. When we got there, the town was occupied exclusively by Americans, who were very busily preparing to assault their next objective, Cologne. Their administration was, as always, perfect. They had the complete files and records of the German authorities in the town, with names and addresses of the responsible officers, including the man responsible for air-raid protection. This man, when visited—his house proved to be one of the few still more or less intact—proved to be very happy—indeed proud—to show us round. So for the next two or three days we had a guided tour. The bunkers, practically undamaged, were indeed impressive—mass concrete walls eight to ten feet thick, roofs even more than that, and entrances designed to give the greatest possible advantage to the defenders against anyone trying to get in.

It was quite evident that the only weapon likely to have any significant effect on them was a large Bee-Hive charge stuck onto an outside wall and detonated to fire inwards. A Bee-Hive charge—this term may not be familiar to everybody—is effectively an explosive drill. It blows a straight narrow hole through a very large thickness of mass concrete or masonry and fires a stream of metal particles through it at extremely high speed. Its limitation is that if the concrete is heavily reinforced with steel, most of these missiles will be deflected and will not reach the interior. In fact, we knew already that in wartime the Germans used very much more steel in reinforced concrete than we did.

When we had completed our tour, it was natural to compliment our guide on the comprehensiveness of his provision. He then confessed that there was still one bunker unfinished, so naturally we asked to see it. There it was, half built, with the reinforcement clearly visible, the contractors huts still on the site, and with the drawings still on the tables inside. It was the work of only a few minutes to transfer about two hundredweight of paper to the back of our Jeep—I think the only time in the war when I was guilty of looting. Then it was a matter of hell for leather for England with me endeavouring to work out a pattern of Bee-Hives which would give the greatest chance of some of them firing through the spaces between the reinforcement.

That was the substance of my last field report to the Ministry of Home Security. It was a disappointment that the Germans seemed very soon to have given up the idea of using the bunkers in this way.

Perhaps, however, all but one of them . . .

POSTSCRIPT

On the day on which I was invited to give this talk, I happened to be reading a recent book, intriguingly titled 'Economics, Peace, and Laughter' by the celebrated economist J. K. Galbraith. He was one of the party sent to Germany immediately after the surrender to study the effects of the allied bombing offensive and, in general, to compare German effectiveness in the economical use of materials and man-power with that of the allies, and particularly the US—very much to our advantage. He also had the opportunity to interview at length all the leading Nazis who were loyal to Hitler to the end and with him in the Berlin bunker.

He discovered that, in the last months of the war, German strategy as dictated by Hitler was extensively motivated not by the hope of victory, not by the hope of avoiding defeat, but by Hitler's efforts to prolong his own life for a few months—a few weeks—a few days—or eventually a few hours. Thousands of young Germans died to buy him this time. 'This aspect of Hitler's character is important and should be better known,' says Galbraith.

Perhaps if the situation had been better appreciated, if the timetable had worked out a little differently, we might have found ourselves arranging an airborne Commando with plenty of Bee-Hive charges to be parachuted into Berlin. Surely, if the bunker on which Hitler placed so much faith had been riddled with holes and had lumps of metal whizzing from wall to wall, even he would have given up sooner, and saved hundreds of thousands, not only of young Germans, but of young Russians, and Americans, and Brits as well.

Chris Baughan had been a Demonstrator in Physical Chemistry at Balliol College, Oxford, had carried out research in Copenhagen, and had just become a Visiting Professor at Princeton when WWII started.

In the spring of 1941, the Air Officer Commander-in-Chief appointed Professor P. M. S. Blackett, who had been until then with Operational Research in AA Command, as his personal Scientific Advisor. Shortly after, following successes achieved by the Operational Research Section of Fighter Command, RAF, the formation of a similar group in Coastal Command was recommended. This recommendation was immediately accepted, and the Operational Research Section Coastal Command (ORS(CC)) came into being with E. J. Williams as its first Director. Although never very strong in numbers compared to some ORSs, the group is able to claim two Nobel Prizewinners, five Fellows of the Royal Society, and one Fellow of the National Academy of Scientists of Australia from among its members.

At ORS(CC) Chris Baughan worked in the 'Anti-U-boat Operations Section', and was referred

to later by Sir John Slessor when he was Air Officer Commander-in-Chief, Coastal Command, as 'one of the men recognized as being responsible for the victory over the U-boat'. In 1946 he was appointed Scientific Advisor to the Commander-in-Chief, Coastal Command, before becoming Professor of Chemistry at the Royal Military College of Science, a post he held until he retired several years ago. His talk below was to the International Symposium on Military Operational Research in 1990 which had 'Logistics' as its theme.

PROFESSOR E. C. BAUGHAN

Coastal Command's many functions included the war against U-boats. As you are experts on the logistic side of Operational Research (OR), I thought that a talk on the other side—the detection and destruction of U-boats—might interest you.

The Operational Research Section (ORS/CC) of Coastal Command was started by Professor Blackett in June 1941. He moved on to the Admiralty and was succeeded by E. J. Williams, Professor of Physics at Aberystwyth. Williams was (I think, and so did Blackett), the best of us all. He was succeeded by Harold Larnder, one of the founders of Operational Research, and then by the biologist C. H. Waddington. Blackett's policy was that an OR section should be small and good. Our average 'First Eleven' strength was never above about a dozen, so the air and naval staff knew us personally. For work needing considerable manpower (Planned Flying, in particular) we obtained Service assistants, and in 1941–3 we could still obtain women scientists.

Operational Research was then new, so the background of this 'First Eleven' is interesting. In all there were three physicists (and one physical chemist), three communications experts (one Australian), four mathematicians, two astronomers (both Canadian), and about eight physiologists and biologists, including an expert on the sex life of the oyster! It was not clear which background was the best; our special skills were not as important as our general scientific ability. And we had visiting scientists from Canada and the USA. One of our mathematicians described Operational Research as 'an Experimental Science where a number is equal to its square root'; this is a bit strong, but many of our greatest successes came from 'rough' estimates, uncertain to $\pm 30\%$, and their subsequent refinement. I would now say that the greatest importance was: *Asking the Right Questions*.

The facts about the war between aircraft and U-boats have never been widely known. By 1941 U-boats had been driven out from inshore waters and operated in the Mid-Atlantic Gap, outside land-based air cover. Their main target was merchant shipping, mainly in convoy. The British showed in 1917 that a convoy was a good answer to U-boats operating singly. The German answer to convoys was the massed attack by a pack of U-boats. But this required exceptional navigation, or a lot of radio signals, on which land-based bearings (D/F) could be taken; ORS, therefore, started work on the accuracy of location by D/F. And such attacks took hours to develop. So convoys could be divided into those in danger and those (so far) safe. And as aircraft then travelled at 100–160 knots, they could be concentrated most economically on endangered convoys.

This was the scene when ORS/CC started, and our two main subjects were to stop ships being sunk, and to destroy U-boats. We also had a good deal of work on a third subject. Every land-based aircraft allocated to Coastal Command was one less for operations like bombing Germany, or Army Cooperation, by which the war might be won. So Coastal's operations had to be justified and had to be economical. In fact, the logistical work on 'Planned Flying' began in Coastal; you know much more about this than I do, so I return to: 'ships not sunk' and 'U-boats destroyed.'

The great success of Coastal in these two functions was dependent on the physics of U-boat propulsion; U-boats had to be surfaced much of the time. World War II U-boats moved on the surface by diesel power with maximum speed about 16 knots, and had sufficient endurance for great successes off the US Coast in 1941–2 before the USA adopted convoying. But their underwater movement was by electric motors fed by accumulators charged by the diesels and was inadequate. They could do (about) 14 miles at 8 knots, 28 miles at 6 knots, 65 miles at 4 knots—distances roughly proportional to the inverse square of the speeds as would be expected. The drag-forces on a ship increase with its speed and are proportional to its surface area, while its power (for a given method) is proportional to its volume. Higher underwater performance from diesel-electric submarines, therefore, requires bigger submarines; the Germans' projected Type XXI was about

twice previous tonnage. (Many biological applications of surface-volume ratio are described in a book which Sir Henry Tizard told me that all Operational Researchers should read: D'Arcy Thompson's 'Growth and Form' published 1917, recently reissued.) So Coastal aircraft could save ships by forcing U-boats to dive and lose contact with their convoys, or could sink U-boats by attacking them while shallow—on the surface or diving. Attack and detection of submerged U-boats by aircraft was only just beginning.

These facts are basic to our two main problems, for although most Atlantic convoys were slow (8–12 knots) they were still too fast for the U-boats to get together submerged, although as Donitz remarked, the operations proceeded 'at bicycling speed'. These general principles were clear—to us and to the enemy—when ORS/CC started. Our job was to put in correct numbers and so to suggest improvements.

To stop ships being sunk, the aircraft had to find their convoys for which, like the U-boats, they needed exceptional navigation and/or radio homing. So ORS did much work on errors in navigation, then carried out mainly by 'classical' methods: air-speed, drift, fixes by Astro or by radio beacons or the island of Rockall. We analysed most navigators' logs and reassessed Astro-fixes, and were able to suggest some improvements. But the errors were still too large, and the uncertainty in convoys' estimated position about as large. And our statistics showed that the aircraft's time on the important convoys at extreme range was multiplied about three times by radio-homing, as so much time was wasted in searching. Radio-homing was accepted (in spite of its risk) and we analysed various procedures.

When the aircraft reached their convoys, what were they to do? Break up the pack, and so fly further from the convoy than if their object was to prevent submerged attack. ORS analysed the distances and bearings of U-boats seen near convoys and were able to put general numbers to existing doctrine. But the air and naval escorts had to assess their own individual situations.

The evaluation of 'Ships not Sunk' sounds a difficult and abstract basis for Operational Research, but in fact it was easy. Very few ships (except stragglers) were sunk from convoys with air escort in the daytime. And, indeed, comparison figures showed that ship-losses were 'roughly' halved in the nights *after* air escort (night-time air escort was seldom attempted). So the deterrent effect of aircraft was very great; this was already clear in World War I (see Reference 1). And the concentration of U-boats near threatened convoys was exceptionally large. The number of U-boats seen there per flying hour was much (ten times, speaking from memory) greater than anywhere else. Those operations which saved most ships also destroyed most U-boats. But to sink U-boats one must first find them. In 1941–2 U-boats and aircraft detected one another mainly by eye; aircraft radar (ASV) was just beginning. On seeing an aircraft, U-boats (before and after the summer of 1943) would dive at once, and often do so unseen. Donitz thought they could almost always do this (Reference 2), but our operational research qualified this simple view.

A classic paper by E. J. Williams in 1941 analysed the time-delays between an aircraft seeing a U-boat and the subsequent attack. He estimated that about two-thirds of U-boats had dived unseen; this led to the white camouflage of Coastal aircraft (worth, from trial, about 20%). And he recommended that aircraft should concentrate on U-boats actually visible or just diving because their positions were better known (*Asking the Right Question*), and therefore that the hydrostatically-fused weapons should explode at a 25 foot depth; up to then, settings of 100–150 feet were used. Since the distance to break the U-boats' pressure-hull was only about 20 feet with the weapons used, this was a major improvement (a factor of 3 to 4 or so (see Reference 3)). It is ironic that a depth-setting of 20 feet was recommended in 1912 (see Reference 1) though for different reasons.

As the eye was so important, we had one scientist specializing on the use of binoculars (for details see Reference 3). I would guess that this improved visual efficiency by about 2%—this seems a poor return for years of work until one realizes that Coastal sank about 200 U-boats; 2% of 200 is four. And we studied the operational effect of visibility. In good visibility, aircraft and U-boats could see one another further away. In bad visibility, neither could see so far, but the U-boats would not have had time to dive; diving took about 30s, 1.5 miles of aircraft travel. OR figures showed that our results were 'roughly' independent of visibility, and the 'statistical sweep-width', deduced from time-delays of attack, could be 'roughly' checked from the density of U-boats on the surface in the Bay of Biscay. (In 1941, U-boats crossed the Bay on the surface.)

Our other method of detecting surfaced U-boats was radar; Operational Research started in Coastal, as elsewhere, from the need to assess this new technique. Through the war, one of us specialized in this, studying ranges, angles, effect of height, and many other problems including 'disappearing contacts' and we arranged for special experiments on operator-fatigue (Reference 3). Again, 'sweep-widths' were evaluated on various hypotheses about whether U-boats could use radar transmissions to dive or not.

Such calculations, though 'rough', were basic to the prediction and analysis of aircraft results against U-boats crossing the Bay of Biscay, and these patrols stimulated ORS/CC studies on Planned Flying. In most RAF operations the aim of maintenance was maximum serviceability (obviously true in the Battle of Britain, escort of convoys against pack attack, bombing Germany, etc). But the Bay provided an almost regular flow of targets, so that maintenance should aim at maximum flying, giving considerable economies. You are experts on such subjects, so I return to Detection and Attack.

By late 1941, aircraft had forced U-boats to do their necessary surface-travel in the Bay by night. So in the winter of 1941-2 Coastal flew night patrols using radar and these were a failure - 'roughly' a factor of 5-10 down on density expectations. Why? Perhaps the U-boats were using our radar transmissions to dive, but they did not do this until later. In fact, the major difficulty lay in the aircrafts' eyes, because in the final stage of approach, the radar returns from a ship disappear behind those due to the sea itself, so the final attack must be made by eye (then assisted by flares).

Should ORS have deduced this? We were beginning to suspect it, and we might have got there sooner if we had analysed the more successful results by Swordfish in the Mediterranean (small, slow, manoeuvrable aircraft with open cockpits in a better climate). But fortunately this problem was solved directly. 1942 saw the new searchlight developed by the personal enterprise of Wing Commander H. de V. Leigh. This was an immediate success - three U-boats seriously damaged in a week - and the results agreed 'roughly' with calculations based on radar sweep-width and U-boat density. The problem of the final stage of night attack was 'roughly' solved.

So then the U-boats crossed the Bay submerged as much as possible (Donitz order of 24 June 1942). What mattered was the time on the surface divided by the total distance made good; a factor of two was about all they could obtain. We checked this carefully. Also they fitted a simple search-receiver.

But the object of the Bay patrols was to destroy U-boats. This, as mentioned, was difficult. And the assessment of individual attacks was very difficult. A successful attack would send a U-boat straight to the bottom, while a failure could let it creep away unseen. Very seldom (less than half-a-dozen times?) did a U-boat re-surface and surrender or abandon ship.

By 1942 it was clear that claims made by aircrew were often not allowed by the Assessment Committee checking weeks later with other intelligence. Who was right? ORS/CC first approached this subject indirectly. If the bombing errors were even 'roughly' Gaussian, a given proportion of straddles would imply a corresponding mean error; the error implied by aircrews' reports was considerably less than that *known* from practice bombing. So what were the bombing errors? The Command fitted special backward-looking cameras, and ORS/CC measured all such photographs; these were low-level obliques whose scale could be established from anything of known size on the water (Reference 3). Such measurements showed that operational errors were indeed larger than practice errors. But they also disclosed a large unsuspected error ahead of the U-boat's own movement (see Reference 3, p. 184). This was presumably due to over-correction to allow for this very movement, and it would be better not to correct at all. This analysis (worth perhaps a factor of 1.5) was circulated to all squadrons. Photographic estimates of random error were used elsewhere for assessment of new weapons and for calculations of optimum spacing and size of those available. They emphasized the need for practice, and more practice, and for a special bomb-sight introduced later.

Some overall statistics (Reference 4) are pertinent here. Up to the end of 1941, naval ships sank 46 German U-boats, land-based aircraft only four (one was captured); for 1942, the figures are 35 and 36; for 1943, 64 and 116 (84 by the British, 32 by the USA); from the beginning of 1944 to the end of the war, 124 and 91. The enormous increase of U-boat losses to land-based aircraft in 1943 is not widely known.

1943 was indeed the critical year. In March, pack-attacks had some great successes; one convoy

lost 21 ships for the loss of one U-boat. Yet on May 24, 1943, Donitz withdrew U-boats from the North Atlantic; their losses were too great, and they were sinking too few ships. Why? Several things were happening together. First, the naval escorts could, in fact, be reinforced by special Support Groups, because the aircraft had effectively halved the width of the North Atlantic. Second, the naval escorts were now able to take bearings on U-boat transmissions and vector aircraft; while aircraft, seeing U-boats, could vector naval ships from these increased escorts. Third, VLR (Very Long Range) Liberators and aircraft carriers (still only a few) were closing the Mid-Atlantic Gap. Fourth, the effectiveness of aircraft attack was continuously increasing; ORS/CC kept a close watch on this. Fifth, aircraft and ships had the new centimetric radar. Sixth, there were favourable developments in cryptography and signal security; these have been made public in the last fifteen years.

So the U-boats returned to distant 'soft-spots'. But they still had to cross the Bay. The Leigh-Light (die 'verdammte Licht') was now backed by centimetric radar against which their search-receiver was, as we now know, not very good. Our aircraft had made the Bay dangerous for them, greatly reduced their successes, and greatly increased their losses. So what could they do against aircraft? Fight it out on the surface, in the daytime, with gunfire. A naval historian describes this as 'Donitz's error', but it was really his last hope for major victory, for the bigger U-boats were not to be ready for almost two years. Certainly our submariners had predicted this, and Coastal Command had borrowed anti-aircraft experts from the Army.

In these gun battles, many expedients were tried: U-boats travelling together for supporting fire (countered by co-ordinated air patrols), use of rockets by aircrafts, support by our own naval vessels, and so on. In the 94 days of these actions (1 May–2 August 1943), 28 U-boats were sunk and 22 damaged. ORS/CC of course studied these actions, but made no major recommendations for the gun duels; brave men were fighting one another by simple methods in which they had been well trained. But our previous work on navigation and radio-homing was useful, and the U-boats were usually forced to dive and were then attacked in the usual way. For about a month no outward-bound U-boats crossed the Bay. They then tried the North Atlantic again, hoping to sink the naval escorts by a new Acoustic Homing Torpedo, but without much success. The pack attack had failed.

They then fitted the 'Schnorchel' air pipe which allowed diesel-charging (but not high speeds) without complete surfacing. So the results from our aircraft were decreased, and the U-boats could return to inshore work, which increased the results from our naval vessels. And as pack attack was impossible, the ships-sunk figure fell away. Thus, the U-boats could not seriously affect the invasion of the Continent in June 1944 within 200 miles of their bases. In the last few months of the war, the importance of the U-boats was probably best represented by the proportionate number of ships and aircraft needed to keep them under control.

This short, incomplete talk on 'battles long ago' may still be directly useful, for diesel-electric submarines still exist. But some general conclusions may perhaps be drawn. First comes the importance of 'rough' estimates to important problems for which precise estimates are not feasible. Second comes the importance of the distinction between systematic and random errors, for systematic errors can sometimes be easily cured. The evaluation of random errors in familiar techniques needs careful analysis and such errors are often difficult to improve. But techniques are familiar because they are often used (the human eye, for example) so small improvements are well worth-while. And the errors need to be known for the planning of operations and for judging where new techniques are most needed.

REFERENCES

You may wish to follow up this talk. Four books seem to me of outstanding value.

1. A. PRICE (1980) *Aircraft versus Submarine*. Jane's, London, 1980. An excellent non-technical account.
2. Admiral DONITZ (1959) *Memories. Ten Years and Twenty Days*, English translation, Weidenfeld and Nicholson, London.
3. C. H. WADDINGTON (1973) *OR in World War II: Operational Research Against the U/Boat*. Elek Science London. By a scientist, for scientists; particularly good on the logistic side.
4. *German, Italian, and Japanese U/Boat Casualties during the War, Particulars of Destruction*. Command Paper 6843 presented to Parliament in June 1946, London, HMSO, Price Sixpence Net but out of print (!!). Based on our own and captured German records.