

The RAE Contribution to All-Weather Landing

Sir John Charnley CB, MEng., FEng., FRIN, FRAeS,

Abstract

Following World War II, renewed interest in the long sought-after goal of ensuring that aircraft could be landed safely in extremely low visibility weather conditions gave rise to automatic landing systems research and development programmes in the United Kingdom, France and the USA. After reviewing the earlier history of landing aids development, this paper describes the work done on guidance systems, autopilot couplers and operational techniques by the Royal Aircraft Establishment's Blind Landing Experimental Unit from 1945 to the early 1960s. The analytical and experimental work performed there, which led to the design of the Avro Vulcan bomber's single channel automatic landing system, is covered in detail. Similarly, it describes the contributions of UK aircraft and avionics manufacturers, the Civil Aviation Authority and the Air Registration Board to the subsequent development and airworthiness certification of the multi-channel systems employed on the Hawker Siddeley Trident, the Vickers VC10 and other civil transport aircraft. The paper concludes with a summary of the autoland capabilities of Boeing's 737, 747 and 767 and Concorde.

1. INTRODUCTION AND EARLY HISTORY

Automatic landing of civil airliners in all weather conditions has become a routine part of civil aviation and has contributed to the safety and reliability of air transport. Britain played a major part in this development, with activity at the Royal Aircraft Establishment's Blind Landing Experimental Unit supported by work in industry and by the Civil Aviation Authority / Air Registration Board. Parallel developments occurred in France and the USA, and it is not possible to claim that any one country or organisation 'invented' blind landing.

This paper focuses on the contribution to all weather landing made by the Royal Aircraft Establishment (RAE) from 1945 to the early 1960s. It is based on the 2006 Cody lecture at the Farnborough Branch of the Royal Aeronautical Society. The sections describing the history of the development of all weather landing were published in 1989 in *The Journal of Navigation* (Charnley, 1989) and are repeated here with the permission of the Royal Institute of Navigation. Because the paper is concerned with the contribution of the RAE, it does not attempt to describe in detail developments elsewhere nor the lengthy debates between research organisations, regulators in a number of countries, and ICAO over the philosophy to be adopted and the safety standards required.

During World War I aircraft began to be used for reconnaissance, as bombers and as fighters, but many operations over France were hampered by bad weather. Strangely enough the earliest known record of experiments to assist pilots to land at night and in fog is of flight tests made in 1916 by the Royal Navy Air Service, using an aircraft height indicator. In those days

aircraft were using grass airfields without the need to land on a particular runway, so judging height and the moment to check the rate of descent was the main problem. The device used was called a 'ground proximeter' and consisted of a weight attached to a length of cord which was lowered by a drum and hung about 15ft beneath the aeroplane. When the weight made contact with the landing surface, the tension in the cord was relieved and a trigger mechanism caused a red lamp in the cockpit to light, providing the pilot with a cue to start his flare-out. The length of string required for a particular aeroplane was determined empirically!

A further early development of a lever and dashpot, mounted on the tail-skid to check the downward movement of the tail, was patented in 1919 by the Experimental Squadron of the Royal Aircraft (by now) Establishment. This device was found to give considerable assistance in fog by preventing the bounce that otherwise occurred and it is even claimed that an entirely automatic landing was made in an SE 5A aircraft but in daylight.



Figure 1 The SE 5A

Figure 1 is a photograph of an SE 5A still flying in the Shuttleworth Collection, but it is unlikely that it is the same aircraft.

Another method for landing in fog was suggested in 1921 by Professor Lindemann (later Lord Cherwell). His paper only claimed to give an outline of the method, '...the details being left to some department that has the necessary data'. The idea was to use a line of captive balloons to define the approach path to the airfield, the landing to be completed by devices similar to those already described. A row of balloons would be arranged to project above the fog at heights arranged to define a visual glide slope and 'all the pilot had to do on entering the fog was to maintain his line of flight and he was bound to touchdown on the airfield'. Refinements included a mark on each balloon to indicate range and even an observer in one balloon to make sure the row projected above the fog - perhaps the first Air Traffic Controller?

Important advances were made at Farnborough during WW1 in the theory of aircraft stability and in 1923 Meredith experimented with the larger Vickers Vimy (Figure 2) again using a 'ground proximeter' but now to indicate to the pilot, through an observer, when to release the control column from a tail-heavy trimmed condition, to take advantage of the ensuing longitudinal phugoid motion and allow the aircraft to land itself.

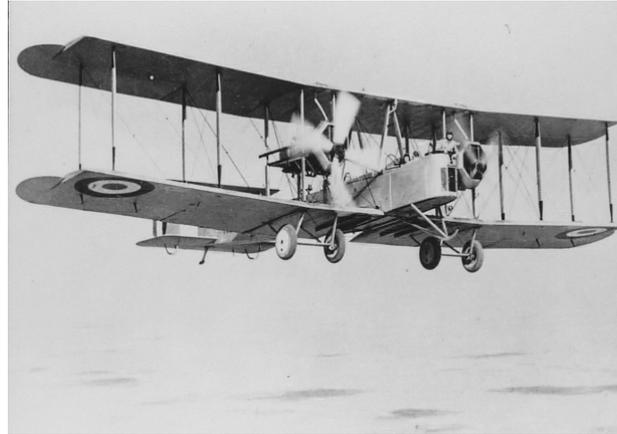


Figure 2 The Vickers Vimy

The January 1925 *Flight* magazine carried an interesting report. “During a dense fog in London, a feat unprecedented in the history of civil aviation took place when signal rockets helped guide down Imperial Airways pilot G. P. Olley flying from Paris to Croydon. The plane made a perfect zero-zero landing, on schedule.”

Despite pioneering work in several countries, automatic assistance to pilots was viewed with some suspicion and played no real part in aircraft design until the mid-twenties, when RAE research began on automatic stabilisers, largely to ease the strain on pilots flying long distances. So, by the early thirties, there were simple autopilots in commercial aircraft throughout the world. In this same period, experiments were being made in the United States and in the RAE on the control laws for coupling autopilots to radio beams for improved navigation, and throughout the thirties RAE was actively developing unmanned radio-controlled aircraft for use as gunnery targets, the aircraft flying under automatic control from take-off to landing.

2. WORLD WAR II

The highly significant factor in the late thirties was the work started in the USA on the Signal Corps System 51 (SCS51), a short range approach and landing aid operating in the VHF/UHF band, the forerunner of the current Instrument Landing System (ILS) (Figure 3)

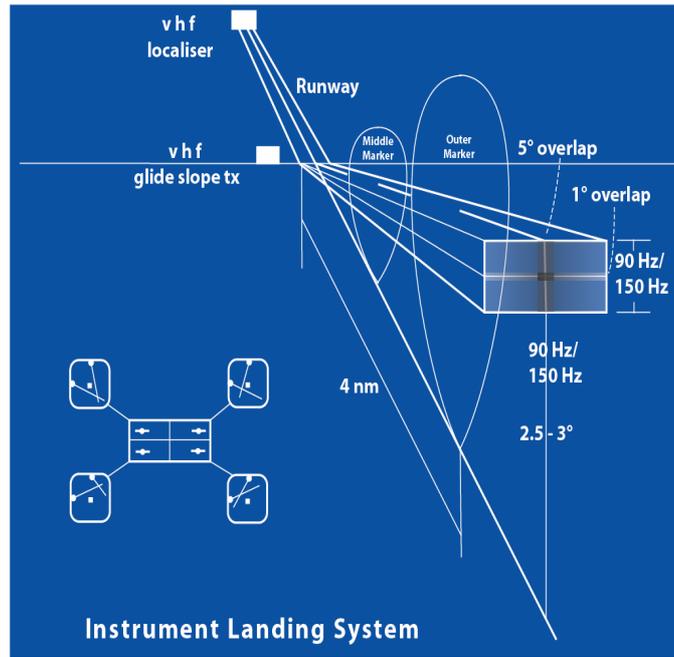


Figure 3 Signal Corps System 51 (SCS51), the forerunner of the current Instrument Landing System

The USAF were more than a little upset by the restrictions placed upon their bombing operations by the European weather, so in 1944 an early version of the SCS51 was brought to England and successful demonstrations of blind approaches in a Boeing 247D (Figure 4) were made to British scientists from both the RAE and TRE (Telecommunications Research Establishment) at TRE's flight test airfield at Defford near Malvern. But it was clear that for an operational system, as well as needing more radio work, which was well within the capabilities of TRE, the full implications of coupling the radio signals into the autopilot needed the Instrument Department of RAE, with an input on stability and control at low speeds from the Aerodynamics Department.



Figure 4 The Boeing 247D

Work continued through 1944 and the early part of 1945 at both establishments under the direction of Ministry of Aircraft Production Headquarters, in response to an Air Staff Requirement for the development of a fully automatic system for the blind landing of large aircraft. The Department of Civil Aviation also showed a high interest and watched developments closely. During the winter of 1944/45, a combined RAE team from the Instruments and Aero departments used the mechanical differential analyser of Manchester University to investigate the stability and flight path performance of an aircraft making an approach and landing under automatic control using SCS51 type inputs. This led, in January 1945, to the first automatic landing of a large aircraft on a runway in complete darkness, any surrounding lights being completely eliminated by the war 'blackout'. With a low approach speed and shallow glide angle the Boeing was flown straight to the ground - nevertheless it was an outstanding feat.

The establishments co-operated well but it became clear that it would be more effective if the two teams were located together on one site, so authority was given by Headquarters for RAE to create a new multidisciplinary unit at Martlesham Heath in East Anglia, with the sole task of solving the blind approach and landing problem for the RAF, as well as naval and civil aircraft. The formation and terms of reference of the Blind Landing Experimental Unit, BLEU, (Figure 5) to be an outstation of the RAE, reporting through the Head of Instrument Department, Mr George Gardner, (later to become Director of RAE) are shown here in this note of 8th August 1945 from the Deputy Director of RAE, Mr William Perring (also later to become Director). In September, staff were transferred from RAE, TRE and the RAF, to provide flying facilities, and were based originally in somewhat Spartan accommodation in Nissen huts on the emergency landing strip at RAF Woodbridge, with the intention of moving to nearby RAF Martlesham Heath when the USAF left. A serious programme of work on radio altimeters, autopilot couplers and the SCS51, now installed on the airfield, was in place by November.

DDRE/Inst/1023C/GWHG/95/144	8 August 1945
<u>Heads of Departments</u>	
<u>Blind Landing Experimental Unit</u>	
A new Unit is being formed at <u>Martlesham Heath</u> known as the Blind Landing Experimental Unit. It will operate as a satellite of RAE and will be responsible for the development of blind approach and landing of RAF, Naval and Civil aircraft, in accordance with DTD's letter reference SB65676/ADRD Inst 2 of 26 June 1945.	
The Superintendent of the Unit will be responsible (through the Head of Instrument Department, RAE) to the Director, RAE for the work of the Unit, and for the efficient use of its personnel, aircraft, transport and other facilities.	
The postal address of the Unit will initially be:-	
The Superintendent, Blind Landing Experimental Unit, Royal Air Force, Woodbridge, Suffolk.	
(Sgd) W.G.A. Perring DDRE	

Figure 5 Memo from W. G. A. Perring establishing the Blind Landing Experimental Unit

In the summer of 1946, the USAF departed and what had been their armoury became the BLEU technical block and later the headquarters building, complete with iron bars on the windows. A point of interest perhaps is that although BLEU had its own local administration, there would seem to have been some concern at TRE as to how RAE would treat the ex-TRE staff, because their personnel (now human resource) matters continued to be handled from Malvern for the next five years. It was not until 1950 that they were formally transferred to RAE. Mr H.C. Pritchard was the first Superintendent of BLEU and in 1947 he was promoted, to be Head of Instrument and Photographic Department back at Farnborough.

3. 1945 TO EARLY 1960s

Let us now take another look at the SCS51 radio guidance system. (Figure 3). Overlapping horizontally polarized beams define a unique equi-signal approach path to the runway, in azimuth lying along the extended runway centre-line (localiser) and in elevation (glide path) inclined at an angle of $2\frac{1}{2}$ -3 degrees, intercepting the runway plane in the touchdown area. Coded fan markers at two or three points on the approach path give indications of range to touch down. Deviations from the approach path can be displayed on the flight deck instruments either as simple position information or better still, as 'what to do' instructions, known as 'flight directors', as shown in the small diagrams.

In 1948 the newly formed International Civil Aviation Organisation (ICAO) adopted as its international radio guidance aid the Instrument Landing System (ILS) based upon the SCS51. It provided adequate guidance down to a height of about 200 feet above the runway, but the characteristics of the glide path beam and the possibility of bends in the localiser beam with unwanted reflections from hangars or nearby buildings, precluded its use for accurate guidance below that height. So BLEU work centred upon developing the autopilot control laws to couple the aircraft to the ILS beam and providing flight instrument displays to enable the pilot to monitor the progress of the approach and disengage the autopilot still with sufficient time and height to take safe corrective action in the event of poor performance or equipment failure.

Civil airfields at about this time were starting to be equipped with high intensity approach lighting patterns on what were termed their 'precision approach runways' to assist pilots make the transition from 'blind' approaches, using instruments or automatics, to a manual visual landing. Outstanding and elegant analysis, backed with simple practical simulations by Calvert and Sparke, in the RAE Electrical Department, demonstrated conclusively the mental processes by which visual judgements on aircraft present position, aiming point and rate of change of position were extracted from the changing perspective of lighting patterns. They exposed serious deficiencies in many of the patterns being proposed, particularly in the vertical plane. Following discussion in ICAO in 1949, the 900 metres Calvert Centre Line and Crossbar pattern (outlined in the lower half of Figure 6) was adopted as an International Standard. It is still in use today. In essence, the lighting pattern extended the visual perspective of the runway beyond the runway threshold and into the approach area, as illustrated in the fog of the upper part the figure.

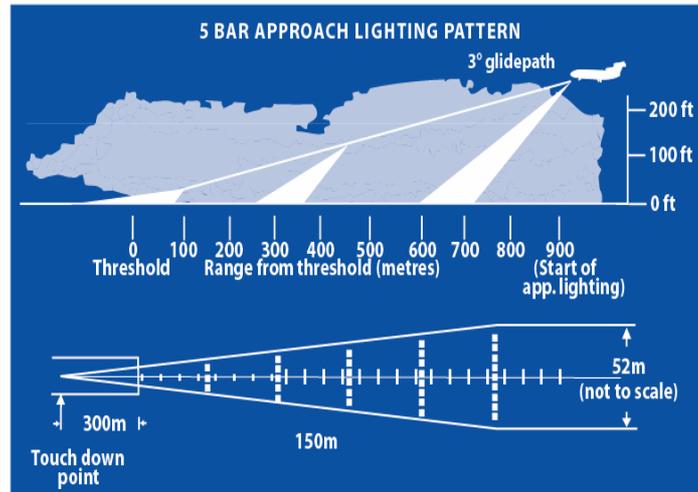


Figure 6 The Calvert 900m Centre Line and Crossbar Approach Lighting Pattern

The lighting pattern shown in Figure 7, installed at Gatwick, illustrates the visual aids that contribute to the modern guidance on a runway approved for low visibility landings. It shows the high intensity approach lights prior to the runway threshold, the red 'Barrettes' indicating a danger 'Don't land here!' area, the more frequent 'Barrettes' of lower intensity set in the runway surface to identify the desirable touchdown area, the visual approach slope indicator (VASI) to the side of the runway for glide-path guidance in clearer weather and the runway edge and centre-line lights for guidance during the ground roll and take-off.

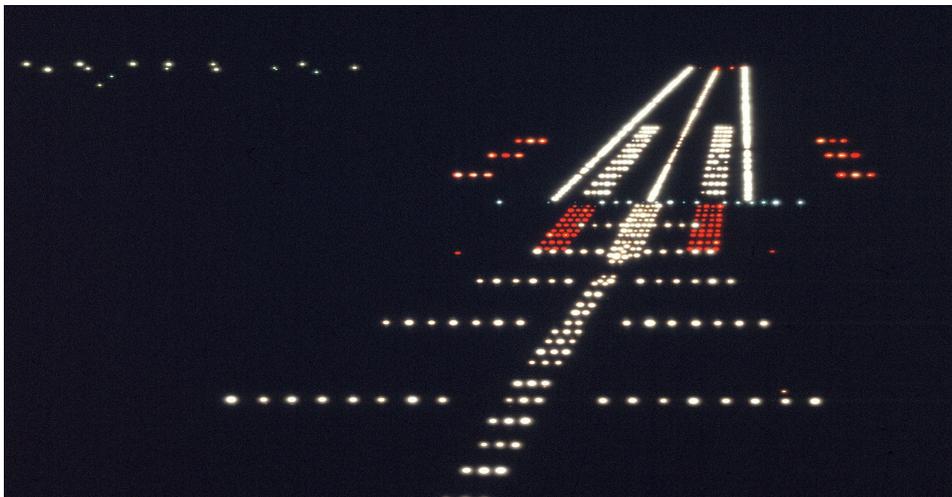


Figure 7 Approach Lighting at Gatwick Airport

Fog is notoriously variable and non-uniform in its variation with height, so detailed examinations were made to determine worst case relationships between visibility measured along a runway, called the 'runway visual range' (RVR) and the 'slant visual range' (SVR) required by the pilot, as he peered through the fog searching for the approach lights. In this way airworthiness authorities and airline operators promulgated limiting 'decision heights' and RVR below which safe manual landings could not have a high probability of success. Typical figures at this time were 200 feet decision height and 800 metres RVR and, as we shall see later, were classified as Category 1 operations.

Excellent tests made by Aerodynamics Flight Division at RAE Bedford on twelve, very different aircraft measured the time taken to correct lateral errors at a range of approach speeds. Height is being lost at a rate of about 10ft per second and from the first visual contact with the ground, ‘time to go to touchdown’ is the important parameter. The time taken by the pilot to acquire and interpret the limited, and often fleeting, glimpse of the visual guidance information through the fog, plus the time taken by the aircraft to correct any flight path lateral errors and rate of descent, then flare and land, soon exceed the very short time available to touchdown. BLEU became convinced that fully automatic landings, in concept, were the only way to achieve safe operations in very low visibility. Not surprisingly, this view was not readily accepted by all pilot fraternities nor in all countries, and for some years there was intense activity on the international scene. Various alternatives to ‘retain the pilot in the loop’, notably, head-up displays, were explored experimentally in the UK, the US and France, but eventually it was accepted that an automatic system, at least to touchdown with perhaps manual control down the runway, offered the best prospects for success in zero-zero conditions.

4. SCHEMATIC

A diagram of the main elements of the proposed automatic landing system is shown in Figure 8. With autopilot engaged, the ILS localiser is acquired and the airfield approached at circuit height, perhaps 1500ft (TRACK). Should it be necessary, an automatic overshoot can be demanded from a very low height, dependent upon the aircraft and engine characteristics.



Figure 8 Main Elements of the Proposed Automatic Landing System

When the ILS glide path beam is joined, descent is started and the approach speed controlled accurately by an automatic throttle control ('GLIDE' in Figure 8). At a height of about 150ft the glide path beam is very narrow and the signal may become unreliable, but as the aircraft may still be too far from the airfield for a useable height signal from a radio altimeter, an

ATTITUDE phase is introduced, in which the autopilot continues to fly the aircraft at a constant pitch attitude derived from information acquired earlier on the glide path. At about 70ft, the precise figure depending upon the aircraft characteristics, height guidance is transferred to the radio altimeter, airspeed is slowly reduced by the automatic throttle and the controlled flare onto the runway is commenced ('FLARE' in Figure 8). Just before touchdown, any aircraft drift due to a crosswind is removed automatically (KICK OFF DRIFT in Figure 8) and the aircraft aligned with the runway centre-line. Visual contact will have been made with the touchdown and runway lighting patterns, so after touchdown the autopilot may be disengaged and the GROUND ROLL completed manually. Should it be necessary, an automatic overshoot can be demanded from a very low height, dependent upon the aircraft and engine characteristics.

5. RESEARCH PROGRAMME

Against this background, the main elements of the research programmes for the period 1945-1954 were:

1. ILS localiser. In its early work, BLEU used a pair of leader cables laid one on each side of the runway to provide accurate azimuth guidance for landing, but it was recognised that installation problems would prevent their use operationally. Research was needed to provide a more stable, cleaner signal with a reduction in beam bends (Figure 9). Methods explored included wide aperture antenna arrays, often combined with capture effect carrier offsets, to minimise the effects of RF energy reflected from buildings, etc.
2. Radio altimeter. The physical means by which the ILS glide path signal is generated, with the antenna offset to the side of the runway by at least 120 metres, prevented its use for guidance close to the transmitter, so research was needed on a radio altimeter to provide a height signal for the final phase of the approach and flare to the runway.
3. Improved automatic control laws for a tighter coupling to the ILS beams and the radio altimeter for a programmed flare.
4. Automatic throttle for an accurate speed control during the approach and controlled speed reduction during the flare.
5. Further investigation of the factors affecting the time taken for a large aircraft to correct lateral flight path errors, and if necessary overshoot from a low height.
6. To provide the signals and coupling required to remove any crosswind drift prior to touchdown.
7. To provide a visual indication of the correct glide path for use when conditions permit.
8. To extend the approach lighting pattern into the runway surface for improved visual guidance in the touchdown zone, and centre-line lights along the length of the runway for guidance during the ground roll and low visibility take-off.
9. To provide instrument displays for monitoring the performance of the total system and its various components, including monitoring ILS nuisance alarms.

10. And last, but by no means least, a means of safeguarding against the failure of any piece of equipment during such a highly critical period of flight.



Figure 9 An Early ILS Localiser Built by BLEU

During the early years the aircraft ‘workhorses’ were the Devon and the Anson (Figure 10). The Devon made the first fully automatic landings in 1950 and the Anson demonstrates that the research was not always straightforward!



Figure 10 a De Havilland Devon VP954 at Blind Landing Experimental Unit



Figure 10 b Avro Anson NK827 at Blind Landing Experimental Unit

As work progressed successfully through the 50s, larger aircraft were introduced into the programme (Figures 11a and b), and the Vickers Varsity became the ‘workhorse’, with aircraft like the Canberra and the Comet more representative of modern military and civil aircraft. Meanwhile throughout the whole period, BLEU was keeping the electronics industry closely involved, with perhaps special mention of Smiths and Marconi-Elliott Industries on autopilots, and Standard Telephones and Cables (STC) on ILS and radio altimeter.



Figure 11a Vickers Varsity at BLEU

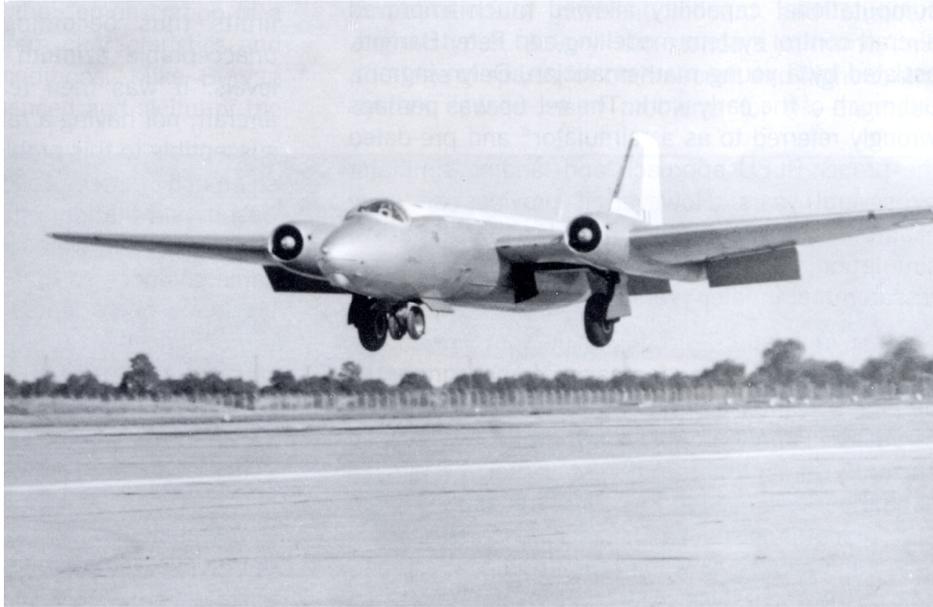


Figure 11b English Electric Canberra and De Havilland Comet at BLEU

6. BEDFORD

In 1954 the Air Staff were impressed with the progress made and issued a formal requirement for automatic landing of the Vulcan bomber (OR 947). This provided a sharp focus for a reliably engineered system and it was shortly after this in 1955 that I joined BLEU. The programme gained added momentum from the planned transfer of BLEU from Martlesham to Thurleigh, the RAE airfield at Bedford, though the move was not popular with all staff, many of whom had long enjoyed the sailing and fishing associated with the River Deben and the East Coast. Eventually the move to Bedford took place in the spring of 1957 when a smaller BLEU joined Aerodynamics Flight Division and Naval Air Department already there from Farnborough. With excellent approaches and little air traffic, the two mile long, 300 feet wide runway was ideal for total system development and very quickly an improved ILS and experimental lighting patterns were installed (Figure 12).

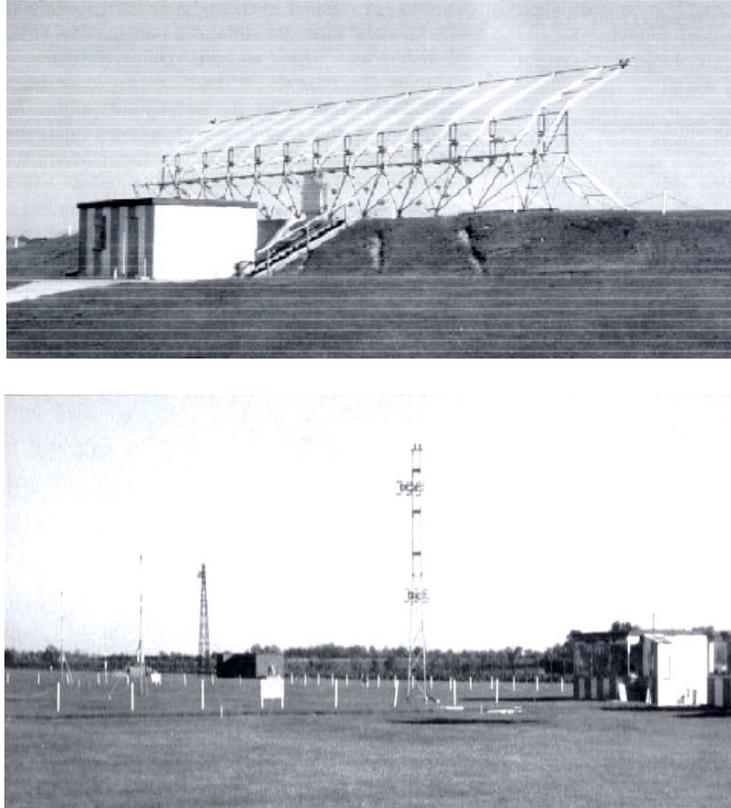


Figure 12 The STAN 37 localiser (top) and STAN 38 Glide Path Transmitter at Royal Aircraft Establishment Bedford

In October 1958, now with more experience and added confidence in a complete system, a series of automatic landing demonstrations were arranged for the Air Staff, airline operators, CAA, Industry and of course the Press. The Varsity was the aircraft used most and Figure 13 is a copy of the headline print of the week, pilot Pinkie Stark and his 'Look no hands' routine



Figure 13 'Look, no hands!' Flight Lieutenant Pinkie Stark in the Vickers Varsity

In due course, the other consequence of the publicity was a request from the Palace for HRH the Duke of Edinburgh to 'have a ride'. Not surprisingly the protocol was daunting. Rather than use the 'old hack' Varsity, the Canberra was thought to be more appropriate but when the time came I felt somewhat nervous, since the aircraft equipment fit was a single 'lane' military system with no redundancy back up. Nevertheless, on 4th December 1959, with the RAE Director watching, I helped strap HRH into the right hand seat of Canberra WJ992 and waved him off. Fortunately all went well and after several fully automatic, accurate landings HRH returned, beaming with a delighted grin of achievement.

7. CIVIL SYSTEM

With the 'single lane' military system now successfully launched in industry (autoland in the Vulcan was accepted into service in 1961) BLEU's attention turned to the conversion of the military system into a safe system for passenger carrying certification. It raised two main problems: the first concerned with performance and the second with safety.

1. Despite the improved antenna design to increase its aperture and thus reduce beam distortions due to reflections, doubt still existed as to whether the performance of the ILS localiser could be made satisfactory for guidance down to and along the runway.
2. The failure probability of any 'single lane' system was too high for civil transport application and some form of redundancy was essential.

BEA and BOAC, UK industry and the Air Registration Board (ARB) combined with BLEU to address these problems and in 1961 the ARB issued a working document BCAR 367 'Airworthiness Requirements for Autoflare and Automatic Landing'. In so doing, the group found it necessary to construct a classification of criteria at different levels of operational capability to provide a means of defining break points in the certification requirements and standards for the related elements of the total system (Table 1). ICAO accepted the thrust of this UK work and in 1964 appointed an All-Weather Operations Panel (AWOP) to pursue the international implementation of these broad criteria. In 1965 they were adopted by ICAO and remain much the same today.

Category	Minimum Decision Height (feet)	Minimum RVR (metres)
1	200	800
2	100	400
3a	zero	200
3b	zero	50
3c	zero	zero

Table 1 All Weather Operations - Early Classifications

Although I had left BLEU in 1962, I was moved back to Farnborough as Head of Instruments and Electrical Engineering Department so was still closely involved with BLEU programmes.

With regard to the safety problem, we had decided here in the UK that protection against the

effects of failure during the critical landing period could only be achieved by adding further automatic 'lanes' so that, should a failure occur, the landing could be completed by the remaining part of the automatic system. Clearly a complete blind landing capability along these lines meant considerable added complexity in the airborne equipment and therefore additional expense to the airline operators. In the USA serious doubts were expressed against this British philosophy and little enthusiasm was shown. In 1961 the US Federal Aviation Agency (FAA) were assessing a Bendix 'pilot in the loop' solution to the all-weather problem, using radio beacons positioned like runway edge lights to provide an outline perspective picture of the runway on a CRT flight deck display. BLEU and Ted Calvert had already experimented with such an idea and were very critical because of the limited information and heavy pilot workload. To gain experience with 'the BLEU automatic landing system', the FAA sent across a Douglas DC7 to RAE Bedford for the installation and testing of the system. After about three months at Bedford and further tests on return to Atlantic City, the FAA were convinced and thereafter strongly supported a fully automatic solution to the all-weather problem.

Figure 14 shows that low visibility is a more frequent occurrence in Europe, and BEA and BOAC decided to take steps towards the installation of a fully automatic capability. In 1959 contracts were placed with Smiths Industries for a triplex system in the BEA Tridents, and with Elliotts for a duplex monitored system in the BOAC VC10s.

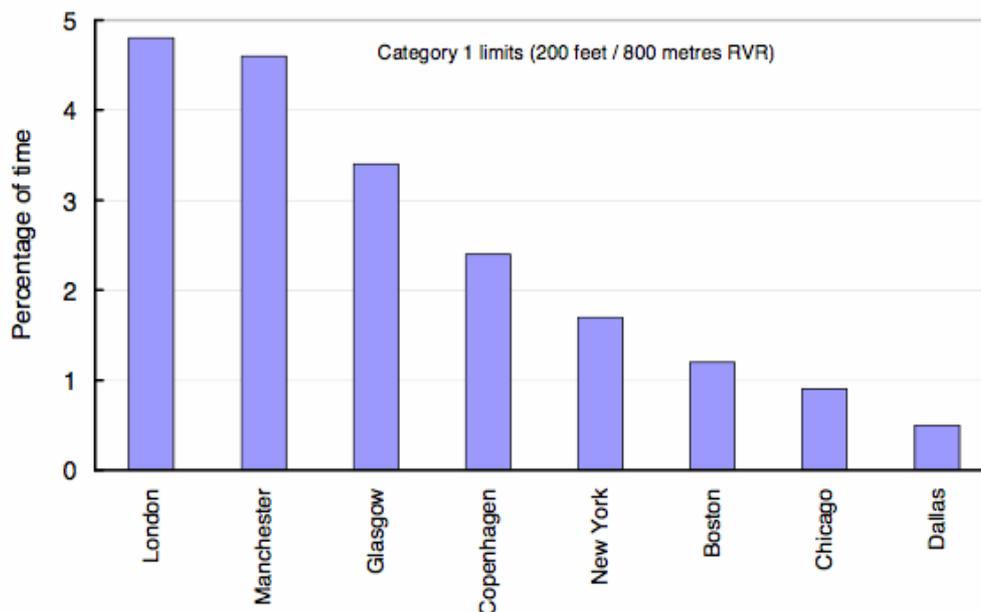


Figure 14 Occurrence of Weather Conditions Below Category 1 Limit

Later consideration by BOAC led them to cancel their VC10 programme but a very similar system was developed for Concorde. Meanwhile the Trident programme continued with the triplex system (Figure 15) in which three independent lanes work simultaneously with a voting system to identify and disconnect a failed lane. The importance of these two programmes cannot be overstated since they established, through the 1960s, the processes by which the airworthiness requirements, system design, equipment specifications and supporting statistical proof of compliance should be formulated. They laid the foundations for techniques to be followed in more widespread use in many other avionics systems.

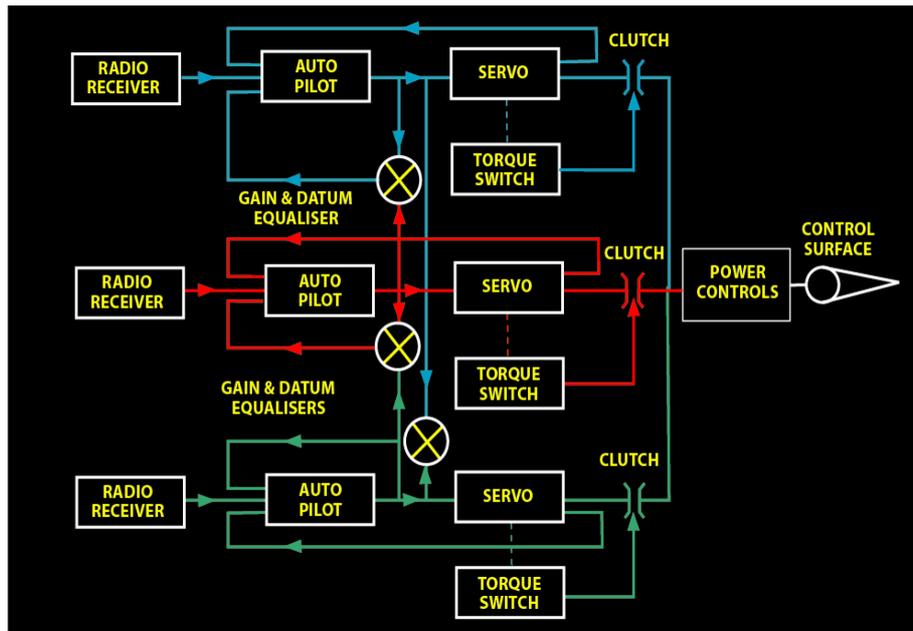


Figure 15 Smiths Industries triplex system for BEA Trident

8. SAFETY

The UK airworthiness authority adopted the concept of a numerical safety level for autoland system certification, together with the need for a rigorous analysis to demonstrate its achievement. Starting from the point that the risk of a fatal accident during an automatic landing should be no greater than the risk in a clear weather manual landing (generally accepted at that time to be 1 in 1 million), a figure of 1 in 10 million was taken as the required fatality risk per automatic landing. It was clear from data on autopilots of the day that low risk levels of this order could not be obtained without the equipment redundancy mentioned earlier. It was equally clear when dealing with such enormous numbers that demonstration in flight was quite impractical, if not impossible, and a statistical analysis was therefore needed, using modelling of the system and its sub-systems to obtain the necessary input data. The analytical technique developed in BLEU became the basis of agreed European Joint Airworthiness Requirements and acceptable means of compliance (JAR 25) to minimise the certification problems of high integrity avionic systems (e.g. fly-by-wire controls, electronic flight instrument displays as well as autoland). Two examples serve to demonstrate the depth of analysis that was required for certification of a safety critical system. Figure 16, taken from JAR 25 of the 60s, indicates guidelines for the conversion of a qualitative severity of failure into a quantitative probability in terms of risk, to be used when numerical compliance is being assessed. For instance, any failure that might result in a large reduction in safety margins, serious injury or death, must be regarded as improbable and extremely remote and the system and associated components must be designed to satisfy a risk probability of not more than 1 in 10 million.

Effect on Aircraft and occupants	Normal	Nuisance	Operating limitations: emergency procedures	Significant reduction in safety margins: passenger injuries	Large reduction in safety margins: serious injury or death of a small number of occupants	Multiple deaths, usually with loss of aircraft					
JAR-25 probability	← Probable →		← Reasonably probable →		← Improbable →						
	← Frequent →				← Extremely improbable →						
	10^0	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}
Category of effect	← Minor →				← Major →		← Hazardous →		← Catastrophic →		

Figure 16 Probability of a failure and its effect

Having established the target risk probability, Figure 17 is a very simple illustration of the ‘top levels’ of an automatic landing statistical model to partition the average risk between all the components. The first level down divides the risk probability requirement, equally in this case, between performance and equipment failure. Continuing only with the performance element, at the next level down a further allocation is made between the risks associated with the longitudinal and lateral performance. The logic is continued down the tree, becoming ever more complex, to such detailed levels as variations in the localiser and glide path signals. Tens of thousands of computer-simulated landings were made using a wide range of variables to assess the risk level, with a limited number of flights to validate the model and explore particular conditions. A similar partitioning is made for all types of failures and by techniques of this nature the degree of redundancy and the standards to be met are defined for all components of the total system.

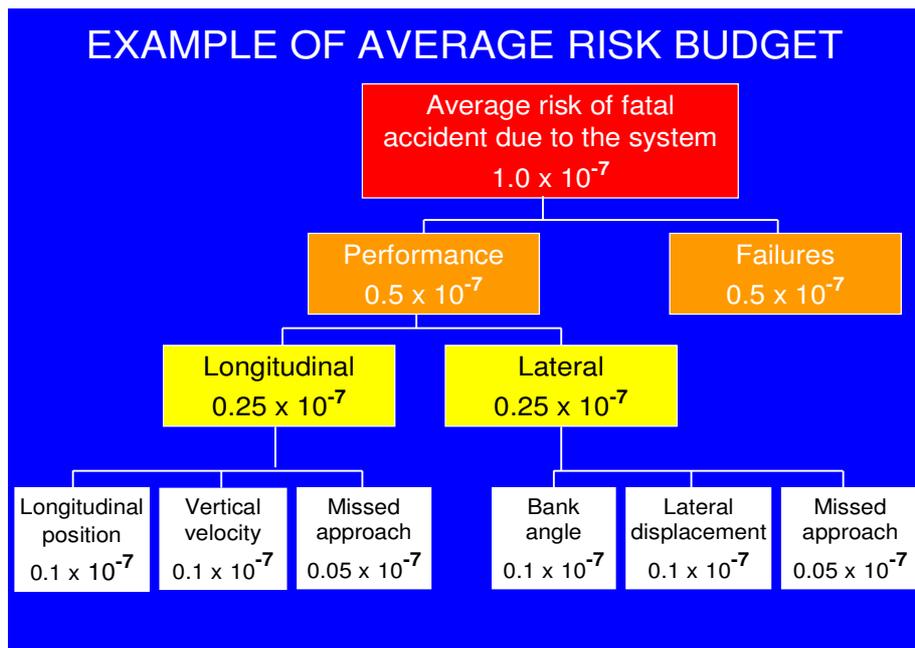


Figure 17 A statistical model to partition the average risk between components

9. CIVIL ACHIEVEMENT

The development of these risk assessments and redundancy techniques was pioneered during the 60s, mainly by Frank Gill, on the Trident and VC10 followed by the BAC 1-11 and Concorde. By far the most extensive experience was gained from the Trident programme (Table 2) in which, over a period of about 15 years, 40,000 automatic landings were analysed. Finally in 1979, the aircraft was certificated for Category 3(c) operation (a 12ft decision height and 100m visual range), provided always that the ground guidance installations were approved to the same standard. It was a long, hard road, breaking new ground with both system complexity and required accuracy, perhaps an order of magnitude greater than anything attempted previously. The Marconi-Elliott VC10 programme followed a similar pattern to Trident and about 3,500 autolands were made in Category 2 conditions before the system was withdrawn by BOAC in 1974. A Sperry system in a Pan-American Boeing 727 was certificated in 1966 for Category 2 conditions and in France a Caravelle carrying mail (and without passengers) was certificated in 1968 for Category 3a. With advances in electronic digital technology Concorde, with a GEC Avionics system, was given a Category 2 certification in 1976, and only 2½ years later, a Category 3a (15ft/200m) in 1979.

1959	Programme started aimed at CAT 3(a) in scheduled passenger operation by early 1970s
1962	Flight test programme started at Hatfield
1965	CAT 1 certification of AUTOFLARE (duplex level)
1965	World's first AUTOFLARE in passenger operation
1966	First AUTOLAND in development aircraft (triplex level) in CAT 3(b) conditions (0ft/50m)
1968	BEA decision to equip all TRIDENT aircraft at triplex level
1968	CAT 2 certification for passenger operations (100 ft / 400 m)
1969	Development programme completed
1972	CAT 3(a) certification for passenger operations (12 ft / 200 m)
1979	CAT 3(b) certification (12 ft / 150 m)
1979	CAT 3(c) with 75 m RVR for take-off (12 ft / 75 m)

40,000 autolands analysed for CAT 3(c) certification

Table 2 Trident programme (Smiths Industries Autoland)

The Collins Automatic Flight Control System in the Lockheed Tristar for BA, conceived about 1968, was the next step in the evolution of high integrity, high performance systems and was designed from the outset as an integrated system, offering an autoland facility as only one of many flight control, navigation and display features within the autopilot. Inertial platform signals were mixed with the ILS signals in new forms, the control laws modified and Category 2 certification obtained in 1976, with Category 3b in 1978 after only 2½ years. The use of inertially-derived information in current systems allows for accurate profiles to be flown from

about 170 feet, where the ILS glide slope may become unreliable, and for the ATTITUDE phase of the original system to be replaced. At about 50 feet, with the aircraft now over the runway, the radio altimeter provides the accurate height information needed to compute the flare. All major avionic systems in later generations of transport aircraft following the Boeing 757 and Airbus A310 make extensive use of digital technology. This has opened up, through the software and its architecture, reconsideration of the various ways of providing the redundancy, monitoring and displays needed to meet the failure risk, along with an intelligent self-test and fault location facility. In so doing of course, it raises the problem of failure of the software itself but, as before in the 60s, techniques have been developed by research agencies, manufacturers and airworthiness authorities for software programming disciplines to ensure acceptable standards. It is a complex task but with modern simulation and modelling, the previously long and expensive period of proving trials has been dramatically reduced. The digital autoland facility in the flight control system of the Boeing 757s for BA was certificated for Category 2 weather conditions in August 1983 and for Category 3b in January 1984 – less than 6 months later. Table 3 lists the range of aircraft that, in particular configurations, had been certificated by the CAA in 1989 to have the capability of landing safely in visibilities less than 200 metres. The limits depend on particular equipment fit and can only be used at airports with approved ground guidance installations.

Cat 3a 0ft/200m	Cat 3B 0ft/50m
Boeing 737	Lockheed Tristar
Boeing 747	Boeing 757
Boeing 767	
BAe Concorde	
BAe 1-11	
McDonnell Douglas DC-10	

Table 3 All weather limits at 1989 approved by CAA

10. CONCLUSION

And that really is the end of my personal story. Appendix 1 is a list of later all-weather programmes that were addressed with success by RAE up to the time it ceased to exist as such in 1991. Since then, of course, although Cat 3 decision height and RVR limits have remained much as indicated in Table 3 above, automatic landings by large civil transport aircraft have become routine.

11. ACKNOWLEDGMENTS

I wish to thank the following sources for providing ready access to material used in the lecture on which this paper is based:

The Royal Institute of Navigation

“Wings over Thurleigh” (edited by Mike Dobson) Farnborough Air Sciences Trust (DVD)

RAE Tech Memo FS 77 (through Bill Makinson)

ex-BLEU Colleagues Tom Prescott, Joe Morall and Peter England

and finally my daughter Katrina Sudell and Dr Kit Mitchell. Without their willing assistance in the collection and editing of the material, the lecture would not have been possible.

Peter Davison re-drew a number of the figures for this paper, and his support is gratefully acknowledged.

12. REFERENCE

Sir John Charnley (1989) Navigation aids to aircraft all-weather landing The Journal of Navigation Vol.42, No2, pp161-186, May 1989, Royal Institute of Navigation, London.

Sir John Charnley

Sir John Charnley began his career as an aeronautical scientist/engineer in the Flight Test Division of the Aerodynamics Department (Aero Flight) of the Royal Aircraft Establishment (RAE) at Farnborough in January 1943. In 1955 he was appointed Superintendent of the Blind Landing Experimental Unit (BLEU) at Martlesham Heath in East Anglia. In 1963 Sir John moved back to Farnborough to head the Instrument and Electrical Engineering Department and then in 1965 moved again to head the Weapons Department. In 1968 he transferred to the Ministry of Technology in London, to be concerned with the planning of R&D across all sectors of manufacturing industry. In 1972 he was appointed Controller of Guided Weapons and Electronics in the Ministry of Defence, responsible for all defence procurement in this rapidly moving field. A posting to Chief Scientist, Royal Air Force, was followed in 1977 by a move to be Controller of the twelve UK defence R&D establishments and professional head of defence scientists. Although formally retired in 1982, he worked with the Civil Airworthiness Authority on R&D concerned with future Air Traffic Management and assisted companies in the aerospace and manufacturing industries. In 1987 he was appointed a Trustee of the Richard Ormonde Shuttleworth Remembrance Trust with responsibility for the preservation and display of its historic aircraft and vehicles.

In 1960 Sir John received, on behalf of the BLEU team, the Bronze medal of the Royal Institute of Navigation, followed in 1964 by the Cumberbatch Trophy of the Guild of Air Pilots and Air Navigators. Later he was awarded the Royal Aeronautical Society's Silver and Gold medals and, in 1980, delivered the Society's Wilbur Wright Memorial Lecture. He was elected an Honorary Fellow of the Society in 1992. He is also a Fellow of the Royal Academy of Engineering, a past President of the Royal Institute of Navigation and a winner of their Gold Medal. He was elected a Companion of the Bath in 1973 and knighted in 1981.

APPENDIX I: RAE ALL-WEATHER LANDING RESEARCH 1965 – 1990**CIVIL ALL-WEATHER**

1979 Trident Category 3c approved (15/200)

VISUAL AIDS

1965 Carrier Requirement leading to
 73 PAPI Precision Approach Path Indicator
 76 ICAO specification for taxiway lighting
 77 PAPI on Hermes HMS Kidd
 83 PAPI approved by ICAO and NATO

MADGE (Microwave Aircraft Digital Guidance Equipment)

1967 Tri-service Requirement for a tactical all-weather landing system leading to prototype demonstrations in 14 countries
 71 MADGE wins NATO Competition
 76 Installed on carriers as a working tool for all-weather trials

MLS (Microwave Landing system)

1969 Research on a Doppler microwave equipment
 73 International Competition
 78 ICAO preferred US Time Referenced Scanning Beam system

HELICOPTER ALL-WEATHER (Wessex XR 503)

1967 Research
 73 Approaches using MADGE at Thurleigh
 77 Approaches using MADGE on Hermes
 81 CAA approved MADGE for helicopter approaches to North Sea platforms

CIVIL NAVIGATION RESEARCH (BAC 1-11)

1972 onwards Mode S transponder, Data Link, Satellite Navigation, Electronic Data Displays, Air Traffic Management

SEA HARRIER

1976 Research aimed at all-weather recovery to carriers and HAPI (Harrier Approach Path Indicator)
 developed from PAPI35
 77 Two week trial on Hermes with A&AEE
 78 Second Hermes trial

VAAC

1982 Vectored Thrust Aircraft Advanced Control System programme
 92 Joint VSTOL programme, NASA/RAE
 now in Joint Strike Fighter Project (JSF) – Lockheed Martin F35