# The Development of Airborne Dead Reckoning. Part II: After 1940 – Staying On Track

Alec Ayliffe

The History of Air Navigation Group commissioned the author to provide a brief account of airborne DR development by discussing both the methods and the equipment used in the air. This second and final part covers the period after 1940 which saw the automation of DR techniques from the Air Position Indicator of the 1940s to the Flight Management Systems in current use.

KEY WORDS

1. History. 2. Dead Reckoning. 3. Air Navigation.

1. INTRODUCTION. The Second World War was to see a dramatic change in airborne DR but, before discussing the key developments, it is worth considering the general context of DR practice. The gradual development of DR up to the Second World War took place in concert with a general development in aviation technology and electronic engineering. The development of the gyroscope has been mentioned with reference to drift meters; however, the gyroscope was far more important to aviation as the basis of first the turn indicator, and later the artificial horizon. The RAF introduced the blind flying panel in the late 1920s, and the development of gyro-magnetic compasses was proceeding in Germany, the USA and Britain.

Aviation had changed dramatically between 1918 and 1938 but, over the same period, there was no fundamental difference in airborne DR despite the availability of thicker textbooks and better equipment. It could be argued that pilot navigation techniques and mental dead reckoning have not changed fundamentally from 1918 to this day; the techniques have merely been adapted according to the speed of the aircraft and the wider availability of fixing aids. When comparing the 1920 notes on Air Pilotage with equivalent documents in the 1940s, very little had changed. The 1942 edition of the Manual of Air Navigation recommends the drawing of 5° rather than 10° drift lines on the map (possibly because faster aircraft suffer less from drift), and the 1951 edition of the Air Navigation Manual (now referring to 'Mental Dead Reckoning') includes additional rules of thumb to check estimated times, perhaps because running out of fuel is rather more critical in a jet aircraft than a biplane.

2. DR PROCEDURES. Despite this apparent continuity in mental DR, a great change in the practice of airborne DR and the navigation process took place in the 1940s. The change is apparent when comparing textbooks before, during and after the Second World War. The concept of the 'Air Plot' is a key example. The plotting of an air position, that is a position derived only from heading and true airspeed vectors,



https://doi.org/10.1017/S0373463301001461 Published online by Cambridge University Press

was described fully in the 1930s, and it was known that a wind vector could be applied to this position to find the DR position. However, this technique was first detailed as a specific procedure called the 'Air Plot' in the Observer's Book of Dead Reckoning Navigation published in October 1940 (Allan & Alexander, 1940). The importance of the air plot is the concept of an air plot wind that was derived by drawing a line between the air position and a fix position for the same time. The method allowed a wind to be obtained easily from a fix position even if the heading had been changed between fixes that made the track and groundspeed method impractical. The air plot was given official sanction in the June 1941 'Alice in Wonderland' edition of AP 1234. Also in this edition the arrow convention, by which heading vectors were marked with one arrow, track vectors with two arrows and the wind vector with three arrows, was established. After the war, the traditional technique of track and groundspeed plotting was also established as a procedure, called the 'Track Plot', in the July 1951 edition of AP 1234.

The reason for this change was that suddenly a large number of navigators was needed for the expanding air forces. The dedicated navigator in the 1930s was a rare man, a skilled aviator and, almost certainly, a master pilot. By 1939 there was no time to let such skills come from experience. In 1940, F. C. (Dickie) Richardson (then a newly promoted Squadron Leader) was tasked to rewrite the navigation manual to encapsulate the skills of the air navigator in a method that could be taught readily to raw recruits with no air experience (Richardson, 1997). The indoctrination and training of the RAF navigator was founded on DR, but it was DR based on procedure not experience. To emphasise this point, it should be noted that later in the war, Dickie Richardson was to develop navigation 'drills' for Coastal Command that were to be adopted throughout the RAF. These drills, and DR doctrine, were publicised through an efficient training machine and effective training publications.

This process did not diminish the skill required for DR. For example, by 1942 the RAF navigator was expected to be able to plan and execute more tactical DR techniques than his predecessors including a moving or relative square search, a parallel track search and a patrol along a constant bearing. In addition, Coastal Command navigators were expected to work with shipping convoys. By 1942 the concept of a *critical point*, which is the position between two bases from which it is equally quick to fly to either, was introduced to cater for aircraft emergencies and, by the end of the war, the navigator was expected to be able to find the *point of no return* on long transit flights. Tactical development continued after the war and, in 1950 textbooks, the navigator was taught to plan for diversions and for fuel reserves at the destination. Also in 1950, the wide variety of searches was expanded to include sector searches and the modified creeping line ahead.

The change in DR practice was also, of course, influenced by developments in aviation and air navigation technology. For aircraft at high levels, above cloud or at night, traditional wind finding techniques were not satisfactory. The Germans and the Americans had, however, addressed navigation problems to a certain extent by innovations in radio navigation aids and not by improvements to DR. There was a tendency between the two World Wars to treat DR as a separate technique required when radio or astro navigation was not available. But if technology brought changes to the DR requirement, it also brought new equipment that was to represent a major break with the past. The introduction of the first automated DR equipment, the Air Position Indicator (API), by the British was to change the practice of DR irrevocably.

3. THE AIR POSITION INDICATOR AND GROUND POSITION INDICATOR. The development of the API was a secret project, revealed to the general public at the end of the Second World War (Scrimshaw and Wells, 1945). The equipment was itself dependent on the prior development of the gyro-magnetic Distant Reading Compass (DRC), which gave a heading feed, and the Air Mileage Unit (AMU), which provided, in effect, a true air speed feed.

The DRC was proposed by Captain L. C. Bygrave, and possibly P. A. Cooke, around 1930. It should be noted that the Germans, with the Patin system, and the Americans, with the Magnesyn system, had developed equivalent equipment to the DRC, but the DRC was probably the first to be used to provide a heading feed to automatic equipment. The DRC was a directional gyroscope the wander of which was automatically monitored and corrected by a magnetic compass. In effect, the DRC combined the short-term stability of the gyroscope with the long-term stability of the magnetic compass. Service trials of the DRC began in 1935, but a production decision was not taken until 1940, and the system did not enter service with No 7 Squadron Stirling aircraft until March 1941. The DRC used an Admiralty 'M' type DC transmission to feed heading to other equipment. *Tee Emm*, the RAF training magazine, explained it to aircrew in 1943 as follows:

> Now the movement of the North-seeking mechanism relative to the aircraft is made to drive a 'transmitter' which pushes electrical impulses along the wiring to the repeater. The repeater contains a motor that is driven round by these impulses, and the motor, in turn drives the dial by which you steer.

The impulses were also used to drive a motor in the API. The DRC transmitted magnetic heading, but true heading was obtained by placing a phase shifting receiver-transmitter in the transmission line between the master unit and the API controlled by a manually set Variation Setting Control.

The other key equipment to feed the API, the AMU, was developed at RAE Farnborough from an idea submitted by Group Captain H. L. Reilly. The idea of developing a true airspeed indicator was not initially progressed in Britain because the aviator is, for aerodynamic reasons, far more interested in indicated air speed that has a direct relationship to the stall and, therefore, an immediate relationship to life and death. True airspeed could be obtained easily enough from indicated airspeed by correcting for air density using the altimeter and the temperature gauge. However, about 1937, when the RAF was taking an increasing interest in navigation, work began on a windmill type machine, the Air Log Mk1, which was finally tested in 1940. These tests were unsuccessful and work on the AMU began.

The AMU was based on a centrifugal fan in an airtight case. Described in a vastly oversimplified way, the principle of operation was that the speed of rotation of the fan was controlled by balancing the pressure at the periphery of the fan against the pressure developed by the pitot tube, thus obtaining a shaft rotation that was proportional to true airspeed. The AMU Mk I began to be fitted to all bomber and coastal aircraft from about 1942. The AMU Mk II was developed to increase the speed range of the equipment from 300 to 400 knots. As an aside, before describing the API, it should be mentioned that an Air Mileage Indicator, taking a feed from a transmitter directly coupled to the output shaft of the AMU, was also produced. But this Indicator was chiefly for the Flight Engineer to compare with a fuel gone meter to calculate the fuel flow per air mile.

There were some attempts to create automatic DR systems based on the rectangular, Cartesian co-ordinates of a grid. These systems were primarily designed for carrier-based aircraft where the ship could be used as the origin of the grid. Towards the end of 1937, the RAE produced an instrument that used a constant speed electric motor to produce an output of nautical miles north-south and east-west on two Veeder type counters from manually set true airspeed, heading, wind speed and wind direction. This instrument also allowed the setting of a ship's course and speed. The French developed a similar system called the 'Totalisator D'Estime' that had an automatic true airspeed input. Attempts were made to create an automated system for the Fleet Air Arm using DRC prototypes and a vane anemometer to feed true airspeed. The vane anemometer did not, however, prove suitable for production and the idea was abandoned.

By 1940 it was apparent that traditional DR techniques were entirely impractical for the new generation of navigators fighting the air war over Europe. An urgent requirement for an API was established. Courtaulds produced a prototype that was not accurate enough and eventually the Bell Punch Co produced the API Mk I to an RAE design. The basic components of this API were the compass repeater system, two resolving gears, a secant gear and the counter mechanism. The resolving gears allowed the input of true air miles from the AMU to be converted to 'Northings' (distance flown times an analogue of the cosine of heading from the DRC) and 'Eastings' (distance flown times an analogue of the sine of heading). The really

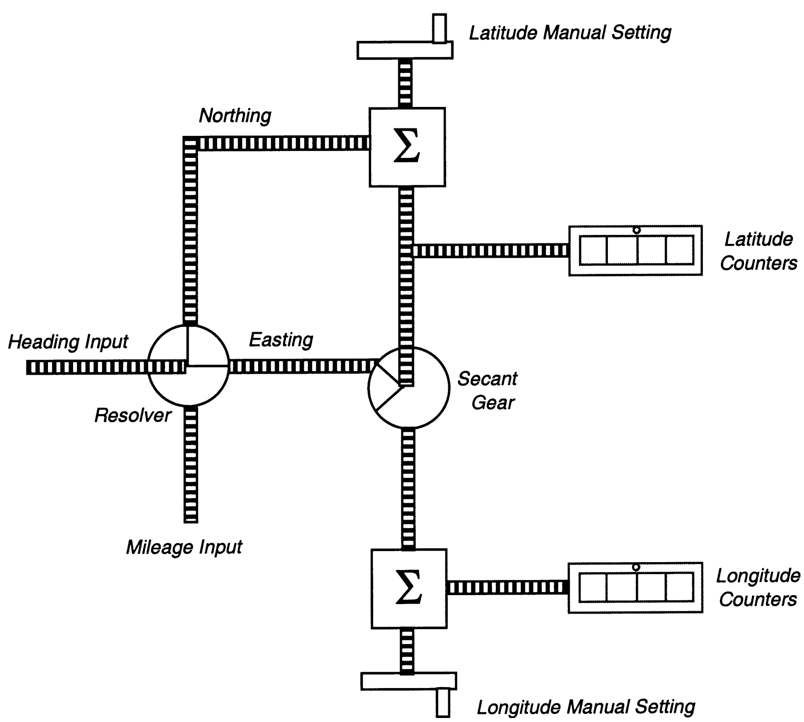


Figure 1. Schematic diagram of the Air Position Indicator.

innovative feature of the API was the secant gear that allowed an output of latitude and longitude. A schematic diagram of the API is at Figure 1. The principle used is based on the fact that, to obtain longitude, eastings must be multiplied by the secant of latitude. With a position output in latitude and longitude, the API could be used easily with normal charts.

The API was first installed, again in a No 7 Squadron aircraft, in February 1943 and was used by No 617 Squadron for the attack on the Möhne and Eder dams in May 1943. The equipment was also installed in a limited number of USAAF Liberators for the attack on the Ploesti oilfields in June 1943. The British provided the Americans with full details of the AMU and the API. In January 1943, a team from the RAE had visited the US to discuss progress. Two of the American hosts, Lieutenant Colonel T. L. Thurlow and Lieutenant P. C. Holt were noteworthy individuals in the history of airborne DR. Thomas Thurlow, who was killed during flight trials of a compass at Wright Field in 1944, had been the navigator for Henry Hughes on his around the world flight in 1938 and, with Harold Gatty, had developed a table to simplify the calculation of double drift winds in the early 1930s (Harbold, 1970). Pliny Holt was to play a significant role in the development of the American API and its successors (Wright, 1972).

In 1943, the main thrust of the American effort was to improve the British AMU and to adapt the API for small carrier-borne aircraft (Pritchard, 1943). Fairchild experimented with the API concept, but it was the Pioneer Instrument Division of the Bendix Corporation who eventually produced a remarkably engineered API. The latitude and longitude counters were neatly displayed inside the compass repeater rose and the whole instrument could be fitted into the dashboard of an aircraft. It should be noted that the pilot was expected to navigate US carrier-borne aircraft and use a chartboard that slid into a slot in the dashboard and pulled out like a drawer when required for use. The aircraft were fitted with a short control stick to make this possible.

It was soon appreciated that if a wind vector could be automatically added to the API output a Ground Position Indicator (GPI) would be produced. The advantage of the GPI was that the navigator would not have to plot an air position and then a wind vector to find his position; a procedure that was rather impractical in the target area when violent evasive action was required. In late 1942, the GPI Mk I was developed by RAE, and a limited number were manufactured by the Instrument Section of Rolls Royce Ltd for installation in No 7 Squadron aircraft in 1943. The GPI Mk I combined a manually set wind velocity with an air position electrically transmitted from the API. By means of a lamp and rotating mirror, the GPI projected an illuminated arrowhead onto a chart. The orientation of the arrowhead showed aircraft heading and the position of a cross at about one third of its length showed ground position.

The Germans also produced a GPI to assist with navigation in winter over the featureless, snow-covered Russian terrain. The German 'Kurskoppler' produced by Siemens entered service in late 1944. It was completely different to the British API, depending on electrical rather than mechanical, analogue computation. A device, called the 'Fahrtzentrale', supplied a DC voltage proportional to true airspeed to a resolving unit consisting of a sine-cosine potentiometer. The resolving unit was rotated by a heading repeating system operated by a Patin compass in some units or by a direct mechanical drive from the servo-unit of a Siemens directional gyro in other units. The wind vector was manually set via two potentiometers with values calculated separately. The Germans produced automatic plotting boards, with position indicated by the intersection of two wires moved by a ratchet mechanism, for use with the Kurskoppler.

By the end of the Second World War, the British and Americans were developing a number of automatic DR systems. The British API Mk II, comparable in size to the Pioneer API, was designed for dashboard fitting in carrier aircraft and was intended for use with the GPI Mk II which showed the DR position in nautical miles north-south and east-west on counters. It was provided with electrical transmitters so that, if fitted to multi-seat aircraft such as the Mosquito, it could operate an automatic plotting board Mk I. Some designs were novel: the lightweight navigation computer developed at TRE Malvern, gave a bearing and range to base or a starting point, and the American GPI Mk III was designed by MIT for use with a search radar.

Perhaps the most important project was the Navigation and Bombing Computer (NBC) Mk I. Work on this complex integrated system began in 1943 in response to a Staff Requirement for a universal DR device closely integrated with the radar (H2S) and radio fixing aids, such as Gee. A secret RAE history described the purpose of the NBC as follows: 'The aim was to relieve the navigator still further of the computation and plotting required in current DR practice and to make frequent checking easy...' (Twiney *et al*., 1945). Two new aspects of the project were particularly challenging at the time: the direct indication of true airspeed and automatic correction of the wind from $H_2S$. A development contract was placed with BTH Co Ltd, but with the end of hostilities the project reverted to experimental status.

The work on a true airspeed indicator proceeded in parallel with the development of the AMU. Another instrument that began to have greater importance with the advent of the turbojet-powered aircraft was the Mach Meter. The development of all these instruments was to lead very quickly to the creation of air data systems combining the many requirements and, by the 1950s, these were beginning to emerge as electro-mechanical Air Data Computers.

Work on an automatic wind finding mechanism was ultimately to be abandoned along with the myriad of wind finding methods developed in the DR textbooks. For a while, much effort was expended on mechanising the air plot. One device devised in 1943 was the Wind Finding Attachment (WFA) to the API. This device effectively magnified the output of the API so that an air plot wind could be found by flying a small circuit over a surface mark, which took about four minutes in a heavy aircraft. If the mark was a smoke float, dropped from the aircraft, allowance could be made for the ballistics properties of the marker to obviate the need to fly two circuits. The WFA was set to zero and switched on at the first 'on-top'; at the second 'on-top', the reading of the north-south and east-west counters was recorded on RAF Form 1956, which was an elaborated piece of graph paper. The device was evaluated by the Coastal Command Development Unit in January 1944 and was considered to be very satisfactory; their report concluded: 'Its accuracy is equal to that of three course methods at approximately 100 knots and above that speed becomes superior.' (CCDU, 1944).

## 4. OPERATIONAL RESEARCH AND THE ANALYSIS OF DR ERROR.

By 1944, accuracy had become a matter for deliberate research. Of course, practical navigators had always thought about error. Air navigation demanded a continual judgement on the value of the information obtained. Professional air navigators between the Wars knew about bands of error and zones of uncertainty, but the analysis methods used to consider error were primitive. The most comprehensive treatment on error was contained in a chapter on the analysis of air navigation exercises contained in the 1938 edition of AP 1456. Three years later in 1941 a new breed of scientist, the Operational Research Scientist (ORS), began to look at navigation errors with intellectual rigour. When the Coastal Command Operational research Branch began to examine DR, they dismissed the methods of AP 1456 as unusable, unrepresentative and meaningless in an operational context (HMSO, 1963).

The scientists developed statistical methods to analyse the practice of DR. Their findings varied from the mundane to the unexpected. In Coastal Command, the analysis of DR errors reinforced the need for improved navigation drills. An investigation into the accuracy of wind finding also found that the prevalent use of the drift and wind lane wind finding method affected the overall accuracy of navigation; there was a marked improvement when three drift winds were used. Bomber Command ORS discovered that the AMUs in the Lancaster were overheating and, therefore, over-reading.

The specific findings of the ORS were less important than the cultural change they brought to the practice of DR. The assessment of error had been part of the navigator's art; it now became a science. The RAF even incorporated the statistical techniques into a DR drill to assess the Most Probable Position (MPP). The MPP was publicised in Wing Commander E. W. Anderson's manual, *Principles of Air Navigation*, first published in 1951. It should be noted that this technique was not discussed in the much thicker textbook, *Air Navigation Theory and Practice* (Williams and Branch, 1952), which outlined the traditional bands of error approach but, nevertheless, the MPP was soon established as a standard DR procedure. Anderson made it clear that the MPP was not designed for the experienced airman but was: 'suited to the beginner because it gives him standards against which to base his experience.' He acknowledged that the experienced airman could afford to laugh at the gross simplifications of the MPP drill, but equally clearly, DR skills could be reduced to a mechanistic process.

Alongside this practical change, theoretical writings on navigation began to adopt a new mathematical approach. Lectures on air navigation delivered to Air Ministry students by Erwin F. Freundlich, the Napier Lecturer in Astronomy in the University of St Andrews, published in 1945, were based almost entirely on theory and mathematics. The approach was appropriate to engineers, not to practical navigators. The human touch was not considered.

5. NEW DR TECHNIQUES. At the end of the Second World War, the British and Americans were developing and producing a large number of navigation systems and there were many practising, professional navigators. Graduates of the RAF Specialist Navigation Course, including a number of distinguished Royal Canadian Air Force (RCAF) navigators, approached navigation and DR issues with inventiveness and enthusiasm. Engineers, operational research staff and scientists at research establishments worked closely with these experienced navigators. New techniques and equipment were evaluated on a succession of long-range flights including the renowned Aries flights.

One technique proven on several Aries flights in the Arctic was use of the grid system. The technique was not available for use on flights in the north and south polar regions in the 1920s. Grid navigation, first proposed by Admiral Tonta of the Italian Navy in 1929, was refined and developed by Group Captain K. C. Maclure RCAF in 1941 as the 'Greenwich Grid System' to overcome the problems with referencing position and direction to rapidly converging meridians at high latitudes. The Grid technique was first used on the 1945 Aries Polar Flight. Flight Lieutenant Keith Greenaway RCAF described the method as follows (Greenaway, 1951):

> In this system some meridian is selected as a reference meridian, grid north is considered to be at an infinite distance along this meridian, and the grid direction of any line is defined as the angle measured clockwise between the direction of grid north and that line.

Greenaway could not see much use for the API at high latitude, mainly because the secant gear tends to slip at latitudes above 70°N (or conversely below 70°S), so he advocated the use of either a manual air plot or a manual track plot. Indeed, Greenaway makes it clear that, in his opinion, if drift and groundspeed were readily available maintaining an air plot would be a waste of time. However, an article in the October 1946 issue of *Air Clues*, the RAF training magazine, described a method of setting the API counters to zero after every fix to overcome this problem, and the 1951 edition of AP 1234 outlines a method of setting the API to co-ordinates based on a false equator. This works because the area within 9° of the equator is effectively defined by a grid where the secant gear has little effect.

The use of grid techniques naturally lends itself to steering with reference to a free gyro directional indicator and following a great circle path rather than a rhumb line (Chichester, 1948). The technique also lends itself to single heading flight that was developed from the practice of pressure pattern flying. Pressure pattern flying, a term coined by Transcontinental and Western Air Inc. (Adams and Hanbury-Brown, 1949), was a collection of techniques based on the geostrophic wind equation and the determination of an isobaric surface. These techniques were made possible because of the advent of radar altimeters, specifically the American SCR-718A, and reasonably precise pressure altimeters, such as the Kollsman Mk 14, that allowed a comparison to be made between altitude measured from a pressure datum and actual height above the surface. Such a comparison allowed a drift to be calculated and could give a form of position line as an across heading distance. The techniques were explained to a wide audience of navigators in the July 1946 issue of Air Clues and were the subject of the first ever meeting of the British Institute of Navigation on 25 July 1947. The techniques were soon included in navigation manuals. Although omitted from the 1947 edition of Clough Smith's book on Applied DR Navigation and Flight Planning, pressure pattern flying was outlined in Wing Commander E. W. Anderson's manual on air navigation (Anderson, 1951). Anderson also includes details of an American computer, similar to the height and airspeed computer, specifically designed to work out the sideways windspeed component. It was also discussed, as pressure comparison technique, in the textbook written by Williams and Branch (1952).

Single heading flight was mentioned in 1939 in a note published by Ernest Zermelo, the German mathematician. Single heading flying was a method of addressing the problem of determining a 'Least Time Track' or 'Minimum Time Path' (MTP).

Shortest time routing had already been investigated with relation to airships, but the availability of oceanic forecasts based on reliable data from weather ships and the ability to update the forecasts in the air using the pressure comparison technique made the development of appropriate techniques practical. In 1947, the issue was discussed in a paper presented by J. S. Sawyer (Sawyer, 1948), which reviewed all aspects of pressure pattern flying. The technique was detailed in both Anderson's book on navigation and in the 1951 edition of AP 1234. AP 1234 makes it clear that the single heading path is not necessarily the same as the least time track but is useful as a first approximation before the route is split into a number of single heading legs. Adams and Hanbury-Brown had noted in their report on navigation techniques issued in 1949 that an American airline had already adopted this approach.

Routing became a three-dimensional issue with the introduction of pressurised aircraft followed by turboprop airliners and almost immediately after that by turbo-jet aircraft. The consideration of the significant shear in high level winds and the exploitation of jet streams were important for airline economics. Williams discussed these aspects of the navigation of turboprops over the North Atlantic in the Journal of Navigation in 1957. However later in the year, in the same Journal, E. W. Pike, Superintendent of Control and Navigation at BOAC, writing on navigation and the airlines, noted: 'The navigation of aircraft in the air with respect to each other is becoming of supreme importance.' Effectively, with the growth in air traffic in the 1960s, optimum routing was to become an air traffic problem. DR and such matters as diversion planning, fuel reserves and track keeping ability became institutional issues.

## 6. AUTOMATIC DR SYSTEMS AND DOPPLER NAVIGATION.

The growth in air traffic and the increasing speed of aircraft encouraged the continued development of automatic dead reckoning systems after the war. Typical of the inventiveness shown by many was the development in Canada of a bearing and distance computer based on polar, Rho-Theta, coordinates rather than Cartesian coordinates. Wing Commander J. G. Wright RCAF who, as a graduate of the RAF Specialist Navigation Course had worked closely with research scientists and engineers, initiated work on this project which led eventually to the Canadian Position and Homing Indicator that was invaluable to the new generation of jet fighters operating in the polar regions.

However, these new computers did not obviate the problem of finding the wind. Various devices to automate wind finding were considered. It was known that the $H_2S$ radar could be used for drift. The scientists at Farnborough began to think about depressing the radar antenna to exploit the shift in frequency of the returning radar energy caused by the Doppler effect to find groundspeed. Events soon overtook them (Adams, 1949). Patents for a radio Doppler system had begun to appear in 1937 and in 1943 the US Naval Research Laboratory were experimenting with a device working on the 12–15 cm wavelength, which proved too complex and heavy for installation in an aircraft. Another problem was that at these low wavelengths the frequency shift was too small to be measured easily. Progress was, however, rapid.

In 1953, the first dedicated Doppler radars operating on wavelengths around 3 cm were entering service trials with the RAF. The earliest practical 'Janus' systems emitted four beams of energy, two either side of track ahead of the aircraft and two to the rear. This arrangement allowed errors caused by pitch and roll to be compensated for. The antenna was rotated about the longitudinal axis of the aircraft to equalise the returned frequency in the beams either side of track enabling a direct measurement of drift angle; groundspeed could be derived directly from the frequency shift observed in the sum of all the beams. Later systems would use only 3 beams and, by the 1970s, lightweight solid-state systems would use fixed antennas and derive drift and groundspeed by computation.

The rapid development of Doppler caught the creators of the new generation of DR systems by surprise, and the complex NBC Mk I in the Valiant and early variants of the Vulcan and Victor, had to be modified to take advantage of a Doppler input. However, the NBC Mk I (and the Mk II used in the later Vulcan and Victor Mks) still retained an elaborate wind finding method based on placing an $H_2S$ marker over a radar return and measuring the error in radar picture stabilisation over a short period of time; this method was retained as an alternative for when the Doppler system became unserviceable, which occurred frequently in the early days. Dedicated Doppler-based systems were soon produced. The British GPI Mk IV, which began trials in 1954, was designed to be used with Doppler systems such as the Green Satin, first fitted to the Canberra. The principles of this computer were very similar to the API Mk I; the air mileage feed was replaced with a ground mileage feed derived from the Doppler groundspeed. The GPI Mk IV had the additional facility to operate in a grid mode, bypassing the secant gear. The system was soon modified to include an along-and-across track mode that was in effect a variant of the grid mode but with the output coordinates based on an angular offset representing required track.

One system that was particularly advanced for the time was the Canadian Air Navigation and Tactical Computer (ANTAC) Mk 1 devised by Wing Commander Wright and developed at CDC for the Argus maritime patrol aircraft first flown in 1957. This GPI allowed the display of latitude and longitude to within about 30 miles of the pole by using an inverse operation for the secant multiplication. The ultimate limitation on northerly latitude depended on the speed of the longitude driving motor (Wright, 1972).

Doppler was taken up by the commercial airline industry very quickly. The systems were openly discussed in 1958, and the April 1959 edition of Interavia showed that Doppler systems were being offered for use on the Boeing 707, Douglas DC-8 and Convair CV-880 by a number of manufacturers. Doppler systems were, in general, used with automatic dead reckoning computers. The description of one such computer in Interavia explains how it was expected to be used to display distance to go to a turning point and distance left or right of track. The article noted: 'If, as is usual over the North Atlantic, the crew follows a minimum time track, this will be broken down into a number of straight legs.' Most civil aircraft automatic DR computers provided only an along-and-across track display.

The use of along-and-across track mode with the GPI Mk IV was hotly debated in the RAF training magazine, *Air Clues*, in 1956 and 1957 prompted by a proposal contained in the October 1956 issue for a new method of DR called 'Gridagraph'. There was little need to elaborate on the growing simplicity of navigation with automatic DR systems. Civil navigation techniques were described by Stanley Stewart in his book *Flying the Big Jets* first published in 1984, by reference to a flight from New York to London. Simply, the pilots used radio aids to take the aircraft to Gander and then followed the Doppler fed automatic DR system. The navigator began his duties at Gander, plotting fixing information and updating the Doppler system to ensure that the aircraft remained on the assigned track. If the Doppler failed: 'the navigator would have to resort to air plotting'.

Much work was done to improve Doppler systems. System errors were examined in detail, and some fine empirical work was completed. It was shown, for example, that the error caused by reflectivity and motion of the surface of the sea was not a linear function. In the 1960s, expensively engineered and complex systems, such as the GPI Mk 6 fitted to the Mk 2 versions of the Vulcan and Victor and the GPI Mk 7, fitted to the Belfast and VC 10, stretched the instrument accuracy of analogue computing to its practical and costly limits. The main error of these systems, however, was known to be the compass error. Better gyro-compasses and heading reference systems were slowly introduced into service, but, ultimately, the solution to this problem lay with the development of a new generation of heading reference systems based on inertial navigation principles.

7. INERTIAL NAVIGATION AND DIGITAL COMPUTING. Doppler navigation systems enjoyed only a short ascendancy before being replaced by Inertial Navigation Systems (INS) as the ultimate development in DR systems. Indeed Wing Commander E. W. Anderson's 1996 textbook on the Principles of Navigation, and the 7th and last edition of Donald Bennett's textbook published in 1967, hardly discuss Doppler systems and concentrate instead on INS. An INS is based on a self-contained system deriving track and groundspeed from the measurement of aircraft accelerations. The history of Inertial Navigation was outlined by Walter Wrigley in this Journal in 1977 (Wrigley, 1977) and so will not be discussed in detail. Its origins lay in the marine gyrocompass, and the V-2 rocket's guidance system can perhaps be considered to be the first practical, if primitive, INS. It was the capture of German research records and the employment of German research staff by the Allies in 1945 that led to a concentrated research effort that saw the first systems designed for cruise missiles being flown in the USA by 1949.

Progress in the 1950s was rapid. In February 1953, a B-29 Superfortress flew from Bedford, Massachusets to Los Angeles with a primitive INS called the Space Inertial Reference System (SPIRE), work on which had started in October 1949. This system weighed 2700 lbs, but in July 1953 work was begun on SPIRE Junior to improve performance and reduce weight. The transcontinental flight of this system in March 1958 was publicised in a popular American television programme. Litton began to market INS systems in the late 1950s and, in 1963, PanAm started to fit Litton LN 3 INS, based on the system developed for the F104G fighter, in DC 8 airliners. As with Doppler systems, although the military initially led the way with the introduction of INS, the airlines followed closely behind. In 1968, the Boeing 747 became the first airliner in which INS was fitted as standard equipment, completing all the basic DR. By the 1970s, strap-down INS were being developed and a new generation of optical gyros based on Laser technology further reduced the weight and cost and increased the reliability of INS.

The effect on the practice of DR by a skilled navigator was abrupt. Amendment List No 1 to the 1973 Edition of British Civil Aviation Authority's guide to the Flight Navigator's Licence issued in February 1975 specifically excluded the use of inertial navigation systems, except as a heading reference system, on flights to be used to demonstrate appropriate navigation experience by candidates. It was not long before the separate trade of commercial Air Navigator became obsolete. The military continued to use navigators, but maintaining a DR plot was no longer their main duty. The RAF eventually removed formal DR plotting from the navigation syllabus altogether in 1989, although mental DR and the development of spatial awareness are key skills all military aircrew are expected to acquire.

The most significant development affecting the cost of INS and DR systems was the introduction of digital technology, itself made practical by the invention of the transistor. Research on airborne digital computers had begun in the late 1940s. American and British scientists discussed progress on digital computing techniques for airborne applications in 1951 when the British 'Red Check' team, who were developing a bombing system, visited the USA. Digital computing was first used in bombing systems in the USA from about 1960 and Kearfott produced the AN/ASN-24, the first airborne digital computer designed to operate with Doppler radars, in 1963. In Britain, the American Verdan computer was fitted to the TSR2, which had an all too brief existence, flying only as a prototype from 1963 to 1965. The Decca Type 9476 computer, fitted to RAF Hercules at the end of 1966 was the first British DR equipment to be based on a digital computer. Although it could be argued that, apart from the digital groundspeed resolver, much of the system was analogue in concept. Indeed, the Latitude and Longitude display of the system was essentially the same as the GPI Mk 7.

In 1969, the Nimrod maritime reconnaissance aircraft was fitted with a digital computer for tactical navigation, but for routine navigation the Automatic Dead Reckoning Information System (ADRIS) was based around an analogue computer fed data from an Elliott E3 INS and a Doppler radar. Analogue was chosen because early digital computers did not yet have the speed or capacity to cope with multiple inputs in 'real time' (Grindon-Ekins, 1974). The sophisticated integration of analogue inputs was, however, too expensive for further development. Consequently, in Canada, the development of the ANTAC 2 computer for the Argus replacement was stopped. Eventually digital computers made such systems obsolete. It was in the basic engineering aspects of avionics design that digital technology had an impact. Large-scale circuit integration reduced weight, increased reliability and, eventually, reduced the cost of avionics. In the mid-1960s analogue electro-mechanical devices in INS and Air Data Computers were replaced rapidly with digital circuitry.

Modern airborne DR in military aircraft and airliners is almost entirely based on Flight Management Computer Systems (FMCS or FMS), which began to be introduced in the mid 1970s. The first examples of such equipment were digital navigation computing units such as the AMBAC Area Navigation (RNAV) systems installed on the L-1011 Tri Star, which entered service in 1972 and the Collins ANS 70 fitted on the DC-10. These computers used both DR and fixing information as inputs. The main incentive for installing an FMS was the perceived benefit in assisting the crew to manage fuel more efficiently and to choose optimum routings. Such benefits were not always achievable in increasingly congested airspace. Concorde, which became operational in 1977, was originally planned to have an FMS and a moving map display but went back to a very much simpler system based on triple INS. The rigid routes that Concorde needed to fly did not justify a system such as that on the Tri Star. However, in the 1980s the cost and advantages of digital RNAV computers and FMS led to their widespread use; the real benefit of the FMS was to reduce crew workload in an increasingly busy air traffic environment.

8. THE SYSTEMS APPROACH. Alongside the introduction of digital techniques was the development of a 'systems approach' to avionics engineering. This approach began to dominate the avionics industry in the 1950s, if not before. An appreciation of this approach can be gained by reading the preface to J. L. Farrell's book on Integrated Aircraft Navigation. Farrell set out to express navigation in terms of Newtonian physics and matrix-vector mathematics. The revolution, however, was not in the terms, but in the analysis. Farrell noted that:

> Concurrent with breakthroughs in computation, there has been a substantial broadening of analytical techniques, notably in estimation. This combination of analytical and digital technology advances has given further impetus to the development of improved algorithms.

The estimation technique referred to by Farrell was first proposed by R. E. Kalman in 1960. The Kalman filter, or the Kalman-Bucy filter, is a complex type of algorithm which, as described by J. E. D. Williams (1992), can be envisaged as an automatic process continually assessing input information and outputting a most probable position. Williams noted: 'In effect they are continuously predicting a DR position and modifying it by the present inputs on the basis of their presumed error distributions.' The initial Kalman filters produced in the 1960s were crude devices dependent on empirically obtained values for the provision of statistical weighting to input data. In the 1970s, the application of mathematical techniques taken from numerical analysis made the filters more adaptable and robust (Stokes, 1997). Kalman filters are used in almost all navigation computers today and lie at the heart of Global Positioning System (GPS) receivers introduced in the 1990s, most of which use DR to aid their fixing calculations and satellite signal acquisition.

The late 1970s saw the introduction of computerised Flight Planning to complement DR based on the FMS. By allowing accurate planning, these systems were successful in reducing the amount of fuel airliners had to carry in reserve (Page, 1981). As an extension to these systems, computer modelling allowed an organisational approach to routing that resulted in the flexible use of airspace concept introduced in Europe in the 1990s. Military mission planning systems began to appear in the late 1980s and were almost universally adopted by the early 1990s. The integration of ground planning and airborne navigation systems is now being extended with plans to control aircraft from the ground, but the process is not yet clear enough to allow an historical appreciation of its significance.

9. CONCLUSION. What is clear now is that DR and DR equipment have become a component of a total navigation system. Navigators might claim that they first saw the benefit of such an approach in the 1930s, but whereas the human was the systems integrator in the 1930s, by the 1960s the human was rapidly becoming just another, expensive, unreliable and error-prone component ripe for replacement. The changes that led to this can be seen in the reduction of DR into procedures and drills which started in Britain in 1940.

Wing Commander Anderson was one of the first practical airmen to understand the significance of the new approach to DR. In his 1951 manual, he wrote with remarkable prescience: 'Since it is evident that dead reckoning only fills in the gaps between fixes, it follows that, as navigation aids improve, so will the need for DR disappear.' However, he still foresaw then an important role for the human: 'It therefore appears that the most valuable type of DR in the future will be the same as the most valuable type of DR in the past, a mental appreciation by the airman of where he is going and when he is likely to get there.'

The human role in DR is starting to be analysed by researchers into animal navigation who refer to DR as the path integration process. This new view of the human science of navigation has a different emphasis to the view held in the first half of the twentieth century. A. J. Hughes, in his History of Air Navigation published just after the Second World War, emphasised the importance of a sense of direction on which the art of the air navigator was founded. Perhaps this contrast in emphasis between the mechanistic 'path integration' and the human 'sense of direction' offers a more telling comment on the history of airborne DR than any account of the development of theory and equipment.

## REFERENCES

Adams, D. E. and Hanbury-Brown, R. (1949). *Review of Navigation* (*Bomber and Military Transport Aircraft*) *– RAE Report No IAP 1456*, July 1949 (page 39).

Anderson, E. W. (1951). *Principles of Air Navigation*, London.

Allan, W. J. D. and Alexander, W. (1940). *Dead Reckoning Navigation*. Unwin, Woking.

Chichester, F. (1948). This point was first noted by Francis Chichester during a discussion following a meeting at the British Institute of Navigation in January 1948 following a paper on Grid Navigation. Harold Gatty had earlier in the discussion suggested that Grid, although here to stay, was not ideal because you could not fly a great circle course.

CCDU. (1994). *Trial Report No 44/7*, 13th January 1944 (Public Record Office Air 65/21).

Greenaway, K. R. (1951). *Arctic Air Navigation*, Ottawa.

Grindon-Ekins, P. M. (1974). *The Impact of Digital Computing*. This *Journal*, Vol. **27**, Jul.

Harbold, N. B. (1970). *The Log of Air Navigation*. Naylor, San Antonio.

HMSO. (1963). *The Origins and Development of Operational Research in the Royal Air Force*. *Air Publication* 3368. Also: Waddington, C. H. (1973). *OR in World War* 2. Elek Science, Old Woking.

Jones, R. V. (1978). *Most Secret War*. (Chapter 4).

Page, D. M. (1981). *Airline Navigation Planning*. This *Journal*, Vol. **34** , Jan.

Pritchard, H. C. (1943). *Navigation and Autopilots in the USA*. RAE Report, Inst 1444, April.

Richardson, F. C. (1997). *Man is Not Lost*. Airlife.

Sawyer, J. S. (1948). *The Meteorologica Limitations on Pressure Pattern Flying*. This *Journal*, Vol **1**, Jan. Also: *Theoretical Aspects of Pressure Pattern Flying*. Meteorological Office Publication 496C, London, 1949.

Scrimshaw, F. H. and Wells, J, A. (1945). *Automatic Air Navigation*. Aircraft Engineering.

Stokes, R (1997). Personal notes of a conversation with Roger Stokes, DERA Farnborough. Also: Carr, J. G. and Stringer, F. S. (1969). *A Commentary upon Aircraft Navigation Systems*. RAE Technical Report 69220, September.

Twiney, F. J., Adams, D. E., Bone, A. G. and Wells, J. A. (1945). *Development of Automatic Dead-Reckoning Navigation 1939–1945*. R.A.E. Farnborough.

Williams, E. B. and Branch, W. J. V. (1952). *Air Navigation Theory and Practice*. Pitman, London.

Williams, J. E. D. (1992). *From Sails to Satellites*, Oxford.

Wright, J. G. (1972). *The State of the Art in Navigation*, *Its Derivation and Direction*. A Navigation Study prepared for the Defence Research Establishment Ottawa. Also: personal notes of a conversation with Wing Commander Wright in 1992.

Wrigley, W. (1977). *The History of Inertial Navigation*. This *Journal*, Vol **30**, Jan.