The Development of Airborne Dead Reckoning. Part I: Before 1940 – Finding The Wind

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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 first part covers the period before1940. The split is arbitrary, although it is obvious from a British perspective that military events around that date had a major impact on the pace of navigation development. However, it is equally obvious that airborne DR developed alongside a worldwide technical and intellectual revolution. This aspect of the story is abstract and involves some conjecture, so the paper takes it for granted and concentrates instead on practical matters. Accounts of air navigators' experiences as well as material on DR theory and descriptions of DR equipment in navigation manuals, journals and various surviving research documents have been used as the source material.

KEY WORDS

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

1. INTRODUCTION. Dead Reckoning (DR) has been used at sea for centuries (Cotter, 1978); however, from the earliest days of aviation it was clear that the air navigator faced different DR problems from his marine counterpart. The obvious difference is that the medium through which the aircraft travels, the air, has the potential to move much faster than ocean tides and currents. For example, an aircraft flying in a mass of air that is moving at 20 knots will, in one hour, be moved 20 nautical miles away from the point it was headed towards. This movement of the air, the wind, could not be readily assessed from an aircraft. So the early days of airborne DR became pre-occupied with the need to find the wind.

Another difference between DR on the sea and in the air is the differences in the craft. All aircraft, even airships and gliders, have a limited endurance and if that endurance expires before the aircraft has landed, the consequences are usually immediate and often catastrophic. Consequently, the practice of DR in the air is governed by the pressure of time. The need for quick decisions, often made in cramped, noisy and uncomfortable conditions, encouraged the development of simplified and often *ad hoc* DR methods, and led to the introduction of equipment to aid DR and, finally, to automatic DR systems, Doppler radar systems and inertial navigation systems. To begin with, DR was a human skill, but one aspect of its story is that engineers and scientists, from 1940 if not before, became just as involved in its development as pilots and navigators.

DR is an English term, and its origins are a matter for debate by English etymologists. The romance languages use the term 'estimated navigation'. However, almost all the textbooks on air navigation in the English language defy etymological considerations to translate the 'dead' as an abbreviation for 'deduced'. So it is the sense of 'estimated' or 'deduced reckoning' that an account of airborne DR must assume.

2. THE DEFINITION OF DR FOR AIRBORNE USE.

At first, when attempting to establish a formal basis for air navigation, the British used the marine definition of DR. The Naval Air Service Training Manual published in 1914 (HMSO, 1915) states:

> Dead Reckoning is the method whereby a pilot calculates the position in which a ship would be had she steered an absolutely steady course and made good her exact speed, not being subjected to outside influences such as variations in force and direction of the wind and variations in engine speed.

But this definition, taken directly from the *Admiralty Manual of Navigation*, was not much use to the airman, as the writer admitted in his next sentence:

> In practice it is seldom found that the dead reckoning position corresponds to the true position.

In 1917, a new Royal Naval Air Service manual for aerial navigation, written by Commander Bosanquet and Lieutenant Commander Campbell (1917), suggested that the old accepted idea of DR should be modified to:

> Dead Reckoning is the position arrived at as calculated from the estimated track and estimated speed made good over the ground.

To add to this definition the manual goes on to discuss the vagaries of the atmosphere and concludes:

> All we can do is to estimate the velocity of the wind and make allowances for drift and increase or loss of speed,..

This definition was soon simplified and clarified so that by 1935 the RAF's Manual of Air Navigation, *AP 1234*, defined DR simply as the calculation of track and groundspeed and the DR position as the position arrived at by this reckoning process.

3. THE EFFECT OF WIND AND THE TRIANGLE OF VELOCITIES.

The first practical airmen to make allowance for the wind were the balloonists. In the nineteenth century, as Wright has shown in his *History of Air Navigation* (1971), balloonists developed techniques to assess where the wind was taking them. However, DR in a balloon is a different process from DR in a powered aircraft that can be steered; the process in the balloon simply involves estimating the speed and direction of the wind at height. Consequently, the theory of DR was of less interest to balloonists than inventing devices to measure groundspeed and height. In a balloon, a direct measurement of the effect of wind is made by observing the progress of the craft over the ground, when it is visible. This measured wind velocity can then be used to estimate progress when the ground is obscured.

The balloonists' assessment of the wind was relatively straightforward because there was no need to consider drift. Drift is the angle between the longitudinal axis of the aircraft, the heading, and the track over the ground. Balloons tend to spin slowly as they are blown by the wind, and the orientation of the longitudinal axis is not important to navigation. In powered aircraft, the motive force is along the longitudinal axis and knowledge of heading is important. If there is a wind blowing at right angles to the heading, the aircraft will not reach any destination ahead because it will appear to be pushed to one side. Either the aircraft must be turned frequently to face the target point, thus flying a curve of pursuit, or the aircraft must be angled off into the wind so that the target point maintains a constant relative bearing. Until formal dead reckoning calculations were widely taught, choosing the angle to offset for wind was a matter for trial and error so that the pilot could 'kill the drift'. Not all pilots bothered with drift, and it was a matter for comment by Claude Graham White that Lieutenant Conneau (known by the pseudonym 'Beaumont') owed much of his success in the cross-country competitions flown in 1911 to his study of 'atmospheric conditions and the question of flying in winds' (White, 1912).

In 1911, the idea of cross-country flying over a designated route was completely novel. The first successful airship was produced by Zeppelin only in 1908, and White states in his book on aviation that powered aircraft only really started to leave the vicinity of their landing grounds in the flying season of 1909. It should be noted that although most developments were initiated on the continent, dead reckoning problems were considered at the highest levels in Britain, as befitted its naval tradition. The report on the proceedings of the Sub-Committee of Imperial Defence on Air Navigation prepared in February 1909 includes the argument put by Captain R. H. S. Bacon, Director of Naval Ordnance, for proper navigational facilities and quotes him as saying 'We must appreciate the effect of the wind on the utility of the dirigible' (Public Record Office, 1912).

With early airships, the effect of the wind was a particular problem because windspeed could often exceed the very low maximum achievable airspeed. The mathematical investigation of this problem led to some fine trigonometric functions. Fortunately, by 1910 French aviation magazines popularised a much simplified approach based on a vector diagram (Wright, 1972). By drawing a vector to represent an aircraft's heading and its true speed through the air and then drawing another vector to represent wind speed and direction with its origin at the end of the first vector, a triangle can be drawn with a vector from the origin of the heading and airspeed vector to the end of the wind vector. This third vector represents the aircraft track and groundspeed. If four parts of the triangle are known, the other two parts can be found. The solution of this 'triangle of velocities' (see Figure 1) is the basis of dead reckoning in the air. Early navigation textbooks describe the solution of this triangle using graph paper. It was not long before a variety of aids was devised to assist the aviator with the solution.

The measurement of parts of the triangle was, of course, a key problem if dead reckoning was to be used. It hardly needs saying that without the development of a practical compass and airspeed indicator, DR is not feasible. The importance of the compass is illustrated by a secret report, prepared in 1912 by Captain Sueter and Mr O'Gorman on continental airships, which noted, with respect to a flight on an Austrian airship, that:

> No compass was used, and the yawing, though not bad, would probably have been kept in better check if steering had been kept by compass.

In contrast, they were impressed with the steadiness of a flight on the German airship, *Victoria Luise*. They were not, however, allowed near the German compass. Despite this German advance, Britain was later to take the lead in developing reliable aircraft compasses during the First World War.

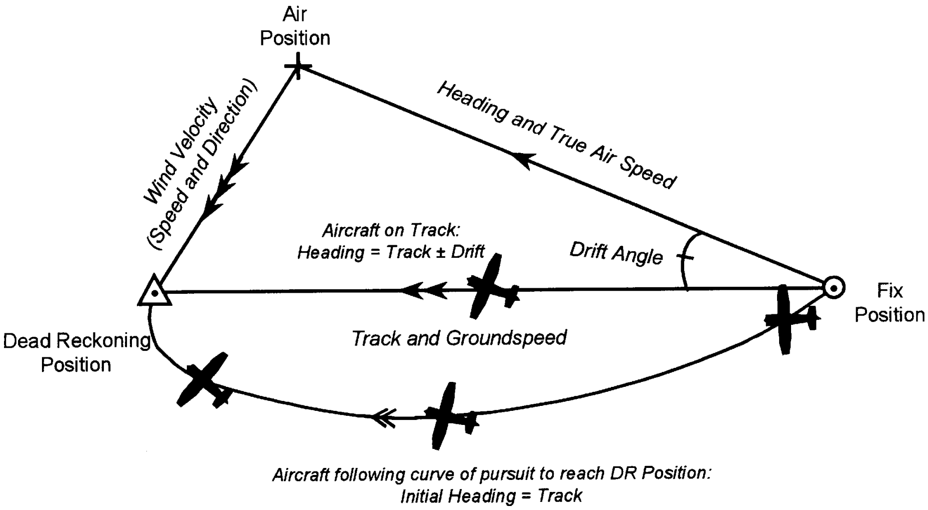

Figure 1. The Triangle of Velocities.

4. PRACTICAL DR BEFORE 1918. It must not be thought that DR, or navigation in general, was conducted in a systematic and knowledgeable fashion by the general aviation community before 1918. Most aviation was crude. Early aircraft tended to have few instruments, and DR was not an important issue for aviators to address; it only became so when the more pressing problems of remaining airborne had been solved. Navigation, if needed, generally involved flying from landmark to landmark or following railway lines. Many pilots got lost, as some still do today. Accidents were so frequent that it is hard to know how many pilots died from want of DR skills. It must also be remembered that it was common for pilots to land in a convenient field to ask the way.

Lacking an organised approach to DR, some methods were entirely empirical. For example, a camera obscura, which was not much more than a hut with a hole in the roof, was used to assess the wind at height. Major E. B. Gordon, of the Royal Flying Corps wrote 'Some Notes on Bombing Attacks' (Jones, 1928) which included the following:

> The arrangement is for one aeroplane to fly over the camera obscura at the various heights at which it is proposed to drop the bombs. The ground speed can be read off with accuracy in the camera.

A bad bombing result, it was remarked, 'was probably due to the wind dropping between the time at which sights were set and the attack'. No further comment need be made on the usefulness of this DR technique!

In contrast to this army approach, airships tended to be run on naval lines and DR was taken seriously, if only because airships were used for relatively long-distance, long-duration flights. Even early airships were well equipped for navigation compared to aeroplanes. In addition to the compass, which was less affected by vibration and turbulence in an airship than in an aeroplane, an airship navigator could expect to be provided with a chart table and an instrument panel including at least an altimeter and an airspeed indicator. With just these facilities, and a routine that included regular wind finding by turning into wind, slowing to a hover and directly reading the wind speed from the airspeed indicator and wind direction from the compass (as a reciprocal bearing), DR navigation could be accomplished with reasonable results (Ventry and Kolesnik, 1982).

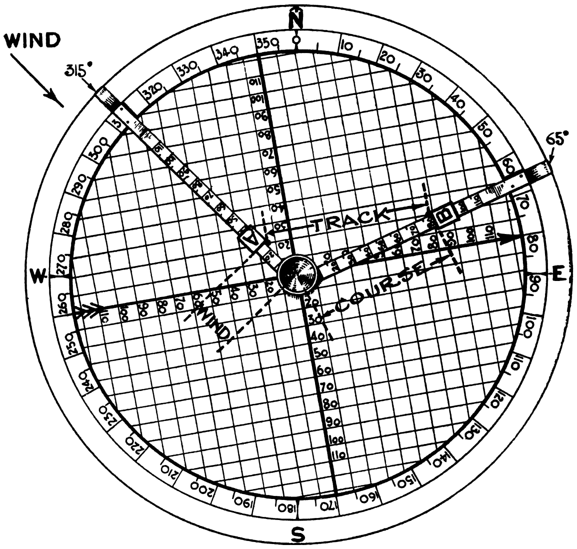

Figure 2. The Course and Distance Calculator.

By 1917, the Royal Naval Air Service manual outlined a practical approach to DR that was to form the basis for subsequent air navigation textbooks. This manual listed thirteen instruments required for navigational purposes in aircraft including, perhaps obviously, a compass and airspeed indicator. Two of the instruments listed, the Aircraft Course and Distance Indicator and the Drift Indicator, were important early developments to assist airborne DR. The Aircraft Course and Distance Indicator was a simplified version of the 'Battenberg Course and Distance Indicator' used by naval navigators to calculate tactical problems involving vector diagrams. Later developed as the Course and Distance Calculator (CDC) (see Figure 2), it became the standard British DR computer until the late 1930s. Nine inches in diameter and bearing a compass rose on the outside, it consisted of a circular rotatable plate engraved with a square graticule on which two moveable arms originated from the centre. The graticule and the arms were positioned to represent the triangle of velocities so that the required solution could be obtained. A circular slide rule, devised by Rollo Appleyard, was placed on the back of the CDC to allow standard time, speed, distance and fuel consumption problems to be solved. However, it was not until much later that the separate computer used to correct indicated airspeed for temperature and altitude to obtain true airspeed (the Computer, Height and Air Speed, Mark 1) was integrated with this slide rule. The French also produced devices similar to the CDC, which they called 'cercle abaque', and one system, much like a pantograph, called a 'cercle calculateur de dérives et de vitesse' (Duval and Hébrard, 1928).

The drift indicator, or drift meter, was adapted from early balloon groundspeed meters. The first versions appeared in France in 1910. At its simplest, a drift indicator is a sighting device, or a hole in the fuselage floor, with a mark aligned with the longitudinal axis of the aircraft. A moveable bearing plate with parallel sighting wires is usually fixed over the sight. The sight is then used during flight to make observations of fixed objects on the ground; by rotating the bearing plate until the objects pass straight along the sighting wires, the amount of drift can be measured by comparing the angle of the bearing plate to the longitudinal axis. In addition, it is theoretically possible, provided the height above the surface is known, to calculate groundspeed by noting the time taken for a surface object to pass underneath two marks placed on the sighting wires at a calibrated distance. In practice, until radar altimeters were developed, groundspeed obtained in this way was too inaccurate to be relied upon.

Without an accurate measurement of the groundspeed, drift meters could not be used directly to solve the triangle of velocities for wind, because only three of the four necessary values were known – heading, airspeed and track (derived from heading and drift). However, it can be shown that the wind velocity can be calculated using separate drifts taken on different headings at a constant airspeed. The graphical solution to this double drift method led to the term 'wind star'. Lieutenant Colonel Crocco of the Italian Air Force developed a drift meter to include a DR computer on which the solution using multiple drifts could be found, but the most successful instrument of this type was invented by Major H E Wimperis, of the RFC. The device, variously called the Wimperis drift sight or wind gauge bearing plate, was developed to improve the accuracy of bombing, but it became one of the most important aids to DR in larger aircraft.

The contrast between airborne DR practice at the beginning of the First World War and its practice at the end is dramatic. The most important difference was that by 1918 aircraft were almost universally equipped with an adequate compass and an airspeed indicator. In addition, the meteorological organisation was well developed and the meteorological knowledge gained in the nineteenth century was imparted to all airmen. The measure of the improvement was that the long-range night bomber forces of both sides were able to complete long missions for which success depended, in part, on sound pre-flight planning, using forecast winds, and accurate DR. Such flights were inconceivable in 1914.

5. BETWEEN THE WORLD WARS.

Between the wars there was a steady improvement and proliferation of DR equipment. First in Europe, and then in the Americas, a slowly expanding aviation industry encouraged a certain amount of innovation, but in general there was no revolutionary development in the theory or practice of DR. To simplify matters, the practice of DR can be split artificially between pilot-navigator techniques and dedicated navigator techniques.

In 1920, the RAF published *AP 44*, *a Manual of Air Pilotage* to provide advice to the pilot-navigator. These notes assumed that the basis of this type of navigation was map reading, but nonetheless emphasised the importance of DR. The well-prepared pilot-navigator would plan the route using forecast winds and use the CDC to solve the triangle of velocities to calculate required heading and estimated times of arrival (ETA). The chart would be marked with a track, time or distance ticks and, possibly, four lines each making an angle of 10° from the planned track; two lines originating from the departure point and two from the destination. These marks were used to estimate corrections to heading and ETAs in flight. Airborne equipment included a chart board that was often just the map cut to foolscap size, pasted and over-varnished on to thin plywood boards. A well-equipped pilot would possess a sophisticated chart board, such as the Bigsworth Chart Board. This was a wooden board in two sizes, either seventeen or fourteen inches square, on which the chart, covered by a sheet of celluloid, was clamped with brass clips. A celluloid protractor was attached to moveable arms that could be clamped to the side. Once airborne the pilot-navigator was expected to assess drift by a number of methods including noting the heading needed to maintain a known track between two points, using a drift sight, or using drift markings painted on to the wings or airframe. The one-in-sixty rule (each one degree error in heading flown will result in a cross track error of one mile after sixty miles) and other rules of thumb were also taught. If rules of thumb were too taxing, the pilot-navigator had ready access to DR tables which, for example, showed drift and groundspeed against wind angle and wind speed (tabulated for different true airspeeds).

The DR methods used by the dedicated navigator tended to be based on track keeping. The 1935 edition of *AP 1234* noted: 'Provided that the required track is maintained, the aircraft must arrive at the destination.' Once airborne, the navigator would assess the drift to check that the forecast wind was reasonable and adjust the required heading, if necessary. The drift would often be taken from the point of departure using a bearing taken on a tail sight. There then followed a routine which depended very much on the nature of the flight and the weather conditions. The dedicated navigator kept a log and plotted on a chart. Estimated track and distance flown could be measured out using conventional plotting equipment (protractor, dividers and parallel rule) to obtain a DR position.

Alternatively, a DR position could be derived using Traverse tables in the nautical fashion. Traverse tables list the solution to the plane right-angled triangle with the different parts being: Course, Distance, Difference of Latitude and Departure (Departure being the distance in nautical miles between two meridians along a given latitude). Traverse tables were used by Arthur Brown on the Atlantic flight with Alcock in 1919, and were useful to airship navigators for calculating a single position after numerous changes of heading. However, the tables fell out of favour with aeroplane navigators. As Lieutenant Commander Weems, the famous US air navigator instructor and founder of the influential Weems System of Navigation (1942), noted: 'traverse tables are seldom used by aviators, since plotting is usually more satisfactory'.

The key to successful DR was obtaining accurate drift information. Weems emphasised its importance: 'In actual practice, finding one's way by dead reckoning hinges largely on the success with which the wind drift may be determined'. That was not always easy. Although Arthur Brown had a six inch drift-bearing plate fitted under his seat in the Vickers Vimy, he could not see the surface for much of the Atlantic flight owing to cloud. However, the practice of DR required the navigator to make the most of whatever information he could gather. By the 1930s a doctrine, almost a philosophy of navigation based on DR had been established that was best summarised by Donald Bennett, the great pathfinder, writing in his famous text book on air navigation, first published in 1936:

> Although Dead Reckoning (DR) is regarded sometimes as something rather elementary, it is the backbone and foundation of all good navigation. Although simple in principle, it benefits enormously from additional knowledge, wide outlook, and versatility. It is the skeleton of calculations, mathematical and plotted, to which are attached the data arrived at from observations of any sort.

The bedrock of this philosophy was wind finding. The textbooks of the time all detailed elaborate methods of finding the wind in flight. The favourite method, called the constant course method by Bennett, or the track and groundspeed method by other authors, required the track and groundspeed to be calculated by plotting two fixes taken 10 to 15 minutes apart and then solving the triangle of velocities using the known heading and true airspeed. Martin (1938) noted that a more accurate result would be obtained if the wind was calculated from fixes taken at an interval of half an hour rather than 10 minutes. The double drift and the multiple drift method were the next favourite. There are numerous other methods including the method called 'partial guess-timation' by Bennett, which includes assessing the wind direction from wind lanes or smoke and measuring its strength by taking a drift reading at 90° to the direction in order to gauge the wind speed. It was, incidentally, appreciated by most navigators that wind at height differed from that observed on the surface and due allowance was made for this based on an individual's experience.

Given the importance of drift and groundspeed for DR calculations, new drift meters continued to be developed. The standard British Course and Drift Indicator of the First World War was bracketed on to the side of the fuselage and required the pilot or navigator to put his head over the side of the cockpit to make observations. This made drift observation particularly arduous. In any case, drift observation was difficult in turbulence. One of the first drift meters to include an averaging device to overcome inaccuracies caused by turbulence or aircraft instability was the Le Prieur Navigraph. Le Prieur attached a pantograph and a pencil to his drift meter so that the navigator, by tracking the surface object on the drift meter, drew a pencil line along a particular drift line. The recorded markings usually resulted in a wavy line from which an average drift value could be judged. The Navigraph remained in service with the French into the 1930s and the principles were, to a certain extent, adopted by Dr Lamplough in 1940 in the design of the Drift Recorder at Farnborough. One notable drift meter was invented by the great air navigator Harold Gatty for his world flight with Wiley Post in 1931. Gatty's periscopic drift meter used a constant speed film whose motion could be synchronised with the apparent ground motion by changing the height of the eyepiece; this height was scaled as a factor that combined with true altitude to give groundspeed. The need to have an accurate altitude led to Gatty persuading Post to fly almost to the surface to reset their pressure altimeter before climbing up to take an observation. Tail sights were often used for taking drifts. Admiral Coutinho, for example, dropped smoke markers to provide a reference point for tail bearings to find drift for his 1922 South Atlantic flights; although on his first leg out to the Canaries from Lisbon, he realised that the markers needed modification because they sank. Night was not necessarily a problem because flame floats were available.

Gyroscopes were incorporated in drift sights in the late 1930s. The gyroscope stabilised the optics, mitigating the effect of aircraft instability and improving the accuracy of drift observations. The American B-17 bomber was fitted with a gyroscopic drift meter in 1938. The American B-3 gyroscopic drift meter was to be introduced into limited service with the RAF in 1943. Bombsights could also add to the large numbers of drift meters developed because they could be used for drift observation.

Although drift observation was a key part of navigation it tended to be neglected by pilots when flying over land in fair weather. The development of radio aids also tended to induce slackness in maintaining DR because there seemed little benefit from the effort required when homing to a beacon. Constant drift observations and wind finding was more an activity for a dedicated navigator flying over the sea. Flight Lieutenant Edwin Shipley, writing in *Newnes Aeronautics* in 1938, advised that drift should be noted at least every fifteen minutes if only to average out errors. The main aim was to maintain track. He also remarked:

> Of course, there is one way of making a sea crossing – that is to set a pre-computed course on leaving land and to carry straight on until a landfall is made.

Shipley's scorn at such stunt flyers might have included Lindbergh, who adopted this method, albeit with meticulous planning, for his Atlantic flight. Lindbergh himself, however, realised the risk of this DR method and had his wife trained as a navigator for his later flights.

For the few dedicated navigators, the range of DR computers slowly expanded. The British CDC remained in service with the RAF until at least 1938 and was taught as a mandatory part of the civil navigator syllabus until at least 1936. However, there were several attempts to improve on it. For his 1927 Far East Flight, Air Commodore Maitland developed a device based on a single arm (called the Drift Bar) hinged at the apex of a triangular base plate on which a rotatable circular dial (the Bearing Plate) was placed. The Royal Aircraft Establishment improved on Maitland's ideas with the Course and Speed Calculator (CSC) which was produced in about 1929 to a design by Captain Bygrave. The CSC was not included in the 1935 edition of *AP 1234* (amended to 1938) which states that 'it is under development to replace the CDC.' The CSC was not adopted for widespread service until the late 1930s, by which time computers adopting the principles patented by the American inventor Philip Dalton were beginning to dominate the market (INE, 1948). The first Dalton computer (Model B) appeared in 1933 and was patented in Britain in 1934 by Henry Hughes Ltd, the well known instrument makers. Dalton's Model G, marketed by Hughes, was adopted by the RAF as the Navigational Computor Mk III in about 1939, and by 1940 the CDC and CSCs had become curiosities. The Dalton computer was also adopted in the USA as the E6B and, after 1940, the Germans introduced a similar computer called the Windrechner WR2. Dalton was killed in an air crash in 1941 but, before his death, he had made a significant contribution to DR. Amongst his inventions was a combined map board and DR computer (US Patent 2, 114, 652, Apr 1938).

It was inevitable that simplicity and robustness would dominate the DR computer market. However, some elaborate machines were produced which are worth mentioning, if only to provide a glimpse on the wealth of ingenuity devoted to DR between the wars. Of particular note, for its fine engineering detail, is the pre-war German Winddreiedsaufgaben (Sönnichsen, 1940). Similar in principle to Maitland's computer, it was intricately engineered. Another example of intricate engineering was the Addison-Luard Course and Wind Calculator which came in two versions: Type B for three-vector problems and Type D for four-vector problems. This device had a complicated arrangement of arms that could be manipulated to solve tactical problems mechanically. Flight Lieutenant Edwin Shipley, writing in *Newnes Aeronautics* in about 1938, asserted that the instrument deserved greater popularity but conceded that it was expensive and cumbersome. It should be noted that the DR computer was a universal tool: the French, the Japanese and the Russians all produced varieties of instruments broadly similar to the CSC (*Air Clues*, 1946).

6. TACTICAL DR.

DR computers were useful in solving the many tactical DR problems. Since the CDC was developed from a naval instrument devised to solve such problems, naval experience was easily adapted first to airship and then to aircraft problems. These problems were not considered to be the province solely of the military. Interception problems, involving the use of a relative wind, and radius of action problems were included in the Civil Navigator's syllabus set by the Air Ministry in the 1930s. Radius of action problems included returning to a moving base, applicable to carrier operations and also to the problem of returning to a different base. Plotting solutions was acceptable, especially as the CDC solution to returning to a moving base involved four successive stages which increased the chance of error. The American, Harvey Holland, in his 1931 textbook *Aviation*, put these sorts of problems into a civil context and discussed endurance and range. Additional problems in the military training syllabus included station-keeping and the conducting of a square search.

7. TRANSALANTIC AIRSHIP DR.

One specific tactical problem given some thought was the finding of a minimum time path for aircraft and for airships in particular. This concept received much attention after the 1919 double crossing of the Atlantic by the R.34 airship; but the solution of the problem requires reliable wind forecasts and an ability to update the forecast while en-route. Williams (1994, Chapter 13), provides a useful synopsis of the development of ideas on the minimum time path. It is notable that the R.34 included a meteorologist as a member of the crew. However, meteorological reports based on a reasonable quantity of data were not readily available for oceanic areas until the end of the Second World War. Major H. E. Wimperis discussed the problem in his paper on navigation presented to the Royal Aeronautical Society and reproduced in their Journal in 1919 and prompted comments from his audience on the inadequacy of meteorological forecasts. Following on from a joint study by the Meteorological Office and the RAF in 1929, route planning to take advantage of favourable winds (and to avoid unfavourable headwinds and bad weather) was a major consideration for the flight of the R.100 airship across the Atlantic in July 1930 (Johnston, 1930). However, Squadron Leader Johnston's en-route navigation techniques depended on orthodox DR. The Germans, too, used orthodox DR techniques based on double drift observations when they began routine trans-Atlantic services by airship, first in the South Atlantic in 1932 and then in the North Atlantic in 1936. Sadly, the *Hindenburg* disaster of 1937 led to the cancellation of these services.

8. THE NEXT STAGE.

The airships, with their leisurely progress, provided a link between the practice of DR at sea and in the air. However, by 1939 when a new generation of air navigators had begun training in Britain, merchant navy navigators – drafted in as air navigation instructors, without the benefit of flying experience – found it difficult to adapt their traditional methods, including DR, to the new air navigation techniques. The practice of airborne DR was one of the significant new techniques. Although basic terminology remained the same, the airman was equipped with newly-developed DR equipment and DR aids with which the mariners were not familiar. The difference between marine and airborne DR was to increase even more markedly after 1940. The Second World War was to see a dramatic change in airborne DR and, before discussing the key developments in Part 2, it is worth considering the general context of DR practice. The gradual development of DR up to 1939 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; the gyroscope was far more important to aviation as the basis of, first, the turn indicator and, then, 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 by 1938, but there was no fundamental difference in airborne DR, despite the availability of thicker textbooks and better equipment, than in 1918. 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. Compared to the 1920 Notes on Air Pilotage, very little changed. But from 1940 onwards, technology took a much greater part in what had previously been a mathematical and graphical skill liberally laced with judgement and luck.

ACKNOWLEDGEMENT

Figure 2 is taken from *AP 1234 Manual of Navigation,* Volume 1, 1935.

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