THE JOURNAL OF NAVIGATION

VOL. 53 SEPTEMBER 2000 NO. 3

Flight Planning Before Computers

Abridged by Philip Steele from a paper by Dries Bulstra

The original paper, entitled *Flight Planning Before Computers 1946–1959*, was written by Mr D. Bulstra in 1995. Written from a civilian operator's point of view, it includes very full explanations of the principles upon which the flight planning techniques were based, including mathematical derivations, examples of meteorological charts, and tables and graphs of aircraft performance. The abridging author has aimed to produce a short and accessible paper that explains the concepts without necessarily involving the reader in further complexities, while departing as little as possible from Mr Bulstra's framework and wording. For those who wish to look more deeply into the subject, the original paper can be seen in the Cundall Library of the Royal Institute of Navigation (Ref. 400.01.14).

KEY WORDS

1. Planning 2. Air Navigation 3. History

1. INTRODUCTION. Shortly after the Second World War, aircraft with a long radius of action became available to civil aviation. This opened possibilities for regular intercontinental flights. The North Atlantic routes, connecting Europe with the USA, were the centre of interest, and it was recognised from experience gained during the war that such flights needed very accurate flight preparation. Because the weather conditions, particularly wind, temperature and cloud, could change considerably during such a long flight, careful meteorological preparation was necessary.

The meteorologist could make use of a system that had been developed during the war, of long weather-reconnaissance flights conducted over the sea. Observations were made at various altitudes, of wind direction and speed, types and quantities of cloud, temperature and relative humidity. The radio altimeter, developed in 1944, enabled measurement of the true altitude of the aircraft above the ocean surface.

https://doi.org/10.1017/S0373463300008961 Published online by Cambridge University Press

Together with the altitude read on the pressure altimeter, it became possible to determine the true altitude of the various pressure surfaces. The data were transmitted using a code of five-digit groups, which could be decoded by airline crews.

At the same time, a network of weather ships had been built up. They made their observations with the aid of radiosonde balloons, which had been in use since 1938. These gave pressure, temperature and relative humidity up to 30 km, and by measuring the drift of the balloon, winds in the upper air could be assessed, provided the balloon remained visible from the weather ship. The accuracy with which its position could be determined was later refined by radio direction finding, and eventually by radar.

The combination of reconnaissance flights and weather ships provided a good picture of the pressure patterns for the ocean, America and Europe by means of a synoptic chart for sea level and of constant pressure charts giving contour lines of altitude for certain upper pressure levels. The 700 millibar chart was used for altitudes between 8000 ft and 12000 ft. With the development of the pressure cabin, the 500 millibar chart was used for 15000 ft to 20000 ft, and when turboprops and turbojets arrived in the late 1950s, the 300 millibar chart for 23000 ft to 30000 ft. Contour intervals were 200 ft on British and American charts and 40 metres on European. Comparison of present synoptic charts or contour charts with preceding ones enabled the meteorologist to draw prognostic charts, in order to make forecasts for the navigator's use of winds and cloud distribution at various altitudes for his selected route, and to assist the selection of suitable alternate landing airfields.

In the post-war years the number of reconnaissance flights and of weather ships decreased, and only intensive international deliberation restored the number of weather ships to nine in the Atlantic and four in the Pacific. By 1981, five remained in the Atlantic, and by 1994 only one. When regular air services over the North Atlantic became established (for example, in 1946 in the case of KLM's New York route with a DC4), the aircraft, frequently equipped with a radio altimeter, transmitted regular weather reports that could be used by aircraft en route. The codes used, POMAR and later AIREP, were similar to those adopted for the wartime reconnaissance flights.

Although it was realised that of all the possible 'trajectories' between two fixed points in a pressure system only one was the most economical, the three-dimensional problem of selecting the optimal flight path presented insoluble difficulties at this time. But as long as only piston-engined aircraft were in use, it was adequate in practical terms to select the most economical flight level, and then solve the two-dimensional problem of finding the Minimum Time Track (MTT) at the chosen altitude, as the Minimum Flight Path (MFP). Pioneering work was done by meteorologist H. M. de Jong and KLM captain F. C. Bik, who developed the MFP computer, enabling the MFP to be plotted on the chart. From this flight preparation, the navigation flight plan was compiled with the two-fold goal of enabling the navigator to control the progress of the flight and make any necessary corrections and presenting a flight plan copy to Air Traffic Control (ATC) for safety purposes.

2. PRESSURE PATTERN NAVIGATION.

The basic principle of pressure pattern navigation was the selection of a flight path by studying the pattern of atmospheric pressure to take advantage of the most favourable wind conditions. At first, the flight path was found by close examination of the weather chart, particularly

https://doi.org/10.1017/S0373463300008961 Published online by Cambridge University Press

the constant pressure chart. In addition to the 700 and 500 millibar charts already mentioned, a 850 millibar chart was available, related to 4780 ft in the standard atmosphere. The meteorologist would often plot temperature, wind direction and speed along with the contour lines. Using a number of prognostic charts, both ground charts (prebaratics) and contour charts, for various future points in time, a composite contour chart was made. Having selected the optimum altitude, using graphs giving fuel consumption for the aircraft type at various altitudes against forecast wind component, the most suitable flight path was found by study of the composite prognostic contour chart for the altitude chosen.

As these charts became better, and as the experience of the meteorologists and the navigators started to play a part, results improved. Eventually a number of standard routes could be prepared from which they could select the one which approximated most closely to the optimum flight path under the prevailing weather conditions. Most weather charts used the Lambert conformal conic projection with two standard parallels, on which a straight line approximates the great circle. The North Atlantic chart had standard parallels of 36 degrees north and 60 degrees north, and was often overprinted with a so-called Greenwich Grid, which played an important role when using the MFP. The theoretical geostrophic wind is assumed to blow parallel to the pressure contour lines, which are themselves assumed to be straight and parallel. In these circumstances frictional effects are negligible, and the Coriolis force and the acceleration due to the gradient force are in equilibrium. The relationship between the two is known as the K-factor, which is dependent upon the latitude and could therefore be extracted from a simple table or graph.

The speed of the geostrophic wind is the rate at which an aircraft drifts perpendicular to the direction of the pressure gradient. If the heading of the aircraft is parallel to the gradient, the change in pressure is maximal and the lateral displacement maximal. For a given true airspeed, the displacement is dependent upon the K-factor and the distance travelled parallel to the pressure gradient (i.e. across the contours), as measured by the change in pressure altitude. The change in pressure altitude is determined by comparison of readings from the radio altimeter and the pressure altimeter, and an amount of lateral drift (known as Bellamy drift) thus established which enables a pressure line of position (PLOP) to be plotted.

Most of the navigation computers in use in the 1950s had facilities to calculate the Bellamy drift. A Drift Angle Computer produced by the US Navy Department carried the detailed instructions:

To obtain data, fly at constant airspeed, heading and pressure altitude (with the pressure altimeter set at 29·92 inches) then:

(a) Read the radio altimeter and pressure altimeter simultaneously. Take the difference D. D = radio altitude minus pressure altitude.
(b) Repeat 2 or 3 times. When you are certain of the value of D, record it with the time of observation. Be sure the + or − sign is correct.
(c) Repeat the above operations every half hour.

The computer enabled inputs of the difference between D2 and D1 (successive readings of D), distance travelled, latitude, and groundspeed to be set, and readings were obtained of the average wind component relative to heading and the drift angle. Pressure pattern has the disadvantage that it is usable only on flights over water where

https://doi.org/10.1017/S0373463300008961 Published online by Cambridge University Press

the radio altimeter reads true altitude rather than height. Also it is not available in latitudes lower than 20 degrees, because the Coriolis force is weak and the geostrophic wind formula therefore unreliable.

3. THE ROUTE.

In conditions of no wind, the great circle route (the shortest) is also the least time track. In practice, the flight time could only be reduced by selecting a route with more favourable winds. This was done, as already described, by use of the contour charts, prognostics and optimal altitude graphs, to select the shortest flight time as the pressure pattern route. The route planned in this way was plotted on the navigation chart. In the early post-war years, this was usually a Mercator chart, so the route had to be divided into rhumbline sections. Later, the Lambert conformal chart was used often with a Greenwich Grid.

3.1. *The Single Heading Flight*. The single heading flight was a special case of the pressure pattern navigation system. An average wind correction angle (WCA) between the point of departure and destination was calculated and applied to the true track between the two points, and the aircraft was allowed to drift with the wind. The calculation of the WCA was simple. From the contour chart, or from other data, the absolute altitude of a certain pressure surface was determined for the points of departure and destination. The difference between these was used to obtain an average drift angle (in this case the WCA) as described above.

If the straight line between departure and destination was a rhumbline, application of the WCA to the track was simple. If it was a great circle (e.g. on a Lambert's chart), the WCA could be applied to a constant track relative to a rectangular grid rather than the changing track relative to the meridians. Hence the value of the Greenwich Grid overprint. Flying a constant heading, different drift values would be experienced along the route, and the direction of drift might even shift between right and left. In practice, the navigator traced by graphical methods on the contour chart 'points of marked windshift', where the drift angle was zero. For each of the zones between these points the lateral drift was calculated, and an expected path over the ground was plotted. The weather encountered on the single heading route was generally better than following the rhumbline or great circle route, since the aircraft was drifting with the wind and seldom would be carried into a low pressure area, while the flying time was usually shorter, because crabbing into wind was minimal.

3.2. *Constructing the Minimum Flight Path* (*MFP*). A method was developed, based on theories of Bossemoulin and Pone (1949), to construct the minimum time path at the most favourable cruising level, as the MFP. Using optimum altitude data, the most economical cruising level was determined and the nearest standard pressure chart was selected. A 'time-front' curve for each hour of flight was plotted on this chart, based on a TAS vector in various directions and the appropriate average wind vector. From the first time-front curve to fall beyond the destination, the flying time was established without any knowledge of the route to be flown. By back-plotting from the destination point, a position on each hourly time-front curve was found that was a point on the MFP, finishing with the plot connecting the point for the first hour to the departure point. The construction of the MFP gave not only the route, but also the required headings (the direction of each TAS vector) and the groundspeeds.

As in the case of the single heading flight, construction was usually on the prognostic weather chart. If, as was usually the case, this chart was a conic projection (such as a Lambert), a Greenwich Grid was constructed to enable the straight-line

https://doi.org/10.1017/S0373463300008961 Published online by Cambridge University Press

great circle directions to be measured relative to grid north. But for the actual flight, navigation was done in the normal way using magnetic and compass directions.

To speed up the process of constructing time-fronts and the MFP, and of collecting the resultant flight plan data (TAS, groundspeed and heading), a MFP computer was designed. This was a perspex instrument incorporating the necessary rotating and sliding parts and graduated scales for all stages of the construction. A different instrument slider was needed for each of the weather chart scales likely to be encountered (1:10000000, 1:12500000 and 1:15000000). When the upper wind chart showed a deep depression, different MFPs could result from this construction depending on which side of the depression's centre the plot was followed. The one with the longer flying time was regarded as a 'relative minimum flight path', and the one with the absolute minimum was the required MFP.

4. FLIGHT PLANNING FOR PISTON-ENGINED AIRCRAFT.

To explain the compilation and contents of the flight plans used in the first years after World War II, the system used by KLM for the North Atlantic is taken as an example. In the course of years, a certain standardisation took place, and flight plans (including the so-called computer flight plans) are still subject to change. The chosen route might be divided into zones of five degrees difference in longitude to conform with the divisions on meteorological charts or, as more often used in later years, sections of about 400 nm or ten degrees of longitude. First, a 'Flight Time Analysis' would often be made to determine which altitude would give the shortest flying time and which the most favourable fuel consumption, assuming a substantial headwind component. In a particular example, it might be found that, whereas the flying time at 18000 ft was much shorter than around 10000 ft, substantially less fuel would be used at the lower altitude, which would thus be chosen for reasons of economy.

The main flight plan could now be completed. Climb tables and cruising charts provided the navigator with airspeed and engine parameters, which could be entered in the appropriate columns. Allowing for the forecast wind in each zone of the route, headings, groundspeeds and elapsed times could be calculated and entered. An alternate airfield had to be chosen and the required fuel to reach this alternate calculated (it later became customary to choose at least two alternates). At the bottom of the flight plan the required fuel was noted. At the top of the flight plan the so-called critical points had to be entered. These were:

(a) The point of equal time (PET); that position from which it would take an equal time to proceed to one airfield (usually the destination or alternate) or return to another (usually the point of departure). The PET was important in the case of technical troubles or medical problems.

(b) The point of safe return (PSR), otherwise known as the point of no return (PNR); the point beyond which it would be impossible to return to the departure point, due to shortage of fuel.

Determination of these critical points involved a calculation that took into account the difference between the groundspeed to be expected if continuing enroute and that to be expected if returning, and proportioning the route distance accordingly. The possibility that the onward or return flight may have to be made on only three engines also had to be allowed for. The complex calculations involved were reduced to practical proportions by the use of tables and formulae that could be simply solved

https://doi.org/10.1017/S0373463300008961 Published online by Cambridge University Press

on the navigation computer. If the PET were required for an alternate that was off the planned track, this further complication might be solved by graphical methods on the weather chart.

One of the duties of the navigator on a long-distance flight was to prepare a range control chart, popularly called a 'Howgozit'. Using flight plan data and specially printed graphs of fuel against distance, a graphic representation of the flight plan was plotted, including PET and PNR. During the flight, the actual fuel consumption was compared with the calculated consumption, thus enabling any unexpected situation to be detected early and acted upon effectively.

4.1. *The Flight Plan for the Minimum Flight Path* (*MFP*). For the MFP system, a flight plan was designed using hourly sections, to conform to the hourly time-front system used for finding the MFP. A simplified 'first flying hour' table indicated the average TAS and total fuel consumption for the first time-front, for various altitudes. The cruising charts gave power settings per hourly bracket instead of per weight bracket, so that power setting and fuel flow for each hour after the first could be established, and filled in for the whole flight. Thus, even before the MFP itself had been constructed, the total fuel consumption was known. Only the section beyond the last time-front had to be computed as part of one hour. Since the MFP construction produced the required headings, the flight plan did not need columns for intended track or for wind data.

4.2. *In-Flight Technique*. By plotting hourly positions on the MFP chart, the navigator could monitor progress. He could also control any deviation from the intended MFP. The pre-planned headings would bring the aircraft close to the destination in spite of wind deviations en route, but only provided the height difference of the pressure surface between the points of departure and destination did not change. In practice, this was rarely found to be the case, so heading corrections were necessary. The simplest method was to measure the difference between intended and actual position and apply it as an angular correction to the MFP, related to the point of destination. As regards any temptation to deviate from the pre-selected optimum altitude, it was found in practice that no significant fuel savings could be made.

4.3. *Strengths of the MFP*. The strengths of using the MFP were:

(a) The gain in time, so saving fuel,
(b) Simplification of the flight plan, navigation administration and in-flight techniques,
(c) From time-front information only, before construction of the MFP:
    i. Determination of total burn-off, and therefore payload,
    ii. Better appreciation of routeing possibilities in terms of times to destination and en route alternatives.
(d) Avoiding bad weather; in many cases the MFP runs north of the low pressure area when flying westerly, whereas the frontal weather is to the south.

4.4. *Weaknesses of the MFP*. The weaknesses of using the MFP were:

(a) It was not usable where ATC regulations imposed restrictions on choice of route. In the early 1950s, there were few such restrictions over the North Atlantic, where routes lent themselves well to the MFP, but this was later changed by increasing traffic density.

https://doi.org/10.1017/S0373463300008961 Published online by Cambridge University Press

(b) It depended on forecast data, which eventually proved less reliable than was understood at the time. The theoretical advantage over conventional techniques was often small, and could be totally discounted when the forecast was wrong.

(c) An unknown compass error could have a detrimental influence, due to the navigator's assumption that the pressure system itself would compensate for unexpected deviations.

4.5. *Use of the Jetstream.* When aircraft were equipped with pressure cabins, it became possible to fly at much higher altitudes. This gave the navigator a chance to use the jetstreams (winds in excess of 100 kt), the existence of which had been known to meteorologists for some time. Jetstreams are caused by a large horizontal temperature gradient, which brings with it a strong thermal wind and a great vertical wind shear. Large horizontal temperature variations are found at frontal surfaces between two air masses of different origin and temperature, such as the polar frontal zone that separates the tropical and polar air masses over the North Atlantic. The maximum windspeed is found near the tropopause in the warm air. Because the cold air is on the polar side, the jetstream blows from a westerly direction, and so could be advantageous on flights from America to Europe. If forecast conditions justified it, the MFP flight plan could be modified in such a way as to intercept the jetstream. Once airborne, the navigator 'hunted' the jetstream by taking frequent readings of the radio and pressure altimeters to determine the increasing height of the pressure surfaces as the frontal zone was approached from the polar side. Near the frontal zone, but always in the cold air, clear air turbulence was encountered as a result of strong vertical and horizontal windshears, and thermometer observations would detect the moment of crossing the frontal zone into the warm air. The aircraft then had to be turned, and if practicable climbed, to enjoy the maximum tail wind component. Once within the jetstream, flying conditions were mostly smooth.

Piston-engined aircraft could not utilise the jetstream fully, yet many flights in the early 1950s did make appreciable time savings. With increasing ATC requirements, single heading flights were restricted from 1956. By 1960, the switch to turboprops and turbojets led to severe competition on North Atlantic routes for the best altitude and minimum time track. New separation criteria were necessary, and the solution was the organised track system.

5. FLIGHT PLANNING FOR TURBOPROP AIRCRAFT.

The transition from piston-engine aircraft to turbine aircraft in civil aviation took place in the years between 1958 and 1961. Flight planning for both turboprop and turbojet aircraft differed from that for piston aircraft, particularly in regard to fuel control techniques and long-distance flying. Turboprop aircraft cruised most economically between 250 kt and 350 kt. Two engine types were in use; single-spool and twin-spool. In the single-spool type, the same turbine drove both the compressor and, via a reduction gear, the propellor. The twin-spool had separate turbines to drive the compressor and the propellor; since the two turbines were independent of each other they could each operate optimally. Fuel consumption for turboprop aircraft was least at high altitudes, but twin-spool aircraft such as the Britannia were less affected by altitude changes than single-spool aircraft such as the Lockheed Electra. Selection of a flight level was a delicate question, because it depended on the following factors:

(a) *Flight Plan Distance and Aircraft Weight.* Because of the need to fly as high

https://doi.org/10.1017/S0373463300008961 Published online by Cambridge University Press

as possible, it was advisable on long-distance flights to increase the cruising altitude as the weight reduced. In the early days, the cruise-climb method was used; the aircraft was climbing gradually after reaching its initial cruising level, but this was later replaced by the step-climb method to prevent difficulties with ATC. For shorter distances, a constant cruising level could save fuel overall by reducing climbing time. A distance of around 1200–1300nm was used in operating manuals to demarcate long-distance from short-distance techniques.

(b) *Wind Component at the Optimal Level.* When strong headwind components existed at the optimum cruising level, it could prove advantageous to descend to a lower level where a weaker headwind component would allow a better rate of consumption in ground nautical miles per kilogram of fuel.

(c) *Temperature Changes.* Temperatures above ISA had a negative effect on the cruising altitude, the TAS and the number of air nautical miles per kilogram of fuel.

(d) *ATC Restrictions.* If the best cruising level was not available due to ATC restrictions, the navigator had to reconsider the fuel consumption and endurance.

Flight plan calculations were made using tables for optimum engine settings. A climb table gave time and fuel used to climb to the initial cruising level, and a cruise table the fuel flow rate per hour, TAS and IAS for a range of cruising levels. The navigator had a normal flight plan and a worksheet at his disposal. Descent was not accounted for. To the total trip fuel thus obtained was added (in the case of KLM Lockheed Electra operations) a basic six percent, an allowance of 100 kg for each hour in possible icing conditions, fuel for climb and cruise to an alternate airfield plus holding, and, at the captain's discretion, a further 600 kg, if the payload permitted it.

6. FLIGHT PLANNING FOR TURBOJET AIRCRAFT.

Like the turboprop, the turbojet must be flown as high as possible, because fuel consumption is least at high altitudes. Curves for each cruise system, showing the specific range (nm/kg) against altitude for various heights, were used to show optimum altitude, which gradually increased with decreasing weight. As in the case of the turboprop, a cruise climb method would be ideal, but would not meet ATC requirements, so a step-climb was used to approximate the optimum altitude.

Effects of excessive wind gradients and of temperatures above ISA have less effect on turbojet aircraft than on turboprops, so variations to the step-climb pattern for these reasons were rare. However, speed limitations were a more important consideration in turbojet flight planning. The power developed by a jet engine can produce speeds that exceed airframe limitations or cause dangerous control characteristics (buffeting). Maximum operational and 'never exceed' values of IAS and Mach Number were therefore enforced. In practice, three cruise systems were used in early turbojet operations:

(a) *Long-Range Cruise*. It was not practicable to fly at the theoretical maximum range cruise speed (i.e. for minimum fuel consumption) because of difficulty in recovering from any speed losses due to turbulence. A faster long-range cruise speed (for the DC8, which joined the KLM fleet in 1961, some 10–15 kt faster) was therefore used. At a given altitude, long-range cruise speeds decrease with decreasing weight.

https://doi.org/10.1017/S0373463300008961 Published online by Cambridge University Press

(b) *Standard Cruise*. Cruise speeds for minimum costs were calculated at various weight/altitude combinations. For a DC8, the minimum cost speed at the optimum altitude was found to be Mach 0·80, which was therefore selected as the standard cruise speed above 30 000ft. For other types of aircraft, a different Mach number might apply. Sometimes minimum cost and long-range cruise speeds coincided.

(c) *High-Speed Cruise*. Over short distances, or in order to gain time, a high-speed cruise might be used, but at the expense of a considerable increase in fuel consumption.

For the North Atlantic, checkpoints at intervals of 10 degrees of longitude (about 450 nm) were chosen for flight planning purposes from the available ATC high-level tracks. Fuel reserves for alternate airfields and other contingencies, and PET and PNR computations, were included in the flight plan on the same principles as for non-turbojet types.

As traffic on the North Atlantic routes increased during the 1960s, and as computers took a more prominent part in ATC procedures, it became both feasible and necessary to adopt a formalised route structure. An Organised Track System (OTS) was therefore introduced, whereby a series of so-called NAT-tracks, based on minimum time tracks from 28000 ft upwards, are selected twice daily, and transmitted to all relevant operators. The westbound, or daytime tracks, serve the flow departing Europe in the morning and early afternoon, and are calculated by Shanwick Oceanic Area Control Centre (OAC). The eastbound, or night-time tracks, serve the afternoon/evening departures from North America for morning arrival in Europe, and are calculated by Gander OAC. The OAC concerned is assisted in determining the NAT-tracks by inputs from the various operators' flight planning computers. The operator selects and requests the track most suitable to his needs, and is provided with a computer flight plan for the route allocated.

Computer developments in subsequent years, and events such as the oil crisis of 1973, influenced operators to seek more flexibility in the OTS structure. Provided they were not in conflict with other operators using the promulgated NAT-tracks, requests would be considered by the ATC authorities for tracks using the operators' own assessment of their most economical cruise profile.

https://doi.org/10.1017/S0373463300008961 Published online by Cambridge University Press