Forum

The Development of North Atlantic Navigation and Flight Planning Procedures in RAF Ferry Command

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Phil Steele's prècis of Dries Bulstra's paper on flight planning prompts me to recall flight planning procedures on the North and South Atlantic in the days of RAF Ferry Command. The sparsity of radio-navigation aids, coupled with few weather reports and even fewer diversion airfields made flight planning and en-route navigation an interesting challenge. RAF Ferry Command rose to the challenge, aided by volunteer captains from American civilian airlines. The catalyst for this success lay in decisions taken in 1935.

KEY WORDS

1. Planning 2. Air Navigation 3. History

1. BACKGROUND. In November 1935, a Commonwealth Conference, held in Ottawa, authorised the creation of the airfield and meteorological infrastructure necessary for a trans-Atlantic air service between the USA, Canada and Europe. The Ottawa Commonwealth Conference was prompted by two main concerns. First, the UK wanted to counter the non-stop mail services planned by the USA across the North Atlantic and, secondly, the deteriorating political situation in Europe caused the UK to strengthen the air link with Canada in case it became necessary to consider producing British military aircraft in Canada.

Relevant to the future RAF Ferry Command, the 1935 Ottawa Conference decided to build a chain of airfields across Canada, from Vancouver to Halifax, including an airfield at Hattie's Camp (later renamed as Gander) and a landing area for flying boats on the adjacent Gander Lake. In addition, the Conference decided to provide a trans-Atlantic meteorological facility at the flying boat base of Botwood, Newfoundland to be headed by Dr P. D. MacTaggart-Cowan (McFog to his friends). He moved from Botwood to Gander as soon as the latter airfield became usable in 1938. At Gander, he built up a reputation as the pre-eminent trans-Atlantic meteorological forecaster.

2. THE FIRST RAF FERRY COMMAND FLIGHTS. The plan for the first trans-Atlantic ferry flight (10 November 1940), led by D. C. T. Bennett, called for the seven Lockheed Hudson aircraft to be flown in formation, for which the aircraft had been fitted with powerful formation lights. Bennett decided to act as the formation navigation leader, and all went well until the aircraft entered an active

weather front three quarters of the way across the ocean. On entering cloud, each aircraft collected a large amount of clear icing. Formation flying was abandoned. Some captains decided to climb to get above the cloud and some decided to descend in the hope that the icing would melt. Then each aircraft went its own way. Not surprisingly, their arrival times at Aldergrove were spread over a period exceeding one hour. Bennett was unhappy with the navigation standard displayed on this and the next two trans-Atlantic groups of Hudson aircraft and decided to lead the fourth group himself. Only four of the seven aircraft in the fourth group made the Atlantic crossing to Aldergrove or Prestwick. One crashed on take-off at Gander, one returned with engine trouble and one landed at Speke near Liverpool with dry tanks after flying for 12 hours 43 min! Bennett was appalled, headed for London and convinced Beaverbrook that RAF Ferry Command should use RAF navigators graduating from the Canadian navigation training schools, after first undergoing a trans-Atlantic navigation training course designed by Bennett himself in Montreal. He also convinced Beaverbrook that it was impractical to envisage formation flying across the Atlantic – far better to let each aircraft have a qualified navigator and fly independently.

3. THE BUILD-UP. Through the winter of 1940–41, a mixed bag of 185 aircraft, including Hudson, B-24 Liberator and B-17 Flying Fortress aircraft set off for the UK from Montreal and 181 made the direct flight to the other side of the ocean. Thus started the Atlantic Bridge which, by the end of the Second World War, saw 10000 aircraft being moved from the North American to the European continents.

Goose Bay, Labrador, was open for routine ferry flights in Spring 1942, but the airfields that enabled very short-range aircraft to cross the Atlantic – notably the Crystal airfields in the Canadian Arctic Archipelago, plus Bluie West 1 and Bluie East 8 in Greenland, and Meek's Field (Keflavik) in Iceland – did not become operational until the autumn of 1942.

4. RADIO NAVIGATION AIDS. When RAF Ferry Command started operations in late 1940, radio navigation aids over the North Atlantic were limited to a low-powered radio range and beacon at Gander, a radio beacon at Derrynacross in Northern Ireland and a radio range at Prestwick. This meagre scattering of radio navigation aids received a significant boost in the Spring of 1942 by the addition of a radio beacon and radio range at the new airport of Goose Bay, on the edge of Lake Melville, Labrador, and further radio beacons at Bluie West 3 Greenland (at the entrance to the fjord leading up to new airfield at Bluie West 1), Bluie East 8 Greenland, and at Meek's Field (Keflavik) in Iceland.

The beacon at Derrynacross was of medium to high power, giving a range over the Atlantic of between 100 and 250 miles, depending on the time of day and the meteorological conditions. It was, however, switched off whenever German aircraft were believed to be heading for Northern Ireland. Moreover, it was also subjected at times to meaconing from a radio station in Norway.

Most aircraft being ferried across the North Atlantic had a D/F capability. For example, PV-1 Ventura aircraft had a large manual D/F loop at the radio operator station while B-24 aircraft had a Bendix SCR 249 automatic radio compass at the navigator station.

The portion of the Southern Ferry route between Montreal and Accra was relatively well supplied with radio navigation aids. The sector from Montreal to Nassau was along Canadian and US airways, all turning points being marked with a radio range or a 75 MHz marker beacon. From Nassau onwards there was a MF beacon or radio range at each terminal airfield, but few radio beacons that could be received en-route. With generally fair trade wind weather conditions, astro navigation – coupled with the occasional pinpoint and fixes deduced from astro-compass bearings – made navigation an enjoyable pleasure.

5. OTHER NAVIGATION AIDS. Non-radio navigation aids on aircraft being ferried across the North and South Atlantic were limited to a drift measuring instrument, a pressure altimeter, airspeed indicator, an outside air thermometer, an astro-compass and an astro dome. Though some aircraft carried a Kollsman Mk VIII sextant, navigators generally preferred the non-averaging Kelvin Hughes Mk IX sextant in the early days and the averaging Kelvin Hughes Mk IXB sextant series in the latter days of WW2. Because of the vital importance of astro, most experienced navigators carried two sextants.

One unique visual navigation aid was provided by the Government of Eire. On the main headlands along the west coast of Ireland, a large number was placed on the ground together with an arrow showing the way to Derrynacross. A printed list of these positions became a standard part of all navigation kits. A second unique visual navigation aid existed on the mid-ferry route via Lagens and Rabat Sale. Crews flying this route were briefed to note the direction of the coastline when reaching North Africa. If the bearing was 199° they were north of Rabat Sale, and if the bearing was 239°, they were to the south.

Daylight flights in the equatorial section of the Southern Ferry route often involved plotting an airman's version of the noon-day fix. Sun altitudes in excess of 85° were obtained and three co-altitudes were determined as the Sun's azimuth changed rapidly from an easterly through north or south to a westerly direction. The sub-solar positions for the three times were determined from the Air Almanac (GHA Sun equals longitude west and Declination equals latitude) and circles equivalent to the co-altitudes were drawn (for example, an altitude of 84° 21′ gives a co-altitude of 5° 39′, which is equivalent to 339 nms). The first two position lines were then transferred by transferring the sub-solar points along DR track and re-drawing the actual co-altitudes.

Night-time flights in the equatorial sector, outside the area of the Inter-Tropical Convergence Zone (ITCZ), were an astro-navigator's dream. The sky was full of the very bright stars associated with the southern hemisphere, perfectly spaced to permit observations of stars separated by about 120°, thus reducing fixed errors. When plotted on charts with an equatorial scale of between 1:5 m and 1:10 m, the resulting small cocked hat did much to boost the ego of the navigator.

6. METEOROLOGICAL FORECASTS. The sparsity and unreliability of radio navigation aids over the North Atlantic led navigators in RAF Ferry Command to take considerable interest in the meteorological forecast. This interest centred on the need to pick a route and height to fly that gave a reasonable fuel reserve, preferably one that enabled astro sights to be taken and which avoided areas of heavy icing. The air over the Atlantic in the period 1940–1945 was free of pollution, so the

old theory that severe icing could only occur from 0 to −7 °C and that only light to moderate icing was experienced from −7 °C to −18 °C was found to be a myth. Icing occurred whenever in cloud in the winter months. And with freezing level on the surface in the Western Atlantic there was no escape at low level.

The forecasters in the Gander meteorological office became renowned for their expertise, giving excellent oral briefings, and providing synoptic charts for the 700 mb and 500 mb levels at 6-hourly intervals, a table of winds at 5000 ft intervals, and landing forecasts for all North Atlantic terminals and diversions.

Cloud cover is such on the North Atlantic in winter that part of the crossing for piston-engine aircraft would be either in cloud or between cloud layers. Although the broad weather patterns were forecast quite well, errors did occur in forecasting the speed and direction of movement of depressions. Similarly, there tended to be a consistent bias regarding the wind direction and speed. So, when winds or weather different from forecast were obtained in flight, the navigator needed to decide whether the bias was likely to be caused by an incorrect forecast movement of a particular weather system or by a combination of compass and forecasting error. He would apply his judgement to anticipate the wind to be used for the next section of the crossing. If there was going to be a break in the cloud cover, then it tended to be in the 9000 to 11000 ft region – which ferry navigators referred to as the 'tunnel'.

Outside the hurricane season, flights on the Southern Ferry route could be characterised as flying in typically trade wind conditions with fair weather, broken cumulus clouds over the ocean and large cumulus clouds over land, the latter often developing into cumulo-nimbus late in the day.

7. THE FLIGHT PLAN. Experienced navigators carried their own book of routes to be used across the North Atlantic. In general, the route flown from Gander to Prestwick was the rhumb line from Gander to Derrynacross and thence directly to Prestwick. When winds or weather were adverse on the rhumb line track, an approximate great circle route was flown, the points being selected at five or ten degrees of longitude. Only exceptionally did crews opt to fly a track to the south of the rhumb line track – for the simple reason that it increased the route mileage. For all other routes on the North and South Atlantic the rhumb line was the norm.

The standard flight plan gave the route, tracks, distances, timings at intervals of 5 degrees of longitude, and the safe endurance of the aircraft. Prudent navigators also calculated the critical point and the point of no return. Though standard RAF navigational instruments were available, the thin E6 type of Dalton computer used by the US Navy was a favourite acquisition.

8. NOTICES TO AIRMEN. An area of each flight planning section was devoted to the serviceability of the few radio aids, the colour of the Very cartridge and the Aldis light code to be used if and when challenged, and the relevant runway information – such as snow cover, ice cover and braking action.

9. ASTRONOMICAL TABLES. To cover the requirement for the reduction of astro sights, new navigators tended to carry the standard RAF Air Navigation Tables (ANTs) covering the North and South Atlantic areas. But with the need to carry clothing and personal effects to cover an absence of about two weeks, plus two sextants, charts and topographical maps covering from Montreal to Europe or

Montreal to the Middle East via Ascension Island, many navigators looked for alternative sight reduction solutions. Experienced navigators, especially those flying from Montreal to the Middle East via Brazil, preferred to carry the slimmer, single volume Hughes or Driesenstock tables, which were freely available from the navigation section at Dorval.

10. NAVIGATION CHARTS. Mercator charts for the North Atlantic area were poor. The US Army Air Force had a coloured 1:3m chart of the area, the sea being shown as medium blue and the land as medium green, neither conducive for the conduct of serious navigational practices. The relevant chart for the North Atlantic was, however, notable for three reasons. First, it was produced with a waxy surface resistant to black lead pencils. Secondly, the location of towns and airfields was unreliable and, thirdly, it showed what appeared to be an island called Flemish Cap, located to the SE of Newfoundland. No navigator ever found the Flemish Cap – which is not surprising because it is 28 fathoms beneath the surface of the ocean. The chart problem was solved by RAF Ferry Command producing two charts, both with a white background on which was printed a light green geographical grid. One chart covered the North Atlantic and another the South Atlantic, the latter extending from Miami through to Accra via Trinidad and Brazil. The scale of both charts was about 1:3 m or 4 m at mid latitude, necessitating the use of very sharp pencils. The consolation factor was that astro fixes tended to have no cocked hats or at worst very small cocked hats. And whenever crews landed at American bases, they eagerly acquired copies of the excellent US Navy 1:2 m V series of charts.

11. NAVIGATION EN-ROUTE. From the above account of flight planning, the reader will readily appreciate that navigation on the main RAF Ferry Command routes was by a combination of astro navigation, drift measurement, radio-compass and astro-compass bearings and dead reckoning, coupled with the occasional pinpoint. But that is another story.

Astrogeodetic Fix by Azimuth Differences; Solution in Rectangular Coordinates

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This paper offers a precise and almost final solution to one of the most debated problems connected with the astrogeodetic 'fix' by azimuth differences. The rectangular and linear solution on the gnomonic plane, tangent to the celestial globe and the dead reckoning position, enables the use of azimuth differences and is connected to Pothenot's solution. Thus this problem may be solved with simple linear algorithms that require neither differential modes, nor the introduction of the unknown origin error.

KEY WORDS

1. Astro. 2. Mathematics.

1. INTRODUCTION. The determination of astrogeodetic fixing by azimuth observations has so far been treated with analytic methods, their limitation resting with the origin error of the azimuths themselves. Adoption of azimuth differences eliminates such errors and reduces the effect – on the fix – of the inevitable inclination error of the main axis of the theodolite. In fact, the presented solution coincides with Pothenot's but is transferred onto the gnomonic plane tangent to the celestial globe at the dead reckoning position.

2. THE PROBLEM. With any azimuth origin, let $L_i (i = 1, 2, 3, \ldots. n)$ represent the instrumental azimuths of n celestial bodies at instants T_{si} of their 'crossing' the vertical line/lines of the theodolite grid. With a good azimuth distribution of observed celestial bodies, and with a symbolic representation of celestial bodies $*_1, *_2, *_3, *_4 \ldots. *_n$, clockwise with respect to the observer (see Figure 1), we may identify the following elements:

$$\left\{\begin{array}{l} \beta_1 = L_2 - L_1 \\ \beta_2 = L_3 - L_2 \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ \beta_{n-1} = L_n - L_{n-1} \end{array}\right. \qquad \left\{\begin{array}{l} T_{S1} = \text{Greenwich Sideral Time of ``cross'' of } *_1 \\ T_{S2} = \text{Greenwich Sideral Time of ``cross'' of } *_2 \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ T_{Sn} = \text{Greenwich Sideral Time of ``cross'' of } *_n \end{array}\right.$$

$$\text{Celestial bodies } *_{\mathrm{I}} = \begin{cases} \alpha_i = \text{right ascension} \\ \delta_i = \text{declination (with } i = 1,2,3,\ldots\ldots n) \end{cases}$$

$$P_O \text{ (Dead reckoning position)} = \begin{cases} \phi_a = \text{latitude} \\ \lambda_a = \text{longitude} \end{cases}$$

$$t*_i = T_{si} + (\lambda) - \alpha_i = \text{Celestial body local time}$$

Rectangular coordinates of celestial bodies and of P_O are:

$$*_i = \begin{cases} x_i = \cos\delta_i \cdot \cos t*_I \\ y_i = \cos\delta_i \cdot \sin t*_i \\ z_i = \sin\delta_i \end{cases}$$

$$P_O = \begin{cases} x_O = \cos\phi_O \\ z_O = \sin\phi_O \end{cases}$$

On the gnomonic plane of the 'horizontal or general gnomonic projection', its plane being tangent at P_O, a grid of rectangular coordinates OXY is fixed, whereby the X axis is tangent at P_O the tangency meridian (λ_O) of the gnomonic projection.

The positions of the celestial bodies on such a plane are:

$$*_1 = \begin{cases} X = \dfrac{x_o \cdot z_i - z_o \cdot x_i}{z_o \cdot z_i + x_o \cdot x_i} \\ Y = \dfrac{y_i}{z_o \cdot z_i + x_o \cdot x_i} \end{cases} \tag{1}$$

The observed azimuth differences β, may be transferred to the gnomonic plane directly, even if this not isogonic. It can be demonstrated that deformation $d\beta$ is so small that it cannot be instrumentally evaluated. Maximum deformation $d\beta_{\max}$ is given by:

$$d\beta = 45° - \tan^{-1}(\cos\sigma),$$

where $\sigma = P_o P$ is the spheric distance between the dead reckoning point and the FIX; thus, also with:

$$\sigma = 3' \equiv 0°{\cdot}05 \quad d\beta_{\max} = 0''{\cdot}04.$$

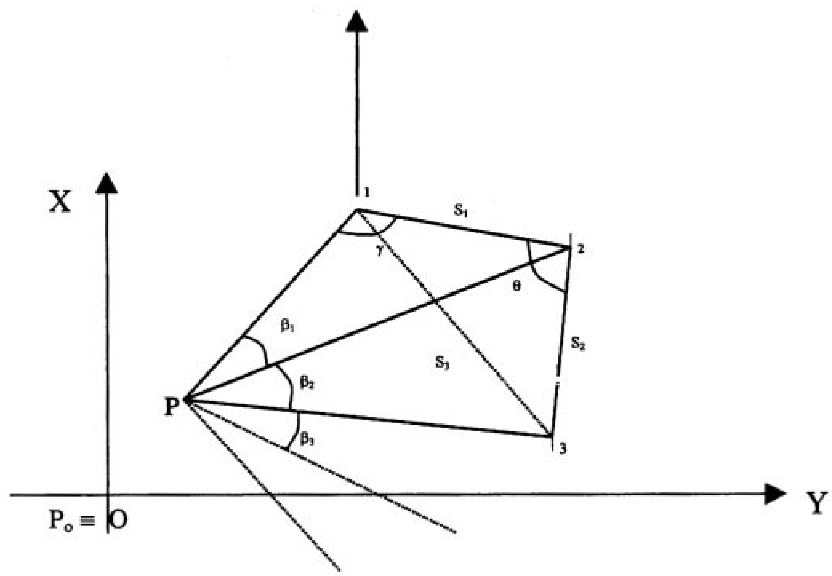

Figure 1.

Pothenot's solution gives the 'FIX' as follows:

$$P \equiv \begin{cases} X \\ Y \end{cases}$$

Because of the inverse relations of (1), let us assume that:

$$\eta = \frac{y}{x} \quad \varsigma = \frac{z}{x}$$

Thus:

$$\begin{cases} X = \dfrac{x_o \cdot \varsigma - z_o}{z_o \cdot \varsigma + x_o} \\ Y = \dfrac{\eta}{z_o \cdot \varsigma + x_o} \end{cases}$$

By solving η and ς we shall have:

$$\begin{cases} \varsigma = \dfrac{z_o + X \cdot x_o}{x_o - X \cdot z_o} \\ \eta = Y \cdot z_o \cdot \varsigma + Y \cdot x_o \end{cases} \tag{2}$$

And finally we shall algebraically have:

$$\text{FIX P} = \begin{cases} (\mathrm{d}t) = \tan^{-1} \eta \\ (\phi) = \tan^{-1} [\varsigma \cos (\mathrm{d}t)] \\ (\lambda) = (\lambda) - (\mathrm{d}t) \end{cases} \tag{3}$$

3. THE SOLUTION. We propose the following solution to Pothenot's problem (Vassallo, 1993); as already said, by indicating clockwise from P the observed celestial bodies ($*_1$ is arbitrary) we have (see Figure 1):

$$\begin{cases} \overline{*_1 *_2} = S_1 = [(X_1 - X_2)^2 + (Y_1 - Y_2)^2]^{\frac{1}{2}} \\ \overline{*_2 *_3} = S_2 = [(X_2 - X_3)^2 + (Y_2 - Y_3)^2]^{\frac{1}{2}} \\ \overline{*_1 *_3} = S_3 = [(X_1 - X_3)^2 + (Y_1 - Y_3)^2]^{\frac{1}{2}} \end{cases}$$

$$*_1 \hat{*}_2 *_3 = \theta = \cos^{-1}\left(\frac{S_1^2 + S_2^2 - S_3^2}{2 \cdot S_1 \cdot S_2}\right)$$

$$\begin{cases} a_1 = \tan^{-1} \frac{Y_1 - Y_2}{X_1 - X_2}\Big) \\ a_2 = \tan^{-1} \frac{Y_3 - Y_2}{X_3 - X_2}\Big) \\ \theta = a_2 - a_3 \end{cases}$$

$$\gamma = P \hat{*}_1 *_2 \quad \text{unknown}$$

$$K = \frac{S_2}{S_1} = \frac{\sin\beta_1}{\sin\beta_2}$$

$$\omega = \beta_1 + \beta_2 + \theta$$

$$\gamma = \tan^{-1}\left(\frac{-K \cdot \sin\omega}{1 + K \cdot \cos\omega}\right)$$

$$a = \tan^{-1}\left(\frac{Y_2 - Y_1}{X_2 - X_1}\right)$$

$$\begin{cases} A_1 = a + \gamma \\ A_2 = A_1 + \beta_1 \\ A_3 = A_2 + \beta_2 \\ \dots\dots\dots\dots\dots\dots \\ \dots\dots\dots\dots\dots\dots \\ A_n = A_{n-1} + \beta_{n-1} \end{cases}$$

We have the following straight lines:

$$\begin{cases} Y - \tan A_1 \cdot X = \tan A_1 \cdot X_1 - Y_1 \rightarrow *_1 P \\ Y - \tan A_2 \cdot X = \tan A_2 \cdot X_2 - Y_2 \rightarrow *_2 P \\ Y - \tan A_3 \cdot X = \tan A_3 \cdot X_3 - Y_3 \rightarrow *_3 P \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ Y - \tan A_n \cdot X = \tan A_n \cdot X_n - Y_n \rightarrow *_n P \end{cases} \quad (4)$$

The quadratic mean solution to the system (4) gives the 'FIX':

$$P \equiv \begin{cases} X \\ Y \end{cases}$$

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With inverse relations (2) and (3) we have:

$$P \equiv \begin{cases} \phi \\ \lambda \end{cases}$$

We may also calculate true azimuths A_i of the observed celestial bodies.

Let us assume:

$$\begin{cases} x_p = \cos\phi \cdot \cos(d\mathrm{t}) \\ y_p = \cos\phi \cdot \sin(d\mathrm{t}) \\ z_p = \sin\phi \end{cases}$$

$$\xi_i = \cos^{-1}(x_p \cdot x_i + y_p \cdot y_i + z_p \cdot z_i)$$

If readings L_i originate from a geodetical target, we may have n azimuths of such geodetical targets, of which we can obtain the most probable value by an arithmetic mean.

4. CONCLUSIONS. Fix determination by differences of azimuths is most suitable to operations in Antarctica. In fact, because the Antarctica summer offers six months of sunlight, it suffices to determine azimuth differences of the Sun at regular intervals, to obtain a point with geodetic accuracy.

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