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MINISTRY OF AVIATION

AEROPLANE AND ARMAMENT EXPERIMENTAL ESTABLISHMENT

BOSCOMBE DOWN

ASSESSMENT OF AUTO-I.L.S. APPROACHES

"DTIC USERS ONLY"

BY

K. EYRE B.Sc., D.I.C.

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AEROPLANE AND ARMAMENT EXPERIMENTAL ESTABLISHMENT 28 NOV 1961
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Assessment of Auto-I.L.S. Approaches

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K. Eyre B.Sc., D.I.C.

Summary

In making flight tests on auto-control systems the effect of tolerances on the various components in the system may have a significant effect on the performance. At A. & A.E.E., in recommending clearance for the Service, it is required to determine the likely limits of performance that will be met in general use, from the smallest practicable number of tests.

This note describes the recommended procedure for flight testing Auto-I.L.S. approaches at A. & A.E.E. and gives a method for estimating the "Aircraft Approach Limitation" height. The method can be applied to other types of approach system. The object of the note is to give a systematic method of testing, which from a practicable number of tests covering what are thought to be the most important variables, will give a reasonable degree of certainty that the A.A.L. height is adequate and that the performance will be acceptable in Service use. No account is taken of power flying control or aerodynamic differences between aircraft.

The report has been written in order to stimulate discussion and exchange of ideas in this comparatively new field of flight testing; it is not intended at this stage to represent a mandatory flight test schedule.

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/1. Introduction...

1. Introduction

The test technique given in this paper is based on established methods but takes into account additional variables which have not previously been assessed systematically. The paper is intended to stimulate discussion and exchange of ideas in this comparatively new field of flight testing but not at this stage to give a mandatory flight test schedule. Certain aspects of the testing will also apply to future "Automatic Landing Systems".

The object of the assessment is to determine whether or not the aircraft type will behave in a safe and comfortable manner during the whole approach on any ground installation and also to determine the minimum safe height to which the aircraft can be allowed to descend under auto-pilot control in non-visual conditions.

As the approach performance is affected by a number of variable quantities (i.e. I.L.S. beam characteristics, auto-pilot characteristics, aircraft configuration, aircraft speed, &c.) it is essential to flight test over a practical range of as many of these variables as possible. In Section 3, which gives the recommended test procedure, most of the variables are listed but as the possible variations in I.L.S. beam characteristics may not be fully appreciated these are described in some detail in Section 2.

In Section 4 a method is given for estimating the "Aircraft Approach Limitation" height. The method is based on estimates of flare and sidestep distances assuming known aircraft characteristics. These estimates are described in detail in Appendices I and II. This method can also be used for assessing A.A.L. values for manual I.L.S. approaches or for other types of approach guidance system such as G.C.A.

2. I.L.S. beam characteristics

The I.L.S. beam system provides angular displacement information to the pilot or auto-pilot, in both azimuth and pitch, by means of two ground radio transmitters. The transmitter providing azimuth information is known as the "Localiser" and it radiates two overlapping beams, equal signals from each being received on the correct path and one or the other predominating if the aircraft deviates from it. Near the beam centre plane the error signal is intended to be proportional to the angle off the centre plane. It is desirable for the Localiser transmitter to be situated on the extended runway centre line as shown in Fig. 1, but in some installations, due to shortage of land in the overshoot area, it has been necessary to place the Localiser at the side of the runway in an "Offset" position. In these installations the equal signal plane is not parallel to the runway centre line but intersects it ahead of the touch down point.

The transmitter providing pitch information is known as the "Glide Path" and it radiates two overlapping beams, in a similar manner to the Localiser but in the vertical plane, with the equal signal plane inclined at approximately 3° to the horizontal.

Two "Marker Beacon" transmitters known as "Outer" and "Middle" markers are also provided and these are placed along the approach path at fixed points to give the pilot positive range information.

The azimuth and pitch angular distances from the two beam centre planes are displayed to the pilot on an "I.L.S. Meter". The meter has two pointers, one vertical and one horizontal. The pointers move over a scale on which is marked a circle, in the centre, and four dots in each direction of movement. The circle radius is one dot and the full scale deflection is said to be five dots, which corresponds to a signal input of 150 micro amps. In an automatic approach the pilot monitors the approach by reference to the I.L.S. meter.

/2.1...

2.1 Localiser

2.1.1 Setting-up requirements. The following are the main beam requirements affecting performance testing as given in AP.2888.H.

(I)a. In-line installation

The direction of the "course line" of the beam must be along the centre-line of the runway. (No limits given but within ±0.1° of the centre-line is thought to be reasonable.)

(I)b. Offset installation

The direction of the "course-line" of the beam must intersect the centre-line of the runway at a distance of 1860 ft. 'down wind' from the glidepath transmitter. (No limits given.)

(II) The preferred angular width for 15.5% D.D.M.* (150 micro amps which is full scale deflection of the I.L.S. meter i.e. 5 dots) is ±2½°. The limits are ±2° to ±3°.

(III) At 4750 ft. from the glidepath transmitter it is recommended that the beam width is ±500 ft. The limits are ±400 ft. to ±650 ft.

It follows from requirement (III), which is intended to give a reasonably standard beam sensitivity round about the break-off height irrespective of runway length, that for in-line installations, as the runway length is increased, the beam angle will have to be reduced. In the case of the A. & A.E.E. runway where the localiser to glide-path transmitter distance is 9,900 ft. the beam angle has to be restricted within the range of 2 to 2.5 degrees as shown in Figs. 2(A) and 2(B). Fig. 2(B) shows the percentage width variations allowable at 4,750 ft. from the glide-path transmitter (approx. middle marker and break-off height region) and also at 8 n.m. (approx. beam capture region) for variation in distance between localiser and glide-path transmitters.

The effective aircraft to beam gearing (i.e. correcting signal to aircraft/linear displacement from beam centre line) will be inversely proportional to distance from the beam origin and at a given distance from the beam origin will be inversely proportional to beam width. The distance effect on gearing is of course inherent in the angular system used and even assuming that all beams are identical the auto-pilot system will always have a large gearing variation to contend with as it proceeds down the beam. In general auto-pilot systems appear to have coped with this effect but trouble has been experienced on one particular aircraft. It is considered that in order to make sure that a system has the best compromise auto-pilot gearing settings and that no difficulties will be experienced on beams having extreme width characteristics, then tests should be made covering the width tolerances allowable. The break-off and turn-on regions are probably the most critical from a gearing point of view and at these approximate ranges Table 1 shows the maximum effective gearing change possible in going from three hypothetical test beams to any other installation and also to some actual installations. The test beams assumed have a glide-path to localiser transmitter distance of 9,900 ft. as at A. & A.E.E. Three angular widths, covering the allowable range, have been given as the widths will vary from time to time when the beam is re-aligned.

/Table 3(A)...

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*Difference in depth of modulation of two tones. See Ref. 1.

The angle or distance on either side of the equal signal plane at which a signal of 150 micro amps is recorded is termed the "beam width". It will be appreciated that the "beam" referred to is hypothetical and is in fact made up of two overlapping radio beams in order to obtain the required characteristics.

Table 3(A) gives the characteristics of R.A.F.-I.L.S. installations as measured in 1959 and Table 3(B) gives the characteristics of some other aerodromes. It will be seen from these Tables and Table 1 that practical installations are likely to cover the whole range of allowable widths and in some cases actually go outside the limits. In testing auto-I.L.S. performance it will thus be necessary to fly the system either on beams having extreme characteristics, if these are known, or else on a test beam having known characteristics with the auto-pilot to beam signal gearing values scaled up and down to simulate the extremes which can be encountered. The gearing changes necessary can be calculated from Fig. 2(B). As beams having the required widths are not always available and on some aircraft it may not be practicable to vary the auto-pilot gearings, it is convenient to have a calibrated test beam which can be adjusted to give the required extreme characteristics.

In general it will be necessary to make flight tests on "offset" as well as "in-line" localiser installations; in particular it is thought that some of the present offset angles in use may introduce course correction difficulties in the break-off region, especially on the higher speed aircraft.

The beam centre line may be somewhat erratic on some installations, due possibly to reflections from various ground objects, and on systems which are rate stabilised from the I.L.S. beam signal this effect may be serious. On this type of system the effect of beams known to be adverse in this respect must be assessed.

2.1.2 Beam safety cut-out requirements. The following are the requirements for alarms to operate and the beam to go off the air:

(1) Shift of the course line by more than 1/3°.
(2) Reduction of power output by more than 50%.
(3) Change in beam width of more than 20%.

Beam variations may be due to variations in the ground equipment performance or possibly fault conditions. The actual amounts of shift likely to be experienced in general operation are not known, but it is conceivable that the beam may be operating anywhere within the cut-out limits. Variation in course line will have obvious effects on the aircraft approach path, change of power output should not appreciably affect the approach performance, but the beam range will be reduced, and change in beam width will have a direct effect on the aircraft to beam gearing.

In order to cater for possible variations in Service use, it is considered that, when testing, some additional bank-to-localiser gearing change should be made to allow for this factor.

In assessing A.A.L. height the possibility of a course line shift should also be considered.

2.2 Glide Path

2.2.1 Setting-up requirements. The following are the main beam requirements affecting performance testing as given in A.P.2828.H.

(i) The glide-path angle should be 3 degrees. The limits are 2.9 to 3.1°.

(ii) The preferred angular widths for 17.5% D.D.M. (150 μa) are:-

(a) above beam centre line, .15 x beam angle. The limits are .11 to .19 x beam angle,

and (b) below beam centre line, .25 x beam angle. The limits are .11 to .33 x beam angle.

/The...

The effect of variation in basic beam angle in the range 2.9 to 3.1° should not appreciably affect the performance. Although not mentioned in AP.2888.H, the I.C.A.O. Specification permits a beam angle of up to 4° if the local terrain gives insufficient clearance with a 3° beam. In considering aircraft which may operate from civil bases it is possible therefore that a 4° beam may be encountered and on auto-pilot systems having variable gearing, on a fixed time base, for the glide phase, this difference in angle is significant as the glide time will be reduced considerably. Engine response also may be more critical and in the case of systems having an auto-throttle facility it may be necessary to check if the throttle servo has adequate authority. It is thought however that there are no 4° beams at present in existence.

Variation of beam angular depth will affect the effective aircraft to beam gearing as for the localiser and Table 2 shows the gearing variations possible for given test beam characteristics. It will be seen that the possible gearing variations are very large and that, as for the localiser installations, the measured values at actual R.A.F. installations appear to suggest that the whole range of allowable widths may well be encountered in practice. It would thus appear essential to fly on beams having known extreme characteristics or else to make the appropriate gearing modifications on a test beam of known characteristics.

2.2.2 <u>Beam safety cut-out requirements</u>. The following are the requirements for alarms to operate and the beam to go off the air:

(1) Shift of the course line by more than .1 x beam angle.
(2) Reduction of power output by more than 50%.
(3) Change in beam width of more than 10%.

The effect of a glide-path angle variation should be considered in relation to time-variable glide path gearing systems, also engine response and the authority of auto-throttle systems.

As in the case of the localiser it is considered that a further gearing change should be made in order to allow for possible variations in the beam width within the cut-out limits.

2.3 <u>Other I.L.S. features affecting performance testing</u>

2.3.1 <u>I.L.S. receiver calibration</u>. Due to variation in standards of modulation depth it is difficult to calibrate the receiver equipment accurately and this fact together with setting up errors results in different aircraft, on a given beam, giving considerably different signal outputs at a given beam position. Table 4 gives figures obtained from tests at B.I.A.E.U. on Service equipment and the order of the errors can be seen from columns 4, 5 and 6. New equipment is being developed to improve the standard of measurement, but it is suggested that allowance should be made for a possible further ±35% localiser gearing variation, when testing, in order to cover this aspect until the new equipment is available. A possible localiser centre line error of ±0.2 degrees should also be taken into account when assessing the A.A.L. height. The effect on the glide path signal is not thought to be very large.

2.3.2 <u>Aerial position on aircraft</u>. On large aircraft where the aerial is a long way from the aircraft centre line the aircraft will have a standing error off the beam centre line. This error should not exceed the distance from the aerial to the aircraft centre line and it is thought that in some cases it will be less, as it appears that the effective beam receiving position is sometimes inboard of the actual aerial position. This factor should be taken into account when assessing the A.A.L. height but it will of course be included if the offset distance from the runway centre line is measured by photographing the approaches.

/3...

3. Recommended test procedure

Each system must be treated on its own particular merits and appropriate features examined in detail, but it is thought that the following programme will cover most of the important aspects which should be examined at some stage.

3.1 Instrumentation

A trace recorder should be fitted in the aircraft and a pilot operated event marker included. A paper speed of about 5 mm/sec. is suitable. The following minimum number of quantities should be recorded and the approximate sensitivities required are given in brackets.

Airspeed (± 1 kt), height (± 5 ft.), normal acceleration (±.05g), I.L.S. signals (± 2 μa), throttle position (± 1%), angle of bank (± $\frac{1}{4}$°), angle of pitch (± $\frac{1}{8}$°), aileron angle (±.2°) and elevator angle (±.1°).

The bank and pitch angular sensitivities quoted are only required for assessing short period oscillations and it is not necessary for the long term datums to be held accurately.

A ground camera system should be available for calibrating the test aircraft and beam combination as indicated in para. 3.3.18.

If possible a radio link facility should be incorporated to record the Marker signals and event mark the aircraft trace record in conjunction with the ground cameras when in use.

3.2 Initial look

In an auto-I.L.S. approach a typical procedure is for the pilot to engage the auto-pilot on the downwind leg of a G.C.A. type of circuit. Max. lift flap and undercarriage down are also selected manually on this leg and at a range of about 8 to 10 miles from the runway, with an offset of some 4 miles, the aircraft is turned onto the base or crosswind leg using the auto-pilot turn controller. When about 1 or 2 miles from the extended runway centre line the pilot, having set up the runway heading corrected for drift on the heading selector, manually selects 'track'. The auto-pilot in response to heading and localiser error signals then turns the aircraft onto the extended runway centre line. The pilot selects max. flap at some convenient stage of the final approach and at about 5 miles range from touchdown, when the I.L.S. glide-path pointer approaches the centre position, he selects 'glide'. The auto-pilot in response to a 3 degree nose down signal and any I.L.S. error signal from the glide-path centre plane then flies the aircraft down the glide-path. If no auto-throttle facility is incorporated then some manual throttle adjustment may be necessary to maintain the right order of speed. At some height, usually between 200 and 300 ft., the auto-pilot is disengaged and manual corrections made to line the aircraft up with the runway, and land.

In the initial tests flights should be made using the optimum procedure as recommended by the Firm on a normal G.C.A. type circuit at 1,500 ft., engaging track at approximately 90° to the beam, 1-2 miles offset and about 8-10 miles from touchdown. The following features should be noted.

3.2.1 In circuit. Ease and speed of engaging and disengaging the auto-pilot system, speed and height holding, ability to hold trim changes due to lowering flaps and undercarriage, residual oscillations, turn controller response and authority, also any tendency for the auto-pilot to trip out if appropriate.

3.2.2 Track phase. Turn response, speed and height holding, ability to stabilise on the beam before the glide phase, ease of breaking off approach and returning to circuit.

/3.2.3...

3.2.3 Glide Phase. Response to glide selection, ability to stabilise quickly on the beam, speed and beam holding in track and glide (in particular the onset of any aircraft/beam oscillations), the azimuth and height of the aircraft relative to the beam and the runway at break-off; the ease of disengaging the auto-pilot and the out-of-trim likely to be encountered if the auto-pilot is cut out or cuts out at any stage of the approach. The minimum height from which a satisfactory overshoot can be made should also be assessed.

3.2.4 Preliminary criteria for satisfactory performance in reasonably smooth air

(I) Circuit

Speed ± 3 kts. Max. bank response about 10°/sec.
Height ± 50 ft. Bank authority ± 30°.

(II) Track

Speed ± 3 kts. Max. bank response about 10°/sec.
Height ± 50 ft. and ± 100 ft. in turn on. Localiser within ± 1 dot at 1 mile before glide (no cross wind component) and held afterwards down to at least 200 ft. A.G.L.

(III) Glide

Speed ± 3 kts. Glide within ± 2 dots after losing 500 ft. height and held afterwards down to at least 200 ft. A.G.L. No oscillations of amplitude greater than ± 2° in pitch angle.

3.3 Detailed assessment

If the performance is considered to be satisfactory using the recommended procedure and the criteria given in 3.2.4 then the effect of the following parameters should be assessed where appropriate.

3.3.1 Speed. The approach speed should be varied by approximately 5 kts either side of the optimum.

3.3.2 Weight, centre of gravity and configuration. These parameters should be varied over the appropriate ranges for the approach. This assessment should include the effect of external stores, selecting flaps and dive brakes, if appropriate, at conditions either side of the optimum time and also the effect of having no flaps (or other high-lift devices) or air brakes operational.

3.3.3 Aircraft to beam displacement gearing. Tolerances on beam width, manufacture, power supplies, atmospheric conditions and the I.L.S. receiver calibration will all affect the value of this parameter. It is considered that the overall gearing values on both localiser and glide path should be varied in some way in order to assess the effect of these tolerances. The amounts the overall gearings should be varied are deduced in the following estimates:

(I) Localiser

(a) Beam width effect

Knowing the test beam characteristics it is assumed that the gearing variations will be most important in the A.A.L. height region (i.e. around 4750 ft. range from the glide path transmitter). The width limits at this range are 400 to 650 ft. and hence if the test beam width is w ft. the possible gearing changes in going to these limits are:

/(1)...

(1) A gearing increase of $\left(\frac{W}{400} - 1\right) 100 = W_1\%$

(2) A gearing decrease of $\left(1 - \frac{W}{650}\right) 100 = W_2\%$

There is also the possibility of a ± 20% variation in gearing due to beam fluctuations. (See para. 2.1.2.)

(b) Specification tolerances in auto-pilot system

This should include the effect of manufacturing, power supply and atmospheric variations. It is assumed that values are available from the manufacturers, say for 95% of auto-pilots the combined effect on the bank angle to localiser signal gearing is within $\pm S_A\%$. The test aircraft gearing should be found from a ground calibration and the error from the nominal setting is assumed to be $t_A\%$.

(c) I.L.S. Receiver calibration errors

The R.A.E. Bedford tests indicate that 95% of receivers will probably have an error within ± 33%. The test aircraft receiver should be calibrated accurately and it's error is assumed to be r%.

(d) Combined effect of (a), (b) and (c)

In allowing for the combined effect of these tolerances it is considered that the possibility of operating on any beam should be included and that the full beam width tolerances should be taken into account. However it is assumed that the probability of encountering a beam at one of it's limits together with the other tolerances at their limits is small. As a practical compromise it is considered that the following overall changes should be made to the initial test gearing.

(1) An increase of $\left[W_1 + \sqrt{20^2 + S_A^2 + 33^2} - (t_A + r)\right]\%$

(2) A decrease of $\left[W_2 + \sqrt{20^2 + S_A^2 + 33^2} + (t_A + r)\right]\%$

t_A and r are taken as positive if the errors tend to increase the overall gearing. If it is not practicable to measure these values then reasonable gearing changes to make are considered to be:

(1) An increase of $\left[W_1 + \sqrt{1490 + S_A^2} + \sqrt{33^2 + S_A^2}\right]$

(2) A decrease of $\left[W_2 + \sqrt{1490 + S_A^2} + \sqrt{33^2 + S_A^2}\right]$

It is however highly desirable to measure t_A and r, as in order to obtain a reasonable degree of confidence in the test results from one or two aircraft, the gearing change required will otherwise be excessive in one direction and may produce unacceptable results which are not representative.

The overall gearing variation can be obtained by assuming a linear auto-pilot gearing calibration and making the appropriate percentage changes to the initial test nominal value. If the total gearing changes are not easily obtained by adjusting the auto-pilot, then part of the required gearing changes can be achieved by operating the test beam at it's limits, thus reducing the required changes by W_1 and W_2 in the two cases respectively.

/It...

It should be noted that in combining the tolerances in the manners indicated it is intended that the overall gearing limits obtained should represent the values which are not likely to be exceeded in the order of 95% of cases, when operating on a beam at it's 95% limits. The method of combination is not strictly valid, but with the actual valuesof the tolerances likely to be encountered it is considered that the order of probability obtained is reasonable for this type of approach, where although extremely undesirable, the pilot can in most cases decide to go round again if the conditions at break-off are too adverse to make a successful landing.

(II) Glide Path

(a) Beam width effect

In this case the beam width at all ranges from the glide path transmitter is proportional to the beam angle and the width limits are .11θ to .19θ above the beam centre line and .11θ to .33θ below the beam centre line, where θ is the angle of the beam centre line. If the test beam width is α_1 above the centre line and α_2 below then the possible gearing changes in going to the limits are:

(1) A gearing increase of $\left(\frac{\alpha 1}{.11\theta} - 1\right)100 = W_{A1}\%$ above the ℄

and $\left(\frac{\alpha 2}{.11\theta} - 1\right)100 = W_{B1}\%$ below the ℄

and (2) A gearing decrease of $\left(1 - \frac{\alpha 1}{.19\theta}\right)100 = W_{A2}\%$ above the ℄

and $\left(1 - \frac{\alpha 2}{.33\theta}\right)100 = W_{B2}\%$ below the ℄

There is also the possibility of a ±20% variation in gearing due to beam fluctuations.

(b) Specification tolerances

These should be obtained as for the localiser case but appropriate to the pitch gearing. Say 95% of auto-pilots are within ± S_E% and that the test aircraft has an error of t_E%.

(c) I.L.S. Receiver

This effect is assumed to be negligible.

In order to flight test the effect of the variations in gearing, the best method, because of the unsymmetrical width limits, is to use a variable beam which can be put to its appropriate limits for the above and below centre line cases. In addition allowance for the effect of fluctuations and specification tolerances should be made by increasing the auto-pilot gearing by $[\sqrt{400 + S_E^2} - t_E]\%$ and reducing it by $[\sqrt{400 + S_E^2} + t_E]\%$ of the nominal setting in a similar way to the localiser tests.

If it is not practicable to vary the test beam in this way then flight tests should be made with auto-pilot gearing values

(1) Increased by $[W_1 + \sqrt{400 + S_E^2} - t_E]\%$

and (2) Reduced by $[W_2 + \sqrt{400 + S_E^2} + t_E]\%$ of the nominal gearing.

/W_1 should...

W_1 should be taken as the greater of the W_{A1} and W_{B1} values and W_2 the greater of the W_{A2} and W_{B2} values. This will give a pessimistic view, as the actual beam limits are unsymmetrical, and wherever possible a test beam having the desired extreme characteristics should be used.

If t_E is not known it should be taken as $\pm S_E$ in the most adverse sense. Whenever possible the actual value of t_E should be assessed.

3.3.4 Circuit pattern. The circuit height should be varied between 1,000 and 2,000 ft. with appropriate variation in the upwind distance at which the track turn-on phase is made. The minimum value of this distance should be ascertained making the track selection at several angles to the beam centre line between 0 and 175°. Both left and right hand circuits should be tried. The ability of the auto-pilot system to change circuit height from straight and level flight and after a turn should also be checked.

3.3.5 Disturbances to the I.L.S. signals. The response to some disturbances will usually be noted in the general flying as other aircraft fly across the beam. If this is not considered sufficient a point should be made of checking the effect of other aircraft.

3.3.6 Wind. The effect on the turn-on performance of the highest possible cross wind speeds up to 35 kts should be assessed and also the effect of similar strength, tail and head winds, on the glide performance.

3.3.7 Wrong heading selection. With heading stabilised systems the effect of $\pm$ 10° wrong heading selection should be tried in order to check the effect of setting up the wrong wind correction. On a normal system $\pm$ 10° should produce the order of $\pm$ 1 dot error in track.

3.3.8 Erratic beam centre line. With systems which are rate stabilised from the I.L.S. signals a point should be made of flying on installations which are known to be adverse in this respect.

3.3.9 Glide selection. This should be tried, say 2 to 3 dots either side of the optimum position, in order to check how well the aircraft damps onto the glide path when initially displaced.

3.3.10 Throttle adjustment. The sensitivity of the beam hold to reasonable throttle adjustments should be checked if no auto-throttle is incorporated.

3.3.11 Offset localiser. As so many offset localiser installations are in general use it is considered that the suitability of the system to cater for typical beam intercept angles must be checked by flying on an appropriate beam.

3.3.12 One engine out. If appropriate the effect of one engine out should be assessed.

3.3.13 Power control failure. The possible effects of a power control system failure should be considered when appropriate.

3.3.14 4° Glide Path. Tests should be made on a 4° glide path if this is likely to be encountered.

3.3.15 Malfunctions. These should be checked as in other flight cases for appreciation plus reaction times of up to 2 secs. In particular, height loss in rolling and pitching manoeuvres and nearness to pre-stall effects should be measured. It is felt that 2 secs. is possibly too long for aircraft having high response rates (especially in a pitching sense), but it is considered that tests should be made or assessed for this period of time about all axes and the risk determined on this basis until a better method can be devised.

/3.3.16...

3.3.16 Turbulence and bad visibility. If the general performance is satisfactory then checks should be made, on the optimum and any marginal cases, of the effect of turbulence (up to No. 6 approx.) and every effort made to gain experience in bad visibility conditions.

3.3.17 Aircraft characteristics. In order to assess the "Aircraft Approach Limitation" height it is considered that at some stage of the flight testing, tests should be made to determine the maximum angle of bank and rate of roll likely to be used in a sidestep manoeuvre at about 200 ft. height. The normal acceleration used in flaring should also be determined.

3.1.18 Number of tests under each condition. It is extremely difficult to be precise in this respect and the number required will to a large extent depend on how the initial flying progresses. In rough figures, on a new system it is considered that a minimum of about 50 approaches should be made and of these about 15 should be in the finalised normal approach condition and about 20 with the most adverse gearings. It is important in these tests to cover as large a range of weather conditions as possible. In order to check if there are any appreciable effect due to other variables at least 3 approaches should be made in each of the appropriate conditions. If a particular variable appears to be significant then further tests will of course be required if a realistic value for the magnitude of the effect is to be obtained.

One flight should be made to calibrate the aircraft/beam combination at the time of testing. This flight should be photographed from the ground and should consist of about 5 manual I.L.S. approaches; the first should attempt to hold both beam centre planes and the others should hold some 4 to 5 dots on each side of the localiser and glide path centre planes in turn. In this way if the I.L.S. signals are assumed to be linear, this calibration can be used on other flights on the same beam to give a reasonable idea of the aircraft displacements, both from the beam centre planes and the runway, if the range is obtained by reference to the Middle and Outer Marker signals recorded on the trace in the aircraft.

4. Estimation of "Aircraft Approach Limitation" (A.A.L.)

4.1 General

In order to estimate the minimum safe height to which the aircraft can be allowed to descend under non-visual conditions it is assumed that the following criteria must be satisfied:

(a) At this height the pilot must be able to appreciate his position relative to the runway.

(b) In the order of 95% of approaches the aircraft must be in a position such that it's vertical and lateral displacements and track from the ideal approach path can be corrected with enough height left to flare onto the runway.

(c) The aircraft must be capable of making an overshoot from this height if the pilot considers this necessary.

In order to satisfy (a) it is stipulated that at the A.A.L. the visibility must be such that a minimum of two cross bars of the Calvert ground lighting system can be seen. In estimating the A.A.L. a time of 2 secs is allowed for the pilot to appreciate his position.

4.2 Vertical criteria

In order to satisfy (b) the vertical and lateral cases are considered separately. In the vertical plane a displacement or tracking error from the

/Glide...

glide path centre plane will if uncorrected, or not fully corrected, affect the actual touch down point and the allowable error will depend on the length of runway available and the position of the nominal touch down point (i.e. G.P. Tx position). Reasonable general criteria are considered to be that when the A.A.L. is reached the aircraft should be not more than $\pm \frac{1}{4}^{\circ}$ away from the beam centre line and should be on an instantaneous flight path inclined at not more than $\pm 1^{\circ}$ to the beam centre line.

The other consideration in the vertical plane is the vertical velocity at touch down. A reasonable value for this is considered to be 2 ft./sec. and on this basis Fig. 3 gives the height which must be allowed for flaring from a 3° approach. The curves are based on the assumption that the speed and normal acceleration are constant during the manoeuvre. The mean speed used during the flare is assumed to be less than the approach speed and the methods used for calculating both the flare speed and the height required for flaring are given in Appendix I. The value of normal acceleration used during the flare will depend on the aircraft type, however if no information is available a typical value for aircraft other than Naval types is about 1.03g. As the instantaneous flight path at the A.A.L. is assumed to be acceptable up to 4° it might be thought necessary to check that the flare is possible from this angle in the available height. It will be found however that in general the time which must be allowed for lateral correction is more than adequate for the necessary adjustment in glide path to be made at the same time as the lateral manoeuvre and this technique is assumed to be used.

4.3 Lateral criteria

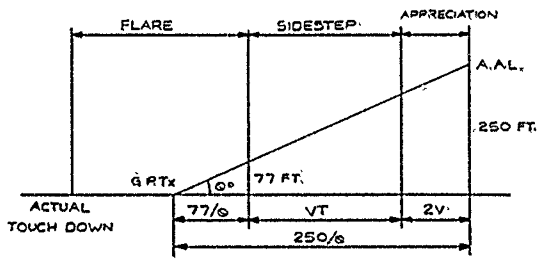
In the lateral plane any offset or tracking error may require correction to enable the aircraft to touch down on the runway and in Appendix II a method is given for estimating the time required to correct the approach path, assuming that the initial conditions are given together with values for the maximum usable angle of bank and rate of roll. The results are given in Figs. 4 and 5 for zero and 5° tracking errors and the figures can be used to plot boundary curves of sidestep distance at a given height on the approach. The method of use is probably best illustrated by the following example:

Ex. Draw the lateral manoeuvre boundary curve for 250 ft. true height, on a 3° approach path, for an aircraft having the following characteristics:

Approach speed 140 kts, maximum angle of bank 15°, maximum rate of roll 12°/sec., mean normal acceleration in flare 1.03g and the tracking error will not exceed 5°. Assume also that the pilot appreciation time is 2 secs, that the aircraft must touch the runway within $\pm$ 25 ft. of the runway centre line and that an allowance should be made for a tail wind of up to 10 kts.

As a tail wind of up to 10 kts may be present the times available for flare and sidestep will be estimated using a true speed of 150 kts.

On this basis from Fig. 3 the height required for flare is 77 ft.



The time available for the sidestep manoeuvre is:

$$T = \left[\frac{(250 - 77)}{\frac{3\pi}{180} \times 150 \times 1.69}\right]^{-2} = 11 \text{ secs.}$$

From Fig. 4

$y6$ = +165 ft. for zero tracking error ($\psi_o = 0$)

Boundary points are $\pm$ (165 + 25) = $\pm$ 190 ft.

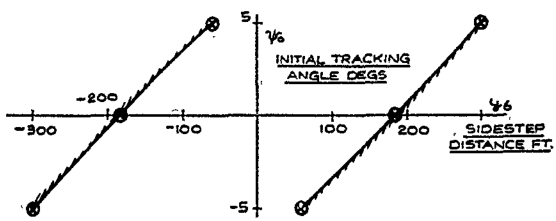
From Fig. 5B

$y6$ = +275 ft. and -30 ft. for 5° tracking error ($\psi_o = +5^{\circ}$)

Boundary points are +275 + 25 and -30 - 25
i.e. +300 ft. and -55 ft. for $\psi_o = +5^{\circ}$

For $\psi_o = -5^{\circ}$ there will be two other points which are numerically the same as for $\psi_o = +5^{\circ}$ but with the opposite sign i.e. -300 ft. and +55 ft.

The lateral boundary curve can now be drawn as shown below:



In the example a figure of $\pm$ 25 ft. from the runway centre line is used as the lateral touch down criterion. This figure is rather arbitrary and will depend on the width of runway available as well as the wheel track of the particular aircraft concerned. If 50 yard runways are to be used then for large aircraft this seems to be a reasonable figure.

Approach speed variations and tail wind will affect the boundary curves calculated in this way and it is considered that 10 kts should be added to the nominal approach speed in order to allow for these effects as indicated in the example.

In order to estimate the A.A.L., boundary curves should be drawn for several heights in the expected A.A.L. height region. Points obtained from the test results should be plotted at each of these heights and the A.A.L. height for the particular system determined as the height at which the boundary curve contains 95% of the test points, providing the vertical and overshoot criteria are also satisfied at this height. The value of height is also subject to the visibility requirement being satisfied on an actual approach. In obtaining the appropriate test points to plot in this way the following features should be noted:

/(a)...

(a) Localiser gearing variations

The results from all tests made with adverse gearings should be included in the plots. If it is not practicable to make the full gearing change required to simulate adverse gearing tolerances then an estimate can be made, from the flight tests, of the effect of the partial gearing variation providing the gearing change possible is at least of the order of 50% of the total change required. An allowance for the full gearing change should then be made by plotting the nominal gearing-value test results scaled-up assuming the gearing effect on offset distance and track to be inversely proportional to the gearing values plus a constant i.e.

$$\left[\text{Offset distance} = \left(\frac{k1}{G} + k2\right)\right]$$

If only a small variation of gearing or none at all is possible then as a very rough first order approximation the offset distances and track angles obtained from the nominal test results should be scaled-up as the inverse of total gearing reduction required i.e.

$$\left[\text{Offset distance} = \frac{k}{G}\right]$$

This latter procedure is very undesirable and should only be used as a last resort.

(b) Offset aerial on aircraft

If no information is available on the possible effect of this feature then in estimating aircraft position from localiser signals in the aircraft, on a beam installation which has been calibrated but not by the particular test aircraft, the effect of the offset from the aircraft centre line (l) ft should be included in the estimates by assuming that the signal appears to be received at the actual aerial position.

(c) Localiser receiver calibration error

As for (b) when estimating aircraft position on a beam installation on which the test aircraft has not been calibrated, an allowance for the effect of the localiser receiver error (β degrees) should also be included.

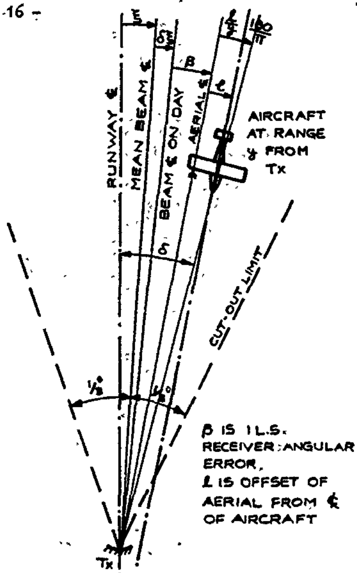
An additional consideration is that the B.L.E.U. tests indicate that in 5% of cases the probable error on the effective centre line position will be outside $\pm$ 0.2 degrees. In order to allow for the possibility of having receiver errors of this order of magnitude in Service use, it is considered that an allowance for an error of (0.2 - β) degrees should be made on all the test results. The allowance for this effect when combined with other similar effects is given in para. (f).

(d) Wrong heading selection

The tests using a 10° wrong heading selection should not be included in the plots directly but the effect of a 2° heading error should be deduced from these results. Because of the difficulty of estimating wind accurately, a factor which may not be brought out adequately by a limited number of tests, it is considered that an allowance should be made for the effect of this 2° heading selection error on all the test results as indicated in para. (f). The effect on tracking angle is assumed to be (γ) degrees.

/(e)...

(e) Localiser centre line error



The beam centre line position may not lie along the runway centre line, due to initial setting up errors or variations with time, due possibly to variation in the ground equipment performance or a fault condition. The centre line is restricted by a monitoring system to roughly $\pm \frac{1}{3}$ degree from the nominal centre position, which is assumed to be at a mean value of ξ degrees from the runway centre line. This position is determined by a specially calibrated aircraft making a series of runs over a reasonable period of time. As aircraft position in the auto-I.L.S. trials will in general be estimated from a limited number of calibration runs made on one flight with the particular aircraft under test, this calibration may give a beam centre line, as shown in the sketch, at an angle of $(\xi + \delta\xi)$ degrees to the runway. There is thus the possibility of error in the estimates of offset distance and track based on this latter calibration as $\delta\xi$ and consequently δ may have varied during the overall test period. In addition the value of ξ will depend on the particular installation and some account should be taken of this in assessing the likely offsets in Service use. Although no evidence is available it is thought that the value of $(\xi + \delta\xi)$ is in general unlikely to exceed the order of $\pm \frac{1}{3}$ degree, although a larger error is possible due to initial misalignment with either ground equipment variations, or fault conditions. These effects could also conceivably be increased by tolerances in the cut-out system. On this assumption it is considered reasonable to make allowance for a centre line error of up to $(\frac{1}{3} - \xi - \delta\xi)$ degrees i.e.

$$\left[\frac{1}{3} - \left(\delta - \beta - \frac{1}{y}\frac{180}{\Pi}\right)\right] \text{ degrees, when plotting all the test results.}$$

The allowance should be made as indicated in (f).

(f) Overall allowance for effects of (c), (d) and (e)

It is considered that a reasonable overall allowance for these effects is to add an offset distance and track angle, to all the test results to be plotted, appropriate to a centre line error of:

$$\left[\sqrt{(\gamma)^2 + (\tfrac{1}{3})^2 + (.2)^2} - \left(\delta - \beta - \frac{1}{y}\frac{180}{\Pi} + \beta\right)\right] \text{ degrees}$$

This simplifies to:

$$\left[\sqrt{(\gamma)^2 + .15} - \left(\delta - \frac{1}{y}\frac{180}{\Pi}\right)\right] \text{ degrees}$$

where γ is the tracking error in degrees due to a 2° heading selector error.

/8..

δ is the apparent beam centre line, in degrees from the runway heading, at a range of y ft. from the localiser Tx. This value is obtained from the test aircraft calibration.

l is the offset of the localiser aerial from the aircraft centre line in ft.

Care should be taken when plotting the results to ensure that a common sign convention is used throughout.

(g) Offset Localiser

In order to cater for the worst offset angle likely to be met in practice, it is considered that in addition to plotting the "In line" localiser results, a separate plot should be made with these results modified to simulate results which would be obtained on a 5 degree offset beam. This is assumed to be achieved by adding the offset distance and track angle appropriate to the 5 degree offset centre line at the range required. Actual results from "Offset" installations can also be plotted directly when corrected as indicated in (a), (b), (c) and (f) for the "In-line" results.

In order to include these test results it will be necessary to extrapolate the lateral boundary curves for tracking angles of up to some 7 to 8 degrees. The extrapolation will in general be satisfactory up to these angles, but if this is not adequate to include all the test points it may be desirable to use the method in Appendix II in order to extend the boundary curves for larger values of tracking angle.

The A.A.L. height should be computed from the most adverse of the "In-line" and the "Offset" plots.

4.4 Malfunction criteria

In general malfunction tests have been made at A. & A.E.E. in order to ascertain at what height a malfunction could be dangerous, and not to modify possibly the value of A.A.L. determined by the vertical and lateral criteria. On most aircraft tested every effort has been made to keep the height loss as small as possible by the incorporation of safety cut-out devices and usually, even allowing a 100% margin, the value of height loss obtained from tests would not have dictated any increase in A.A.L. if this had been an additional criterion. When the height loss has been critical this factor has been stated in the terms of the Release, but it is felt that the chance of a failure in the final stage of the approach is not high enough in general to justify an increase in A.A.L. value, which in itself could increase the accident risk by increasing the "diversion" rate with more chance of running out of fuel.

5. Conclusions

The method of testing indicated in this report is intended to give an A.A.L. value which is adequate on performance grounds for 95% of the aircraft type, operating on any ground installation which is normally within the setting up limits. The criterion used in determining the A.A.L. value is, that any of the 95% aircraft should have not less than the order of a 95% chance of making a successful approach on any one of those installations.

This criterion may be thought to be too adverse as the overall chance of having a 1 in 20 aircraft operating on a beam at it's limits is by itself small. However as there will in general be a small number of the aircraft type involved and these aircraft may operate on an adverse installation over a considerable period of time it is difficult to make an overall statistical assessment and the criterion used is considered reasonable.

/In...

In the past A.A.L. heights have been assessed without taking as much account of the effect of system tolerances and consequently it is possible that some of the previous A.A.L. heights quoted would appear to be on the low side if the suggested method had been used. In marginal weather conditions a low value of A.A.L. is likely to reduce the frequency of diversion but will probably increase the frequency of overshooting due to adverse performance. On slant visibility grounds the relationship between overshooting and the value of A.A.L. is not obvious because of the difficulty of relating slant visibility to the cloud base. As there is little operational data available it is impossible to assess whether or not the present A.A.L. values in use do in fact give the right order of compromise between diversion and overshooting.

It is considered that the test technique given in this report will give an A.A.L. value which is satisfactory on performance grounds and only a systematic assessment of actual operational experience will show whether or not the value should be modified to give a better compromise.

References

Ref. No.	Author	Title, etc.
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Table 1

Gearing variations possible due to tolerances allowed in setting up the Localiser beam

Test Beam Characteristics				
Glide path transmitter to localiser transmitter distance 9900 ft.				
Beam angular width either side of ℄ degs.		2.0	2.25	2.5
% Increase from preferred width at 4750 ft. range		2	15	28
Actual width at 4750 ft. range	ft.	510	575	640
Actual width at 8 n.m. range	ft.	2040	2300	2550
Limits of effective % gearing change possible in going to any other beam, assuming that the beam widths are within the specified boundaries.	At 4750 ft.	+28 -22	+44 -12	+60 -2
	At 8 n.m.	+6 -31	+19 -22	+33 -13
Actual maximum % gearing change possible using stations having width characteristics as given in Table 3.	At 4750 ft.	+22 -23	+38 -13	+54 -3
	At 8 n.m.	+5 -32	+18 -24	+31 -15

Notes Gearing is defined as the signal to the aircraft control system per unit linear displacement from the beam centre line.

+ sign indicates a tighter gearing due to a narrower beam.

- sign indicates a slacker gearing due to a wider beam.

Table 2

Gearing variations possible due to tolerances allowed in setting up the Glide Path beam

		Test Beam Characteristics								
Beam ℄ angle degs		2.9			3.0			3.1		
		Min.	Opt.	Max.	Min.	Opt.	Max.	Min.	Opt.	Max.
Width above ℄ degs.		.32	.435	.55	.33	.45	.57	.34	.465	.59
Width below ℄ degs.		.32	.725	.96	.33	.75	.99	.34	.775	1.02
Limits of effective % gearing change possible in going to any other beam assuming that the beam widths are within the specified boundaries.	Above ℄	0 -46	+36 -26	+72 -7	+3 -44	+41 -24	+78 -3	+6 -42	+45 -21	+84 0
	Below ℄	0 -69	+126 -29	+200 -6	+3 -68	+134 -27	+209 -3	+6 -67	+143 -24	+219 0
Actual maximum % gearing change possible using stations having width characteristics as given in Table 3.	Above ℄	0 -47	+14 -28	+45 -9	0 -45	+18 -25	+50 -5	0 -43	+22 -23	+55 -2
	Below ℄	0 -64	+45 -19	+92 0	0 -63	+50 -16	+98 0	0 -62	+55 -13	+104 0

Notes Gearing is defined as the signal to the aircraft control system per unit linear displacement from the beam centre line.

\+ sign indicates a tighter gearing due to a narrower beam.

\- sign indicates a slacker gearing due to a wider beam.

Table 3(A)

I.L.S. Beam Characteristics for R.A.F. Stations (1959)

Station	Localiser to Glide Path Distance ft.	Localiser to Touch Down End of Runway ft.	Angle of Offset degs.	Localiser Beam Width degs.		% from Preferred Width		Glide Centr Angle
				Port	Stbd	500 ft. at 4,750 ft.	2,400 ft. at 8 n.m.	
						(Limits +30 -20)	(Limits +23 -21)	
Abingdon	5239	6239	3.7	2.83	2.8	-2	+11	3.
Acklington	5292	6557	3.6					
Aldergrove	-	-	-					
Ballykelly	4313	5328	4.16					
Bassingbourn	6964	7964	-	2.4	2.32	-3	-5	3.
Benson	6756	7756	-					
Binbrook	4510	5371	3.6	2.8	2.8	-10	+8	3.
Bruggen	6500	7540	3.06					
Coltishall	5780	6390	3.37					
Coningsby	9520	10520	-	2.18	2.2	+10	-8	3.
Cottesmore	9500	10500	-	2.2	2.21	+9	-7	2.
Dishforth	4262	5262	4.2	2.62	2.75	-15	+5	2.
Finningley	7850	8560	2.66	2.38	2.41	+5	-2	2.
Gaydon No.1	10010	11110	-	2.36	2.23	+19	-2	3.
Gaydon No.2	9980	10980	2.18					
Guilenkirchen	6234	7140	3.18					
Honington	10400	11200	-	2.5	2.23	+25	+1	2.
Kinloss	4607	5607	3.97					
Larbruch	8200	9208	3.4					
Leconfield	5270	6270	4.0					
Leeming	-	-	-					
Leuchars	6840	7840	2.47	2.5	2.33	-3	-3	2.
Lyneham	4576	5589	4.0					
Manston	9738	10988	-					
Marham	10169	11215	-	2.07	2.07	+8	-11	2.
Middleton St. George	5721	6721	3.42					
Scampton	6850	7850	2.96	2.7	2.7	+9	+9	2.
Shawbury	4937	5556	3.78					
Strubby	6340	7380	-					
St. Mawgan	9800	10800	-	2.58	2.58	+31	+10	3.
Thorney Island	6200	7260	3.18					
Upwood	3988	4988	4.4					
Valley	4680	5693	3.93					
Waddington	7385	8144	2.71	2.42	2.59	+5	+2	2.
Wattisham	4600	5612	3.98					
Watton	3499	4499	4.8	3.0	2.8	-18	+9	
West Malling	5800	6810	3.37					
West Raynham	-	-	-					
Wildenrath	6800	7798	2.65					
Wittering	10400	11500	-	2.37	2.3	+24	-1	3.
Wyton	5900	7022	3.32	2.56	2.32	-11	-5	2.

Notes: + sign indicates wider beam.
- sign indicates narrower beam

Table 3(A)

I.L.S. Beam Characteristics for R.A.F. Stations (1959)

...ide Centre ...gle θ	...er to Down of ... ft.	Angle of Offset degs.	Localiser Beam Width degs.		% from Preferred Width		Glide Path Centre Line Angle θ degs.	Glide Path Beam Width degs.		% from Preferred Width	
			Port	Stbd	500 ft. at 4,750 ft.	2,400 ft. at 8 n.m.		Above ℄	Below ℄	.15θ Above ℄	.25θ Below ℄
					(Limits +30 -20)	(Limits +23 -21)				(Limits +27 -27)	(Limits +32 -56)
3.07	39	3.7	2.83	2.8	-2	+11	3.07	.38	.61	-17	-21
	57	3.6									
	-	-									
	28	4.16									
3.0	64	-	2.4	2.32	-3	-5	3.0	.39	.64	-13	-15
	56	-									
3.0	71	3.6	2.8	2.8	-10	+8	3.0	.41	.64	-9	-15
	40	3.06									
	90	3.37									
3.0	20	-	2.18	2.2	+10	-8	3.0	.45	.83	0	+11
2.93	30	-	2.2	2.21	+9	-7	2.98	.52	.62	+16	-17
2.98	52	4.2	2.62	2.75	-15	+5	2.98	.53	.56	+19	-25
2.94	40	2.66	2.38	2.41	+5	-2	2.96	.42	.79	-5	+7
3.0	10	-	2.36	2.23	+19	-2	3.0	.42	.69	-7	-8
	80	2.18									
	40	3.18									
2.96	00	-	2.5	2.23	+25	+1	2.98	.50	.56	+12	-25
	07	3.97									
	08	3.4									
	70	4.0									
	-	-									
2.94	40	2.47	2.5	2.33	-3	-3	2.94	.44	.65	0	-12
	29	4.0									
	18	-									
2.9	15	-	2.07	2.07	+8	-11	2.9	.52	.89	+20	+23
	11	3.42									
2.94	40	2.96	2.7	2.7	+9	+9	2.94	.44	.65	0	-12
	16	3.78									
	10	-									
3.08	00	-	2.58	2.58	+31	+10	3.08	.49	.68	+6	-12
	10	3.18									
	18	4.4									
	13	3.93									
2.92	24	2.71	2.42	2.59	+5	+2	2.92	.47	.60	+[illegible]	-18
	12	3.98									
	19	4.8	3.0	2.8	-18	+9					
	10	3.37									
	-	-									
	18	2.65									
3.0	10	-	2.37	2.3	+24	-1	3.0	.60	.74	+33	-1
2.99	12	3.32	2.56	2.32	-11	-5	2.99	.38	.63	-15	-16

Notes: + sign indicates wider beam
- sign indicates narrower beam

Table 3(B)

I.L.S. Beam Characteristics for Miscellaneous Aerodromes (1960)

Aerodrome	Operator	Localiser to Glide Path Distance ft.	Localiser to Touch Down End of Runway ft.	Angle of Offset degs.	Localiser Beam Width degs.		% from Preferred Width		Glide P Centre Angle θ
					Port	Stbd	500 ft. at 4,750 ft.	2,400 ft. at 8 n.m.	
							(Limits +30 -20)	(Limits +23 -21)	
Boscombe Down	M.O.A.	9900	11400	-	2.0	2.25	+8	-10	3.1
Bedford	M.O.A.	10200		-	1.9	1.9	0	-19	-
Cranfield	College of Aeronautics	6200		-	2.4	2.4	-8	-4	2.8
Warton	English Electric	6600		2	3.1	3.1	+22	+24	-

Table 3(B)

T. L. S. Beam Characteristics for Miscellaneous Aerodromes (1960)

...e Path ...re Lan... ...θ deg	...iser to ...h Down ...d of ...ay ft.	Angle of Offset degs.	Localiser Beam Width degs.		% from Preferred Width		Glide Path Centre Line Angle θ degs.	Glide Path Beam Width degs.		% from Preferred Width	
			Port	Stbd	500 ft. at 4,750 ft.	2,400 ft. at 8 n.m.		Above ℄	Below ℄	.15θ Above ℄	.25θ Below ℄
					(Limits +30 -20)	(Limits +23 -21)				(Limits +27 -27)	(Limits +32 -56)
..1	400	-	2.0	2.25	+8	-10	3.1	.40	.70	-14	-10
-		-	1.9	1.9	0	-19	-	-	-	-	-
..8		-	2.4	2.4	-8	-4	2.8	.45	.50	+7	-29
-		2	3.1	3.1	+22	+24	-	-	-	-	-

Table 4

Results of Controlled Check of I.L.S. Localiser Receivers

Rx No. IDEAL	Station	Date Set Up	Input Signal = 1m Volt at 108.3 mc/s modulated 20% by 150 c/s and 20% by 90 c/s. Localiser Meter Current (μamps): Tone ratio 0dbs * 0	+4dbs 90	-4dbs 90	Remarks
796	Bedford	8.1.59	0	90	80	
966	"	7.1.59	-5	90	96	
H65	"	5.11.58	+5	83	72	
AN81	Bassingbourn	7.4.59	+5	100	95	Set up at Wyton
890	Wyton	7.4.59	+3	100	93	
AE56	"	10.4.59	+3	105	95	
AG10	Cottesmore	20.4.59	0	85	85	
AN10	"	"	-2	85	87	
892	Honnington	17.4.59	+2	125	120	)Checked on
AN26	"	"	+10	105	85	)20.4.59
631	Duxford	?	+3	105	95	) New Rxs Makers
D39	"	?	-5	105	115	) Seal Unbroken
AF1	Waterbeach	?	-5	95	105	? " "
A8	"	?	+13	103	75	
E91	Gaydon	1.1.59	-2	80	82	
1022	"	approx. 20.3.59	0	68	67	Set up at Cottesmore
AL54	Scampton	17.3.59	-8	105	118	)Checked on
AL55	"	"	-20	105	140	)17.4.59
H17	Wittering	? 3.59	+1	84	80	) Checked on
F85	"	"	+4	85	78	) 20.4.59
1263	Tangmere	17.4.59	+1	75	72	
A2(R 1964A)	"	20.4.59	-2	90	92	
968 "	"	16.4.59	0	78	78	
F91	Finningley	20.4.59	-1	90	89	)Checked on
AL57	"	"	-2	100	100	)20.4.59
AF22	Waddington	"	-7	126	112	
J84	"	"	+6	110	86	
E45	Binbrook	25.1.59	-3	84	88	
AA60	"	"	+2	88	80	
822	Watton	?	+5	109	93	
F44	Odiham	27.2.59	-12	70	88	
J19	"	4.2.59	-8	43	57	
AP5	Stradishall	?	+4	110	98	)Makers unbroken
AP21	"	?	+1	99	91	)seal

* (N.B. μAmps in this column are approx. equal to minutes of arc course error)

Appendix I

Method for Estimating Height Required for Flare

Assumptions

Given that the aircraft is initially on a 3° approach path and is required to touch down at 2 ft./sec. vertical velocity it is assumed that the normal acceleration during the manoeuvre is a known constant value. The speed during the manoeuvre is also assumed to be constant but less than the approach speed and the value used is obtained by taking a flight path deceleration of 0.1g at $n = 1.0$. This deceleration is assumed to be proportional to n over the range of values considered.

On these assumptions $V_A = V_{TD} + 0.1\,ngt$ where t is time for flare.

$$t = \frac{R(\theta - \theta_o)}{V_F} = \frac{V_F(\theta - \theta_o)}{(n-1)g}$$

hence $\dfrac{V_A}{V_{TD}} = 1 + \dfrac{0.1\,n\,V_F\,(\theta - \theta_o)}{(n-1)\,V_{TD}}$ and for $\theta = 3^\circ$

this gives
$$\frac{V_A}{V_{TD}} = \frac{1 + \dfrac{2.62 \times 10^{-3} n}{(n-1)}\left(1 - \dfrac{38.2}{V_{TD}}\right)}{1 - \dfrac{2.62 \times 10^{-3} n}{(n-1)}\left(1 - \dfrac{38.2}{V_{TD}}\right)}$$
where V_{TD} is expressed in ft./sec.

This expression is plotted in Fig. 1, Appendix I for values of n and the approach speed V_A.

The mean flare speed V_F is assumed to be given by

$$V_F = \frac{V_A + V_{TD}}{2}$$

and this can be obtained from Fig. 1.

Now $h = R \sin\theta \tan\theta/2 - R \sin\theta_o \tan\theta_o/2$

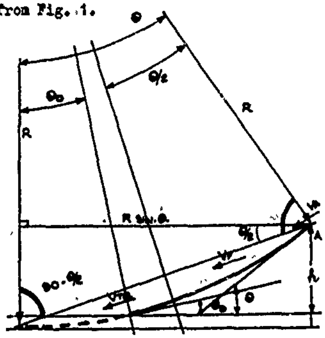
For small angles $h = \frac{R}{2}(\theta^2 - \theta_o^2)$

where $R = \dfrac{V_F^2}{(n-1)g}$ and $\theta_o = \dfrac{2}{V_{TD}}$

Hence for $\theta = 3^\circ$

$$h = \frac{V_F^2\left[\left(\frac{3\pi}{180}\right)^2 - \left(\frac{2}{V_{TD}}\right)^2\right]}{2g\,(n-1)}$$

$$h = \frac{V_F^2\left[1 - \left(\frac{38.2}{V_{TD}}\right)^2\right]}{23{,}500\,(n-1)}$$
ft. where V_F and V_{TD} are expressed in ft./sec.



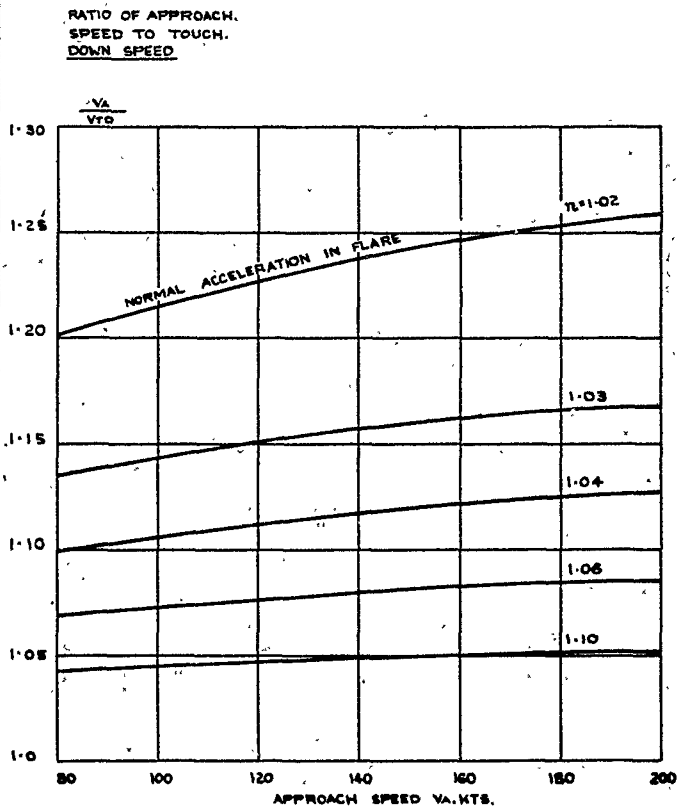
This expression is plotted in Fig. 3 for values of n and approach speed V_A.

APP. I. FIG. 1.

ASSUMPTIONS:

FLARE FROM 3° APPROACH TO 2 FT/SEC VERTICAL VELOCITY AT TOUCH DOWN. THE FLIGHT PATH IS ASSUMED TO BE A CIRCULAR ARC WITH CONSTANT MEAN SPEED $\frac{V_A + V_{TD}}{2}$ AND CONSTANT NORMAL ACCELERATION.

THE MEAN SPEED IS OBTAINED BY ASSUMING THE FLIGHT PATH DECELERATION AS 0·1g AT n=1·0 AND PROPORTIONAL TO n.



RATIO OF APPROACH SPEED TO TOUCH DOWN SPEED.

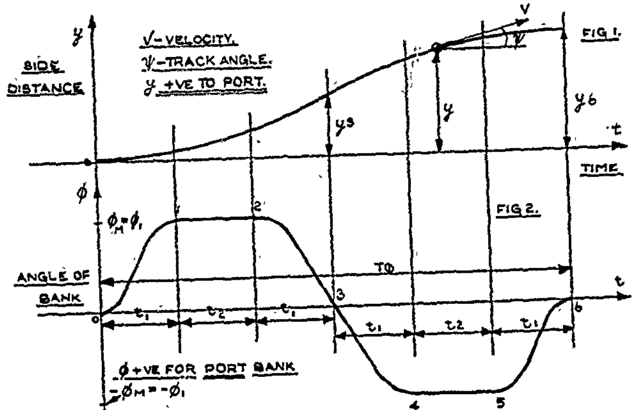
Appendix II

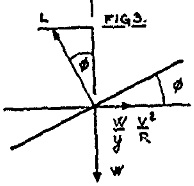
Method for Estimating Sidestep Distance

Assumptions

Given, the time to complete the manoeuvre (T), the maximum angle of bank (ϕ_M), the maximum rate of bank application (p_M), it is assumed that bank angle applications are sinusoidal with time up to the maximum values. (Assumed equal in port and starboard directions.) In all cases the maximum allowable rate of bank application is attained and if the time available is large the maximum bank angles are attained and maintained constant for some period depending on the total time available.

Case (1). No Tracking Angle at Start of Manoeuvre ($\psi_0 = 0$).





Assuming a correctly banked turn then:

$$\phi = \tan^{-1}\frac{1}{g}\frac{V^2}{R} \text{ if } \phi \text{ small } R \doteqdot \frac{V^2}{g\phi}$$

Tracking angle turned through in time $\delta t = \delta\psi$

$$\delta\psi = \omega\,\delta t = \frac{V}{R}\,\delta t = \frac{g\phi}{V}\,\delta t$$

In limit $\dot{\psi} = \frac{g\phi}{V}$ also $\dot{y} \doteqdot V\psi$ if ψ small

Hence $\ddot{y} \doteqdot g\phi$ (for ϕ & ψ small angles)

In Fig. 2 it is assumed that the bank application from 0 to 1 is given by:

$$\phi = \frac{\phi_1}{2} - \frac{\phi_1}{2} \cos \left(\frac{\pi}{t_1}\right) t \quad \text{-------------} (1)$$

where ϕ_1 may equal ϕ_M or may be less and where $\frac{\pi}{t_1} = a$

Hence from time 0 to 1

$$\ddot{y} = g\phi = \frac{g\phi_1}{2} \left(1 - \cos a\, t\right)$$

$$\dot{y} = \frac{g\phi_1}{2}\left(t - \frac{1}{a} \sin a\, t\right) + C_1$$

$$y = \frac{g\phi_1}{2}\left(\frac{t^2}{2} + \frac{1}{a^2} \cos a\, t\right) + C_1 t + C_2$$

$$\left.\begin{matrix} t = 0 \\ \dot{y} = 0 \end{matrix}\right\} C_1 = 0 \qquad \left.\begin{matrix} t = 0 \\ y = 0 \end{matrix}\right\} C_2 = -\frac{g\phi_1}{2a^2}$$

$$y_1 = \frac{g\phi_1}{2}\left(\frac{t_1^2}{2} - \frac{1}{a^2}\right) - \frac{g\phi_1}{2a^2}$$

$$y_1 = \frac{g\phi_1}{4}\left(t_1^2 - \frac{4t_1^2}{\pi^2}\right)$$

$$y_1 = .149\, g\phi_1\, t_1^2 \quad \text{-----------------} (2)$$

From time 1 to 2 $\phi = \phi_1$ is const $= \phi_M$, only applicable for cases where ϕ_M is attained in time available i.e. $t_2 > 0$

$$\ddot{y} = g\phi_1$$

$$\dot{y} = g\phi_1 t + C_1$$

$$y = g\phi_1 \frac{t^2}{2} + C_1 t + C_2$$

$$\left.\begin{matrix} t = 0 \\ \dot{y} = \dot{y}_1 = \frac{g\phi_1 t_1}{2} \end{matrix}\right\} C_1 = \frac{g\phi_1 t_1}{2} \qquad \left.\begin{matrix} t = 0 \\ y = y_1 \end{matrix}\right\} C_2 = y_1$$

$$\dot{y}_2 = g\phi_1 t_2 + g\phi_1 \frac{t_1}{2}$$

$$y_2 = \frac{g\phi_1 t_2^2}{2} + \frac{g\phi_1 t_1 t_2}{2} + y_1$$

$$y_2 = \frac{g\phi_1}{2}\left(t_2^2 + t_1 t_2\right) + .149\, g\phi_1\, t_1^2 \quad \text{-------} (3)$$

From time 2 to 3 It is assumed that the bank application over this period is given by

$$\phi = \phi_1 \cos \frac{\pi}{2t_1} t \qquad \text{where } \frac{\pi}{t_1} = a$$

Hence $\ddot{y} = g\phi_1 \cos \frac{a}{2} t$

$$\dot{y} = \frac{2g\phi_1}{a} \sin \frac{a}{2} t + C_1 \quad \text{-----------------} (4)$$

$$y = \frac{-4g\phi_1}{a^2} \cos \frac{a}{2} t + C_1 t + C_2$$

$$\left.\begin{array}{l} t = 0 \\ \dot{y} = \dot{y}_2 = g\phi_1\left(t_2 + \frac{t_1}{2}\right)\end{array}\right\} C_1 = g\phi_1\left(t_2 + \frac{t_1}{2}\right)$$

$$\left.\begin{array}{l} t = 0 \\ y = y_2 \end{array}\right\} C_2 = \frac{4g\phi_1}{a^2} + y_2$$

$$y_3 = g\phi_1\left(t_2 + \frac{t_1}{2}\right) + \frac{4g\phi_1}{\pi^2} t_1^2 + \frac{g\phi_1}{2}\left(t_2^2 + t_1 t_2\right) + .149\, g\phi_1 t_1^2$$

$$y_3 = g\phi_1\left(1.053\, t_1^2 + .5\, t_2^2 + 1.5\, t_1 t_2\right)$$

i.e. when $t_2 > 0$ $\phi_1 = \phi_M$

$$y_3 = g\phi_M\left(1.053\, t_1^2 + .5\, t_2^2 + 1.5\, t_1 t_2\right) \text{ - - - - - - - - - - - - - (5)}$$

when $t_2 = 0$ $\phi_M = \phi_1$

$$y_3 = g\phi_1\left(1.053\, t_1^2\right) \text{ - - - - - - - - - - - - - - - - - - (6)}$$

The manoeuvre is assumed to be symmetrical with the same maximum angle of bank used in port and starboard directions hence:

$$y_6 = 2y_3$$

Now assuming that the maximum rate of roll $\left(\frac{d\phi}{dt}\right)_M = p_M$ is always attained, this value will be reached in time $t = t_1/2$

From (1) $p_M = \frac{\phi_1 \pi}{2 t_1} \sin\left(\frac{\pi}{t_1} \frac{t_1}{2}\right)$ at $t = \frac{t_1}{2}$

$$p_M = \frac{\pi}{2} \frac{\phi_1}{t_1} \text{ - (7)}$$

If T is the total time available for the manoeuvre then in the general case where $t_2 > 0$ and $\phi_1 = \phi_M$

then $T = 4\, t_1 + 2\, t_2$ hence $t_2 = \left(\frac{T}{2} - 2\, t_1\right)$

where $t_1 = \frac{\pi}{2} \frac{\phi_M}{p_M}$

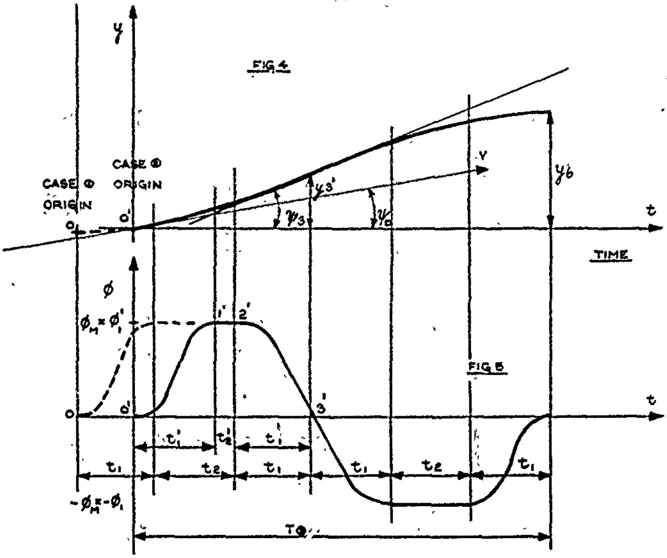
Hence $y_6 = 2g\, \phi_M\left(1.053\, t_1^2 + .5\, t_2^2 + 1.5\, t_1 t_2\right)$ - - - - - - - - (8)

In the case where $t_2 = 0$ and $\phi_M = \phi_1$

then $t_1 = T/4$ and $\phi_1 = \frac{2}{\pi} p_M t_1$

Hence $y_6 = 2\, g\phi_1\left(1.053\, t_1^2\right)$ - - - - - - - - - - - - - - - - - - (9)

Case (2) Tracking Angle of Start of Manoeuvre ($\psi_o \neq 0$).



Assumptions

In comparing this case with Case (1) it is assumed that after having attained ψ_3 in both cases the manoeuvres are identical, for given values of t_1 and t_2 but that these values are modified in the first part of the manoeuvre to $t_1{}^1$ and $t_2{}^1$ as indicated in Figs. 4 and 5.

From time 0^1 to 1^1

$$\phi = \frac{\phi_1{}^1}{2} - \frac{\phi_1{}^1}{2}\cos\left(\frac{\pi}{t_1{}^1}\right)t \quad \text{where} \quad \left(\frac{\pi}{t_1{}^1}\right) = a$$

$$\dot{y} = \frac{g\phi_1{}^1}{2}\left(t - \frac{1}{a}\sin a\,t\right) + C_1$$

$$y = \frac{g\phi_1{}^1}{2}\left(\frac{t^2}{2} + \frac{1}{a^2}\cos a\,t\right) + C_1 + C_2$$

$\left.\begin{array}{l} t = 0 \\ \dot{y} = V\psi_o \end{array}\right\} \; C_1 = V\psi_o$ $\qquad$ $\left.\begin{array}{l} t = 0 \\ y = 0 \end{array}\right\} \; C_2 = -\frac{g\phi_1{}^1}{2a^2}$

$$y_1{}^1 = \frac{g\phi_1{}^1}{2}\left(\frac{t_1{}^{12}}{2} - \frac{t_1{}^{12}}{\pi^2} - \frac{t_1{}^{12}}{\pi^2}\right) + V\psi_o t_1{}^1$$

$$y_1{}^1 = .149\,g\phi_1{}^1 t_1{}^{12} + V\psi_o t_1{}^1 \quad \text{--------} \quad (10)$$

From time 1^1 to 2^1 $\phi = \phi_1^1$ is const $= \phi_M$

$$y = g\phi_1^1 \frac{t^2}{2} + C_1 t + C_2$$

$$\left.\begin{array}{l} t = 0 \\ \dot{y} = \dfrac{g\phi_1^1 t_1^1}{2} + V\psi_o \end{array}\right\} \quad C_1 = \frac{g\phi_1^1 t_1^1}{2} + V\psi_o \qquad\qquad \left.\begin{array}{l} t = 0 \\ y = y_1^1 \end{array}\right\} \quad C_2 = y_1^1$$

$$y_2^1 = \frac{g\phi_1^1}{2} {t_2^1}^2 + g\phi_1^1 \frac{t_1^1 t_2^1}{2} + V\psi_o t_2^1 + .149 g\phi_1^1 {t_1^1}^2 + V\psi_o t_1^1$$

$$y_2^1 = \frac{g\phi_1^1}{2}\left({t_2^1}^2 + t_1^1 t_2^1\right) + .149 g\phi_1^1 {t_1^1}^2 + V\psi_o\left(t_1^1 + t_2^1\right) \qquad \text{-------- (11)}$$

From time 2^1 to 3^1 $\phi = \phi_1^1 \cos\left(\frac{\pi}{2t_1^1} t\right) = \phi_1^1 \cos \frac{a}{2} t$

$$y = -\frac{4g\phi_1^1}{a^2} \cos \frac{a}{2} t + C_1 t + C_2 ,$$

giving $y_3^1 = g\phi_1^1\left(1.053 {t_1^1}^2 + .5 {t_2^1}^2 + 1.5 t_1^1 t_2^1\right) + V\psi_o\left(2t_1^1 + t_2^1\right)$

and as before

when $t_2^1 > 0$ $\phi_1^1 = \phi_M$

$$y_3^1 = g\phi_M\left(1.053 {t_1^1}^2 + .5 {t_2^1}^2 + 1.5 t_1^1 t_2^1\right) + V\psi_o\left(2t_1^1 + t_2^1\right) \qquad \text{-------- (12)}$$

when $t_2^1 = 0$ $\phi_M = \phi_1^1$

$$y_3^1 = g\phi_1^1\left(1.053 {t_1^1}^2\right) + V\psi_o\left(2t_1^1\right) \qquad \text{-------- (13)}$$

In general the problem is to plot the maximum allowable sidestep distance (y_6) for varying values of track angle (ψ_o), assuming a constant speed (V) and given total time (T) to carry out the manoeuvre. The maximum allowable bank angle (ϕ_M) and rate of roll (p_M) will also be given.

In order to do this it is necessary to consider particular cases as the shape of the curve of bank angle against time will vary with both the total time T and also ψ_o. With $\psi_o = 0$ and large values of T the distribution will be symmetrical with flat tops, as in Fig. 2, where ϕ_M is attained, but for small values of T the distribution will have no constant ϕ_M portion. The effect of varying ψ_o and T is easily seen by considering Figs. 4 and 5. In the particular cases shown when $\psi_o = 0$ we have Case (1) already considered and when ψ_o has a value as indicated we have Case (2). For the given values of t_1 and t_2 but varying T then ψ_o may have any value up to ψ_3. As ψ_o is increased the value of t_2^1 will reduce to zero with t_1^1 constant $= t_1$ and $\phi_1^1 = \phi_M$ and after t_2^1 becomes zero both t_1^1 and ϕ_1^1 will reduce until they are both zero when $\psi_o = \psi_3$. In this particular case when $\psi_o = \psi_3$ the bank acceleration will initially be infinite but for practical values of ψ_o this condition will not normally be attained.

Consider now the practical case where the total time T is fixed then for any value of ψ_o we have:

$$T = 2t_1 + t_2 + 2t_1^1 + t_2^1$$

For particular cases it will be necessary to obtain values for t_1 t_2 t_1^1 and t_2^1 in order to evaluate y_3 y_3^1 and hence y_6. It will thus be necessary to obtain a relationship between t_1 t_2 t_1^1 and t_2^1.

From equation (4) $\dot{y}_3 = \dfrac{2gt_1\phi_1}{\pi} + g\phi_1 \left(t_2 + \dfrac{t_1}{2}\right)$

hence $\psi_3 = \dfrac{\dot{y}_3}{V} = \dfrac{g\phi_1}{V}\left(1.137t_1 + t_2\right)$ - - - - - - - - (14)

This angle ψ_3 is turned through in time $(2t_1 + t_2)$

The angle turned through in time $(2t_1^1 + t_2^1)$ is $(\psi_3 - \psi_o)$

Hence $(\psi_3 - \psi_o) = \dfrac{g\phi_1^1}{V}\left(1.137t_1^1 + t_2^1\right)$

and the required relationship between t_1 t_2 t_1^1 and t_2^1 is:

$$\frac{g\phi_1}{V}\left(1.137t_1 + t_2\right) - \frac{g\phi_1^1}{V}\left(1.137t_1^1 + t_2^1\right) = \psi_o \quad \text{- - - - - (15)}$$

This equation together with $T = 2t_1 + t_2 + 2t_1^1 + 2t_2^1$

where $t_1 = \dfrac{\pi}{2}\dfrac{\phi_M}{p_M}$ if $t_2 > 0$ and $\phi_1 = \phi_M$

and $t_1^1 = \dfrac{\pi}{2}\dfrac{\phi_M}{p_M}$ if $t_2^1 > 0$ and $\phi_1^1 = \phi_M$

also if $t_2 = 0$ $\phi_1 = \dfrac{2p_M}{\pi} t_1$

and if $t_2^1 = 0$ $\phi_1^1 = \dfrac{2p_M}{\pi} t_1^1$

enables the required quantities to be determined for all possible cases.

The method of obtaining particular points on the $y_6 \sim \psi_o$ boundary will now be dealt with in detail.

<u>Method for obtaining points on $y_6 \sim \psi_o$ boundary curve</u>

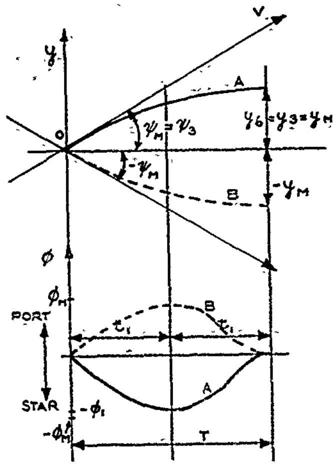
Given T, ϕ_M, p_M and V it is required to plot y_6 against ψ_o.

It will be found in evaluating the points that the time $\left(\dfrac{\pi}{2}\dfrac{\phi_M}{p_M}\right)$ is significant in determining the shape of the bank angle distribution curve and this will be called the <u>Critical Time</u> (t_M).

$$t_M = \left(\frac{\pi}{2}\frac{\phi_M}{p_M}\right)$$

a. Boundary when $t_M > \frac{T}{2}$ (ϕ_1 always less than ϕ_M)

1. Find maximum values of ψ_o and y_6 (ψ_M and y_M)



A & B are the two limiting cases. Case A only is considered as case B will give the same values with the opposite signs. In the limiting cases all the bank is applied in one direction.

$\psi_M = \psi_3 \quad t_1^1 = t_2^1 = t_2 = 0$

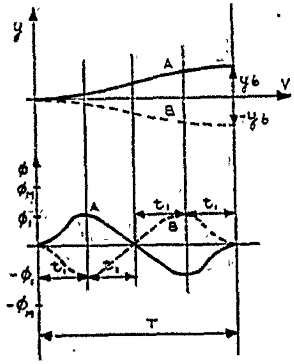
$$T = 2t_1, \ \phi_1 = \frac{2}{\pi} p_M t_1$$

hence $y_M = y_3 = \pm g\phi_1 \left(1.053 t_1^2\right)$ from (6)

and $\psi_M = \frac{\pm g\phi_1}{V}\left(1.137 t_1\right)$ from (14)

Note (In this case $\ddot{\phi} = \infty$ at start of manoeuvre, hence results will be optimistic)

2. Find values of y_6 when $\psi_o = 0$



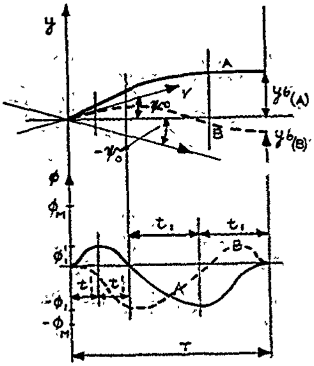
A & B are the two possible cases. Case A only is considered as case B will give the same value for y_6 with the opposite sign.

$t_1 = \frac{T}{4} \qquad \phi_1 = \frac{2}{\pi} p_M t_1$

hence

$$y_6 = \pm 2g\phi_1 \left(1.053 t_1^2\right) \text{ from (6)}$$

3. Find intermediate values of y_6 for $-\psi_M < \psi_0 < \psi_M$



For values of $\psi_0 < \psi_M$ there will be two possible values for y_6 depending which way the bank is made initially. In case A the bank is to port initially and in case B to starboard. The values of y_6 for ψ_0 -ve will be the same numerically as the +ve ψ_0 values but having the opposite sign.

In Case A

$$t_2 = t_2^1 = 0, \quad T = 2t_1 + 2t_1^1$$

Now from (15) $\quad 1.137t_1 \dfrac{g\phi_1}{V} - 1.137t_1^1 \dfrac{g\phi_1^1}{V} = \psi_0$

also $\phi_1 = \dfrac{2p_M}{\pi} t_1$ and $\phi_1^1 = \dfrac{2p_M}{\pi} t_1^1$

hence $\dfrac{1.137g}{V} \times \dfrac{2p_M}{\pi} \left(t_1^2 - t_1^{1\,2}\right) = \psi_0$

and subs. $t_1 = \dfrac{T}{2} - t_1^1$ we have

$$\frac{T^2}{4} - Tt_1^1 = \frac{1.38V\psi_0}{gp_M} \qquad \text{or } t_1^1 = \left(\frac{T}{4} - \frac{1.38\psi_0 V}{gp_M T}\right) \text{- - - - - (16)}$$

Hence $y_3^1 = g\phi_1^1\left(1.053t_1^{1\,2}\right) + V\psi_0\left(2t_1^1\right)$ from (13)

$y_3 = g\phi_1\left(1.053t_1^2\right)$ from (6) and $y_6 = \pm\left(y_3^1 + y_3\right)$

In Case B
(Interchanging t_1 with t_1^1 and ϕ_1 with ϕ_1^1)

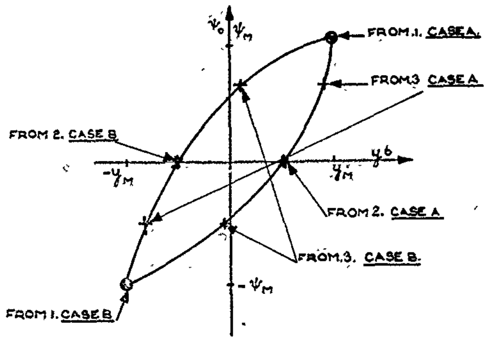
$$y_3^1 = -g\phi_1\left(1.053t_1^2\right) + V\psi_0\left(2t_1\right)$$

$$y_3 = -g\phi_1^1\left(1.053t_1^{1\,2}\right)$$

$$y_6 = \pm\left(y_3^1 + y_3\right)$$

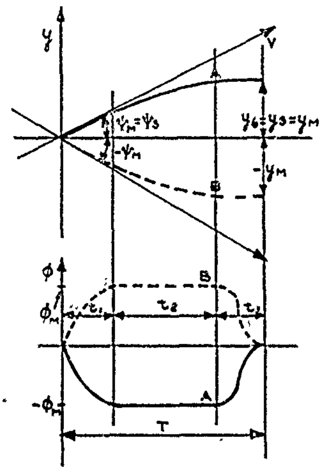
Using values of t_1, t_1^1, ϕ_1 and ϕ_1^1 worked out for Case A.

The Boundary can now be plotted and will appear as below:



b. Boundary when $\frac{T}{4} < t_M < \frac{T}{2}$ ($\phi_1 = \phi_M$ when $\psi_0 = \psi_M$ but $\phi_1 < \phi_M$ when $\psi_0 = 0$)

1. Find maximum values of ψ_0 and y_6 (ψ_M and y_M)



A & B are the two limiting cases. Case A only is considered as case B will give the same values with the opposite signs. In the limiting cases all the bank is applied in one direction.

$\psi_M = \psi_3 \quad t_1{}^1 = t_2{}^1 = 0$

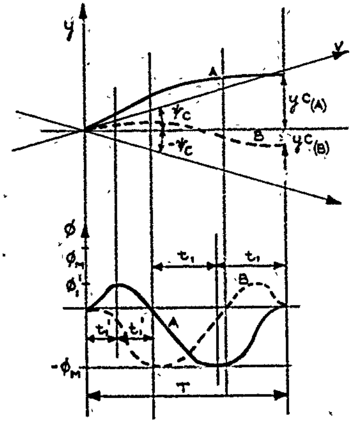
$T = 2t_1 + t_2$

$t_1 = \frac{\pi}{2}\frac{\phi_M}{p_M}$ hence t_2

hence $y_M = y_3 = \pm g\phi_M\left(1.053t_1{}^2 + .5t_2{}^2 + 1.5t_1 t_2\right)$ from (5)

and $\psi_M = \frac{\pm g\phi_M}{V}\left(1.137t_1 + t_2\right)$ from (14)

2. <u>Find values of ψ_c and y_6 when $\phi_1 = \phi_M$ and $t_2 = 0$</u> (ψ_c and y_c)



This case is similar to a.3 the only difference being that $\phi_1 = \phi_M$ and ψ_c is unknown. Hence from a.3 we have for

<u>Case A</u>

$$\phi_1 = \phi_M, \quad t_1 = \frac{\pi}{2}\frac{\phi_M}{p_M}$$

$$\phi_1^1 = \frac{2p_M t_1^1}{\pi}, \quad t_1^1 = \frac{T}{2} - t_1$$

$$\psi_c = \pm \frac{1.137g}{V}\left(\phi_M t_1 - \phi_1^1 t_1^1\right)$$

and $$y_3^1 = g\phi_1^1\left(1.053 t_1^{1\,2}\right) + V\psi_c\left(2t_1^1\right)$$

$$y_3 = g\phi_M\left(1.053 t_1^2\right)$$

$$y_6 = y_c = \pm\left(y_3^1 + y_3\right)$$

<u>Case B</u>

ψ_c as for case A

$$y_3^1 = -g\phi_M\left(1.053 t_1^2\right) + V\psi_c\left(2t_1\right)$$

$$y_3 = -g\phi_1^1\left(1.053 t_1^{1\,2}\right)$$

$$y_6 = y_c = \pm\left(y_3^1 + y_3\right)$$

Using values of t_1, t_1^1 and ϕ_1^1 worked out for <u>Case A</u>

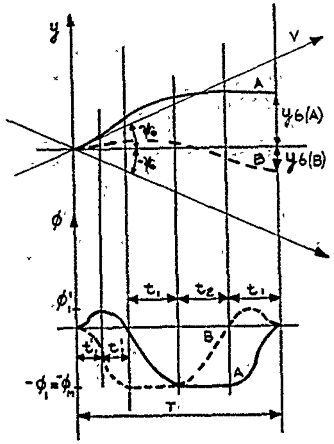
3. <u>Find values of y_6 when $\psi_c = 0$</u>

As for case a.2 as $\phi_1 = \phi_1^1 < \phi_M$

4. <u>Find intermediate values of y_6 for $-\psi_c < \psi_c < \psi_c$</u>

As for case a.3 as ϕ_1 & $\phi_1^1 < \phi_M$

5. **Find intermediate values of y_6 (when $\phi_1 = \phi_M$ and $t_2 > 0$)** $\psi_o < \psi_o < \psi_M$



Case A

$$t_2{}^1 = 0, \quad t_1 = \frac{\phi_M}{p_M} \cdot \frac{\pi}{2}$$

$$T = 2t_1 + 2t_1{}^1 + t_2$$

$$\phi_1{}^1 = \phi_1 \frac{t_1{}^1}{t_1} \text{ from (7) as } p_M \text{ const.}$$

From (15)

$$\frac{g\phi_1}{V} \times 1.137t_1 + \frac{g\phi_1}{V} t_2 - \frac{g\phi_1{}^1}{V} \times 1.137t_1{}^1$$

$$= \psi_o$$

Subs. for $\phi_1{}^1$ and t_2 we get

$$(t_1{}^1)^2 + 2t_1{}^1 \left(\frac{t_1}{1.137}\right) - \frac{t_1}{1.137} \times \left(T - .863t_1 - \frac{\psi_o V}{g\phi_M}\right) = 0$$

hence $t_1{}^1$ and t_2

$$y_3{}^1 = g\phi_1{}^1 \left(1.053t_1{}^{12}\right) + V\psi_o \left(2t_1{}^1\right)$$

$$y_3 = g\phi_M \left(1.053t_1{}^2 + .5t_2{}^2 + 1.5t_1 t_2\right)$$

$$y_6 = \pm \left(y_3{}^1 + y_3\right)$$

Case B

ψ_o as for case A

(Interchange t_1 with $t_1{}^1$, t_2 with $t_2{}^1$ and ϕ_M with $\phi_1{}^1$)

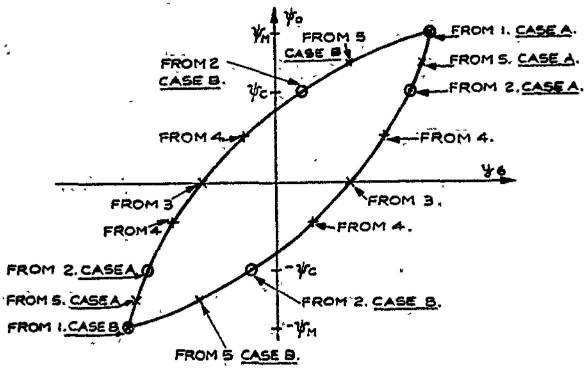
Then $$y_3{}^1 = -g\phi_M \left(1.053t_1{}^2 + .5t_2{}^2 + 1.5t_1 t_2\right) + V\psi_o \left(2t_1 + t_2\right)$$

$$y_3 = -g\phi_1{}^1 \left(1.053t_1{}^{12}\right)$$

$$y_6 = \pm \left(y_3{}^1 + y_3\right)$$

Using values of t_1, t_2, $t_1{}^1$ and $\phi_1{}^1$ worked out for Case A.

The Boundary can now be plotted and will appear as below:



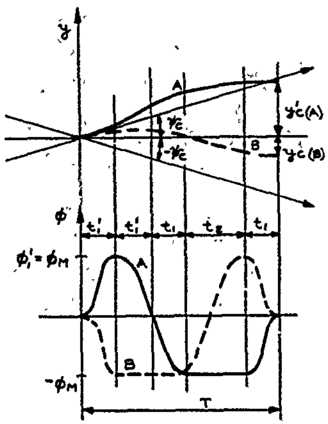
c. Boundary when $t_M < \frac{T}{4}$ ($\phi_1 = \phi_M$ when $\psi_o = \psi_M$ and also when $\psi_o = 0$)

1. Find maximum values of ψ_o and y_6 (ψ_M and y_M)

   As for case b.1.

2. See over.

2. <u>Find values of ψ_o and y_6 when $\phi_1^1 = \phi_M$ and $t_2^1 = 0$</u> (ψ_c and y_o)



In this case ψ has been reduced from ψ_M to ψ_c and ϕ_1^1 reaches ϕ_M before t_2 becomes zero. The case otherwise is similar to b.5.

<u>Case A</u>

$$T = 2t_1^1 + 2t_1 + t_2$$

where $t_1 = t_1^1 = \frac{\pi}{2}\frac{\phi_M}{p_M}$

hence t_2

from (15)

$$\psi_c = \frac{g\phi_M}{V}\left(1.137t_1 + t_2\right) - \frac{g\phi_M}{V}\left(1.137t_1^1\right)$$

$$\psi_c = \pm\frac{g\phi_M}{V}\left(t_2\right)$$

$$y_3^1 = g\phi_M\left(1.053{t_1^1}^2\right) + V\psi_o\left(2t_1^1\right)$$

$$y_3 = g\phi_M\left(1.053t_1^2 + .5t_2^2 + 1.5t_1t_2\right)$$

$$y_o = y_6 = \pm\left(y_3^1 + y_3\right)$$

<u>Case B</u>

ψ_c as for case A.

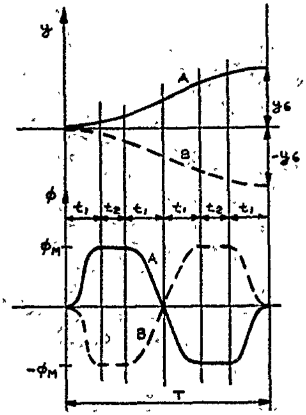
$$y_3^1 = -g\phi_M\left(1.053t_1^2 + .5t_2^2 + 1.5t_1t_2\right) + V\psi_o\left(2t_1 + t_2\right)$$

$$y_3 = -g\phi_M\left(1.053{t_1^1}^2\right)$$

$$y_o = y_6 = \pm\left(y_3^1 + y_3\right)$$

Using values of t_1, t_2, t_1^1 worked out for Case A.

3. Find values of y_6 when $\psi_0 = 0$

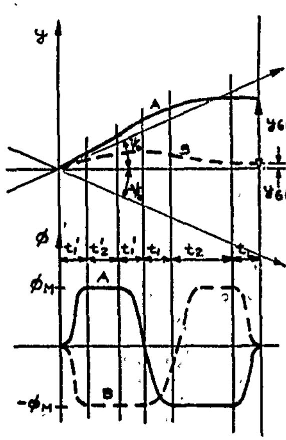


$T = 4t_1 + 2t_2$

where $t_1 = \frac{\pi}{2}\frac{\phi_M}{p_M}$ hence t_2

$$y_6 = 2y_3 = 2g\phi_M\left(1.053t_1^2 + .5t_2^2 + 1.5t_1t_2\right)$$

4. Find intermediate values of y_6 for $-\psi_0 < \psi_0 < \psi_0$



Case A

$T = 2t_1^1 + t_2^1 + 2t_1 + t_2$

where $t_1 = t_1^1 = \frac{\pi}{2}\frac{\phi_M}{p_M}$

from (15)

$$\frac{g\phi_M}{V}\left(t_2 - t_2^1\right) = \psi_0$$

hence subs. above $t_2 = \frac{T}{2} - 2t_1 + \frac{V}{g\phi_M}\left(\frac{\psi_0}{2}\right)$

hence $t_2^1 = T - 4t_1 - t_2$

and $y_3^1 = g\phi_M\left(1.053t_1^{1\,2} + .5t_2^{1\,2} + 1.5t_1^1t_2^1\right) + V\psi_0\left(2t_1^1 + t_2^1\right)$

$$y_3 = g\phi_M\left(1.053t_1^2 + .5t_2^2 + 1.5t_1t_2\right)$$

$$y_6 = \pm\left(y_3^1 + y_3\right)$$

Case B same ψ_0 as Case A

$$y_3^1 = -g\phi_M\left(1.053t_1^2 + .5t_2^2 + 1.5t_1t_2\right) + V\psi_0\left(2t_1 + t_2\right)$$

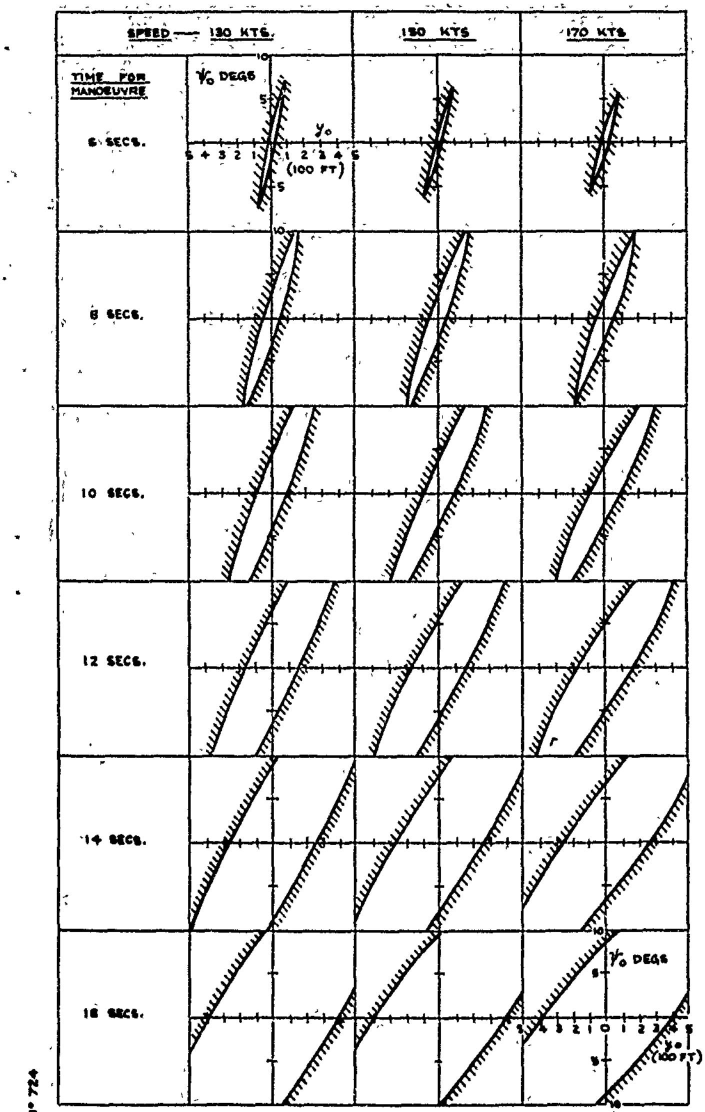
$$y_3 = -g\phi_M\left(1.053t_1^{1\,2} + .5t_2^{1\,2} + 1.5t_1^1t_2^1\right) \text{ and } y_6 = \pm\left(y_3^1 + y_3\right)$$

Using values of t_1, t_2, t_1^1 and t_2^1 worked out for Case A.

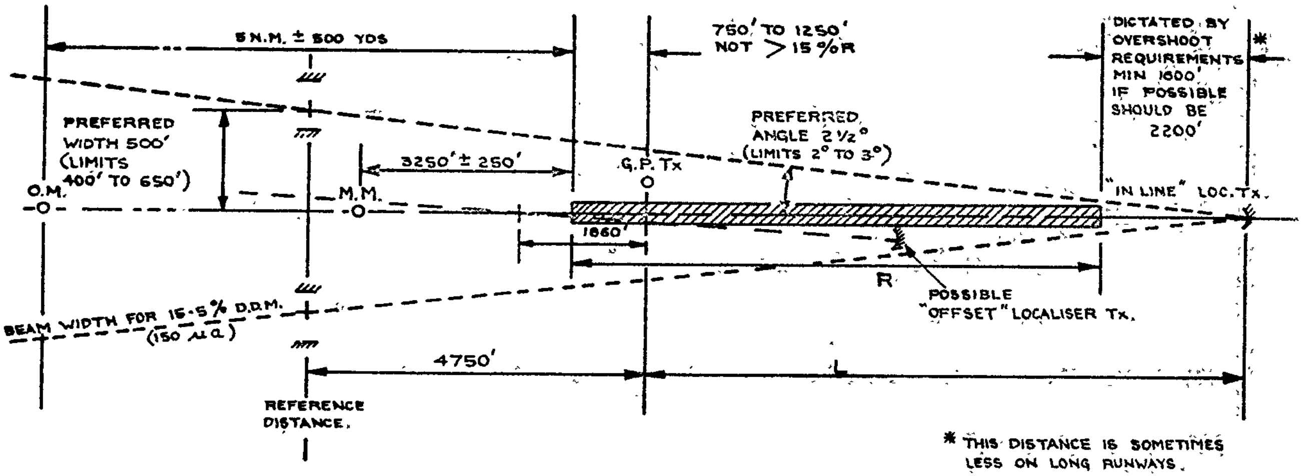
5. **Find intermediate values of y_6 for $\psi_c < \psi_o < \psi_M$**

As for case b.5 as ϕ_1^{1} or $\phi_1 < \phi_M$

The Boundary can now be plotted and will appear as for case (b).



TYPICAL LATERAL SIDESTEP MANOEUVRE BOUNDARIES $\left(\begin{array}{l}\phi_M = 20^\circ \\ p_M = 8^\circ/\text{SEC}\end{array}\right)$



I.L.S. BEAM POSITIONING IN RELATION TO RUNWAY.

FIG. 1.

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THE PHYSICAL WIDTHS SHOWN ARE AT A DISTANCE OF 4750 FT. FROM THE GLIDE PATH TRANSMITTER.

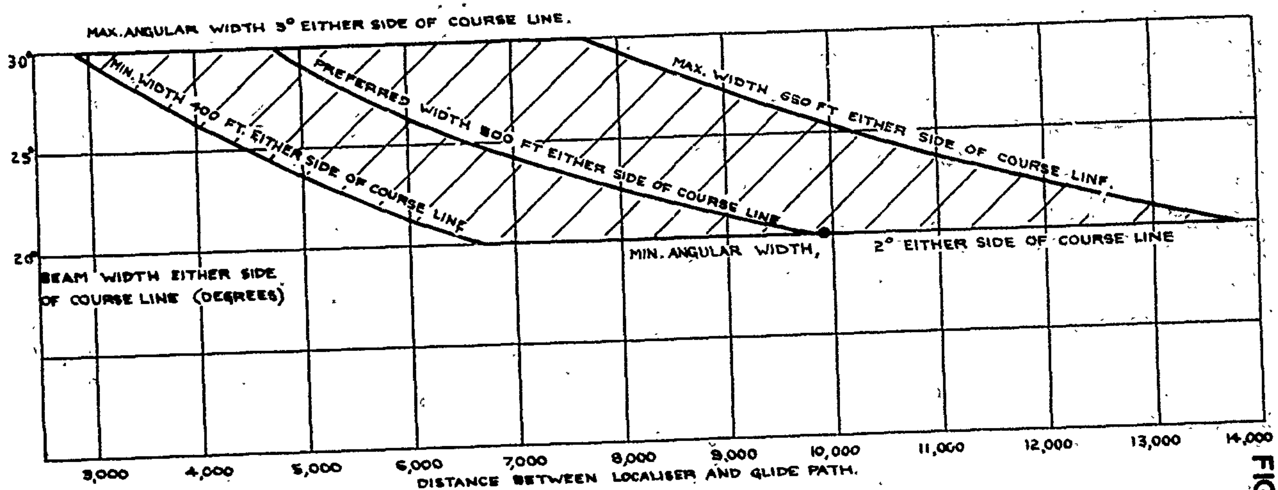
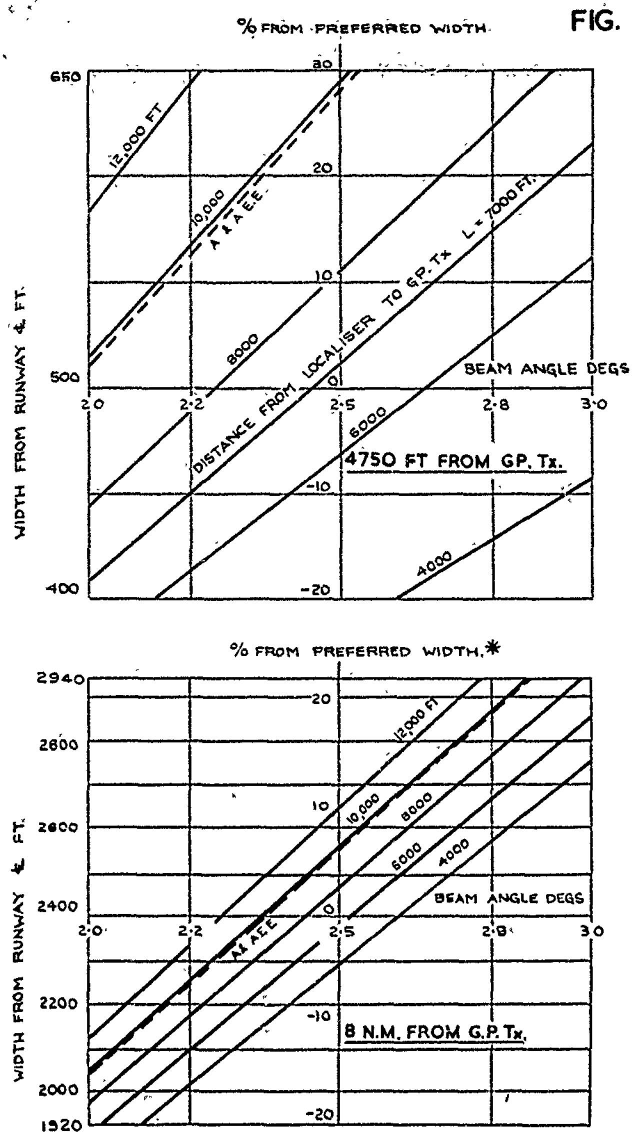


FIG. 2 (a)

I.L.S. LOCALISER BEAM-WIDTH CHART.

FIG. 2.(b)



* NOT STATED FOR 8 NM. RANGE BUT ASSUMED TO BE WIDTH GIVEN BY 2½° BEAM HAVING A 500 FT. WIDTH AT 4750 FT RANGE.

LOCALISER BEAM WIDTH CHARACTERISTICS.

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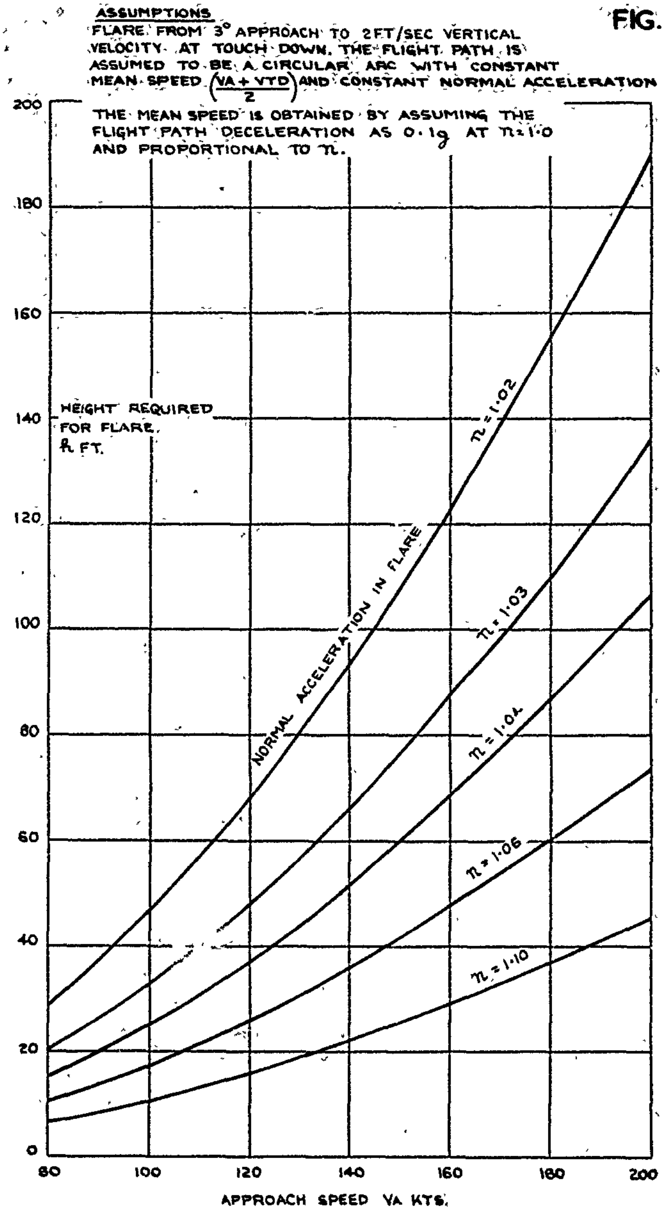
FIG. 3.



HEIGHT REQUIRED FOR FLARE.

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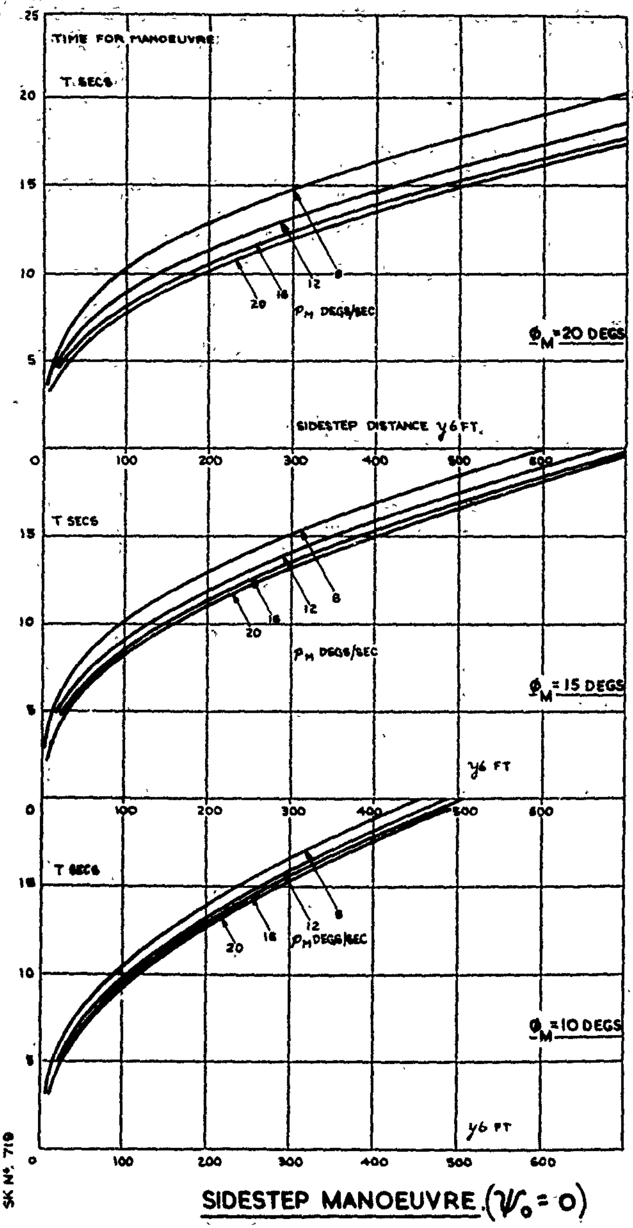
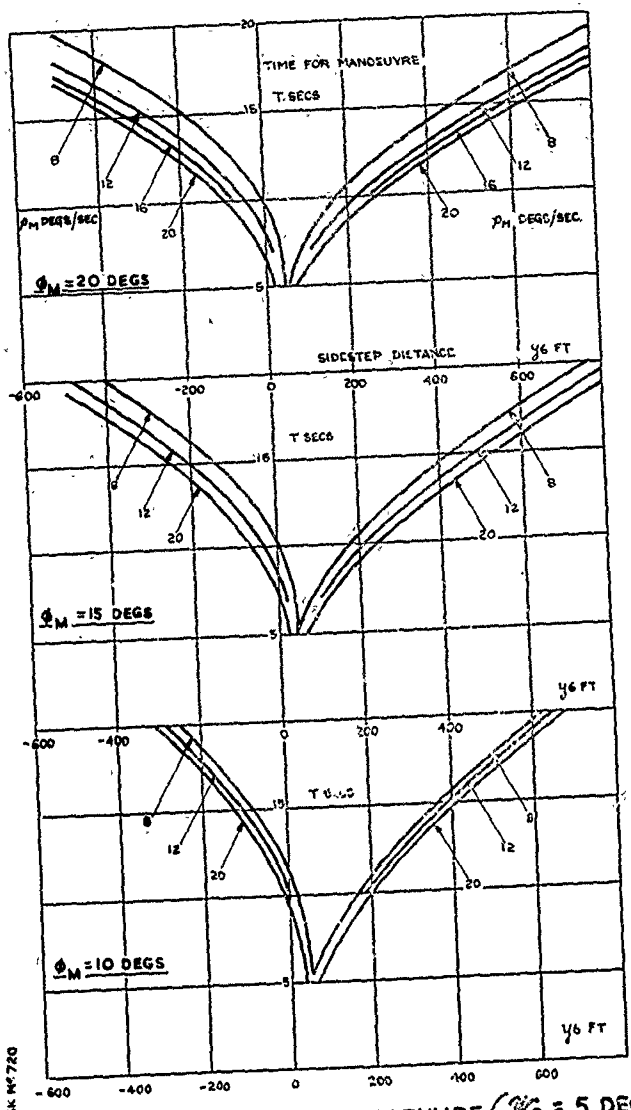
FIG. 4.



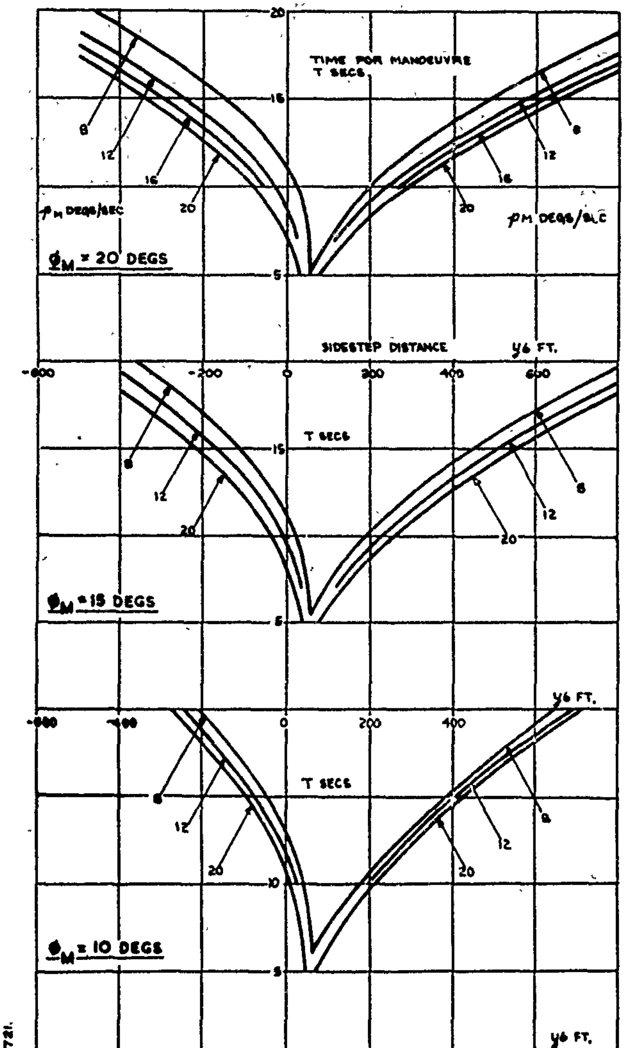
SIDESTEP MANOEUVRE. ($\psi_0 = 0$)

FIG. 5(a)



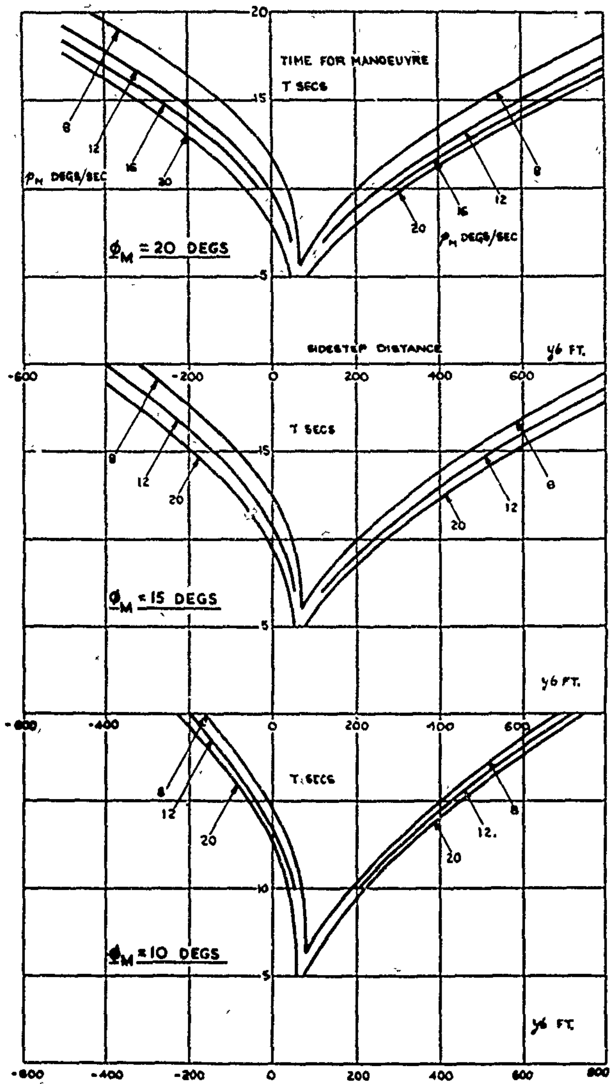
SIDESTEP MANOEUVRE $\left(\begin{array}{l}\psi_0 = 5 \text{ DEGS} \\ V = 125 \text{ KTS}\end{array}\right)$

FIG. 5(b)



SIDESTEP MANOEUVRE $\left(\begin{array}{l}\gamma_0 = 5 \text{ DEGS} \\ V = 150 \text{ KTS}\end{array}\right)$

FIG. 5(c)



SIDESTEP MANOEUVRE $\left(\frac{\gamma = 5 \text{ DEGS}}{V = 175 \text{ KTS}}\right)$

Sk. Nº 722

dstl

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