FINAL APPROACH SPACING TOOL

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Abstract

National Air Traffic Services Ltd (UK) has developed an ATC arrival spacing tool which is now planned for operational trials at Heathrow during winter 1999/2000. The tool has been designed to support the current operational concept and provides guidance to controllers on the timing of the turns onto the ILS which are used to achieve the required minimum spacing at 4 Nm DME. The advice to the controllers is provided through a process of automated monitoring of aircraft in the terminal manoeuvring area and trajectory prediction. This paper briefly describes the tool and associated concept and presents results gained from real time trials of the tool during January and June 1998.

0. Introduction

Heathrow airport is capacity constrained; in order that Heathrow airport achieve its arrival runway capacity it is vital that aircraft achieve their required minimum spacing crossing the outer marker, some 4 Nm prior to touchdown. At present the controllers do this solely on the basis of their expertise. Late in 1995, a business case was raised to develop a computer based tool to assist controllers achieve arrival landing rates with accuracy and consistency.

Section 2 of this paper summarises the operational environment in which FAST has been designed to operate, whilst section 3 details FAST functionality and components. Section 4 provides a description of the FAST user interface and section 5 provides a summary of the results of the trials to date.

1. Heathrow Approach Concept

Heathrow Approach controls aircraft from just prior to their arrival at the Heathrow stacks, namely Lambourne, Bovingdon, Biggin and Ockham, having been released by the London Terminal Control Area (TMA), to when they are handed over to Heathrow Tower (see Figure 1).

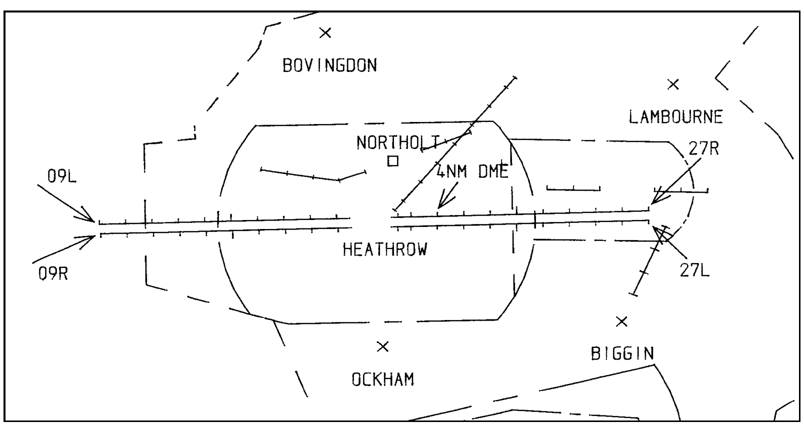


Figure 1 - Heathrow Approach airspace

Heathrow has two main runways during any period of operation, 27R and 27L in westerly operations and 09L and 09R in easterly operations. Normally, one runway is used for arrivals and the other for departures. In both westerly and easterly operations, arrivals can be directed onto the departure runway subject to specified operational conditions, such as airborne holding being in excess of 30 minutes.

Heathrow Approach has a Final Director (FIN) controller position and two Intermediate Director (INT) positions: INT North (INT N) and INT South (INT S). There are also two support positions, INT Support North (INT N SPT) and INT Support South (INT S SPT), which are open whenever the workload on the corresponding INT position dictates. Controllers validated for Heathrow Approach can work at any of the above positions, as required.

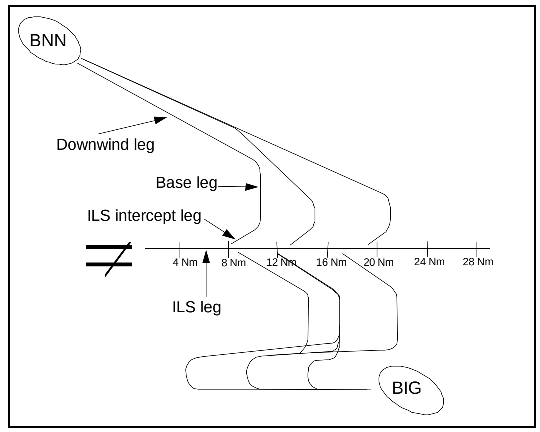


Figure 2
Examples of Heathrow Approach Paths

During very quiet periods, the roles of the FIN, INT N and INT S may be combined (bandboxed).

INT N is responsible for traffic arriving at Heathrow from the North and East, that is Bovingdon (BNN) and Lambourne (LAM) traffic; INT S is responsible for traffic arriving at Heathrow from the South and West, that is Biggin (BIG) and Ockham (OCK) traffic (see Figure 1). This includes:

- controlling the aircraft while they are holding at the stacks after transfer from the London TMA;
- guiding the aircraft out of the stacks and handing them over to the FIN, normally when they are established on a downwind leg (see Figure 2).

The INT N will normally merge traffic from the two northerly stacks into a single arrival stream from the North, whilst the INT S will normally merge traffic from the two southerly stacks into a single arrival stream from the South. The overall responsibility for determining the arrival sequence rests with INT N. The traffic is then handed over to the FIN, who implements the arrival sequence by merging the northerly and southerly arrival streams. FIN must also space aircraft according to the specified minima for each pair of aircraft types. The required minimum spacing is measured as the track distance from the lead aircraft to the following aircraft as the lead aircraft crosses the 4Nm distance measurement equipment (DME) point. (Whilst the required minima must be enforced during the whole approach, the decreasing aircraft speeds mean that the achieved spacing decreases toward the 4Nm DME point.)

The required minimum spacing depends on the wake vortex category of the lead and the following aircraft and on the current meteorological conditions. There is also an overriding minimum, the radar separation minimum, when no separation for wake vortex purposes alone is required.

In busy situations, the Traffic Manager (TM), who manages all traffic arriving at the main London airports, is responsible for defining the arrival sequence. In less busy situations, it is INT N who defines the sequence assisted by INT S.

The FIN uses a set of preferred headings which depend on the current meteorological conditions, to achieve a base leg and an ILS intercept leg. The primary method by which the required spacing is achieved is through varying the timing of the turns from the downwind leg to the base leg and from the base leg onto the ILS intercept leg (see Figure 2).

The FIN uses the ILS centre line distance markings on the radar display (see Figure 1) as reference for judging the spacing between aircraft. These markings aid in applying rules of thumb for when to turn the aircraft from their downwind legs onto their base legs so as to achieve the required minimum spacing.

Typically, aircraft are instructed to maintain an airspeed of 220 kts as they leave the stacks, reduce airspeed to 180 kts at the time of the turn to the base leg and reduce airspeed to 160 kts when they are on the ILS. In addition to adjusting the timing of the turns onto the base leg and onto the ILS intercept leg, the FIN uses variations in airspeed to maintain or fine tune the spacing. The controller can instruct the pilot to maintain a higher speed for longer, or implement a reduction of speed earlier, in order to decrease or increase the achieved spacing.

The FIN carries out his or her responsibilities by observing aircraft in the approach airspace using the radar display and issuing instructions to the arriving aircraft under his or her control through their radio telephony equipment (R/T). When an aircraft is handed over by the INT, the aircraft's flight strip is passed over to the FIN. In busy periods the intended arrivals sequence numbers, as established by the TM, are displayed on a closed-circuit TV (CCTV) screen, or hand-written on the controllers' flight progress strips. Information on the current airfield meteorological conditions is provided through a Central Control Function Display and Information System (CDIS) display.

The FIN R/T channel is normally very busy, and at times can become congested. R/T activity can be initiated by both the FIN and the pilots. Thus, the FIN cannot always control the precise timing of the delivery of the turn instructions to the pilots. At times, this results in the FIN having to allow contingency for 'recovery' from delays in transmission of instructions. If this delay happens on the turn from the downwind leg to the base leg, then the FIN may be able to recover the required spacing through modifying the timing of the turn from the base leg onto the ILS intercept leg. If the delay happens on the turn from the base leg to the ILS intercept leg, then the FIN may be able to recover through the tactical use of airspeed on the ILS.

2. FAST Functionality

The FAST Concept

The FAST concept was developed over a 6 month period on the basis of an analysis of recorded data and detailed observations and debriefing of in-situ controllers. The analysis resulted in a number of high-level requirements for the tool, summarised below:

- FAST shall assist the controllers in achieving the minimum required spacing; the controllers will remain responsible for achieving the spacing, for maintaining separation, and for deciding whether or not to use the guidance provided by FAST.

- FAST shall provide spacing guidance to the controllers alone. All communication with the pilots will be carried out by the controllers through their RT in the same way as current practice.
- FAST shall operate within existing operational procedures as outlined in Section 2.
- FAST shall not add to the overall workload of the controllers. FAST shall operate without the need for tactical intervention from the controllers and shall minimise the overall need for controller input.
- FAST shall operate using currently available system data only.
- FAST shall provide guidance to the FIN concerning the turn from the downwind leg to base leg and turn from base leg to the ILS intercept leg. Analysis has shown that the these turns have the greatest influence on achieving the desired spacing.
- The controllers shall remain responsible for establishing the headings to be used to achieve the desired path leg tracks. The actual headings to be used are dependent on the prevailing wind conditions and the tracks required. FAST will not provide guidance on the headings to be used in the turn from the downwind leg to the base leg or in the turn from the base leg to the ILS intercept leg.
- The FIN shall remain responsible for refining the spacing achieved through the tactical use of airspeed control. FAST will not provide guidance on the airspeed to be used to refine the spacing between aircraft.
- The controllers shall remain responsible for maintaining the required radar separation between all aircraft in the approach airspace. FAST will not provide guidance for maintaining the required radar separation between aircraft prior to gaining the ILS, and will not provide specific warnings concerning potential losses of radar separation on the ILS.
- The controllers shall remain responsible for establishing the arrivals sequence. FAST shall use available LATCC system data to predict the sequence that is being used. The controllers shall be responsible for monitoring and correcting the sequence predicted by FAST.

The Proposed FAST Design Functionality

FAST becomes interested in Heathrow arrivals shortly before they cross into the radar manoeuvring area, just prior to when the aircraft arrive at the stacks or cross through stack space. FAST then tracks the aircraft in the radar manoeuvring area to monitor aircraft's progress across the approach paths from the stacks to the 4 Nm DME threshold. FAST identifies the approach path legs of the aircraft as they leave the stacks and keep track of the progress of the aircraft through the path legs onto the ILS (e.g. upwind leg, downwind leg, base leg, ILS intercept leg, ILS leg).

When aircraft are on their downwind leg FAST predicts when each aircraft should carry out their turn onto the base leg in order to achieve the required spacing. Once aircraft are turning on to their base leg and during their base leg FAST predicts when each aircraft should carry out their turn onto the ILS intercept leg in order to achieve the required spacing.

FAST Core Component Functionality

Five principal FAST functions were identified to meet the requirements described in section 2. Each function was designed, prototyped and tested individually. The functions are as follows:

- track capture, which detects aircraft of interest to FAST;
- path leg tracking, which monitors the progress of the aircraft towards and along the ILS;
- sequence insertion, which places each aircraft in the sequence at the correct time according to its sequence number;
- turn advice, which calculates the advice on the timing of the turns to the base and the ILS intercept legs.
- heading tracker and manoeuvre onset detection
- FAST speed tracker and decelerate detection

Track Capture

Two sets of boundaries are defined, so that FAST may detect aircraft of interest. One set, approximately 20Nm prior to the stack entry point, is necessary to identify aircraft of interest to FAST and

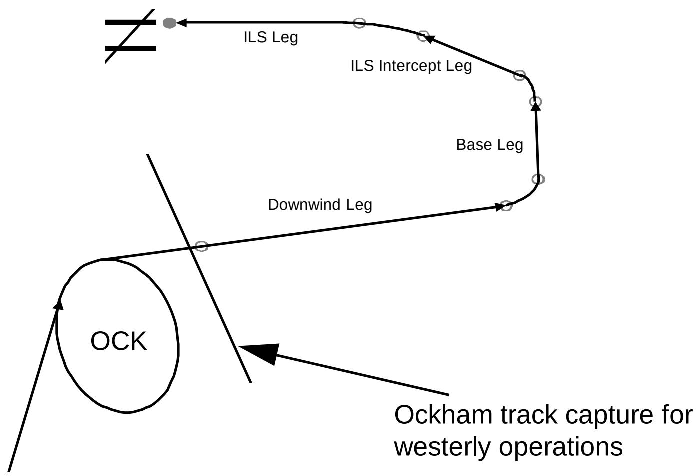


Figure 3 -Example of FAST track capture

to show them to the controllers on FAST's stack-based display.

The second set of boundaries is placed 'inside' the area delimited by the Heathrow stacks. As each aircraft crosses one of these boundaries, FAST captures the aircraft's track and starts to monitor the aircraft's progress toward the ILS (see path leg tracking below).

The aircraft tracks are maintained within FAST until they are 'released', which happens when no relevant radar updates are received for a period of time (i.e. the aircraft has landed). This idea is illustrated Figure 3. In this example the track is captured as the aircraft leaves the Ockham hold, as indicated by the diagonal line, and released once the aircraft has landed.

Path Leg Tracking

FAST tracks the aircraft's progress to the ILS so that it can provide guidance to the controller on the timing of the turns from downwind to base leg and from base leg to ILS intercept leg without controller input. Of particular importance are the transitions onto the downwind and base legs; only when an aircraft is identified as being on a downwind leg does FAST attempt to calculate the timing of its turn onto base leg. Similarly, only when an aircraft is identified as being on the base leg does FAST calculate the timing of its turn onto ILS intercept.

The possible path legs from each stack and the possible transitions between them were identified using recorded radar data from a number of days of operations together with controller questionnaires which had been compiled for the EU project Advanced Runway Arrivals

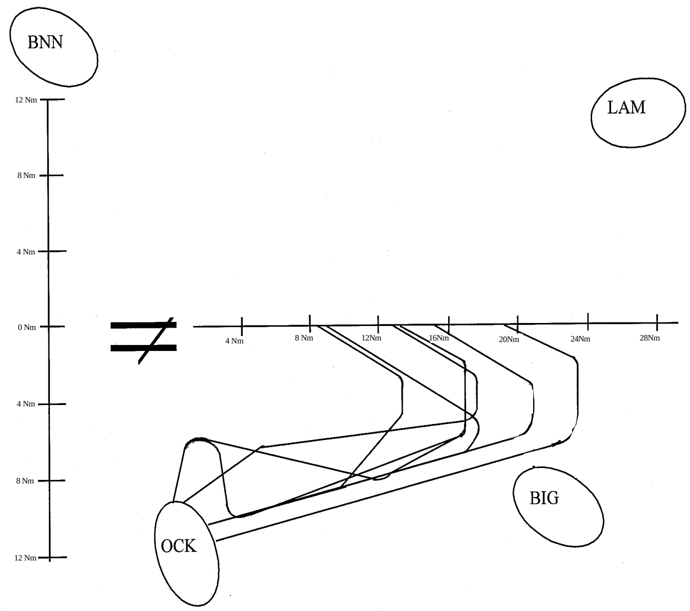


Figure 4 - Observed tracks from Ockham to the ILS

Management to Improve airport Safety and efficiency (ARAMIS).

The process of path leg tracking is achieved by monitoring the aircraft's position and track. For instance, in Figure 3 the aircraft leaves the stack on a downwind leg. Once the aircraft's track changes from 080° towards 360°, FAST recognises that the aircraft is on its base leg. Similarly, FAST then recognises the transition onto ILS intercept and ILS legs by monitoring the aircraft track as it turns to 300° and then 270° respectively. The paths captured by the analysis include both the more straightforward cases, such as that in Figure 3, as well as more unusual cases, such as those illustrated in Figure 4.

Sequence Insertion

Once aircraft have left the stack and FAST is maintaining a record of their progress toward the ILS, FAST uses information on the landing sequence so that it can provide advisories.

FAST does not attempt to optimise the landing sequence, but uses available information about the sequence that the controllers are implementing. This information comes from the Expected Approach Time (EAT) PC, a software package designed to help the TM assign a landing sequence and provide estimates of in-bound delay.

During busy periods the landing sequence is determined by the TM with reference to the EAT PC. FAST uses this sequence. However, the TM does not always maintain the landing sequence. When the sequence is not being maintained by the TM, the EAT PC still produces EAT times following the ‘first come first served’ principle. FAST will use the EAT times and a standard time from each stack to the threshold to produce a landing sequence. Thus FAST uses the EAT times whether or not they are being maintained by the TM. It displays the sequence it is assuming in the sequence display, where controllers may modify it if necessary.

The FAST sequence displays aircraft from the time that they are due to imminently leave the stack to the time they cross 4 Nm DME.

FAST Turn Advice

The turns from the downwind leg onto the base leg, and the turn from the base leg onto the ILS intercept leg are used by the FIN to control the time at which aircraft arrive at the 4Nm DME point and hence the spacing between each pair of aircraft. The final turn, from the ILS intercept onto the ILS, happens without intervention by the FIN controller when the aircraft intercepts the ILS localiser.

FAST provides guidance to the controller on the timing of the turns to the base and ILS intercept legs. FAST calculates the timing of these advisories for a particular aircraft based upon a prediction of the behaviour of each aircraft ahead of it in the sequence, and the required spacing rules. Figure 5 shows a typical aircraft track.

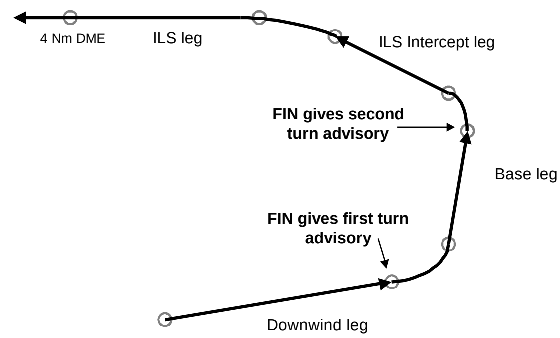


Figure 5 - FAST advice shown on typical aircraft track

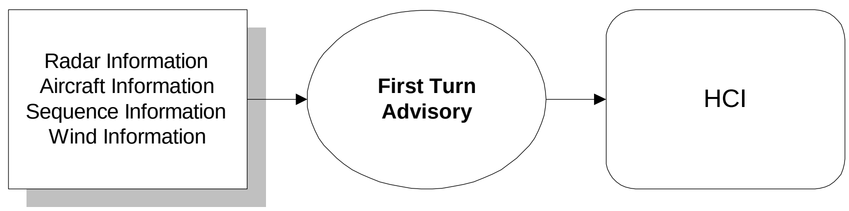


Figure 6- Calculation of first turn advisory

FAST fits into the current ATC procedures, as follows:

When an aircraft becomes established on the downwind leg, FAST uses the aircraft position, altitude, heading, position in the sequence, wake vortex category and the wind vector to construct a predicted track satisfying the spacing requirements at the 4Nm DME point. The predicted length of the downwind leg, and the predicted mean speed on the downwind leg, can then be used to determine the timing of the first turn advisory (Figure 6), which is displayed in the track data block by the Human Computer Interface (HCI). It is assumed that the wind data for FAST will be available within the operational environment.

FAST monitors the aircraft on the downwind leg, and regularly re-computes the first turn advisory.

When the aircraft starts the turn onto the base leg, FAST estimates the actual position and time of the beginning of the base leg, and constructs a new predicted track starting from that point and satisfying the spacing requirements at the 4Nm DME. The length of the predicted base leg, and the predicted mean speed along it, can then be used to determine the timing of the second turn advisory (see Figure 7).

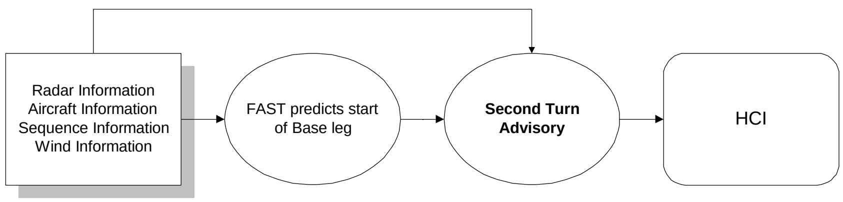


Figure 7 - Calculation of second turn advisory

FAST monitors the aircraft on the base leg, and regularly re-computes the second turn advisory.

A new predicted track is computed for the second turn advisory because the aircraft may not have followed the first predicted track exactly; this will be due to a combination of factors, such as:

- differences between the actual and predicted aircraft performance;
- the time differences between when FAST suggested the advisory should be given, the FIN actually giving the advisory, and the pilot's acting upon it.

The second turn advisory provides a chance to make up for these deviations by increasing or shortening the length of the base leg. The achieved spacing on the ILS can then be refined through the controller giving tactical speed instructions on the ILS. This remains the controller’s decision and is outside the scope of FAST.

In order that FAST fit into current operational practices, there assumptions which need to be made and constraints that the tool must satisfy. These include:

- the only means of varying the aircraft track is through the timing of the two final turn advisories;
- the tool will not ‘know’ the heading advisories that the FIN will issue to the aircraft, it will only assume the tracks that the FIN is trying to achieve;
- the turn from the base leg occurs approximately 2Nm from the ILS line;
- controllers give headings to the nearest 5° when compensating for wind.
- aircraft continuously descend from the downwind leg to the end of the ILS intercept leg. The aircraft are then assumed to descend continuously along the ILS with a constant glide-slope of 3° with respect to the ground;
- aircraft turn with a constant bank angle of 20° onto the base leg and intercept leg, and 25° onto the ILS;
- aircraft begin the downwind leg at 220kts (CAS); are given a 180kts advisory either on the downwind leg or as they start turning onto the base leg; and are given a 160kts advisory when the join the ILS;
- the CAS to true air speed conversion is linear for fixed height (this assumption avoids complex calculations without introducing significant errors);
- aircraft decelerate linearly, with one rate for each the two declarations; these rates do not vary across aircraft type;
- wind speed and direction data are available; the wind vector is assumed constant over the aircraft path.

Heading Tracker and Turn Onset Detection

The aircraft heading information is required by the FAST advisory algorithms in order to accurately predict the intended path of the aircraft. An indication of whether the aircraft is turning and the direction of the turn is needed by FAST to allow both path leg tracking and the calculation of FAST turn advice.

Current track processing within the ATC system is intended for display purposes. This processing smoothes the track position satisfactorily, but at the cost of introducing distortions into the track velocity vectors, and hence into the track heading data. It is not possible to generate aircraft heading information of sufficient quality for FAST from the existing radar track velocity information. There is therefore a need for a heading tracking algorithm in order to improve the quality of the heading information available to FAST. FAST Heading Tracker utilises a Kalman filter to maintain estimates of the heading, Turn Manoeuvre Detection monitors the output of the Heading Tracker to identify significant changes to the heading value.

Turn Manoeuvre Detection

It is relatively straightforward to set up a filter which tracks and smoothes the heading satisfactorily. What is difficult is robustly detecting turn manoeuvres, i.e. discontinuities in the state variables: if the filter tracks the heading too well, the errors will never become significant; conversely, if the filter errors become large every time the measurements and predictions differ, then turn manoeuvre detection will be over-sensitive to noise in the data. This section describes an approach to using the filter to detect turns.

Much of what is known about the data input to the tracker is easy to use to invalidate assumptions, but is harder to use constructively in a mathematical sense; e.g. the knowledge that the measurement noise is correlated explains some of the tracker performance problems, but if the correlation is difficult to quantify, then it is of no help in improving the tracker.

An alternative approach is to encode this knowledge heuristically, i.e. in the form of rules which are applied outside of the mathematical algorithm. Four heuristics were combined with a single point χ^2 test to form the tracker's turn manoeuvre detection algorithm.

If a prediction/measurement error at step N is deemed to be significant, the prediction at N+1 is calculated from the extrapolation at N, and compared to the corresponding measurement:

If the new error is not significant, then the failure of the χ^2 test at step N is ignored, and the tracker continues. This corresponds to a single glitch in the data and is illustrated in Figure 8 where step N is at time = 3.

If the new error is significant, but in the opposite direction to the old error, then the prediction at N+2 is calculated from the extrapolation at N+1, and the

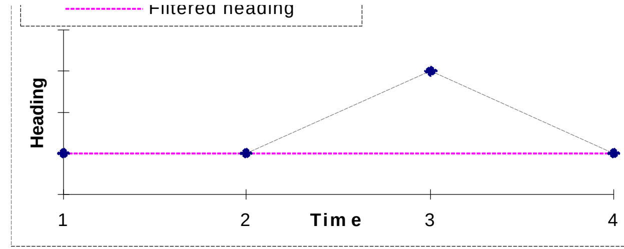


Figure 8: Single Significant Measurement Errors

above step is repeated. This is illustrated in Figure 10 where step N + 1 is at time = 4 and step N+2 will be at time = 5.

If the new error is both significant, and in the same direction as the old error, then a turn is detected at step N. The predictions at N and N+1 are calculated by fitting a line through the measurements at N-1, N, N+1, minimising the squared prediction errors at these points. This is illustrated in Figure 9 where step N-1 is at time = 2, step N is at time = 3 and step

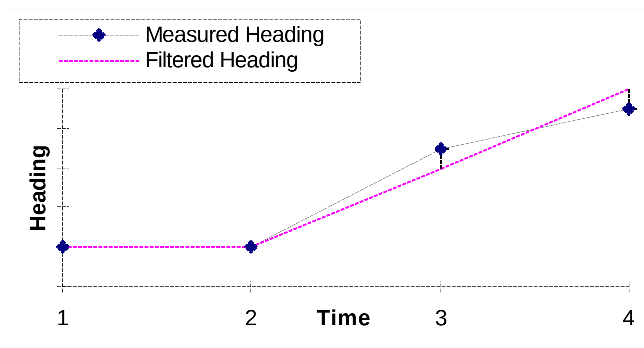


Figure 9: Consecutive Significant Measurement Errors in the Same Direction

N+1 is at time = 4.

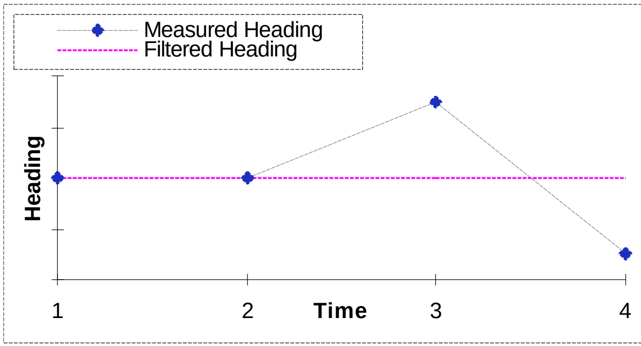


Figure 10: Consecutive Significant Measurement Errors in Opposite Directions

These rules cover all two point patterns; heuristics could also be formulated for patterns of more points; however the complexity of the formulation, and the number of rules required, soon outweighs the benefits of such an approach.

FAST Speed Tracker and Deceleration Detection

Controllers will normally use a 220 or 210 knot CAS downwind leg, although at times aircraft are cleared to decelerate to 180 knots whilst on the downwind leg. In order that FAST provides an accurate advisory for the turn from down wind to base leg FAST must detect this deceleration. This is achieved through speed tracker and deceleration detection.

Accurate aircraft speed tracking has proven difficult to achieve using available radar data. However, for the purposes of FAST it is sufficient to be able to detect a deceleration from (e.g.) 220 knots to 180 knots for aircraft on a downwind leg. Analysis to date indicates that this is possible with sufficient track history (i.e. approx. 5 radar returns). There is, of course, a trade off between timely and accurate detection of such deceleration.

3. The FAST User Interface

Information concerning FAST is displayed both on the radar screen and through a dedicated touch-sensitive panel located on the console beneath the radar display. The radar display is used to show FAST advisories and sequence information; all controller input to FAST is made using the FAST touch panel.

Turn to Base Leg Countdown - A countdown is shown in the track data block on the radar display from 15 seconds before until the time that the aircraft is due to begin to turn on to its base leg (see Figure 11). The decision on when to give the instruction to the pilot is the responsibility of the FIN.

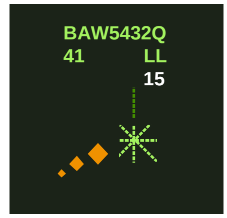
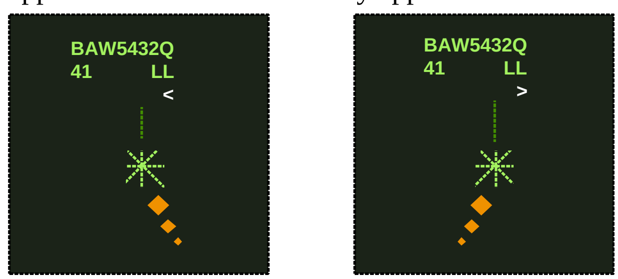


Figure 11 - Example of countdown for turn to base leg

Turn to ILS Intercept Leg Indicator - A chevron is displayed in the track data block on the radar display from 15 seconds before until the time that the aircraft is due to turn to its ILS intercept (see Figure 12). Half way through this period the chevron changes from steady to flashing. The chevron indicates the expected direction of turn: ‘<’ for westerly approaches and ‘>’ for easterly approaches.



Westerly Approach Easterly Approach

Figure 12- Example indications for turn to ILS intercept legs

Radar Sequence Display - The radar sequence display shows the FAST landing sequence at the bottom of the radar screen. The aircraft are ordered from left (the next aircraft to land) to right (the last one to land of those shown) for westerly approaches and from right to left for easterlies. The runway to be used for each arrival (for example 27L or 27R) is indicated by the vertical position of the aircraft block in the display. Figure 13 shows an example radar sequence display, with GABDX landing on 27L, the remainder on 27R. The radar sequence display is not interactive; changes to the landing sequence are made

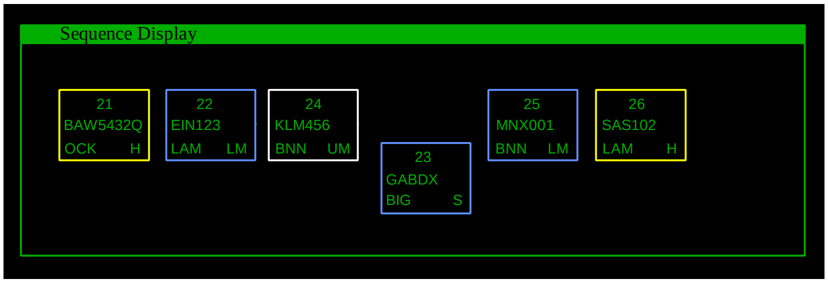


Figure 13 - Example radar sequence display (westerly operations)

from the FAST touch panel and are reflected in the radar display.

Each Approach radar position has a FAST touch-sensitive panel installed next to the flight strip board. Each touch panel is individually controlled but all touch panels work from the same data, and any change to that data is reflected on all touch panels, and also on all radar sequence displays.

An example of the FAST touch panel is shown in Figure 14. There are three components to this display, the header, the sequence display and the stack-based display. The touch panel shows the header information at all times and can be set to show one or both of the other components.

4. Trial Results

The first trial of the FAST prototype was conducted in January 1998. It demonstrated that the provision of turn advice to the FIN was indeed feasible without substantially changing current operational practice. In addition it highlighted areas for improved functionality which were implemented for the second trial.

The second trial of the FAST prototype, conducted in June 1998, showed that the prototype was both robust and effective. The trial focused on: assessing the impact of FAST on the accuracy and consistency of spacing; measuring its impact on controller workload; assessing the usability of the tool; and making recommendations for development of the tool for operational trials.

In many circumstances, FAST provided guidance which allowed Heathrow Approach controllers to space aircraft accurately and consistently and without asking them to change their methods of control. Overall, the advisories from FAST significantly reduced the FIN's workload:

- subjectively, the FINs felt they experienced less mental demand when using FAST; the NASA-TLX scores were 25% lower for the FIN with FAST;
- objectively, controllers had the confidence with FAST to make the downwind to base leg turn in one instruction, contributing to 16% fewer heading instructions and the R/T channel being occupied for 10% less time.

INT N had an additional responsibility with FAST, namely using the touch-sensitive screen to keep FAST up-to-date with sequence changes. However, this did not increase the workload significantly and with improvements to the touch panel implementation and design described here, sequence changes should be easier to make. The other controllers' workload was also unchanged.

Overall, the controllers found FAST easy to learn and to use. The radar sequence display in particular reduced the time that the controllers spent looking away from the radar. The trial also identified a number of refinements to the system which are under development, for instance

- FAST could be extended to be of more use, such as by giving the range to touchdown and allowing more flexibility in adding aircraft to the sequence.

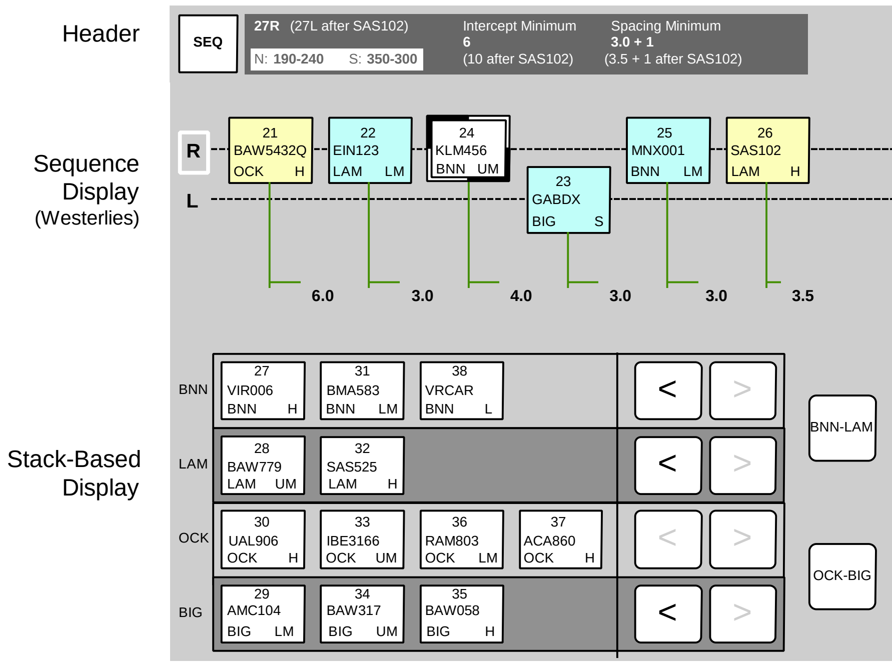


Figure 14 - Example of the FAST touch panel

The results from the trial suggest that FAST has the potential:

- to support accurate and consistent spacing of aircraft on the ILS;
- to reduce the workload of the FIN;
- to reduce the occupancy of the FIN's R/T channel;
- to support the training of controllers;
- to reduce the incidence of missed turn instructions;
- to provide an effective means for communicating the landing sequence;
- to enable the future use of a wider range of wake vortex separation minima;
- to support any future change from distance- to time-based separation minima.

5. CONCLUSION

The development of the Final Approach Spacing Tool (FAST) started in the Autumn of 1996 and the first trial of a prototype took place in January 1998. That trial demonstrated the feasibility of the FAST concept and led to further development and refinement of the FAST concept and prototype between February and June 1998. A follow-up trial took place in June 1998, providing evidence that the tool could usefully affect the accuracy of achieved spacing on the ILS with an associated decrease to workload. It is now planned to implement an operational version of FAST for large-scale simulation in Spring 1999, prior to operational trial during Winter 1999/2000.