AN OPERATIONAL EVALUATION OF A TAKE-OFF PERFORMANCE MONITORING ALGORITHM

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Abstract

A take-off performance monitor is a system that monitors the performance of an aircraft during take-off to determine whether the take-off is progressing in a satisfactory manner or otherwise. This information would assist the pilot to confidently and objectively assess the viability of continuing or aborting the take-off. Given the nature of the function, it is evident that the indication of the monitor needs to be very reliable. The interpretation of system reliability in this context refers to how closely the quantification of performance perceived by the crew relates to that actually achieved by the aircraft. Whilst this requirement implies the qualities of the display system, reliability is fundamentally dependent on the methodology adopted to monitor aircraft performance and the accuracy of the algorithms developed. In order to adequately quantify these qualities, the system developed at Cranfield University has been extensively flight tested on operational flights of the host vehicle. This paper presents the findings of this operational evaluation and describes how the design methodology contributed towards the achieved performance figures.

1 Introduction

The performance of an aircraft during take-off is critical to flight safety. This is well appreciated within the aviation industry, as testified by the rigorous framework surrounding the manoeuvre. In fact, at the aircraft type-certification level, manufacturers are required to specify the runway requirements for various dispatch weights and conditions. At the operational level, operators are then required, prior to the departure of every flight, to estimate the distance requirements for the successful[1] completion of the take-off and then ensuring that this distance is indeed available on the runway. This latter activity constitutes the basis of scheduled performance. If, then, the aircraft operates within the expected limits of scheduled performance, the take-off manoeuvre will be completed successfully.

During the actual take-off, the crew's responsibilities focus on flying the aircraft off the runway using airspeeds to identify salient events during the run. The crew is also required to monitor the situation and to react to any detected anomaly according to the progress of the take-off run in relation to the decision speed V_1. Their monitoring activities, however, are limited to ensuring that critical systems are operating normally and checking the various engine instruments to ensure that adequate thrust is being provided. They also intuitively monitor the performance of the aircraft through visual and other sensory cues. This practice, however, is highly subjective to individual perception and interpretation and is therefore not reliable. As a result, the crew is effectively forced to assume that the aircraft's actual performance is indeed within the limits allowed for by scheduled performance unless an anomaly distinct enough to be identified by the mechanisms discussed is experienced.

[1] A take-off attempt is, in this text, defined as successful if the manoeuvre is completed without an accident and unsuccessful otherwise.

In order to ensure a reasonably high probability of success in a forthcoming take-off (which translates to an acceptable level of safety), statistical leeways in runway allowances are introduced in the process of performance scheduling. These are perhaps best typified in large transport aircraft category (Part 25 Certified) operations. In this category of operations, the leeways introduced and contingencies addressed cater for, amongst others, variations in performance expected of different aircraft in the fleet, the eventuality of an engine failure at any moment in the run and variations in surface wind, runway slope and runway conditions. The consideration for the variation in performance between different aircraft is the most significant to this discussion. The allowance introduced to cater for this contingency is 15% over the expected (average), or 'normal', all engines operative performance in terms of runway requirements. The selection of this particular percentage figure is based on the assumption that aircraft performance exhibits a normal distribution with a standard deviation of 3%. By introducing an allowance of five standard deviations, the probability of exceeding the scheduled allowance is reduced to the order of 10^{-7} [1]. The allowances associated with the engine failure case are also calculated to reduce the probability of exceeding the scheduled runway allowances to the same order of magnitude.

The basis of safety assurance in current procedure, therefore, focuses on providing excess runway to reduce the risk of failing to clear obstacles (exceeding runway distances) to an acceptable level. This approach is probably the only realistic means with which to ensure safety prior to dispatch. Indeed, it has proved to be reasonably satisfactory throughout the whole period of jet operations in air transport to date. Statistical figures indicate that take-off related accidents have constantly been of the order of 12% of all accidents in the last 4 decades [2,3].

This approach towards aviation safety effectively addresses the issue in a global perspective. It is understandable that this would be an acceptable viewpoint to the regulatory bodies and operators, particularly since the public generally tends to associate risk factors with particular activities. The approach, however, can be grossly inadequate to the protection of a particular flight because it lacks the mechanisms that are sensitive to the conditions of each individual take-off.

In fact, current procedure fails to view safety on a flight-by-flight basis. This may result in situations where an aircraft, during a particular take-off run, would become committed to a situation resulting in an accident well before it occurs, but well in time for it to be avoided if there had existed a framework in which corrective action could be taken in good time. In fact, in unfavourable circumstances, a take-off will not exceed the scheduled distances if the leeways introduced to allow for other contingences that do not occur during that run make up for the deficiencies in performance. Although these leeways in practice have provided an adequate level of safety, thus justifying the validity of current practice, they mask the implications of under-performance and can induce a false sense of security that would distract the industry from appreciating the value of improving on current procedure to obtain higher levels of safety during take-off.

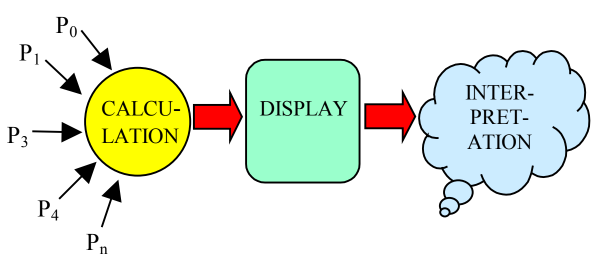
The improvement that is realistic and reasonable is the provision of that framework supporting the application of corrective action as necessary. This would be possible with the introduction of the take-off performance monitor on the flight deck.

2 Instrument reliability

It is immediately appreciated that a take-off performance monitor has to be very reliable. Indeed, it must be capable of detecting unsatisfactory performance with a high success rate, otherwise the effectiveness of the instrument would be compromised. Likewise, the instrument must avoid the provision of erroneous and misleading information that would result in un-necessary take-off rejections. This would defeat the instrument's purpose by inadvertently increasing the risk of accident.

The issue of take-off monitor reliability has been a major concern to the industry [2] and has surely contributed to the reason why no instrument has to date been introduced into commercial operation. Instrument reliability is also relevant in 'normal' take-offs, as the indication would provide further reassurance to the crew that the continued take-off is indeed viable and safe.

Reliability, in the context of take-off performance monitoring, should be interpreted as the capacity of the instrument in leading the crew to take the correct action - that is, to continue or abort the run - that will ultimately result in a successful manoeuvre. The information chain leading to this decision is presented schematically in Figure 1. The performance estimate, calculated from the relevant performance and ambient parameters, is estimated by the algorithms and then displayed. The information is assimilated and interpreted by the crew. The crew's judgment is then taken on the basis of this and other contributory inputs relating to situational awareness. The probability of an incorrect action being taken, therefore, is the product of the individual probabilities at each stage that will cause a wrong action to be taken.



KEY: $P_n = n^{th}$ parameter used in the performance calculations.

Figure 1: The information chain.

Whereas the final go/no-go decision is discrete in nature, the information provided by each stage is not necessarily so. Indeed, at some stage of the calculation, an analogue quantity is invariably generated and the probability of the information resulting in a wrong decision by the crew must, in these circumstances, be quantified by the accuracy of the quantity. The scope of the operational evaluation presented in this work is specifically to establish the accuracy of the algorithms used in a take-off performance monitor developed at Cranfield University.

3 The implications of design methodologies

The accuracy of the instrument's estimate of take-off performance constitutes the core requirement for a reliable monitoring system.

Algorithm accuracy clearly depends on the qualities and capabilities of the models used and on the accuracy of the values of the various parameters used in the algorithms. The methodology with which the aircraft performance is quantified, however, can also significantly affect reliability and, consequently, the overall value of the instrument. Monitoring methodologies can conceptually be divided into two categories, namely non-predictive systems that are capable of estimating only the current performance achieved, and predictive systems that are capable of predicting the performance of the aircraft further down the run.

With non-predictive systems, a particular performance estimate may not, with a satisfactory level of confidence, translate correctly to the viability of continuing or aborting the run. This effectively compromises system reliability. Predictive systems are thus conceptually preferred. An uncertainty, however, is inherently associated with any prediction. This uncertainty is a function of how far ahead the predictive algorithm is required to look. Since the system cannot take into account or predict unknowns before they occur, errors (or uncertainties) so caused can be so significant as to render the prediction useless. Therefore, care is required when attempting to formulate a reliable method of take-off performance monitoring.

4 The Cranfield approach

Following detailed consideration of the implications of various design methodologies, the solution considered optimal for the reliable quantification performance was the prediction of the distance requirements to the decision speed V_1. This followed the acknowledgement of the shortcomings of non-predictive systems and the appreciation that post-V_1 distances cannot be predicted with adequate reliability [4]. Indeed, the instant of rotation, the rotation and transition distances[2] are highly dependent on piloting technique and introduce such a large uncertainty that a prediction is effectively relegated to an estimate of the accuracy comparable with that of scheduled performance.

The authors believe, therefore, that, it is justifiable to use scheduled performance for the post-V_1 distance requirements. Scheduled performance introduces the statistically necessary and industry-accepted allowances to ensure the level of required safety and the use of these distances, therefore, will be acceptable to both the authorities and operators.

This approach effectively reduces the task of real-time performance prediction to estimating the distance the aircraft will cover to V_1. In the acceleration phase of take-off (up to V_1), conditions are generally steady, suggesting that predictions could, indeed, be adequately reliable. If the monitor correctly estimates aircraft performance to be adequate up to V_1, then the aircraft is performing better than the minimum threshold specified by scheduled performance. A positive indication by the monitor would therefore add confidence to the crew that the aircraft will indeed successfully complete the take-off within the post-V_1 distance allowances. Besides, an aircraft with satisfactory performance will have covered less than the scheduled distance to V_1, rendering any excess distance available for the latter part of the manoeuvre and this effectively increases the probability that the remainder of the run will be completed successfully.

The adopted methodology is also capable of successfully handling and identifying instances of inadequate performance. Inadequate performance is generally caused by any of the following effects:

- inadequate thrust
- high runway-related drag
- high aerodynamic drag
- inadequate lift
- any discrete incident adversely affecting performance
- incorrect piloting technique and
- poor braking capacity in the case of an aborted run.

Inadequate thrust would be identified by the monitor early in the acceleration phase of the run due to the latter's predictive capability. The system would therefore be capable of adequately protecting against such an eventuality. The system would likewise be capable of handling and identifying the effects of high runway-related drag.

High aerodynamic drag and inadequate lift are generally the result of either wing icing or mis-set flaps. Although these effects become more significant in the latter part of the run and are therefore difficult to detect early in the acceleration phase, current procedure adequately protects against such eventualities through anti-icing procedures and pre-take-off checks.

The event and effects of a discrete anomaly such as an engine failure, tyre burst or bird strike are considered impossible, in practical terms, to predict prior to their occurrence. Indeed, such a consideration is arguably beyond the scope of a performance monitor. Current procedure effectively protects against such events by the provision of the leeways in scheduled performance. The same applies for variations in piloting technique[3] and braking performance.

The Cranfield methodology of performance monitoring, therefore, is capable of adequately supporting the robust and reliable quantification of whether the scheduled runway allowances will indeed be adequate for the particular take-off. This methodology, however, needs to be matched with accurate

[2] The rotation distance is defined as the distance between the initiation of rotation and lift-off. The transition distance herein refers to the distance between lift-off and the achievement of the screen height, currently set at 35ft above runway level for dry take-off conditions.

[3] Piloting technique significantly affects the rotation and transition distances and the take-off director is an instrument that was intended to reduce this variation by guiding the pilot towards flying the aircraft along an optimal flight path.

algorithms that are capable of realising the potential of the discussed approach.

5 Validation of the performance estimate

The validity and combined qualities of the Cranfield approach towards take-off performance monitoring and the algorithms developed for the purpose were analysed through flight testing. The requirement for flight testing, rather than simulator testing, was, in this particular application, fundamental. This is because simulator models have, to date, not been developed sufficiently to take into account several of the conditions and disturbances experienced normally in flight that can significantly affect the prediction algorithms. As a result, it was considered that only through flight testing could a realistic estimate of the capability of the monitor to handle real situations be evaluated[4].

Preliminary flight testing was carried out at an early stage of the development programme in order to obtain an estimate of the qualities of the algorithms. These flight tests yielded very encouraging results [6], justifying further development of the system and a more extensive flight test programme. This would not only allow the evaluation of the system's operation over a wider range of dispatch conditions, but also provide a statistically meaningful estimate of the performance expected in normal line operation.

To this effect, the algorithms were developed to into an autonomous, real-time monitoring system that runs automatically on start-up, monitors the taxi, identifies the start of the take-off, performs the monitoring process and finally exits on rotation or rejection of the run. This allowed the operation of the monitor to be independent of pilot or engineering intervention and effectively resulted in a system that constitutes the core of an actual take-off performance monitor.

[4] Simulator testing, however, was utilised for the evaluation of the algorithm's performance in conditions that were either difficult or hazardous to replicate in normal operations [5].

6 The flight test vehicle

The aircraft on which the flight test was carried out was the College of Aeronautics' Jetstream-100 flying laboratory (Figure 2). The aircraft is equipped with a data acquisition system interfacing with six lap-top computers organised in five engineering stations and one instructor station, all located in the cabin of the aircraft (Figure 3). An IRS, GPS and a suite of sensors measuring a number of parameters such as TAT, static pressure, airspeed and engine data are connected to the data acquisition computer.

Figure 2: The College of Aeronautics' Jetstream-100 flying laboratory.

Figure 3: Internal view of the Jetstream-100 flying laboratory.

The Jetstream is normally used to conduct aerial laboratory sessions and demonstrations.

Operating predominantly from Cranfield University's 1800m runway, it is regularly dispatched with a wide range of weight and balance configurations, depending on the particular exercise. The Jetstream requires a runway length of the order of 400m to rotation, taking about 17s to reach this salient point in the run.

7 The operational flight test programme

In order to conduct the operational flight test, the software was integrated into one of the aircraft's engineering stations. The algorithms were interfaced with the aircraft's data acquisition system and the output generated was recorded and stored on hard disk for later retrieval and analysis, rather than being displayed as would be expected in normal operation of a take-off performance monitor. The absence of a display was specifically required so that, whilst performing the monitoring process in real-time during the take-off, the system would be transparent to all the stations and crew on board. This approach ensured the operation of the monitor would not interfere with normal operations in any way whilst avoiding compromising the effectiveness of the flying programme.

No restrictions were imposed on the take-offs throughout the flight test programme. The crew, however, was requested to allow scheduled thrust to develop prior to brake release on most of the monitored runs, although rolling start runs were also permitted. This permitted the analysis to focus on 'standard' start take-offs, whilst also supporting the provision of data for the assessment of rolling start departures. In this way, the value obtained from the evaluation process could be maximised. The aircraft was operated in various environmental conditions, although significantly adverse weather situations such as excessively contaminated runway conditions were not encountered.

One particular consideration introduced in the flight test programme to assist in the evaluation of the results involved the selection of V_1, the prediction target speed of the algorithm. V_1 is an airspeed and it is clearly very sensitive to variations in the instantaneous wind vector. The instantaneous wind vector at the instant and location of the attainment of V_1, however, cannot be predicted and therefore a pre-assumed value would need to be adopted. The decision speed for the Jetstream is around 90kts (46m/s) and at that moment the aircraft will be accelerating at about 0.2g (4kt/s). Consequently, a 1kt error in the value of the wind speed used in the calculations will introduce a prediction error of the order of 12m. The uncertainties involved would definitely swamp the overall error, effectively masking the true qualities of the algorithm and significantly reducing the value of the evaluation programme. It was consequently decided to use ground speed for the target speed in the prediction process. It is relevant to note, however, that such an approach, whilst effectively assuming the surface wind at the moment of V_1 will be that used at the time of a particular prediction, does not mask the capabilities of the algorithm to handle the effects on performance of instantaneous variations in the wind component before V_1.

8 Performance results and analysis

Over fifty monitored take-offs were recorded and later analysed. The accuracy of prediction of each run was quantified by a comparison between the instantaneous prediction of the distance required to V_1 and the distance eventually traveled, as determined using IRS data. In order to obtain an objective and meaningful interpretation of the analysis, however, the results had to be rationalised and harmonised. As the run progresses, the monitor will have to look progressively less far ahead and consequently the uncertainty associated with the output of the algorithm falls accordingly. This effect has indeed been noted in the similar decrease in the estimated error exhibited on every run.

It was therefore decided to quantify algorithm accuracy in terms of the maximum error exhibited in particular stages of the take-off run. To this effect, 3 stages were identified.

The first stage comprises all the run to V_1. In the second stage, a quarter of the distance to V_1 will have been passed and the algorithm will therefore have to predict ahead less than 75% of the run to V_1. In the third stage the forward prediction will progressively fall from 50% of the distance to V_1 to no forward prediction at all (Figure 4). This segmentation effectively allows the determination of the maximum error experienced in the last 75% and last 50% of the run to V_1, in terms of distances covered. The quarter and half distance to V_1 were chosen to identify the transit into particular stages since, as the aircraft transits these points, the crew still have approximately one half and one third of the total time to V_1 respectively to act on any decision before V_1 is transited. These two salient points are transited about 9s and 5s respectively before V_1 in the case of the Jetstream (Table 1). The risk associated with the decision to continue or abort the run increases as the aircraft approaches V_1, not only because the aircraft is approaching the far end of the runway at an accelerating rate, but also because the time available for the crew to react is reducing towards zero. The time remaining to V_1, therefore, is of significant relevance to this analysis.

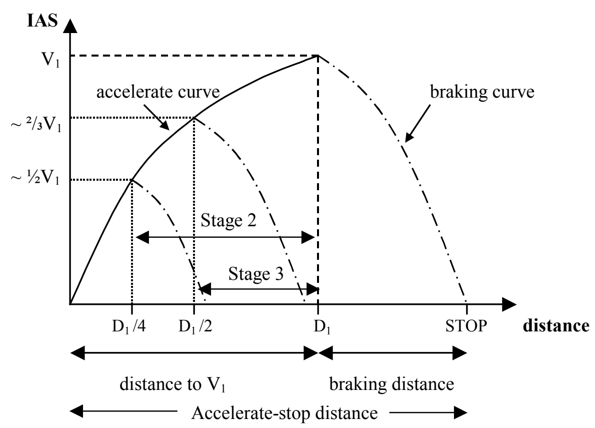


Figure 4: Segmentation of the run to V_1 for the purpose of quantifying system accuracy .

Assuming that the maximum exhibited error is a statistically random variable over different runs it can either be positive (corresponding to the over-estimation of distance requirements) or negative. The sign of the error was considered irrelevant to the evaluation on the grounds that an over-prediction of the distance requirements would be as detrimental to instrument reliability as under-prediction. To this effect, the absolute value of the maximum error was considered. This supported the determination of a meaningful average and standard deviation of the maximum error exhibited in particular stages of the run.

All take-offs were separated into two groups, namely those having a rolling start and those in which scheduled thrust was allowed to develop before brake release, the latter herein referred to as 'standard' start take-offs.

8.1 'Standard' start take-offs

40 runs were recorded and analysed. The details and results are presented in Figures 5 and 6 and in Table 1.

Parameter	Min.	Ave.	Max.
Target ground speed	79kts	90kts	99kts
Time	14.4s	16.8s	20.4s
Distance Traveled	318m	410m	549m
Time left after ¼ dist.	7.4s	8.6s	10.5s
Time left after ½ dist.	4.4s	5.1s	6.3s

Table 1: Summary of salient parameters measured on the 40 'standard' start take-offs.

Assuming that the maximum prediction error experienced in a run is random in nature, thus exhibiting a normal distribution, the average maximum error per run and the standard deviation were calculated. These quantities, expressed in terms of absolute distance and percentage of the distance to V_1, are presented in Table 2. The 99% confidence limit is calculated as the sum of the average error and 2.3263 times the standard deviation.

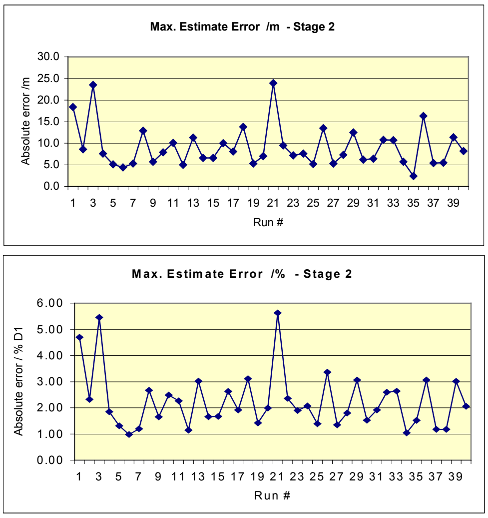


Figure 5: **Graphs of the maximum absolute error experienced in the last 75% of the run to V_1 (Stage 2) on the 40 'standard' start take-offs.**

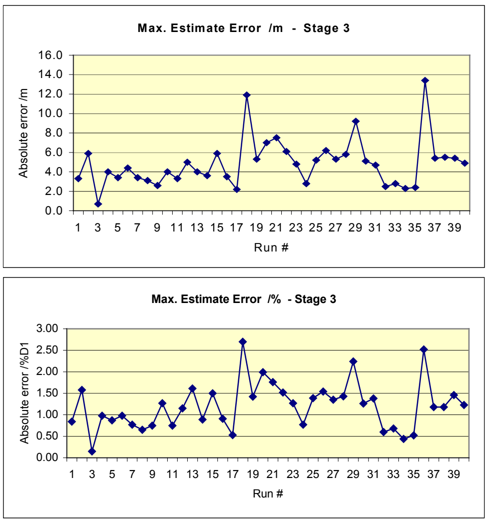


Figure 6: **Graphs of the maximum absolute error experienced in the last 50% of the run to V_1 (Stage 3) on the 40 'standard' start take-offs.**

Max. error	Stage 2		Stage 3	
Average	9.13m	2.26%	4.84m	1.20%
Std. Dev.	4.88m	1.11%	2.49m	0.56%
99% conf.	20.48m	4.83%	10.63m	2.49%

Table 2: **Summary of the estimated accuracy of the prediction algorithm during 'standard' take-offs.**

8.2 Rolling start take-offs

Rolling start take-offs are characterised by an extended initial section in which the thrust will be dynamic and will not yet have reached its target value under steady conditions. The resulting dynamic nature of the initial sections introduces several difficulties in the analysis and quantification of the prediction qualities of the predictive algorithm. The effects are particularly acute on short duration take-offs, as is the case of the Jetstream aircraft.

In practice, it is not possible to provide a reliable prediction of performance before the final target thrust and steady state conditions will have developed. This is mainly due to the fact that the manual control by the pilot cannot be accurately predicted. Indeed, a large variability in the time and motion profile of the engine control lever inputs has been recorded during the initiation of a rolling start take-off.

Any prediction in the initial dynamic section, therefore, can be expected to exhibit relatively large prediction errors. If these errors are encountered at any moment in Stage 2, they will consequently disrupt the objective analysis of the algorithm qualities.

It was therefore decided to discard runs in which the thrust settled more than 6s after initial actuation of the engine controls. 8 qualifying rolling starts were analysed, the results of which are presented in Figures 7 and 8 and in Table 3:

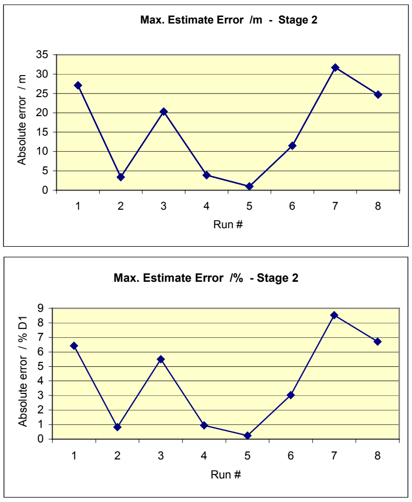


Figure 7: Graphs of the maximum absolute error experienced in the last 75% of the run to V_1 (Stage 2) on the 8 rolling start take-offs.

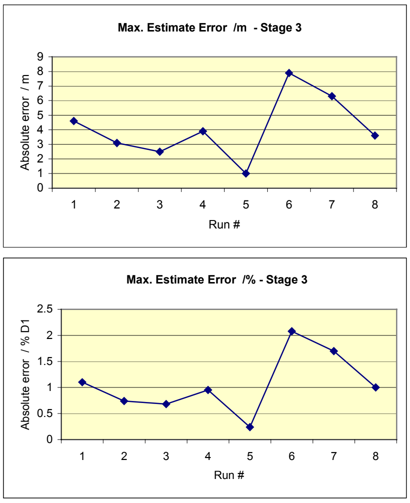


Figure 8: Graphs of the maximum absolute error experienced in the last 50% of the run to V_1 (Stage 3) on the 8 rolling start take-offs.

Max. error	Stage 2		Stage 3	
Average	15.5m	4.03%	4.1m	1.06%
Std. Dev.	12.0m	3.17%	2.2m	0.58%
99% conf.	43.4m	11.40%	9.2m	2.41%

Table 3: Summary of the estimated accuracy of the prediction algorithm during rolling start take-offs.

9 Discussion and conclusion

The analysis of the accuracy exhibited by the predictions indicates that the algorithms are quite robust. Figures 5 and 6 indicate that the maximum error is generally below 15m (3%) in Stage 2 and within 10m (2.5%) in Stage 3. It is relevant to note that these estimates incorporate all the errors that are in practice experienced in real take-offs other than that caused by the uncertainty of the wind vector at V_1. Consequently, the stated error figures also account for effects such as those caused by any changes in runway gradient; those caused by errors in the estimates of the various parameters used (including thrust, aircraft weight and undercarriage drag); those caused by signal noise (including IRS data) and those caused by variations in the wind vector. Indeed, the flight test programme provided a confirmation of the monitor's capability of handling uneven runways. Cranfield's runway has an average slope of 0.03% but features a number of undulations in excess of 2.5m in height. It therefore has ideal characteristics for evaluating algorithm robustness.

Errors due to incidents and disturbances that cannot be predicted before they occur (except for the wind vector at V_1, as already discussed) are also accounted for. The flight testing programme, therefore has indeed allowed a realistic estimate of the accuracies expected in 'normal' take-offs. Moreover, the programme has effectively not only validated the algorithms but also confirmed the validity of the Cranfield approach.

The error figures presented in Tables 2 and 3 are those relative to the calculated distance traveled to V_1 using IRS data. Therefore, in order to estimate the real error of the prediction, which would involve the discrepancy between the estimated distance to V_1 and that actually covered by the aircraft, the error of the IRS must be taken into account. The IRS errors (or uncertainties) increase as the run develops and are estimated to have a standard deviation of about 0.5m at V_1[5]. Although this error is insignificant compared with the prediction error estimates presented in Tables 2 and 3, it quantifies the 'residual error' expected at V_1. The prediction error is by definition zero at V_1 and therefore the overall error in the calculation at that instant would be that due to the IRS uncertainties. This error would consequently be within 1.2m (equivalent to approximately 0.3%) on 99% of the runs.

It is evident that the resulting overall prediction uncertainties are well within the requirements of Aerospace Standard AS8044 [7] and the more stringent in-house standard developed at Cranfield University [8]. It can therefore be confidently concluded that the algorithms should prove adequate for adoption in commercial operations.

The figure can, in fact, be considered to be quite conservative. Indeed, the error can be fairly expected to be much lower than the maximum specified in Tables 2 and 3. For example, although the maximum error (at a 99% confidence level) is expected to be within 4.83% in Stage 2, it will be less than 2.49% in the latter part of that stage and less than 0.3% by the end of it. Furthermore, slight disturbances can delay the convergence of prediction error, resulting in a higher maximum error that does not provide a fair indication of the accuracy on that run. The major effect of such conditions is the increase in the standard deviation of the maximum error. The extreme case of such situations is typified by rolling start take-offs and the effects are reflected in the results presented in Table 3. Whilst the high average error in the early part of the run is a clear indication of the aircraft's dynamic condition, the large standard deviation reflects the variation in pilot input between individual take-offs. Indeed, in Stage 3 (the last 50% of the run), by which time steady conditions will have been achieved, the prediction error exhibited by the algorithm is equivalent to that exhibited on 'standard' start take-offs.

In conclusion, therefore, this evaluation exercise has successfully demonstrated the robustness that can be expected of the algorithm in normal line operation, indicating that the monitor could be useful even during rolling start take-offs on aircraft with short take-off runs.

[5] This value has been estimated following personal communication with the manufacturers of the aircraft's IRS.

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