A PRACTICAL INVESTIGATION OF A TAKEOFF PERFORMANCE MONITOR FOR TURBOPROP AIRCRAFT

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ABSTRACT

The purpose of an aircraft Takeoff Performance Monitoring System (TOPMS) is to provide to the pilot information pertaining to the level of safety with which a takeoff is proceeding. The concept of a TOPMS is not new. Instruments have been developed and flight tested, however the inclusion of a TOPMS as a standard instrument has yet to be embraced by manufacturers and operators.

The authors have investigated the feasibility of using an observer system during the roll and takeoff phase of aircraft operation to provide to the pilot the information that is needed to maneuver safely. Unlike previous work in this field, this investigation focussed on various factors that are unique to the far-northern environment. Further, the Global Positioning System (GPS) was proposed as the sole source of kinematic information. This provided the possibility that a TOPMS could be devised that would require no additional ground-based installation.

A theoretical dynamic model of an aircraft in contact with the ground appears in AIAA 2001-4374, together with an uncertainty analysis and a description of the signal processing technique. A GPS receiver and data acquisition system were installed in an aircraft operated by an airline servicing far-northern Canadian airports. The objective of this investigation was to collect data to validate the theoretical model. It was concluded that a projection of displacement can be determined to within an uncertainty of 15 metres in sufficient time to alert the pilot of an unsafe situation.

AIRCRAFT LANDING AND TAKEOFF PERFORMANCE MONITORING

Aircraft landing and takeoff performance monitoring is an area of research aimed at improving the information available to the pilot for decision making during takeoff or landing. In secluded far-northern regions, where a monitoring system would be particularly useful given adverse weather, few airports are equipped to attempt frictional measurements. In such instances, a monitoring system would need to be totally self-contained and able to determine aircraft ground speed, acceleration, and position relative to the end of the runway. Prediction of the aircraft’s location at rest is then possible. The authors have proposed that a GPS receiver be used to determine aircraft acceleration, ground speed, and position relative to the end of the runway. A practical evaluation of the feasibility of this proposal showed clear superiority of a GPS-derived acceleration over a more traditional method employing accelerometers. Advantages of the GPS-derived measurement included a modest noise level, insusceptibility to gravity and temperature-influenced variations, and far simplified mounting requirements.

Landing and takeoff performance monitoring systems are aimed at averting runway overrun. In northern regions, this has been identified as a common problem. Typical causes of runway overrun include engine failure on takeoff and reduced braking resulting

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from runway contamination.

The “critical engine failure recognition speed” \( (V_r) \) is defined as the speed above which take off could continue safely if the most critical engine failed.\(^3\) \( V_r \) is often calculated prior to startup based on aircraft parameters and estimation of runway and weather conditions. In the event that the aircraft has reached a point such that the remaining runway is equal to the required safe stopping distance and has not yet reached a speed of \( V_r \), the takeoff must be aborted. It is standard practice for pilots to reduce takeoff thrust to a level that would allow acceleration to \( V_r \), followed by deceleration to rest such that the entire length of the runway would be used. This practice prolongs the service life of the aircraft engines.

Operators often use the so called “balanced field concept” to calculate the lowest possible power setting for use during takeoff. Then, at speeds below \( V_r \), there is always enough runway remaining to abort takeoff. Once \( V_r \) is reached, the aircraft could safely takeoff even in the event of the failure of one engine. With this in mind, \( V_r \) becomes a “decision” speed. Figure 1 shows this scenario with a takeoff rejection initiated at a decision speed of 80 m/s on a 2400-metre runway.

![Graph](image-url)

**Figure 1** Theoretical Rejected Takeoff

In 1985, a study was completed at the University of Kansas\(^4\) regarding the design of a TOPMS. By 1987 such a system was developed at NASA’s Langley Research Centre for potential implementation in Boeing’s B777. Simulator evaluations were completed in 1992, and flight testing\(^5\) was performed in 1994. The proposal to include the instrument in the B777 was rejected\(^6\) due to practical shortcomings.

Specifically, there was concern over the non-predictability and variability of wind and runway conditions and the manner in which the device would compensate for this lack of information. Manufacturers predicted that the device may do more harm than good, potentially distracting the pilot unnecessarily.

A similar system for use during approach and landing is currently unavailable because of the inability for the pilot to provide remaining runway length. It is proposed that runway length information be measured independently by way of precise positioning from a GPS receiver. With this innovation, the same observer system could be used for both takeoff and landing.

#### THE FAR-NORTHERN ENVIRONMENT

The runway overrun problem is further aggravated in inclement weather where runway surfaces are contaminated by water or ice. Far-northern regions experience this sort of climate over six months of the year. Further, as such regions are relatively less populated, facilities may receive infrequent maintenance. These factors contribute to the difficulty that pilots experience.

Many airports in far-northern regions are gravel surfaced. The behaviour of a gravel runway may be unpredictable, especially when temperatures are near the freezing point. Measurements of runway friction attempted in such conditions would be relatively unreliable.

The availability of radio navigation systems in far-northern regions is also an issue. While such facilities exist, they are sparsely distributed and tend to service the airports of major population centres. Air carriers that service airports in support of mining and forestry are less likely to have reliable access to radio navigation facilities. The Global Positioning System has provided some relief to this problem.
Some parameters of importance in a TOPMS include wheel bearing viscous friction, aircraft drag, runway slope, engine thrust, aircraft velocity, position relative to the end of the runway, and frictional coefficient between the aircraft tires and the runway. In the far-northern region, however, the majority of airports consist of gravel runways. On gravel runways, the principal means of reducing speed is through the application of reverse thrust. While braking is available to aircraft operating in these circumstances, it is used sparingly and only when absolutely necessary. As a result, a measurement of runway frictional coefficient may not be needed. This serves to improve the likelihood that a monitor specifically suited to gravel runways can be successfully developed. The relative importance of the remaining parameters remains to be determined. It is expected that some parameters may be negligible and the influence of others may be combined.

**GPS**

The Global Positioning System is a satellite navigation system that provides a means of calculating time, position, and velocity data using coded signals which can be processed using a receiver. A minimum of four satellite signals are used to compute three-dimensional positions. A GPS receiver derives position information by measuring the time required for a signal to be transmitted from a satellite with a known position. There are several sources of inaccuracy in this process including receiver noise, tropospheric delay, multipath error, satellite clock errors, orbit errors, and ionospheric delay. The resulting velocity error from time differentiation is less than one metre per second. Further, the velocity error changes slowly resulting in a virtually negligible acceleration error. With the exception of receiver noise, these errors are highly repeatable when considering time intervals of less than one second.

**ACCELERATION FROM GPS**

The notion of acquiring a measurement of acceleration from GPS is not new. When compared to the measurement obtained from an accelerometer, a GPS-derived measurement of acceleration can be used to determine the gravity vector. This technique has been used in airborne gravimetry to determine the gravitational constant with accuracies on the order of $10^{-9} \text{ m/s}^2$, but requires a substantial amount of data to filter out vibrational disturbances.

Although accelerometers have been historically used to determine aircraft acceleration, it is impossible to remove the significant and adverse influence of the gravity vector without additional instrumentation to accurately measure aircraft attitude. Accelerometers do not measure purely acceleration, but rather the force per unit mass on an element of known mass. This problem is avoided through the use of a GPS-derived measurement. This is an especially appropriate choice given the need to locate the aircraft with respect to the end of the runway, an application in which GPS is well employed.

In aircraft landing and takeoff performance monitoring, the desired acceleration measurement should reflect the overall vehicular acceleration as opposed to vibration of sub-components. Accelerometers are well suited to measurement of vibration, where the influence of gravity need not be removed from the measurement, but a GPS-based measurement is clearly superior in stable, piecewise constant vehicular acceleration.

It is important to note that, by virtue of the nature of the GPS signal, an accurate acceleration measurement can be obtained using a single-frequency GPS receiver. A performance monitoring system could be designed in the absence of differential corrections which may be unavailable in far-northern regions where performance monitoring is most needed. This application of GPS appears to be novel.

In a recent study, testing was undertaken to verify the accuracy of the acceleration measurement derived from GPS data. The apparatus consisted of a vehicle-mounted GPS receiver, a bank of accelerometers, and a data acquisition system. The vehicle was rail mounted with no suspension system. Four identical accelerometers provided a confident measure of acceleration. The data acquisition system collected these data at a rate of 20 Hz, electrically synchronized with the GPS receiver’s collection of raw pseudorange. During constant-speed trials, the accelerometers were used to determine the slope of the rail surface so that the influence of the gravity vector could be calculated. This slope information was cross matched with geographic location through the use of
differential GPS. Twenty constant-speed trials were conducted, yielding a reliable measurement of slope. During trials where the vehicle speed varied, the accelerometer data were corrected for the influence of minor pitch changes by subtracting the known slope at the instantaneous position. Both measurements of acceleration were filtered using the same algorithm. The GPS-derived acceleration measurement was then compared with acceleration data from the bank of accelerometers, after accounting for the effect of gravity. The standard deviation of the difference was 0.054 m/s². Closer analysis showed that the calculated difference was within a maximum uncertainty of 0.10 m/s² over 90% of the time.

**PARAMETRIC MODEL**

To construct a theoretical dynamic model of an aircraft accelerating along a runway the various forces acting on the aircraft as functions that vary with the speed of the aircraft relative to the air were described. For a given geometry, the drag acting on an aircraft is proportional to airspeed. It was desirable to show how drag varied with the speed of the aircraft relative to the ground. The relationship for drag,

\[ D = D_3 v_{a}^2 \]  

where: \( D_3 \) is a constant parameter for a given aircraft geometry, and;

\( v_{a} \) is the speed of the aircraft relative to the air.

Applying the convention that a headwind is positive while aircraft speed is positive forward,

\[ D = D_3 (v_a + V) \]  

\[ D = D_3 v_{a}^2 + 2 D_3 v_a V + D_3 V^2 \]  

\[ D = D_1 + D_2 v + D_3 v^2 \]  

where: \( D_a \) are constant parameters for a given aircraft geometry;

\( V \) is the component of wind in the direction of the runway, and;

\( V \) is the speed of the aircraft relative to the ground.

Similarly for thrust,

\[ T = T_0 + T_3 v_{a}^2 \]  

where: \( T_0 \) is a parameter representing the throttle setting, and;

\( T_3 \) is a parameter that accounts for increased thrust at higher engine inlet air pressures.

As before,

\[ T = T_0 + T_3 (v_a + V)^2 \]  

\[ T = T_0 + T_3 v_{a}^2 + 2 T_3 v_a V + T_3 V^2 \]  

\[ T = T_0 + T_2 v + T_3 v^2 \]  

where: \( T_n \) are constant parameters for a given throttle setting.

Simple relationships exist for viscous friction,

\[ F = F_2 v \]  

and for the component of weight in the direction of motion,

\[ W = W_1 \]  

where: \( F_2 \) and \( W_1 \) are constants provided that the runway slope is constant.

Grouping similar parameters,

\[ a = P_1 + P_2 v + P_3 v^2 \]  

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where: \( P_a \) are parameters representing the combined forces acting on the aircraft, and:

\[ a \] is the acceleration of the aircraft in the direction of motion.

A detailed uncertainty analysis for this model and a comprehensive description of the signal processing techniques used appear in Pinder et al\(^9\). Based on the uncertainty analysis, prediction of the displacement of the aircraft was deemed feasible to within an uncertainty of 15 [m]. Validation of this model was performed through experimental investigation. A GPS receiver and data acquisition system were installed in an aircraft operated by an airline servicing far-northern Canadian airports. The data collected in this manner were used to validate the theoretical model and to draw conclusions regarding the feasibility of implementing such a model in a takeoff performance monitor.

### REQUIRED ACCURACY

In a functional takeoff performance monitor, the device would project the displacement that would occur between the instantaneous speed and a decision speed, \( V_i \). This displacement would be added to the projected displacement that would occur when decelerating from \( V_i \) to rest. The total displacement would be compared to the instantaneous measurement of the remaining runway length, and the difference would be displayed to the pilot as a margin of safety. There are several factors that could affect the actual margin of safety, most notably the reaction time of the pilot.

Assuming that pilot would compensate for reaction time by selecting a comfortable margin of safety, the required accuracy of the margin measurement must be selected. For larger aircraft, a larger margin would be selected. It is therefore appropriate to establish required accuracy based on the length of the aircraft. In the most conservative case, a takeoff rejection is initiated at \( V_i \) and the pilot has selected a margin of safety that would be completely consumed by reaction time. In this instance, the remaining runway would be completely consumed during the deceleration phase. It is therefore desirable that the runway remaining when the aircraft has come to rest is no less than one aircraft length. The authors have therefore selected the length of the aircraft, measured from nose to tail, as the required accuracy in the measurement of projected displacement. The aircraft used in this experimental investigation measured 15 metres from nose to tail.

### EXPERIMENTAL INVESTIGATION

A NovAtel 3151RE GPS receiver capable of collecting pseudorange measurements at a rate of 20 Hz was selected for use in the prototype takeoff performance monitor. The prototype monitor was certified for use as a Global Positioning Data Recorder (GPDR) and was installed in a 19-passenger British Aerospace 3112 operated by an airline servicing far-northern Canadian airports. The particular aircraft was equipped with a navigational Bendix King KLN 89B GPS receiver with a Bendix King KA 92 permanent active patch antenna installed over the cockpit with a clear view of the sky. A Starlink BT-2DGPS signal splitter was installed that allowed the GPS antenna signal to be shared by the navigational GPS receiver and the GPDR. Figure 2 depicts the electrical configuration of the complete system. Figure 3 shows the internal configuration of the GPDR. The receiver contained in the GPDR logged position and velocity at a rate of 10 Hz to a portable computer that stored the data to a disk drive. The velocity measurement from the GPS receiver in the test apparatus was derived from time differentiation of position or carrier phase Doppler measurements owing to the manufacturer’s proprietary algorithm.

![Figure 2 Global Positioning Data Recorder - System Electrical Schematic](image)

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During a typical takeoff, the pilot adjusted control settings until the aircraft had reached a speed of 25 metres per second. In view of this, the signal processing technique was designed to determine parameters beginning after a speed of 30 metres per second had been reached to ensure that the dynamics of the aircraft could be reasonably determined with reference to the theoretical model. Once this speed had been reached, the signal processing algorithm continuously projected the displacement that the aircraft would have at an arbitrary speed of 50 metres per second. This speed was chosen as a common reference for all takeoffs as it was always less than the takeoff speed of the aircraft. The projected displacement was then compared with the actual displacement of the aircraft when it reached a speed of 50 metres per second. Figure 4 shows the projected displacement as a function of the instantaneous speed for a typical takeoff where the displacement of the aircraft was 473 [m] when its speed was 50 [m/s]. Note that the variation during the period between 30 metres per second and 40 metres per second corresponded to the time required for parameter convergence. Figure 5 shows a scatter plot of all data collected during 176 takeoffs. Note that as the speed of the aircraft approaches 50 [m/s], the accuracy of the predicted displacement improves as would be expected. This diagram is intended to describe the accuracy with which displacement can be projected throughout a broad range of external factors including varying runways, weather conditions, pilots, and times of day.

With regard to the parametric model, it was hypothesized that the parameter, $P_1$, would be a
characteristic of the aircraft engines and would therefore change slowly, rendering it a constant for any single takeoff. A filter with an effective time constant of several takeoffs in length was used to identify this parameter. In theory, the parameter, \( P_1 \), combines the effects of runway characteristics, weather conditions, and wheel bearing friction. A filter with a time constant a few seconds in length was used to identify this parameter. The convergence of the remaining parameter, \( P_2 \), showed that this was an entirely acceptable treatment of the parameters, \( P_3 \) and \( P_2 \).

**CONCLUSIONS**

The objective of this investigation was to collect data to validate a theoretical model and signal processing technique intended to be used for a TOPMS. The aircraft used in this experimental investigation measured 15 metres from nose to tail. From the data collected, it was concluded that a projection of displacement can be determined to within an uncertainty of 15 metres in sufficient time to alert the pilot of an unsafe situation.

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**REFERENCES**


