Aircraft Performance Monitoring
In Far-Northern Regions

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BIOGRAPHY

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Peter Nikiforuk spent twenty three years as Dean of the College of Engineering. Now retired, he remains actively involved in research as Dean Emeritus.

ABSTRACT

The feasibility of using an observer system during the roll and takeoff phase of aircraft operation was investigated. Unlike previous work in this field, this investigation focussed on various factors 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 an aircraft takeoff performance monitoring system (TOPMS) could be devised that required no additional ground-based installation.

Some parameters considered to be of importance in a TOPMS included 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. While braking is available to aircraft operating in far-northern regions, gravel runways limit its use. On gravel runways, the principal means of reducing speed is through the application of reverse thrust. As a result, a measurement of runway frictional coefficient was assumed unnecessary. This served to improve the likelihood that a monitor specifically suited to gravel runways could be successfully developed. It was expected that some of the remaining parameters may be negligible and the influence of others may be combined.

A theoretical dynamic model of an aircraft in contact with the ground has been devised. A Global Positioning Data Recorder (GPDR) was constructed and 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 such a performance monitoring system.

AIRCRAFT LANDING AND TAKEOFF PERFORMANCE MONITORING

The purpose of an aircraft 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. Prototype monitoring devices 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.

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. It has been 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.

Unlike instrument landing systems, which rely on precise positioning to guide the aircraft to touchdown, 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 from runway contamination.

The “critical engine failure recognition speed” ($V_f$) is defined as the speed above which take off could continue safely if the most critical engine failed. $V_f$ is often calculated prior to startup based on aircraft parameters and estimated 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 $V_f$, the takeoff must be aborted. Choosing a throttle setting to reach $V_f$ is a more complicated matter. If a low throttle setting is chosen, takeoff rejection initiated at a speed below $V_f$ may result in runway overrun if the required stopping distance is longer than the remaining runway. On the other hand, the likelihood of an engine failure on takeoff increases with increased power setting. It is standard practice for pilots to reduce takeoff thrust to a level that would allow acceleration to $V_f$, 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 $V_f$, there is always enough runway remaining to abort takeoff. Once $V_f$ is reached, the aircraft could safely takeoff even in the event of the failure of one engine. With this in mind, $V_f$ becomes a “decision” speed. Figure 1 shows this scenario with a takeoff rejection initiated at a speed of 80 m/s. If a takeoff rejection is initiated at $V_f$, the aircraft would come to rest at the end of the runway.

In 1985, a study was completed at the University of Kansas 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 concluded in 1992, and flight testing was performed in 1994. This instrument was not included in the B777 due to 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.

![Figure 1 Theoretical Rejected Takeoff](image)

A similar system for use during approach and landing is currently unavailable because of the difficulty in measuring instantaneous 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.

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, runway frictional coefficient may be unnecessary. This serves to improve the likelihood that a monitor specifically suited to gravel runways can be successfully developed.

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.

THE GLOBAL POSITIONING SYSTEM (GPS)

The Global Positioning System is a satellite navigation system that provides a means of determining 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 $10^{-5}$ 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.

To allow aircraft landing and takeoff performance monitoring, the desired acceleration measurement must 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/s$^2$. Close analysis showed that the calculated difference was within a maximum uncertainty of 0.10 m/s$^2$ 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 were described as functions that vary with the speed of the aircraft relative to the air. For a given geometry, the drag acting on an aircraft is proportional to the speed of the aircraft relative to the ground. The relationship for drag,

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

where: \( D_3 \) is constant 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, and assuming that the wind velocity is constant,

\[ D = D_3 (v_a + v)^2, \]  

\[ D = D_3 v_a^2 + 2 D_3 v_a v + D_3 v^2, \]  

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

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

\[ v_a \] 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 in the relationship for drag,

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

\[ T = T_0 + T_3 v_a^2 + 2 T_3 v_a v + T_3 v^2, \]  

\[ T = T_1 + T_2 v + T_3 v^2, \]  

where: \( T_n \) are constant 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,

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

where: \( P_n \) are parameters representing the combined forces acting on the aircraft per unit mass of the aircraft, and;

\( a \) is the component of acceleration of the aircraft in the direction of motion.

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.

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. The aircraft had been equipped with a Traffic/Collision Avoidance System (TCAS) whose directional antenna was located less than a metre aft of the GPS antenna. The TCAS processor was unserviceable and had been removed. The GPDR was constructed to dock in the station vacated by the removed TCAS processor. This
station provided power for the GPDR. A cable formerly connecting the TCAS processor to the TCAS directional antenna was slightly rerouted and 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 generated position and velocity logs at a rate of 10 Hz. These logs were stored on the disk drive of a portable computer. 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.

In the first two months of data collection, the GPDR recorded 200 takeoffs and landings. The theoretical model could not be validated using landing data, as there was significant variability in control settings. During a normal approach and landing, the runway length was ordinarily far in excess of that required. The pilot typically applied reverse thrust by moving the throttle levers slowly. As a result, the reverse thrust setting was not constant. At most, a modest evaluation of typical

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**Bill of Materials**

<table>
<thead>
<tr>
<th>Part</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1 - Enclosure</td>
<td>04 MCU Aluminum Enclosure, 4.88&quot; x 7.62&quot; x 12.68&quot;</td>
</tr>
<tr>
<td>3.2 - Antenna Adaptors</td>
<td>TNC Male to Male Adaptor / TNC Female to Female BH</td>
</tr>
<tr>
<td>3.3 - Power Cable</td>
<td>2 Conductor 18 Gauge Power Cord</td>
</tr>
<tr>
<td>3.4 - GPS Receiver</td>
<td>Novatel PWRPAK 3151RE GPS Receiver</td>
</tr>
<tr>
<td>3.5 - Power Control Unit</td>
<td>Power Converter and Relay Logic Circuit</td>
</tr>
<tr>
<td>3.6 - Fuse</td>
<td>3.0 Amp Normal Blow Fuse</td>
</tr>
<tr>
<td>3.7 - Interface Patch</td>
<td>4 Conductor 24 Gauge Interface Wiring</td>
</tr>
<tr>
<td>3.8 - Serial Patch</td>
<td>9 Conductor 28 Gauge Serial Communications Cable</td>
</tr>
<tr>
<td>3.9 - Laptop Computer</td>
<td>Compaq LTE 5000 Pentium 75 Portable Computer</td>
</tr>
</tbody>
</table>

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**Figure 2** GPDR - System Electrical Schematic

**Figure 3** Internal Configuration of Global Positioning Data Recorder
values of the parameter, $P_1$, was possible.

To assess the feasibility of a takeoff performance monitor that uses solely GPS-derived information, multiple takeoffs were examined.

**EXPERIMENTAL RESULTS**

Figure 4 shows the speed profile for a typical takeoff. The shape of the speed profile matched the theoretical model between speeds of 20 metres per second and 60 metres per second. At speeds below 20 metres per second, the pilot had yet to finalize the thrust setting. At speeds above 60 metres per second, the aircraft was airborne. Consequently, the collected data agreed with the theoretical model between speeds of 20 metres per second and 60 metres per second. These boundaries varied for each takeoff because speed was measured with respect to the ground. The pilot lifted the aircraft off the ground shortly after reaching $V_1$, which was a speed measured relative to the air.

Figure 5 shows the speed profile for a takeoff that demonstrated ideal adherence to the theoretical model.

Note that once the aircraft reached a speed of 55 metres per second, the model underestimated the speed of the aircraft for five seconds. This was consistent with a gradual movement of the control column which would remove weight from the landing gear and reduce viscous friction in the wheel bearings. Once the aircraft was airborne and climbing, the speed stopped increasing and the model overestimated the speed of the aircraft.

The data described represent actual commercial flights. As a result, over thirty different runways were used. At the time of the writing of this report, no more than twenty takeoffs from any single runway had been recorded. The statistical significance of parameter variability is therefore of little use at this point. However, from a qualitative examination of the data collected, the authors have formulated hypotheses that are currently under investigation.

It is hypothesized that the parameter, $P_3$, is a characteristic of the aircraft engines and is therefore a parameter that will change slowly, rendering this parameter a constant for any single takeoff. A filter with a time constant of a few minutes in length, and therefore

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**Figure 4** Model performance for a typical takeoff. The parameters used in the model for this comparison were:

- $P_1 = 2.10$ [m/s²];
- $P_2 = 0.039$ [s⁻¹], and;
- $P_3 = -0.00080$ [m⁻¹].

**Figure 5** This is an example of a recorded takeoff that matches the model very well. The parameters were:

- $P_1 = 2.42$ [m/s²];
- $P_2 = 0.034$ [s⁻¹], and;
- $P_3 = -0.00080$ [m⁻¹].

Collected: Mon 27 Nov 2000 at 8:11 am CST Runway 31, Regina (CYQR)

Collected: Fri 06 Oct 2000 at 8:03 am CST Runway 31, Regina (CYQR)
spanning a few takeoffs, will be adequate to identify this parameter.

It is further hypothesized that the parameter, \( P_2 \),
combines the effects of runway characteristics, weather
conditions, and wheel bearing friction. Each runway is
expected to have a characteristic mean and standard
deviation of this parameter, governed mostly by
characteristic surface wind variation. A filter with a time
constant a few seconds in length will be adequate to
identify this parameter.

**PROBLEMS ENCOUNTERED**

Figures 6 and 8 show a potential signal processing
problem. The problem is emphasized in Figure 7, where
raw acceleration data were calculated by simple unfiltered
time differentiation of the speed measurement. For
reasons yet unknown but likely owing to the receiver
manufacturer’s proprietary algorithm, there is a low
frequency jitter in the speed measurement. This has
occurred in approximately one in ten of the takeoffs
recorded to date. Clearly, this does not represent a
dynamic property of the aircraft.

**Figure 6** In some instances, the speed error contains
a low frequency variation. Model parameters:

\[
P_1 = 1.70 \text{ [m/s}^2\text{]};
\]

\[
P_2 = 0.045 \text{ [s}^{-1}\text{]}, \text{ and;}
\]

\[
P_3 = -0.00080 \text{ [m}^{-1}\text{]}. 
\]

Collected: Thu 26 Oct 2000 at 3:07 pm CST
Runway 31, Regina (CYQR)

**Figure 7** Raw acceleration was determined using simple
time differentiation to emphasize speed jitter.

**Figure 8** Another example of speed jitter, as emphasized
in Figure 7. In this instance, the model parameters were:

\[
P_1 = 1.84 \text{ [m/s}^2\text{]};
\]

\[
P_2 = 0.034 \text{ [s}^{-1}\text{]}, \text{ and;}
\]

\[
P_3 = -0.00080 \text{ [m}^{-1}\text{]}. 
\]

Collected: Thu 02 Nov 2000 at 4:16 pm CST
Runway 31, Regina (CYQR)
The magnitude of the variability is within the manufacturer’s published uncertainty, which was deemed wholly acceptable at the commencement of this project. Depending on the signal processing strategy used to identify the model parameters, the nature of the signal variability may result in unacceptable delay.

CONCLUSIONS

The data collected support the theoretical model. This indicated a likelihood that a takeoff performance monitor using data derived solely from the Global Positioning System can be devised.

Future plans involve the likelihood of developing receiver firmware capable of integrating the measurement of position, velocity, and acceleration with the determination of the model parameters. It is anticipated that the signal processing challenges encountered stem from a sub-optimal combination of the manufacturer’s proprietary algorithm and the methods used to filter the model parameters.

Data collection will continue until the end of March 2001. The weather conditions experienced throughout the data collection period represent some of the most extreme in North America. It is expected that further scrutiny of the data trends throughout this period will yield interesting results that may lead to a refinement of the theoretical model.

Industrial partners have shown interest in the development of a TOPMS for trial use by a small segment of air operators. This initiative will be explored later this year.

ACKNOWLEDGEMENTS

The management and maintenance staff of Transwest Air generously provided crucial advice as well as space aboard a Jetstream 31 aircraft for the installation of the GPDR. Neil Larsen and Jonathan Tonn deserve special thanks. Doug Bitner of the University of Saskatchewan Control Systems Laboratory offered timely advice and technical guidance. Daniel Aspel of TR Labs, Saskatoon, provided collaborative technical support. Their efforts are sincerely appreciated.

REFERENCES