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TRAJECTORY RECONSTRUCTION TOOL FOR INVESTIGATION OF RUNWAY OVERRUNS

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Abstract. *This paper describes a software tool to help the investigation of Runway Overruns. A Trajectory Reconstruction method based on the FDR (Flight Data Recorder) data is described. The aircraft trajectory on the final approach segment is reconstructed based on parameters recorded on this device. The involved parameters, the calculations and the method's anticipated shortcomings are discussed.*

Keywords: *Flight Data Analysis, Accident Investigation, Flight Data Recorder*

1. INTRODUCTION

This study focuses on the analysis of events known as *Runway Overruns*. A runway overrun occurs when the aircraft roll-out extends beyond the end of the landing runway (ALAR, 2000). Runway overruns can be considered a particular type of a *runway excursion*, which is defined as a veer off or overrun off the runway surface (CICTT, 2006).

In the recent years from 1984 to 1997, runway excursions were registered in 11.8% of 76 serious accidents (FSF, 1999). Another study conducted by Boeing came to the conclusion that runway excursions were the third deadliest accident category from 1999 through 2008 in accidents involving worldwide commercial jet fleet (Boeing, 2009). Factors that usually are associated with runway overruns are: unanticipated runway conditions, inaccurate surface wind information, unanticipated wind shear, incorrect assessment of the landing distance, unstable approach path, extended flare, failure to arm ground spoilers (or noticing the lack of their deployment), power-on touchdown, bouncing, late braking and differential braking/thrust reverser (ALAR, 2000).

In order to address the need to aid the investigation of this recurrent accident category, a software tool is conceived to calculate the aircraft's trajectory from the final approach to the touchdown point on the runway. This tool performs its calculations based on data recorded by the *Flight Data Recorder* (FDR), popularly known as the "black box", which is a recording device installed to help investigators to reconstruct the events leading to an aircraft accident (NTSB, 2004). The FDR is designed to have an elevated impact tolerance, resistance to fire exposure and water pressure. As the tool is conceived to depend basically from the FDR data, it is possible to perform the trajectory reconstruction even if the aircraft is completely destroyed. Another advantage of an FDR-based reconstruction tool is that it allows the calculation of the aircraft's trajectory in a fast and standardized way, aiding the investigators to comprehend what are the contributing factors to the occurrence.

2. CALCULATION METHODS

The reconstruction tool is built up by two different calculation methods. The first is the *Instrument Landing System* (ILS) method. The second is based upon the integration of the rigid-body aircraft's *Equations of Motion*. The reason for using a dual method approach lies on the first method's incapacity to reconstruct the trajectory all the way to the touchdown point. Each method is discussed in greater detail as follows.

2.1. ILS Method

The ILS is a collection of radio transmitting stations used to guide aircraft to a specific airport runway, especially during times of limited visibility (VICKERS *et al.*, 1997). The ILS is comprised of two signals: the Glideslope and the Localizer. Both consist of space-oriented radio signals that lead the way down to the touchdown point on the runway, which is located at approximately 1,000 feet from the threshold. The glideslope provides the vertical orientation whereas the localizer provides lateral orientation. The glideslope antenna is located besides the runway, nearly 1,000 ft from the runway threshold. It contains transmitters installed in a mast. The upper transmitters send a 90 Hz signal directed slightly above the intended approach slope, and the bottom transmitters send a 150 Hz signal directed slightly below the desired slope. The ILS equipped aircraft has at least one receiver that senses the intensities of each signal and determines the difference in depth of modulation (DDM) between them. If the 90 Hz signal is dominant, it means that the aircraft is above the intended glideslope. Conversely, if the 150 Hz signal is dominant, it indicates that the aircraft is below the glideslope. The localizer works using the same principles of the glideslope. The localizer is located on the opposite threshold, exactly on the projection of the runway centerline. It contains several loop antennas. The leftmost antennas transmit a signal of 150 Hz, whereas the rightmost transmit a 90 Hz signal. **Figure 1** and **Figure 2** illustrate how the system works.

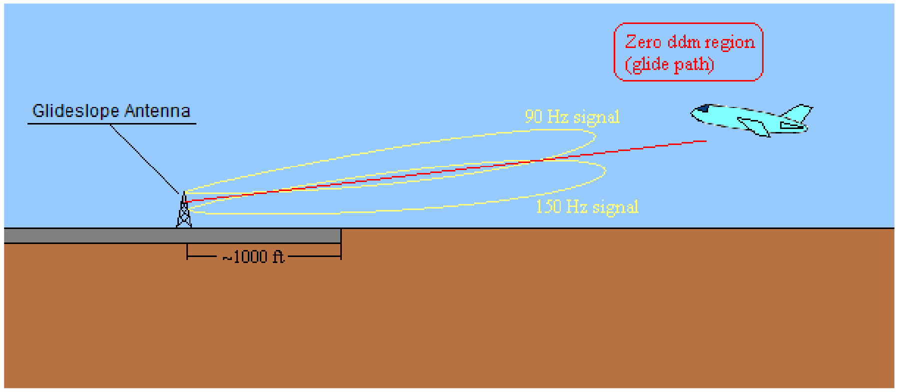

Figure 1. Glideslope working principle

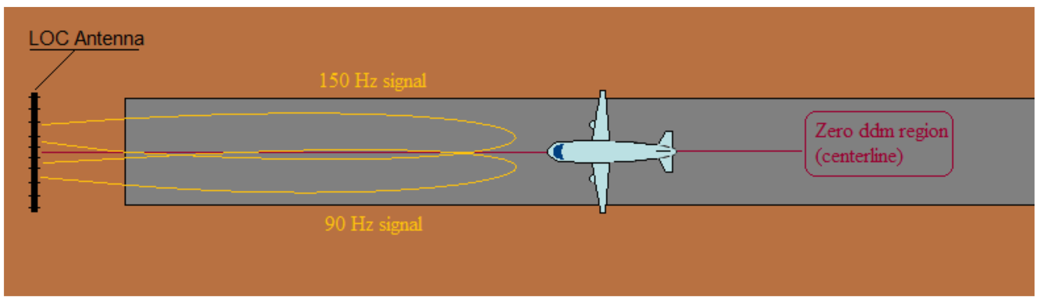

Figure 2. Localizer working principle

In order to calculate the aircraft trajectory from the ILS parameters recorded on the FDR, it is necessary to establish the aircraft's angular deviation from both the glideslope and the localizer references. Once the angular deviations are known, it is possible to determine the aircraft distance from the glideslope antenna (x) as well as the aircraft distance from the centerline (y) by means of simple trigonometric calculations. Equations (1) and (2) show how to accomplish this. In Equation (1), θ is the nominal glideslope angle, δ is the angular deviation from the glide path and h is the aircraft elevation. In Equation (2), δ is the angular deviation from the centerline and D is the aircraft distance from the localizer antenna. Of course, D can be derived from the computed value of x in Equation (1) and the runway dimensions.

$$x = \frac{h}{tan(\theta + \delta)} \quad \textbf{(1)}$$

$$y = \tan \delta \cdot D \quad \textbf{(2)}$$

However, the FDR does not register ILS parameters in terms of angular deviations. Instead, the FDR records the deviations in terms of DDM. In order to calculate the angular deviation from the DDM data, it is necessary to refer to the Annex 10 to the Convention on International Civil Aviation from the *International Civil Aviation Organization* (ICAO). This document specifies aeronautical communications, including the ILS. From it, it is possible to obtain the correlation between the DDM-based measurements and the corresponding angular deviations. From that, it is possible to compute the aircraft trajectory from each FDR sample by using the aforementioned equations.

Unfortunately, this method cannot be used to reconstruct the trajectory until the touchdown. The reason for this is related to the glideslope signal. Due to the antenna location, the deviation signal presents oscillation as the aircraft approaches the touchdown point. Figure 3 illustrates this. Thus, from this moment, the trajectory reconstruction method must be switched so that the results aren't comprised by the glideslope noisy data..

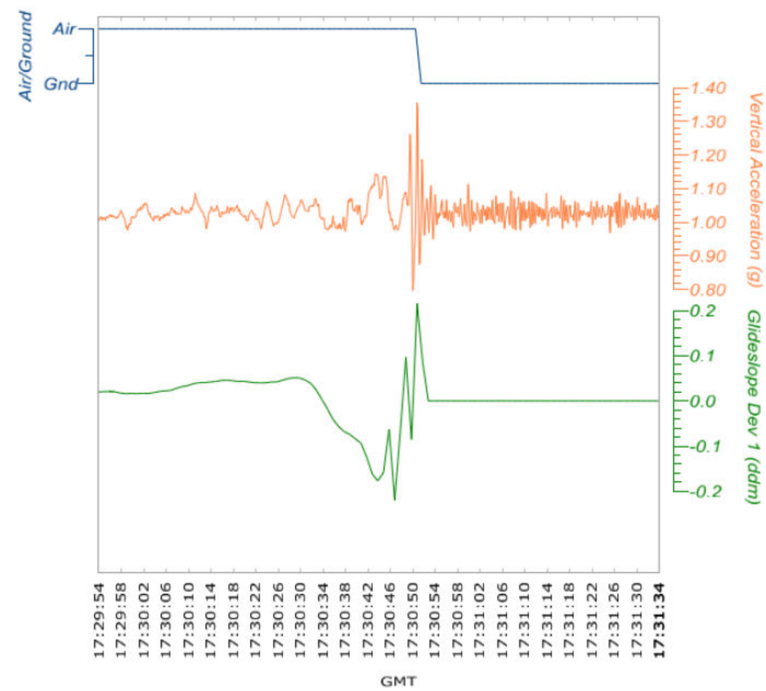

Figure 3. Glideslope deviation behavior during landing

2.2. Integration of the Equations of Motion

Once the glideslope deviation parameter is found to be noisy, the tool begins to calculate the trajectory by integration of the equations of motion. The technique of calculating the trajectory based on inertial measurements has been vastly explored in the literature, especially in the field of identification of stability and control aerodynamic derivatives from flight tests (JONKERS, 1976). The process is often referred to as *Flight Path Reconstruction* (FPR) which consists of properly combining the kinematic model of the aircraft's state trajectory with a compatible set of transducers such as inertial, barometric and flow angle transducers for the measurement of the input and output signals. The method first integrates the equations of motion in order to obtain the time series of the state variables, including the aircraft's coordinates (MULDER *et al.*, 1999). Then, barometric flight data such as airspeed and pressure-altitude, are used to compare the accuracy of the integrated time series and estimate the calibration error present on the measured data. The process is then repeated until the error between the integrated data and cross-check data is smaller than a predefined target. For the scope of this tool, only the integration step of the FPR shall be considered.

The equations of motion are presented in Equation Set (3) (ETKIN, 1972).

$$
\begin{aligned}
\dot{u} =&\ A_x - g\sin\theta - qw + rv \\
\dot{v} =&\ A_y + g\cos\theta\sin\phi - ru + pw \\
\dot{w} =&\ A_z + g\cos\theta\cos\phi - pv + qu \\
\dot{\phi} =&\ p + q\sin\phi\tan\theta + r\cos\phi\tan\theta \\
\dot{\theta} =&\ q\cos\phi - r\sin\phi \\
\dot{\psi} =&\ q\sin\phi\sec\theta + r\cos\phi\sec\theta \\
\dot{x} =&\ u(\cos\theta\cos\psi) + v(\sin\phi\sin\theta\cos\psi - \cos\phi\sin\psi) \\
&+ w(\cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi) + W_x \\
\dot{y} =&\ u(\cos\theta\sin\psi) + v(\sin\phi\sin\theta\sin\psi + \cos\phi\cos\psi) \\
&+ w(\cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi) + W_y \\
\dot{z} =&\ u(-\sin\theta) + v(\sin\phi\cos\theta) + w(\cos\phi\cos\theta)
\end{aligned}
\qquad (3)
$$

In Equation (3), u, v and w are the airspeed components; θ, ϕ and ψ are the Euler angles; p, q and r are the angle rates along the aircraft axes; A_X, A_Y and A_Z are the specific aerodynamic forces; x, y and z are the aircraft coordinates with respect with the inertial reference frame; W_x and W_y are the wind components along the x and y axes of the Earth reference frame.

The Euler angles can be directly obtained from the FDR, and the angle rates can be derived from the Euler angles measurements, by means of differential calculation. The specific aerodynamic forces can be easily obtained from the accelerometer measurements along the aircraft axes, which are recorded on the FDR.

The inertial reference frame is chosen to be the glideslope antenna, for convenience, as the ILS method calculates the aircraft distances from this point. The reference frame is an orthogonal frame. The x-axis is coincident with the runway heading, oriented towards its opposite threshold. The y-axis is perpendicular to the x-axis and points towards the runway's right side. The z-axis, due to the orthogonality, is perpendicular to both x and y axes and points towards the center of the Earth.

In order to begin the integration of the equations of motion, it is necessary to provide the numeric algorithm with the initial conditions of the state vector. To calculate the initial condition of the airspeed components, the angle of attack and sideslip angle measurements can be used. The airspeed components can be obtained by the trigonometric relationship between these parameters. The initial condition of the Euler angles is straightforward as these are directly recorded by the FDR. Finally, the aircraft coordinates correspond to the last valid calculated data by the ILS method, immediately prior to the loss of the glideslope signal. Once the initial conditions are obtained, the numerical integration can be performed using the specific aerodynamic forces and the body rates.

Figure 4 presents the tool's working principle, illustrating the moment in which the transition of calculation method occurs.

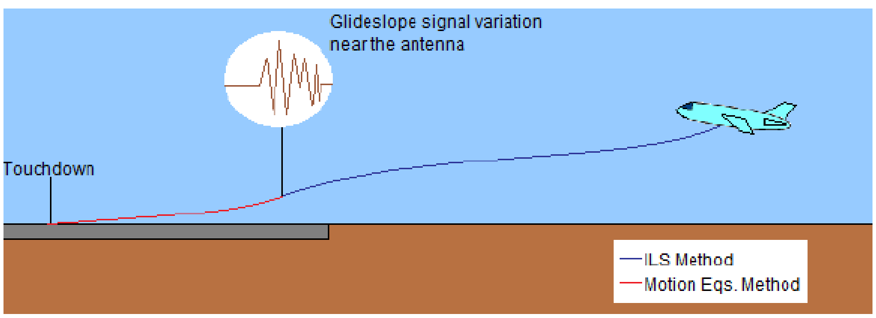

Figure 4. Trajectory Reconstruction Tool working principle

3. TOOL EXECUTION

The proposed computational tool is implemented and a few real FDR flights are tested in order to determine if the algorithm can reconstruct the final trajectory during the final approach. Figure 5 presents the tool's output for a regular landing. The trajectory, as calculated by the ILS method is drawn in green, whereas the trajectory as calculated by the method of the Integration of the Equations of Motion is drawn in blue. The ideal approach path, as defined by the glideslope reference, is drawn in red. When the glideslope deviation signal starts to oscillate, the trajectory reconstruction is accomplished by the integration of the equations of motion. Figure 5 also shows the flare maneuver, defined by the reduction of the sink rate when the aircraft is a few meters above the runway surface. The flare can be easily identified by the point in the trajectory in which it assumes a curved shape.

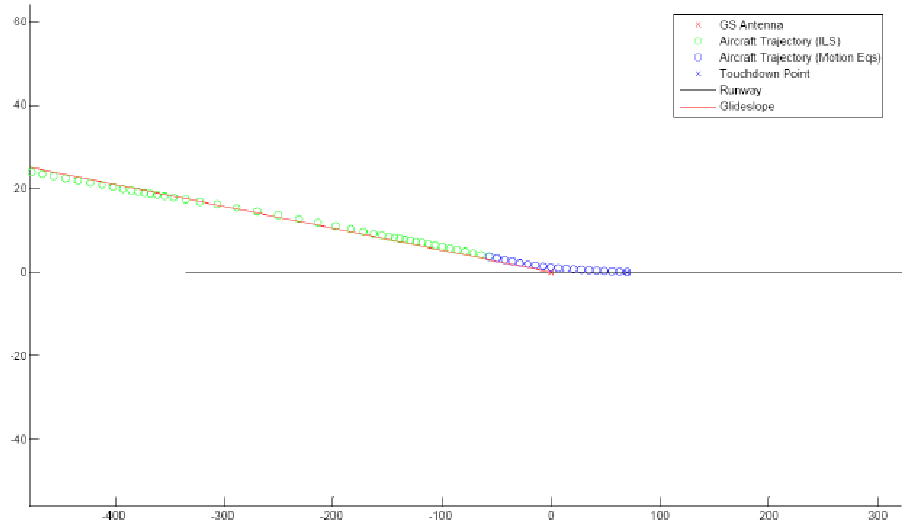

Figure 5. Reconstructed trajectory as calculated by the tool (side view)

4. ERROR SOURCES

The implemented trajectory reconstruction tool has inherent sources of imprecision. They are:

- Varying sampling rates;
- Runway inclination;
- Terrain imperfections;
- Accelerometer bias;
- Pitch angle interference on radio altimeter.

The FDR parameters are recorded under **different sampling rates** which may vary from 0.5 Hz to 8 Hz, depending on the parameter's importance to an accident investigation. The parameters involved in the trajectory reconstruction are not the same. For example, the Normal Acceleration is recorded under 8 Hz whereas the Radio Altimeter is recorded under 1 Hz. This demands the FDR data to be interpolated before performing the trajectory reconstruction. The interpolation process associated with the recording delay constitutes an imperfection source and is likely to reduce the tool's accuracy.

The **runway inclination** is not taken into account by the proposed method. However, some runways present differences in height of some meters between the thresholds. As the tool uses the radio altitude parameter for the aircraft's height, the final approach descent might seem steeper or softer than it really is depending on the inclination. This limitation, however, does not affect the touchdown point position calculated by TRT.

The **terrain imperfections** affect the radio altimeter readings. Of course, the Earth surface is not flat and this characteristic is observed by the radio altimeter. For example, consider a building that is aligned with the runway. When an airplane flies above it, the building's outline can be identified in the radio altimeter parameter. The impact of this is in the fact that this parameter is used to calculate the distance from the glideslope antenna in the ILS reconstruction method. Thus, if the surface has a large quantity of imperfections, such as buildings or hills, the ILS distance is affected. This problem, however, is drastically mitigated when the aircraft crosses the runway threshold, which, for being plain, does not present imperfections detectable by the radio altimeter.

The **accelerometer bias** is an intrinsic characteristic to the acceleration sensors (SMITH, 2005). This characteristic of the accelerometers' readings leads to increasing errors in results if these measurements are integrated for a large amount of time. This is a serious restriction and is the most critical source of imperfection of this calculation method. In order to address this problem, it is necessary to take the bias into account. There are studies that allow for compensation of accelerometer bias. For example, Mulder *et al.* describe the *Flight Path Reconstruction* technique as a means to achieve that (MULDER *et al.*, 1999).

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Depending on the aircraft model, the **radio altimeter** transceiver is not located near the aircraft's center of gravity. This causes the radio altimeter readings to be influenced by the pitch angle rate of change. When the pitch angle is varying during a maneuver, the center of gravity's relative rate of descent is different from the point in which the radio altimeter is located. For the aircraft type used in this experiment, the radio altimeter is located aft from the center of gravity. Thus, during the flare maneuver, the relative rate of descent registered by the radio altimeter is greater than the one on the center of gravity.

5. CONCLUSION

This paper describes a reconstruction tool based on the FDR data. This tool is capable of calculating the aircraft trajectory in the final approach segment using only this source of data with relative accuracy. This imposes some restrictions due to the varying sampling rate of the parameters and leads to results imprecision. Therefore, in order to make the tool more robust to these restrictions, the implementation of the *Flight Path Reconstruction* technique is advisable.

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7. RESPONSIBILITY NOTICE

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