FINAL TRAJECTORY OF THE TU-154M IN SMOLENSK BY THREE INDEPENDENT METHODS

Glenn Arthur Jørgensen

Abstract

This paper summarizes the results from three completely different and independent methods of determining the final trajectory of the TU-154M airplane that crashed on the 10th of April 2010 in Smolensk. The first method is a bottom-up approach where the final trajectory is found by calculating backwards from the crash site and up, utilizing aero dynamic results based on state of the art CFD calculations obtained through a precise 3D model of the TU-154M in landing configuration and performed by Metacomp Inc. - one of the worlds most competent within this field and sub supplier for companies like Boeing. The second method is a top-down approach based on a simple integration of calibrated vertical acceleration data in combination with height recordings based on the three independent GPS units onboard plus the barometric height at TAWS38. The third method utilizes the knowledge of the behavior of aviation fuel released in air at high speed obtained through the past many decades together with the knowledge of wind speed and direction at the time of the crash compared to the extent of the damaged vegetation as can be seen 2 months after the crash east of the runway. The results from all three completely different methods based on completely different sets of data all give the same result within 15m: the plane was at 45m±15m when it first lost the left 5.5m wing tip, followed 1.6s later by a loss of additional lift by a central left wing damage mainly destroying the upper skin of the next 4.5m wing section and then experienced a damage to the central fuel tanks releasing a major portion of the remaining fuel into the air (fuel jettison). The study of the damaged vegetation also confirms the two other studies as the location of the three zones agrees extremely well with the predicted location of the wing damages. The implication of the result of these three studies is that the plane was at about 100 m height above runway, when the pilots called and initiated the go-around (abort of landing). This is the decision height of the particular flight and as such the final height during the descend, by which the pilots according their procedures must take the decision : To either continue or abort the landing approach. With other words the result of the three independent methods is indirectly confirmed by a forth independent observation of the time of the pilot's call of go-around. Furthermore the results obtained by the three methods are individually confirmed by a large number of recorded data and hard core observations. The barometric and radio heights at Taws 35 to Taws 37 disagree with the recorded GPS heights and disagree with the barometric height at Taws 38 and a trajectory based on the barometric/radio heights of TAWS 35 to Taws 37 and passing through TAWS 38 would require accelerations of the TU-154M fare beyond the possible performance of this plane and furthermore disagree with the recorded vertical acceleration data. Disregarding Taws 38 does not solve the problem for the low trajectory based on barometric/radio heights of Taws 35 to Taws 37 as such low trajectory is incompatible with the recorded roll of the plane - the left wing would have to plough through the ground. There exists therefore strong reasons to believe the barometric/radio heights recorded during the final approach up to and including Taws 37 are systematically incorrect by about 60m.

Keywords *- GPS data, wing damage, roll, Smolensk, TU-154, Monte Carlo technique..*

Streszczenie

Praca podsumowuje wyniki trzech zupełnie różnych i niezależnych metod określania końcowej trajektorii samolotu TU -154M, który rozbił się w dniu 10 kwietnia 2010 w Smoleńsku. Pierwsza metoda jest podejściem „od dołu do góry”, przy którym końcowa trajektoria jest znajdywana przez obliczenia wstecz od miejsca katastrofy przez wykorzystanie aerodynamicznych obliczeń CFD przeprowadzonych dla dokładnego modelu 3D samolotu TU -154M w konfiguracji lądowania i wykonanych przez firmę Inc Metacomp. - jedną z najbardziej na świecie kompetentnych w tej dziedzinie i współpracującej z firmą Boeing. Druga metoda stanowi podejście „z góry w dół” i polega na prostym całkowaniu skalibrowanych przyspieszeń pionowych w połączeniu z zapisami wysokości opartymi na trzech niezależnych jednostkach GPS znajdujących się na pokładzie samolotu oraz wysokością barometryczną w punkcie TAWS 38. Trzecia metoda wykorzystuje wiedzę o zachowaniu paliwa lotniczego wypuszczonego z samolotu przy dużej prędkości (uzyskaną w ubiegłych dziesięcioleciach) jak też wiedzę o prędkości i kierunku wiatru w czasie katastrofy w konfrontacji z zasięgiem uszkodzenia roślinności, jakie było zaobserwowane 2 miesiące po katastrofie na wschód od pasa startowego. Wyniki trzech zupełnie różnych metod, opartych na kompletnie różnych układach danych, wszystkie dają ten sam rezultat z dokładnością do 15 m – samolot był na wysokości 45 m ± 15 m kiedy najpierw utracił końcówkę 5,5 m skrzydła, następnie 1,6 s później utracił dodatkowo siłę nośną na skutek uszkodzenia środkowej części lewego skrzydła (głównie niszczącego górne poszycie następnego odcinka o długości 4,5 m), a następnie doświadczył zniszczenia centralnego zbiornika paliwa wypuszczając główną porcję paliwa w powietrze (ang. jettison). Badanie uszkodzeń roślinności również potwierdza dwie pozostałe analizy, jako że położenie trzech stref ściśle zgadza się z przewidzianą lokalizacją uszkodzeń skrzydła. Wyniki tych trzech analiz wskazują, że samolot był na wysokości około 100 m powyżej pasa startowego, kiedy piloci zapowiedzieli rozpoczęcie odejścia na drugi krąg, czyli rezygnację z lądowania. Jest to wysokość decyzyjna każdego lotu – końcowa wysokość podczas zniżania, przy której pilot zgodnie z procedurami musi podjąć decyzję – kontynuować, czy przerwać procedurę lądowania. Innymi słowy - wynik trzech niezależnych metod jest pośrednio potwierdzony przez czwartą niezależną obserwację, tj. czas zapowiedzi pilota o odejściu na drugi krąg. Ponadto wyniki uzyskane przez trzy metody są osobno potwierdzone przez wielką liczbę zarejestrowanych danych i istotnych obserwacji. Barometryczna i radiowa wysokości w punktach TAWS 35 i TAWS 37 nie zgadzają się z wysokościami zarejestrowanymi przez GPS i nie zgadzają się z barometryczną wysokością przy TAWS 38, a trajektoria oparta na baromatrycznych/radiowych wysokościach od TAWS 35 do TAWS 37 i przechodząca przez TAWS 38 wymagałaby przyspieszeń od TU-154 daleko poza możliwymi osiągami tego samolotu i ponadto nie zgadzają się z zarejestrowanymi przyspieszeniami pionowymi. Zignorowanie TAWS 38 nie

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Ms. Sc. Mech. Eng. Glenn Arthur Jørgensen (e-mail: gaj@xtern-udvikling.dk).

rozwiązuje problemu dla niskiej trajektorii opartej na barometryczno/radiowych wysokościach od TAWS 35 do TAWS 37, jako że niska trajektoria jest niezgodna z zarejestrowaną beczką samolotu – lewe skrzydło musiałoby zaryć się w grunt. Dlatego istnieją silne powody by uwierzyć, że barometryczne/radiowe wysokości zarejestrowane podczas odchodzenia w górę włącznie z TAWS 37 są obarczone systematycznym błędem o wielkości około 60 m.

Słowa kluczowe* - *dane GP, uszkodzenie skrzydła, Smoleńsk, TU-154, metoda Monte Carlo..

1. INTRODUCTION

This paper summarizes the results from three completely different and independent methods of determining the final trajectory of the TU-154M airplane that crashed on the 10th of April 2010 in Smolensk.

2. BRIEF DESCRIPTION OF THE MODELS

2.1. Aero dynamic approach

The resulting aero dynamical forces and moments of a TU-154M plane exposed to a left wing loss of 5.5 m and 10 m respectively with and without interaction of the right aileron and right outer interceptor surface are found through the computational fluid dynamics technique (CFD) using validated CFD++ software by Metacomp Inc. and by use of a detailed model of the TU-154M aircraft in cruise and landing mode [1] (see Fig. 2 and Fig. 3). The loss of the wing tip occurs during pulling up in the go-around just prior to exiting the middle marker zone shown in Fig. 2 between the blue triangles at a height of H_{rwy} = 53 m (above runway). The calculated trajectory of the center of gravity of the plane agrees reasonably with the logged GPS height of the TAWS 38 and fits well with the baro corrected height and GPS position stored by the FMS (green squares). The velocity towards the ground at this point is recorded as V_z = 22.2 m/s and agrees well with the calculated V_z = 23 m/s.

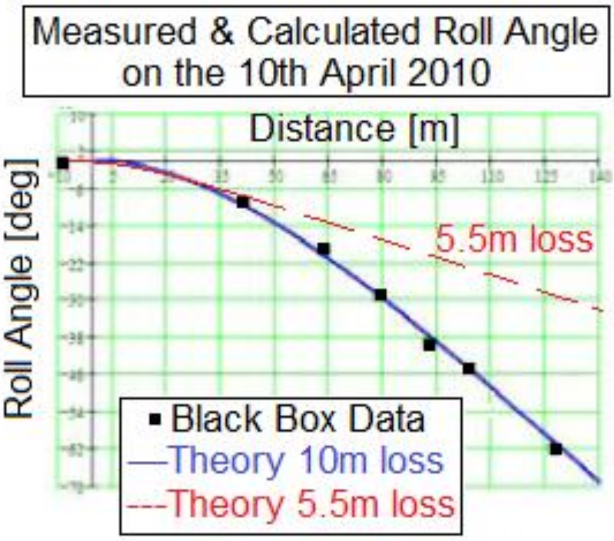

Fig. 1. The measured and calculated roll angles based on the aero dynamic work [1].

The results found correlate well with the manufacturers data for the plane in both cruise and landing modes, thereby confirming the models and method and bringing a level of assurance that the CFD has being solved consistently. Using the found resulting aero dynamical forces and moments as input to the model of dynamics enables the prediction of the flight kinematics when the plane is treated as a rigid body, and the last seconds of TU-154M flight trajectories are calculated. The model predictions are confirmed through the recorded vertical speed and baro corrected height at the time of the FMS power loss. The model predictions are furthermore confirmed through the recorded roll speed during the first 1.6 s of flight after the first wing damage and the recorded GPS and baro corrected height at TAWS 38. As seen in **Fig. 1**, the wing loss of only 5.5 m can explain less than half the measured roll angle about 1.6s after the loss of first wing area, whereas a very good agreement is obtained between theory and recorded data assuming a wing loss of 10m in total. The roll speed and trajectory predictions are in good agreement with results obtained by a totally independent model [2] based on equations solved in a completely different manner, provided the models are presented for the same correct input in form of resulting aero dynamic forces and moments of the plane with the damaged wing. Finally the larger wing loss of 10 m rather than 5.5 m is confirmed by the distance between the ground trace of the left wing and that of the tail [3], (see Fig. 5).

2.2. Integration of vertical acceleration Data

In theory an integration of the black box recorded vertical acceleration data should lead to knowledge of the change in the planes velocity, and another integration of these velocity data should lead to knowledge of the change in the planes height. In practice however it is well known, that the results hereof will be strongly influenced by any existing signal error such as a simple scale or bias error or an error in the signal caused by an average instrument angle etc. The work presented here utilizes the height changes as measured by the three GPS units and recorded at the TAWS 35 to TAWS 38 events *plus* the barometric height recorded at Taws 38 together with the logged vertical speeds at these points to reduce the effect of the various sources of error on the vertical acceleration sensor data, allowing for an accurate determination of the planes height through a simple double integration [4]. The trajectory by this top-down approach giving equal weight to GPS heights and the barometric height of TAWS 38 is shown in Fig. 4. An indication of proper calibration and integration can be found by comparing the recorded vertical speeds with the calculated ones, and the difference between these are found to correlate well and be within the expected measurement uncertainties [5] thereby confirming the model and results.

2.3. Study of zones of damaged vegetation

Airborne military and civilian aircraft must occasionally jettison unburned aviation fuel into the atmosphere [6]. This has therefore been investigated and characterized over the past several decades. As early as 1959, Lowell developed a computer model to investigate the fate of jettisoned fuel [7, 8, 9]. In the 1970's, the United States Air Force (USAF) began comprehensive research into the fate of jettisoned fuel, culminating in a series of technical reports by Clewell. The work presented in [10] is founded on this work but limited to the case of near ground jettison at temperature near 0° C with a low ambient advection velocity for the low volatile jet fuel. Therefore, the overall evaporation plays a minor effect, and the fuel is characterized by bulk "soup" parameters rather than by a sum of parameters connected to the mixture of a finite number of species that approximate the physical behavior of the actual compounds in the actual

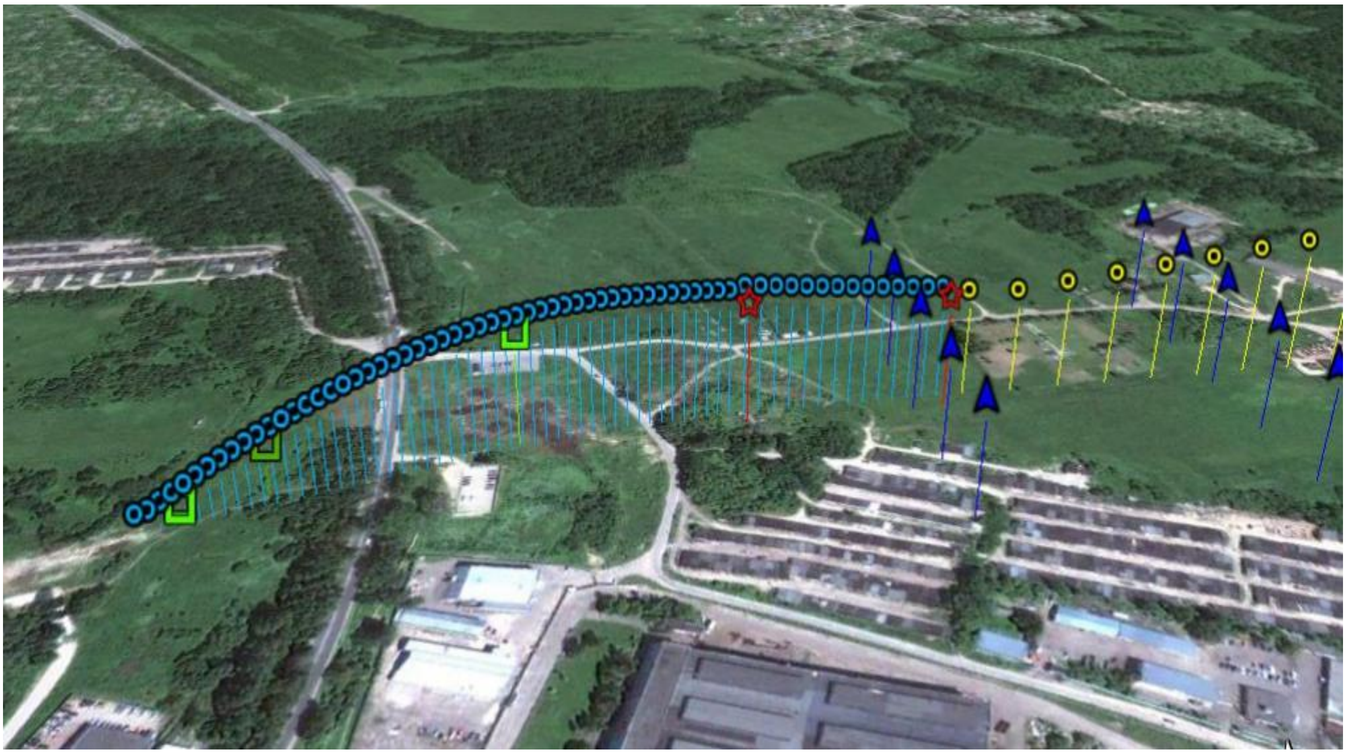

Fig. 2. The trajectory based on the aero dynamic work [1].

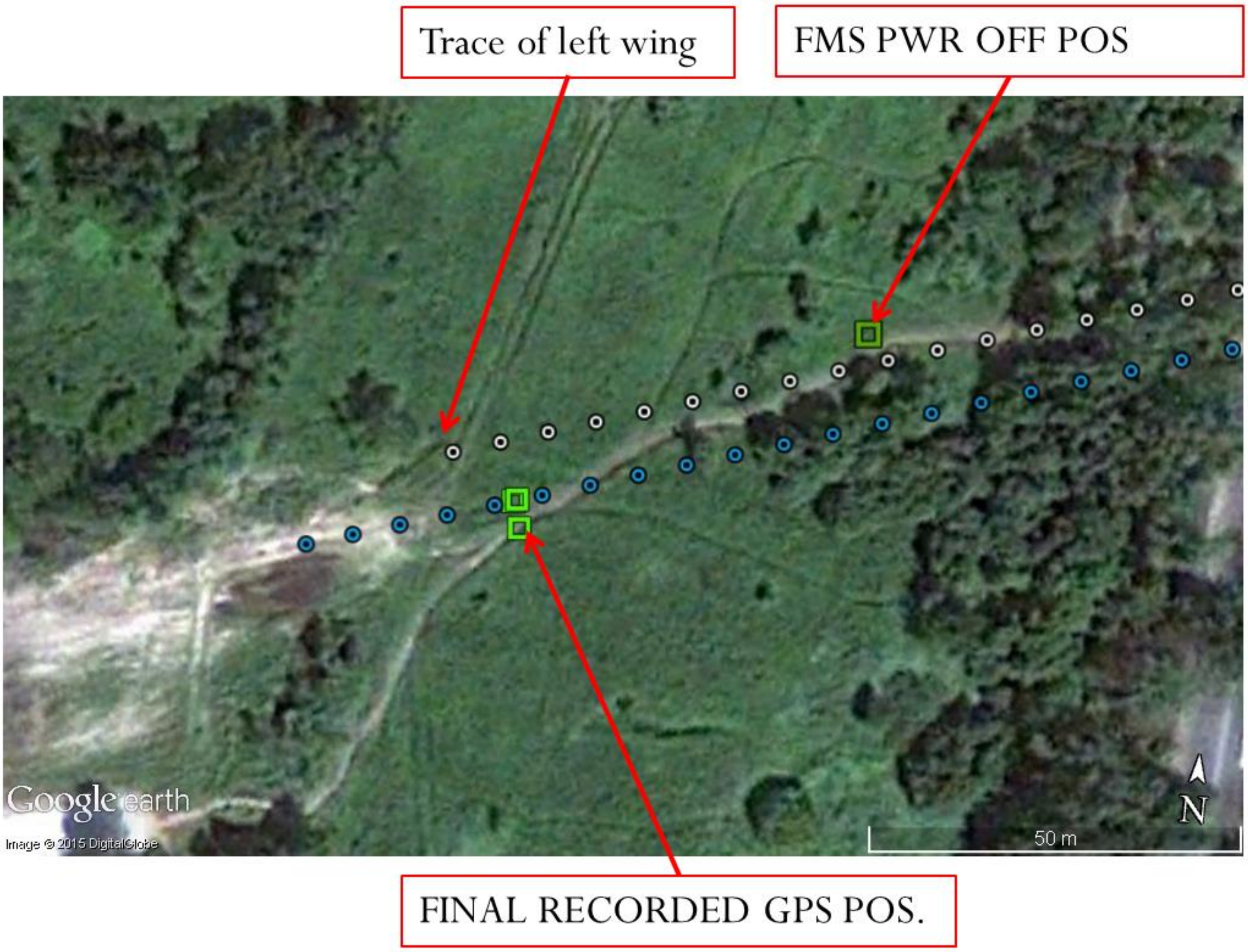

Fig. 3. The trajectory based on the aero dynamic work presented at the Smolensk Conference 2014. The trajectory of the left wing (white circles) agrees with the position the left wing made ground contact, and the trajectory of the center of gravity (blue circles) agrees with the final heading of the plane.

mixture. The bulk evaporation constant is found in this work as to give good agreement between the results reported by [6] for the case of ground temperature of 0° C , low volatile fuel and jettison altitude of 1500 m and the result found in this work for the same. The droplet size distribution produced during the fuel jettison will depend strongly on the conditions of the jettison. The results presented here are based on two important sets of data obtained with two different airplane velocities (175 m/s and 120 m/s). The initial aircraft velocity (and thereby fuel velocity) has a strong influence on the size of the droplets formed. The higher the aircraft velocity the smaller the droplets will be. The effect of airspeed on the formation of sprays has been studied intensively for various commercial reasons. Roughly the characteristic diameter (say measured by Sauter mean diameter or other characteristic diameter) will be inversely proportional to the speed of the air forcing the atomization process [11]. Based on the experimental and theoretical data of the two experiments the droplet distribution for the case investigated in this work (V =75 m/s) are estimated from both sets of data. Assuming the droplets are spherical shaped the fate of the droplets can be found just as the travelled distance can be calculated as a function of wind speed and initial height when released.

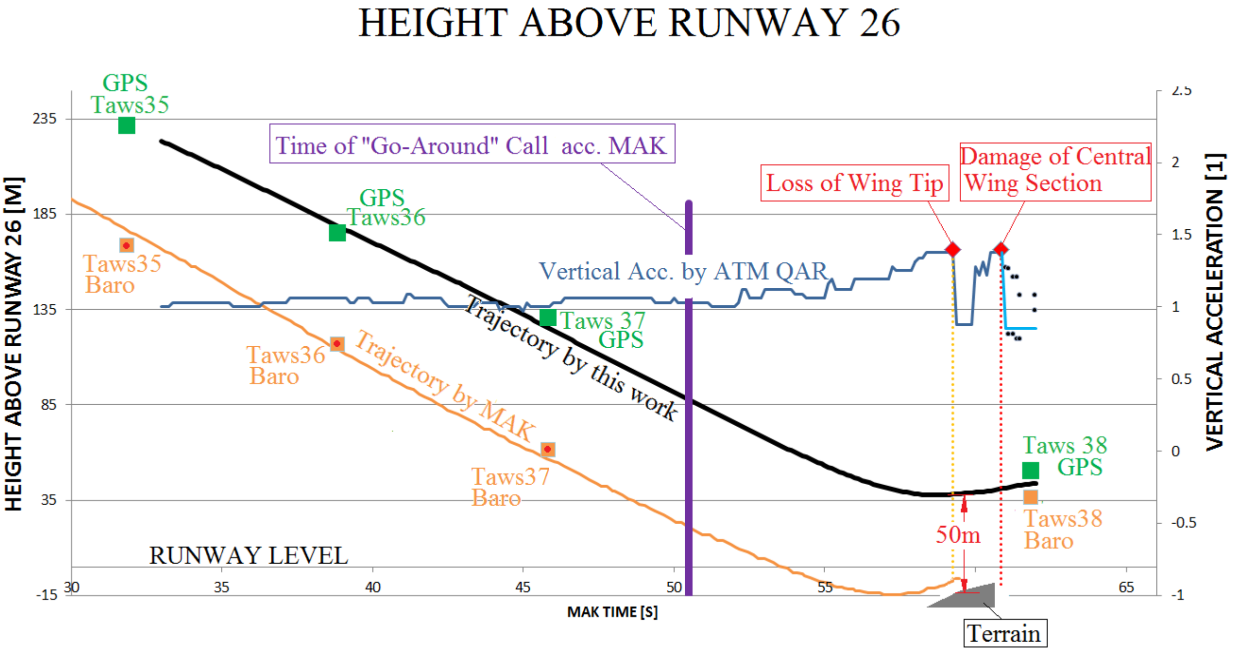

Fig. 4. The trajectory found in this work by integrating the calibrated vertical acceleration data twice and giving the baro corrected height of Taws 38 and all GPS heights equally weight. The calibration procedure is based on a simple least mean squared error method [4]. The height above the runway H_{rwy} = 38 m at the time of the first wing damage.

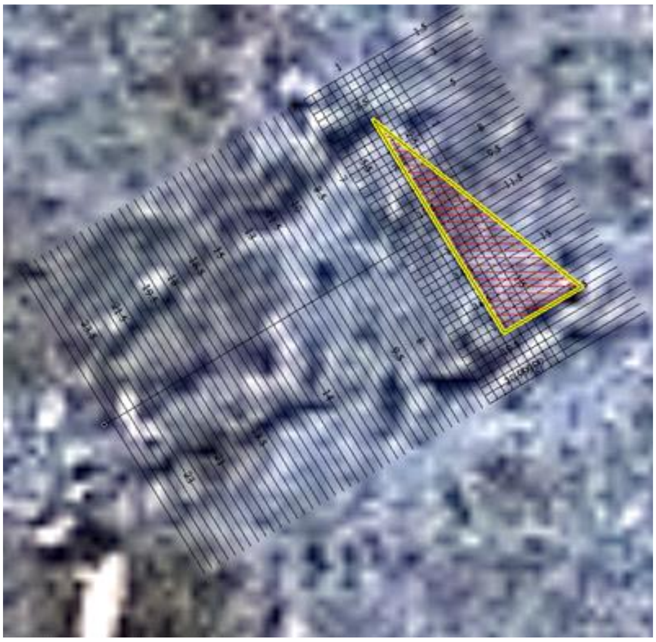

Fig. 5. Satellite photo of ground traces from 11-th of April 2010 (bought from GeoEye). The traces agree with the calculated rotation of the plane and the wing shortened by several meters more than explained by only loosing the wing tip.

3. MAIN RESULTS

3.1. By aerodynamic data

The height of the plane above runway when it lost the wing tip is found as H_{rwy} = 53 m.

3.2. By recorded vertical Acceleration & GPS data

Fig. 6 shows the trajectory based on the work presented in [4] and [5] and assuming the GPS measured heights and the baro corrected height at Taws 38 all have same weight. The height above the runway is found as H_{rwy} = 38 m at the time of the first wing damage. The Fig. 6 shows the measured and calculated vertical sink rate as a function of time, and the good correlation brings a level of assurance that the calibration and integration has being done consistently, and that the calculated trajectory is consistent with all available data (except for the previous mentioned baro corrected/radio heights of Taws 35, Taws 36 and Taws 37 that are offset by about 60 m and disagree with baro corrected height of TAWS 38).

3.3. By study of vegetation damage assuming fuel jettison

By the report of the official Russian investigation the wind direction at the time of the crash was 110° - 130° and the wind speed U = 2 m/s [12:48]. Two months after the crash the ground east of the runway showed three distinct zones of damaged vegetation (see figure 13 of [10]). The locations of the three zones correlate extremely well with the direction of wind and the calculated positions of the two wing damages plus the jettison of fuel from the central fuel tanks (creating zone 3 closest to the crash site). Calculations based on the work of many researchers within the field of fuel jettison and droplet formation show the zones can be produced by an airplane flying along the expected trajectory of the TU-154M in an height above local ground of 50 m and with a speed of 75 m/s. The calculations also clearly show, that the zones cannot be produced when the jettison occurs at 15 m height above the local ground with an airplane speed of 75 m/s. In order to create contamination patterns that can result in such vegetation damage the speed of the plane would have to be about 170 m/s or more than twice the speed of the TU-154M on the fatal approach. The study can furthermore explain how the vegetation damage can start in the direction upstream to the wind as a result of the largest droplets with a diameter of more than 2.5 mm (see figure 7 of [10]). The estimated ground hit of parts released from the plane at the position and height of the largest jettison (of fuel most likely from the central tanks) agrees with the position of parts found into the ground near the Kutuzov street 100 m before the main crash site (see figure 17 of [10]).

Also the part moved by the Russians 35m closer to the crash site on the night between the 11th and 12th April could be the result of the underlying plane damage causing the third fuel release.

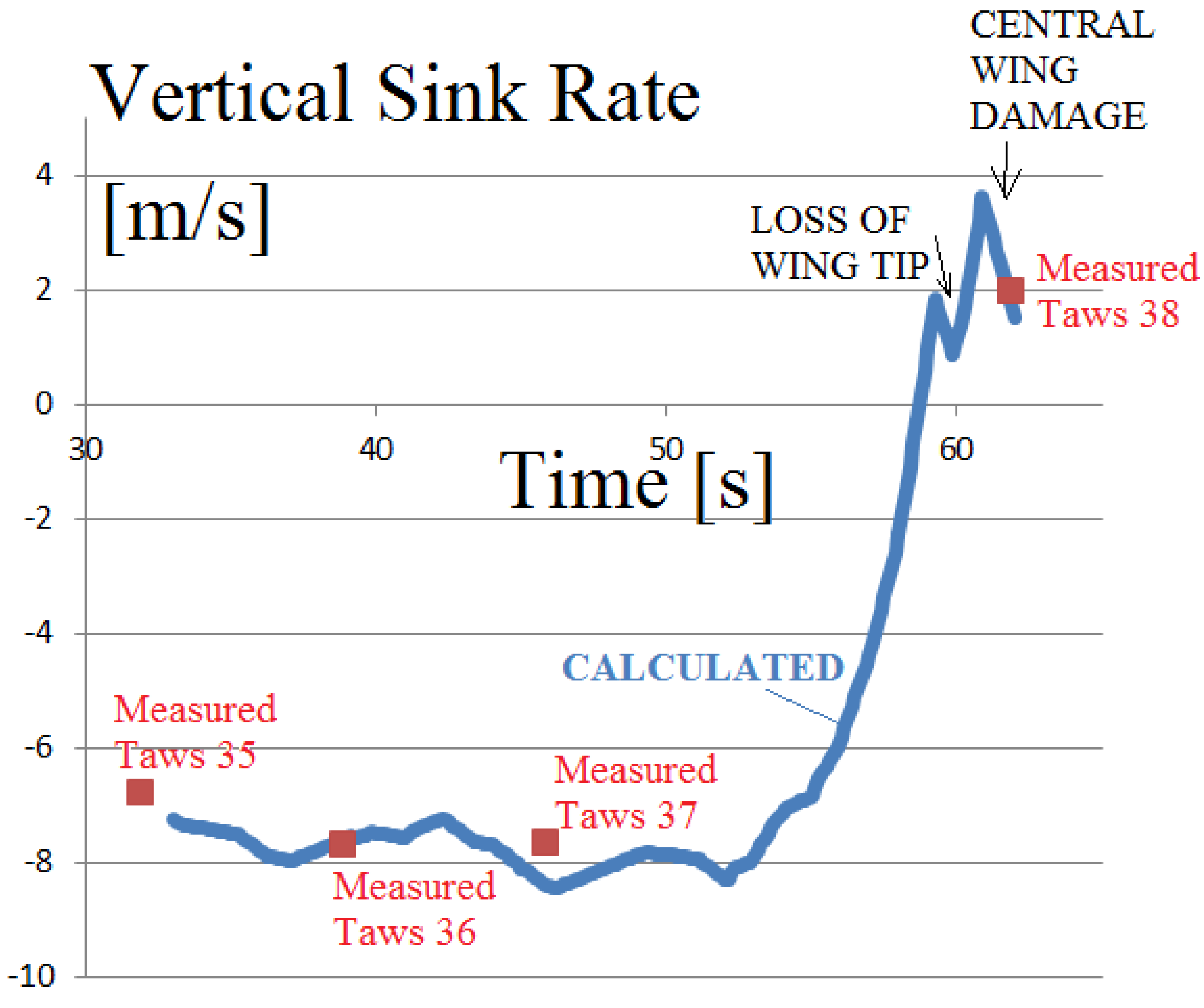

Fig. 6. The vertical sink rate found in this work by integrating the calibrated vertical acceleration data and giving the baro corrected height of Taws 38 and all GPS heights equally weight.

4. SUMMARY

The height of the plane above the runway when the first wing damage occurred (loss of wing tip) based on the three independent methods and including uncertainty of each is shown in Tab. 1.

5. CONCLUSION

Three completely different and independent methods of determining the final trajectory of the TU-154M airplane that crashed on the 10th of April 2010 in Smolensk have been compared. The first method is a bottom-up approach where the final trajectory is calculated backwards from the crash site and up based on the aero dynamic forces and moments found through state of the art CFD work performed by one of the worlds leading companies within this field. The second method is a top-down approach based on a simple integration of calibrated vertical acceleration data in combination with height recordings based on the three independent GPS units onboard plus the barometric height at TAWS 38. The third method utilizes the knowledge of the behavior of aviation fuel released in air at high speed obtained through the past many decades together with the knowledge of wind speed and direction at the time of the crash compared to the extent of the damaged vegetation as can be seen 2 months after the crash east of the runway. The three methods show the height above the runway of the plane when the first wing damage occurred (loss of wing tip) is

Tab. 1. Summary of airplane height at the time of the first wing damage by three independent methods.

Method	H_{rwy} [m]
Aero Dynamic work based on state of the art CFD results	53
Integration of calibrated vertical acceleration data, GPS heights at Taws 35 to Taws 38 and Baro corrected height at Taws 38.	38
Vegetation damage and Fuel Jettison	>30
All results	**45±15 m**

$$H_{rwy} = 45\,^{+15}_{-15}\ m$$

Furthermore the results obtained by the three methods are individually confirmed by a large number of recorded data and hard core observations that are incompatible with the official low trajectory.

References

[1] Glenn A. Jørgensen *"CFD Assessment of Aerodynamic Degradation of the Tu-154M Plane due to Wing Damage"*, Materiały Konferencyjne, Konferencja Smolenska III 20.10.2014, Warszawa 2015

[2] "*Rekonstrukcja Ostatniej Fazy Lotu Samolotu TU-154M.*" Prof. dr hab. inż. Grzegorz Kowaleczko, 31-dec-2013. (Published 04.01.2014).

[3] Glenn A. Jørgensen, "*Reconstruction of Trajectories of Tu-154M in Smolensk during Last Seconds of Flight*". Materiały Konferencyjne, Konferencja Smolenska II, 21-22.10.2013, ISBN 978-83-936018-1-3

[4] Glenn A. Jørgensen "*Combining Vertical Acceleration Data with GPS and Vertical Velocity Data"* Aug. 2015.

[5] Glenn A. Jørgensen " *Comparing Trajectories based on GPS Altitudes and Baro Corrected Altitudes"* Materiały Konferencyjne, Konferencja Smolenska IV, 2015.

[6] Karl Durant Pfeiffer *"A Numirical Model to Predict the Fate of Jettisoned Aviation Fuel"*, AFIT/GCS/ENC/94D-01

[7] Lowell, Herman H. *"Dispersion of Jettisoned JP-4 Jet Fuel by Atmospheric Turbulence, Evaporation, and Varying Rates of Fall of Fuel Droplets."* Technical Report, Washington, DC: National Aeronautics and Space Administration, October1959. NASA TN D-84.

[8] Lowell, Herman H. *"Free Fall and Evaporation of JP-4 Jet Fuel Droplets in a Quiet Atmosphere."* Technical Report, Washington, DC: National Aeronautics and Space Administration, September 1959. NASA TN D-33.

[9] Lowell, Herman H. *"Free Fall and Evaporation of JP-1 Jet Fuel Droplets in a Quiet Atmosphere."* Technical Report, Washington, DC: National Aeronautics and Space Administration, March 1960. NASA TN D-199.

[10] Glenn A. Jørgensen, Chris Cieszewski, Roger Lowe "*Vegetation Damage, Fuel Droplet Distribution and Airplane Height*", Materiały Konferencyjne, Konferencja Smolenska IV, 2015.

[11] K. Ohmer and N. Ashgriz *"Handbook of Atomization and Sprays: Theory and Applications"*. University of Toronto. Published by Springer New York. ISBN 978-1-4419-7263-7.

[12] "*Final Report Eng. Ver. Jan. 10th 2011*", Interstate Aviation Committee, Air Accident Investigation Commission.