

# Ballistic Trajectory Analysis for the CI611 Accident Investigation

Wen-Lin, Guan<sup>1</sup>, Kay Yong<sup>2</sup>

Aviation Safety Council

16th Floor, 99 Fu-Hsing North Road, Taipei 105, Taiwan, R.O.C.

Tel:+886-2-25475200, Fax: +886-2-25474975, Email: Michael@asc.gov.tw/kayyong@asc.gov.tw

## ABSTRACT

On May 25, 2002, approximately 1528 Taipei local time ( UTC 0728), China Airlines Flight No. CI611, a Boeing 747-200 aircraft, with 209 passengers and 16 crewmembers on board, vanished from the ATC radar screen. The CI611 departed from Taipei en-route to Hong Kong. It was later found that the aircraft had an in-flight break-up and crashed into the ocean of Taiwan Strait near Penghu Islands. The crashed site located approximately 15 nm northwest from Makung of the Penghu proper, covered an area 30 square nautical miles with an average depth of the ocean about 70 meters (230 ft). All 225 people on board Flight CI611 were perished.

Aviation Safety Council, an independent government investigation agency of the ROC, is the investigation authority of the CI611 accident. This paper presents the ballistic trajectory analysis to assess the CI611 accident aircraft break up sequence immediately after its in-flight break-up. The results have been validated with ATC radar, Doppler weather data, and salvaged wreckage positions. The ballistic trajectory analysis confirms that the in-flight break up of CI611 aircraft initiated from the aft fuselage. Furthermore, ballistic trajectory analysis also indicated that airborne debris (papers and light materials) from the aft fuselage area, departed from the aircraft about 35,000 ft altitude, and then traveled more than 100 km to the central part of Taiwan.

**Keywords:** ATC radar, ballistic trajectory, CI611, in-flight break-up, wreckage.

## I. Radar information

### Radar Sites that Tracked CI611

There were five radars that detected the accident flight. These radars include: Chiang Kai-Shek, Makung, Lehshan, and Sungshan from Taiwan, and Xiamen radar from Mainland China.

On June, 2003 Aviation Safety Council published the CI611 Accident Investigation Factual Group Collection Report [1]. More detail of the radar data and flight data are describing in that report. Figure 1.8-1 shows the radar track of CI611 and debris spread (radar track: red line; debris

spread: green circle), the five radar sites tracked the CI611 flight are also marked in Figure 1.

### Correction of PSR return signals

Three initial Primary Signal Returns (PSR) surrounding the SSR radar track of CI611 at 1528:08. It is important to note that, because there were no mode-C altitudes in those returns, their positions were all assumed to be zero altitude for general radar surveillance purpose; it means that the slant range between the return signals and radar site

<sup>1</sup> Investigator, Investigation Lab/Deputy Chief

<sup>2</sup> Sensor Investigator, Managing Director

were considered lying in the same horizontal plane. In order to analyze the initial breakup conditions of the CI611 from the PSR returns, FL320 and FL200 are selected to re-process the positions of the return signals during two time durations, 27:55 ~ 28:35 and 28:35 ~29:20.

After correction, one position was re-located to the up-wind side and two positions were re-located to the down-wind side. Figures 2 and 3 superimpose the corrected PSR return signals, the SSR radar track from 1527:58 to 1528:10, and positions of major wreckage. Three dash lines on Figure 2 represent the three initial primary radar returns at FL320, FL200, and FL000. Before correction, there were no relevant PSR returns appeared within 1,500 ft of the recovered positions of engines #1, #2, and the main wreckage field. Figure 4 shows the superposition of the PSR returns, SSR track from 15:28:06 to 15:28:14, and positions of major wreckage.

## II. Ballistic Trajectory Analysis

It should be noted that since it is impossible to obtain the attitude knowledge of the wreckage pieces during rapidly descend with partial body, one can only assume constant ballistic coefficients for this analysis. Thus, the ballistic analysis can only be used as additional information to support the break up of CI611 aircraft.

### Introduction

Ballistic trajectory analysis is applied to selected wreckage pieces salvaged to assist the determination of the break-up sequences [2] [3]. Trajectory of a wreckage piece is traced with a time step simulation from its initial conditions to the

position of that piece recovered from the seabed. The initial condition is described with six parameters; positions (East, North, and Altitude), airspeed, flight path angle and heading.

The ballistic trajectory of a wreckage piece can be calculated based on its mass and aerodynamic characteristics, or the Ballistic Coefficient ( $BC^1$ ).  $BC$  is the function of the mass, aerodynamic drag, and its effective cross section area. From the recovered wreckage piece, specific  $BC$  can be assumed. The ballistic trajectory of that wreckage piece can then be computed based on the wind profile, its  $BC$ , and an assumed initial condition. The computed trajectory will then be compared with the wreckage-salvaged position. Trajectory with higher  $BC$  will asymptotically approach its initial heading of the wreckage object. Trajectory with lower  $BC$  would asymptotically follow the wind drift. Thus, for the pieces with higher  $BC$ , the trajectory matching to the recovery location would be more accurate.

### Mathematics Model of the Ballistic Trajectory

The wreckage distribution showed that wreckage pieces were initially separated from the aft section of the accident aircraft. The Safety Council selects the major items in the red zone, main wreckage, and the engines for the ballistic analysis. Ballistic trajectories analysis has been used successfully for many years, such as **Pan Am 103**<sup>[4]</sup> and **TWA800**<sup>[5]</sup>. In addition, Columbia STS 107 flight accident investigation team adopting the ballistic analysis to reveal that the possible “FD2” object separated from shuttle during the launch phase<sup>[6]</sup>.

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<sup>1</sup>  $BC=Weight/(Drag\ coefficient* Area)=W/(CD*S)$

Dynamic Model of the ballistic trajectory is given as follows:

$$\begin{aligned}\dot{V}_x &= -\frac{Dg}{W} \cos \gamma \sin \psi + a_x = -\frac{\rho V^2}{2BC} g \cos \varphi \sin \psi + a_x \\ \dot{V}_y &= -\frac{Dg}{W} \cos \gamma \cos \psi + a_y = -\frac{\rho V^2}{2BC} g \cos \varphi \cos \psi + a_y\end{aligned}\text{Eq. (1)}$$

$$\dot{V}_z = \frac{Dg}{W} \sin \gamma - g + a_z = -\frac{\rho V^2}{2BC} g \cos \varphi \sin \psi - g + a_z$$

$$BC = \frac{W}{CD^* S}; \quad D = 0.5\rho V^2;$$

$$\gamma = \tan^{-1}\left(-\frac{V_z}{V_{xy}}\right); V_{xy} = \sqrt{V_x^2 + V_y^2}$$

$$\rho = 0.002378e^{-z/30000}, \quad y < 30000 \text{ ft}$$

$$\rho = 0.0034e^{-z/22000}, \quad y \geq 30000 \text{ ft}$$

$$\dot{X} = \int \dot{V}_x dt + V_w \cos \psi_w(h)$$

$$\dot{Y} = \int \dot{V}_y dt + V_w \sin \psi_w(h)$$

$$\dot{Z} = \int \dot{V}_z dt$$

Eq. (2)

Symbols of D and W denote the aerodynamic drag and weight of ballistic object.  $\rho$  Represents air density,  $a_x$ ,  $a_y$ , and  $a_z$  are longitudinal, lateral and vertical un-modeled accelerations along the 3-axes position variables of X, Y and Z, respectively. These un-modeled accelerations are assumed to be zero for this study. Symbols of S and CD represent the reference area of a ballistic object and zero-lift drag coefficient. Terminal velocity is defined as the point at which aerodynamic drag equals the weight of ballistic object, so that it producing zero acceleration in Z-axis. After integrating equation (1) in time, and inputting the wind profile, the 3-axes position variables in equation (2) can be obtained. Applying the initial position and integrating equation (2), the ballistic trajectory of the wreckage piece can then be obtained.

The last recorded altitude, airspeed and heading recorded by the FDR and the time of the last transponder returns are used as the known initial conditions of the simulation. The program outputs a

three-dimensional trajectory of the specific wreckage object when it hits water. The unknown initial position was then obtained by translating the final coordinates of the trajectory to match the coordinates of the wreckage object recovered.

Section of III shows the result of ballistic trajectories, indicating that the red zone pieces separated from the accident aircraft in the first few seconds after the flight recorders lost their power. Since the main fuselage and engines were all very heavy items with high inertia, their airspeed and heading are assumed to be constant. In order to evaluate the timing of the engine separation from the forward body, a specific initial condition was assumed that the forward body was still at high altitude. The damaged aircraft could undergo a very erratic attitude change that may cause the separation of those engines. However, due to its extremely dynamic nature, no attempt was made by the Safety Council to calculate the force required that may cause separation of the engines from the main fuselage after the break up of the aircraft.

### Description of Error sources

There are several sources of error in the ballistic trajectory analysis that should be taken into account when interpreting the results. These error sources are: accuracies of the SSR data, wreckage salvaged position, uncertainties in the estimation of the wreckage weight, aerodynamic drag coefficient, wind profile, buoyancy and ocean currents.

Accuracy of the SSR data is as follows:

- Makung radar: Cross Area > 2m<sup>2</sup>; Separation range: ±1/8 NM (±760ft); min. strength > -104 dB
- Alt error: slant range greater 150 NM, ±1000 x (slant range/150)3 ft

- Accuracy of the wreckage salvaged position: GPS and ROV, better than 50 ft.

About 1,500 pieces of wreckage has been salvaged as refer to the article of “CI611 and GE791 Wreckage Recovery – Operations and Comparisons and Lessons learned.”<sup>[7]</sup>

The Ballistic trajectory analysis assumes that the wreckage pieces fell with a constant BC from the moment of separation from the aircraft main body. Wreckage orientation during decent was nearly impossible to predict. During the initial separation, dynamic forces on the wreckage would result in an initial separation condition from a pure ballistic trajectory for a period, which could induce an error of the final descent point. Furthermore, the ballistic trajectory generated did not consider the possible sub-separations of the wreckage pieces. Ballistic trajectory analysis also assumes that wreckage objects separated from the main fuselage with initial airspeed and heading equal to the last recorded flight condition.

The accuracy of wind profiles would also impact the accuracy of the results. The wind profile would affect the initial positions of the wreckage items, and may also affect their sequence of the separation during the rapidly descent. The wind profiles are predicated by based-on ground metrological data and MM5 model<sup>2</sup>, which is provided by Taipei Aeronautical Meteorological Center (TAMC).

The estimated drift effect of ocean current does not take into account the effect of buoyancy. Ocean depth at the accident site is about 230 ft. The ocean

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<sup>2</sup> The PSU/NCAR mesoscale model (known as MM5) is a limited-area, nonhydrostatic, terrain-following sigma-coordinate model designed to simulate or predict mesoscale atmospheric circulation.

current at the time of the accident was predicted by NCOR to be 2.5 knots to 5.0 knots, northern direction. It is desirable to determine the drift effect of the current on wreckage locations; Figures 4 shows the relationships of drift distance and different ballistic coefficients (BC). The drift effect of ocean currents on heavy wreckage position (BC greater than 10) is less than 500 ft; 1,000 ft to 2,000 ft for the light wreckages (BC less than 10).

### III. Discussion and Results

There were 18 pieces of wreckage analyzed, for which the initial breakup was assumed to have occurred at 1528:03, 34,900 ft, 287 knots, +3 deg flight path angle, and 220 deg of heading. Those 18 pieces separated into four groups; the first group of plots indicates the trajectories of engines; the second group of plots shows the trajectory of the main forward body; the third group of plots shows the trajectories of aft cargo door, the tail empennage, and the recorders; the fourth group of plots indicates the trajectories of the wreckage recovered in the red zone.

Table 1 summaries the ballistic trajectories in the red zone, the main forward body (including cockpit), tail section and engines. Impact time, ballistic coefficients and ID numbers of wreckage pieces are also included. Superposition of the ballistic trajectories, the SSR transponder returns, the PSR returns, and wreckage-salvaged position are shown in Figures 6 and 7.

All the ballistic trajectories were consistent with the salvaged wreckage positions. The average distance error is better then 1,000 ft. Figure 8 (denoted as blue and green) shows the superposition of ballistic trajectories, SSR track, PSR returns,

Doppler weather radar trajectory, and airborne debris distribution. Two trajectories using different wind profiles with the same break up initial condition (BC assumed to be 0.28). These trajectories indicated that airborne debris initiated descent at the altitude about 35,000 Ft. Doppler radar trajectories and the recovered location of those light pieces of debris match with the computed the ballistic trajectory.

### **Higher Accuracy Tracking Radar**

This analysis could be accomplished with better accuracy and in a timelier manner for salvage operation had the better accuracy tracking radar data were available for the investigation effort. It is worthy to note that the US /NTSB has an agreement with its Department of Defense to obtain military and intelligence-gathering ground-based and airborne radar data, as well as satellite data, if available. Plots of data from such sources, if it contains information about an aircraft accident, are provided to the NTSB without compromising the classified nature of the source. For example, when the cargo door separated from the UAL Boeing 747 Flight 811 on 100 miles from Hawaii, US military height-finding radar were used to plot the descent of the door and other pieces of wreckage<sup>[8]</sup>. Those data were used to eventually search for and recovered the remains of the cargo door from the deep ocean.

If the tracking radar data were available, it would have made the task of evaluating the break up and final descent of the wreckage pieces more accurate.

## **V. Conclusions**

This study concludes that the ballistic analysis is consistent with aft fuselage structure of the CI611 separating at FL350. Break-up of CI611 may have occurred in very short duration after the end of the flight recorders, for all or some of the segments or larger segments may have separated into smaller segments after the initial breakup. The engines most likely separated from the forward body in high altitude. Airborne debris (papers and light materials) initially departed from the aircraft most likely about 35,000 ft, and then traveled more than 100 km to Taiwan.

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Table 1 Summary of ballistic trajectories

Obj ID	3-T Trajectory at release (h, m, s)	Ballistic Coefficient (BC)	Wreckage Weight (LBS)	Obj ID
ENG 1&2	07:29:12 UTC	280.00	ENG 1 & 2: 14050	ENG 1&2 (NEW)
ENG 3&4	07:29:18 UTC	220.00	ENG 3 & 4: 11980	ENG 3&4 (NEW)
#1201	07:30:54 UTC	45.00	361100-409400	Crew Cab New
#1201/1202	07:32:59 UTC	1.00		Star STA 194-2040: 08*08
#2011	07:39:44 UTC	1.75	75	Portion of Frame/Screen 40 lbs. 4in*1.7in
#2030	07:38:01 UTC	2.40		1.8in Dia. 40 lbs. with 7 windows. STA 1900-2000
#2034	07:34:58 UTC	5.00		Internal 40-150 Palletage Stack with DR
#2034	07:33:33 UTC	8.00		DR DR
#630	07:32:01 UTC	15.00	16000-24000	Tail
#640	07:34:54 UTC	5.00	714	Sub Cargo DR
#723	07:31:36 UTC	20.00		off cargo door upper
#738	07:36:23 UTC	3.20	309	Large piece wreckage 10in Dia. with Area Base ST 41 400 pounds 5.4 DR and 11 windows
#740/767	07:36:21 UTC	2.10	10.5	After Cargo DR under floor base (2in*1.5in) AFT skin-mount 011023, 6in*2.5in
#741	07:33:01 UTC	10.00	777	off cargo door lower 141 window panel with particles from structure (2in*1in*1in)
#751	07:32:20 UTC	13.00	599	1.5 Area. 40in*40in*2in
#768	07:36:23 UTC	2.00	395	Star with 11 windows near the BARISTA 1000-1100, 1in high
#769	07:36:22 UTC	2.00		Star STA 2230-2340
#870	07:31:15 UTC	25.00		off floor, 3.4in*3.2in (STA 1000-1100)

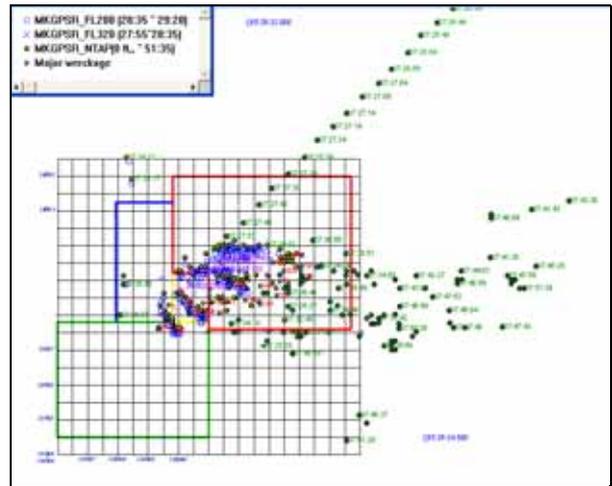


Fig. 2 Superposition of the SSR track, PSR returns, the recovery zones (red, blue, yellow, and green) and positions of major wreckage.

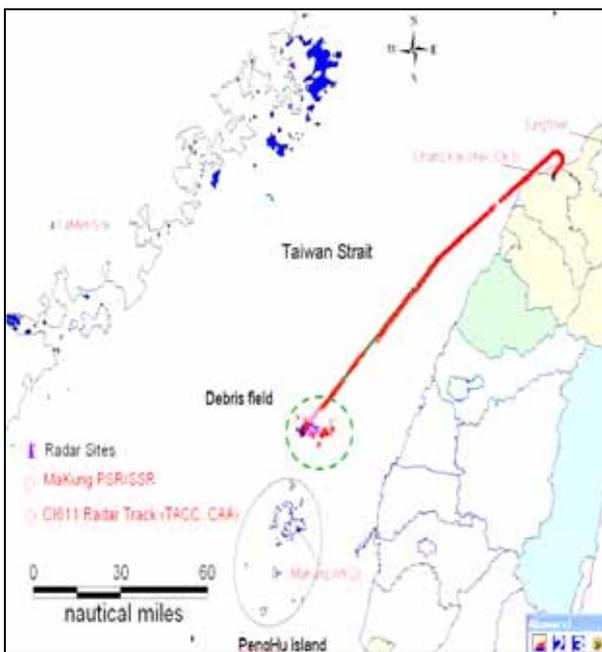


Fig. 1 CI611 radar track, radar sites, and debris field (radar track: red line; debris spread: green circle)

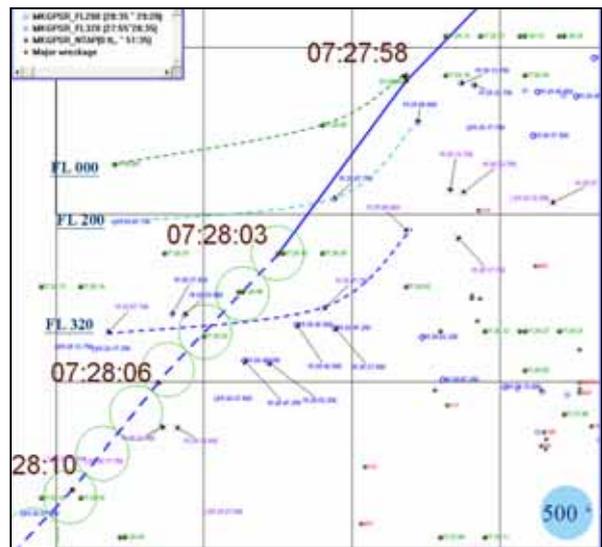


Fig. 3 Superposition of SSR track, PSR returns with altitude correction (red zone).

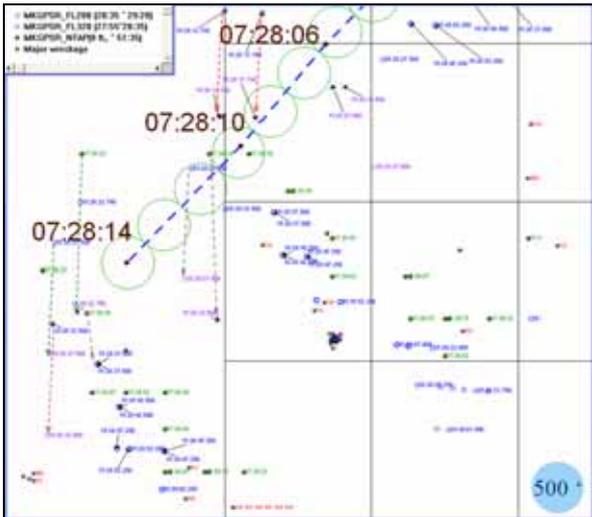


Fig. 4 Superposition of SSR track, PSR returns with altitude correction (yellow and green zones).

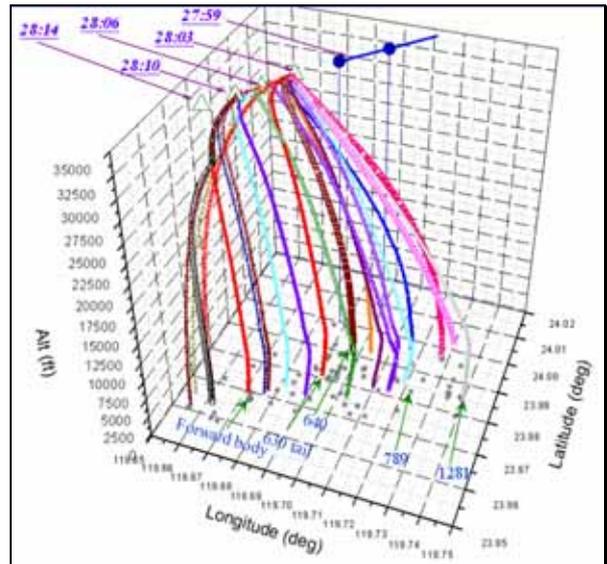


Fig. 7 Three-Dimensional plot of ballistic trajectories

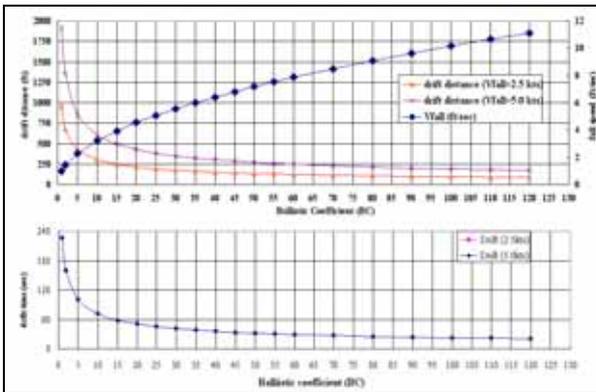


Fig. 5 Comparison of ocean drifts distance on the wreckage and different ballistic coefficients.

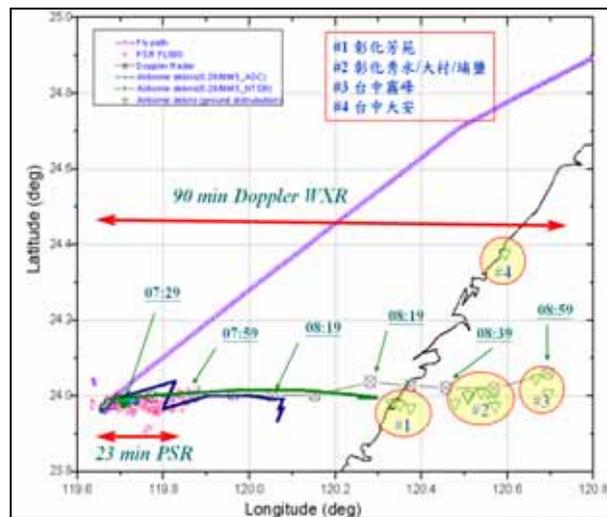


Fig. 8 Two-dimensional ballistic trajectories superimposed with SSR track, PSR returns, and airborne debris.

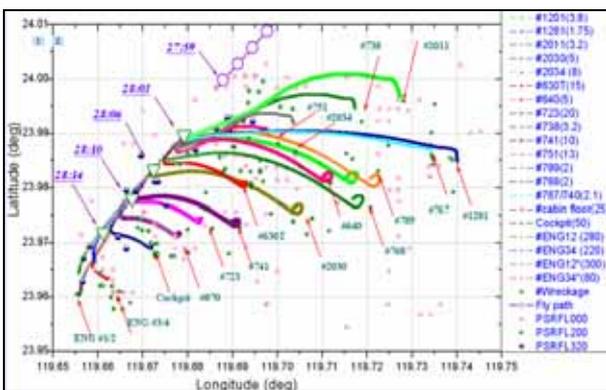


Fig. 6 Two-Dimensional plot of ballistic trajectories