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NATIONAL TRANSPORTATION SAFETY BOARD
WASHINGTON, D.C.

TRAJECTORY STUDY
(15 Pages)

NATIONAL TRANSPORTATION SAFETY BOARD
Office of Research and Engineering
Washington, DC

October 14, 1997

Trajectory Study

A. ACCIDENT: DCA-96-MA-070

Location: East Moriches, New York
Date: July 17, 1996
Time: 2031 Eastern Daylight Time
Airplane: Boeing 747-131, N93119

B. GROUP IDENTIFICATION

No group was formed for this activity.

C. SUMMARY

On July 17, 1996, at 2031 EDT, a Boeing 747-131, N93119, crashed into the Atlantic Ocean, about 8 miles south of East Moriches, New York, after taking off from John F. Kennedy International Airport (JFK). The airplane was being operated on an instrument flight rules (IFR) flight plan under the provisions of Title 14, Code of Federal Regulation (CFR), Part 121, on a regularly scheduled flight to Charles De Gaulle International Airport (CDG), Paris, France, as Trans World Airlines (TWA) Flight 800. The airplane was destroyed by explosion, fire, and impact forces with the ocean. All 230 people aboard were killed.

D. DETAILS OF INVESTIGATION

Overview of Ballistic Analysis

Ballistic analysis is applied to selected wreckage objects found in wreckage scatter fields to help determine break-up sequences. In ballistic analysis, the trajectory of a wreckage object is traced with a time step simulation from an initial condition to the location of the wreckage object on the ground. The initial condition is described with six quantities. Three of these describe the object's initial position (East-West coordinate, North-South coordinate and altitude). The remaining three describe the object's velocity vector (airspeed, flight path angle and heading).

A wreckage object's trajectory from its initial condition is determined by its mass and aerodynamic characteristics. These characteristics are combined into one term, the ballistic coefficient[1] which determines the trajectory of the object. A foam ball, for example, has a very low ballistic coefficient. When released from an initial condition, a foam ball, having very low inertia compared to its drag, will decelerate very rapidly and then fall slowly moving almost exclusively with the wind to its ground location. A bowling ball, on the other hand, is an example of a high ballistic coefficient object. A bowling ball, having a high inertia compared to its drag, will decelerate slowly and continue along its initial heading with very little displacement due to the wind.

Each initial condition corresponds to a curve of wreckage location points representing the possible ground locations for objects launched from this initial condition. The position of an object on this ballistic scatter curve is determined by its ballistic coefficient. On the high ballistic coefficient end the ballistic scatter curve will asymptotically approach the initial heading of the object. On the low ballistic coefficient end, the ballistic scatter curve will asymptotically approach the wind direction.

1. Ballistic Coefficient = Weight/(Drag Coefficient * Area)

Ballistic Analysis for TWA800

The wreckage distribution shows that parts were initially shed from the area just forward of the wing. This was followed by the separation of the forward fuselage. This study concentrated on items in the red field, the first ground search area along the flight path. This corresponded to items shed between the initial event and the separation of the forward fuselage.

Trajectories were determined using the BREAKUP program. BREAKUP was developed at the Safety Board and has been used successfully for many years. The items were launched using the last altitude and velocity vector recorded by the FDR to obtain the coordinates of the item when it hit the ground. The unknown initial position was then obtained by translating the final coordinates of the trajectory so that the trajectory ground coordinates matched the coordinates where the object was found. The translated initial point in the trajectory is then the approximate point where the object separated from the aircraft.

As will be seen, the trajectory study shows that the red zone pieces departed the aircraft in the first few seconds after the initial event. Since the 747 has very high inertia, its velocity vector was assumed to be constant for this period while the red zone pieces separated. With the altitude and velocity vector known, the ballistic coefficient can be treated as an unknown. Ballistic coefficients were thus allowed to vary from the calculated value in order to line up the trajectory origin points with the aircraft heading line obtained from the radar. The order of the origin points along this heading line is then representative of the order of aircraft breakup.

Implicit in trajectory analysis is the assumption that the wreckage items fell in a ballistic manner, without a stable lift vector. In this particular analysis, wreckage items were assumed to have the final FDR velocity as their initial velocity. These assumptions may not be valid for wreckage items CW504 and RF35. These parts are addressed separately in following sections.

Error Sources in Trajectory Analysis

There are several sources of error in trajectory analysis. These should be taken into account when interpreting results. A plot in attachment 1 shows the predicted origin locations for wreckage groups with circles sized to indicate the approximate level of uncertainty.

Trajectory analysis assumes that the wreckage fell with a constant ballistic coefficient from the moment of separation from the aircraft main body. In reality, wreckage will fall in a dynamic mode initially and can, on occasion, switch between falling modes as it descends. During this dynamic mode forces on the wreckage will result in a departure from a pure ballistic trajectory for a period which can introduce error in the ground location.

Trajectory analysis also assumes that objects depart the main wreckage with an initial velocity equal to the main wreckage. The dynamics of the breakup can, in some cases, impart initial velocities relative to the main wreckage. In the case of TWA 800, some velocity could be imparted from the explosion.

The accuracy of the input winds will impact the accuracy of the trajectory results. However, any inaccuracy in the winds would affect the absolute initial positions of the wreckage items but would not affect their sequence unless the winds were changing rapidly with time.

Ocean Engineering has estimated the resolution of wreckage location to be 100 Meters. This error will translate directly into error in initial position. At the initial altitude, the course line itself may be slightly different than used due to the accuracy limitations of radar. This could effect the ballistic coefficients which in turn would move the origin of the trajectories forward or aft along the heading line. This potential error, however, will not effect the order of the wreckage items along the heading line.

Winds for TWA800

Winds used in the trajectory analysis are summarized in the following table. These winds were interpolated to even altitudes from upper air data contained in the meteorological factual report (exhibit 5A).

Altitude	Wind Direction (deg)	Wind Speed (kts)
0	270	12
1000	270	12
2000	280	14
3000	285	17
4000	290	17
5000	303	19
6000	310	19
7000	315	17
8000	320	16
9000	330	12
10000	335	12
11000	320	12
12000	295	16
13000	290	16
14000	300	17
15000	303	19
16000	305	21
17000	315	29
18000	315	33

Effect of Ocean Current

The ocean current at the time of the accident was reported by the Navy to be ½ knot from 090. The depth of the ocean at the accident location is 120 ft. It is desired to determine the effect of this current on wreckage item locations.

To determine the drift due to ocean current the time to fall 120 ft in the ocean must be determined. To do this, the terminal velocity is first calculated as follows.

$$Wt = \tfrac{1}{2}\,\rho\, V_{fall}{}^{2}\, S\, C_D$$

$$Wt/C_D S = \tfrac{1}{2}\,\rho\, V^2$$

$$V_{fall} = (\ Wt/C_D S\ /(1/2\ \rho\ )\ )^{1/2}$$

where:

Wt	=	weight of the wreckage item
ρ	=	density of the ocean (1025 kg/m^3 (Hoerner 1-11)
V_{fall}	=	terminal velocity of the wreckage item in the ocean
S	=	a characteristic area of the wreckage item
C_D	=	the drag coefficient of the wreckage item
$Wt/C_D S$		is the ballistic coefficient for the wreckage item

The time to fall to the ocean floor from the surface is simply

$T = H/V_{fall}$

where:

H = depth of the ocean

With the time to fall known, the displacement due to the current is simply

$D = V_{current}\ T$

The calculations are made in the following table for various ballistic coefficients

W/C_DS (lb/ft)	V_{fall} (ft/sec)	T (sec)	D (ft)
1	1.015	118.2	59.1
5	2.27	52.9	26.4
10	3.21	37.4	18.7
15	3.99	30.1	15.0
20	4.54	26.4	13.2
25	5.08	23.6	11.8
30	5.56	21.6	10.8
40	6.42	18.7	9.3
50	7.18	16.7	8.3
60	7.86	15.3	7.6

As can be seen from the table, the effect of current on wreckage position is negligible when compared to the size of the wreckage scatter and the resolution of the measured wreckage locations (100 meters).

Results

Two separate approaches were used to present the results. The first group of plots shows the trajectories of parts grouped by position in the red zone wreckage field. Inspection of the red zone Debris field shows bands of wreckage concentrations (note: A complete 3' by 4' plot was used, the plot in attachment 2 does not contain all the wreckage locations). The most westerly band is "Wreckage Row 1" with the rows progressing as one looks east. For lower ballistic coefficients, the bands represent the order in which wreckage departed the main body going west to east. For higher ballistic coefficients association with a band cannot be made by inspection. These bands are graphed in attachment 1 and explored in detail in attachment 2. The origin of the wreckage rows are very close together in time. For example (using the last FDR speed), the origin point of row 1 and row 2 are just under a second apart.

It is important to note that, because of the error sources listed in a previous section, wreckage items in adjacent wreckage bands may have departed the aircraft simultaneously. The plot in attachment 2 has the wreckage band origin point symbols sized to approximately indicate the uncertainty. Note however that the radar report shows a radar beacon hit from the Trevose, PA FAA ARSR long range radar ½ second after the last Islip beacon hit. Assuming that the aircraft was intact at the time of the beacon hit, the origin of wreckage row 1 can only be East of the center of the origin point symbol. The plots present the origin of the trajectories assuming pure ballistic behavior. Using these, wreckage items LF74, RF35 and CW504 seem to originate before the last transponder return. The origin position of LF74 is close enough to the last transponder hit that its position is well within the uncertainty of being a post transponder hit event. Wreckage items RF35 and CW504 are addressed below.

The second group of plots shows the trajectories of parts grouped by position in the aircraft. These include red zone fuselage skin, red zone center fuel tank parts, red zone lower fuselage interior parts, and red zone cabin interior parts. These plots are presented in attachments 3 through 7. In these plots, the symbols on the time history positions are nominally 10 seconds apart.

Using the last FDR speed and pitch angle, it is possible to roughly calculate the time from the initial event to the nose separation. However, because of the large uncertainty, this time ranges from 3.9 seconds to 7.5 seconds. The 7.5 seconds represents time from the last beacon hit to the edge of wreckage row six uncertainty rather than to the maximum uncertainty for the nose since the last structure for the nose to be attached to is in wreckage row six

Wreckage Item RF35

Item RF35 is a section of the right side of the fuselage with windows on the lower end. The location this item was found would, assuming that RF35 departed the aircraft with the same initial velocity as the other wreckage items and behaved in a ballistic manner, require that RF35 depart the aircraft at a point on the course line well prior to the last transponder radar hit. Since the initial event would most likely have disrupted electrical power to the transponder, the initial event is believed to have occurred after the last transponder radar contact. This means that either the assumption of a common initial velocity and/or the assumption of pure ballistic behavior for the entire trajectory is invalid.

Further evidence that this part did not behave in a ballistic manner can be found from the required ballistic coefficient to get to its ground location. The lowest ballistic coefficient will be achieved at the highest drag. The highest drag will be achieved if RF35 fell with the maximum area of the part into the airflow as a "flat plate". Calculation of the ballistic coefficient for this falling mode results in a ballistic coefficient of 3.8 lbs/ft^2. However, a lower than minimal ballistic coefficient of 1.0 is required to reach the flight path line. A ballistic coefficient of 1.0 would require a drag coefficient of 4.23 based on the maximum area of the part. This drag coefficient is over three times higher than a flat plat perpendicular to the wind. This is ridiculously high again indicating that RF35 did not behave in a pure ballistic manner.

RF35 is heavy on the windows side and has curvature corresponding to the fuselage frames for most of its length. At the top, the skin curves away from the fuselage frames. With weight on one side followed by camber followed by inverse camber, a stable flying mode is likely for RF35. One measure of gliding performance in the ratio of lift to drag which indicates how far a gliding object will fly forward for a given loss in altitude. A typical general aviation aircraft has a lift to drag ratio of 6 to 7. A lift to drag ratio of only 0.177 is required for RF35 to reach its ground position from the starting position of wreckage row one. Therefore flying is the most probable reason for the position of RF35.

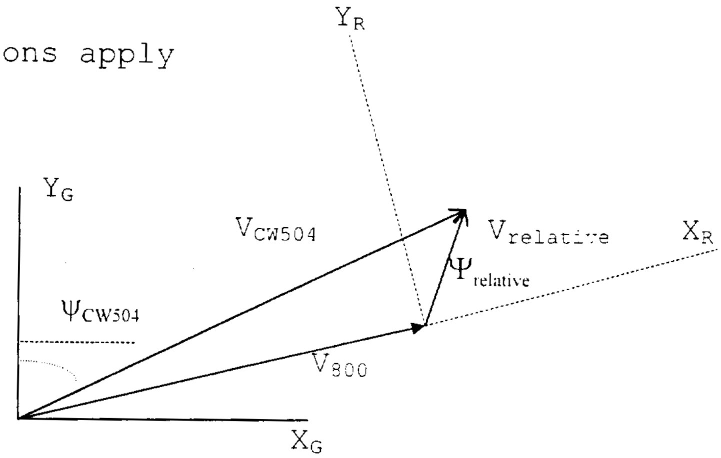
Wreckage Item CW504

Wreckage item CW504 is a flat irregularly shaped portion of the front spar on the far left side of the center tank. As with RF35, the location this item was found would, assuming that CW504 departed the aircraft with the same initial velocity as the other wreckage items and behaved in a ballistic manner, require that CW504 depart the aircraft at a point on the course line well prior to the last transponder radar hit. Since the structural breakup of the front spar would most likely have disrupted electrical power to the transponder, the initial event is believed to have occurred after the last transponder radar contact. This means that either the assumption of a common initial velocity and/or the assumption of pure ballistic behavior for the entire trajectory is invalid. Wreckage item CW504 has no characteristics to suggest that its equilibrium falling mode would be anything but purely ballistic. However, it is possible that item CW504 departed the aircraft with significant angular momentum. Such a rotation will both generate aerodynamic force and delay the equilibrium falling mode until the rotation rate decays. Both the effect of aerodynamic force from rotation and the effect of an initial velocity relative to the aircraft will be investigated.

Initial velocities relative to the aircraft were investigated with program BALLISTIC using the program's search mode. Program BALLISTIC is a Windows 95 program developed at the Safety Board that will search for an initial condition that best matches the ground location of the wreckage item(s). Program BALLISTIC was validated against manual calculations and against the older BREAKUP program. In this case, the initial position for the trajectory was fixed at the location which had been found to be the initial position for the first items to depart the aircraft after the last transponder radar return. To obtain the best initial condition vs. heading, the heading was fixed and the program allowed to search for the initial airspeed and flight path angle combination that best matched the ground position of CW504. As there are several combinations of initial flight path angle and airspeed that can reach a given point, other combinations of initial flight path angle and airspeed were explored by fixing flight path angle and searching for airspeed.

The flight path angle and airspeed vs. heading obtained with program BALLISTIC is relative to the "fixed" Earth. It is desired to resolve the Earth relative velocities into velocities relative to the TWA800.

The following vector relations apply



$$V_{CW504} = V_{800} + V_{relative}$$

$$V_{relative} = V_{CW504} - V_{800}$$

where:

- V_{CW504} is the initial velocity of CW504 relative to the ground
- V_{800} is the velocity of TWA800 relative to the ground at the time of CW504's separation
- $V_{relative}$ is the velocity of CW504 relative to TWA800 at the time of CW504's separation

The scalar components are:

$$V_{x\ relative} = V_{CW504} \cos(\gamma_{CW504}) \sin(\psi_{CW504}) - V_{800} \cos(\gamma_{800}) \sin(\psi_{800})$$

$$V_{y\ relative} = V_{CW504} \cos(\gamma_{CW504}) \cos(\psi_{XW504}) - V_{800} \cos(\gamma_{800}) \cos(\psi_{800})$$

$$V_{z\ relative} = V_{CW504} \sin(\gamma_{CW504}) - V_{800} \sin(\gamma_{800})$$

where:

- γ_{CW504} is the initial flight path angle of CW504 relative to the ground
- ψ_{CW504} is the initial heading of CW504 relative to the ground
- γ_{800} is the initial flight path angle of TWA800 relative to the ground at the time of CW504's separation

ψ_{800} is the heading of TWA800 relative to the ground at the time of CW504's separation

With the initial 71 deg heading, 363kt true airspeed and 2.1 deg flight path angle of TWA800, the equations reduce to:

$$V_{x\ relative} = V_{CW504} \cos(\gamma_{CW504}) \sin(\psi_{CW504}) - 343$$

$$V_{y\ relative} = V_{CW504} \cos(\gamma_{CW504}) \cos(\psi_{CW504}) - 118$$

$$V_{z\ relative} = V_{CW504} \sin(\gamma_{CW504}) - 13.3$$

These components are resolved into their more familiar polar form using the earth axis for angular reference as:

$$V_{relative} = (V_{x\ relative}{}^2 + V_{y\ relative}{}^2 + V_{z\ relative}{}^2)^{1/2}$$

$$\psi_{relative\ earth} = \tan^{-1} (V_{x\ relative}/V_{y\ relative})$$

$$\gamma_{relative\ earth} = \sin^{-1} (V_{z\ relative}/V_{relative})$$

where:

$\gamma_{relative\ earth}$ is the initial flight path angle of CW504 relative to TWA800 at the time of CW504's separation in Earth axis.

$\psi_{relative\ earth}$ is the initial heading of CW504 relative to TWA800 at the time of CW504's separation in Earth axis.

Relative to TWA800's last known velocity vector the angles are:

$$\psi_{relative\ 800} = \psi_{relative\ earth} - 71$$

$$\gamma_{relative\ 800} = \gamma_{relative\ earth} - 2.1$$

where:

$\gamma_{relative\ 800}$ is the initial flight path angle of CW504 relative to TWA800 at the time of CW504's separation in TWA800 flight axis.

$\psi_{relative\ 800}$ is the initial heading of CW504 relative to TWA800 at the time of CW504's separation in TWA800 flight axis.

The above equations are solved in an EXCEL spreadsheet and the results plotted in attachment 8. These plots show flight path angle, initial speed and error (distance from the predicted position of CW504 to the actual position of CW504). Data plots are presented for both relative to the ground and relative to the airplane (after the transformation discussed above).

The breakup sequence indicates that CW504 may have left the airplane with significant angular momentum. The departure sequence would result in CW504 rotating counter clockwise when viewed from the top and left of the aircraft. This will result in an aerodynamic force down and to the left until this angular momentum bleeds off and the equilibrium falling mode can be established. Such a force is in the correct direction to produce a change in position velocity and flight path angle which could account for the position of CW504. To get an idea of the possible magnitude of the aerodynamic force, lifting line theory was applied. For example, if Wreckage item CW504's angular momentum decays in 2 seconds, an average rotation rate of 115 RPM will produce a velocity of 340 Knots relative to the aircraft (the minimum velocity required from attachment 8). A combination of an initial velocity due to the breakup and the response to the aerodynamic force from rotation could result in the final wreckage location of item CW504.

Ballistic Coefficient Calculations

For most wreckage items in the red field (i.e. those items that departed the aircraft in the first five or six seconds), the ballistic coefficient was determined from the object's position on the scatter curve. This was possible since the initial velocity vector and altitude were known from the FDR.

The attached plots are grouped by the positions the wreckage objects were found on the ocean floor and by the object's original position on the aircraft. For objects in the later category, the ballistic coefficients were estimated. The calculations for these estimates are presented in attachment 9. The ballistic coefficients are summarized in attachment 10. Note that, due to their probable non-ballistic behaviors, the ballistic coefficients for wreckage items RF35 and CW504 could not be determined from their position on the scatter curve.

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Attachments

1. Scatter curve summary
2. Trajectory plots organized by wreckage position on the ground
3. Red zone fuselage skin trajectories
4. Center tank trajectories
5. Lower fuselage interior trajectories
6. Forward cargo structure trajectories
7. Selected cabin interior
8. Item CW504 required initial conditions from wave 1
9. Ballistic coefficient calculations
10. Ballistic coefficient summary