Missing Aircraft Crash Sites and Spatial Relationships to the Last Radar Fix

Robert J. Koester; Ian Greatbatch

BACKGROUND: Few studies have examined the spatial characteristics of missing aircraft in actual distress. No previous studies have looked at the distance from the last radar plot to the crash site. The purpose of this study was to characterize this distance and then identify environmental and flight characteristics that might be used to predict the spatial relationship and, therefore, aid search and rescue planners.

METHODS: Detailed records were obtained from the U.S. Air Force Rescue Coordination Center for missing aircraft in distress from 2002 to 2008. The data was combined with information from the National Transportation Safety Board (NTSB) Accident Database. The spatial relationship between the last radar plot and crash site was then determined using GIS analysis.

RESULTS: A total of 260 missing aircraft incidents involving 509 people were examined, of which 216 (83%) contained radar information. Among the missing aircraft the mortality rate was 89%; most occurred in mountainous terrain (57%); Part 91 flight accounted for 95% of the incidents; and 50% of the aircraft were found within 0.8 nmi from the last radar plot. Flight characteristics, descent rate, icing conditions, and instrument flight rule vs. visual flight rule flight could be used to predict spatial characteristics.

CONCLUSIONS: In most circumstances, the last radar position is an excellent predictor of the crash site. However, 5% of aircraft are found further than 45.4 nmi. The flight and environmental conditions were identified and placed into an algorithm to aid search planners in determining how factors should be prioritized.

KEYWORDS: search & rescue, radar forensics, crash factors.

Koester RJ, Greatbatch I. *Missing aircraft crash sites and spatial relationships to the last radar fix*. Aerosp Med Hum Perform. 2016; 87(2):114–121.

In 2013, within the continental United States, 63 missing aircraft incidents were reported to the Air Force Rescue Coordination Center (AFRCC). Search missions typically account for approximately 4% of the AFRCC missions.[3] However, they often account for a disproportionally larger amount of resources and cost. The challenge of finding a missing aircraft is immense, especially when a distress signal has not been received.

The 63 incidents resulting in searches is a much smaller subset of reported crashes. In 2013 the National Transportation Safety Board (NTSB) recorded 1431 aviation accidents with 339 fatalities.[17] Several papers have examined sport crashes,[8] helicopter crashes,[4,25] aeromedical crashes,[16] general aviation crashes,[18] instrument-rated private pilots,[21] and commercial aviation crashes.[19] In addition, the spatial distribution of crashes has also been examined.[10,13] Studies specific to missing aircraft include the New Two Area Method (given this name since it defines two different rectangles based upon the flight path with different probability densities)[20] and a similar study conducted in the United States.[7] Both of these studies looked at the spatial distribution of missing aircraft relative to the intended trackline to report track offset distances and percentage of route covered. These studies allowed the creation of probability of containment (probability of area) maps which have been incorporated into computer software that allows the optimal allocation of search and rescue resources.[1,2] However, the search areas created are quite large and only suitable for searches by aircraft or vessels. Limited work has also looked at the relationship between the crash site and where the aircraft first intersected with a weather front.[24]

From Kingston University London, Kingston upon Thames, United Kingdom.

This manuscript was received for review in June 2015. It was accepted for publication in November 2015.

Address correspondence to: Robert J. Koester, B.A., M.S., Department of Geography & Geology, School of the Natural and Built Environment, Faculty of Science, Engineering and Computing, Kingston University London, Penrhyn Road, Kingston upon Thames, KT1 2EE, United Kingdom; r.koester@kingston.ac.uk or robert@dbs-sar.com.

DOI: 10.3357/AMHP.4396.2016

The purpose of this work was to perform data acquisition and analysis that looks at retrospective search data for aircraft radar track, aircraft flight characteristics, and weather. One of the most powerful tools, when available, is radar track data collected by the Federal Aviation Administration (FAA) and/or military radar and forwarded to the AFRCC. This data, when properly understood and used by search planners, may generate more confined "areas of highest probability density" where missing aircraft may have crashed. The aircraft's radar track and last radar plot in particular provides the opportunity to update the last known position from the point of departure to the last radar plot. Determining the correct radar track and then the last radar plot is a component of radar forensics provided by the AFRCC, FAA, and 84th Radar Evaluation Squadron (84 RADES).[15] NASA developed a software tool known as World Wind Air Search and Rescue that displays previous radar tracks.[14]

In a search and rescue incident the most operationally critical information is making probabilistic projections of where the aircraft will travel beyond the last radar plot. Syrotuck was the first to describe Euclidian distances from the last known position to the eventual find location in ground search and rescue.[23]

In the extensive search for Air France flight AF477, no radar data was available.[5] However, this incident illustrates the value of search theory and the application of different models to establish a posterior probability distribution. The last known position of 2.98°N/30.59°W was provided by GPS in an Aircraft Communications Addressing and Reporting System. This message is sent every 10 min, which results in a 40 nmi search area.[5] A database of nine airline transport accidents involving loss of control while at cruise altitude was obtained by the Bureau d'Enquêtes et d'Analyses from the Russian Intrastate Airframe Group.[22] This data showed a median of 4.3 nmi and a maximum of 20 nmi (when adjusted to the 35,000-ft altitude to match AF477 altitude). An additional probability model was constructed by back drifting the floating debris from the wreckage. All three probability maps were combined and then adjusted for prior search efforts.[22] Using the new combined posterior distribution, the wreckage was found 6.5 nmi from the last known position in one of the highest probability areas.[5]

Ultimately, the goal of this research is to create spatial models that provide a probability of containment map that can be updated, in a Bayesian fashion, as new information is learned. Such a map will allow the use of formal search theory first described by Koopman for the nautical environment.[12] However, Stone has found it to be highly effective for many different search situations.[9] While Abi-Zeid and Frost[1] were the first to incorporate probability of area based upon route information into aircraft software, this study is the first to look at radar data as a key factor. The blending of radar track, mountainous versus flat terrain, intended route of flight, and observed weather in a computer generated visual presentation will aid search planners in identifying "areas of highest probability density." Search planners can then concentrate their efforts in those areas which will improve search efficiency, reduce search risk, and ultimately save search resources and more lives.

METHODS

Missing aircraft incidents within the continental United States that resulted in search efforts are recorded by the AFRCC. Data was collected for incidents covering a time period from 2002 to 2008. Data was collected during three trips to the AFRCC. The data was collected chiefly from the Honeywell SARMaster software (Ottawa, Canada) and associated file attachments. The file attachments (typically PowerPoint presentations showing the entire radar track and detailed information for the last part of the track) were collected under a nondisclosure agreement that limits their use and marks them as "For Official Use Only." Since the AFRCC area of responsibility is limited to the continental United States, the incidents are for the most part limited to the continental United States. The inclusion criteria from the AFRCC incidents included several factors. Only closed incidents were considered. However, some of these closed incidents represented previously suspended searches in which the aircraft was found after the formal search was concluded. Only those incidents that involved actual searches (versus rescues) for missing aircraft were selected. Only those incidents classified as distress were included. This precluded missions that were a result of a pilot failing to close out a flight plan or simply flying to another airport and failing to report. Finally, a find location for the aircraft must have been reported with coordinates.

After applying the data inclusion rules, only a few exclusion criteria applied. Three reasons to throw out data emerged. An entire incident would be excluded if the plane landed at an improved runway. This would be regardless of distress or nondistress. This only applied to two cases. The second exclusion criterion was conflicting information. Often information could be obtained from AFRCC fields, AFRCC comment section, NTSB reports, or online. If conflicting information existed about one of the data collection subtasks (such as route or crash site elevation), then that specific element would be excluded. Finally, data elements of an incident would be excluded if missing information existed. Therefore, throughout this report different results are based upon different numbers of cases. The number of cases a result is based upon is stated in the "count" field.

The collected data fields from the AFRCC included 31 fields. These fields included the AFRCC incident number, mission number, general location (town or county) of the last known position, state of the last known position, latitude/longitude of the last known position, date, time, registration number of the aircraft, make/model of the aircraft, intended route, weather, secondary weather, number of subjects on board, number found alive, number found deceased, who found the aircraft, general location of find, latitude/longitude of find, find date, find time, source of radar data, FAA coordinates of last location, Mode 3 setting, Mode C reported altitude, second to last radar point coordinate, last change in vertical feet per minute, any predicted find coordinates, number of emergency locator transmitter updates, emergency locator transmitter coordinates, AFRCC controller comments, and if the AFRCC had added attachments to the file.

In order to obtain the distance traveled from the last recorded radar position, it was necessary to know the coordinates of the last recorded radar position and the find site coordinates. Radar plot coordinates were obtained from either 84th RADES or the FAA and both were recorded by the AFRCC. When radar data was reported by both sources, the 84 RADES data was used.

The NTSB maintains an online database of aviation accidents called the "Aviation Accident Database & Synopses."[17] Using the aircraft's registration number collected from the AFRCC data, it was possible to obtain the NTSB factual report—aviation, brief of accident, and probable cause reports. Data was then extracted from these reports and entered into the database. In several cases where the registration number had been entered incorrectly or was incomplete, it was possible to use other search parameters (date, location, type of aircraft, fatalities) to locate the reports. This also allowed updating the database with the correct registration number.

From the NTSB reports it was possible to add additional fields to the database and to verify information found in the AFRCC reporting system. The NTSB reports often provided information that might have been missing from the AFRCC report. The added fields included; NTSB ID number, flight part, flight type, light conditions, basic weather, ceiling, visibility, wind, precipitation, obscuration, flight hours total of pilot, flight hours in aircraft of pilot, flight hours instrument, pilot certification, flight plan, elevation of the crash site, crash bearing (magnetic), NTSB calculation of crash site to last radar, flight activity, terrain, accident cause, and NTSB find location coordinates. In some cases the NTSB had performed additional analysis of radar data and reported additional radar data than the AFRCC. However, the AFRCC data of the last known position from radar data was always used since this is the only data that operational search planners will have available at the time of an actual search.

When the NTSB supplied a crash site coordinate it was more likely to be based upon a GPS reading taken at the point of initial impact with the ground. Therefore, when find location coordinates came from both NTSB aviation accident investigation reports and from AFRCC reports, the NTSB coordinates were used.

Not all of the AFRCC incidents had an NTSB report. NTSB reports were obtained in 239 of the 262 incidents. Reasons for a missing report included the following: a more recent search where the report was not available at the time of data collection; a military flight; the incident did not meet the NTSB criteria for making a report; or insufficient information to locate a report.

Additional fields were added for calculations and data obtained from the source data of the AFRCC and NTSB. All of the various distances needed to be calculated from the various coordinates using batch processing of coordinates from GPSwaypoints.com.za, which uses great circle calculations estimated to be accurate to one part in one million. Aircraft were placed into the appropriate category (e.g., twin engine) after viewing a photograph of the aircraft using Google images. Airport and navigational aid (navaid) identifiers were verified using www.airnav.com, if required. Flight routes were entered into www.skyvector.com to determine the route length and also to verify all waypoints. Google Earth was also used to determine whether the aircraft's find location plotted to an airport and the elevation of the crash site. Coordinates were provided in at least four different systems: decimal degrees (DD.DDD), degrees decimal minutes (DD MM.MMM), degrees minutes seconds (DD MM SS.SS), or Universal Trans Mercator. All coordinates were converted to the decimal degree format using Degree Format Convertor from GPSwaypoints.co.za. USGS 1:24,000 topographic maps used to determine the highest ridge or mountain summit were also obtained using ExpertGPS (TopoGrafix, Stow, MA).

The search duration (h:min) was calculated as the difference between the time the aircraft was last seen and when it was located. In the AFRCC records, the time last seen was not based upon the last radar track but rather on when the aircraft departed. In several incidents, the aircraft was not located during the initial search effort. These caused durations that in some cases exceeded 4000 h. Therefore, for the purpose of calculating averages for instrument flight rules (IFR), visual flight rules (VFR), and no flight plans, incidents with durations of greater than 2 wk (336 h) were excluded.

The heuristic for determining which particular flight characteristic to select for displaying probable Euclidian distance quartile rings from the last radar plot was based upon each of the following flight characteristics: aircraft type, flight plan, meteorological conditions, flight phase, final flight characteristic, and elevation changes. These characteristics were evaluated for statistical significance. Among the factors that achieved statistical significance with $P < 0.05$, the probability density (P_{den}) was evaluated by the summation of the P_{den} within the 50% ring, the 50–75% annulus, and the 75–95% annulus. This was sorted in rank order so that the flight characteristic with the largest summed P_{den} would be examined first.

RESULTS

A total of 260 missing aircraft incidents involving 509 persons were collected that met the inclusion/exclusion criteria. A mortality rate of 89% was found. Radar information was available for 216 incidents (83%). Among the missing aircraft, 241 incidents indicated the type of flight, of which 95% were Part 91, 4% were Part 135, and 1% were Part 137. The majority of search incidents took place in mountainous terrain (148; 57%), followed by flat/hilly (104; 40%), and over water (8; 3%). The average time to locate the missing aircraft was 42:24 (h:min) if no flight plan was filed, 37:18 for VFR, and 13:06 for IFR or flight following. The overall distribution of where missing aircraft were located is shown in **Fig. 1**.

The distance traveled from the last recorded radar position was obtained from 216 incidents (**Table I**). The descriptive statistics of count (*N*), quartiles, 95%, average, and standard deviation (SD) are provided. Search and rescue practitioners often use the 95% distance (based upon $2\sigma + x$) as the practical limit

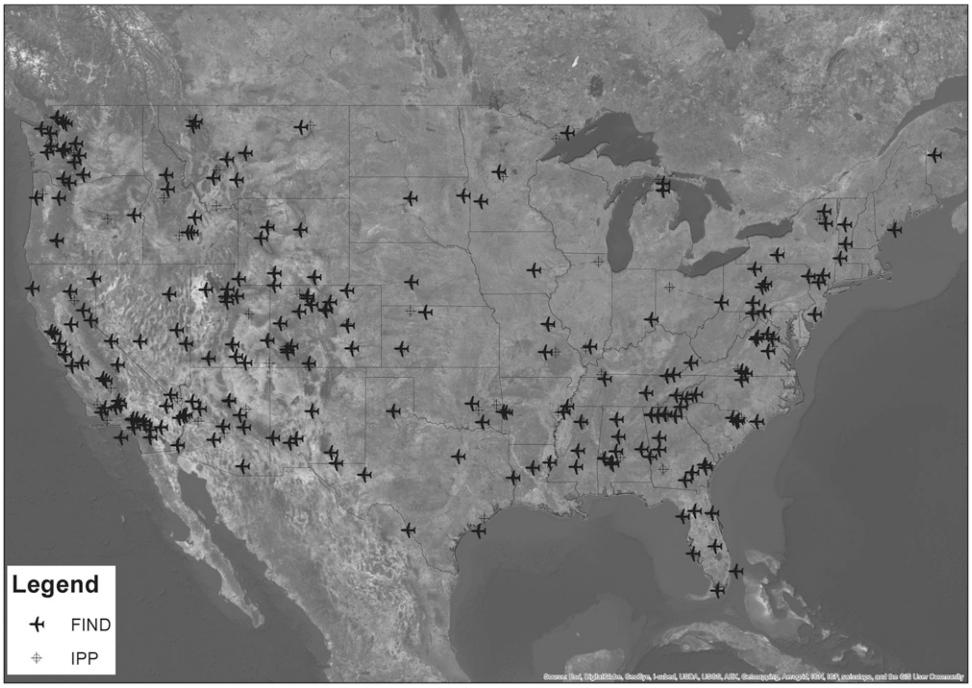

Fig. 1. Spatial distribution of location of missing aircraft along with last radar plot.

of where to search for ground searches. All distances are given in nautical miles unless otherwise stated. The first column (All) represents the entire dataset. For the entire dataset it can be seen that half (median) the aircraft are located within 0.8 nmi from the last radar position. This represents a significant clustering of the probability of containment (POC). The overall median has a probability density of 0.25 POC/nmi^2. The probability density is high enough to warrant a ground search if the terrain or conditions do not allow a high probability of detection in an air search. The overall spatial distribution of crash site locations relative to the last radar plot (center of graph) is shown in **Fig. 2**. No statistical differences were seen in distances among the four cardinal quadrants (ANOVA $P = 0.91$) or between the NS versus EW quadrants (Kolmogorov-Smirnov $P = 0.88$).

The first modifying factor that was examined was the type of aircraft. The table shows the results from helicopters, jet aircraft, twin (propeller), and single (propeller) engine aircraft. Some clear differences appear between the various types of aircraft. An ANOVA between the four groups just missed statistical significance ($F = 2.463, P = 0.063$). No significant difference was seen between single and twin engine propeller aircraft using a Kolmogorov-Smirnov test ($P = 0.85$) nor between jets and propeller aircraft ($P = 0.096$).[11] Jet aircraft tend to be carefully flight followed and can be significantly above ground level (AGL), where radar coverage is excellent. Helicopter incidents show the largest SD. They could be found quite close to the last radar plot (25% within 0.2 nmi) or much further out. A working hypothesis that helicopters typically fly at low AGL altitudes, making it easier to fly out of radar coverage long before the actual incident.

A major factor in aircraft incidents is the weather. The NTSB accident report classified the weather as either instrument meteorological conditions (IMC) or visual meteorological conditions (VMC). In addition, the NTSB reported if icing conditions existed.

It appears that the aircraft flying in IMC are located closer to the last radar position than in VMC (**Table II**), with the 25%, 50%, and 75% annulus being roughly half the distance. However, statistical outliers appear to be more common for flights during IMC. A significant difference was seen between icing conditions and VMC using a Kolmogorov-Smirnov test ($P = 0.032$), but no difference was seen between VMC and IMC ($P = 0.158$).

Another significant factor may involve the type of flight plan profiles followed. The database recorded four types of flight plan profiles: flight plans filed under IFR, flight plans filed under VFR, no filed flight plan (none), and VFR flights with flight following requested. Requests for flight following are made during the flight; however, the pilot may or may not have filed a flight plan. Although these flights are conducted under visual rules, flight followed aircraft were placed with instrument rules aircraft for statistical analysis purposes.

Aircraft flying under instrument rules were found significantly closer to the last radar plot than visual rules using a Kolmogorov-Smirnov test ($P = 0.007$). This result it not too unexpected: since instrument rules aircraft are issued a discrete code, it is much easier to find the correct radar track for these aircraft. When no flight plan is filed, the aircraft is typically found significantly closer than visual rules (using the Kolmogorov-Smirnov test, $P = 0.032$).

Table I. Distance (nmi) of Crash Site from Last Radar Fix for All Data and by Aircraft Type.

	ALL	HELICOPTER	JET	TWIN	SINGLE
N	216	11	6	21	177
25%	0.4	0.2	0.6	0.5	0.4
50%	0.8	3.2	1.5	1.5	0.7
75%	5.5	17.6	2.4	7.2	4.8
95%	45.4	105.7	4.2	24.6	42.5
Avg.	7.4	22.0	1.7	6.2	6.8
SD	19.0	41.8	1.2	9.2	17.8

The NTSB report classified the flight phases of when different

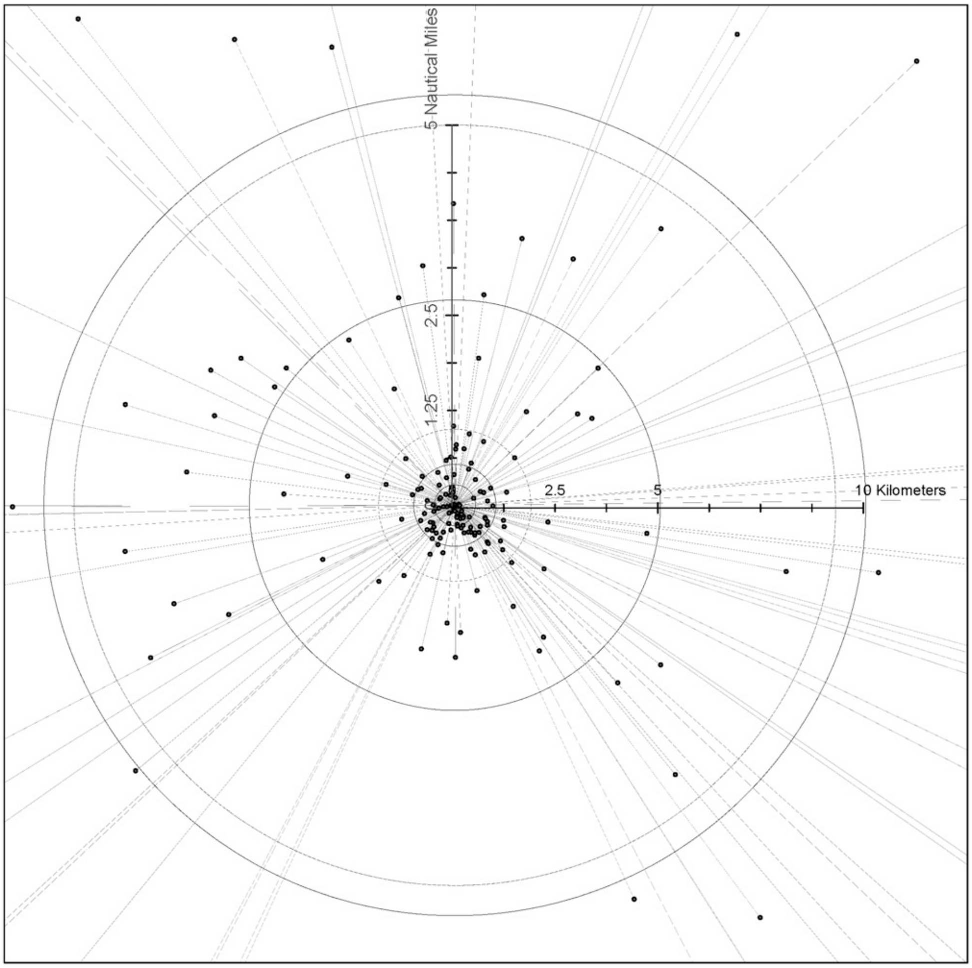

Fig. 2. Spatial distribution of crash location (black dot) to the last radar plot (center).

factors or causes of the accident occurred. With a radar track available, it should be possible for a skilled search planner to determine the phase of flight that is occurring at the time of the last radar plot. Some phases of the flight did not have sufficient incidents and were grouped with the next best match. The phases of flight that were examined were climb, cruise, maneuvering, descent, and approach. An ANOVA showed that none of the phases of flight (**Table III**) had a statistically significant difference ($P = 0.88$).

In most cases, the radar data is not restricted to the last radar plot, but instead tends to show the last minute, last 5 min, or even the entire flight; therefore, it is possible to characterize what the aircraft was doing during the last minute of recorded flight. The terms used during this analysis were straight, straight (and level), straight and descending, bearing right or left (turn of 5-45°), turning right or left (turn of 45-90°), hooking right or left (turn of $>90°$), and spiraling right or left (turn of $>180°$ and it crosses over itself). For this analysis, only the major terms were used and right and left differences were ignored. The flight characteristics were determined by looking at a map of the plots looking at only the horizontal aspects of flight. Only straight and descending factored in a vertical component. An ANOVA showed a difference exists among the categories ($P = 0.027$).

While flight characteristics looked at the horizontal characteristics of the last few plots, the change in feet per minute (FPM) looked at the vertical change in the last plot. Change in FPM were obtained from Mode C transponder returns, which are only precise to 100 ft. For the sake of making tables, the data was placed into bins, with the first bin containing incidents where the descent in FPM was greater than 2000 ft (**Table IV**). The second bin contained descents of 1000-2000 FPM, the third bin 1-1000 FPM, in the fourth bin the flight was level (0 FPM), and the last bin contained 8 cases where the aircraft was climbing. No significant differences were seen using an ANOVA test among the different bins ($P = 0.11$). However, using the Kolmogorov-Smirnov test, a significant difference was seen between the descent rate of >2000 FPM and 0 FPM ($P < 0.001$) and 999-1 FPM ($P < 0.001$). Only eight cases exist in the database where the aircraft was climbing; Kolmogorov-Smirnov testing was not possible.

Table II. Distance from Last Radar Fix from Crash Site (in nmi) for Type of Flight Plan and Different Meteorological Conditions.

	FLIGHT PLAN			METEOROLOGICAL CONDITIONS		
	IFR	**VFR**	**NONE**	**IMC**	**VMC**	**ICING**
N	79	42	80	102	112	11
25%	0.3	0.5	0.4	0.3	0.4	0.1
50%	0.5	3.0	0.8	0.7	1.3	0.4
75%	3.1	13.1	9.6	3.1	7.1	0.8
95%	14.3	55.8	58.1	47.9	28.9	1.7
Avg.	2.9	10.4	9.8	6.3	6.5	0.5
SD	5.7	22.7	24.1	20.8	11.2	0.6

Table III. Distance (nmi) of Crash Site from Last Radar Fix by Flight Phase.

	FLIGHT PHASE					FLIGHT CHARACTERISTIC					
	CLIMB	CRUISE	MANEUVER	APPROACH	DESCENT	STRAIGHT	STRAIGHT DESCEND	BEAR	TURN	HOOK	SPIRAL
N	14	31	42	94	17	67	14	10	13	34	13
25%	0.5	0.4	0.4	0.3	0.1	0.7	0.1	0.1	0.5	0.3	0.3
50%	0.7	0.6	0.8	0.8	0.5	2.8	0.3	0.7	0.7	0.4	0.7
75%	5.3	7.4	7.0	3.6	2.6	13.9	0.5	1.0	2.1	1.5	6.8
95%	14.6	20.4	25.1	51.4	22.0	65.4	15.6	17.1	3.6	6.3	13.6
Avg.	3.6	5.0	6.1	7.3	4.1	12.7	2.1	2.9	1.2	1.4	3.7
SD	5.5	7.7	9.5	22.1	8.9	26.4	6.8	7.1	1.2	2.4	5.0

DISCUSSION

The typical missing aircraft profile involves flying under Part 91 (95%), in a single engine aircraft (82%), flying without a flight plan (40%) or an IFR flight plan (39%), over mountainous terrain (57%), in the approach phase (47%), did not survive (89%), and is found within 0.8 nmi of the last radar plot (50%). The AFRCC was able to obtain a radar track in 83% of the incidents. This percentage might be even higher if the aircraft has been quickly located; then efforts to determine the track will cease. The overall distribution of missing aircraft is similar to the spatial distribution of fatal crashes described by Grabowski et al.[10]

No significant differences were seen among the different types of aircraft for the distances from the last radar plot. However, jets just missed statistical significance ($P = 0.096$), most likely due to a small sample size ($N = 6$). From an operational perspective, the 4.2 nmi 95% ring is different than the 19.0 nmi 95% ring seen for the entire database. While the median ring was greater than the entire database, this is not unexpected for a faster moving aircraft.

The meteorological conditions were significant if icing conditions were present. The possibility of icing conditions was determined by the NTSB, but during actual search incidents could be assigned a probability as a scenario. When icing conditions existed, 95% of aircraft were found within 1.7 nmi of the last radar position. No significant difference was seen between IMC and VMC conditions.

While no significant difference was found in the phase of flight (climb, cruise, maneuver, approach, or descent), the most common phase was during the approach (47%). In most cases, not only is the last radar position available, but many of the previous radar returns have been obtained. Since each radar return is time coded, it is possible to characterize the final flight characteristics as determined by radar. Turns and hooks appear to be the best predictor of finding the aircraft nearby, all the way out to the 95% ring. Descending or bearing to the left or right also predicts shorter distances. Straight and descending had a significantly high probability zone, with 75% of the incidents within 0.5 nmi. Spirals demonstrate some variability. If an aircraft was flying straight (and usually level), that proved to be a poor predictor of the distance from the last radar plot.

One of the best predictors of the aircraft being located near the last radar position was when its final descent rate exceeded 2000 ft/min. If this was the case then 95% of the aircraft were found within 1.8 nmi. Descents of 1-999 ft/min often represent normal descent rates for landing. Also, the limited precision of transponder reported altitudes means the plane could have been flying level, but reported as descending for the last two Mode C reports. The distances are slightly greater than the median of 0.8 seen for the entire database. Level flight (0 ft/min) also shows a median greater than the median value of the entire database.

The report clearly defined that the probability of finding the aircraft close to the last radar plot is significant. In fact, 50% of all aircraft are found within 0.8 nmi of the last plot. This gives a potential search area of only 2 nmi^2—a size (depending upon terrain and weather) easily searched on the ground, even at night. However, the study could easily be improved by examining several other factors. Radar information depends upon the radar forensic analyst finding the correct track that relates to the correct aircraft, then finding the last possible track, often from many segments that have gaps. The input of the analysts of their confidence in the track is clearly needed. The simple proxy for "confidence" in the database was the 40 incidents in which the radar analyst forwarded a formal prediction of where the aircraft might be found. Analysis of those predictions showed 68% were found within 1 nmi and 76% were within 2 nmi. The 75% quartile for the overall database was 5.5 nmi. This might be even more important if two or more candidate tracks are possible. While the tracks could be weighted evenly from a statistical point of view, it might be more useful to have the analyst weigh the probability.

Ultimately, statistical information must be translated into tactical decisions by the search

Table IV. Distance (nmi) of Crash Site from Last Radar Fix by Vertical ft/min Rate.

	>2000 ft/min	1999-1000 ft/min	999-1 ft/min	0 ft/min	CLIMBING
N	34	14	18	28	8
25%	0.2	0.4	0.5	0.6	0.3
50%	0.4	0.6	1.5	1.8	0.9
75%	0.5	3.6	6.6	9.3	2.4
95%	1.8	15.7	101.2	27.7	6.8
Avg.	0.5	3.3	15.4	7.0	1.9
SD	0.6	6.2	42.9	10.3	2.4

planner. In many cases this involves simple paper and pen technology. Even the utilization of more sophisticated optimal allocation of resources algorithms (Charnes Cooper) requires assigning probability of area.[6] Therefore, the search planner faces the task of selecting the most appropriate model or combining them all. We propose a simple algorithm based upon factors that were statistically significant and designed to maximize the probability density. This would allow the least amount of effort to achieve the greatest amount of success.

The factors that were determined to be statistically significant included the type of flight plan (IFR, VFR, or none), the meteorological conditions (if icing conditions were present), the final flight characteristic (straight, straight and descending, bearing right or left, turning, a hook, or a spiral), and vertical changes (descent greater than 2000 ft/min). The probability density for each factor was determined as described in the Methods section. The summed P_{den} values were then shortened to create the algorithm shown in **Fig. 3**. The last three factors (no flight plan, straight flight, and VFR flight plan) had a lower P_{den} value than the overall score. In particular, a final flight characteristic of flying straight ($\sum P_{den} = 0.021$) or a VFR flight plan ($\sum P_{den} = 0.018$) had a lower summed P_{den} value by a factor of more than 10 compared to the entire database ($\sum P_{den} = 0.252$). While some aircraft were still found relatively close for these conditions, search planners would be well advised to look at all factors, including the range of radar coverage prior to committing ground resources.

The approach used in this study was to attempt to identify factors that result in more probability being found closer to the last radar plot. An equally valid approach is to look at factors that might identify when the last plot has nothing to do with the aircraft final location. Such a measure would help to avoid putting too much emphasis on the last radar track. A formal study of all those incidents where the aircraft was not found near the last radar plot should look at radar coverage. This study already identified that straight and level flight might be another good predictor of a "non-relevant" last radar plot. However, it is noteworthy that two cases mention that the last radar plot occurred at a point of known end of coverage, but the aircraft was found near those plots. It would be prudent to eventually examine the actual model of aircraft, if the aircraft entered a thunderstorm, day or night light conditions, the visibility, the ceiling, the last radar's position AGL altitude, and certain key scenarios.

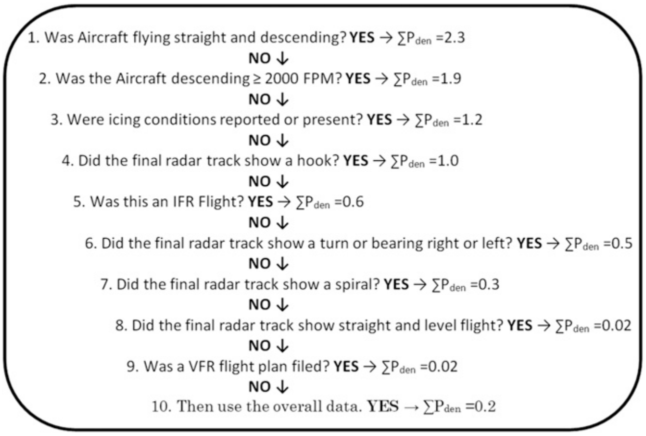

Fig. 3. Hierarchy of flight characteristics to provide best $\sum P_{den}$.

The ultimate goal of search and rescue is to locate and rescue the subject. To find the subject, search resources must be placed in the correct location. Formal search theory can help determine the placement of resources, but it is dependent upon identifying how much probability of containment exists in each search grid. Therefore, it is of paramount importance to develop a model that correctly allocates probability into different areas contained in the search area. The raw data and preliminary results presented here are the foundation to achieving this goal. However, radar data is not the only source of developing probability models for location. Additional models from cell phone forensics and Automatic Dependent Surveillance will become increasing important. In the Air France Flight AF447, it was the Aircraft Communications and Addressing Reporting System broadcast that provided the critical information. However, the full value of that information was not realized until a formal probability map was created.[22] Since humans by nature are poor at visualizing probability and statistics, it is imperative to provide the information in a way that is easy to digest, visualize, and allows for making operational decisions.

ACKNOWLEDGMENTS

We would like to acknowledge Lt. Col Harold C. Hicks, Director of the USAF Inland SAR School, for reviewing the manuscript and making suggestions. Funding was provided by NASA contract GS-23F-0092K and USDA contract USDA 2004-02667. The authors declare no financial or other relationships that could be viewed as causing bias or conflict of interest.

Authors and affiliations: Robert J. Koester, B.A., M.S., and Ian Greatbatch, M.Phil., Ph.D., FRGS, MEPS, Department of Geography & Geology, School of the Natural and Built Environment, Faculty of Science, Engineering and Computing, Kingston University London, Kingston upon Thames, United Kingdom.

REFERENCES

1. Abi-Zeid I, Frost JR. SARPlan: a decision support system for Canadian Search and Rescue Operations. Eur J Oper Res. 2005; 162(3):630–653.
2. Abi-Zeid I, Nilo O, Schvartz S, Morin M. Towards a knowledge-based system prototype for Aeronautical Search and Rescue Operations. In: 2010 13th Conference on Information Fusion (FUSION) (pp.). New York: IEEE; 2010:1-8.
3. AFRCC 2013 Annual Report. [Accessed September 7, 2015.] Available from http://www.1af.acc.af.mil/shared/media/document/AFD-140411-034.pdf.
4. Baker SP, Shanahan DF, Haaland W, Brady JE, Li G. Helicopter crashes related to oil and gas operations in the Gulf of Mexico. Aviat Space Environ Med. 2011; 82(9):885–889.
5. BEA 2012 Final Report: On the Accident on 1st June 2009 to the Airbus 330-203 Registere F-GZCP Operated by Air France Flight AF 447 Rio de Janeiro-Paris. Le Bourget (France): Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation Civile; 2012. [Accessed September 7, 2015.] Available at http://www.bea.aero/en/enquetes/flight.af.447/rapport.final.en.php.
6. Charnes A, Cooper WW. The theory of search: optimum distribution of search effort. Management Science 1958; 5(1):44-50.

7. Desmarais J. Search planning guidance for use in general aviation missing aircraft searches in the continental United States. Maxwell Air Force Base (AL): Civil Air Patrol National Headquarters; 2000. [Accessed September 7, 2015]. Available from http://members.gocivilairpatrol.com/media/cms/Missing_Aircraft_Search_Methodologies_Paper.pdf.
8. de Voogt AJ, Van Doorn RA. Sports aviation accidents: fatality and aircraft specificity. Aviat Space Environ Med. 2010; 81(11):1033–1036.
9. Frost JR, Stone LD. Review of search theory: advances and applications to search and rescue decision support (No. CG-D-15-01). Fairfax (VA): Soza and Company LTD; 2001.
10. Grabowski JG, Curriero FC, Baker SP, Li G. Exploratory spatial analysis of pilot fatality rates in general aviation crashes using geographic information systems. Am J Epidemiol. 2002; 155(5):398–405.
11. Kirkman TW. Statistics to use. 1996 [Accessed September 7, 2015]. Available from http://www.physics.csbsju.edu/stats/.
12. Koopman BO. Search and screening: general principles with historical applications. New York: Pergamon Press; 1980.
13. Li G, Pressley JC, Qiang Y, Grabowski JG, Baker SP, Rebok GW. Geographic region, weather, pilot age and air carrier crashes: a case-control study. Aviat Space Environ Med. 2009; 80(4):386–390.
14. NASA. Air Search and Rescue Instructions. [Accessed on September 7, 2015.] Available from http://worldwind.arc.nasa.gov/java/apps/SARApp/help/v6/SARHelp.html.
15. National Search and Rescue Committee. Land Search and Rescue Addendum to the National Search and Rescue Supplement to the International Aeronautical and Maritime Search and Rescue Manual Version 1.0; 2011. [Accessed on September 7, 2015.] Available from: http://www.uscg.mil/hq/cg5/cg534/nsarc/Land_SAR_Addendum/Published_Land%20SAR%20Addendum%20(1118111)%20-%20Bookmark.pdf.
16. National Transportation Safety Board. National Transportation Safety Board Safety Recommendation A-09-102 and A-09-103. Washington (DC): NTSB; 2009. [Accessed on September 7, 2015.] Available from http://www.ntsb.gov/doclib/recletters/2009/A09_102_103.pdf.
17. NTSB Accident Database & Synopses. [Accessed September 7, 2015.] Available from http://www.ntsb.gov/_layouts/ntsb.aviation/index.aspx.
18. O'Hare D, Chalmers D, Scuffham P. Case-control study of risk factors for fatal and non-fatal injury in crashes of civil aircraft. Aviat Space Environ Med. 2003; 74(10):1061–1066.
19. Reveley MS, Briggs JL, Evans JK, Sandife CE, James SM Causal factors and adverse conditions of aviation accidents and incidents related to integrated resilient aircraft control. Washington (DC): NASA; 2010. Report No.: NASA/TM–2010-216261.
20. Saunders PH. A new search method based on an analysis of air distress cases: 1981–1986. CFB Trenton, Astra, Ontario (Canada): Department of National Defense, Canada; Operational Research Branch, Air Transport Group Headquarters; 1987. ATGOR Staff Note 2/87.
21. Shao BS, Guindani M, Boyd DD. Fatal accident rates for instrument-rated private pilots. Aviat Space Environ Med. 2014; 85(6):631–637.
22. Stone LD, Keller CM, Kratzke TM, Strumpfer JP. Search for the wreckage of Air France flight AF 447. Stat Sci. 2014; 29(1):69–80.
23. Syrotuck WG. In: Syrotuck JA, editor. Analysis of lost person behavior: an aid to search planning. Mechanicsburg (PA): Barkleigh Productions, Inc.; 2000.
24. Syrotuck W, McIver M. Preliminary investigation. In: Syrotuck W, editor. An introduction to land search: probabilities and calculations. Mechanicsburg (PA): Barkleigh Productions, Inc.; 1975.
25. Taneja N, Wiegmann DA. Analysis of injuries among pilots killed in fatal helicopter accidents. Aviat Space Environ Med. 2003; 74(4):337–341.