A Structured Approach to Acquiring Search Planning Data

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Abstract – Search planning based on a Bayesian updating of the prior location distribution of the search object, to account for search effort expended, forms the basis of current approaches. This approach has been very successful in practice. Based on experiences of planning the deep ocean search for the South African Airways Flight SA295, and search planning for the Air France Flight AF447, a set of principles are proposed for guiding the gathering and relating of data on which to build the prior location distribution. These principles bring structure and rigour to a phase of the planning that is very difficult and unstructured conceptually. These principles guide one in what data to look for, how to look for such data, and helps one improve planning scenarios by relating the data to each other on a common basis. These principles also apply in general contexts where evidence is sought to explain phenomena.

Keywords: Search planning, prior location distribution, evidence gathering, accident investigation, search theory.

1 Introduction and Scope

This paper presents an outline approach to search planning such as was used in the South African Airways Flight SA295 search in 1987-1988, and which also provided for the Air France Flight AF447, which crashed on June 1 2009. By the very nature of these events one can not be prescriptive and detailed as to the exact methods and approaches that will be followed. At best we can list some of the principles that was and could be followed.

Both incidents were characterised by:

- Loss of aircraft over the ocean, far from land;
- Night time incident;
- High altitude incident;
- Total loss of the aircraft, with a break-up of the aircraft likely either in the air or on impact;
- Very large location uncertainties
- Deep ocean (2-5 km deep in the vicinity of the Air France accident, 2-6 km for the SAA incident)
- Ocean conditions moving the debris both on the surface and underwater to great distances from the initial impact;
- Significant uncertainty as to nature of the incident

Background to the South African Airways Flight SA295 Boeing 747 “Helderberg”, which crashed North East of Mauritius in 1987, can be found in [1] and [2]. Currently the best source of information on the Air France Flight AF447, which crashed in the mid-Atlantic near the Equator on June 1, 2009, can be found in the preliminary investigation reports, [3] and [4].

This paper provides guidelines for initiating and preparing for a search similar to these two cases. By the very nature of these events one can not be prescriptive and detailed as to the exact methods and approaches that should be followed. At best we can list some of the principles that will/should be followed.

2 Search Phases:

Search planning and execution for similar incidents will likely follow four distinct phases, each requiring different resources and presenting unique problems:-

1. Initial ocean surface search for debris and bodies. In all probability this will continue for 2 to 4 weeks, depending on the extent of debris diffusion due to weather and current effects. It is critical to record and study the pattern of debris recovery, alongside ongoing current and wind patterns in order to develop a debris dispersion pattern.
2. Underwater search for the flight recorder acoustic locator beacons (pingers). This search has a duration of 4-5 weeks after the aircraft accident. The sound from the pingers is likely to be audible at distances less than 1 to 1.5 km, meaning that the locating instrument has to be near the bottom, up to 3000 meters deep, for a good chance of hearing the pinger.
3. Underwater search for the bottom wreckage. This may be done via side scan sonar or photographically. In either case a very detailed

chart of the sea bottom will be required for these operations to be successful. This mapping may need to be executed before the bottom wreckage search is conducted. This search is likely even in the event that the pingers are located in step 2.

4. Underwater search of the wreckage field for the flight recorders, if they are not found through the search in step 2. This search can only be initiated once the failure scenario of the aircraft accident is better understood, in order that a specific portion of the wreckage field can be searched photographically or visually for the recorders themselves.

3 Objectives of the Search Phases:

In practice, there is often great confusion about the search objective in these different phases. The objectives differ for different search phases:

1. In the initial ocean surface search the ***search is for debris and bodies***.
2. Underwater search for locating the flight recorder ***acoustic locator beacons*** (pingers).
3. Underwater search for locating the ***sea bottom wreckage***. This may be done via side scan sonar and/or photographically. This is the search for which the AF447 search is currently (March 2010).
4. There may have to be an underwater search within the wreckage field for the ***flight recorders*** themselves, and selected debris, normally photographically or visually.

4 Search planning

Each of the four phases of searching requires very specific and differently detailed search planning. Search planning is ultimately a very detailed, rigorous and scientific approach to managing the information in the search problem. These principles put in place a *style of working* which is important to make visible to clients and participants. These are not listed here with the innuendo that they are not followed in practice.

- ***The care, precision and rigour in acquiring relevant search information, and the careful methodical handling of this information lies at the core of a successful search. This cannot be over emphasised.***

- ***Ocean search planning is hugely complicated by working with dynamic locations: The sea water moves and keeping track of the wreckage movement introduced by the ocean current movements results in a very complicated information tracking problem. Unless this is done properly, one can not be systematic in searching the ocean surface and bottom.***

- ***If any one source of information was definitive about the location of the aircraft wreckage, there would not be a search problem, as the location would be known with certainty. It follows that each potential source of search planning information is inherently uncertain – it is just a matter of degree of uncertainty between the different information sources. The principle is that one utilises ALL information sources, regardless of the degree of uncertainty associated with the particular set of data.***

- ***It follows therefore that there needs to be a conscious and conscientious searching out of different (alternate) sources of data for the search planning. One should not pre-judge, or let any one particular party pre-judge, the validity of a particular source of search planning information. The search planners' obligation is to keep an open mind and include ALL information sources, regardless of (possibly valid) arguments against the source of information.***

- ***However, one has an equal obligation to be objective and scientific about the incorporation of the information in the search plan, so as to reflect as accurately as possible the true scientific merits of the different information sources. One can not let any one source of information dominate the shape of the search plan, beyond what the relative validly of the information allows.***

- ***Eclectic principle: Apart from seeking out as many as possible meaningful and different information sources, the eclectic principle requires that the research or inquiry be conducted with as many different means as possible. In practice this means to employ different disciplines to look at the situation, and seek out fundamentally different ways of arriving at an answer. ("Meaningful" is taken to mean information sources that has a scientific validity underlying it.)***

The above principles are embedded in the following proposed process of working towards a search plan.

5 Search Theory

Search theory is a Bayesian approach to representing and managing the information present in a search problem.

Classic references on search theory applied in practice are [5] and [6]. Typically the process follows the following steps:

1. Develop an initial, or prior, distribution for the search object. This prior distribution contains all information known about the geographic location of the search object. It may be based on different "scenarios" of what could have happed prior to the object going missing, and may incorporate uncertainties, such as drifting, where the object is lost at see. In such cases the prior distribution itself is time specific and may change over time even if no search is carried out.
2. The search method or equipment is characterised mathematically to express the probability of finding the search object, under specified circumstances, given a certain amount of search effort.
3. Available search effort is optimally allocated by combining (1) and (2) in a mathematical optimisation.
4. The real trick in search theory lies in the Bayesian updating of the search object location distribution, to account for search effort expended: As you search, and do not find the search object, you are effectively gathering information about where the search object is not. Bayesian updating of the prior distribution (1) to take into account negative search results, produces a posterior search object location. The steps are then repeated.

This search theoretical approach has proven enormously successful in the management of complex search problems.

The work that we cover in this paper is focussed on the development of a prior search object location distribution, using vague and uncertain information sources. This phase of search theory, in contrast to the latter phases, is not well structured and lacks a rigorous foundation. This paper helps to add rigour to that part of the search planning, making it less dependent on direct experience.

6 Defining an information source:

Proposed here is a concept "search planning information source", which has a different meaning to that of "scenarios" traditionally used in computer assisted search planning. This distinction helps in the initial information gathering, prior to the formulation of the "scenarios" for the search planning. This distinction has no effect on the computer based processing of the information in the search planning, but does aid in the establishment of the facts. ***Crucially, this distinction brings a more objective principle to judging the relative validly of the different information sources***, and hence for the scenario weightings to be used in the computer information processing.

6.1 Definitions:

- A "**search planning information source**" is a set of internally consistent data, independent of other, external data, that provides a basis for drawing a conclusion about where the search object (aircraft debris in this case) can be found. Specifically, the data is sufficient to draw this inference in that no other data needs to be taken into account when deciding where to search. "Internally consistent" means that it refers to data that is not contradictory in itself, taken as a whole. The data may have uncertainty associated with it, which reflects in a larger or smaller uncertainly around the predicted location of the search object. Lastly, the information source refers to a particular type of data, e.g all data associated with a known flight path, or all data associated with witnesses observations.
- "**Key data**" associated with the information source is data that defines the ***basic reference points*** of the particular information source. For example, for witnesses, key data would be the location of the witnesses at the time of the accident, the direction they were looking at, and the angle above the horizon at which they observed the accident. Associated with key data, is the ***degree of uncertainty of the data***; this uncertainty estimate forms part of the key data. For example, how accurately is the location of the witnesses known? How accurately are the angles of observation (direction, azimuth) determined?
- "**Critical assumptions**" are assumptions that are inherent in the viewpoint of the information source. It can be understood as follows: The information source represents a *viewpoint* (perspective) on where the aircraft impacted, based on selecting a particular source of information. This source of information is by definition incomplete, in that it does not unambiguously tells one where the aircraft is located. If it did indicate the location of the aircraft unambiguously, there would be no search problem. Since the data in the information source is incomplete, we need to make one or more assumptions in order to derive a conclusion about where the aircraft may be. In a sense, these conclusions are used to "fill in" missing data. What we need to identify are those assumption which are made, sometimes unconsciously, to "complete the data". These are critical assumptions, in the sense that if we are wrong about this assumption(s), it would invalidate the use of

the information source.

The process of seeking out the data associated with each information source, has not only to identify the critical data, but also identify the critical assumptions, and then actively look for evidence that refute or confirm the critical assumptions. The care with which assumptions are identified, and the diligence in searching out confirming, but more particularly, disconfirming evidence, in support of the assumption(s), plays a *critical* role in building a sound information foundation for the search planning. The logic rules of the scientific method, and legal reasoning around evidence are good guidelines for reasoning around the evidence for and against the hypothesis, namely the assumption.

- **Scenario**: A hypothesis, or story, about what could have happened with the aircraft before and during the accident. This is *a combination of known facts*, drawn from one or more of the information sources as described above, to build a story over time, describing a particular hypothesis about the accident.

  A scenario as used to in the input to the computer aided simulations can also be simply an information source as defined above, without a particular story attached to it.

In the sub-sections below we provide examples of "Information source", "key data", and "critical assumptions", to illustrate the above definitions.

6.2 Examples from the South African Airways flight SA295 accident:

For a full description for the search planning for the SA295 search, refer to the referenced articles. Listed here are simply the brief extrracts to illustrate the above definitions.

6.3 Examples of Information sources for Search Planning in SA295 underwater sonar search phase:

1. Flight path information
2. Pinger search results
3. Observer data
4. Underwater photography results
5. Wreckage drift calculations

6.4 Examples of key data:

1. **For flight path information**: Location (vector: origin and direction) of flight path, last known position, time of accident, speed of aircraft. Key data uncertainties: speed of aircraft between 420 knots and 240 knots (determined from flight considerations); time of impact know to less than 1 minute accuracy from watches recovered; deviation off the intended flight path +/- 0.5 nm.
2. **For observer data**: Location of observers, bearing of their observations, azimuth of their observations, time of observations, nature of their observations. Key data uncertainties: Directional measurements uncertainties (taken by surveyors using surveying instruments from the exact location of the observers. This was quantified in +/- fractions of a degree.
3. **Underwater photography results**: Nature and locations of objects photographed, state of objects photographed (clean/fresh on ocean bottom, or covered in silt.) Uncertainties on data were primarily location uncertainties.
4. **Back-drift calculations:** Key data included the initial location and time of debris position, the location and time of second debris observation (the following morning), the nature of the debris in the surface wreckage field; key data uncertainties were the means of position location, the accuracy of position location of the debris field.

6.5 Examples of critical assumptions:

1. **Flight path information**: The pilot was asked by the Mauritius tower to report his position. Some time later the pilot reported "65", which was taken to mean 65 nm from Mauritius. However, when that location was searched after the accident no wreckage was found. A Boeing 747 pilot who stayed on Mauritius privately hired an aircraft and flew out to a location 65 nm before the last waypoint before the Mauritius waypoint. He found the wreckage there, 12 hours after the accident. Therefore, one must assume that the pilot as selected the wrong reference point from which to read his location when he reported the position. The critical assumption for the last know position is that the pilot had used the wrong waypoint as reference point for his report on his location. If one does not make this assumption, one can not use the last know position as indicated in the SA295 search planning paper. The evidence supporting this assumption is that the wreckage was found in the corrected location. Nevertheless, this was the critical assumption one had to make in using that information source.

2. **Observer data**: The most critical assumption was that these people had seen the incident. they described balls of fire that appeared at a certain altitude, fell some distance and then disappeared. At the time, there was great controversy about whether they saw the accident, with significant pressure from virtually all sources to reject this information source. One argument was that there was no evidence at that time that the aircraft had broken up, or that fire was outside of the hull. However, when calculations were done on the direction of their observations, the azimuth where the balls of fire appeared and disappeared, it was found that the direction corresponded to the known accident locations, the appearing azimuth corresponded to the known flight level of the aircraft at the last know position, and the disappearing azimuth corresponded to the location of the aircraft disappearing below the horizon for the distance that the observers were away form the accident scene. In addition, the time of the observations corresponded to the known time of the accident. All of this was evidence that they actually saw the accident, although the nature of their observations was difficult to explain at that time. In hindsight, it is known that what they observed was the tail section of the aircraft breaking off, with the fire that was in rear main cargo deck. (Despite the strong evidence for this data source, it did not provide sufficient accuracy to determine the search area accurately; this information source was used in that the remaining information sources with high credibility was consistent with this search area implied by this information source.
3. **Underwater photography**: During the underwater pinger search, as possible pinger sources were located, an attempt was made to photographically investigate the locality of the suspected pinger. This was done by means of a non-manoeuvrable photographic sled of the German oceanographic research vessel 'Sonne'. Plots of the tracks of two of these investigations are shown in Figure 5 (a and b). In the location (a) light material (paper) was photographed, and in location (b) heavier material (cool drink bottles, toy car, twisted objects0>

In the case of the underwater photography, unless one assumed that the objects photographed came from the aircraft, one cannot come to the conclusion that the area (c) in Figure 5 from [2] (repeated here), should be searched. This was the critical assumption for this data source

In reality, strenuous investigations cast increasing doubt about the likelihood that material photographed in location (b) originated form the aircraft. This discredited this information source, relative to other information sources.

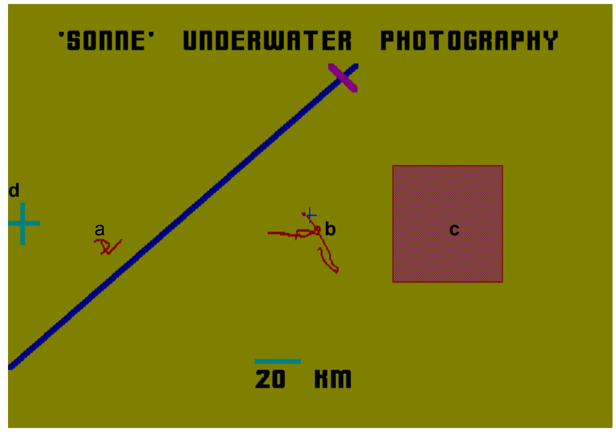

FIGURE 5: UNDERWATER PHOTOGRAPHIC INVESTIGATIONS

7 A suggested Search Planning Process

In broad outline, the suggested process of gathering search information could proceed as follows. Listed here are simply the generic steps:

1. Identify different (independent) sources location information and gather this information diligently, checking every single piece of data rigorously.
2. Prepare an information representation (composite sketch map) of the areas suggested by the different sources of information. This representation serves as a visual (graphic) listing of the different information sources and not as definitive search areas.
3. Identify the (a) critical data associated with the information source and (b) critical assumption(s) underlying each source of information.
4. Embark on a diligent information search/research program to verify and establish the critical data for each information source, as well as establishing the evidence supporting or refuting the critical assumptions underlying each information source.
5. The information in (1) to (4) are used to build the prior search object location distribution, most likely by using scenarios that draw on these data. The scenario weights are allocated on the basis of the relative strength of the evidence for and against the critical assumptions underlying the respective information sources.
6. The most effective allocation of available search effort need to be determined and search resources allocated to execute the search accordingly.

7. The effectiveness of the search needs to be evaluated mathematically and this is to be used to evaluate the likelihood of finding the aircraft wreckage within a certain period of time. Also, this allows one to determine the expected cost and the expected duration of the search to achieve a reasonable chance of detecting the wreckage (for example, to have a 90% chance of success).
8. As the search progresses, one updates the likelihood of the wreckage being in any particular area, on the basis of un-successful searches. Un-successful searches provides information on where the wreckage is likely not to be, and this information needs to be taken into account.
9. This process is repeated, continuously paying careful attention to every piece of information.

8 Suggested Action steps in search planning

1. Obtain consensus on planning principles and process.
2. Build agreement on, and finalise the list of potential information sources.
3. Identify key data, uncertainties, and critical underlying assumptions. We have found specially developed Excel worksheets may be used as a convenient shared workspace.
4. After identifying the information requirements in steps 2 and 3, a very concerted information gathering process should take place. Data capturing in the spreadsheets to track progress is a good idea.
5. Debate with key planners and all stakeholders the merits of the different information sources to arrive at consensus relative weightings to be attached to the different information sources: Find, by careful research the evidence supporting or rejecting key assumptions
6. Prepare an information representation (composite map) of the areas suggested by the different sources of information. This map should be computerised to allow one to attach probabilities to the different areas. Google Earth can work well here. (The purpose of this step is to build a visual reference framework of all data, to enable meaningful discussions.)
7. Developed key scenarios and assign weights according to the information sources used.
8. Developed probability estimates of the effectiveness of the proposed search systems for the area under consideration, paying particular attention to the nature of the search target , which is different for visual search (a large field of debris) to a sonar search (large aircraft wreckage pieces).
9. Use computer aided support to plan search and manage the search: Build the probability distribution for the location of the aircraft, assign search effort optimally, and as the search progresses, one updates the likelihood of the wreckage being in any particular area, on the basis of un-successful searches. (Un-successful searches provides information on where the wreckage is likely not to be, and this information needs to be taken into account.)This process is repeated, continuously paying careful attention to every piece of information

9 Conclusion

Search theory has proven hugely effective in managing the information flow in a complex search problem. Its departure point is to build a location probability distribution, and then update this. In this paper guidelines were provided for seeking out information from situations like over ocean aircraft accidents, to utilise in building the prior distribution. These principles improve the effectiveness of the search planning in that they structure a very difficult part of the information management.

10 References

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