Search Analysis for the Underwater Wreckage of Air France Flight 447

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On 1 June 2009 Air France Flight 447, with 228 passengers and crew aboard, disappeared over the South Atlantic during a night flight from Rio de Janeiro to Paris. An international air and surface search effort located the first floating debris during the sixth day of search. Three phases of unsuccessful search for the underwater wreckage ensued. Phase I was a passive acoustic search for the aircraft's underwater locator beacons. Phases II and III were side-looking sonar searches scanning the ocean bottom for the wreckage field. In July of 2010 the French Bureau d'Enquêtes et d'Analyses tasked Metron to review the searches and produce posterior probability maps for the location of the wreckage. These maps were used to plan the next phase of search beginning in March 2011. On April 3, after one week of search, the wreckage was located in a high probability area of the map.

Keywords: Search, Bayesian, Posterior Distribution.

1 Introduction

On 1 June 2009 Air France Flight 447, an Airbus 330-200 with 228 passengers and crew, disappeared over the South Atlantic during a night flight from Rio de Janeiro to Paris. An international air and surface search effort recovered the first wreckage on June 6^{th}, five and one half days after the accident. More than 1000 pieces of the aircraft and 50 bodies were recovered and their positions logged. A French submarine as well as French and American research teams searched acoustically for the Underwater Locator Beacons (ULBs, or "pingers") on each of the two flight recorder's "black boxes" for 31 days from 10 June to 10 July 2009 with no results.

In early July of 2009 the French Bureau d'Enquêtes et d'Analyses pour la sécurité de l'aviation civile, abbreviated as BEA, contacted Metron for assistance in preparing for Phase II of the search, utilizing side-looking sonar to scan the ocean bottom for the wreckage field.

The Phase II side looking sonar search, performed by the *Pourquoi Pas?* from 27 July to 17 August 2009, proved unsuccessful. The Phase III search, which took place from 2 April to 24 May 2010, consisted of additional side looking sonar searches using REMUS AUVs operated by the Woods Hole Oceanographic Institute (WHOI) and using the ORION towed side-looking sonar operated by the US Navy with assistance from Phoenix International. The search also used a Triton ROV provided by Seabed AS (Norway). It was likewise unsuccessful.

In July of 2010, Metron was tasked by the BEA to review the search and to produce an updated posterior probability map for the location of the underwater wreckage. To accomplish this Metron reviewed and modified the distributions developed in 2009. A new prior was developed based on studies by the BEA, the Russian Interstate Aviation Group (MAK), and a new reverse drift analysis using updated current estimates.

Metron analyzed the effectiveness of Phase III side looking sonar searches performed by the WHOI REMUS and the US Navy ORION sensors and computed an updated posterior probability distribution for the location of the wreckage using the new prior distribution and incorporating the unsuccessful phase I and II searches performed during 2009, as well as the unsuccessful Phase III searches performed by REMUS and ORION in 2010 as well as the Triton ROV searches. Metron also accounted for the unsuccessful surface searches performed by aircraft and ships between 1 and 6 June 2009.

Metron's previous work in search applications, detailed in references [1,2,3], includes searches for the U.S. nuclear submarine *Scorpion*, the *SS Central America*, and Steve Fossett's crash site. In addition, Metron played a key role in developing the U. S Coast Guard's Search and Rescue Optimal Planning System (SAROPS) which has been successfully employed to plan and execute searches for ships and personnel lost at sea [4]. This paper describes the results of Metron's Air France 447 (AF 447) analysis.

2 Approach

Our approach to this search planning problem is rooted in classical Bayesian inference, which allows the organization of available data with associated uncertainties and computation of the Probability Distribution Function (PDF) for target location given these data. In following this approach, the first step was to gather the available information about the location of the impact site of the aircraft. Using a Bayesian approach we organized this material into consistent scenarios, quantified the uncertainties with probability distributions, weighted the relative likelihood of each scenario, and performed a simulation to produce a prior PDF for the location of the wreck. This is the same methodology that was pioneered in [1] and incorporated into SAROPS.

Next we estimated the effect of the unsuccessful search efforts. These efforts included air and surface searches for floating debris and underwater searches in Phases I, II, and III. The goal of the Phase I search was to detect signals from the flight recorders' ULBs. The Phase II and III searches involved the use of side-looking sonar and cameras to detect the underwater debris field of the wreck of the AF 447 flight. For each search, we enlisted sensor experts and knowledge of the sea state, visibility, underwater geography, and water column conditions to estimate sensor performance. The results of the search assessment, combined mathematically with the prior PDF of the impact site, yielded the posterior PDF for the impact location given the unsuccessful search efforts. Posterior PDFs after each phase of the search are presented in Section 4 along with the estimated effectiveness of the search in terms of Cumulative Detection Probability (CDP).

The posterior distribution given in Section 4 provided guidance for the location of the wreckage and the amount of additional search effort required to obtain a high probability of success.

Section 3 of this paper describes the method for producing the prior (to the surface search) PDF for impact location. This distribution is composed of two components. The first component, called the Flight Dynamics (FD) prior, is based on flight dynamics considerations and information from past crashes. The second component of this prior is derived from the information provided by the detection and recovery of floating debris from the wreckage of the aircraft on 6 June – 10 June. This information was used to produce a Reverse Drift (RD) prior. The FD and RD priors were blended to produce a surface search prior.

In section 4, the effect of the unsuccessful surface searches during 1 June – 6 June 2009 conducted by aircraft and ships was used to compute the surface search posterior. This posterior became the prior for the passive and side-scan sonar searches in Phases I, II, and III. The remainder of section 4 computes the posterior PDF and estimates CDP at the conclusion of each underwater search phase.

The following chart summarizes the various steps of this approach and also references other figures that are used throughout this report. In Phase I, the Reverse Drift and Surface Search blocks, shown in green, use the SAROPS environmental module that simulates winds and currents in the search zone. The other Phase I blocks are based on flight dynamics computations and a study undertaken on loss of control accidents during flight.

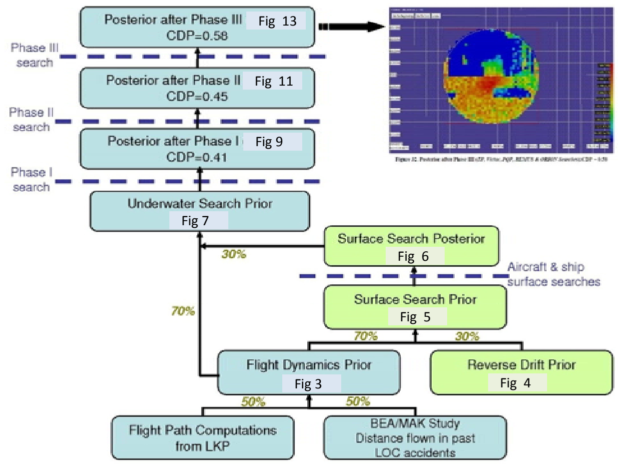

Figure 1. Summary of PDF Computation

As an excursion, we computed the posterior PDF assuming that both ULB "pingers" failed to function during the Phase I search. On 3 April 2011, the wreckage was found in a high probability area of this distribution (Figure 14). From the location of the wreckage, it appears that the ULBs either failed to operate properly or failed to be detected, which greatly increased the difficulty of the search. In early May the Flight Data Recorder and Cockpit Voice Recorder were recovered.

3 Prior PDF for Impact Location

In this section we compute the prior (before surface search) PDF for impact location. This PDF has two components, a flight dynamics and a reverse drift component.

3.1 Flight Dynamics Prior

This prior is the mixture of two distributions. The first is based on purely flight dynamics considerations about the maximum distance the aircraft could have feasibly traveled from the time of its last reported position (last known position (LKP)) at 35,000 ft. altitude to the time when a scheduled response from the Aircraft Communications Addressing and Reporting System (ACARS) was not received. ACARS is a maintenance and logistics reporting system that sends out position reports based on GPS roughly every 10 minutes. The impact time was estimated based on the time of the last ACARS message received and the expectation (unfulfilled) of a subsequent message in the next 60 seconds. The end of the flight occurred between 2 h 14 min 26 sec and 2 h 15 min 14 sec - see page 39 of [5]. An analysis was performed by the BEA and reported in reference [6] which produced a uniform distribution over the disk of radius 40 NM centered at the LKP. This is the first distribution.

The second distribution is based on data from nine commercial aircraft accidents involving loss of control. This analysis was performed by the Russian Interstate Aviation Group [7] and the BEA. Figure 2 shows the cumulative distribution of distance (pro-rated to 35,000 ft. altitude) flown from the beginning of the emergency situation to impact of the aircraft.

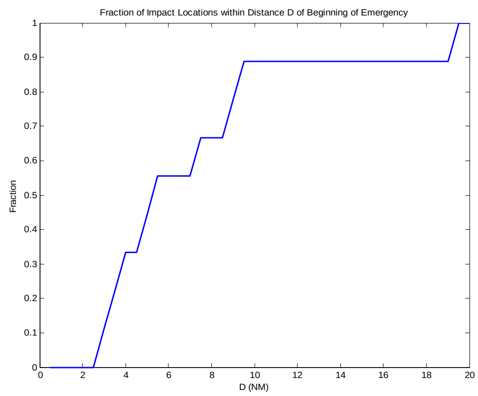

Figure 2. Cumulative Distribution of Distance Traveled from Beginning of Emergency to Impact Location

The analysis shows that all impact points are contained within a 20-NM radius circle from the point at which the emergency situation began. These results are represented by a circular normal distribution with center at the LKP and standard deviation 8 NM along both axes. For the Flight Dynamics (FD) prior, we chose a mixture weighted by 50% for the uniform over 40 NM distribution and 50% for the circular normal distribution truncated at 40 NM from the LKP. This distribution is shown in Figure 3

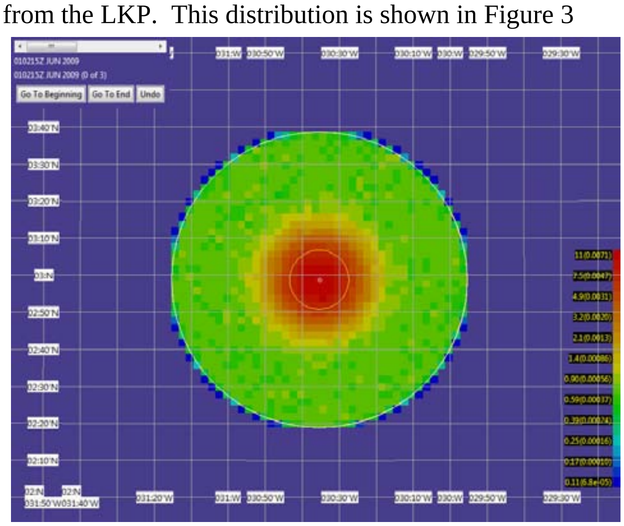

Figure 3. Flight Dynamics Prior

3.2 Reverse Drift Prior

The reverse drift (RD) prior was computed using SAROPS and data on currents and winds to reverse the motion of recovered floating debris pieces back to the time of impact.

The U. S. Coast Guard employs SAROPS for all their search and rescue planning. SAROPS allows a search planner to define scenarios, obtain the winds and currents necessary to compute drift trajectories, estimate effective sweep widths for search sensors, develop probability distributions for search object location, and find near optimal search plans given the amount of search effort available.

In order to compute an RD scenario, one must have an estimate of the surface currents in the area of the crash during 1 – 10 June 2009. The BEA commissioned a group of oceanographic experts to review the data available for estimating these currents. The results are reported in the Drift Group Report [8]. Because the area is near the equator and in the middle of the Atlantic, the currents are complex and difficult to estimate. In addition the remote nature of the crash site meant that there were few meteorological measurements to provide a basis for current estimates. Because of the complexity of the currents and the lack of data, there is substantial uncertainty in these estimates.

Metron used the ANALYSE_75KM_LPO current estimates to compute a reverse drift prior. These estimates were produced as a result of the work of the Drift Group. However, we have given the results based on these estimates a low weight (30%) in producing the prior and posterior distributions because of the great uncertainty associated with the estimates.

To produce the RD Prior Metron used the positions and recovery times of the 33 bodies that were located from 6 – 10 June 2009 [5]. Some bodies were recovered in groups. The positions of the bodies or groups of bodies were drifted back in time using the ANALYSE_75KM_LPO current estimates.

There are two components of drift. Drift due to ocean current and drift due to wind which is called leeway. We did not apply reverse drift to pieces of debris that were recovered during this time because we do not have good models for the effect of leeway on this type of debris.

Data obtained in September 2009 from experiments on the drift of a manikin modified to simulate a deceased person floating in the water (PIW) is reported in [9]. From these experiments, the authors produced the leeway model shown by equation (1) below. This model, which is based on empirical data, produces a total drift speed of roughly 2.35% of wind speed and includes a cross wind component. The equations in (1) were used in SAROPS to account for the leeway of the bodies.

$$\begin{aligned} D_{WL} &= 1.17 W_{10m} + 10.2 \text{ cm/s} \\ C_{WL} &= 0.04 W_{10m} + 3.9 \text{ cm/s} \end{aligned} \quad (1)$$

where W_{10m} is in m/s and D_{WL} and C_{WL} are in cm/s.

Figure 4 shows the reverse drift distribution produced in this fashion and truncated at the 40 NM circle.

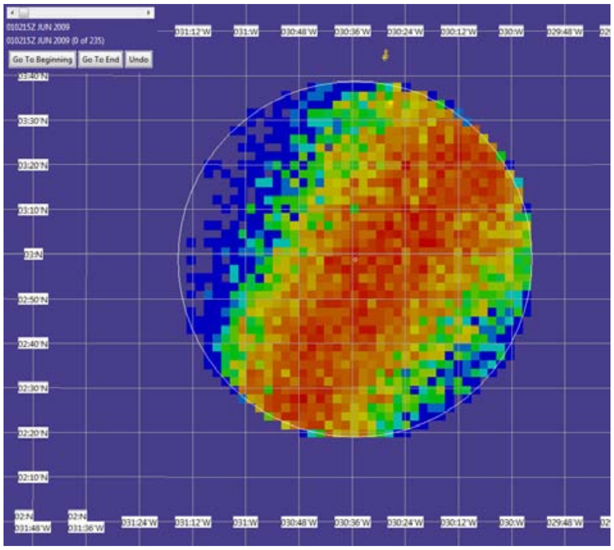

Figure 4. Reverse Drift Prior

3.3 Prior Before Surface Search

The prior distribution before surface search by aircraft and ships is a mixture of 70% of the FD Prior given in section 3.1 and 30% of the RD Prior given in section 3.2. The resulting distribution is shown in Figure 5.

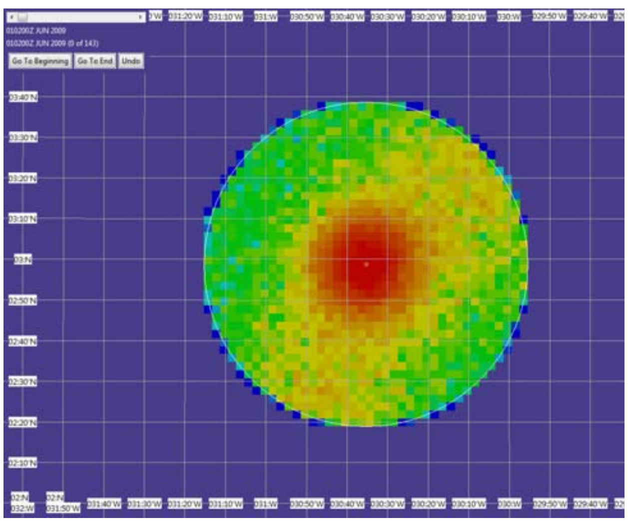

Figure 5. PDF for Impact Location Prior to Surface Search

4 Posterior Distribution Given Unsuccessful Search

Effort that fails to find the search object provides (negative) information about the object's location. This information is incorporated into the posterior distribution on impact location through the use of Bayes' rule in the fashion described in Section 4.1 In this section we estimate the effectiveness of the surface search effort and the search efforts in Phases I – III, and combine them to compute the posterior PDF on impact location given failure of these efforts.

The unsuccessful searches considered in this analysis include the ones listed below.

Unsuccessful Surface Searches: 1 June to 5 June 2009.

- The air and ship search efforts failed to positively identify and recover floating debris or bodies during the period from 1 June to 5 June. The first piece of debris was recovered and identified on June 6th.

Phase I: 10 June to 10 July 2009

- Passive acoustic searches for the "black box" Underwater Locator Beacons (ULBs) by the US Navy Towed Pinger Locators (TPLs).
- Search by the IFREMER Victor Remotely Operated Vehicle (ROV)

Phase II: 27 July to 17August 2009

- Side looking sonar search by the IFREMER deep sonar towed by the *Pourquoi Pas?*

Phase III: 2 April – 24 May 2010

- Side-scan sonar search by three REMUS Autonomous Underwater Vehicles (AUVs) and visual/sonar search by the Triton ROV.
- Search by the USN Orion towed side-scan sonar system.

4.1 Accounting for Unsuccessful Search

The SAROPS program uses a large number N of simulated points or particles to represent the probability distribution on the path or location of a search object. The n^{th} particle has weight w_n for $n = 1, \ldots, N$. Initially all weights are set equal. The weight is the probability that the particle represents the search object's location or path. The SAROPS PDF in Figure 5 was produced by adding the weights (probabilities) of the particles in each cell to obtain the probability that the impact point is in that cell. These probabilities are represented by the color code progressing from red to yellow to blue as cells progress from high to low probability. The particles form the actual distribution computed by SAROPS. The cells are used simply as a method of display.

If an unsuccessful search takes place, we compute the probability $p_d^1(n)$ that the search would have detected the search object if it were located where particle n is for $n = 1, \ldots, N$. From this we compute the posterior distribution on object location using Bayes' rule as follows).

$$w_n^1 = \frac{\left(1 - p_d^1(n)\right) w_n}{\sum_{n'=1}^{N} \left(1 - p_d^1(n')\right) w_{n'}} \quad \text{for } n = 1, \ldots, N \qquad (2)$$

where w_n^1 is the posterior probability that particle n represents the object's location. We can see from (2) that if $p_d^1(n)$ is close to 1, the posterior probability on particle n will tend to be low. Correspondingly those particles with low values of $p_d^1(n)$ will tend to have high posterior probabilities.

If the particles are moving and the search sensor is moving, SAROPS accounts for both of these motions in calculating $p_d(n)$ for each particle.

4.2 Aircraft and Ship Surface Search

Searches for debris by Brazilian and French aircraft were conducted from June 1st to June 26th 2009. These searches were unsuccessful until June 6 when debris and bodies from the aircraft were first recovered. Analysis of the unsuccessful air searches and ship searches prior to 6 June provides negative search information that we use to decrease the probability on some particles and increase it on others according to Bayes' rule.

Search paths for each sortie were entered into SAROPS, along with information on altitude, speed, aircraft type, meteorological visibility, sea state, and expected sensor performance against a raft-sized target (specifically a four-man raft), which was taken as a surrogate for the detectability of a large piece of debris such as the galley. In addition to the air search, we included the effort of the ship *Douce France* that searched in the vicinity of LKP on June 1st.

Two Brazilian Air Force Embraer R-99 and a French Air Force E-3F (AWACS) were also involved in the search. They patrolled at high altitude and used their airborne radars to search for possible reflections from the ocean surface. The (vast) surfaces that they covered are not accounted for in the search analysis. Only the low altitude visual searches in the vicinity of the 40 NM circle are included.

To evaluate the effect of the unsuccessful surface search, we started with the surface search prior distribution given in Figure 5. We allocated simulation particles in accordance with the probability density in each cell. We then used SAROPS to "drift" these particles forward in time from the time of impact though 6 June. In the process of doing this we accounted for the unsuccessful aircraft and ship search during that time. The search object was assumed to have the drift and detection characteristics of a four-person life raft. If the particles were predicted to pass through an area searched by aircraft or the Douce France, their weight was appropriately reduced according to the estimated detection probability for that platform sortie as described in section 4.1. The result is a set of particles whose weights (probabilities) have been updated to incorporate the unsuccessful air and ship search effort during those days.

Surface Search Posterior. We then pulled each particle back to its position at the time of impact keeping its weight the same as it was at the end of unsuccessful surface search. From these reweighted particles, we calculated a new PDF for the impact point. The result of this calculation is shown in Figure 6.

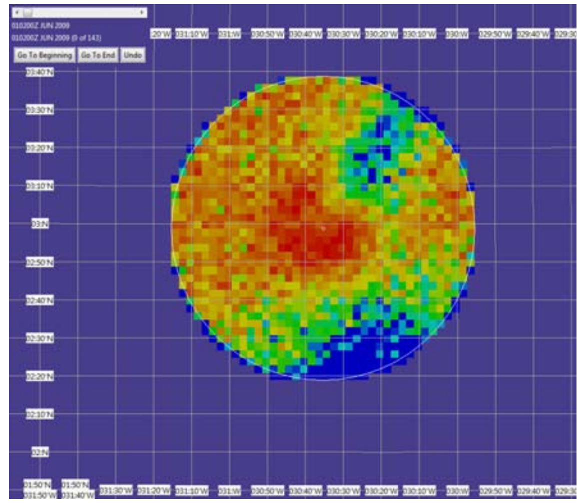

Figure 6. Surface Search Posterior PDF

Underwater Search Prior. For the purpose of evaluating the underwater search, we formed a prior which is a mixture of 30% of the Surface Search Posterior in Figure 6 and 70% of the FD Prior in Figure 2. This PDF is shown in Figure 7. We have given the Surface Search Posterior a low weight in this PDF because it depends heavily on estimates of currents in the area of the crash during 1 – 10 June. For the reasons discussed in Section 3.2, we have low confidence in these estimates

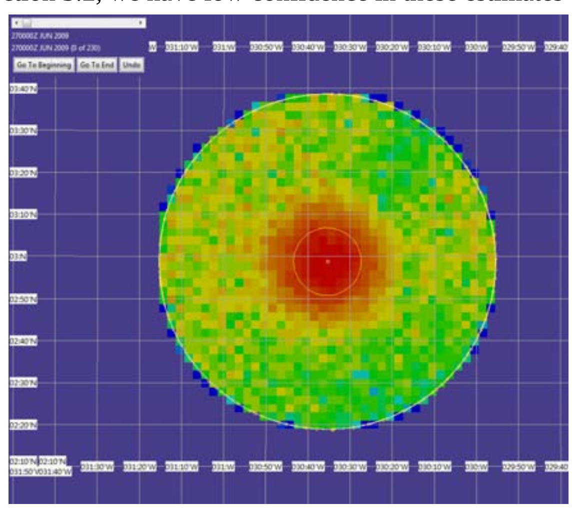

Figure 7. Underwater Search Prior PDF

4.3 Phase I Searches

In this section we describe the searches performed during Phase I and compute the posterior PDFs resulting from these unsuccessful searches.

Acoustic Searches for the ULBs. The aircraft was equipped with two "black boxes", the digital Flight Data Recorder (FDR) and the Cockpit Voice Recorder (CVR). These ruggedized devices are designed to withstand the high impacts expected in a crash, and are fitted with an

Underwater Locator Beacon (ULB) that activates when contact is made with water. The batteries on the ULBs are certified to last at least 30 days. In the case of the ULBs fitted on this aircraft, the manufacturer stated that the duration of the transmission was of the order of forty days.

The passive acoustic search for the FDR and CVR, which lasted 31 days and ended on 10 July 2009, primarily involved two tugs hired to assist in the search, *Fairmount Glacier* and *Fairmount Expedition*.

The Fairmount ships' search efforts overlaid the aircraft's intended track. Both ships employed Towed Pinger Locators (TPLs) supplied by the US Navy. Personnel from Phoenix International operated the equipment. On-site tests indicated the equipment was functioning properly.

The TPL sensors were assessed to detect the ULBs at a lateral range of 1730m with a POD of 0.90. This detection range accounted for the frequency of the ULBs' emissions (37.5 kHz) and the assumed source level (160 dB). The TPLs were flying above the underwater terrain, so we estimated that degradation due to terrain shadowing was minimal. Environmental calculations showed that deep water propagation in this area is basically direct path and the transmission loss and ambient noise are sufficiently low to provide detection probabilities of 0.90 or above, a number that we feel is conservative provided at least one of the ULBs was operating properly. The ships' tracks, reconstructed from GPS data, are shown in Figure 8 below.

The calculation of the probability of detection for the TPL search must account for the possibility that the ULBs were destroyed in the crash. Based on the condition of the wreckage recovered and after conferring with the BEA, we assumed a probability of 0.8 that a single ULB survived the crash If ULB survival is considered independent, then the probability of detecting at least one ULB given it is within lateral range 1730 m of the TPL as follows:

$$
\begin{aligned}
P_D &= \Pr\{\text{detect}|\text{both working}\}\Pr\{\text{both working}\} \\
&\quad + \Pr\{\text{detect}|\text{one working}\}\Pr\{\text{one working}\} \\
&= \left(1-(0.1)^2\right)(0.8)^2 + (0.9)\left(2(0.8)(0.2)\right) = 0.92
\end{aligned}
$$

If the ULBs were mounted sufficiently close together to consider their chances of survival to be completely dependent, then the probability of detecting at least one ULB drops to 0.9×0.8 = 0.72.

It is difficult to say whether the survival of the two ULBs should be considered independent events. In light of this uncertainty, it was decided to use a weighted average of 0.25 for the independent and 0.75 for the dependent probabilities yielding a 0.77 detection probability given a ULB is within lateral range 1730 m of a TPL search during the 30 day period from June 1 – June 30 , 2009 which corresponds to the pingers rated 30 day lifetime. During the additional 10 days that the pingers were likely to be working according to the manufacturer, we discounted the TPL detection probability to 0.385.

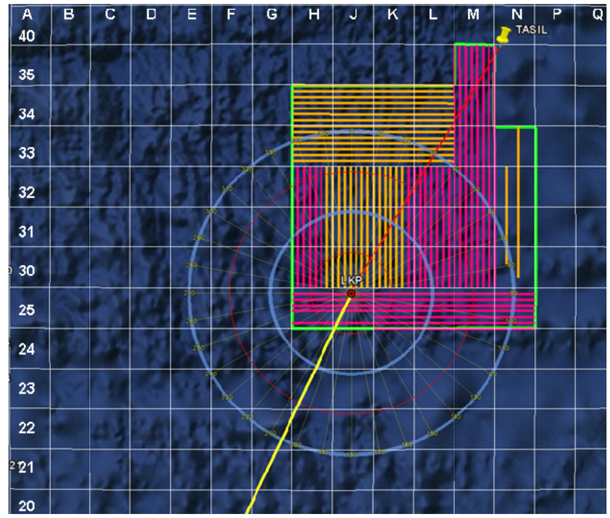

Figure 8. *Fairmount Glacier* (orange) and *Expedition* (pink) TPL Search Tracks

The posterior distribution after unsuccessful ULB searches by the Fairmount ships is shown in Figure 9. This is the posterior for the location of the underwater wreckage after the Phase I searches. The Cumulative Detection Probability for the TPL searches is 0.41.

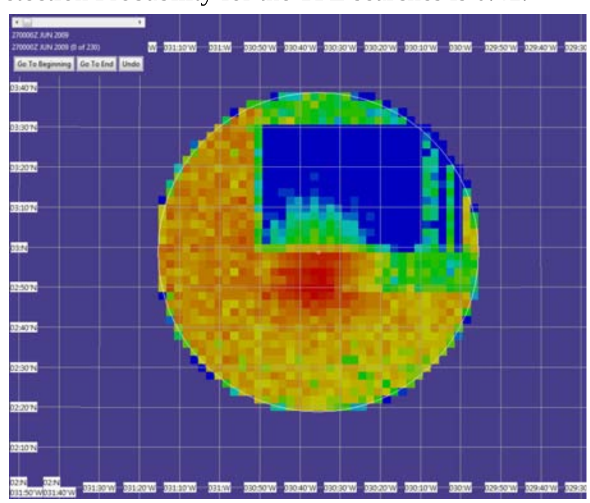

Figure 9. Posterior PDF after Phase I: CDP = 0.41

4.4 Phase II Search

To continue the search after the pingers' extinction, the BEA decided to use the IFREMER side-looking sonar towed by the *Pourquoi Pas?* which had the capability to complete the bathymetry survey of the area thanks to its hull-mounted multi-beam sonar.

Metron's 2009 analysis of the Phase I search efforts was presented to the BEA during the planning for the second phase of search. It was estimated that the *Pourquoi Pas?* could cover three-to-four cells in the three weeks in which it would be on station at the accident site, achieving a 0.9 POD in those cells.

The BEA chose to search the eastern half of J24, all of K24 and L24, and the western half of M24 as shown in yellow in Figure 10. This constituted three full cells in a row south/southeast of the LKP, 19 – 36 NM away at the farthest point. Figure 11 shows the posterior PDF after the unsuccessful Phase II search.

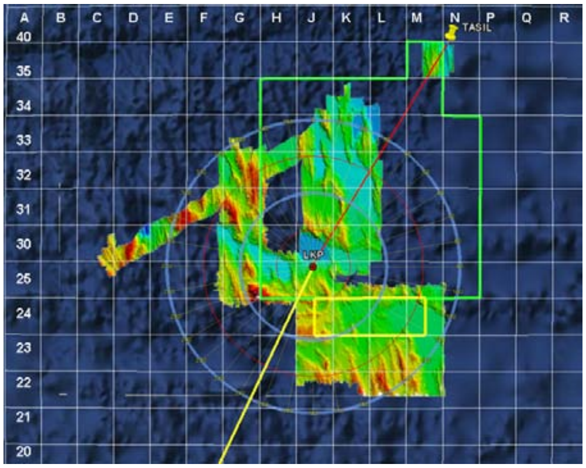

Figure 10. *Pourquoi Pas?* Search Cells (yellow).

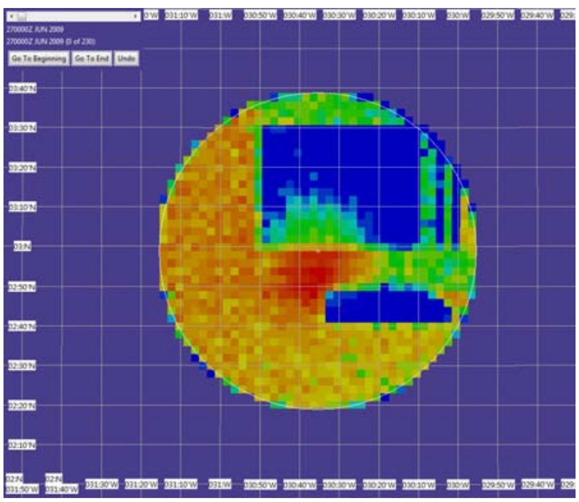

Figure 11. Posterior PDF after Phase II: CDP = 0.45

4.5 Phase III Searches

There were two search efforts during Phase III. One involved the US Navy/Phoenix International with assets onboard the *Anne Candies* and the other involved assets operated by WHOI. Both efforts used side-scan sonar. The search area covered by these searches was, for the most part, determined by the search area recommendations made by the Drift Group in [8].

US Navy/Phoenix International. The US Navy/Phoenix International search was performed using the USN ORION towed side-scan sonar system which covered the 1900 square kilometer area of orange swaths shown in Figure 12. The ORION was operated to cover a 2400 meter swath. Adjacent lines were spaced no greater than 2000 meters apart. All records were monitored in real time. During turns between track lines, the data were reviewed in accelerated playback and all items of interest were further processed with sonar enhancement software.

US Navy/Phoenix International operators/analysts evaluated the 1743 km^2 as having been covered with the highest degree of confidence. Two patches of bottom, located in the peaks of some of the steepest slopes produced returns that were not interpretable. These were subsequently covered by REMUS 6000 AUVs. In the high confidence areas, we used a detection probability of 0.90. For the rest, we set the detection probability to 0.50 with the exception of the ridge areas which received 0.10.

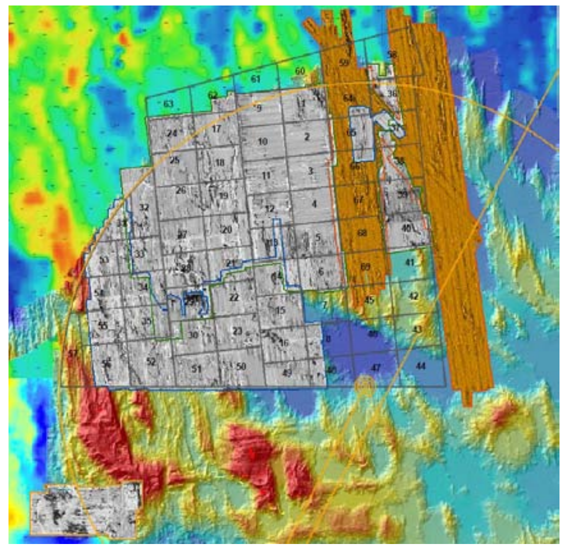

Figure 12. Search Areas for ORION (orange) and REMUS/Triton (grey)

Within the searched area Phoenix International operators identified a number of small targets which BEA planed to investigate during search operations in 2011.

Woods Hole Oceanographic Institution. The *Seabed Worker* deployed to the search area with three REMUS 6000 AUVs — two belonging to the Waitt Institute for Discovery and one to GEOMAR, and the Seabed Triton XLX 4000 ROV. The three REMUS vehicles covered the 4,375 km^2 area shown in grey in Figure 12. The REMUS side scan sonar maximum range is 600 – 700 m. Search legs were spaced a distance apart equal to the maximum range less 50 m which produced double coverage almost everywhere within its search area. Most regions of steep terrain, such as ridges, were imaged from both sides and were thus well searched. Exceptions were regions that contained ridges that were not suitable for side-looking sonar coverage. The Triton ROV was deployed in some of these.

We attributed a detection probability of 0.90 to the areas shown in grey in Figure 12 with the exception of the areas noted where we set the detection probability to 0.10.

4.6 Posterior After Phase III Searches

Figure 13 shows the posterior PDF after the unsuccessful searches from Phases I, II, and III.

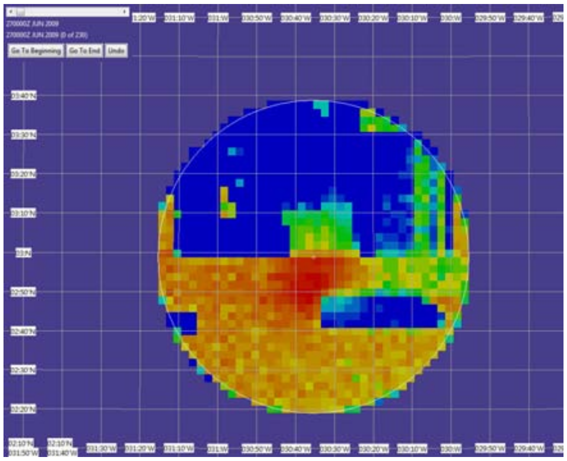

Figure 13: Posterior PDF after Phase III: CDP = 0.58

Posterior Assuming Pingers Failed. If both pingers failed to activate, the ULB search would have had no chance of detecting the wreckage. If this were the case we would remove the ULB search in computing the posterior. The result of doing this is shown in Figure 14 below.

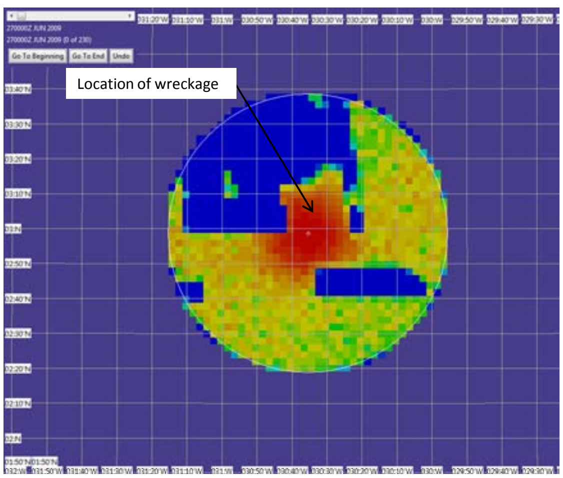

Figure 14. Posterior Assuming Pingers Failed: CDP = 0.29

5 Conclusions

The posterior PDFs in Figures 13 and 14 provided good guidance for the phase IV search [10]. The wreckage is located in an area thoroughly covered by the TPL passive acoustic search (see Figure 8) which suggests the locator beacons were not functioning properly. Figure 14 shows the wreckage is located in a high probability area assuming the ULBs failed to operate properly. These results suggest is likely that either both ULBs failed or failed to be detected for some reason, and that this failure resulted in a long and difficult search for the wreckage. The BEA began recovery operations in April 2011. One of the goals is to recover the ULBs to determine if they were functioning during the 30 day period after the crash.

Methodology. Our approach used careful and methodical consideration of all data available, with associated uncertainties, to form an analytic assessment of the highest likelihood areas for future search efforts. The weighted scenario approach allowed inconsistent information to be combined with subjective weights that capture the confidence in each piece of data. The analysis of the detection effectiveness of each component of the search which produced the Bayesian posterior distributions shown in Figures 13 and 14 formed a solid basis for planning the next increment of search. In fact the phase IV search commenced in the center of the distribution and quickly found the wreckage.

The success of this effort provides a powerful illustration of the value of this methodical, Bayesian approach to search planning. The full report [11] of this work is available on the BEA website.

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