

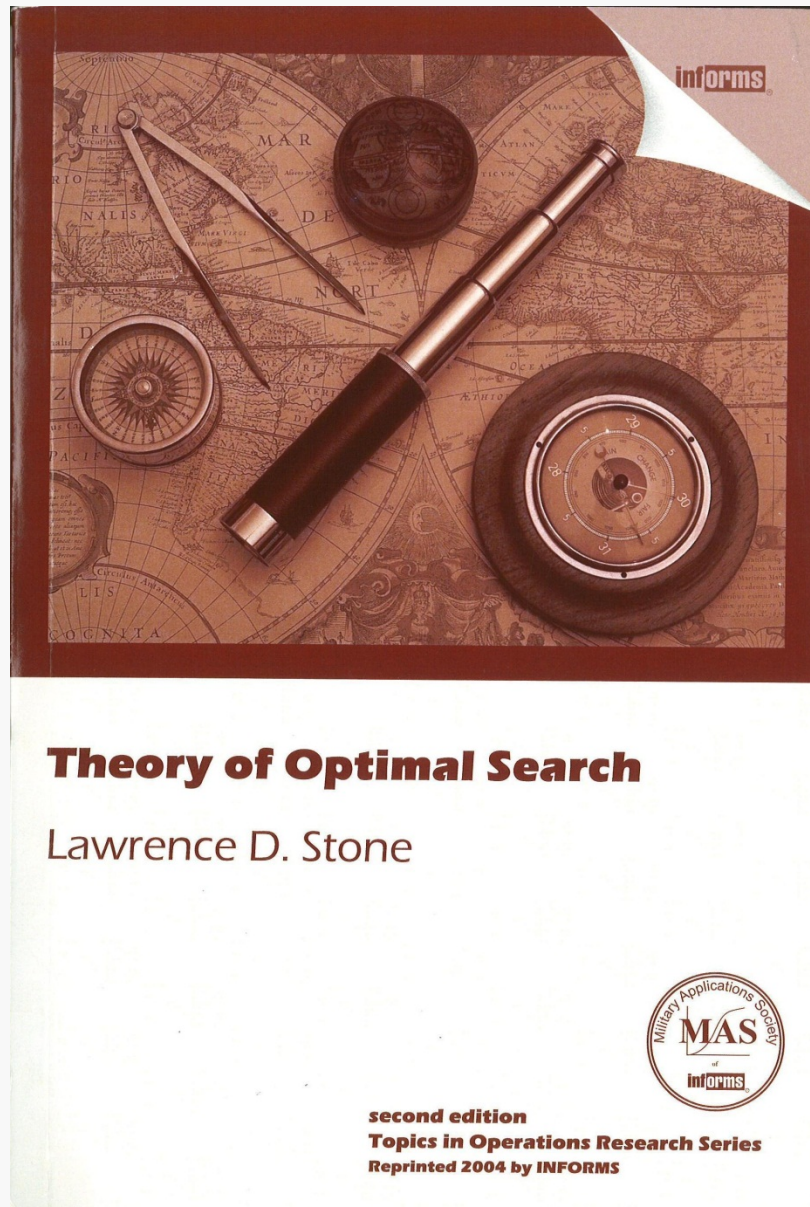
Search Analysis for the Underwater Wreckage of Air France Flight 447

Fusion 2011 - July 7, Chicago, USA

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Background



- Lanchester Prize Book:
Theory of Optimal Search, 1975
- Searches:
 - US Submarine *Scorpion*, 1968
 - SS *Central America*, 1988
 - Steve Fossett, 2008
- Search Planning Aids: USCG
 - CASP: 1974
Computer Assisted SAR Planning
 - SAROPS: 2007
Search And Rescue Optimal Planning System

Air France Flight 447 Disappears

- In the early morning hours of 1 June 2009, Air France Flight AF 447, with 228 passengers and crew aboard, disappeared during stormy weather over the South Atlantic



Last Known Position
(LKP) 2.98°N, 30.59°W

Searches

- Air and surface search for floating debris and signs of survivors begins 1 June 2009
 - On 6 June the first bodies and floating debris are found 38 NM north of LKP
- Three unsuccessful underwater search phases in 2009 and 2010
 - Phase 1: Passive sonar search for Underwater Locator Beacons (ULBs)
 - Phases 2 & 3: Side-looking sonar search for underwater wreckage



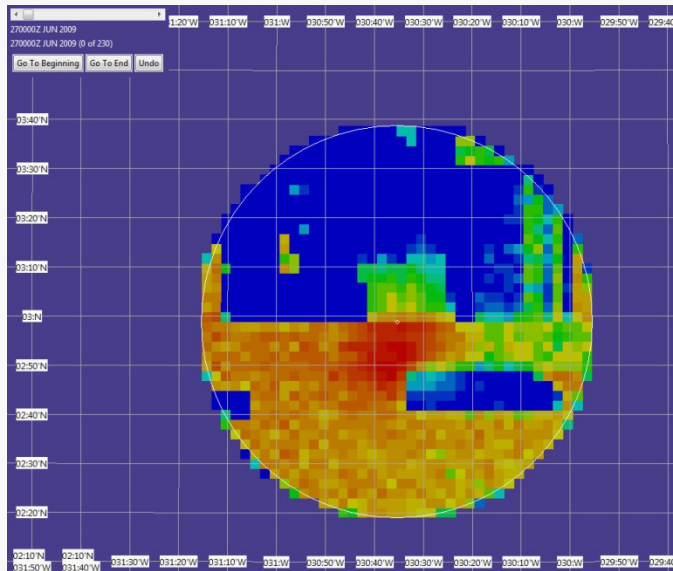
Tail Section



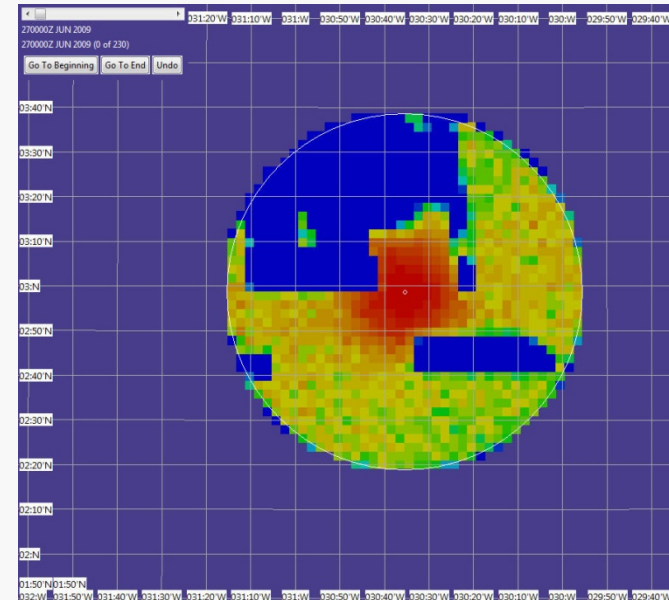
Galley

Probability Map for Phase 4 Search

- July 2010, the French Bureau d'Enquêtes et d'Analyses (BEA) tasked Metron to produce posterior Probability Distribution Function (PDF) for the location of AF 447 *given failure of previous searches*
- Resulting PDFs¹ produced by SAROPS showed area near LKP be high probability



PDF after Phase 3 search: Red cells indicate high prob

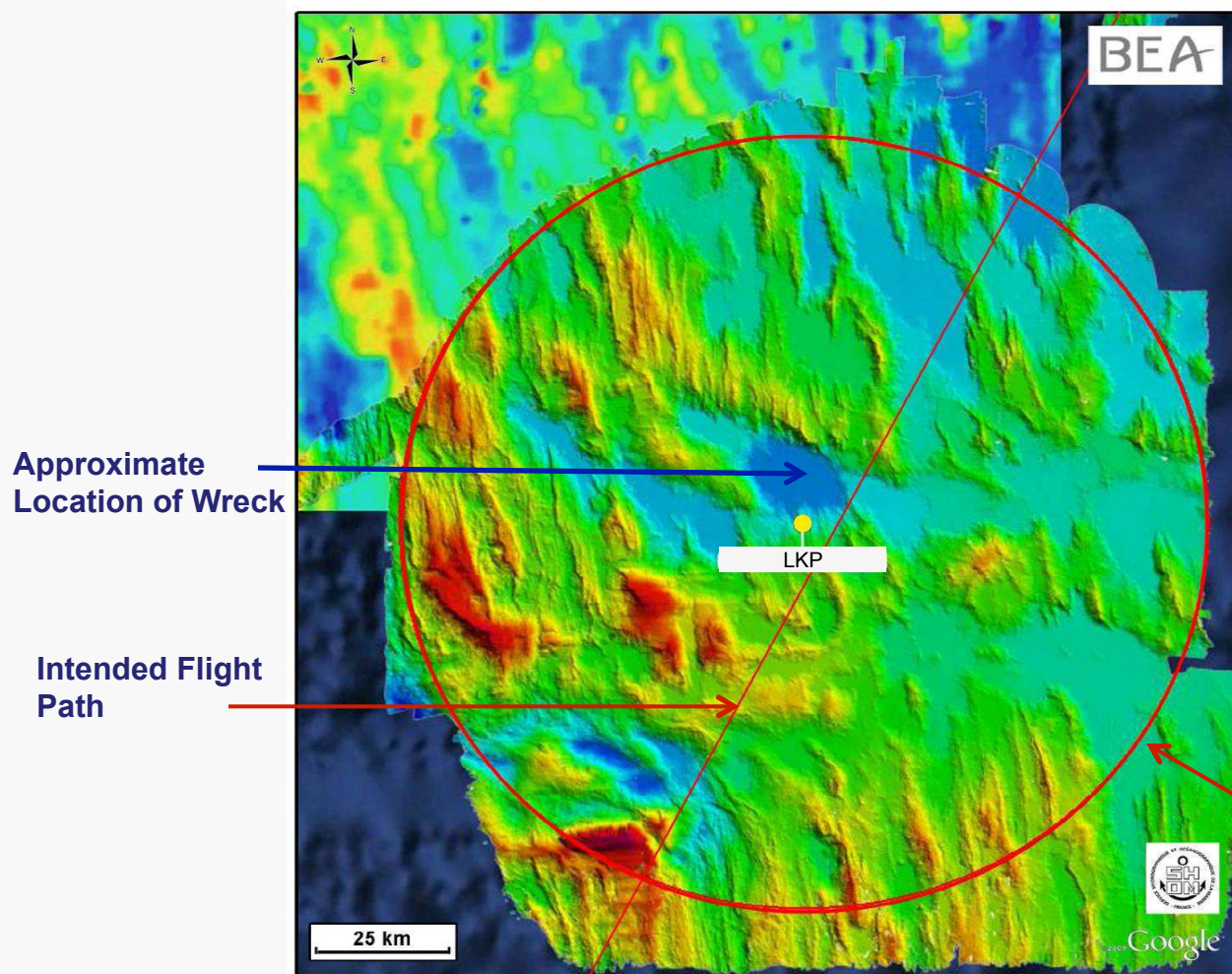


PDF after Phase 3 assuming pingers failed

1. Stone, Keller, Kratzke, Strumpfer, *Search Analysis for the Location of the AF447 Underwater Wreckage*
Metron Report to BEA, 20 January 2011

Phase 4 Search Finds the Wreck

- On 3 April 2011, the underwater wreckage was found.



BEA said on 8 April 2011¹

“This [Metron] study, published on the BEA website 20 January 2011, indicated a strong possibility for the discovery of the wreckage near the center of the Circle. It was in this area that it was in fact discovered after one week of exploration...”

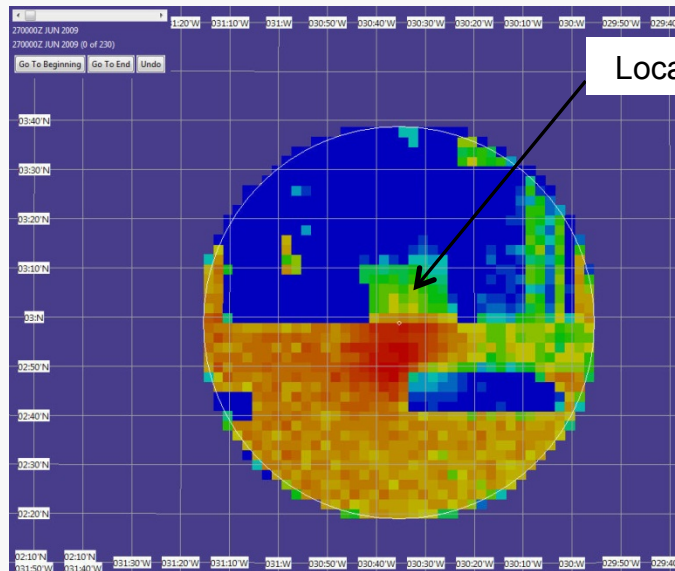
40 NM Circle:

The BEA determined that the plane could have flown no farther than 40 NM from LKP

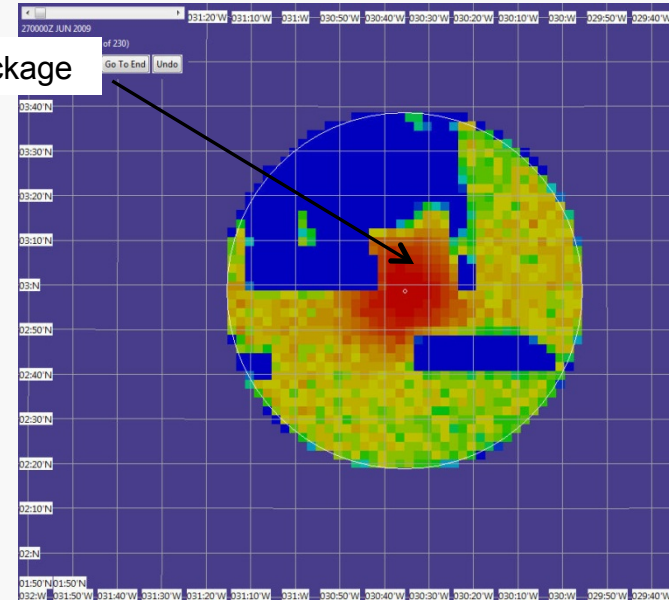
1. Troadec, Jean-Paul. *Undersea search operations to find the wreckage of the A 330, flight AF 447: the culmination of extensive searches*. Note from BEA Director, 8 April 2011, on the BEA website at <http://www.bea.aero/en/enquetes/flight.af.447/note.from.bea.director.end.phase4.pdf>

Probability Map for Phase 4 Search

- July 2010, BEA tasked Metron to produce posterior Probability Distribution Function (PDF) for the location of AF 447 given failure of previous search
- The resulting PDFs¹ showed area near center of circle to be high probability



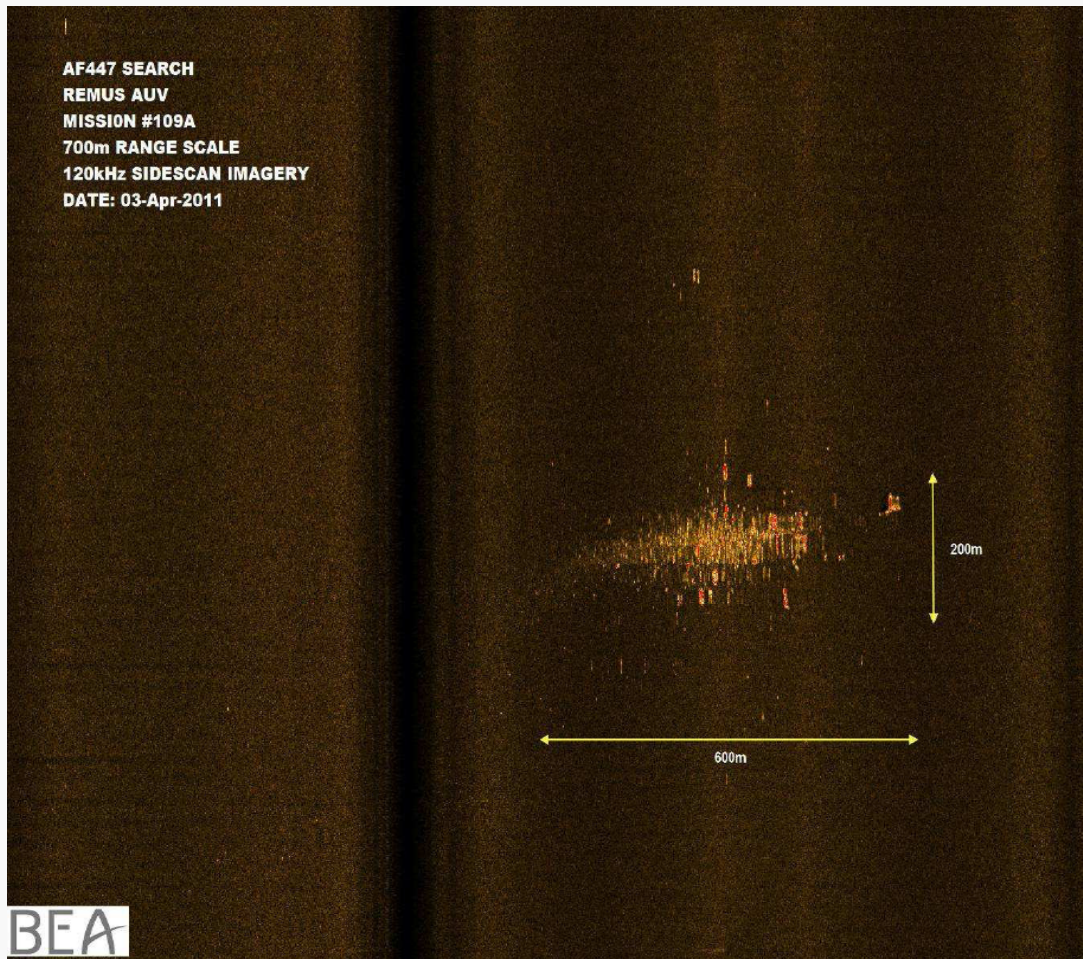
PDF after Phase 3 search: Red cells indicate high prob



PDF after Phase 3 assuming pingers failed

1. Stone, Keller, Kratzke, Strumpfer, *Search Analysis for the Location of the AF447 Underwater Wreckage* Metron Report to BEA, 20 January 2011

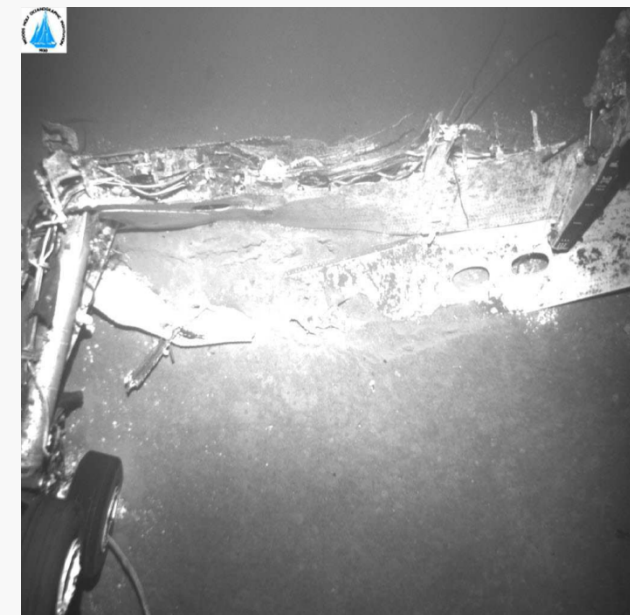
Wreckage



Side-Scan Sonar Image of Wreckage



Engine



Landing Gear

FDR and CVR with ULB Recovered



Flight Data Recorder (FDR) being recovered up by a mechanical arm of the Remora 6000 ROV



Cockpit Voice Recorder (CVR) capsule with the Underwater Locator Beacon (ULB) attached to the housing at top left

Questions

- Why did it take almost two years to find the underwater wreckage?
- Why weren't the ULBs detected by the passive acoustic search?
- How did Metron perform the analysis indicating the center of the circle was a high probability area for search in phase 4?

Searches

- After the air and surface searches, there were four search phases
 - **June and July 2009 Phase 1:** Passive acoustic search along intended aircraft track to detect the ULBs on the FDR and CVR
 - **August 2009 Phase 2:** Side-looking sonar search south of LKP
 - **April and May 2010 Phase 3:** Extensive side-looking sonar search north of the LKP
 - **March and April 2011: Phase 4:** Successful side-looking sonar search near center of 40 NM circle

Phase 1: Passive Acoustic Search

- Used Towed Pinger Locators (TPLs) from US Navy on two tugs, *Fairmount Glacier* and *Fairmount Expedition*
 - Equipment operated by Phoenix International personnel
- Searched for 31 days ending on 10 July 2009.
- TPLs are hydrophones designed to detect the 160 dB, 37.5 kHz signal from ULBs
 - ULBs designed last roughly 40 days
 - Environment: Deep water, direct path, low ambient – high detection probability (> 0.9) within lateral range of 1730 m.
 - Search paths designed to provide lateral ranges less than 1730m
 - TPL sensors tested on-site at beginning of search

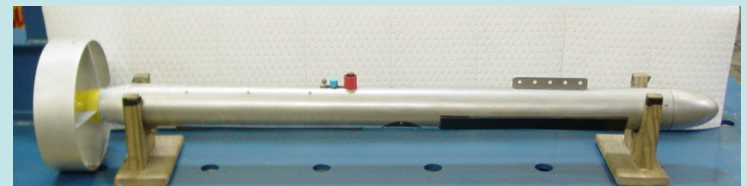
TPL System Descriptions

TPL 20

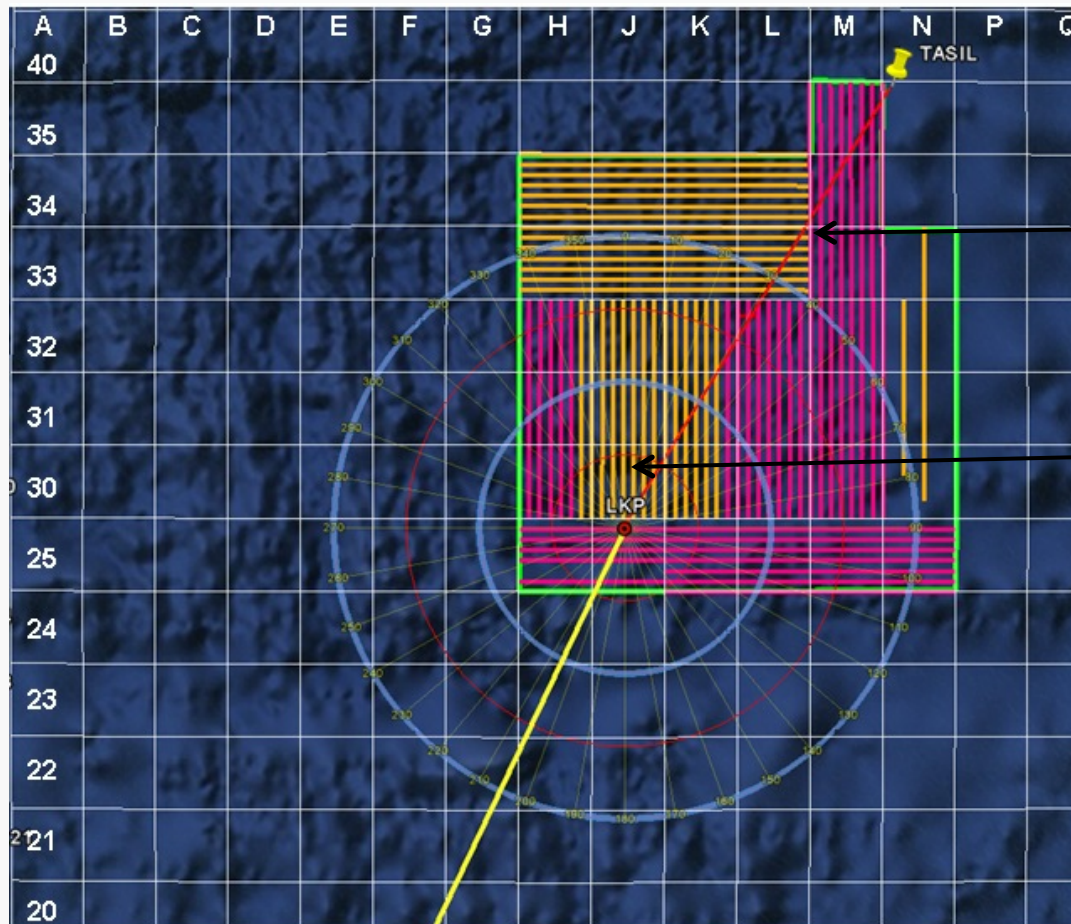
- 6000m Depth Capability
- 1 Hemispherical Omni Array

TPL 40

- 6000m Depth Capability
- 1 Hemispherical Omni;
3 Directional Line Arrays
- Surface Controllable Gain
- In-water Bandwidth Test
- Pitch, Roll, Depth,
Heading, & Temperature



Phase 1: TPL Search Paths



Failure of TPL search led to long and difficult search

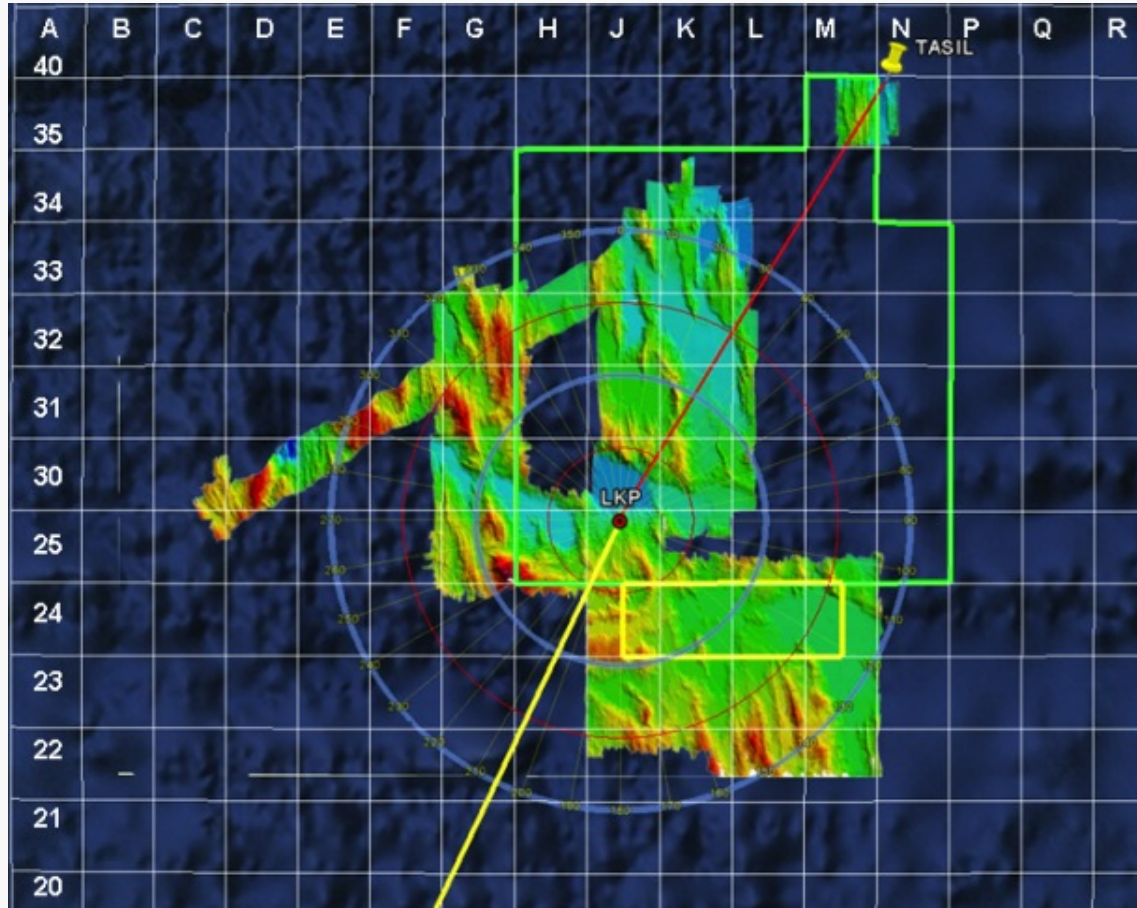
Intended flight path

Approximate location of wreckage

Fairmount Glacier (orange) and Fairmount Expedition (pink) Search Tracks.

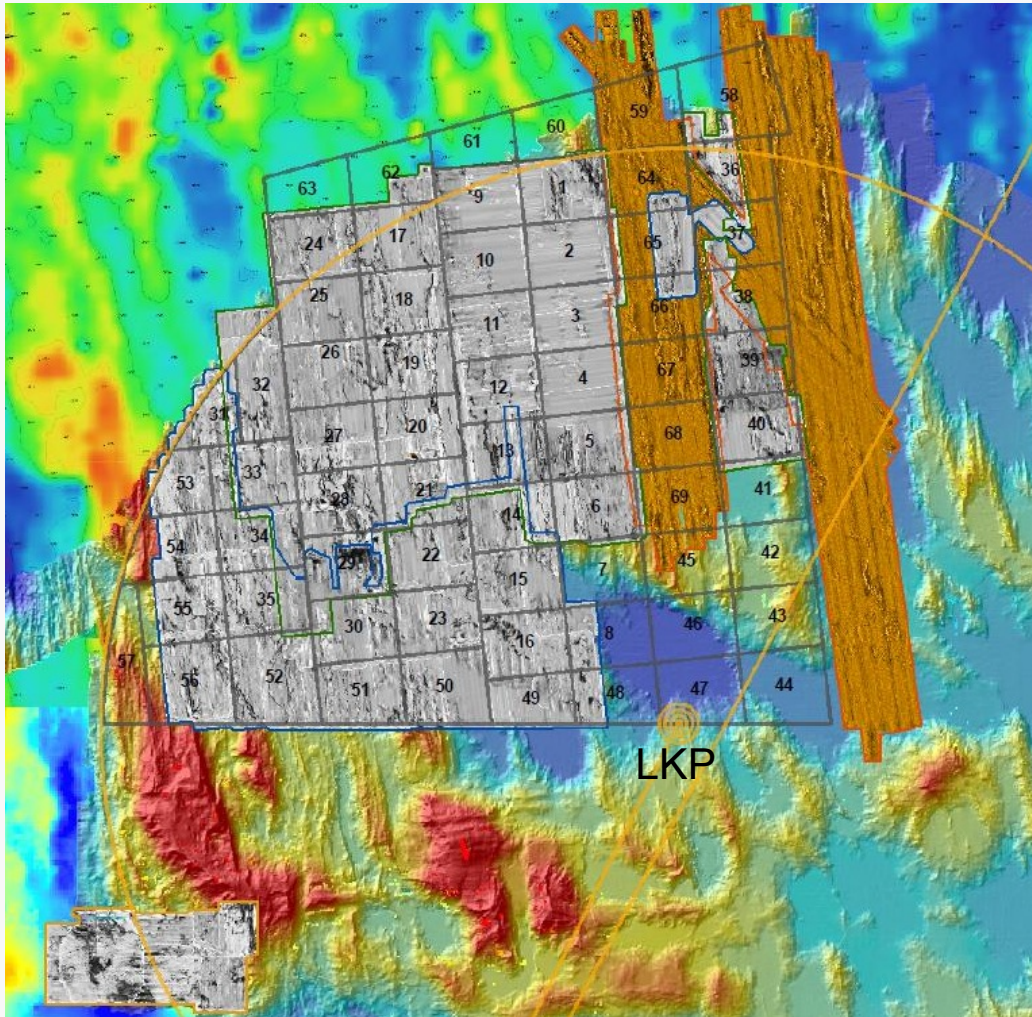
Blue circles are 20 NM and 40 NM circles about the LKP

Phase 2: Side-Looking Sonar



- In August 2009, the BEA decided to search in the cells outlined in yellow with a side-looking sonar towed from the *Pourquoi Pas?*
- Area relatively flat
- Pd estimated at 0.9
- Search performed by IFREMER – French Research Institute for Exploitation of the Sea
- Green area shows TPL search

Phase 3: REMUS and ORION Searches



- Woods Hole Oceanographic Institute (WHOI) deployed 3 REMUS 6000 AUVs which searched the grey area.
- US Navy/Phoenix International performed search in orange area using ORION towed side-looking sonar
- Both searches rated highly effective, $P_d > 0.9$
- Search area based on reverse drift analysis by an international group of oceanographers - the Drift Group

REMUS and ORION Sensors

- **REMUS 6000 AUV**
- AUVs operating in up to 30 degree slopes
- AUV sonar swath - 1400 meters
- Remus AUVs have ability to take still photographs to investigate potential sonar targets

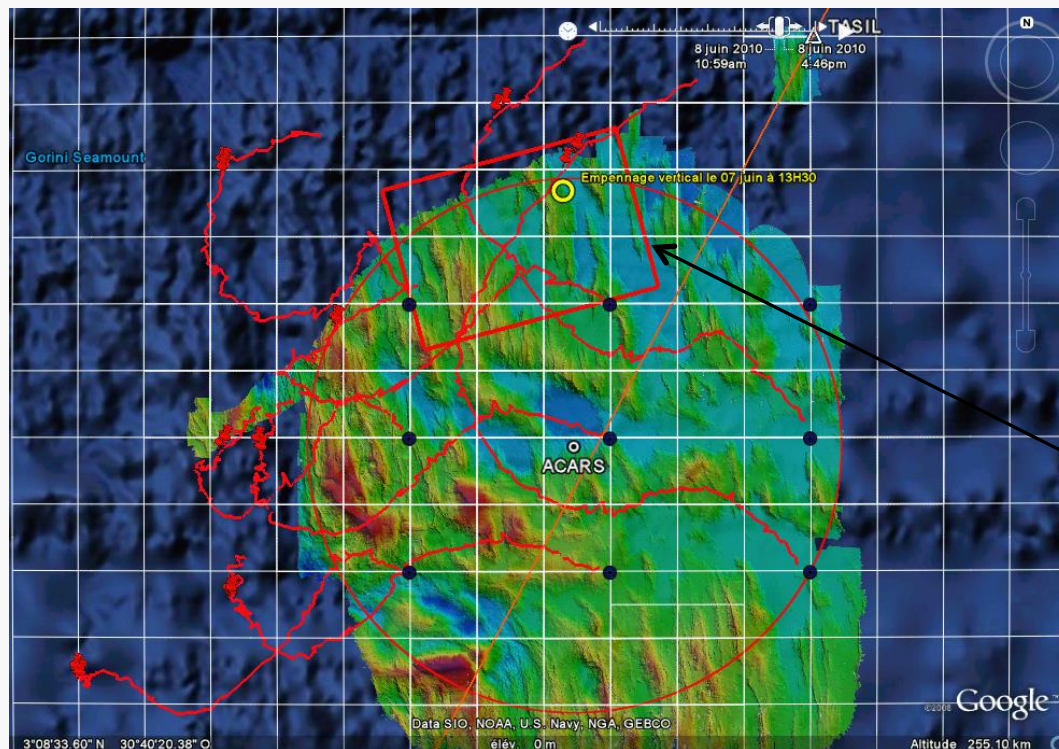


- **ORION 6000 Search System**
- Towed side scan sonar
- 6000m operational depth
- Dual frequency 56/240 kHz



Drift Group Recommendation

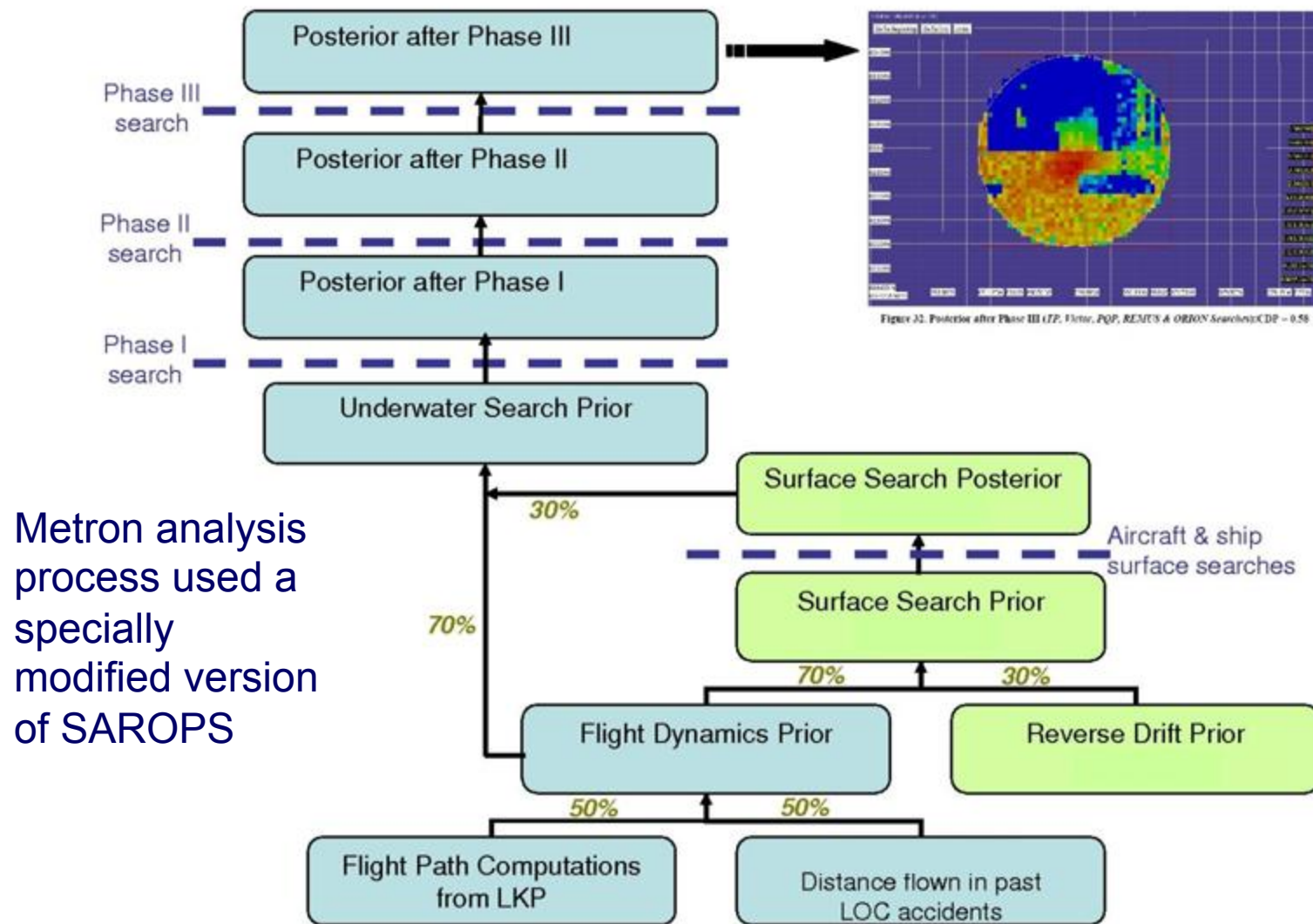
- Drift Group – International group of oceanographers
 - Used data from Argo floats, AOML surface drifters, and fishing buoys drifting in area at time of crash
 - Used several different models to reverse drift positions of bodies and debris found on June 6 - 7
 - Took average of most consistent backward predictions to obtain rectangle



2010 Drift experiment:

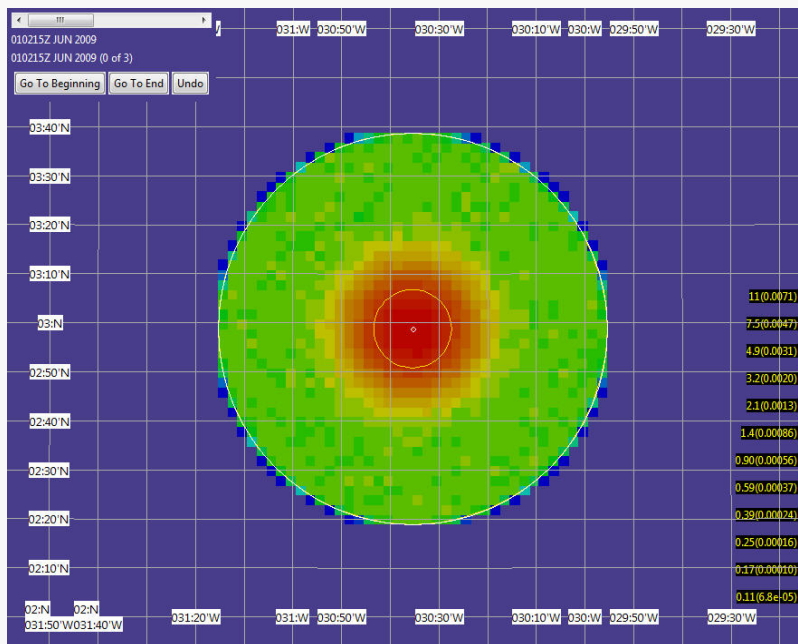
- 8 SLDM buoys placed inside 40 NM circle on 3 June 2010.
- Paths show drift to 8 June 2010
- Rectangle is area recommended by Drift Group for Phase 3 search

Metron Analysis Process

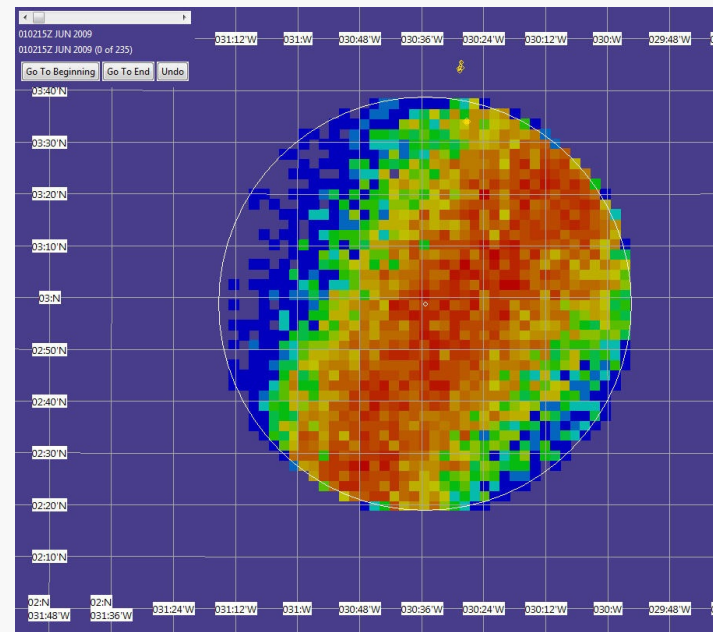


Flight Dynamics (FD) and Reverse Drift PDFs

- Prior PDF for impact prior to surface search - mixture
 - Flight dynamics (70%)
 1. (50%) Uniform over 40 NM circle about LKP
 2. (50%) Distribution based on nine commercial accidents involving emergency crashes – represented by circular normal with std dev = 8 NM
 - Reverse Drift (30%) prior truncated at 40 NM circle



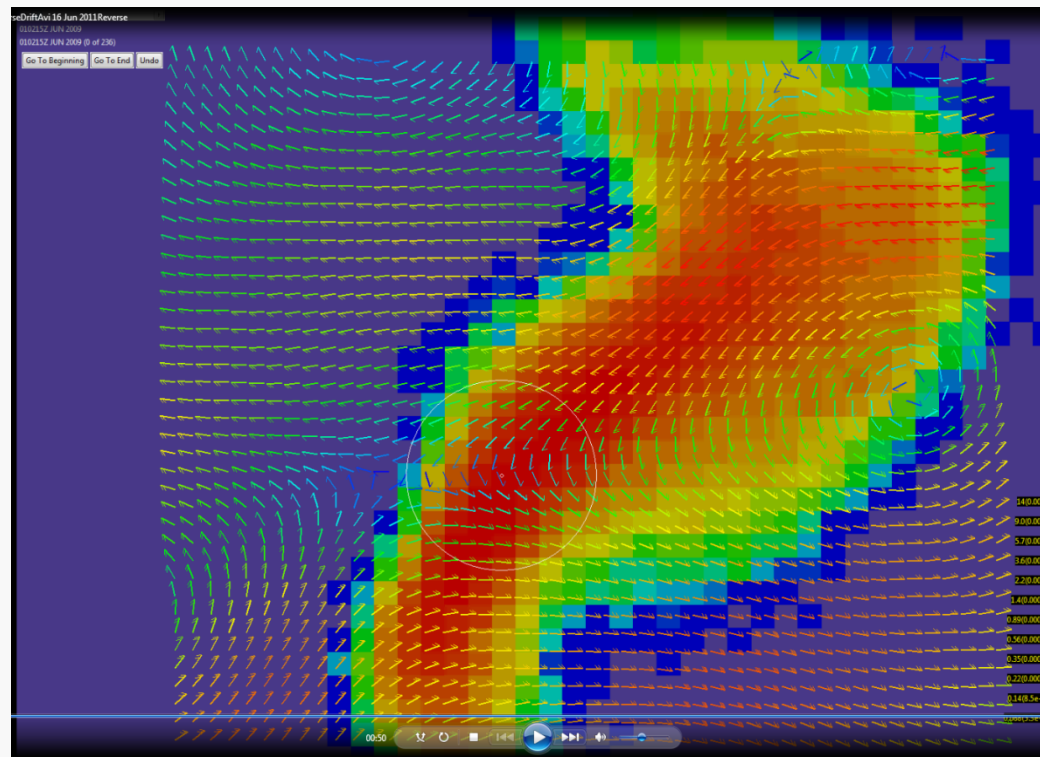
Flight Dynamics PDF



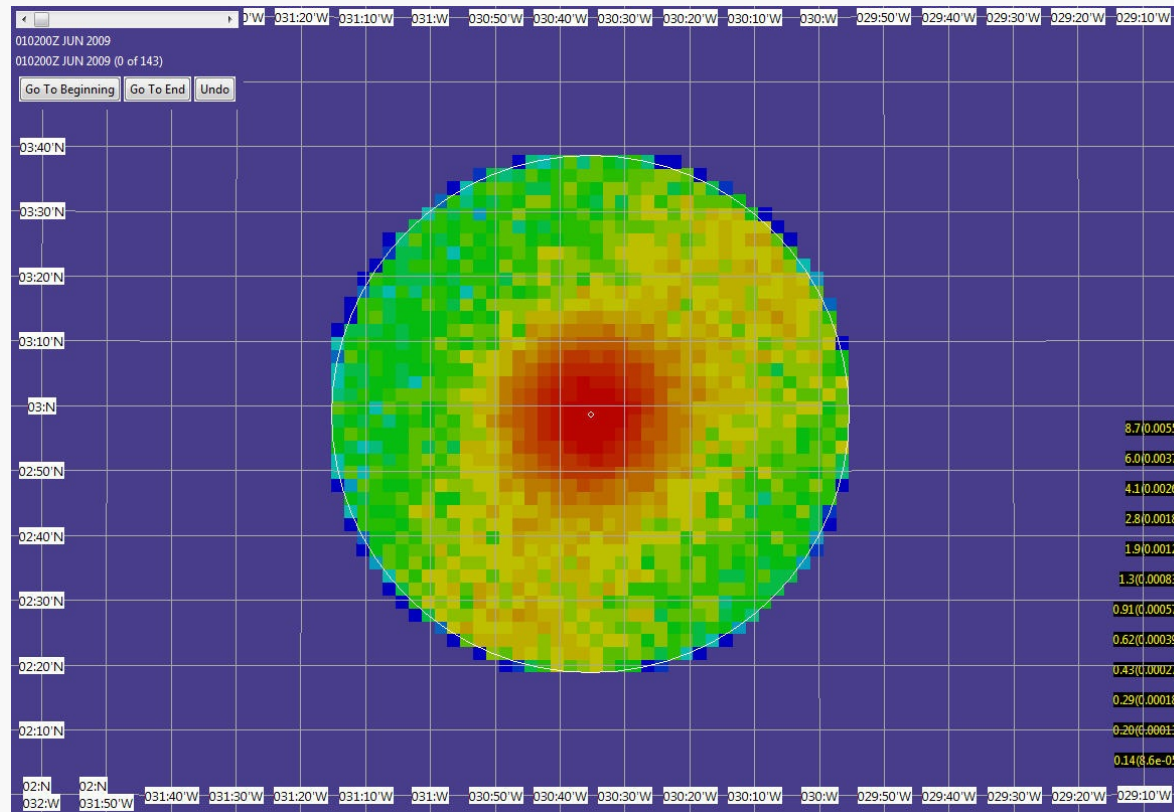
Reverse Drift PDF

Reverse Drift (RD) Prior PDF

- RD prior computed using the locations of bodies found 6 – 10 June and reverse drifting them back to the time of impact on 1 June
 - Requires estimates of winds and currents in region at time of crash
 - Estimates highly uncertain
 - Used currents estimated by Drift Group and Navy NOGAPS winds
- [Reverse Drift Video](#)



Surface Search Prior

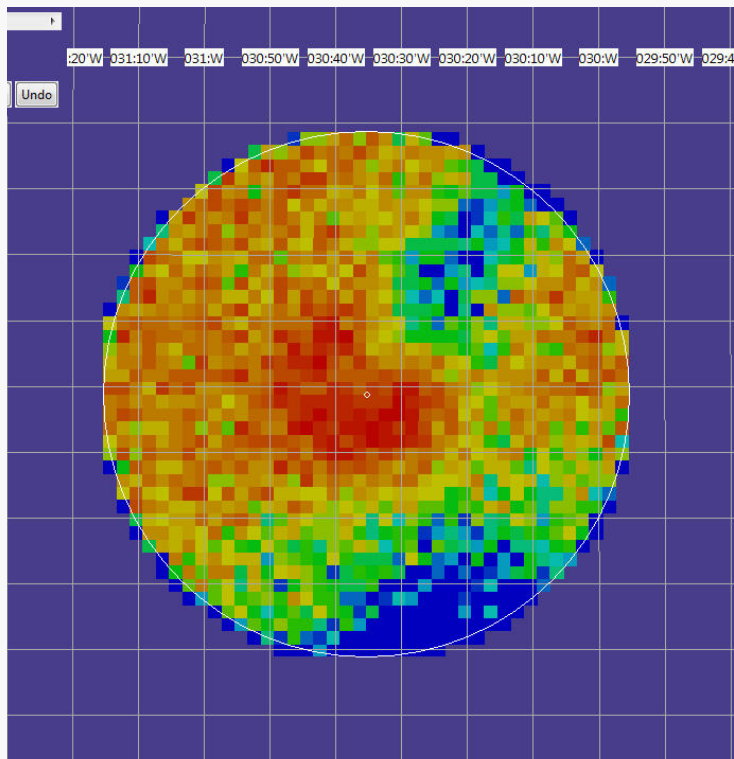


70% Flight Dynamics + 30% Reverse Drift

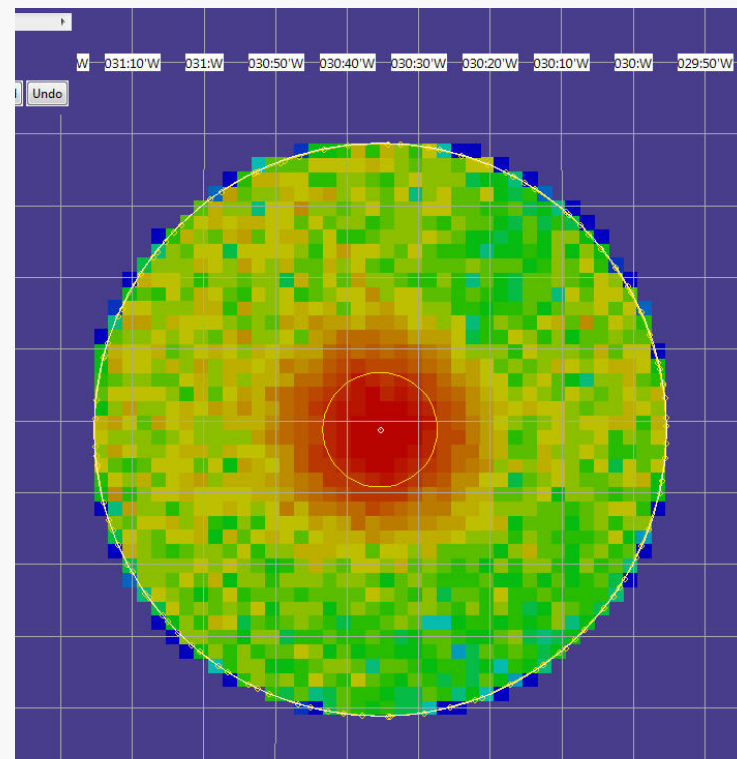
Accounting for Failed Surface Search

- Aircraft and Ships searched the surface from 1 June to mid-day on 6 June before detecting floating debris – Galley
- Search paths for aircraft and ships put into SAROPS along with estimate of detection capability
- Surface Search Prior PDF drifted forward in time = 40,000 particles or paths
 - Paths start with equal probabilities
 - For each path SAROPS computed probability the searches from 1 – 6 Jun fail to detect
 - Weight on each path multiplied by failure probability
- Weighted paths pulled back to position at time of impact to form posterior on impact position given failure of surface search

Surface Search Posterior and Underwater Search Prior



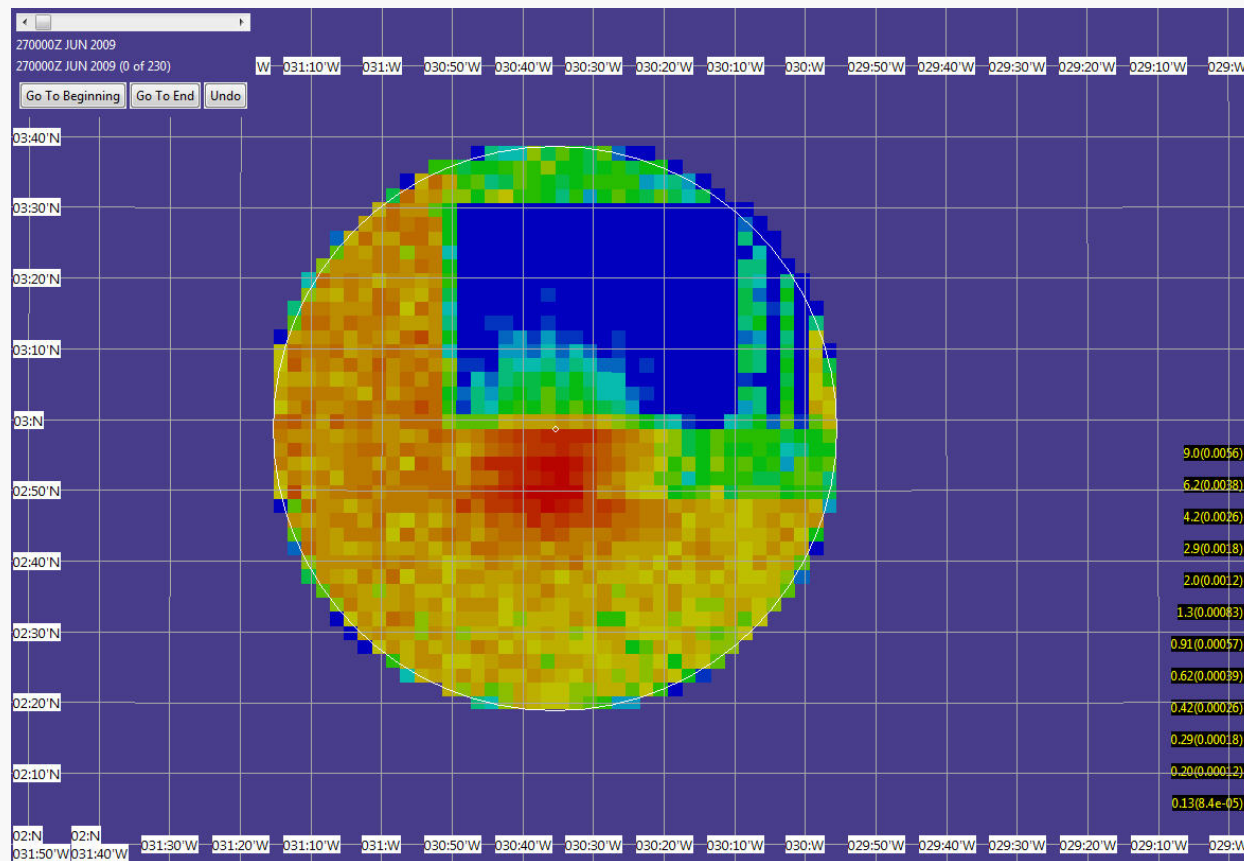
Surface Search Posterior



Underwater Search Prior
70% FD + 30% Surface Search Posterior

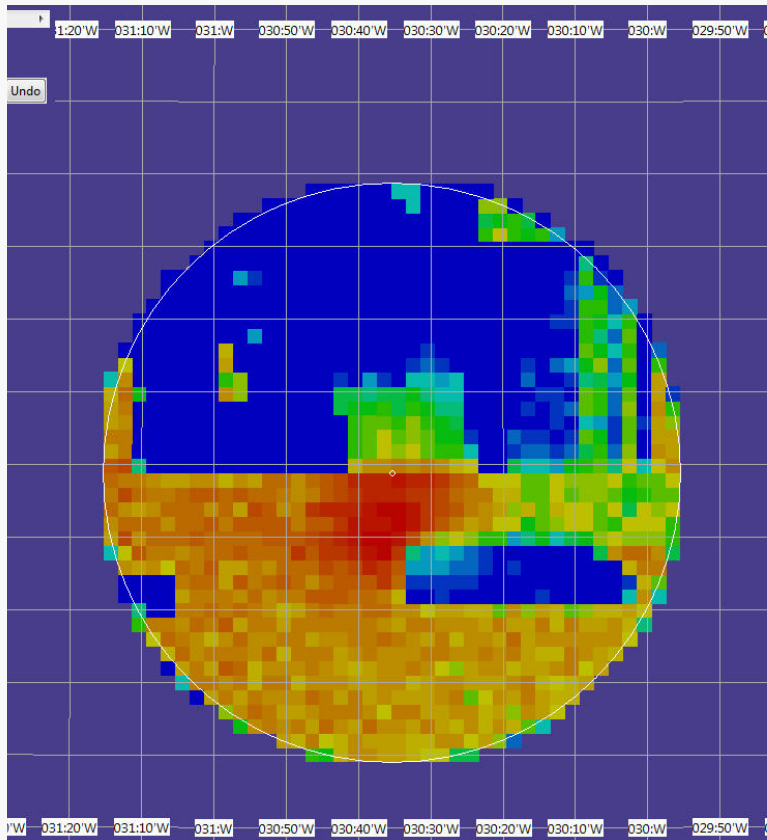
Posterior after TPL Search (Phase 1)

- Assumed 0.8 probability of survival of ULB.
 - If survival is independent then 0.92 detection prob within 1730m lateral range
 - If dependent = 0.72. We used $0.77 = (.25)(.92) + (.75)(.72)$

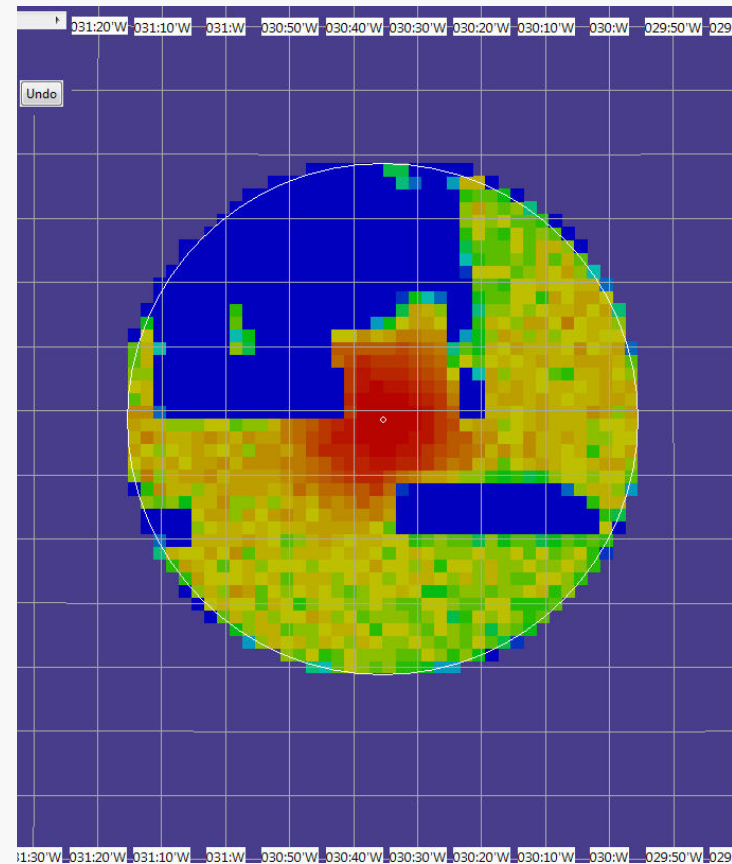


Posterior after Phases 2 and 3

- Using 0.9 detection probability within areas covered by side-looking sonar in phases 2 and 3 we obtained the posterior PDFs –
 - one assuming that ULBs functioned the other that they didn't



Posterior Assuming ULBs Worked



Posterior Assuming ULBs Failed

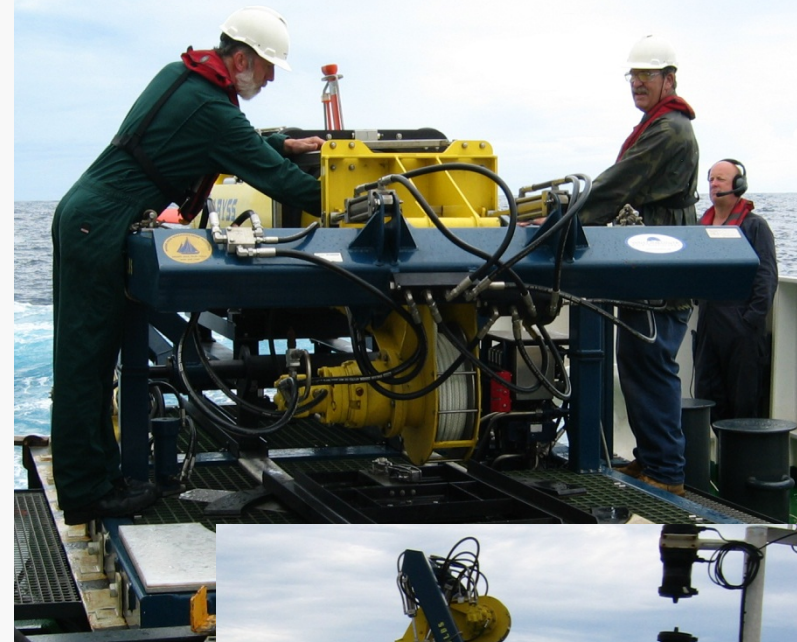
Phase 4: Successful REMUS 6000 AUV Search by WHOI

- **REMUS Sensors**

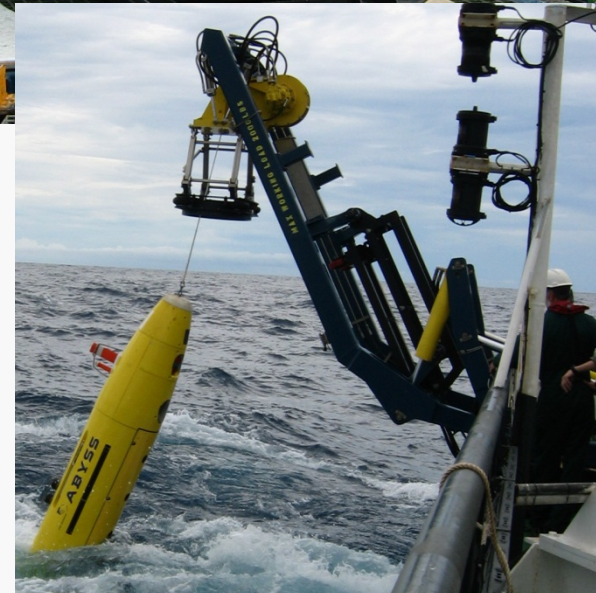
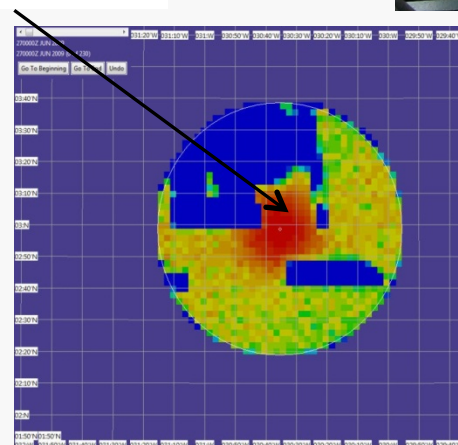
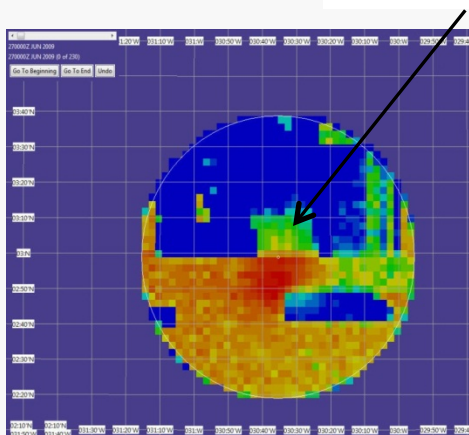
- 4 MEGA PIXEL ELECTRONIC STILL CAMERA
- EDGETECH 120/410 KHZ SIDE SCAN SONAR

120 KHZ – 400, 500, 600 AND
700 METER RANGE PER SIDE
DEPENDING ON TERRAIN AND
VEHICLE

410 KHZ – 125, 150 AND 175
METER RANGE



Location of wreckage



Conclusions

- Major Conclusion
 - The success of this effort provides a powerful illustration of the value of a methodical, Bayesian approach to search planning
- Minor Conclusions
 - The failure of the TPL search to detect the ULBs led to a long and complicated search
 - Despite record of reliability it appears likely that ULBs failed
 - Examination of recovered ULB may shed light
 - Use of Drift Group recommendation delayed success of search by a year
 - Used ad-hoc methods to determine search rectangle