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Data handling methods and target detection results for multibeam and sidescan data collected as part of the search for SwissAir Flight 111

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Abstract

The crash of SwissAir Flight 111, off Nova Scotia in September 1998, triggered one of the largest seabed search surveys in Canadian history. The primary search tools used were sidescan sonars (both conventional and focussed types) and multibeam sonars. The processed search data needed to be distributed on a daily basis to other elements of the fleet for precise location of divers and other optical seabed search instruments (including laser linescan and ROV video).

As a result of the glacial history of the region, many natural targets, similar in gross nature to aircraft debris were present. These included widespread linear bedrock outcrop patterns together with near ubiquitous glacial erratic boulders. Because of the severely broken-up nature of the remaining aircraft debris, sidescan imaging alone was often insufficient to unambiguously identify targets.

The complementary attributes of higher resolution, but poorly located, sidescan imagery together with slightly lower resolution, but excellently navigated multibeam sonar proved to be one of critical factors in the success of the search. It proved necessary to rely heavily on the regional context of the seabed (provided by the multibeam sonar bathymetry and backscatter imagery) to separate natural geomorphic targets from anomalous anthropogenic debris.

In order to confidently prove or disprove a potential target, the interpreter required simultaneous access to the full resolution sidescan data in the geographic context of the multibeam framework. Specific software tools had to be adapted or developed shipboard to provide this capability. Whilst developed specifically for this application, these survey tools can provide improved processing speed and confidence as part of more general mine hunting, hydrographic, engineering or scientific surveys.

Introduction

At ~10pm, September 2nd 1998, SwissAir Flight 111 crashed just off the Nova Scotia coastline. Initial radar tracking of the rapidly descending aircraft was sufficient to place the crash location only to within about a 10 km radius. As a result a massive search and rescue mission, which ultimately became a search and salvage mission, was undertaken. This mission (Operation Persistence) involved a collaborative effort between civilian fisherman and several branches of the government including the Navy, the Coastguard, the Mounties, the Hydrographic Service and the Geological Survey.

Within a period of about 12 days a complete 300% multibeam and sidescan survey of the crash site and vicinity was acquired rendered and distributed. During that time, the growing database had to be made available to other units in the combined fleet to support simultaneous close-range optical search and salvage operations (including laser linescan, ROV and diver operations).

Initial search efforts were focussed in the vicinity of the surface debris fields. Within 72 hours, however, the 30kHz pingers attached to the two flight recorder units were triangulated using the passive sonar arrays on board the submarine HMCS Okanagan. All subsequent surveying was focussed within about a 5km radius of this site and extending landward along the assumed last track of the aircraft.

Survey Methodology

Before and after the triangulation of the transponders by HMCS Okanagan, the acoustic search surveys were carried out from four platforms simultaneously. HMCS Anticosti deployed a Simrad MS972 towed conventional sidescan sonar. CCGS Matthew deployed a Simrad MS992 towed conventional sidescan sonar. HMCS Kingston deployed a Klein 5000 focussed sidescan sonar. And CSL Plover deployed a Simrad EM3000S multibeam sonar.

Whilst the three sidescan platforms were mid to large sized survey vessels, the Plover is merely a 31 ft survey launch. This launch is normally used for daytime operations only and normally in nearshore, protected areas. Due to the urgent nature of this operation, however, and the fact that it was the only platform with this resolution the launch was used. Previous experimental trials (Brissette et al, 1997) had shown that this system had the potential to resolve small targets. The two other available multibeam instruments, the EM100 sonar on the Matthew and the EM1000 sonar on the CCGS Frederick G Creed (36 hours away) both have significantly inferior target detection capability when compared to the EM3000.

For this operation, the launch was deployed around the clock with just a two man crew (coxswain and hydrographer). This was done by having crew changes at 6 hour periods (done by hoisting the launch up by its forward davit only) and refueling every 24 hours (by completely recovering the launch).

Data Processing and Dissemination

All search and survey data had to collated and distributed to all the vessels in the fleet taking part in the operation. This required a dedicated at-sea parallel processing effort to ensure that the multibeam data (delivered in 6 hour chunks) was processed (cleaned, tidally reduced and georegistered) to be ready for delivery to other field units on a daily basis. All shipboard processing of the EM3000 swath bathymetry and backscatter data was performed by OMG staff using the OMG/UNB SwathEd software toolkit.

The data deliverables included the following:

- ***Hard copy map sheets*** of the EM3000 bathymetry
- EM3000 topographic and backscatter imagery converted to BSB format for ***electronic chart navigation*** on CCGS Hudson (laser line scan) and MV Anne S. Pierce (dragging).
- EM3000 topographic and backscatter imagery used as underlay for field based and shore based ***interactive sidescan image analysis*** (see description below).

For the sidescan data, the majority of the early analysis was made from scrolling real time hard or soft copy images. This was all done by looking at a single corridor of sidescan imagery in isolation. In order to compare overlapping swath corridors, the data had to be referenced manually by time and, using a hard copy navigation plot, the adjacent swaths identified and then retrieved. This was a time consuming process. To try and alleviate this analysis bottleneck, the GSC sidescan mosaicking software was utilised to try and build a regional picture showing the interline relationships. This mosaicking approach is a standard procedure for all GSC scientific surveys.

The Complementary Attributes of Multibeam and Sidescan Data

The hull mounted multibeam sonar has the notable advantage over towed instrument packages of confident positioning. Because the sonar is rigidly attached to a surface vessel and the position and orientation of that vessel is known to within ~1m and 0.05 degrees on all axes, this confidence can be propagated to the seabed information (derived from narrow (1.5^o) beams steered at known vessel-relative angles). This position confidence is sufficient, for example to try to detect the introduction of new small bathymetric targets such as mines by differencing one survey with a pre-survey (Brissette and Hughes Clarke, 1999).

In contrast, the sidescan towfishes employed were all at least 80m from the mother vessel. Only on CCGS Matthew was a short baseline acoustic transponder positioning system available. The MS992 on the Matthew had the added advantage of being deployed using a two-body tow geometry. The MS992 thus had the benefit of decoupling from the surface vessel motion together with a far steeper cable angle than the other towfishes (which results in increased tracking confidence). In all cases, the instrument packages on the towfishes consisted of no more than a magnetic compass. Thus neither the position, nor the exact orientation of the sidescan instruments could be guaranteed better than about 20-30m and about two degrees in azimuth. As a result, the total horizontal positioning confidence of the towfish-based systems was at least an order of magnitude worse than the data collected from the hull mounted multibeam sonars.

Because, however, the hull-mounted sonar remained close to the surface, the total slant range to the seafloor and the aspect ratio of the imaging path are larger that that used by a sidescan. Further more, the sidescan systems all had beam width of less than 0.75 degrees in azimuth (compared to 1.5 for the multibeam). It is thus clear that from a backscatter based target detection capability, the sidescan systems had a greater advantage in resolution.

Separating natural from anthropogenic targets.

Traditionally the identification of anthropogenic targets using sidescan imagery is based on an assumption that the targets will differ significantly in character from natural seabed features. Man made features are commonly angular, and solitary.

For most temperate (mid-latitude) continental shelves, the Holocene transgression has covered the shelf with at least a surface veneer of fine-grained sediments (muds and sands). Such unconsolidated materials generally maintain low seabed slopes (< 10 degrees). The only common short wavelength targets visible in sidescan images of these type of seabeds are current-driven features such as ripples, dunes, furrows and ribbons. All these features are normally quite characteristic and do not occur in isolation. Under such conditions it is reasonable to assume that any angular solitary targets might be man made.

For those higher latitude continental shelves, however, that were affected by the Quaternary glaciations, , the sedimentary processes were very different. Due to the fact that much of the material was deposited at random during melting of rock impregnated glaciers, widespread anomalous targets are very common (glacial erratic boulders). Furthermore, because much of effect of glacial activity is erosive, extensive bedrock outcrop is common. Where the bedrock consists of lithified sediments with layers, sharp linear seabed targets are very common.

As a result, of the ubiquitous glacial erratic boulder fields and extensive bedrock outcrop, regions such as the Scotian Shelf contain a wide variety of natural targets that are difficult to separate from anthropogenic debris. Therefore, to be able to make decisions about the origin of angular or pseudo-randomly distributed small objects, one needs to be familiar with the patterns common to natural features. This requires an intimate knowledge of :

- **The spatial distribution of the targets**
  - *? Are targets distributed along a corridor or spread out ?*
  - *? Do they lie only in topographic lows, or equally on highs and lows?*
- **The regional geomorphic framework**
  - *? Does an angular target line up with regional fault/outcrop patterns?*
  - *? are there other patchy boulder fields at this depth range ?*
- **The geological context**
  - *? Do we expect glacial boulders in these types of sediments ?*
  - *? Have the sediments in the vicinity of the target been modified ?*

Because of the limited field of view captured in just a single pass of sidescan imagery, these questions can often not be addressed from that single pass alone.

One way around this problem is to georegister adjacent swaths of the sidescan imagery (mosaicking). The mosaicking algorithm, however, is plagued by four notable problems:

1. imperfect towfish position and orientation which results in swath to swath misalignment
2. overlap between adjacent swaths which obscures multiple possible views
3. the mosaciking transformation tends to smear the data resulting in loss of resolution
4. limitations in memory or disk space result in compromises in mosaicked pixel sizes. This normally results in a drop in resolution (commonly from the max. ~20cm possible to between 50 and 200cm).

Even the slant range correction process, commonly considered an essential first step toward providing a true aspect ratio, requires resampling and potential loss of resolution.

Where is a potential sidescan target?

Given the poor positioning confidence of targets visible in the sidescan, how can one come up with a more precise position? The Navy divers operating as part of the search and salvage operation required that they be dropped within 10m of any suspicious targets. This was so that the divers did not expend all their energy just swimming in a radial search pattern about the drop site in order to confirm or deny a target reported from sidescan.

Most sidescan analysis packages can perform the transformations required to provide precisely calculated positions of any target interrogated. These positions, however, are based upon the quality of the supplied towfish navigation, the slant range correction algorithm (usually involving just a flat seafloor assumption) and towfish azimuth. In practice, all these measurements are poorly constrained.

Therefore a means of arriving at a more confident position was imperative. One possible way was to use the higher positioning confidence inherent in the multibeam data. Even if the target of interest is not well resolved within the multibeam data, as long as other larger common targets in the vicinity are visible in both data sets, then the two images can be coregistered. In this way the sidescan target can inherit a much-improved positioning confidence.

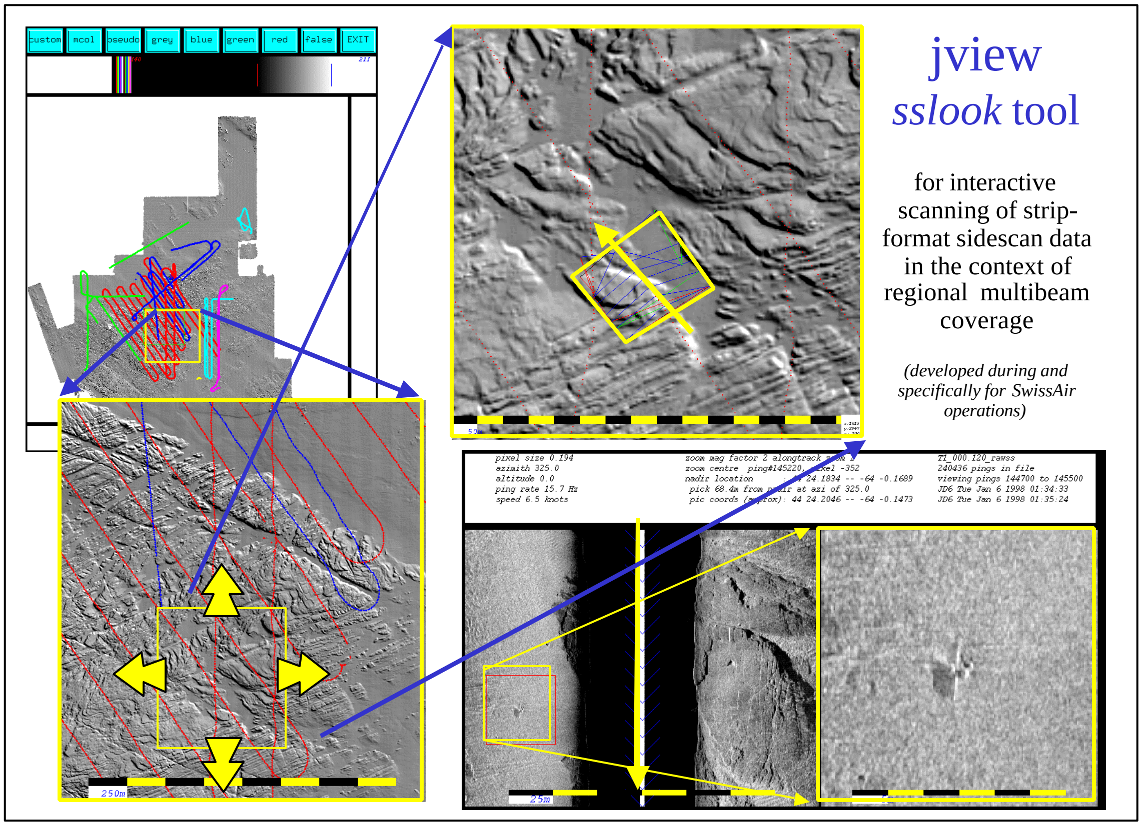
Rapid interactive comparison of possible sidescan targets with regional geomorphology

Whilst sidescan strip imagery provides one of the highest resolution data sources currently available, it is limited by a number of factors:

- Without mosaicking the regional context cannot be established.
- If mosaicked, the resolution of the imagery is degraded.
- Even if mosaicked ambiguities about the topographic context cannot be resolved.

One thus ideally would like to examine the strip data in the context of the multibeam sonar terrain model and backscatter imagery. One would further like to be able to rapidly access overlapping sidescan coverage without compromising target resolution.

In order to meet this need, a new software tool was developed shipboard. This tool allowed the user to simultaneously view EM3000 sun-illuminated topography and regional backscatter at the same time as the full-resolution time-series sidescan data.



jview

sslook tool

for interactive scanning of strip-format sidescan data in the context of regional multibeam coverage

(developed during and specifically for SwissAir operations)

```
pixel size 0.194            zoom mag factor 2 alongtrack zoom 1          T1_000.120_rawss
azimith 325.0               zoom centre  ping#145220, pixel -352         240436 pings in file
altitude 0.0                nadir location      : 44 24.1834 -- -64 -0.1689   viewing pings 144700 to 145500
ping rate 15.7 Hz            pick 68.4m from nadir at azi of 325.0       JD6 Tue Jan 6 1998 01:34:33
speed 6.5 knots              pic coords (approx): 44 24.2046 -- -64 -0.1473   JD6 Tue Jan 6 1998 01:35:24
```

Two complementary approaches can be used:

Either- one pages through the strip sidescan data using an interactive zoom and pan facility to pick up potential anomalous targets. At all times however, the approximate seafloor polygon images by the viewed strip section of sidescan is plotted over the well registered EM3000 georeferenced products.

Or – one zooms and pans around the EM3000 georegistered products looking for potential small topographic targets that look suspicious. At any time one is free to call up the corresponding full resolution strip-sidescan imagery that happens to overlap the area of interest.

By using a combination of the two approaches, suspicious targets may be viewed:

- At the fullest sidescan resolution
- Within the regional topographic and backscatter framework
- With the ability to provide precise coordinates by correlating features common to the sidescan and multibeam data.

At any time, if a suspicious target is identified, its location with respect to other targets in the vicinity is noted from the strip sidescan and the corresponding location in the EM3000 data can selected. Note that even if there are no significant topographic targets in the vicinity, sediment boundaries identified by the EM3000 backscatter can be correlated with textural changes in the strip sidescan.

Analysis of target detection capability of the EM3000S

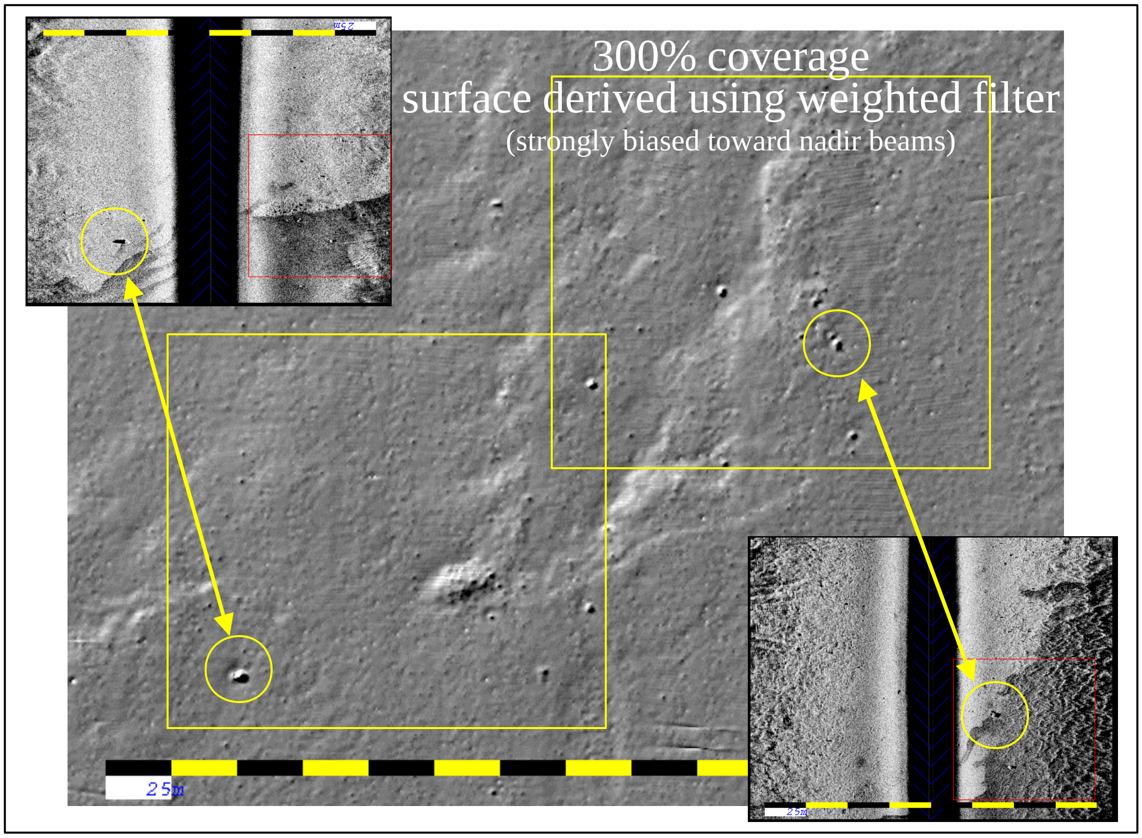
Because there was simultaneous overlapping coverage for all areas from both the hull-mounted multibeam and the deeply towed sidescan data, the opportunity to quantitatively analyse the target detecting capability of the EM3000S was available.

In the figure below, a sun-illuminated image of the seabed reveals large numbers of small point like targets distributed over an otherwise near featureless terrain. From this image, little more than the presence of the targets can be established. Each target, however, is located with a positioning confidence of about 2m. By using the overlapping sidescan imagery, one can learn more about the nature of the target whilst inheriting the position of that targets from the multibeam.

it is important to realise that the surface viewed represents a weighted average of 300% coverage capability. The weighting function employed is optimised to reflect two things:

- The size of the projected beam footprint at that depth and grazing angle.
- The relative confidence of any one beam with respect to beams in the vicinity.

Because 300% coverage was employed, the final topographic image was strongly biased toward the near nadir data in which both the bottom detection quality and the beam solution density is the highest.



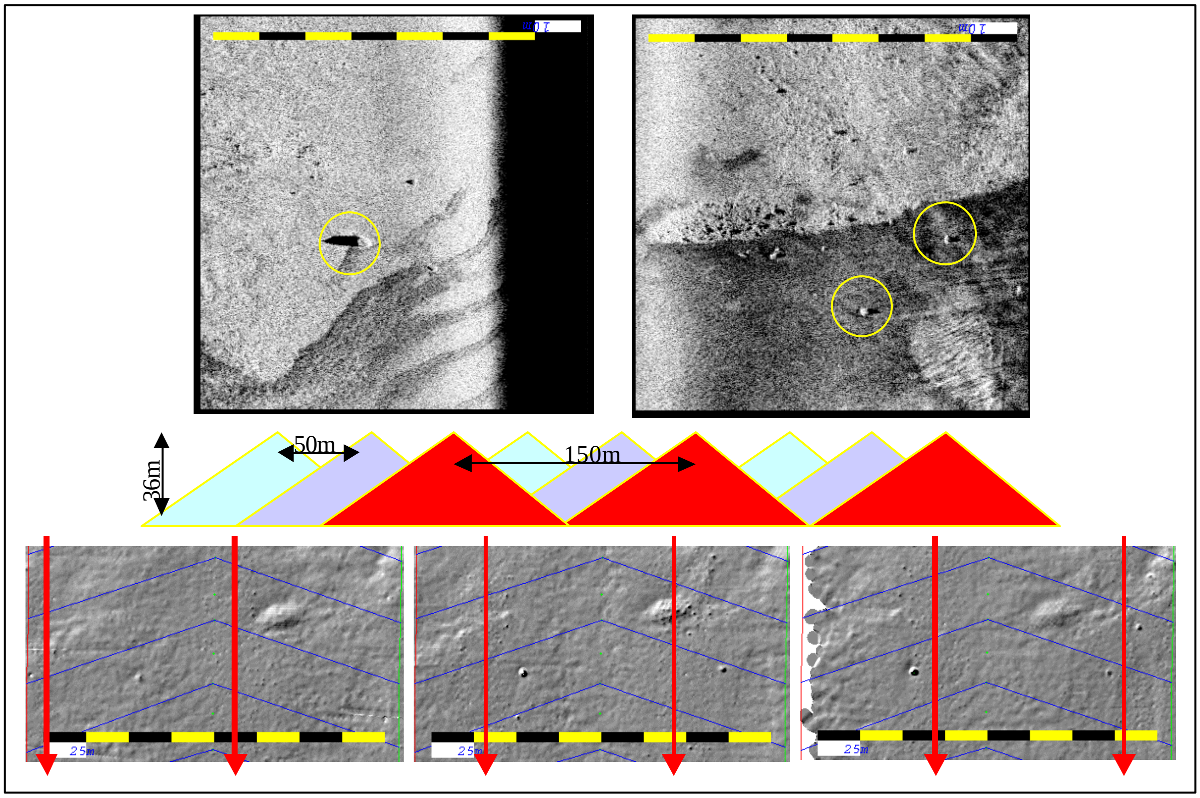
Because we have 300% coverage, we have the unique opportunity to view the same target from three different grazing angles. For this reason, in the figure below we deliberate separate every third survey line into separate images. Again because the area has complete sidescan coverage we can examine in detail the size of the targets that are resolved. Perhaps more significantly, we can identify targets that the multibeam sonar ***fails*** to resolve, thus provide a means of quantifying the limit of resolution.

In the image below we examine the appearance of three different targets sizes:

1. To the left there is a solitary 4m diameter boulder.
2. To the lower right there are two solitary 2m diameter boulders
3. In the centre right there is a small hillock covered in boulders of about 1m in size.

For all data acquired, the survey speed was 11-12 knots, in ~36m of water with a ping rate of 5-6 Hz.

As can be seen, the 4m boulder is resolved at all grazing angles, although clearest at the highest ones. In contrast the pair of 2m boulders are only observed within about 45 degrees of nadir. And lastly, the cluster of 1m boulders shows no hint of being resolved except when they lie immediately beneath the nadir beams.



What factors are influencing this loss of resolution with decreasing grazing angle?

The effect of sounding density

In order to adequately describe a target bathymetrically, there must be sufficient bathymetric solution density to cover, and delineate the shape of, that target. Coverage had been described in many ways. Early definitions focused on achieving just interswath overlap. Within a single swath however, most multibeam systems available today leave along track gaps between pings at survey speeds above 10 knots (Miller et al., 1998).

For a single transmit plane, the along track spacing is controlled by the ping rate, which in turn is fundamentally limited by the two-way travel time from the source to the furthermost point imaged. Most swath sonars will commonly have ping periods that are longer that this minimum time by a factor of about 1.2 to 1.5. For the case of EM3000S operation as part of this survey, the ping rate in 35-40m of water was observed to be 5-6 Hz. At speeds of 11-12 knots this translated into along track coverage spacing of solutions of about 1m. It is thus clear that, just having a single strike on the target along-track is not sufficient to be able to see the target.

The effect of beam spacing

The previous discussion only considers along track spacing. If we consider, furthermore, the across track spacing direction, however, we need to examine the angular spacing of the beams. Most swath bathymetric sonars provide solutions at either equiangular or equidistant spacing.

For example, the ATLAS Fansweep 20 provides a choice of either of these spacing. Furthermore, from 80 to 1440 depth solutions can be provided for a single ping. In this case solution spacings of as close at 0.5% of water depth can be provided. Whether such dense spacing (not clearly related to a physical dimension such as beamwidth) is justified is open to debate.

In contrast the RESON Seabat 8101 provides fixed angular spacing of 1.5 degrees that matches the across track beam width of that sonar (101 beams in a 150 degree angular sector). This translates to an across track spacing of 2.7 % of the depth at nadir, yet about 10% of water depth at 60 degrees.

The EM3000S has a beam spacing that is controlled entirely by the angular quantisation of the FFT used in the beam forming process. This provided a particularly unusual beam spacing pattern whereby the beam angular spacing actually grows away from nadir. At nadir the beams are only 0.9^o apart but the spacing grows to 1.8^o at 60^o. This translates to about 1.6% of water depth at nadir but 13.3% of water depth at 60^o.

Thus one would expect a notable degradation of the target detection capability of the EM3000S with incidence angle. This figure above supports this.

The effect of beamwidth.

However, tight the beam spacing, the size of the physical beams formed must have an influence on the ability to detect the target. Theoretical models that incorporate amplitude and phase detection methods (Hughes Clarke, 1998) suggest that as the target dimension shrinks within the beam footprint, the size of the resulting topographic anomaly decays.

Almost all of the modern shallow water sonars now have transmit beam width of $\sim1.5^o$ or finer. This translates to a fore-aft dimension of 2.6% at nadir growing to ~5.2% at 60^o off nadir. The receive beamwidths used, however, are much more variable. None is stated for the Fansweep implying that across track resolution is based strongly on phase detection methods. The Seabat 8101 however, maintains the same 1.5^o receive beamwidth at all incidence angles resulting in an across track projected beamwidth of 2.6% at nadir but ~10.4% at 60^o. For the EM3000, the receive beamwidths are only 1.5^o for those broadside to the receive array (at nadir). Off nadir, the beams are steered and thus grow with the cosine of the steering angle . Thus at 60^o, the beamwidth is actually 3.0 degrees resulting in an across-track footprint of about 20% of the water depth.

Clearly, the target detection capability is going to decay as a result of the growing projected beam footprint. Interestingly, other sonars which also employ phase detection methods like the EM3000 or 8101 choose to space their outer beam solutions much tighter than the physical beam width. A comparison of theoretical models and field results for the EM300 (Hughes Clarke et al., 1998) show that, using a tighter beam spacing, target resolution can be achieved for features significantly smaller than the across track beamwidth. This presumably is the justification for the tighter ATLAS solution spacing. Neither the EM3000 nor the 8101, however, currently take advantage of this capability.

The effect of yaw

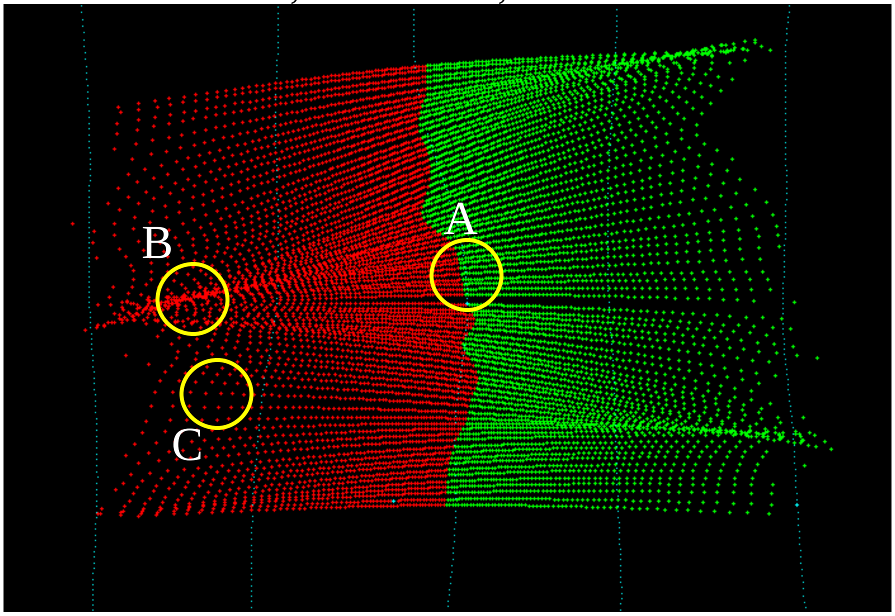
All the calculations about along-track spacing are normally simplified to ignore the inter-ping yaw perturbations. In shallow water, as the ping period is short with respect to the yaw period of mid to large survey vessels this is not usually a crippling effect. However, for a small survey launches, such as the 31ft vessel used in this case, the yaw periods are much shorter and the yaw magnitude can be up to +/10 degrees at times (the survey was undertaken in open ocean conditions).

The figure below shows a typical sequence of 80 pings recorded from the CSL Plover during the Swissair operations. As can be clearly seen, the sounding density in the outer part of the swath is reduced as a result of the unusual beam spacing employed. Furthermore, however, the severe yaw perturbations experienced by the launch are resulting in significant bunching and dispersion of the outer beam solutions. As can be seen this will alternately increase and decrease the sounding density. In general this will lower the likelihood of finding even quite large targets in the outermost part of the swath.

At this time, active transmit yaw stabilisation, now employed by both the Simrad EM300 and ATLAS Hydrosweep MD2 has not been implemented in any of the shallow water systems.

The problem of short-period yaw deviations

80 pings, EM3000 (*pitch stabilisation. only*),
36m water depth (6 Hz)
12 knots, 31 ft launch, seastate 4.



A : inner swath
near-invariant.
(tight across track)

B: outer swath
convergent
(loose across track)

C: outer swath
divergent
(loose across track)

Conclusions

The joint availability of both surface mounted multibeam sonars and deeply towed sidescan sonars was a major factor in the rapid completion of the SwissAir flight 111 search and recovery operation. The role of the multibeam data was fourfold:

1. Recognition of suspicious large scale (> 2m) bathymetric anomalies.
2. Provision of regional context for sidescan interpretation.
3. Provision of accurate seabed positioning for poorly navigated sidescan towfish
4. Use as a raster data layer in electronic charting software for real time navigation of deep towed instrumentation (laser line scan, dragger and ROV).

Acknowlegements

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