EVALUATION OF ARCTIC MULTIBEAM SONAR DATA QUALITY USING NADIR CROSSOVER ANALYSIS AND COMPILATION OF A FULL-RESOLUTION DATA PRODUCT

BY

ASHTON FLINDERS
Bachelors of Science, Applied Physics, University of Wisconsin River Falls, 2005
Bachelors of Science, Chemistry, University of Wisconsin River Falls, 2005
Master of Science, Geology and Geophysics, University of Hawaii, 2010

THESIS

Submitted to the University of New Hampshire
in Partial Fulfillment of
the Requirements for the Degree of

Master of Science
in
Ocean Engineering: Ocean Mapping

September, 2014

This thesis has been examined and approved.

Thesis Director, Larry A. Mayer
Professor of Ocean Engineering and Earth Sciences

Brian R. Calder
Research Associate
Professor of Ocean Engineering and Marine Sciences

Andrew A. Armstrong
Co-Director Joint Hydrographic Center

08/05/2014
Date

ACKNOWLEDGEMENTS

Thank you to P. Johnson and J. Beaudoin of CCOM for help with data management and processing. J. Hughes Clark and I. Church provided access and support for data collected aboard the *CCGS Amundsen*. My continued thanks to P. Wessel and the entire GMT community. A very special thank you to the *USCGC Healy* for allowing the author to sail with them and without whom this work would not be possible. Much of the *USCGC Healy* data would not have been available without the effort of S. Roberts. C.L. Boomer provided critical last minute support. Work funded by NOAA Grant NA10NOS4000073.

TABLE OF CONTENTS

LIST OF TABLES

PAGE

LIST OF FIGURES

ABSTRACT

EVALUATION OF ARCTIC MULTIBEAM SONAR DATA QUALITY USING NADIR CROSSOVER ANALYSIS AND COMPILATION OF A FULL-RESOLUTION DATA PRODUCT

by
Ashton Flinders

University of New Hampshire, May, 2014

Documented and evaluated here is a new high-resolution multibeam bathymetry compilation for the Canada Basin and Chukchi Borderland in the Arctic Ocean–*United States Arctic Multibeam Compilation* (USAMBC Version 1.0). The compilation preserves the highest native resolution of the bathymetric data, allowing for more detailed interpretation of seafloor morphology than has been previously possible in existing compilations. The compilation was created from multibeam bathymetry data available through openly accessible government and academic repositories. Much of the new data was collected during dedicated mapping cruises in support of the United States effort to map potential extended continental shelf regions beyond the 200 nautical miles (nmi) Exclusive Economic Zone. Data quality was evaluated using nadir-beam crossover-error statistics, making it possible to estimate the minimum uncertainty of multibeam depth soundings collected from a wide range of vessels and sonar systems. Data were compiled into a single high-resolution grid through a vertical stacking method, preserving the highest quality data source in any specific grid cell. The crossover-error analysis and method of data compilation can be applied to other multi-source multibeam datasets, and is particularly useful for government agencies targeting extended continental shelf regions but with limited hydrographic capabilities. Both the gridded compilation and an easily-distributed geospatial PDF map are freely available through the University of New Hampshire's Center for Coastal and Ocean Mapping. The geospatial PDF is a

full resolution, small file-size product that supports interpretation of Arctic seafloor morphology without the need for specialized gridding/visualization software.

Introduction

Advances in multibeam echosounding (MBES) and navigation technology, along with decreased summer sea ice extents and the recognition of potential economic, scientific and geopolitical advantages, have led to increasing acquisition of MBES data in the Arctic Ocean over the past decade. These new data have provided critical insights into the evolution of the Arctic Basins (*Lawver et al.*, 2011), the nature of deep-water circulation (*Björk et al*, 2007), oceanic mixing processes (*Nghiem et al.*, 2012), and the history of ice in the Arctic Ocean (*Jakobsson et al.*, 2010). With the commissioning of the ice-breaking vessel *United States Coast Guard Cutter* (*USCGC*) *Healy* in 1999 and its operation as a multibeam sonar-equipped platform for Arctic science, the quantity of Arctic MBES data has increased dramatically. A large portion of the MBES bathymetry collected by the *USCGC Healy* was done so as part of the United States effort to map regions beyond the 200 nm Exclusive Economic Zone, that may be considered "extended continental shelf" (ECS) under Article 76 of the Convention on the Law of the Sea (*Mayer et al.*, 2010; *UNCLOS*, 1982). The University of New Hampshire's (UNH) Center for Coastal and Ocean Mapping (CCOM) and the National Oceanic and Atmospheric Administration (NOAA) Joint Hydrographic Center (JHC) have taken a lead role in this effort, with seven dedicated ECS cruises aboard the *USCGC Healy*, four in collaboration with the Geological Survey of Canada and the *Canadian Coast Guard Ship* (*CCGS*) *Louis S. St-Laurent*. Much of the data collected by the *USCGC Healy* and other vessels are now in the public domain, available through government and academic repositories. The availability of data allows for the creation of high-resolution MBES compilations. Foremost amongst these compilations has been the International Bathymetric Chart of the Arctic Ocean—IBCAO (*Jakobsson et al.*, 2012). Although IBCAO provides an indispensable representation of Arctic bathymetry, its large scope and incorporation of single-beam/spot-sounding sources inhibit it from preserving the highest resolution of the MBES data–a critical need for detailed interpretation of ECS regions.

The quality of MBES data sets collected in the Arctic Ocean–essential for their potential use in an ECS submission–was evaluated, and a subset of these data is presented in a manner that preserves the highest level of spatial resolution. This newly compiled data set, the United States Arctic Multibeam Compilation (USAMBC Version 1.0), with a maximum spatial resolution of 40 meters, is available both as a gridded bathymetric data set and a stand-alone geospatial PDF.

Methods

Multibeam Data Sources

MBES data were compiled from publicly available repositories (Figures 1/2, Table 1/A1), specifically the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) which operates the *R/V Mirai* (8 cruises), and U.S. holdings from the National Geophysical Data Center (NGDC) for the *USCGC Healy* (17 non-ECS cruises excluding transits, 1 United Stated Geological Survey ECS cruise), *R/V Marcus G. Langseth* (1 cruise) and the *R/V Nathaniel B. Palmer* (1 cruise). The majority of these data were unprocessed MBES depth soundings. The Ocean Mapping Group at the University of New Brunswick provided processed data from the *CCGS Amundsen* upon request (43 cruises). These data were supplemented with processed and cleaned MBES data collected during ECS dedicated mapping cruises aboard the *USCGC Healy* (8 cruises), and publicly available from the University of New Hampshire's Center for Coastal and Ocean Mapping.

Table 1: MBES Sources, Crossover Statistics, and Compilation Weighting

Repository	Vessel	Sonar	Cruises	Length km	Crossings	Δ-Nadir m/%wd	σ m/%wd	Weight
CCOM	*USCGC Healy*	EM122	3	29234	380	5/0.4	13/1.2	1
CCOM	*USCGC Healy*	SB2112	5	34313	971	7/0.6	22/1.6	2
NGDC	*USCGC Healy*	EM122	1	5461	12	10/1.6	18/2.4	2
NGDC	*USCGC Healy*	SB2112	29	99936	34071	10/3.0	56/14.7	3
NGDC	*RV Marcus Lang.*	EM122	1	7077	17	7/1.3	11/1.6	2
NGDC	*RV Nathaniel Pal.*	EM120	1	3289	35	37/3.9	70/7.0	4
JAMSTEC	*RV Mirai*	SB2112	8	49922	1617	21/4.8	104/24	4
OMG	*CGCS Amundsen*	EM302	21	30984	2318	2/0.6	5/1.7	2
OMG	*CGCS Amundsen*	EM300	22	38530	386	2/1.1	3/1.6	3
		Total	**91**	**298746**	**40870**	**8/2.4**	**32/11.2**	

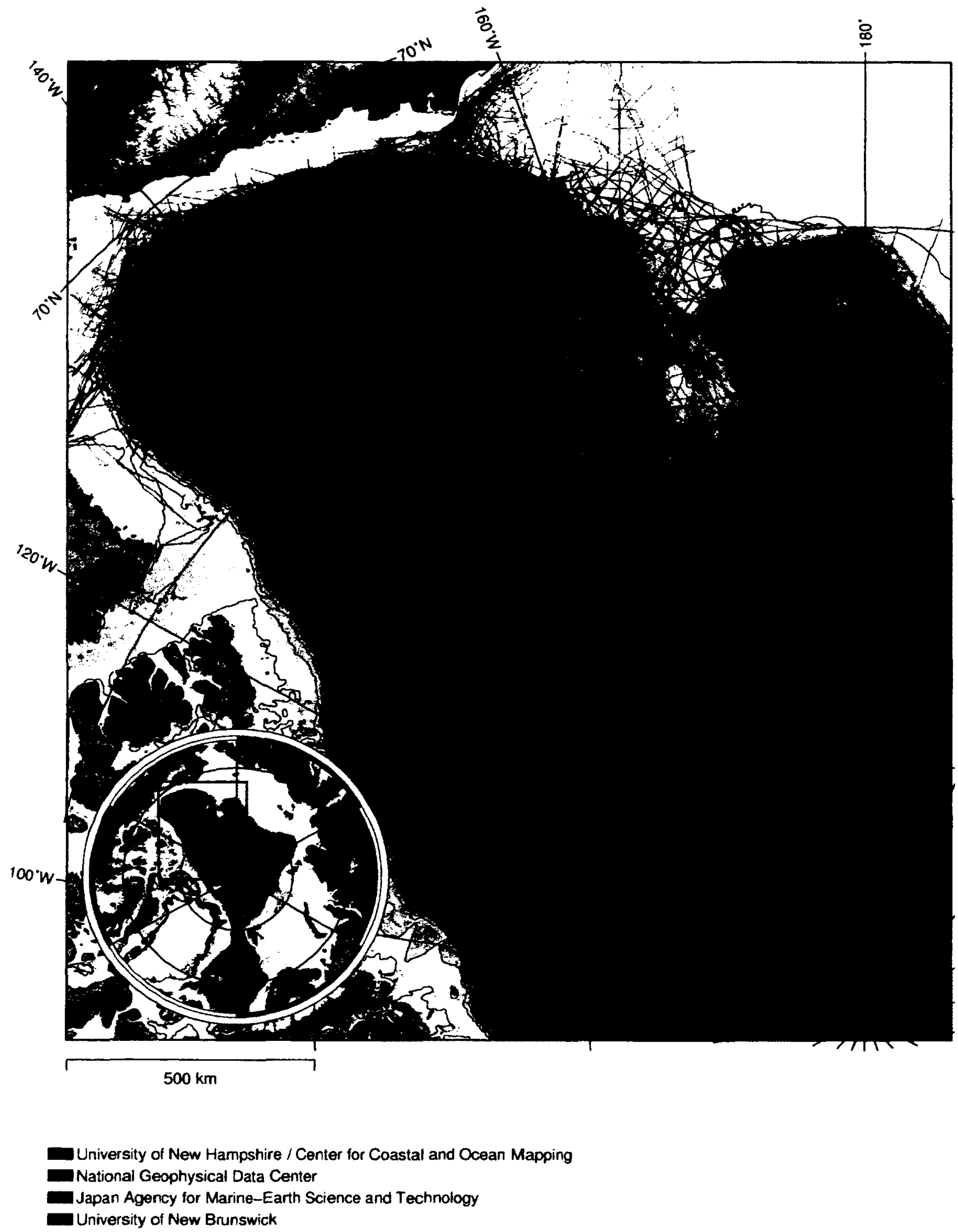


Figure 1: A Polar stereographic map (center meridian 0° W, true scale 75° N) showing the coverage area and bathymetry data sources of the newly compiled United States Arctic Multibeam Compilation (USAMBC V1.0), overlain over the International Bathymetric Chart of the Arctic Ocean (IBCAO V3.0) in gray. Mulitbeam bathymetry data is shown in Figure 2, nadir crossover error analysis for the region is shown in Figure 3.

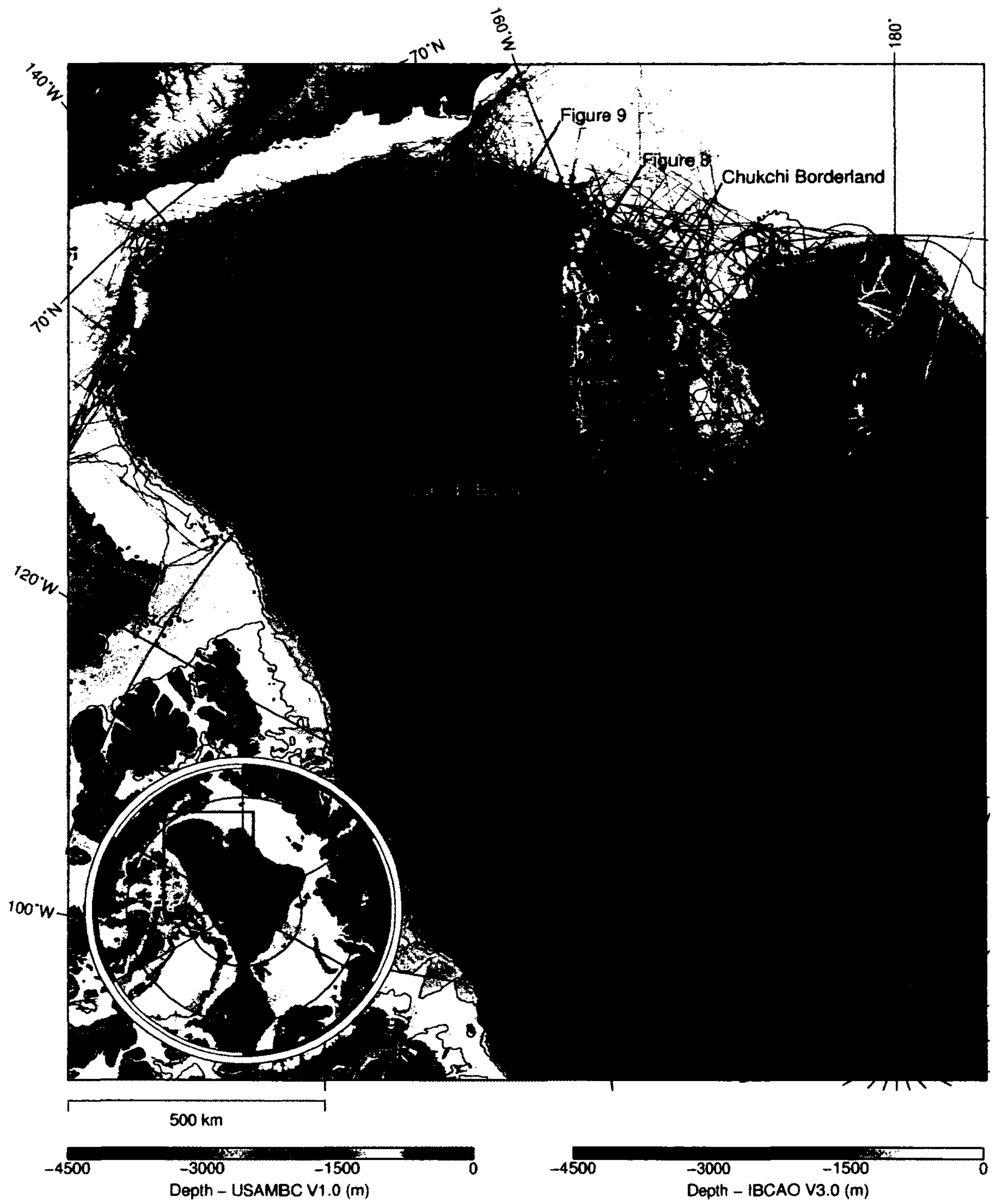


Figure 2: Map view showing the bathymetry of the newly compiled United States Arctic Multibeam Compilation (USAMBC V1.0), overlain over the International Bathymetric Chart of the Arctic Ocean (IBCAO V3.0) in gray. Multibeam bathymetry nadir crossover error analysis for the region is shown in detail in Figure 3. The majority of data are from dedicated ECS cruises operated in cooperation with the University of New Hampshire's Center for Coastal and Ocean Mapping (CCOM). The three red boxes outline regions of closer detail shown in Figures 8-10.

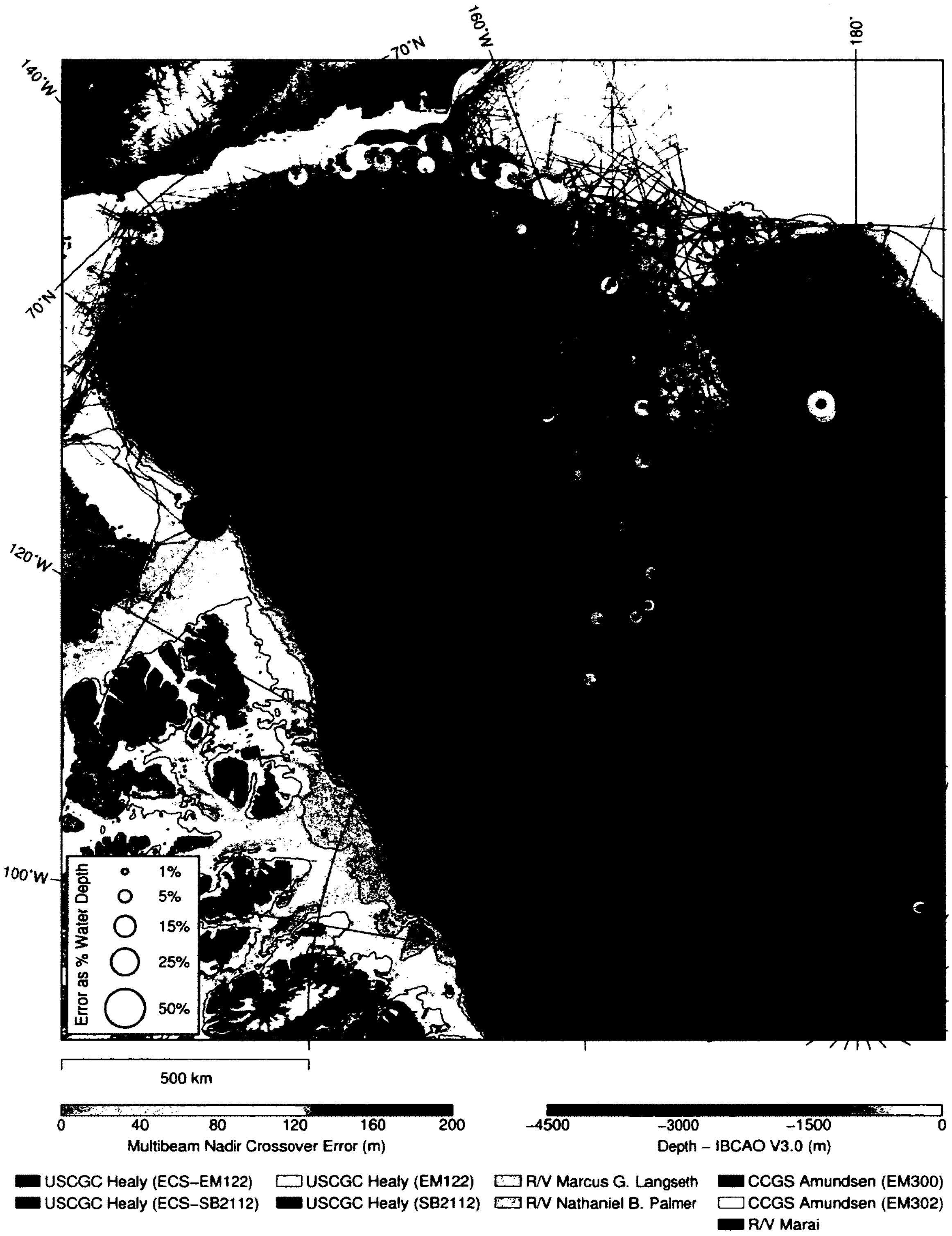


Figure 3: Map view of the multibeam bathymetry nadir-depth crossover errors for the USAMBC V1.0, over the Chuchki Cap, Canada Basin and northern portion of the Alaskan continental shelf. Absolute depth differences between overlapping MBES segments appear as colored circles, with the size of the circle proportional to the difference scaled by mean water depth. MBES coverage for each segment is shown in black under their respective trackline, color-coded by data source.

Data Processing

As deep-water mapping surveys are typically performed with minimal track-line overlap, automated uncertainty estimates are unreliable. The lack of uncertainty models combined with the high level of acoustic background noise while operating aboard an active ice-breaking vessel, required a processing approach heavily based on physical inspection of the returned depth soundings. Although automated methods were generally limited, bathymetry filters were applied to all data to reject depth soundings shallower than 50 m and deeper than 5000 m, as well as any sounding that had a beam-to-beam slope greater than 85° (*CARIS* , 2007). Data collected during dedicated ECS cruises aboard the *USCGC Healy* (Table A1) were processed at sea in near real-time (non-ECS cruises aboard the *USCGC Healy* were not processes in this manner). Processing involved visual inspection of each sonar swath and removal of erroneous returns (swath-editing), often based on subjective interpretation of seafloor morphology. The complete data set was visually inspected, and variations between overlapping area-based regions were minimized by removing conflicting depth soundings (area-based editing) using the Caris HIPS & SIPS processing environment. Cleaned data were exported from Caris HIPS & SIPS as generic sensor format files (GSF).

Crossover Analysis

The reliability of all data used in the compilation was assessed by calculating nadir depth differences between crossing multibeam segments (Figure 3). A running three-ping average of the nadir-beam depth was used to down-sample the cleaned MBES data for each individual cruise (1) using MBsystem (*Caress and Chayes*, 2006), and crossover-error (COE) analyses were performed using the Generic Mapping Tools x2sys package (Appendix B; *Wessel*, 2010), described below. Averaging the nadir-beam depth over multiple pings (1) helped ensure that the depth would not be subject to erratic/erroneous returns in the COE analyses. Similarly, ping-averaging reduced the total number of data points thereby reducing total computation time, with no bias in vertical uncertainty. The lack of introduced bias was verified by comparing the crossover error analysis within a cruise with and without the prescribed ping averaging. The number of pings used in the depth average need not be uniform between multiple cruises or multiple depths. As shallower depths result in more closely grouped along-track returns, a depth dependent ping-averaging may be more computationally beneficial in the future. The UNIX time (in integer seconds) of data collection was also extracted from the clean MBES data ("U" option), and used in subsequent vessel speed discriminations[1].

The x2sys package is a set of tools designed to detect intersections among tracks in 2-D Cartesian or geographic coordinates, and evaluate crossover errors (COE). These errors are defined to be the difference between two repeated measurements at these intersections (*Wessel*, 2010). The package implements the general line intersection algorithm of *Sedgewick* (1990) to find crossover locations, and observations at the intersections are based on a linear interpolation of nearby points. X2sys additionally allows for the analysis of COEs to determine appropriate linear models of systematic corrections for each track, and application of these corrections to eliminate crossover discrepancies from the final 2-D compilations.

Crossover errors can result from a variety of sources, including uncertainties in the location of the measurement, resulting in the location of the track intersection not truly corresponding to the correct repeat measurement point (a navigational uncertainty), improper system calibrations, or time varying phenomena (e.g., improper heave sensor filtering). Unless the source of the uncertainty is systematic and constant, where the magnitude and sign of the returned depth uncertainty remains unchanged between multiple crossing tracks (e.g., an uncertainty in the vertical offset of the sonar relative to the ship's waterline) the crossover error will be non-zero between any two crossing track line pairs within a given cruise. However, systematic constant uncertainties between different cruises, particularly among those of different vessels/system, will likely be different and result in non-zero COEs. Uncertainties within the same

---

[1] MBsystem command: mblist -I $input file list -OXYZU -P3 > $output file

cruise and between cruises, could similarly be due to unaccounted for/incorrect angular corrections applied to the sonar system's collection software (e.g., a roll bias) or uncertainties proportional to a parameter used to convert the sounding travel time to depth (such as the sound speed structure of the water column). Assuming a flat seafloor, nadir-beam soundings will have the shortest range through the water column, and are thereby least affected by these uncertainties. The nadir-beam crossover error analysis thereby provided a minimum estimate of the total multibeam swath uncertainty. However, as the nadir-beam defined in this study refers to the center beam of the multibeam sonar, and the ship may roll or pitch causing the center beam to not necessarily be the vertical below-ship sounding, this assumption is a simplification. It is not the goal of this analysis to provide an uncertainty budget detailing the source of uncertainties between crossing multibeam tracks, but instead to estimate the minimum crossover error present within the swath. If the variance of the crossover error for any particular cruise approaches the variance of the sounder and system's observational uncertainty, assuming all of the aforementioned uncertainties have been minimized, the error is likely random.

While COE analyses has been commonly applied to trackline data (gravity, magnetics, single-beam sonar) its application to swath data (MBES) has been limited, as there are no longer lines of intersection but areas of overlap. Extraction of nadir depths from the MBES data allowed the direct application of the x2sys COE routines using the standard available x2sys package (Appendix B). X2sys was used solely to identify intersecting tracks and calculate nadir-beam COE's at these intersections, and in an effort to preserve the bathymetric depths, was not used to apply corrections for crossover discrepancies.

As many of the cruises departed from the same locations and traveled overlapping courses before leaving the continental shelf for deeper water, it was necessary to remove the statistical bias towards the numerous shallow water crossings (Figures 3/4). Similar biases resulting from erroneous navigation information and/or times where a vessel was maintaining an approximate fixed position, causing the shiptrack to wander over its own course within a small area, were also removed. As such, the analyses were constrained to crossing MBES segments with nadir depths deeper than 250 m and at vessel speeds greater than two knots. Analyses were performed individually for each cruise, to characterize a cruise's MBES internal self-consistency (Table A1), between different cruises aboard the same vessel with the same MBES system (Table 1), and for the compiled data set as a whole (Table 1). It is important to stress that these analyses are an estimation of each group's (whether cruise specific, or system/vessel specific) internal self-consistency. A constant systematic uncertainty that does not change within an analysis group will not produce a crossover-error. The returned depths could therefore be self-agreeing, but not accurately represent the true seafloor depth. Extracted nadir-beam tracks from different overlapping vessels/systems would not likely contain the same constant systematic uncertainties, and therefore the final analysis, performed on all cruises available, is the best estimate of the crossover error.

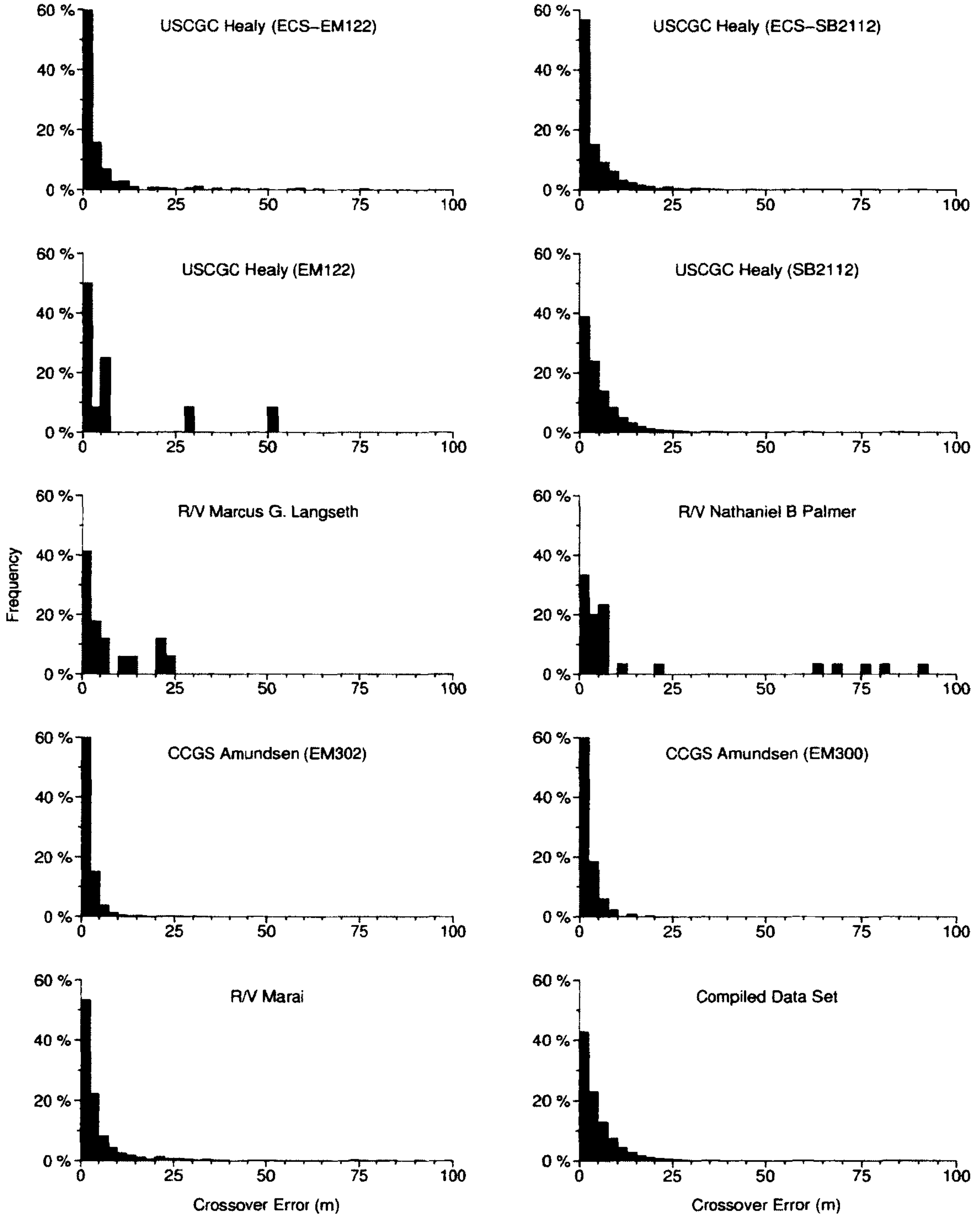


Figure 4: Crossover-error (COE) statistics grouped by similar vessel, sonar system aboard, and whether the cruise objective was ECS related. The red histograms bars show absolute crossover error in meters. The quality group grids shown in *Table 1* were created from these subgroups. The bottom right-hand histogram shows the COE histogram for treating all sources as one dataset.

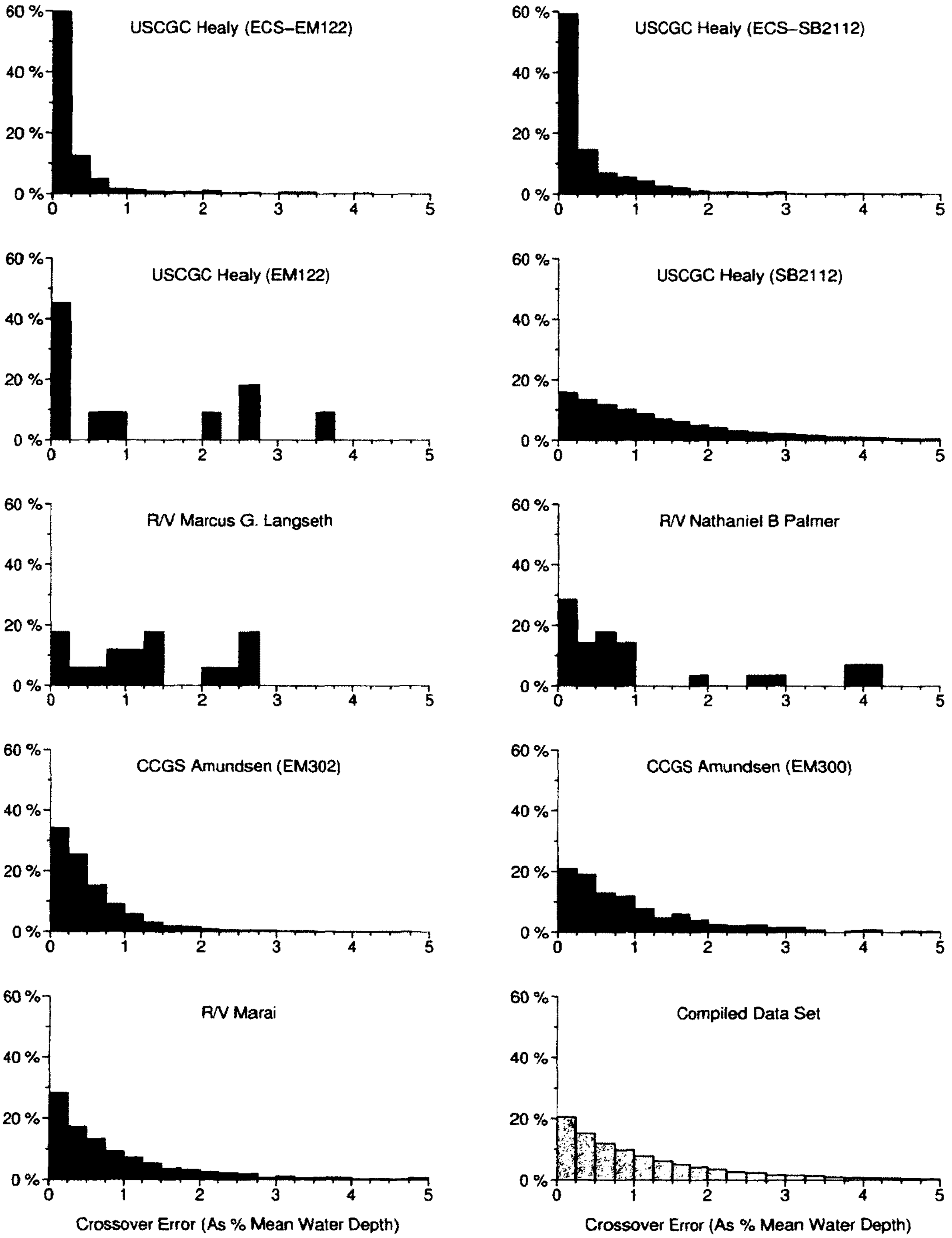


Figure 5: Crossover-error (COE) statistics grouped by similar vessel, sonar system aboard, and whether the cruise objective was ECS related. The blue histograms bars show absolute crossover error as a function of mean water depth. The quality group grids shown in *Table 1* were created from these subgroups. The bottom right-hand histogram shows the COE histogram for treating all sources as one dataset.

Grid Compilation

MBES cruises were subdivided into similar data-quality groups based on the vessel of operation, the sonar system aboard, and whether the cruise objective was ECS related (Figures 1-4, Table 1/A1). Separate MBES grids (quality group grids) were created for each group using a "swath-angle" beam-footprint based gridding algorithm (*CARIS*, 2007). This algorithm weights a sounding's contribution to a grid node as a function of the sounding's grazing angle—soundings from larger grazing angles (near vertical beams), have been shown to be of higher quality (*Calder and Mayer*, 2001). Beams with a grazing angle between 90-75° were given a weight of 1.0, with the weight linearly decreasing to 0.01 as the angle with the seafloor decreased to 15° and below. This weighting becomes critical in areas with adjacent or overlapping MBES segments, particularly when soundings were from multiple sources. This method of preliminary grid construction ensured higher weight was given to soundings from the inner part of a MBES swath rather than to outer beam soundings from adjacent segments, regardless of the cruise from which the data was collected.

In addition to the "swath-angle" weighting function, a standard range weighting function is also applied. The range weighting is inversely proportional to the distance of the sounding from the grid node, so that soundings close to a grid node are given a greater weight than soundings further away. As the sounding is not a discreet point on the seafloor, but a surface area of possible sounding locations (beam-footprint)—dependent on the depth and angular beam width of the sonar system—the distance used in the range weighting was calculated from the center of this region. As the grid node spacing increases relative to the beam-footprint, the number of soundings used to determine the depth at a grid node increases. Conversely, as the grid node spacing decreases, so does the number of soundings used to determine that cell's depth value and it's robustness. If the grid node spacing is significantly smaller than the average beam-footprint, then multiple grid nodes could be assigned depths from a single sounding. Given there is a positional uncertainty of the sounding equal to the beam-footprint half-width (assuming the ping is assigned a geographic position in the center of the footprint, but could originate from anywhere within the footprint), there will be a similar positional uncertainty in the depth locations of the final grid. This positional uncertainty, along with a situation where multiple overlapping beam-footprints contribute to a grid node, could lead to a short wavelength artificial seafloor fabric (noise). Therefore for an oversampled grid, it is important not to interpret structure (either qualitatively or quantitatively) where the beam-footprint is larger than the grid node spacing.

Quality group grids were then assigned a quality value (1–4), reflecting the group's overall MBES data reliability and uncertainty (Figure 4/5, Table 1). A quality value of one represented the most reliable data, four the least reliable. ECS cruises operated aboard the *USCGC Healy* were assigned a value of one or two, depending on the sonar system used to collect the data–one for the Kongsberg Maritime EM122 system, two for the older L3 SeaBeam (SB) 2112 system. These data represent the most reliable data available, shown by their low mean MBES nadir crossover values (Δ-Nadir). Data from these sources consistently have more than 50% of the crossover errors with < 0.25% the mean nadir water depth (w.d., Figure 5). The low uncertainty of the ECS cruises is due to the at-sea real-time processing and quality assurance involved in their data collection (Figure 4/5). A quality value of two was assigned to all non–ECS data collected aboard the USCGC Healy with its newer EM122 MBES system, as well as data from the R/V Marcus G. Langseth and the CCGS Amundsen with its Kongsberg Maritime EM302 system. Data collected aboard these two vessels, with older MBES systems (SB2112 and EM300, respectively) were assigned a value of three. The *R/V Mirai* and *R/V Nathaniel B. Palmer*, both showed particularly high depth uncertainties (>10% w.d.; Table 1), and were assigned a quality value of four.

Quality group grids were exported as ASCII xyz data from Caris HIPS & SIPS and then converted to grids using Generic Mapping Tools[2], using the previously defined polar stereographic projection (Figure 1).

---

[2] GMT Command:

```
xyz2grd G1_40m_PS_75N.xyz -GG1_40m_PS_75N_xyz.grd -I40 -R$REGION –V
xyz2grd G2_40m_PS_75N.xyz -GG2_40m_PS_75N_xyz.grd -I40 -R$REGION –V
xyz2grd G3_40m_PS_75N.xyz -GG3_40m_PS_75N_xyz.grd -I40 -R$REGION –V
xyz2grd G4_40m_PS_75N.xyz -GG4_40m_PS_75N_xyz.grd -I40 -R$REGION –V
```

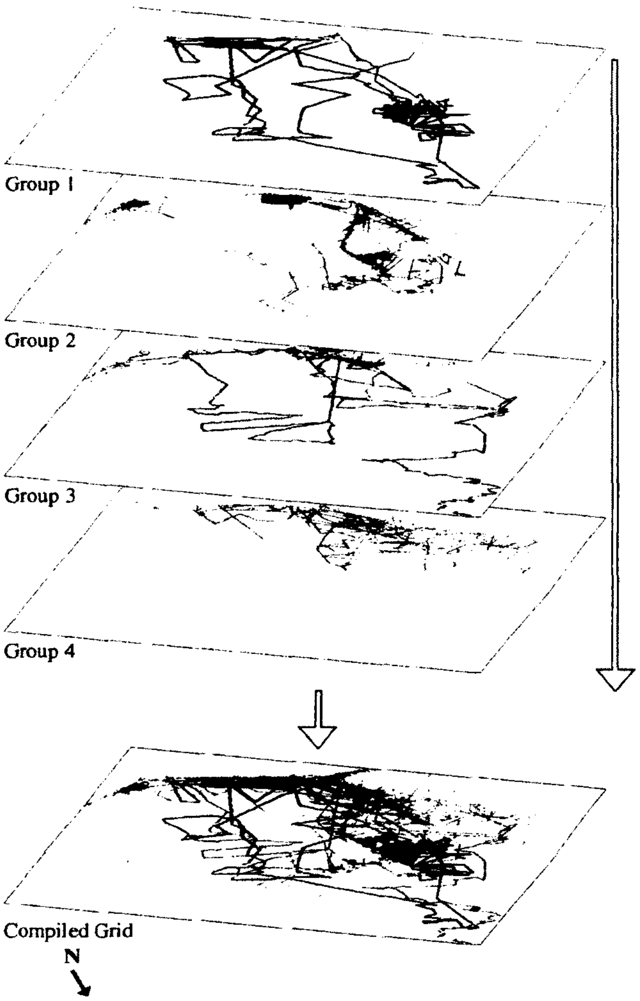


Figure 6: Visualization of the Generic Mapping Tools *gmtmath* exclusive-disjunction based vertical stacking method. Group 1 contains the highest quality multibeam data sources, Group 4 the least.

These quality group grids were then merged into a final bathymetric compilation using a vertical stacking method. The quality value assigned to each group described the position of a grid in the stacked compilation (one at the surface, four at the base, Figures 6/7). The method made use of GMT's "grdmath" routine to iteratively combine two grids using an exclusive disjunction (XOR) logical operation (*Wessel and Smith*, 1991). The exclusive disjunction combined two grids (a primary and secondary), using the cell value of the secondary grid only if there was no value in the primary grid cell. The operation resulted in a compiled grid where the primary grid overlaid the secondary grid. The exclusive disjunction was first performed on quality group grids one and two. This intermediate product was then combined with quality group grid three, and then in turn quality group four[3], ensuring only the highest quality source available would be used in any grid cell (Figures 6/7).

---

[3] GMT Command:
```
grdmath G1_40m_PS_75N_xystd.grd G2_40m_PS_75N_xystd.grd XOR
        G3_40m_PS_75N_xystd.grd XOR G4_40m_PS_75N_xystd.grd XOR =
        ARCTIC_40m_PS_75N_xystd.grd
```

Figure 7: Map view of the generic Mapping Tools *gmtmath* exclusive-disjunction based vertical stacking method, and the resulting bathymetry overlays. Quality Group 1 (black) contains the most reliable data, and is comprised of the UNH-CCOM ECS multibeam cruises.

The vertical stacking method allowed the highest quality data to be preserved, without contamination from overlapping low signal-to-noise or low-resolution MBES soundings (Figure 6). Similar grids were generated for sounding density and depth standard deviation (Appendix C). All grids were created using a Polar Stereographic projection, with a true scale at 75° N, and a cell spacing of 40 m. While much of the deep-water data does not support 40 m cell spacing, this oversampling was necessary to preserve other high-resolution data sources, particularly in shallow waters. The final compiled gridded datasets were converted to both netCDF grids and high-resolution geospatial PDFs for distribution.

Results and Discussion

Internal Consistency Through Crossover Analysis

MBES depth uncertainties (*Hare et al.*, 1995; *Lurton and Augustin*, 2010) tend to increase in deeper water, and therefore cruises spending more time in deep water have larger crossover errors and variations. This depth scaling is minimized by looking only at nadir MBES depth (opposed to outer beam depths), and further mitigated by examining the crossover errors as a function of water depth (Figures 5, Table 1). Low nadir-depth crossover errors and variations are seen for all MBES groupings, particularly among the dedicated ECS cruises, where the mean difference is less than 1% of water depth (Table 1). Data collected aboard the R/V Mirai and R/V Nathaniel B. Palmer showed particularly large nadir-depth crossover errors, and hence assigned the lowest weighting factor in the compilation. The compiled data set, consisting of 91 cruises and approximately 298,000 km of trackline multibeam data, had a mean nadir-depth crossover error of 2.4 % of water depth, calculated from more than 40,000 crossings.

Crossover errors are shown in detail for the three selected areas outlined in Figure 2. Two of these areas (Figures 8/9) share the same data sources as the International Bathymetric Chart of the Arctic Ocean (IBCAO), while the third (Figure 10) is comprised of predominantly more recent multibeam tracks.

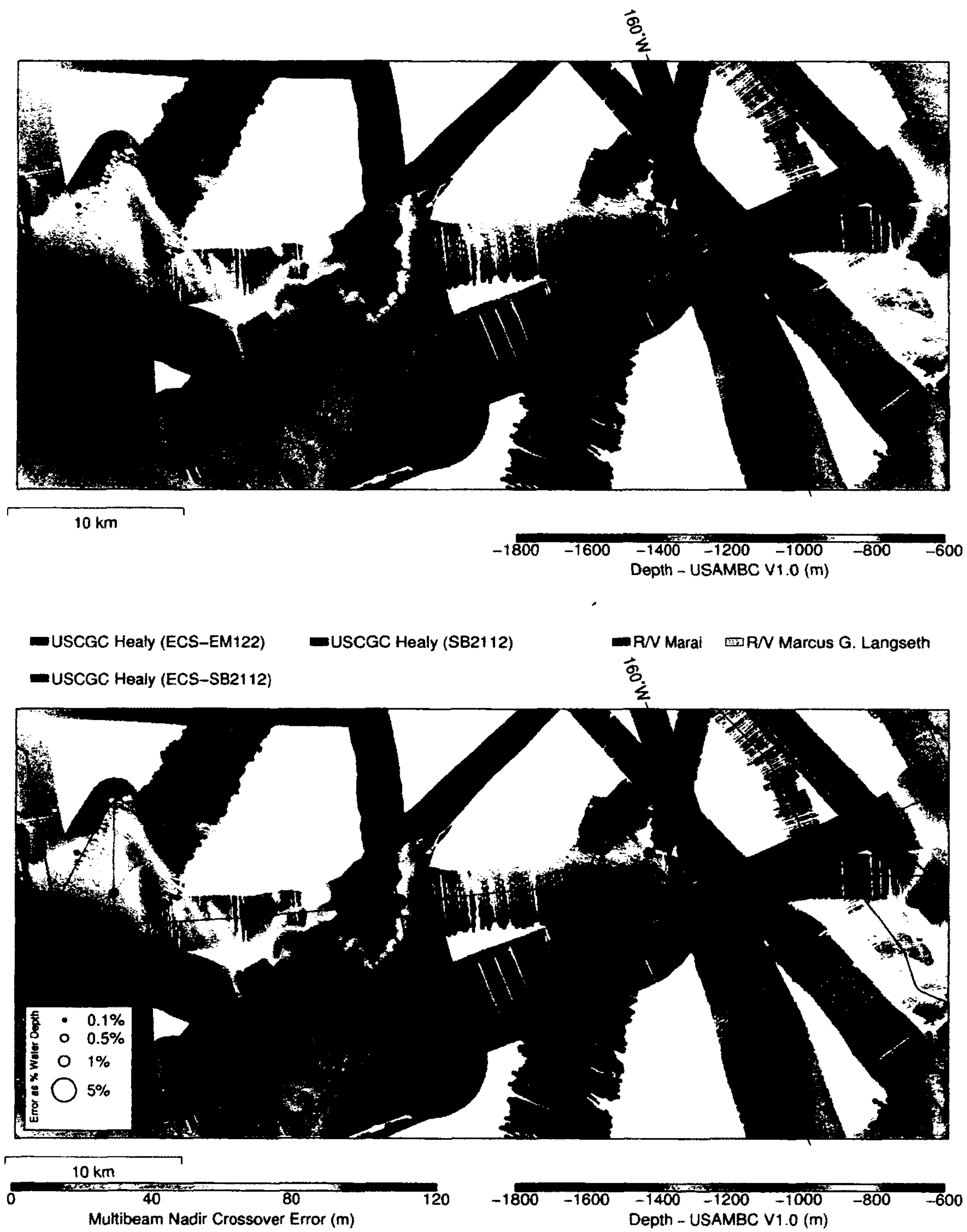


Figure 8: A detailed map view of a portion of the crossover-error analysis showing a submarine valley on the Chukchi Borderland. This area is further compared to the International Bathymetric Chart of the Arctic Ocean (IBCAO) in Figures 11.

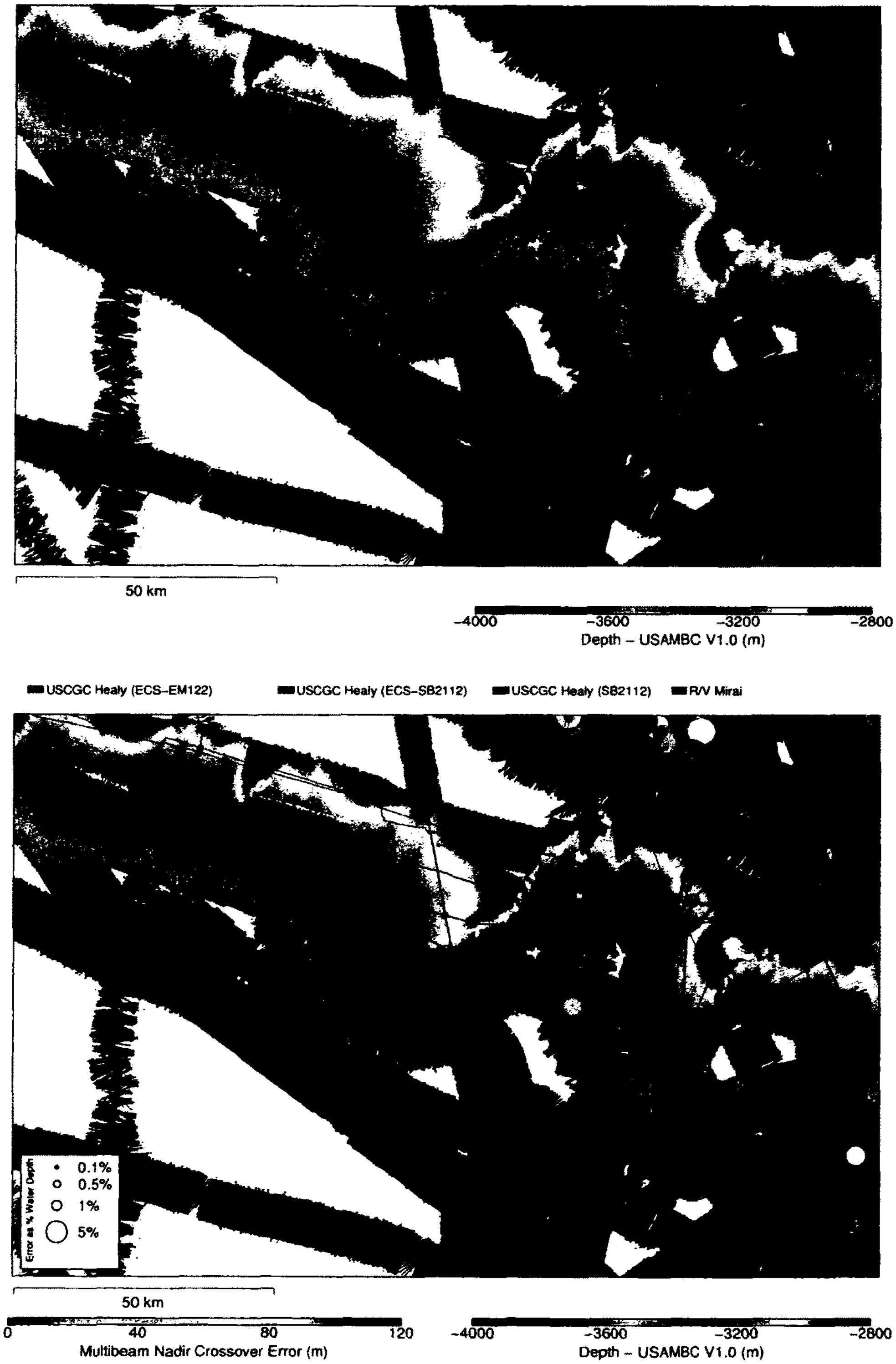


Figure 9: A detailed map view of a portion of the crossover-error analysis showing sediment waves off of the Alaskan continental shelf. This area is further compared to the International Bathymetric Chart of the Arctic Ocean (IBCAO) in Figures 12.

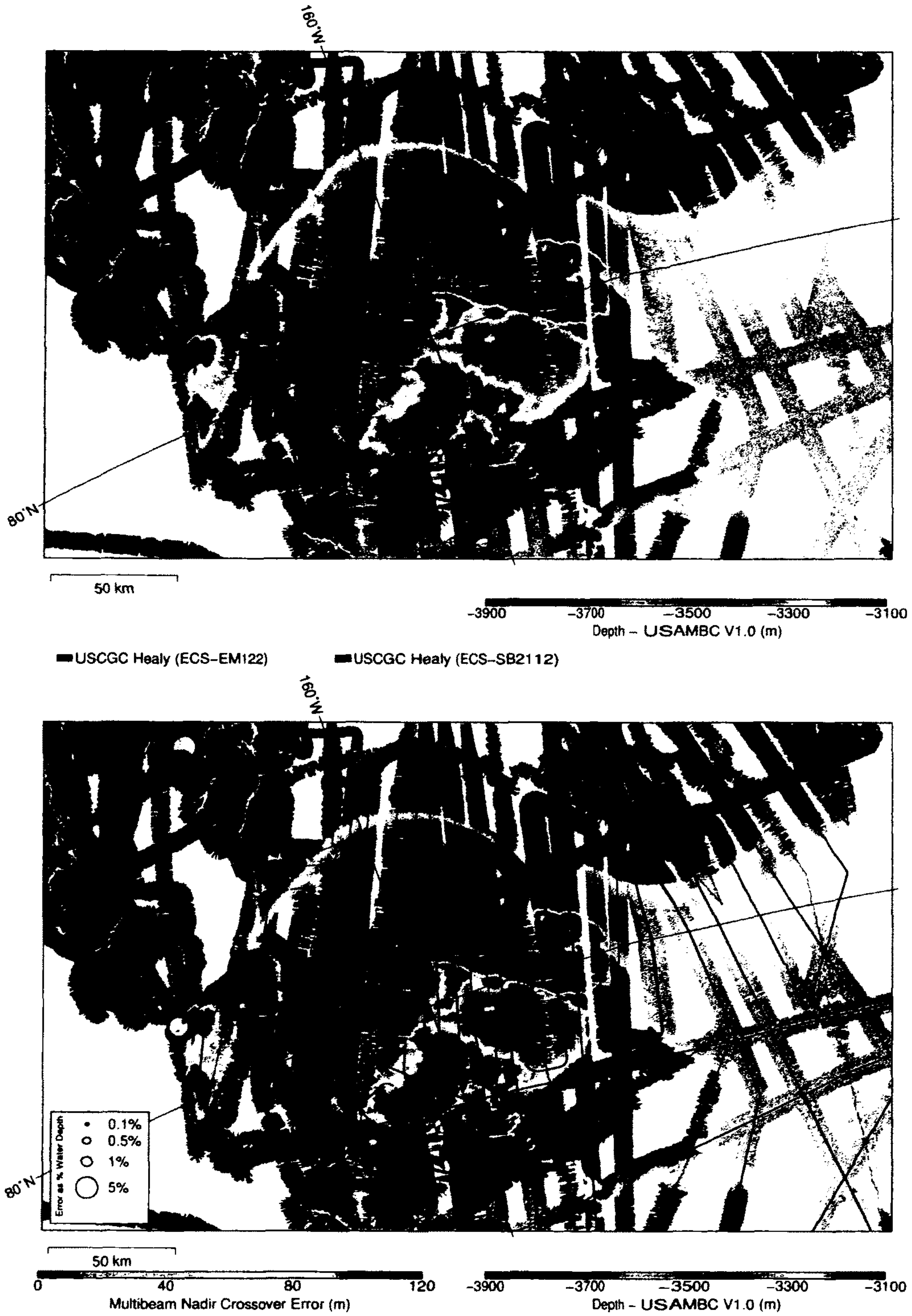


Figure 10: A detailed map view of a portion of the USAMBC (V1.0), showing a submarine sediment channel north of the Chukchi Borderland.

Comparison to IBCAO

The International Bathymetric Chart of the Arctic Ocean (IBCAO) provides an unparalleled portrayal of the entire Arctic seafloor. Its most recent iteration (V3.0) takes advantage of many of the recent MBES cruises compiled here (Table A1). While IBCAO Version 3.0 uses an improved gridding algorithm, resulting in higher spatial resolution, the final gridded compilation is still limited to 500 meter spacing (*Jakobsson et al.*, 2012). While its extensive coverage makes it an indispensable tool for planning ECS mapping cruises, its coarse resolution makes it less useful for direct ECS related interpretation. Figure 12 shows an area comprised of source data from the *R/V Mirai* and *USCGC Healy* (SB2112; both ECS and non-ECS), with the area in Figure 11 additionally supplemented with a small portion of data from the *R/V Marcus G. Langseth*. Both IBCAO V3.0 and the USAMBC V1.0 use these same multibeam data sources in their compilations–the newer USAMBC V1.0 does not contain any additional sources beyond those used in IBCAO V3.0.

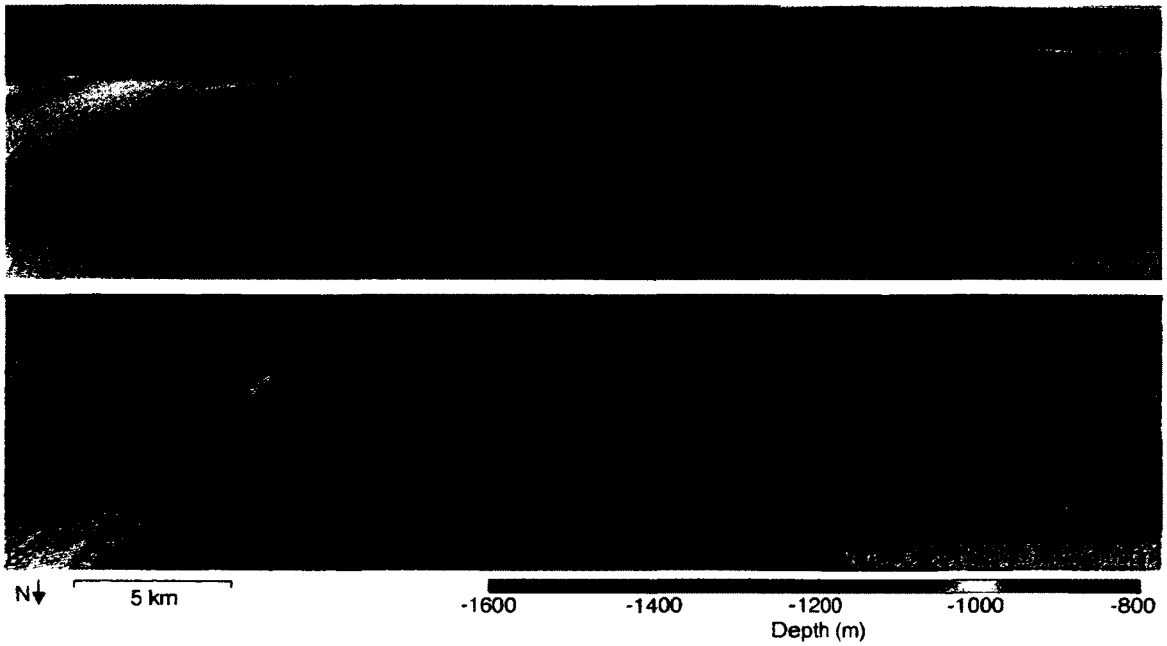


Figure 11: A detailed comparison of resolution differences provided by the USAMBC V1.0 (B) compared to IBCAO V3.0 (A) for a subset of the region shown in Figure 2 (incorporating multiple data sources). While IBCAO V3.0 (A) provides an indispensable digital representation of Arctic bathymetry, its large scale and more coarse resolution masks the higher supported native resolution of the MBES data.

Geological features that are lost in the 500-meter resolution of IBCAO V3.0 are easily identifiable in USAMBC V1.0 (Figures 11/12). Marine valleys and sediment channels spanning the shoaler portions of the Chukchi Borderland are seen clearly in the USAMBC, while they are smoothed over in IBCAO (Figure 11). Similar detail is lost along the slopes of the continental shelf (Figure 12), where slumped sediment, derived from up slope, has created a pervasive wave-like seafloor fabric. Comparisons have been intentionally made only where IBCAO and USAMBC have the same multibeam data content, emphasizing the difference in product resolution and not source data availability. Data gaps in the USAMBC (Figures 11/12), result from USAMBC being a data-only compilation, compared to IBCAO, which interpolates between areas where data are not available. Similarly, as IBCAO creates a low-pass smoothed interpolated surface, small discrepancies between adjacent multibeam data tracks will appear less prominent. While USAMBC preserves the high-resolution seafloor, it similarly preserves these discrepancies. While USAMBC will not match the extent of IBCAO coverage, it does allow for more in-depth geological interpretation of seafloor morphology, making it a highly useful companion to IBCAO.

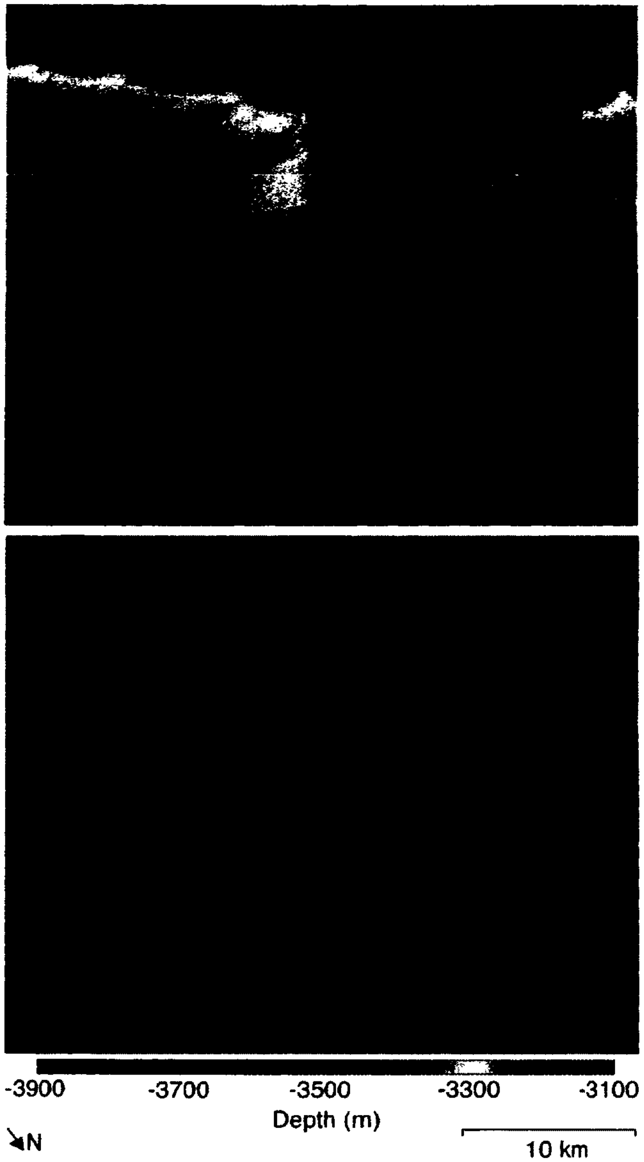


Figure 12: A second comparison of the resolution differences provided by the USAMBC V1.0 (B). The USAMBC high-resolution compilation allows for in-depth geological interpretation of depositional sediment waves.

Chukchi Borderland

The largest potential region for a U.S. Extended Continental Shelf in the Arctic Ocean is in the area of the Chukchi Borderland. The Chukchi Borderland occupies a roughly rectangular area 600 by 700 km, some 4% of the Arctic Ocean (*Mayer et al., 2002*; *Mayer*, 2003), jutting northward between eastern Siberia and western Alaska, north of the Chukchi Sea (Figure 2). Comprised predominantly of a tightly clustered group of generally N-S trending topographic highs, the area forms a natural prolongation from the Chukchi Shelf north of Alaska (*Hall*, 1990). The area was identified early in the ECS project as an area where the existing database of bathymetric data was too sparse to support a well-defended ECS submission (*Mayer*, 2003) and was thus the focus of significant mapping efforts.

Low nadir-depth crossover errors in this compilation are seen throughout the Chukchi Borderland, particularly on the eastern high-sloping transition from the relatively shallow Chukchi Cap to the abyssal Canada Basin (< 1.5% w.d., < 50 m, Figures 4/5). The low difference in this transition region is surprising given that five different MBES sources cross the slope (Figure 3). Similarly low nadir-depth crossover differences are seen in the northern-most region of the Chukchi Borderland where the MBES compilation consists of only ECS collected data (Figures 2/3).

Conclusion

Our new multibeam bathymetry compilation provides the highest spatial resolution currently available for the Arctic seafloor in the Canada Basin and Chukchi Borderland. As new data becomes available they should continued to be incorporated into both full-coverage (e.g., IBCAO) as well as multibeam-only (e.g., USAMBC) data products. Both the gridded compilation of USAMBC and an easily-distributed geospatial PDF are freely available through the University of New Hampshire's Center for Coastal and Ocean Mapping (*http://ccom.unh.edu/theme/law-sea*). This geospatial PDF is a fully-resolvable, small file-size product that provides easy access for interpretation of Arctic seafloor morphology without the need for specialized gridding/visualization software.

LIST OF REFERENCES

Björk, G., M. Jakobsson, B. Rudels, J. H. Swift, L. G. Anderson, D. A. Darby, J. Backman, B. Coakley, P. Winsor, L. Polyak., and M. Edwards, (2007), Bathymetry and deep-water exchange across the central Lomonosov Ridge at 88-89N, *Deep–Sea Res. I*, *54*, 1197–1208.

Calder, B. R., and L. Mayer (2003), Automatic Processing of High-rate, High-density Multibeam Echosounder Data, *Geochem. Geophys. Geosyst.*, *4*, 1–24.

CARIS HIPS & SIPS 7.0 Users Guide (2007).

Caress, D. W., and D. N. Chayes (2006), MB-System: Mapping the Seafloor, http://www.mbari.org/data/mbsystem

Hall, J. K. (1990), Chukchi borderland, The Arctic Ocean Region, *The Geology of North America*, *50*, 337–350.

Hare, R., A. Godin, and L. A. Mayer (1995), Depth and position error budgets for multibeam echosounding, *Int. Hydro. Rev.*, *72*, 37–69.

Jakobsson, M., J. Nilsson, M. O'Regan, J. Backman, L. Löwemark, J. A. Dowdeswell, L. Mayer, L. Polyak, F. Colleoni, L. Anderson, G. Björk, D. Darby, B. Eriksson, D. Hanslik, B. Hell, C. Marcussen, E. Sellen, and A. Wallin (2010), An Arctic Ocea Ice shelf during MIS 6 constrained by new geophysical and geological data, *Quatern. Sci. Rev.*, *29*, 3505–3517.

Jakobsson, M., L. A. Mayer, B. Coakley, J. A. Dowdeswell, S. Forbes, B. Fridman, H. Hodnesdal, R. Noormets, R. Pedersen, M. Rebesco, H. W. Schenke, Y. Zarayskaya A, D. Accettella, A. Armstrong, R. M. Anderson, P. Bienhoff, A. Camerlenghi, I. Church, M. Edwards, J. V. Gardner, J. K. Hall, B. Hell, O. B. Hestvik, Y. Kristoffersen, C. Marcussen, R. Mohammad, D. Mosher, S. V. Nghiem, M. T. Pedrosa, P. G. Travaglini, and P. Weatherall (2012), The International Bathymetric Chart of the Arctic Ocean (IBCAO) version 3.0, *Geophys. Res. Lett.*, *39*, L12609.

Lawver, L. A., L. M. Gahagan, and I. O. Norton (2011), Paleogeographic and tectonic evolution of the Arctic region during the Palaeozoic, in *Arctic Petroleum Geology*, edited by A. M. Spencer, A. F. Embry, D. L. Gautier, A. V. Stoupakova and K. Sorensen, Geological Society, London, Memoirs *35*, 61-77.

Lurton, X., and J. Augustin (2010), A measurement quality factor for swath bathymetry sounders, *J. Ocean. Eng.*, *35*(4), 852–862.

Mayer, L. A. (2003), U.S. Law of the Sea cruise to map the foot of the slope and 2500-m isobath of the U.S. Arctic Ocean Margin, Barrow to Barrow, Cruise Report, *University of New Hampshire, Center for Coastal and Ocean Mapping/Joint Hydrographic Center*, 1–47.

Mayer, L. A., A. A. Armstrong, B. Calder, and J. V. Gardner (2010), Seafloor mapping In the Arctic: support for a potential U.S. extended continental shelf, *Int. Hydro.*

Rev., *3*, 14–23.

Mayer, L. A., J. Martin, and A. A. Armstrong (2002), The compilation and analysis of data relevant to a U.S. claim Under United Nations Law of the Sea Article 76: A preliminary report, *University of New Hampshire, Center for Coastal and Ocean Mapping/Joint Hydrographic Center*, 1–75.

Nghiem, S.V., P. Clemente-Colon, I. G. Rigor, D. K. Hall, and G. Neumann (2012), Seafloor control on sea ice, *Deep–Sea Res. II*, *77-80*, 52–61.

Sedgewick, R., 1990. In: Algorithms in C. Addison-Wesley, Reading, MA 657 pp.

General Assembly of the United Nations (1982), United Nations Convention on the Law of the Sea.

Wessel, P. (2010), Tools for analyzing intersecting tracks: the x2sys package, *Comp. & Geosci.*, *36*, 348–354.

Wessel, P. and W. H. F. Smith (1991), Free software helps map and display data, *EOS Trans.*, AGU, 72(*441*).

APPENDIX A: Source Data and Individual Crossover Statistics

Table A1. An expanded listing of multibeam source data and crossover statistics for individual cruise legs. Crossover statistics were calculated only for data greater than 250 meters water depth, at vessel speeds greater than two knots. Distances include all tracklines greater than 50 meters water depth. The number of crossings in an individual cruise has a tendency to be exaggerated when cruise lines are nearly co-located; resulting in multiple crossings. U.S. Extended Continental Shelf specific cruises are highlighted in yellow.

Vessel	**Cruise**	**Year**	**Sonar**	**Distance**	**Crossings**	**Δ-Nadir**		**σ**		**Weight**	**Repository**
				(km)		m	%*wd*	m	%*wd*		
USCGC Healy	HLY0201	2002	Seabeam 2112	1529	39	7	0.7	8	0.9	3	NGDC
	HLY0202			3148	192	4	1.2	5	1.4		
	HLY0203			7566	1694	7	1.8	54	9.8		
	HLY0204			5834	18	20	4.3	25	5.6		
	HLY0302	2003		3035	18	9	1.5	13	2.3	2	UNH/CCOM
	HLY0303			3034	7640	7	1.8	14	7.2	3	NGDC
	HLY03TD			5442	1	0	0.0	0	0.0		
	HLY0402	2004		8277	637	37	15.8	85	40.7		
	HLY0403			10867	9851	4	1.3	7	1.8		
	HLY0404			13888	2033	4	1.3	6	1.8		
	HLY0405			6715	61	7	0.5	11	1.0	2	UNH/CCOM
	HLY04TG			2259						3	NGDC
	HLY0502	2005		1991	27	11	1.7	18	3.1		
	HLY0503(1)			10115	470	11	0.8	57	3.6		
	HLY05TC			833							
	HLY05TD			1055							
	HLY0601	2006		477							
	HLY0602			4913	87	41	5.8	94	12.6		

	HLY06TG			1021	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]		
	HLY06TH			1139	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]		
	HLY0702	2007		374	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]		
	HLY0703			9399	308	1	0.2	8	0.6	2	UNH/CCOM
	HLY07TG			964	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	3	NGDC
	HLY07TH			1000	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	3	
	HLY0804	2008		1628	19	4	0.6	5	0.7		
	HLY0805			5717	225	11	0.7	33	1.9	2	UNH/CCOM
	HLY0806			5509	57	6	0.4	10	0.6	3	NGDC
	HLY08TH			931	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]		
	HLY08TI			1100	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]		
	HLY0904	2009		2653	31	13	2.1	33	5.6		
	HLY0905			9447	71	2	0.2	3	0.4	2	UNH/CCOM
	HLY09TD			1001	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	3	NGDC
	HLY09TE			1388	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]		
	HLY1002	2010	Kongsberg EM122	9414	41	3	0.2	4	0.3	1	UNH/CCOM
	HLY1003			5461	12	10	1.6	18	2.4	2	NGDC
	HLY1102	2011		9672	148	1	0.1	5	0.4	1	UNH/CCOM
	HLY1202	2012		10148	147	10	0.7	21	1.9		

R/V Mirai	MR99-K05	1999	Seabeam 2112	1879	20	7	1.4	10	2.1	4	JAMSTEC
	MR00-K06	2000		4663	51	10	2.6	25	5.7		
	MR02-K05	2002		8803	68	10	2.8	33	6.9		
	MR04-K05	2004		8900	67	4	0.7	4	1.0		
	MR06-K04	2006		56	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]		
	MR08-K04	2008		11147	86	3	1.1	5	1.8		

	MR09-K03	2009		5450	73	2	0.7	3	1.0		
	MR10-K05	2010		9024	156	3	0.6	6	0.9		
CCGS Amundsen	(multiple)	2003 – 2008	Kongsberg EM300	30984	386	2	1.1	3	1.6	3	UNB/OMG
CCGS Amundsen	(multiple)	2009 – 2011	Kongsberg EM302	38530	2318	2	0.6	5	1.7	2	UNB/OMG
R/V Nathaniel B. Palmer	NBP0304A'	2003	Kongsberg EM120	3289	36	36	3.8	69	7	4	NGDC
R/V Marcus G. Langseth	MGL1112'	2011	Kongsberg EM122	7077	17	7	1.3	11	2	2	NGDC

Cruise References

(1) Darby, D., M. Jakobsson, and L. Polyak (2005), Icebreaker Expedition Collects Key Arctic Sea Floor and Ice Data, *EOS Transactions, American Geophysical Union, 86*(52), 549-556.

(2) Mayer, L. A., A. A. Armstrong, B. R. Calder, and J. V. Gardner (2010), Seafloor Mapping In The Arctic: Support For a Potential US Extended Continental Shelf, *International Hydrographic Review, 3*, 14-23.

(3) Data provided through the JAMSTEC Data Research System for Whole Cruise Information (DARWIN) http://www.godac.jamstec.go.jp/darwin/e

(4) Downey, N. J., J. M. Stock, R. W. Clayton, and S. C. Cande (2007), History of the Cretaceous Osbourn spreading Center, *Journal of Geophysical Research B: Solid Earth, 112*(4).

(5) Coakley, B., and I. Ilhan (2011), Abstract T33A-2365: Chukchi Edges Project – Geophysical Constraint on the History of the Amerasian Basin, *American Geophysical Union Fall Meeting 2011.*

Appendix B: X2sys Example Code

An example workflow for using *Generic Mapping Tools* x2sys crossover codes is hosted through the *Computers and Geosciences* GitHub website; **https://github.com/cageo/Flinders-2014**. The included GitHub files give a working example of how to calculate the crossing errors for a set of extracted multibeam nadir lines. We reproduce the annotated code here (*x2sys_example.bash*), but the interested party should visit the link to download the example multibeam lines files and to properly set up the directory structure.

Github Files:

Make the proper directory structure, prior to running example script;

x2sys_makedir.bash

Main example script (performs the crossover analysis);

x2sys_example.bash

Example lines;

Healy_HLY0602_1_NADIR.xyzt

Healy_HLY0602_2_NADIR.xyzt

Healy_HLY0602_3_NADIR.xyzt

Healy_HLY0602_4_NADIR.xyzt

Healy_HLY0602_5_NADIR.xyzt

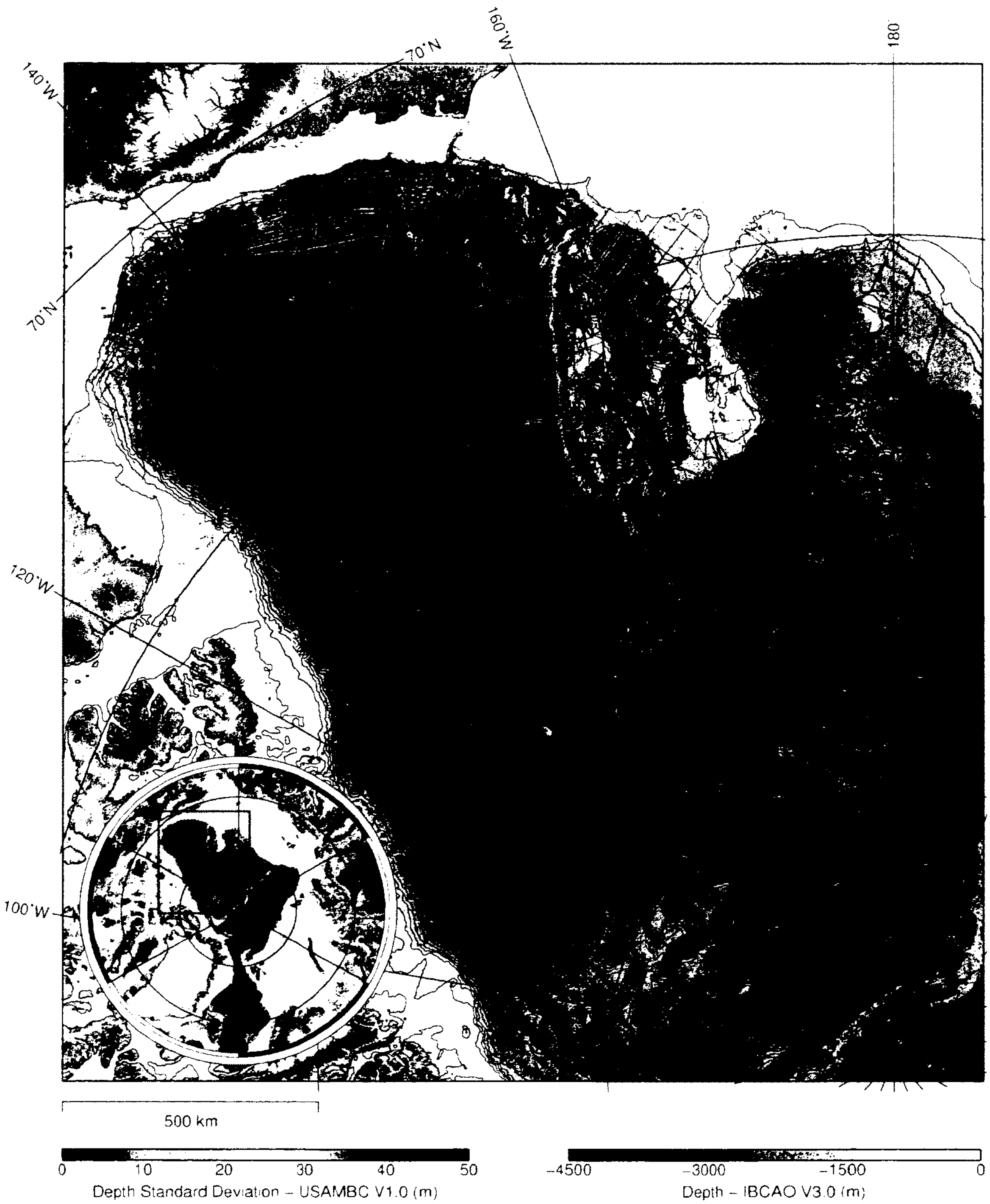
```
#!/bin/bash
#
# x2sys_example.bash
#
# A. Flinders
# ashton.f.flinders@gmail.com
#
# February 13th, 2014
#
# This is an example script for running Generic Mapping Tools (GMT) x2sys crossover
# analysis on extracted multibeam nadir lines. This script can be used as it for a single
# cruise, or batched to run through multiple.
#
# This script is not necessarily specific to multibeam nadir lines, but can be used as a
# general example of how to use the x2sys package.
#
# Before using, make sure that you have downloaded all required example lines from the
# Github repository, as well as run the script to set up the proper directory structure (or
# created it yourself).
#
# Example lines:
# Healy_HLY0602_1_NADIR.xyzt
# Healy_HLY0602_2_NADIR.xyzt
# Healy_HLY0602_3_NADIR.xyzt
# Healy_HLY0602_4_NADIR.xyzt
# Healy_HLY0602_5_NADIR.xyzt
# Healy_HLY0602_6_NADIR.xyzt
#
# Make directory structure (run prior to this script!)
# x2sys_makedir.bash
#
# Then change into the X2SYS_EXAMPLE directory, and run this script:
#
# X2SYS_EXAMPLE ]$./x2sys_example.bash
```

```
# On some machines its necessary to change the maximum stack size for large data sets
ulimit -s 12288

# Cruise identifier
fileID="Healy_HLY0602"

ROOT_DIR=`pwd`
CRUISE_DIR=$ROOT_DIR"/"$fileID
X2SYS_DIR=$CRUISE_DIR"/X2SYS"
NADIR_DIR=$CRUISE_DIR"/XYZT"

# remove existing x2sys system directories\files for example cruise, make a blank ones
if [ -d "$X2SYS_DIR" ]; then
rm -rf $X2SYS_DIR
fi
mkdir $X2SYS_DIR

# Create xyzt definition file
cat > $X2SYS_DIR"/xyzt.def" << EOF
# Define file for X2SYS processing of ASCII xyz files
# This file applies to a 4-column ASCII files, generated from dumping the nadir beam;
# longitude, latitude, depth, unix time
# from mbsbystem using the command;
# mblist -I $input file list -OXYZU -P3 > $output file
#---------------------------------------------------------------
#ASCII # The input file is ASCII
#SKIP 1 # The number of header records to skip
#---------------------------------------------------------------
#name intype NaN-proxy? NaN-proxy scale offset oformat
x a N 0 1 0 %g
y a N 0 1 0 %g
z a N 0 1 0 %g
time a N 0 1 0 %g
EOF
```

```
# Save the default x2sys home location (if set)
X2SYS_HOME_OLD=$X2SYS_HOME

# Change the default x2sys home directory to the local directory for our example
cd $X2SYS_DIR
export X2SYS_HOME=`pwd`

# Initialize the TAG folder
x2sys_init $fileID -Gd -Cg -Dxyzt -F -V -Wd1
cd $fileID

# Copy cruise trackline filenames to datalist.d
ls $NADIR_DIR > datalist.d

# Create path file
# the absolute path to the folder with the extracted nadir beams
echo $NADIR_DIR > $fileID"_paths.txt"

# Calculate crossovers
# Set speed constraint so that we dont calculate crossings for speeds less that 1.0289 m/s
# e.g. 2 knots......(helps remove self crossings from holding position)
x2sys_cross --TIME_SYSTEM=UNIX =datalist.d -T$fileID -2 -Qe -V -Sl1.0289 > $fileID.CROSS

if test -s $fileID.CROSS; then
        echo "CROSSOVERS FOUND";

        # Output the crossovers from the database
        x2sys_list -Cz -T$fileID $fileID.CROSS -FNc -V > tmp

        # x2sys_list has a tendency to find "self crossings" along straight line segments (yes,
        # even with the speed constraint). We will remove these from the list. It is thereby
        # important to make sure your lines are not obscenely long and self-crossing.
        awk '{if ($1 != $2) {print $0} else next}' tmp > $fileID.LIST
        /bin/rm tmp
```

```
    # Find corrections (although we dont apply any)
    x2sys_solve -Cz -T$fileID $fileID.LIST -V -Ec > $fileID.SOLVE

    touch N_`awk 'NR > 3 {print $0}' *.LIST | minmax | awk '{print $4}'`

    else
    echo "NO CROSSOVERS.....ABORTING...."
fi
```

Appendix C1: United States Arctic Multibeam Compilation Standard Deviation



Appendix C2: United States Arctic Multibeam Compilation Sounding Density