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Developing Techniques to Determine Arctic Bathymetry from Airborne Gravity - Final Report

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This report covers work to develop a remote sensing method based on airborne gravity to determine bathymetry under ice covered oceans for mapping economic and military critical regions of the Arctic Ocean. An iterative forward modeling technique to modify initial admittance function based estimates of bathymetry from airborne gravity measurements to incorporate a sediment layer has been developed and evaluated Possible future improvements are discussed.

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Abstract

This report covers work to develop a remote sensing method based on airborne gravity to determine bathymetry under ice covered oceans for mapping economic and military critical regions of the Arctic Ocean, expanding on the work presented in memorandum report NRL/7230/MR-2021/1. An iterative forward modeling technique that modifies initial estimates of bathymetry from airborne gravity measurements to incorporate a sediment layer has been advanced Some problems in the algorithm implementation and the test data set are discussed.

Introduction

In FY2020, The Coastal and Ocean Remote Sensing Branch in NRL's Remote Sensing Division began a program to develop a remote sensing method based on airborne gravity to determine bathymetry under ice covered oceans. Approximately 90% of the ice-free world's oceans have been mapped using derived bathymetry obtained from satellite altimetry (Smith and Sandwell, 1997), which is much less expensive and time-consuming than ship surveying. However, this method does not work for ice-covered oceans and does not work well in heavily sedimented areas, both conditions existing in the strategically important Arctic. The goal of this project was to advance algorithms for replaceing satellite-based altimetry derivation with airborne gravity data, while utilizing NRL's historic Arctic airborne data sets. The project aimed to develop improved methods to incorporate sediment depths as well as gravity into the estimation process through iterative gravity modeling, creating a hybrid method. An interim report on the work performed through February 2021, was published (NRL/7230/MR-2021/1 Peters et al., 2021). In the latest developments, we focused on implementing and executing the hybrid method to estimate bathymetry from gravity in one area of interest (AOI), encompassing the region centered on the Gakkel Ridge from 84 to 87 degrees north and 128 km East and West of the ridge (Fig. 1), and then to evaluate the result in comparison to existing (sparse) bathymetry datasets, collected by other means, e.g. ship borne sonars. This would quantify the accuracy of the resulting bathymetry estimates, and provide an estimate how much this improves bathymetry knowledge in these sparse areas.

This approach was broken into the following tasks:

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- determining the applicable geologic and geophysical parameters for the AOI;
- implementing/integrating the software tools that use or calculate those parameters to produce a bathymetry estimate through iterative forward modeling;
- using those tools and parameters to produce bathymetry estimates;
- evaluating the resulting bathymetry estimates in comparison to actual bathymetry in the AOI.

This report describes work performed on and results from these tasks. It also outlines difficulties encountered, discusses possible remedies, and future development.

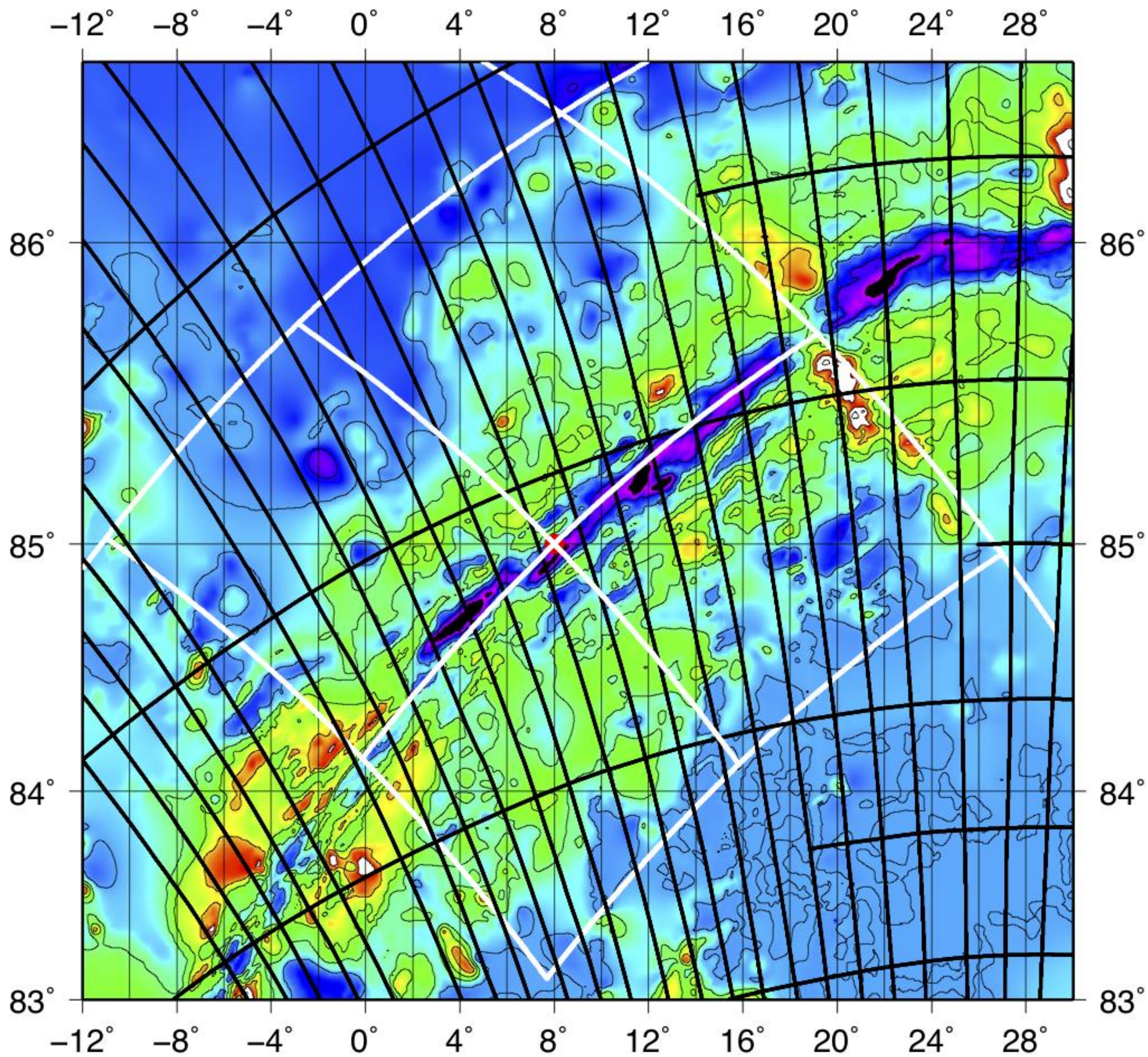

Figure 1. The area of interest (AOI) chosen to test the hybrid method. The background is the regional bathymetry contour map based on the International Bathymetry Chart of the Arctic Ocean data set.. The dark black lines are airborne gravity tracks, which are not parallel and perpendicular to the ridge whose center valley is the dark blue, purple and black region in the center of the contour map. The white lines are the center lines and boundaries of the AOI. The map projection is Mercator, so what the airborne tracks and AOI sides are really straight lines.

Regional parameter selection

The forward gravity models for sediment-modified admittance calculations, as well as the iterative modeling for bathymetric estimation, require density estimates for the geologic mass layers sea water, sediment, sediment thickness, and crust. After a review of published geology studies of the Arctic, the densities used for the Bouguer corrections (accounting for the sea-water and sediment layers) were chosen as follows: 1.03 g/cc water, 2.0 g/cc sediment and 2.7 g/cc upper crust following those in chapter 3: Eurasian Basin, from Geologic Structures of the Arctic Basin (Piskarev et al., 2018). The gravity modeling using these parameters have proven acceptable in the hybrid estimation process.

Implementation of tools for bathymetry estimations

GMT (Generic Mapping Tools, https://www.generic-mapping-tools.org, Wessel et al., 2019) and Linux scripts were used to calculate the regional Bouguer gravity anomaly and the residual anomaly after removal of the Bouguer anomaly. These tools work on the regional data grids created in FY20, which resampled the NRL free-air gravity measurements, International Bathymetric Chart of the Arctic Ocean 30-arc second bathymetry grids from https://www.ngdc.noaa.gov/mgg/bathymetry/arctic/arctic.html (Jakobsson et al., 2012) and the GlobSed total sediment thickness model of the world's oceans, recently extended to the Arctic (Straume et al., 2019). Scripts to implement the sediment layer as a polygonal mass difference in FastGrav (a two-dimensional gravity modeling package at https://fastgrav.com) for iterative forward gravity modeling of the bathymetry estimate have been created. However, the iterative gravity modeling with FastGrav proved to be slower and more subjective with respect to the individual doing the modeling than an operational method should be, so not all of the synthetic profiles have been modeled and estimated. In addition to these inconsistencies, the algorithms FastGrav employs (based on Parker, 1973 and Talwani et al., 1959) do not perform well when the off-profile topography is not sufficiently similar, as the mathematical assumptions are far from valid. An alternate forward modeling technique should be used and this alternative will be discussed.

Regional admittance calculation, lithospheric response classification

The proposed method to improve bathymetry estimation in sedimented areas requires the construction of a modified admittance function between the bathymetry and a modified gravity anomaly that has the contribution due to the sediments removed. This requires the calculation of the contribution to the gravity anomaly due to the sediments and has been completed using the selected parameters and the regional data grids. NRL airborne gravity tracks are not oriented in line with crust creation or spreading from the ridge so interpolated tracks based on a regular grid, parallel and perpendicular to the ridge, were created to calculate the admittance functions that are used for lithospheric response classification and the initial bathymetry (sea water-sediment boundary) estimation (Fig. 2). Bouguer and the sediment component of gravity anomalies have been calculated along these tracks. Spectral estimation/admittance calculations have been completed for all the synthetic/interpolated tracks. Differences in the responses between perpendicular and parallel tracks as well as unexpected differences between like-oriented tracks at differing distances from the center of the AOI presented difficulties in the identification of a suitable regional admittance function (see Fig. 3 for calculated admittances). The ridge-parallel tracks were oriented and created in geological provinces (Fig. 4) that would be expected to yield similar, consistent admittance relationships but this was not observed. We will present a hypothesis to explain the cause of the variance in the method evaluation section.

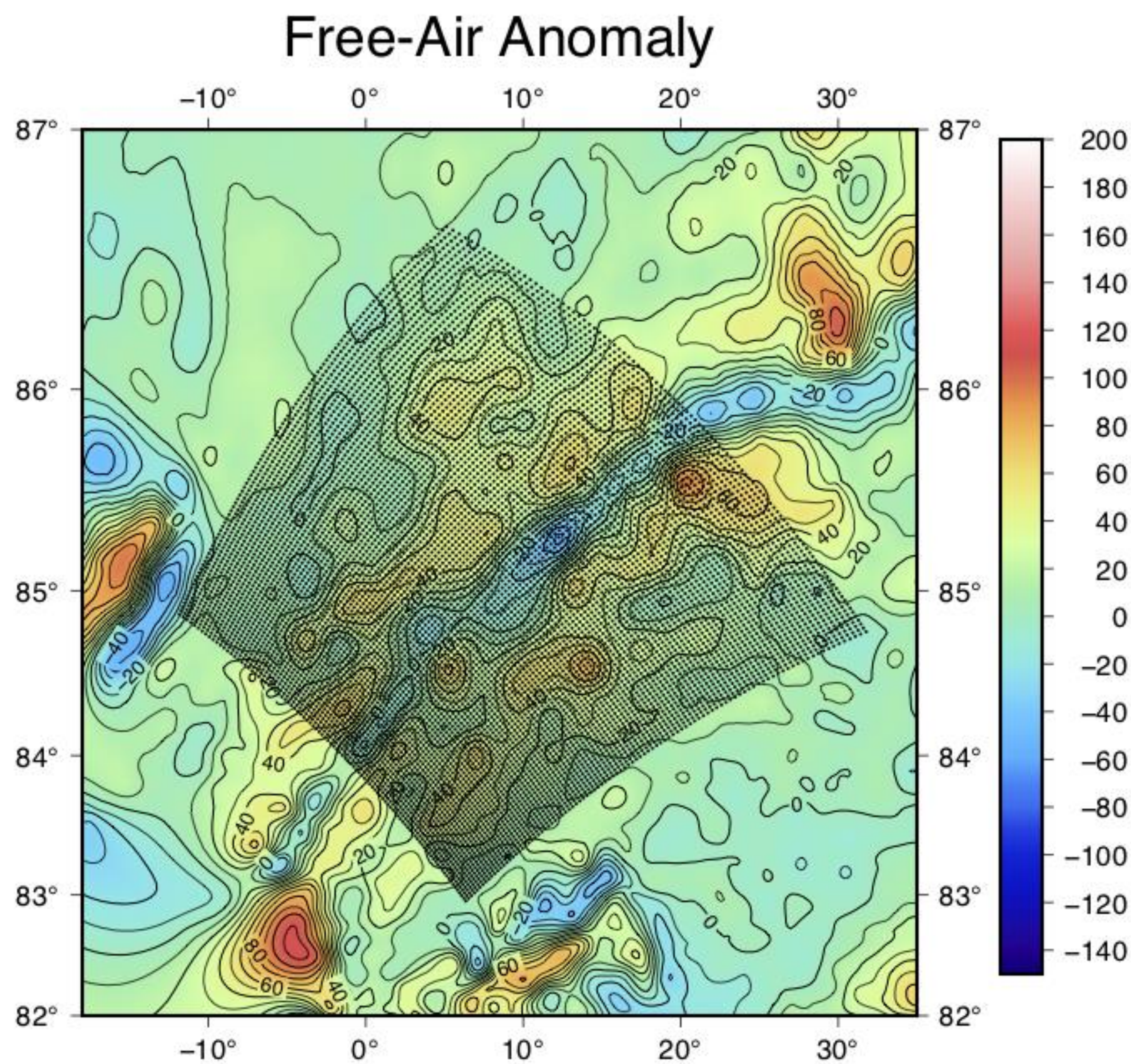

Figure 2 Free-air gravity anomalies around the Gakkel Ridge. The black dotted lines show the synthetic tracks based on the NRL airborne gravity profiles and analyzed parallel and perpendicular to the ridge. The map is a Mercator projection and the tracks are great circle segments and so appear curved.

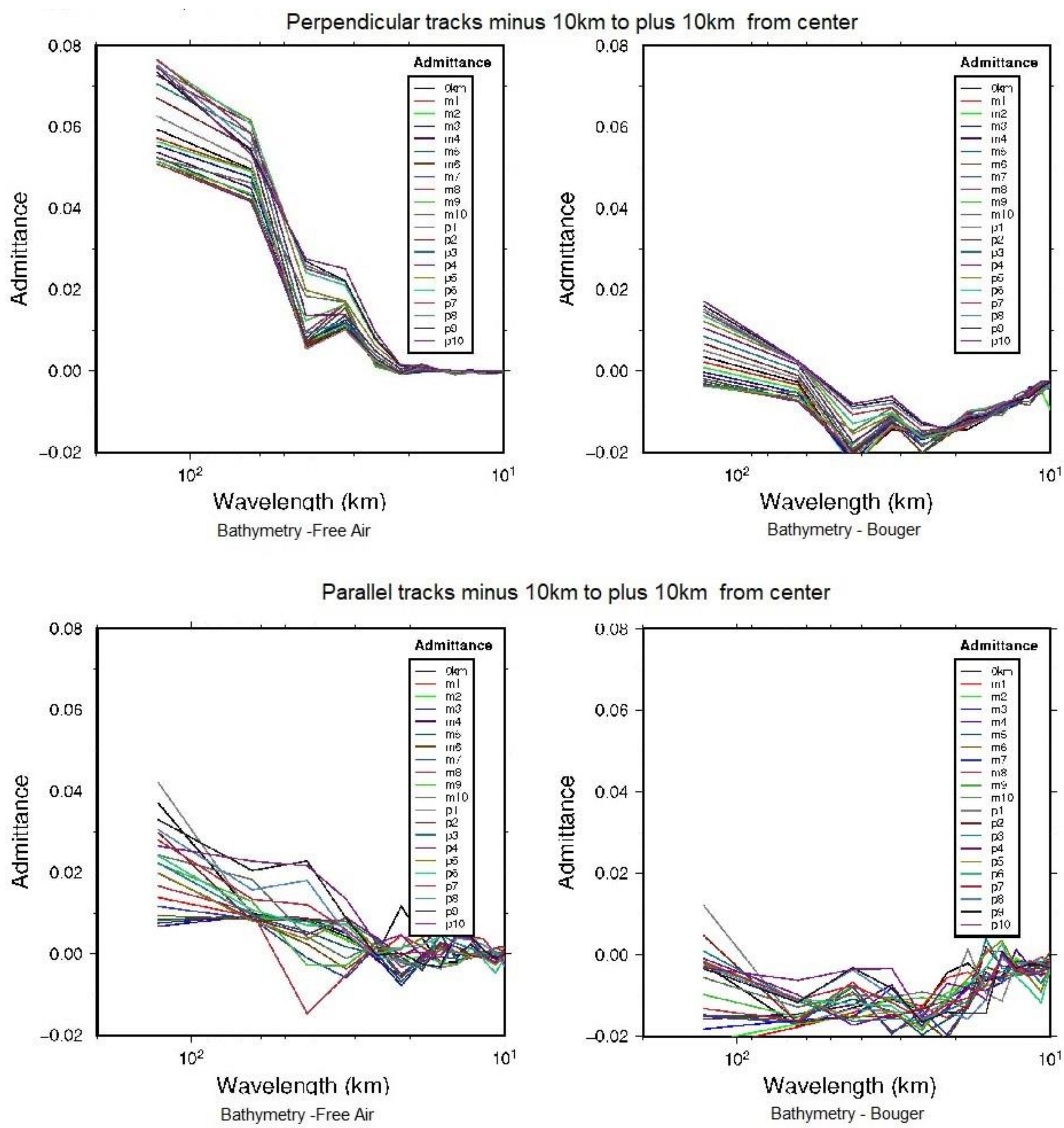

Figure 3. Admittance functions for tracks within 10 km of the central tracks, parallel and perpendicular to the ridge. The admittance functions were calculated using both free-air and modified Bouger gravity anomalies. Tracks are labeled m10 (for 10 km South-West) to p10 (for 10km North-East) of the center tracks (0km).

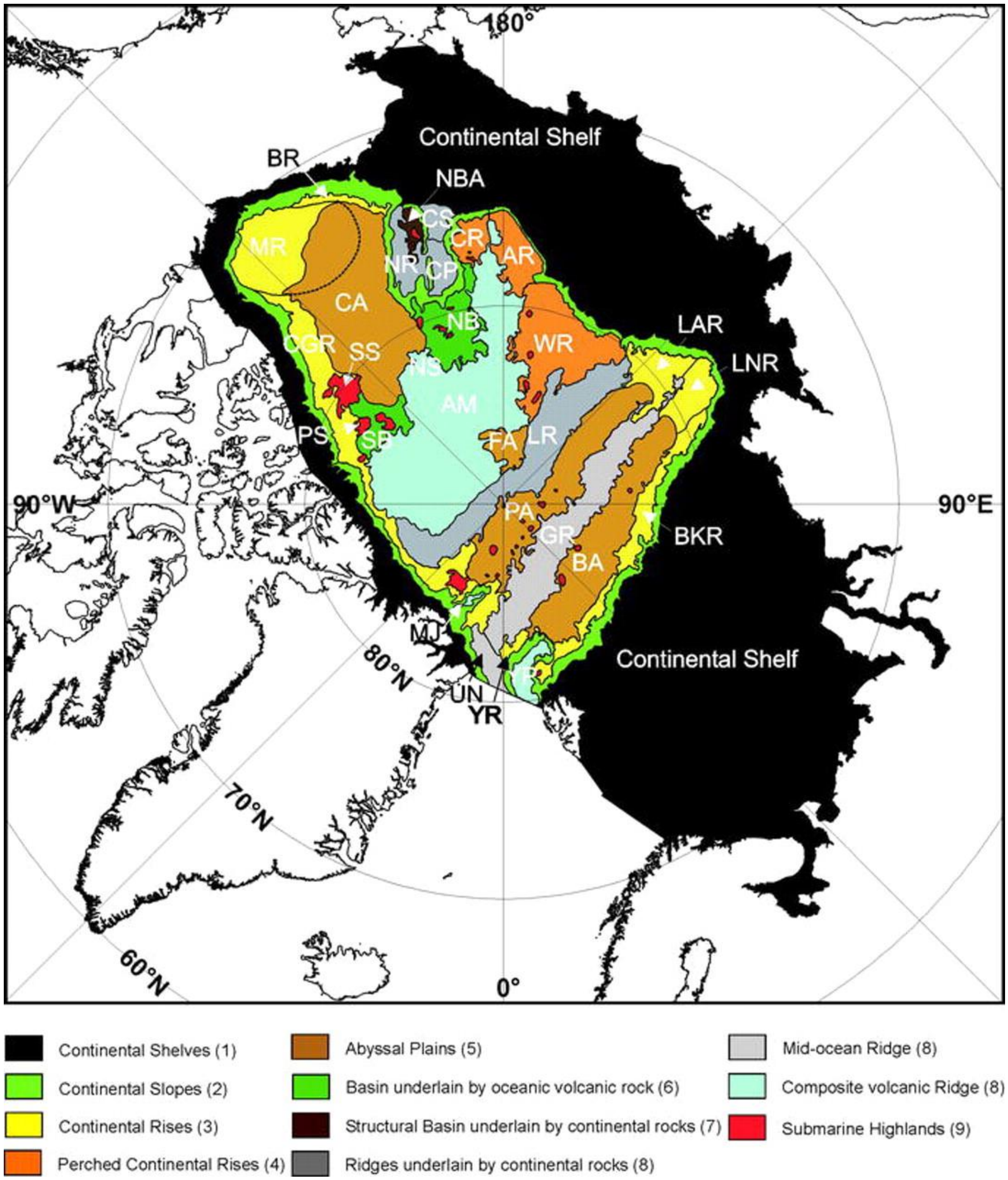

Figure 3. This figure from Jakobsen et al. (2003) shows a regional breakdown based on geology. The abyssal plain regions on either side of Gakkel (mid-ocean) Ridge would be similar in age and geology; therefore, we expected similar, consistent admittance functions for the parallel tracks in these regions.

Evaluation of bathymetry estimations

In preparation to calculate how well the bathymetry estimates fit the actual gravity, the spectral properties of the IBCAO bathymetry, as gridded for this AOI and the estimates, are compared. The airborne gravity data were compared to the modeled anomalies of bathymetric features in a range of widths and heights representing seamounts at nominal regional depths to determine what wavelengths should be detectable and to determine over what wavelength range the comparison should be calculated. A complete evaluation of the agreement of the bathymetry estimates to the gridded bathymetry would require evaluation over those wavelengths in each data set. This approach should be used in future calculations. Our evaluations were based on comparison of tracks reduced by best-fit linear trend, because of time constraints, and were poor.

Evaluation and interpretation of the Hybrid Estimation Method

Doing initial estimates track by track in MATLAB was not efficient and so a program to apply the admittance function as a gain filter was written in the C language to run under CentOS Linux in automated scripts, the way GMT components run, and to provide initial profile estimates of bathymetry from the gravity profiles. A script was written to extract the initial bathymetry estimate and format it to be a bathymetry/topography profile in FastGrav, and another to take the sediment depth along a profile to create a sediment volume However, there is no automated way yet to adjust the sediment and bathymetry based on differences between the FastGrav modeled gravity and the observed airborne gravity profile. This makes the generation of a gravity estimate over a region subjective, versus deterministic, and slow. Moreover, modelling along tracks parallel and perpendicular to the track, indicated why the admittance functions of parallel tracks were varied: the influence of the large mass of the adjacent mid-oceanic ridge. When using gravity modeling efforts that assume bodies and profiles extend as a cylinder, better results come from profiles that are selected to be perpendicular to the ridge, as the topographic extensions along the ridge are more nearly cylindrical. As for the parallel profiles, this cylindrical assumption fails. The large mass differential with the ridge size has a significant, asymmetrical impact on the gravity field along the profile, and forcing the iterative model to match the observed gravity fails: the gravity model can be made to agree well with the airborne measurements but the resulting bathymetry estimate is poor.. For perpendicular tracks across the ridge, however, the topography on adjacent tracks is similar and in the real world and such models, there is a strong correlation between the bathymetry (topography) and the gravity. This may account for the better results seen with perpendicular profiles, even though they cross different geologic/geophysical provinces and even cross a tectonic plate boundary at the ridge.

Future Directions

It was discovered that building the iterative model loop on a two dimension gravity modeling algorithm did not produce the desired results. The program's intent to add off-profile bodies could not be made to handle to extreme adjacent topography of the ridge and the asymmetrical effect on the actual gravity field. It is necessary to go to a three-dimensional model to account for the changes in depth (one dimension for sediment over bathymetric topography) and (two dimensions) for off-profile track topography and sediments. This will make the problem of automating the adjustment of the sediment and rock (upper crust) layer more difficult, as well as being more computationally involved. However, there do exist (open source) programs that can accomplish this. Sideris has released a C++ program that can calculate gravity anomaly and geoid potentials via three-dimensional FFT (Sideris, 2013). It would still be necessary to account for/remove the deep crust variations (compensation). The method we used, to compute a sediment free Bouguer style anomaly, may be adaptable and would have the advantage of using empirical observations. When a region is fairly well classified and can be explained by a "loading from the top" elastic plate model or a "loading from below" isostatic model (Watts, 2001, the **gravfft** function in GMT version 6 now has the capability to compute the geopotential anomaly due to the topography or the geopotential response due to the topography and plate flexure (Wessel et al., 2019). It does, however, have some reported bugs.

Finally, we considered areas for the future application and further development of this work, that others might follow. The method we developed was tested in the West Gakkel Ridge (Area 1 in Fig. 5 below). If the results from this region using three dimensional gravity modeling algorithms prove successful, they would demonstrate how bathymetry estimation process might progress geographically/geologically. Based on the data sets we have, two further areas in the Arctic have been identified as additional test scenarios.

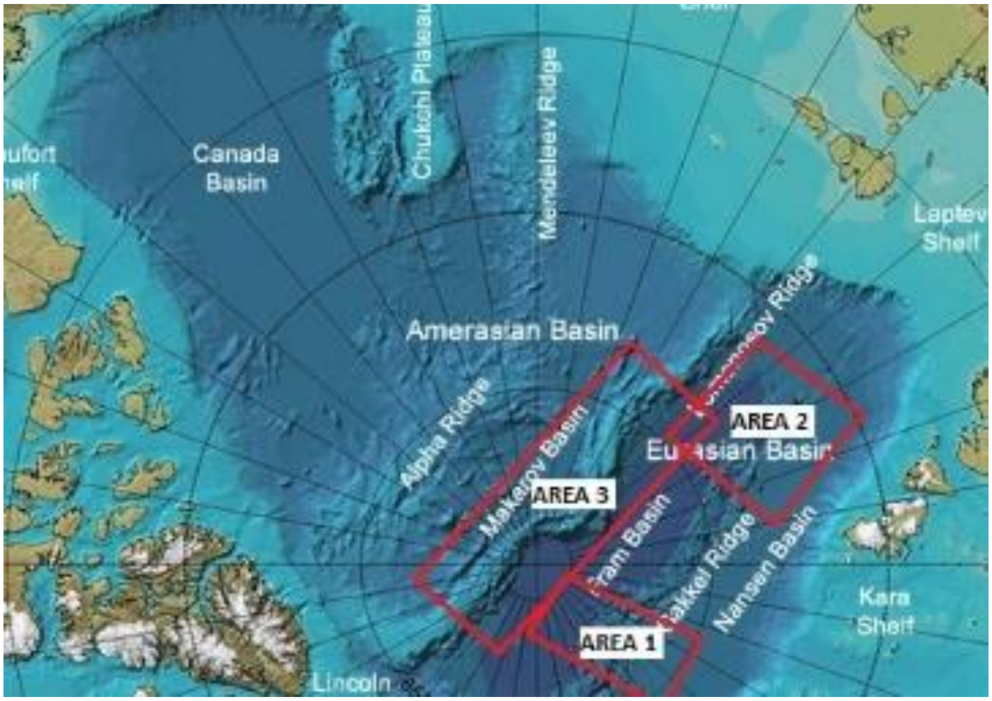

Figure 4 Background image form the International Bathymetric Chart of the Arctic Ocean (IBCOA) from https://www.ngdc.noaa.gov/mgg/bathymetry/arctic/arctic.html

- Test Area 2 - East Gakkel Ridge – Similar geologically to the West Gakkel Ridge, but the sediment thickness increases progressively toward the east until the ridge is completely buried. Less geological/geophysical data are available in this area. The NRL airborne gravity dataset only covers the eastern end of this area and would need to be supplemented for the full area coverage. This area will test the ability to model properly the sediment contribution to the model.
- Test Area 3 – Lomonosov Ridge – A narrow sliver of continental crust with deep basins on either side. Not a lot of geological/geophysical data available. The NRL airborne gravity dataset covers most of this area. Whereas the Gakkel Ridge was oceanic crust with unconsolidated/lightly consolidated sediment, this area has thick layers of consolidated sediment/sedimentary rock over granitic basement that are applicable to the margins of the Arctic Basin.

Finally, it may be possible to extend these methods to areas where satellite altimetry is available, but bathymetric prediction has not been successful due to the presence of sedimentation. Such extension could also have a high operational relevance, e.g. for undersea navigation.

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