Naval Research Laboratory
Washington, DC 20375-5320

NRL/7230/MR—2021/1

Developing Techniques to Determine Arctic Bathymetry from Airborne Gravity and Geophysical Measurements

MARY F. PETERS
RICK A. HAGEN
ANDREI ABELEV

Coastal & Ocean Remote Sensing Branch
Remote Sensing Division

March 26, 2021

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
26-03-2021

2. REPORT TYPE
NRL Memorandum Report

3. DATES COVERED *(From - To)*
01 OCT 2019 – 28 FEB 2021

4. TITLE AND SUBTITLE
Developing Techniques to Determine Arctic Bathymetry from Airborne Gravity and Geophysical Measurements

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Mary F. Peters, Rick A. Hagen, and Andrei Abelev

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
1R26

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Research Laboratory
4555 Overlook Avenue, SW
Washington, DC 20375-5320

8. PERFORMING ORGANIZATION REPORT NUMBER
NRL/7230/MR--2021/1

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Naval Research Laboratory
4555 Overlook Avenue, SW
Washington, DC 20375-5320

10. SPONSOR / MONITOR'S ACRONYM(S)

11. SPONSOR / MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. 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. An iterative forward modeling technique to modify initial admittance function based estimates of bathymetry from airborne gravity measurements to incorporate a sediment layer is under development.

15. SUBJECT TERMS
Arctic; Bathymetry; Bathymetric Prediction; Airborne Gravity; Gravity Modeling

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	U	21	Mary F. Peters

19b. TELEPHONE NUMBER *(include area code)*
(202) 404-1112

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

This page intentionally left blank.

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. An iterative forward modeling technique to modify initial admittance function based estimates of bathymetry from airborne gravity measurements to incorporate a sediment layer is under development.

Introduction

The Arctic is a critical region of the world that lacks the accurate bathymetry required for a number of purposes that include definition of the continental margin extent for economic reasons, as well as navigational safety for commercial vessels and, most importantly, US Navy submarines. The Arctic bathymetry map currently available (Figure 1) was assembled from a variety of disparate sources; its accuracy is highly variable and spatial coverage is sparse and uneven (Figure 2). While some areas of the Arctic Ocean have seen somewhat higher density of surveys, especially near the US Alaskan coast, much of it remains underexplored. A more accurate and reliable Arctic bathymetry map is critically important.

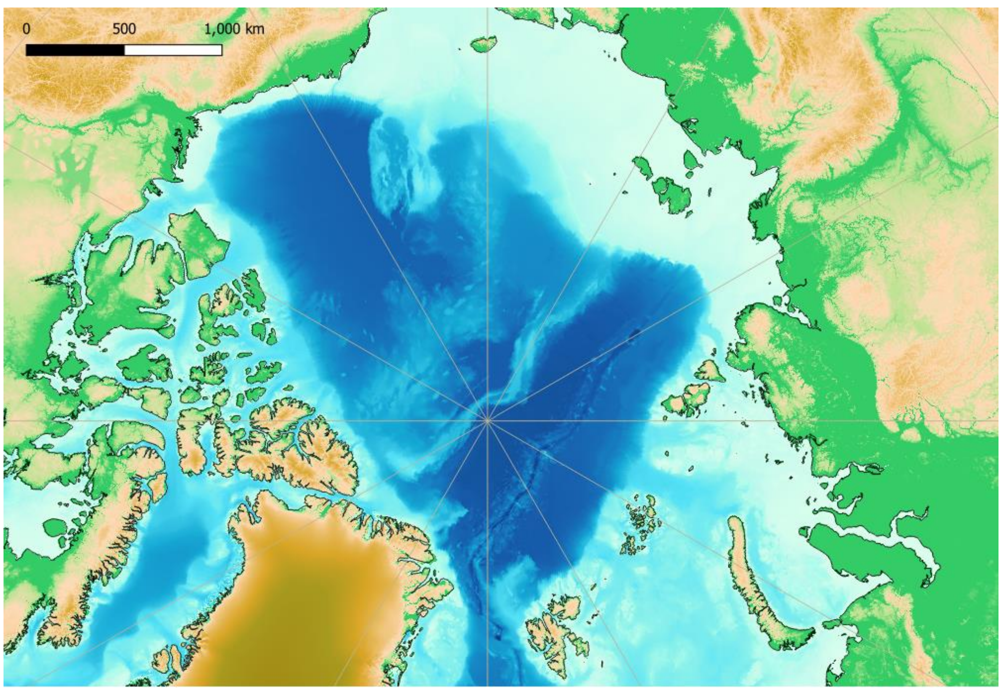

Figure 1 GEBCO (General Bathymetric Chart of the Ocean), of IHO (International Hydrographic Organization) latest 2020 gridded bathymetry

Manuscript approved March 25, 2021.

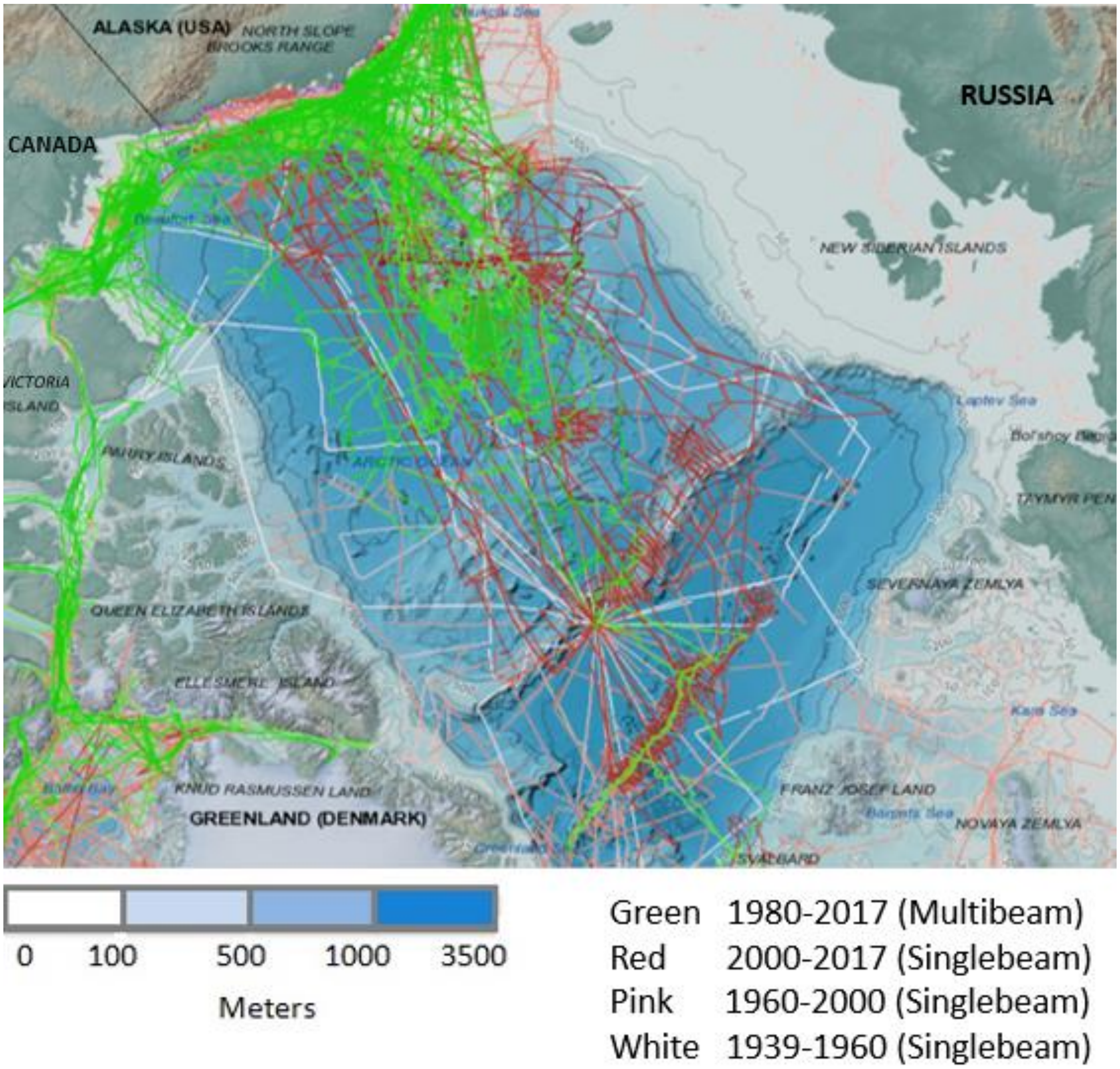

Figure 2 Existing Bathymetric Data Collected from Ships and Submarines from 1939-2017

Seafloor mapping is presently done in one of two ways: via ship using multi-beam acoustic mapping or using satellite altimetry. Multi-beam mapping provides depth information with meter-level depth accuracy at a 5-10 m spacing over 5-10 km swathes (in deep water) but is time-consuming and expensive, and more so in the Arctic where an icebreaker is required. Worldwide, only about 5% of the ocean floor has been mapped this way due to cost. In contrast, approximately 90% of the ice-free world's oceans have been mapped using derived bathymetry obtained from satellite altimetry (Smith and Sandwell, 1997). In this technique water, depth is derived from undulations of the sea-surface as the water conforms to gravity's potential. It can detect bathymetric features with relief in the 100's of meters range and kilometer scale spatial resolution. This technique does not work in ice-covered oceans because, unlike open water, the ice surface does not follow the equipotential geoid. Since these two widely used bathymetric mapping methods are either inappropriate or infeasible, we must adopt a different approach for mapping the ice-covered Arctic Ocean.

Bathymetric variations in the ocean bottom cause anomalies in the gravity field. These anomalies can be measured by ship or aircraft, e.g. Figure 3,where a profile of shipborne gravity measurements is compared with that of the crust, measured using seismic profiling, and bathymetry, from traditional acoustic measurements (Jung and Vogt, 1992).

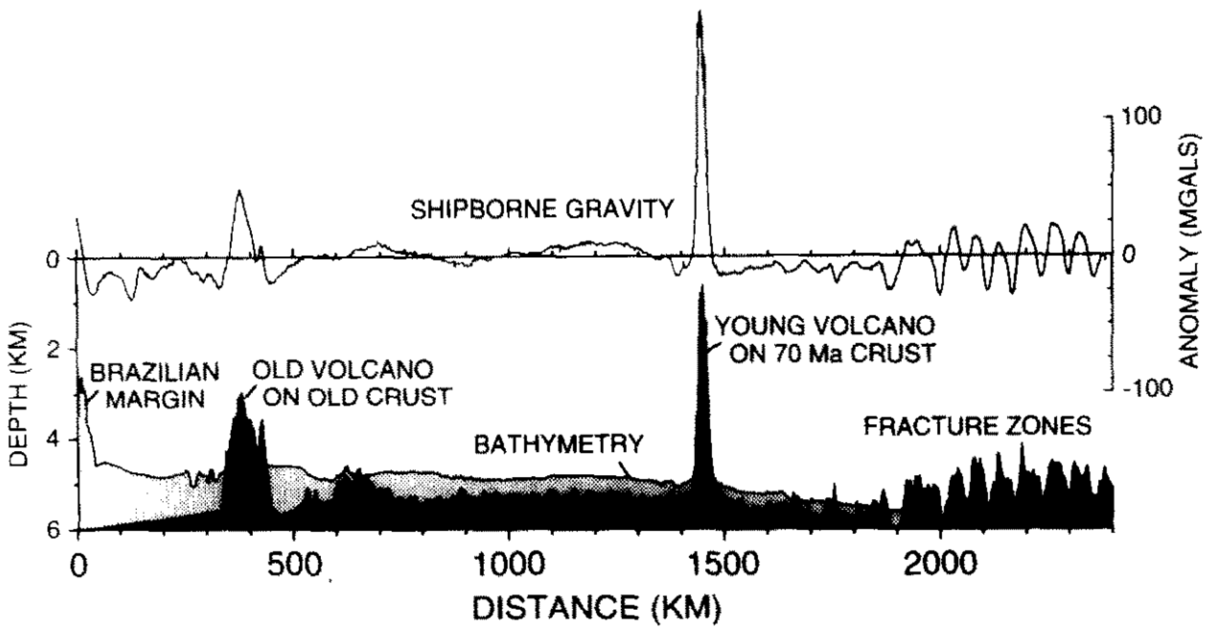

Figure 3 Illustration of vertical, shipborne gravity, bathymetry and seismic profiles (Brazil Basin, (Jung and Vogt, 1992). Black color indicated depth to crust from seismic data, grey – bathymetry based on acoustic measurements,

In ice-covered areas like the Arctic, airborne gravity measurement is faster and more economical than shipboard measurements. The gravity field can and has been measured from aircraft over wide, but not complete, portions of the Arctic: NRL collected over 200,000 km of airborne gravity track data, between 1992 and 1999 as part of NGA's Arctic Gravity Project (Figure 4). This data set covers almost half of the Arctic Ocean and includes magnetometer measurements. By solving the inverse problem, airborne gravity data can be used to determine bathymetry, even in ice-covered areas, because mass changes in sea floor hills or valleys affect the total gravity signal. Our goal is 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. This work aims to establish a fundamental basis for more comprehensive bathymetric charts that could be used to construct risk maps for Navy submarine navigation and to prioritize regions where more detailed bathymetry from high-resolution multi-beam surveys is needed.

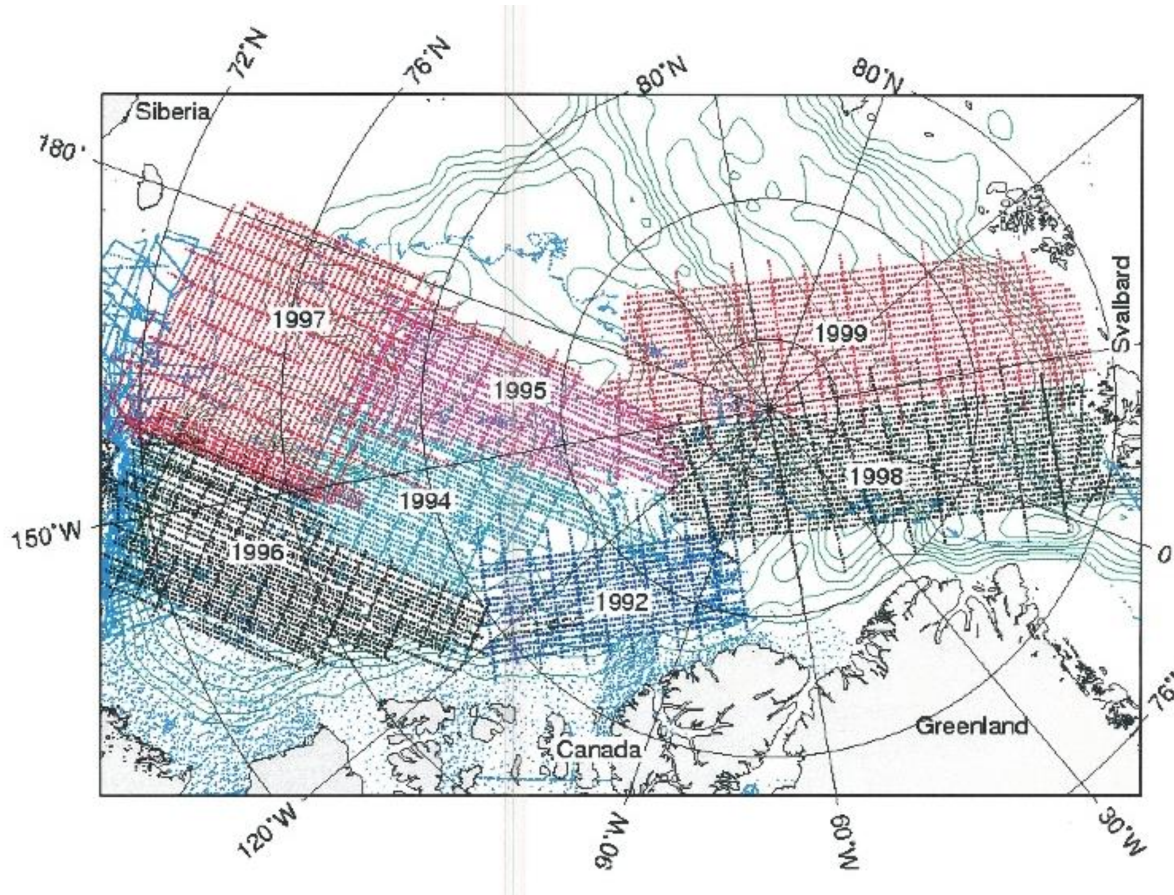

Figure 4 Airborne gravity track data, collected by NRL between 1992 and 1999 as part of NGA's Arctic Gravity Project (Brozena et al, 1997)

Approach

Bathymetric relief is only one possible varying factor that can cause gravity anomalies. A key challenge is to account for other geophysical factors that contribute to the measured gravity anomaly through changes in the crust, mantle and sediments. Conceptually, this can be expressed as in Eq. (1), where Δg is the total change in the gravity field, Δg_{water} – is a component due to water (bathymetry), $\Delta g_{sediment}$ – is that due to sediment (above crustal structure), and Δg_{crust} is that due to crust itself. All of these components are functions of thickness and thickness variation and density variations.

$$\Delta g \sim \Delta g_{water}(\Delta\rho, \Delta z, z) + \Delta g_{sediment}(\Delta\rho, \Delta z, z) + \Delta g_{crust}(\Delta\rho, \Delta z, z) \quad (1)$$

In this study, we employ an iterative approach using a hybrid of forward gravity modeling and admittance (transfer) function techniques in order to solve the inverse problem of determining bathymetry from gravity measurements. In general, admittance is defined as a set of functions that can scale the topography (or bathymetry) to gravity anomaly, as a function of wavenumber (or wavelength of the topographic load). The most general definition is given in Eq. (*2*):

$$Z(k) = \Delta g(k)/H(k) \quad (2)$$

where $Z(k)$ is the admittance function (of wavenumber k) and $H(k)$ is the height or bathymetry, calculated in the Fourier domain.

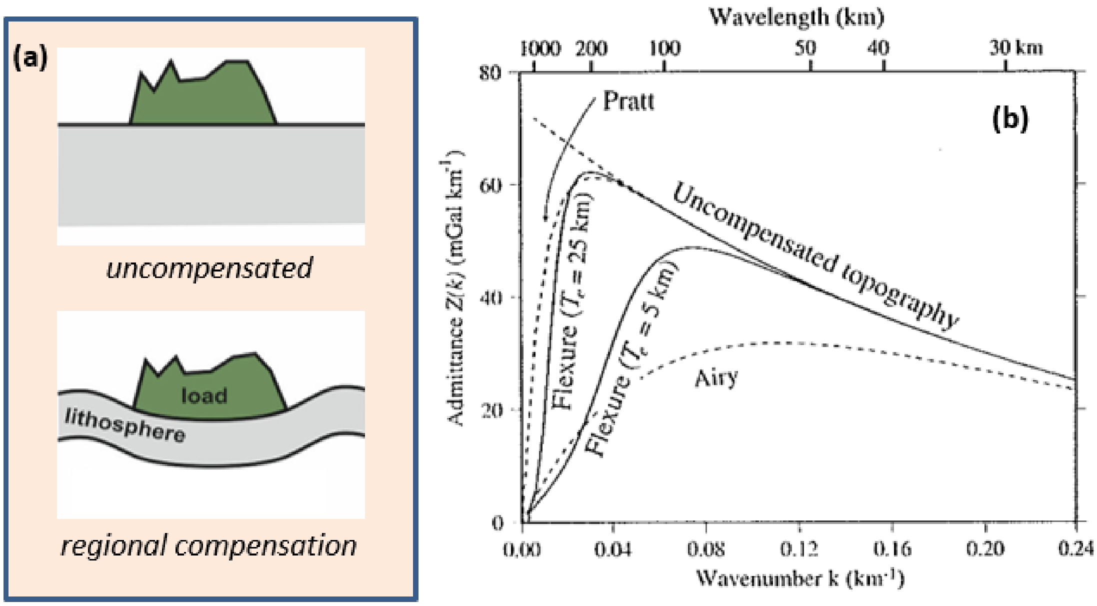

Figure 5 Schematic representation of the flexure of the lithosphere (a) and the gravitational admittance functions assuming uncompensated model, Airy model, Pratt model and flexure model (b), from (Watts, 2001)

While several models are shown in Figure 5, the current state-of-the-art in gravity processing, yielding the most accurate results for topography or bathymetry estimation would rely on the Flexure model ((Watts, 2001)), with the properly selected elastic parameters. Although deeper crustal variations do affect the gravity anomaly, we believe a simpler forward model consisting of water, sediments and the top portion of the crust can be employed if adjustments are made to account for those gravity effects. We aim to construct a set of admittance functions relating the bathymetry to the gravity anomaly to estimate the shape of the bathymetry in the initial forward model and we adjust the gravity anomaly to be matched in the forward model using generalizations of the admittance function to compensate for deeper crust and mantle contributions. The forward model will be iteratively modified until the modeled gravity anomaly matches the adjusted gravity, with the constraint that densities and depths will not be allowed to vary outside the range of the geological knowledge. The final bathymetry estimate will be the depth of the water layer in the last iteration of the forward model. These admittance functions and gravity adjustments can be determined with co-located bathymetry and gravity measurements. An initial task includes identifying locations where both - the NRL's gravity data and the existing bathymetry measurements - are co-located, and then using existing Arctic-wide geophysical and lithological data to evaluate and select regions to investigate with the highest quality bathymetry data. We use some of these data to construct initial admittance functions while the rest will be used later to evaluate the bathymetry calculated using our hybrid admittance and iterative forward modeling approach at other locations.

The calculated admittance functions and adjustments include contributions from sources other than bathymetry, so they are only applicable in regions with the similar underlying geology and geophysical profiles. We expect that they will be valid across sufficiently similar geologic/geophysical regions. However, the geologic and geophysical parameters involved are highly variable across the Arctic so another challenge is to identify the appropriate regions so that these tailored approaches can be applied to each one. The Arctic includes a variety of geologic and geophysical provinces including ridges, basins, and continental margins, with a few select primary features shown in Figure 6. Major geophysical features can be identified from existing maps, but it will require analysis of additional sources such as geologic reports, published literature and data held by NRL, to determine their full spatial extent. We have considerable auxiliary information from which to characterize geologic regions including NRL's magnetic measurements coincident with the airborne gravity data; the existing bathymetric data; and geologic and geophysical (i.e., seismic) data from other sources. The airborne magnetic data can be useful in constraining the age of the crust, which, in turn, helps define the elastic thickness parameters (T_e) in the local admittance function construction (see Figure 5).

Once a geologic region has been defined, the initial admittance function determined at a location with known bathymetry can be applied to gravity measurements elsewhere in the region, yielding bathymetric anomalies. These anomalies will then be used to initialize the water/ocean floor interface in the density model. The thickness of the water layer will be solved for by iterative forward calculation of a gravity anomaly, comparison to the regionally adjusted gravity anomaly, and adjustment for the water thickness/depth. The accuracy of the final bathymetry prediction process will be tested against established ground truth bathymetric data at locations with existing measures of bathymetry from other sources. We expect that all steps in this approach will require iteration - initial distinctions between geologic regions or estimates of depth to the crust/mantle boundary may have to be adjusted.

While this approach would allow us to derive the bathymetry in areas of the Arctic Ocean where we have airborne gravity data, the NRL airborne gravity surveys were designed only to recover accurately the longer wavelength portion of the gravity field over large regions. Furthermore, the art of airborne gravity measurement has advanced in the last 20 years. Therefore, the goal is not to produce a bathymetry map from the existing NRL gravity data, but to develop and validate the techniques to produce such maps in the future, using the latest advances in airborne and space-borne gravity measurements. The initial priority is the identification of one well-defined geological regions, within the limits of NRL's airborne gravity surveys, with a comprehensive set of publicly available high-quality bathymetry and seismic and core data if possible for regional density information. The goal is to implement and execute our planned hybrid method to estimate bathymetry from gravity in this one region, then to evaluate the result in comparison to existing bathymetry. This would quantify the accuracy of the resulting bathymetry estimates, and provide an estimate how much this improves bathymetry knowledge in sparse areas.

There are three major task areas in development and validation of the proposed technique. The first is to select a suitable study area in the Arctic. Second, is to identify the basic tools to resample, grid and calculate the gravimetric contribution from bathymetry and sediment layers. Lastly, the most important component includes the construction of the initial form of the Admittance Functions and tools for estimating bathymetry. The following sections describe these components.

Geographic Area of interest - selection

The shelf area adjacent to the North Slope of Alaska was first investigated as a possible study region – due to the abundant availability of multi-beam bathymetric survey data in the area - but two flaws were identified: 1) the majority of the high quality bathymetry data was closer to the shore than the extent of the gravity survey data, providing for insufficient data set overlap for our analysis and 2) the sediment depths in this region were high, unnecessarily introducing the added complexity for the admittance function development at this early stage in the project. Much of the Arctic includes areas with geologically young crust, and as such, it tends to have less sediment. We next considered including the Lomonosov Ridge to our analysis domain (see Figure 6). Upon further investigation of the available geologic data, however, we decided to focus instead on the mid-oceanic Gakkel Ridge, which is an active, albeit slow, divergent tectonic plate boundary between the North American Plate and Eurasian Plate in the Eurasian basin of the Arctic Ocean. It is relatively free of complicating fracture zones and the sediment thickness is low, presenting an advantage for our approach at this early stage. For our ground truth comparison data set, in addition to submarine multi-beam bathymetry data, we were able to find additional submarine-measured gravity data in this region, originating from SCICEX96, 98 and 99 - SCience ICe EXercise - conducted between 1993 and 1999 (Edwards and Coakley, 2004), which we have now acquired. We initially planned to include the gravity data set, also acquired during the SCICEX program, in addition to our air-borne gravity set. While not ideal, because it is much closer to the source than airborne altitudes (~1km), it nonetheless promised to augment our existing data after appropriate frequency filtering to compensate for this difference in distance/altitude. While analyzing this data set, we discovered, however, that the submarine inertial navigation was not corrected for ridge gravity anomalies and is very inaccurate. We have realized that the correction of this data set would be a substantial effort, beyond what was originally planned at this stage of the program. We have therefore decided not to include these data in our analysis at this stage. The Gakkel Ridge navigation positions in the multi-beam data, which were also acquired during SCICEX and provided by the University of Hawaii to the International Bathymetric Chart of the Arctic Ocean (IBCAO), were, on the other hand, properly corrected by IBCAO before inclusion in the 30-arc second grid. We have now obtained this corrected data set from NOAA (https://www.ngdc.noaa.gov/mgg/bathymetry/arctic/arctic.html) (Jakobsson et al., 2012). Additionally, an updated and extended global sediment gridded data set (GlobSed, a 5-arc-minute total sediment thickness grid for the world's oceans and marginal seas was also acquired (Straume et al., 2019).

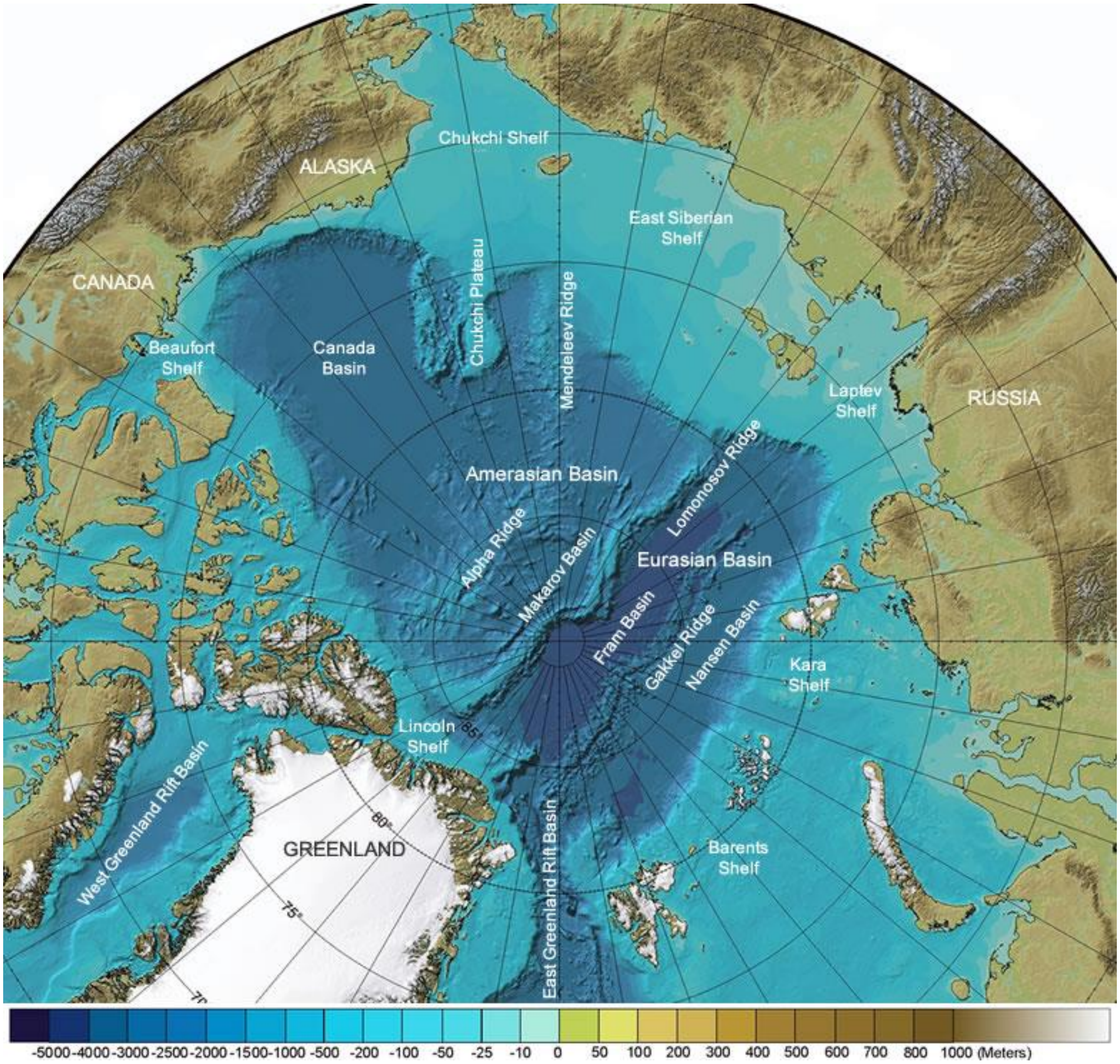

Figure 6 Bathymetry of the Arctic Basin, showing the location of the Gakkel Ridge, which was selected as the initial study area (King, 2021)

Consequently, we now believe that we have compiled a multi-sourced and rich set of geologic and sedimentary information, allowing us to proceed with our planned analysis, with additional gravity data potentially added at a later stage. We have also collected select bathymetric datasets of the Arctic Ocean, allowing us to perform ground-truth comparison and error analysis for our evolving algorithms.

Software – selection and development

The capabilities that we identified as necessary for the project were (1) general mapping and spatial data interpolation, (2) admittance/power-spectrum estimation, (3) forward gravity modeling, and (4) general computation. Candidate software packages were evaluated and acquired. For general mapping and spatial data interpolation, we chose GMT (Generic Mapping Tools, https://www.generic-mapping-tools.org/) (Wessel et al., 2019). GMT is open-source and lends itself well to scripting and batch processing on the Linux sever that hosts the gravity data set. For admittance/power-spectrum estimation, our scripts also utilize tools in GMT. For the iterative gravity modeling along tracks, we picked FastGrav (http://fastgrav.com/), a package for 2-D gravity modeling. We also need to have 3-D gravity modeling capability to compute and remove sediment layer effects from free-air gravity anomalies (for a description of and comparison of methods, see (Wu, 2018)). From version 5 onward, GMT has implemented Parker's 2-D FFT method (Parker, 1973) for gravity estimation and this was chosen over computation via prisms due to speed and the need of GMT for equal area transformation from geographic coordinates to a projected rectilinear grid. For general computation, we chose MATLAB and the Python language with Numpy library for scientific computing in Python. The numerical code developed in our group for estimation of free-air gravity anomalies from topography (Jung et al., 2013)uses geophysical parameters inferred from the admittance between measured tracks of gravity anomalies and mountain topography to shape gravimetric potentials in the spatial domain calculated by Parker's 2-D FFT method. It cannot be directly switched to estimate bathymetric topography profiles from gravity anomalies via transformation from the spectral domain. We are now developing code to work directly with the admittance functions from the gravity and topography profiles to estimate topography profiles from the gravity anomalies using MATLAB and Python.

Regional admittance calculation, lithospheric response classification and bathymetry estimation

Admittance functions construction is the next stage in our planned project execution. We have sampled bathymetry tracks from the 5-minute grids, coincident with the airborne tracks for the Arctic 1998 and 1999 surveys. These two surveys covered portions of the Gakkel Ridge that we selected as our primary study area, as described above (Figure 7). Our initial analysis indicates that cross spectrum admittance functions along the tracks may be crossing too many varied geologic/structural regions to discern a clear pattern at present. Simply restricting admittance function analysis to limited sections of these tracks is also not ideal because of the relative orientation of the ridge: the tracks are not in line with crust creation and spreading from the ridge. To overcome this difficulty, we have generated some synthetic tracks – not actual survey tracks flown but with values re-sampled at chosen locations from a grid of values generated from the survey. These tracks are parallel and perpendicular to the ridge to see if those give more consistent admittance functions (see Figure 8). The region for the synthetic tracks has been chosen over the Gakkel Ridge from 0 to 17 deg. East in longitude, because it is geologically homogeneous (Cochran et al., 2003) with extension to get profiles long enough to contain wavelength information out to 100 km. The generated profiles have 1km sampling. This is oversampled with respect to the sediment grid, which has no content shorter than 18km and the

NRL Arctic airborne gravity, which was filtered during its original survey processing to remove wavelengths starting at about 15 km (Childers et al., 1999). This spacing, however, is consistent with state-of-the-art airborne gravity surveying and wavelength resolution capabilities (NOAA GRAV-D manual (Damiani et al., 2011) and to the IBCAO bathymetry grid which is about 900m spacing. The central along-ridge profile and cross-ridge profile are shown in Figure 7below along with the IBCAO bathymetry: the generated profiles are all great circle arcs for spectral and admittance calculations.

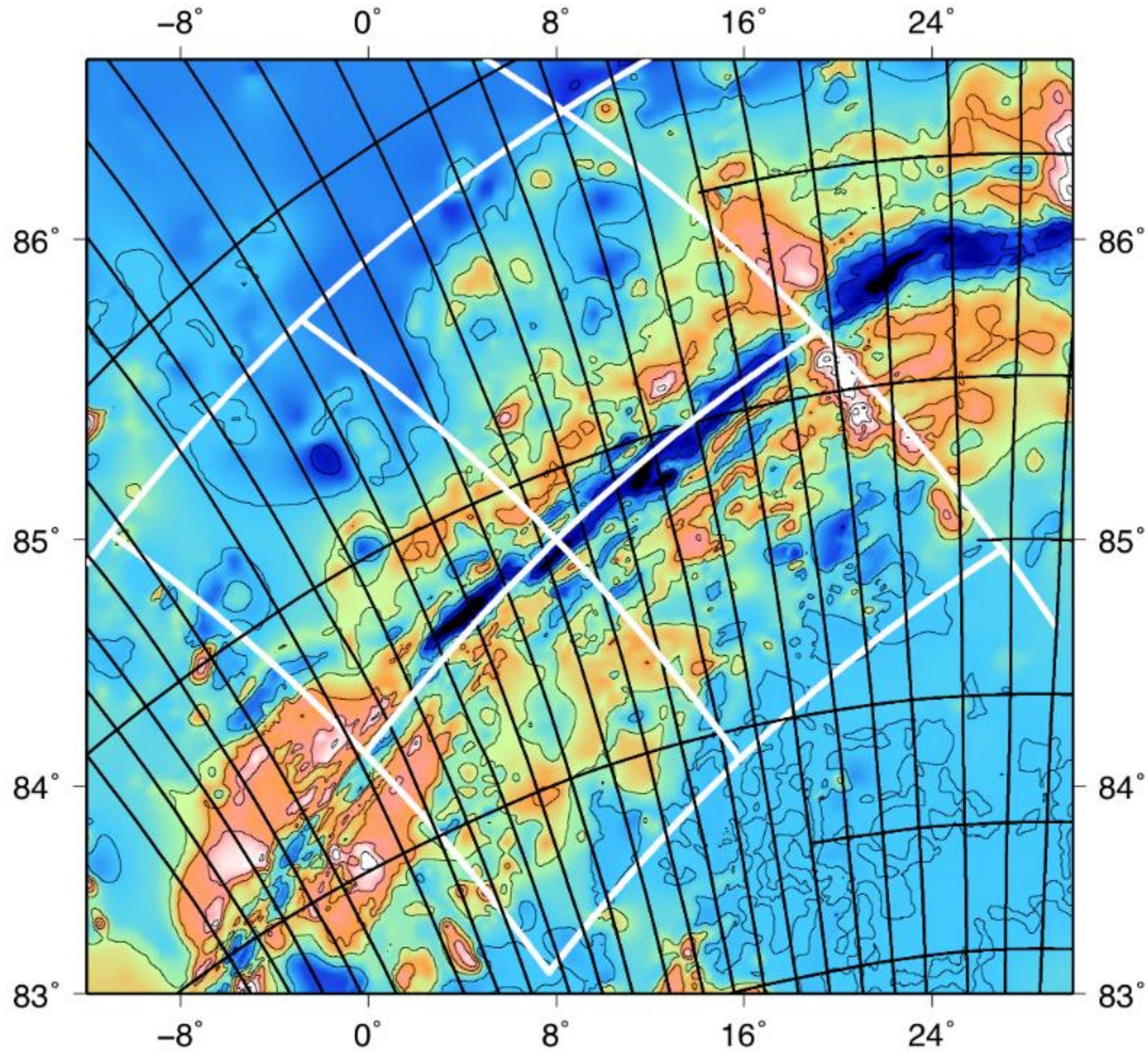

Figure 7 Airborne tracks for the Arctic 1998 and 1999 surveys over the Gakkel Ridge (black lines). Sample parallel and perpendicular synthetic tracks over the Gakkel Ridge (white lines).

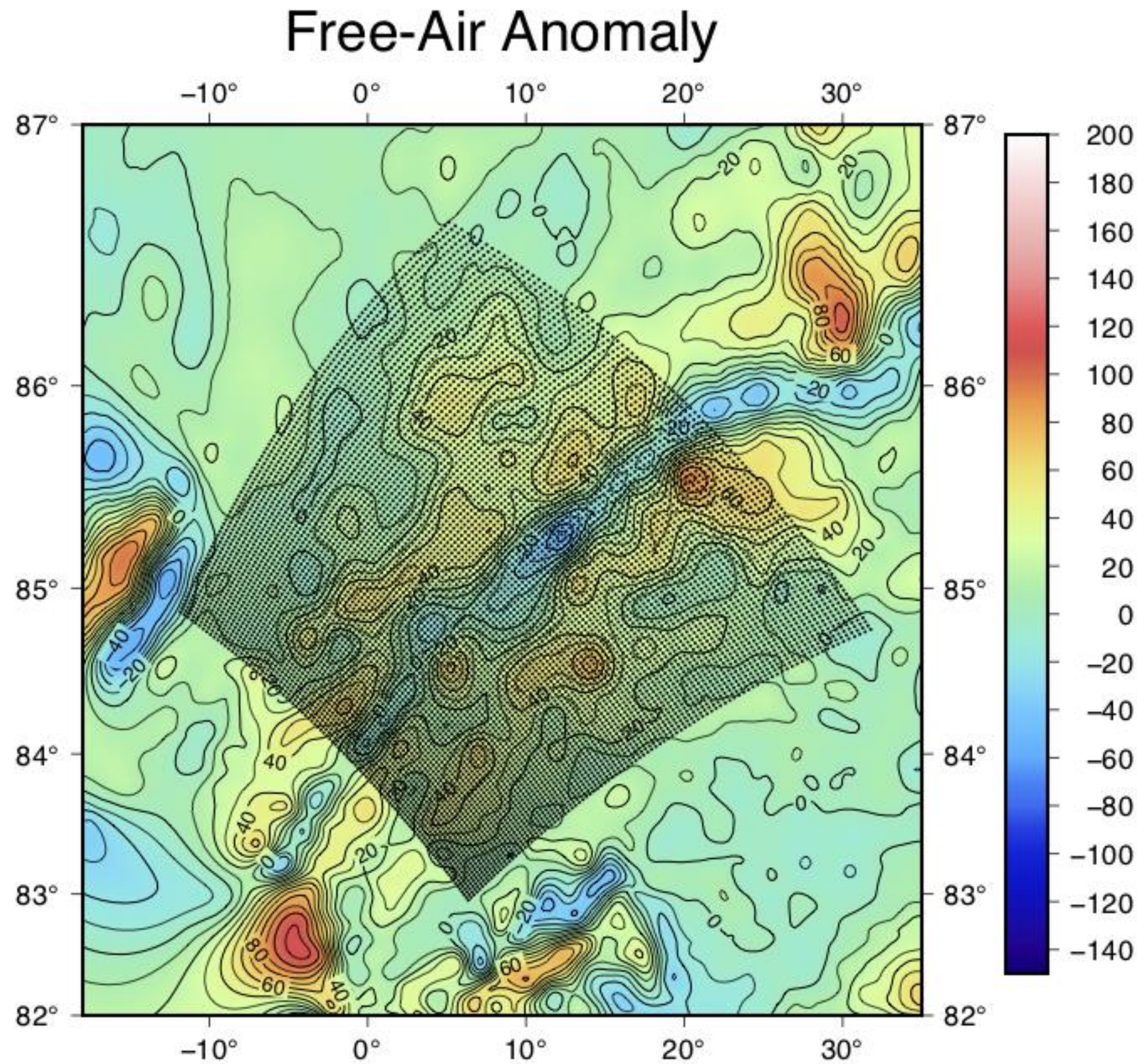

Figure 8 Free-air gravity anomalies around the Gakkel Ridge. The black dotted lines show the synthetic tracks generated and analyzed parallel and perpendicular to the ridge. The map is a Mercator projection and the tracks are great circle segments and so appear curved

The proposed method to improve bathymetry estimation in sedimented areas requires the construction of a modified admittance function between the bathymetry and a gravity anomaly that would be measured if there were no sediments present. This requires the calculation of the contribution to the gravity anomaly due to the sediments. Although airborne gravity measurements are done along linear profiles, off-track sediments also contribute to gravity. There are gravity modeling algorithms that work along profiles by making assumptions about off-track mass distributions, but given the existence of global sediment models, it seems reasonable to use a regional two-dimensional method using gravity measurements from multiple tracks. In this way, suitable gravity models calculated using the bathymetry (sea water/sea bottom interface) and the sediment bottom interfaces can be combined to produce two-dimensional grids of the modified anomaly. Any method to calculate gravity from topography/bathymetric relief specified in geographic coordinates requires transformation into a system with fixed distances. We chose to estimate gravity effects of the sediment with GMT routines since GMT was used to transform the geographic coordinates and it now implements Parker's 2-D FFT gravity modeling method. Based on densities published and used in the Eurasian Basin (Chapter 3, *Geologic Structures of the Arctic Basin* (Piskarev et al., 2018)), the densities used for the Bouger corrections (due to layer thicknesses and densities) were chosen as follows: 1.03 g/cc water, 2.0 g/cc sediment and 2.7 g/cc upper crust. Figure 9 shows the modified Bouger-style anomaly created by removing the gravity contributions of the water and sediment layers from the free-air gravity anomalies. The modified admittance functions can be calculated along profiles sampled from the modified anomaly grids. Figure 10 shows profiles sampled from the Bouger anomaly, free-air anomaly, sediment thickness and bathymetry depth grids along the central perpendicular synthetic track. Spectral estimation/admittance calculations have been completed for all the synthetic tracks. Figure 11 shows the admittance functions between the bathymetry and free-air anomalies and bathymetry and Bouger anomalies, for the parallel and perpendicular tracks within 10 km of the central tracks. However, differences in the responses between perpendicular and parallel tracks as well as differences between like-oriented tracks at differing distances from the center of the AOI are hindering identification of a suitable regional admittance function. Work to understand the geophysics and cause of the variance are ongoing.

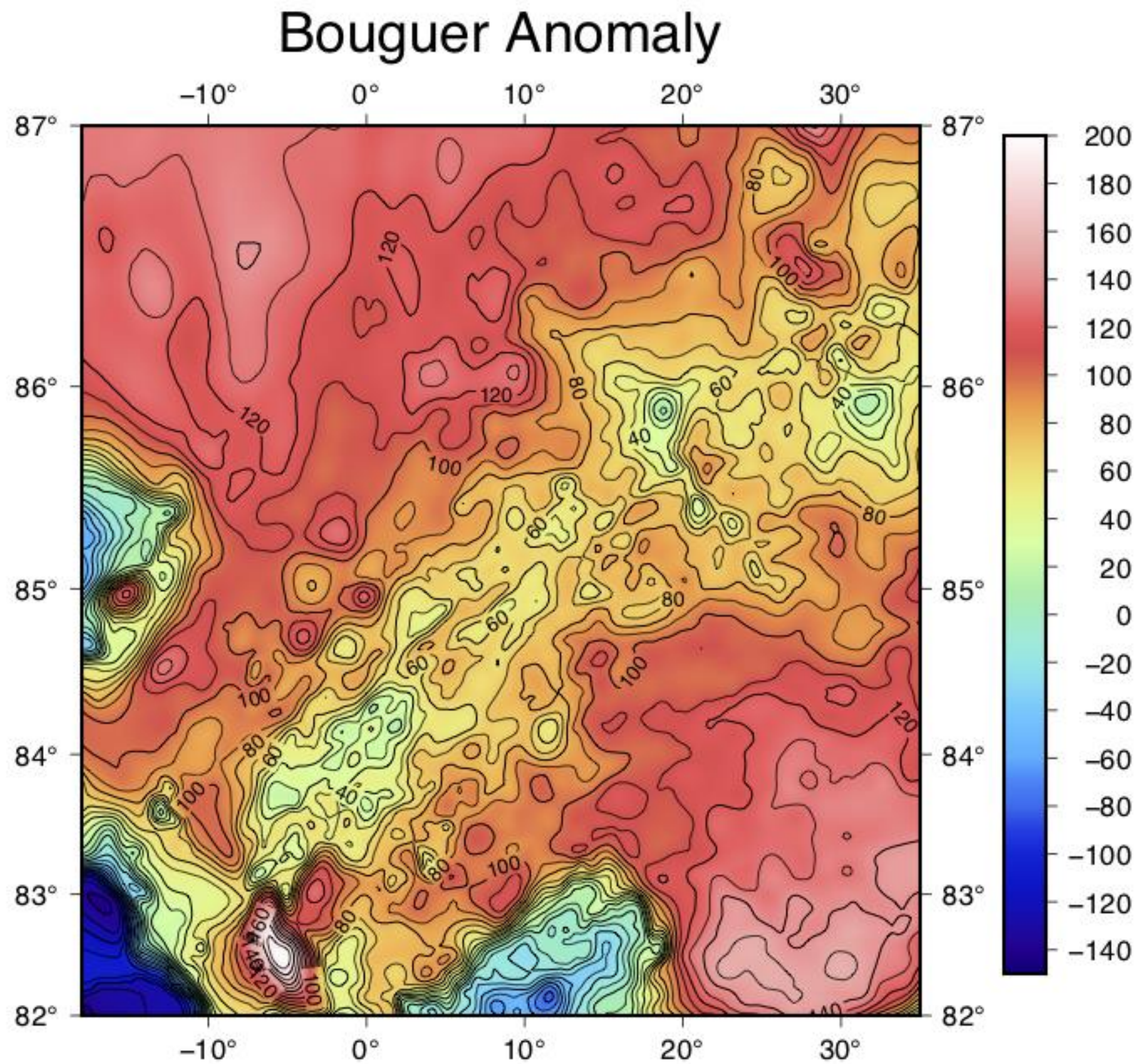

Figure 9 The modified Bouger-style anomaly (scale is in mGal) is created by removing the gravity contributions of the water and sediment layers from the free-air gravity anomalies. It is shown here with the same color scale as the Free-air anomaly map in Figure 8. A reduced overall range of values can be noted, after removing contributions of the sediment, indicating deeper crustal effects on the regional gravity field

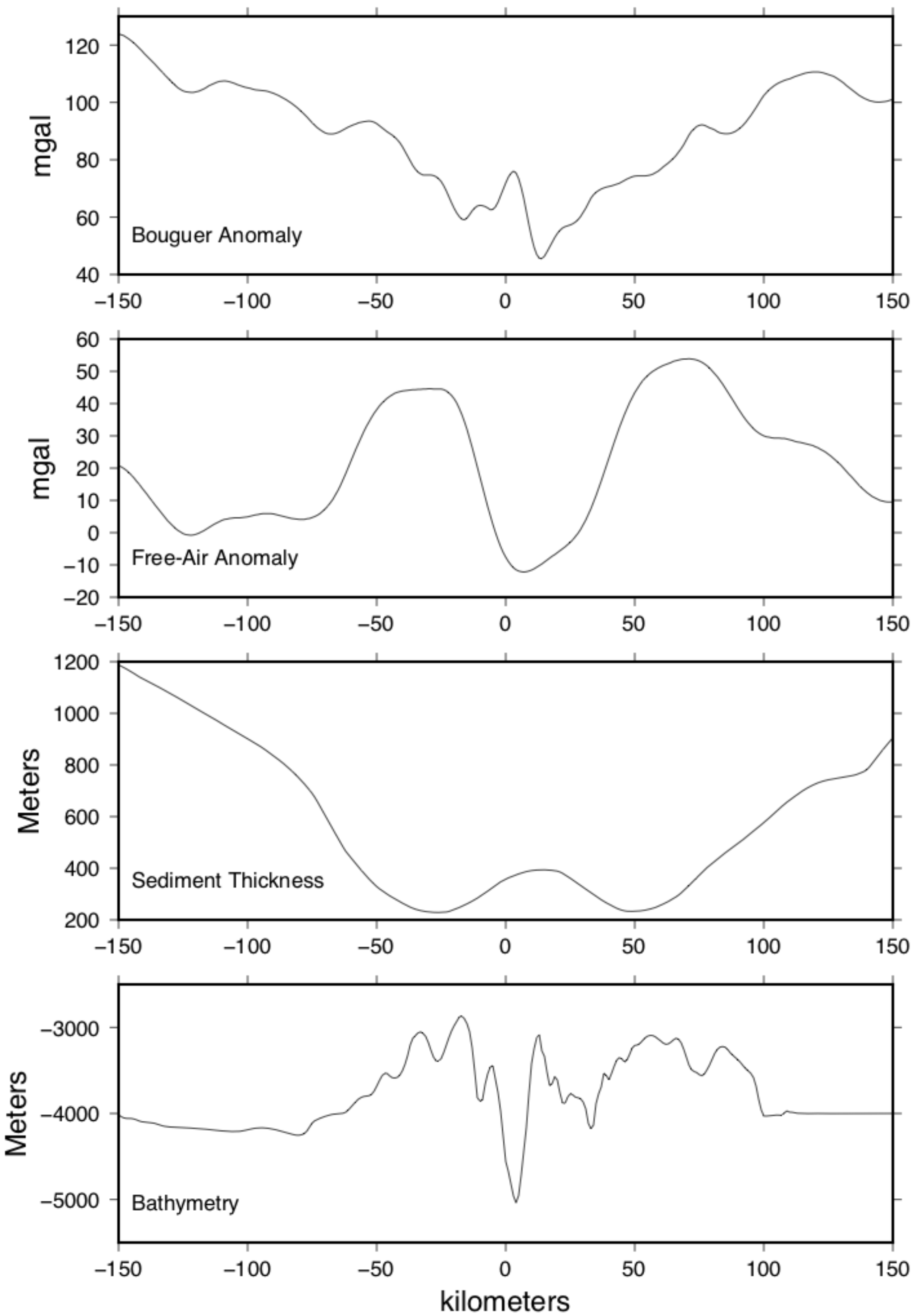

Figure 10 Profiles along the central track perpendicular to the Gakkel Ridge, sampled from the Bouger, free-air, sediment and bathymetry grids

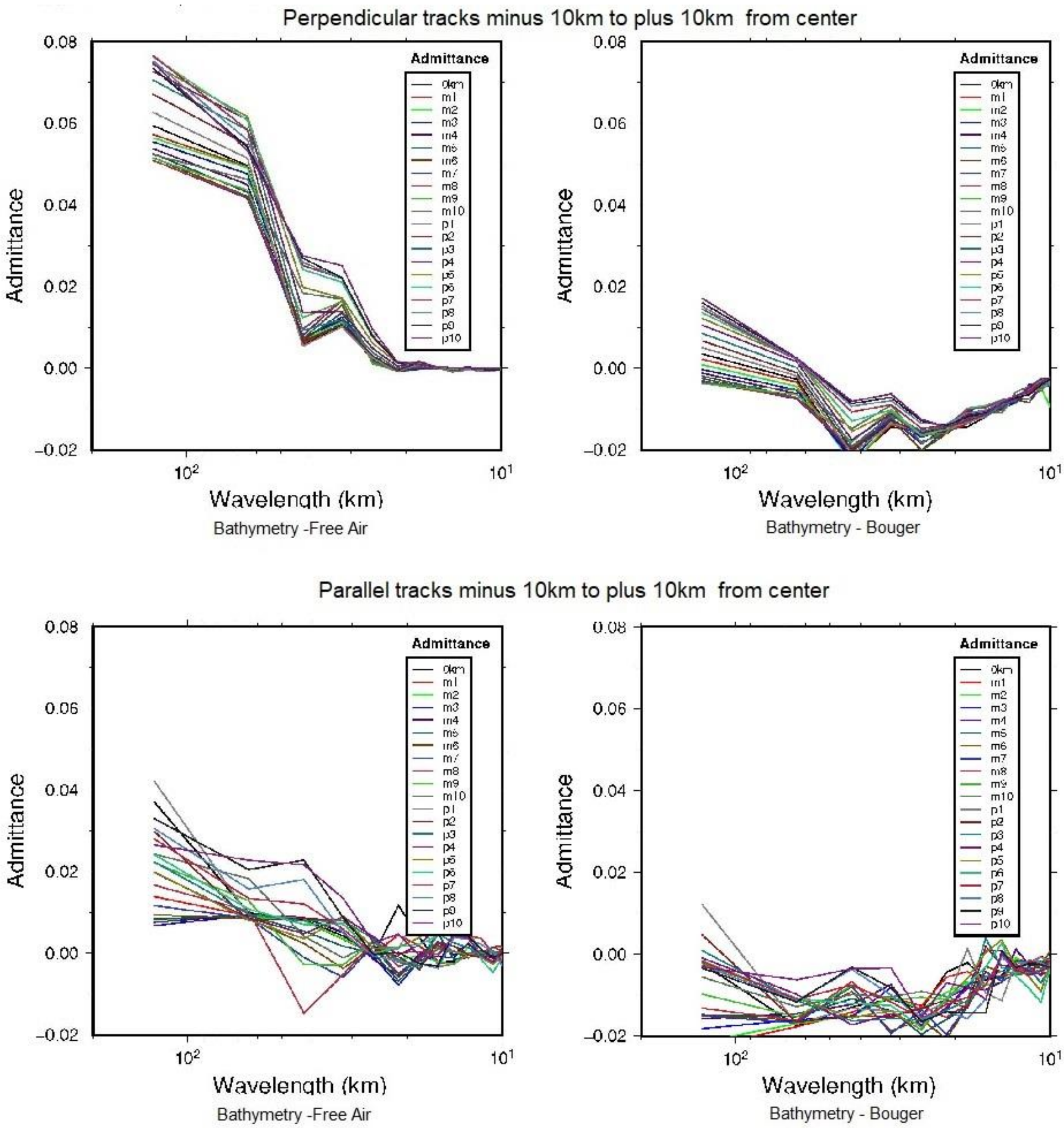

Figure 11 Admittance functions for tracks within 10 km of the central tracks, parallel and perpendicular to the ridge. The admittance functions were calculated using both free-air and modified Bouger gravity anomalies. Tracks are labeled m10 (for 10 km South-West) to p10 (for 10km North-East) of the center tracks (0k)

Estimation of the bathymetry along these tracks via iterative modeling and evaluation are ongoing. The iterative forward model to estimate bathymetry requires an initial water/ocean bottom interface estimated from the gravity anomaly and the admittance functions. The admittance functions are calculated in the Fourier domain, and serve as transfer functions from the gravity anomaly to the initial bathymetry. They must then be returned to the spatial domain (via an inverse FFT) before iterative forward gravity modeling can be used to refine the bathymetry profiles by incorporating sediments. The finite extent of the profiles limits the frequency content of the spectra, so the corresponding bathymetry estimates from them also lacks long-wavelength content. Figure 12 shows the limitations of the data, both missing information longer than 128 km wavelength and the effects of the airborne gravity processing filters on the free-air anomaly for wavelengths shorter than 20 km.

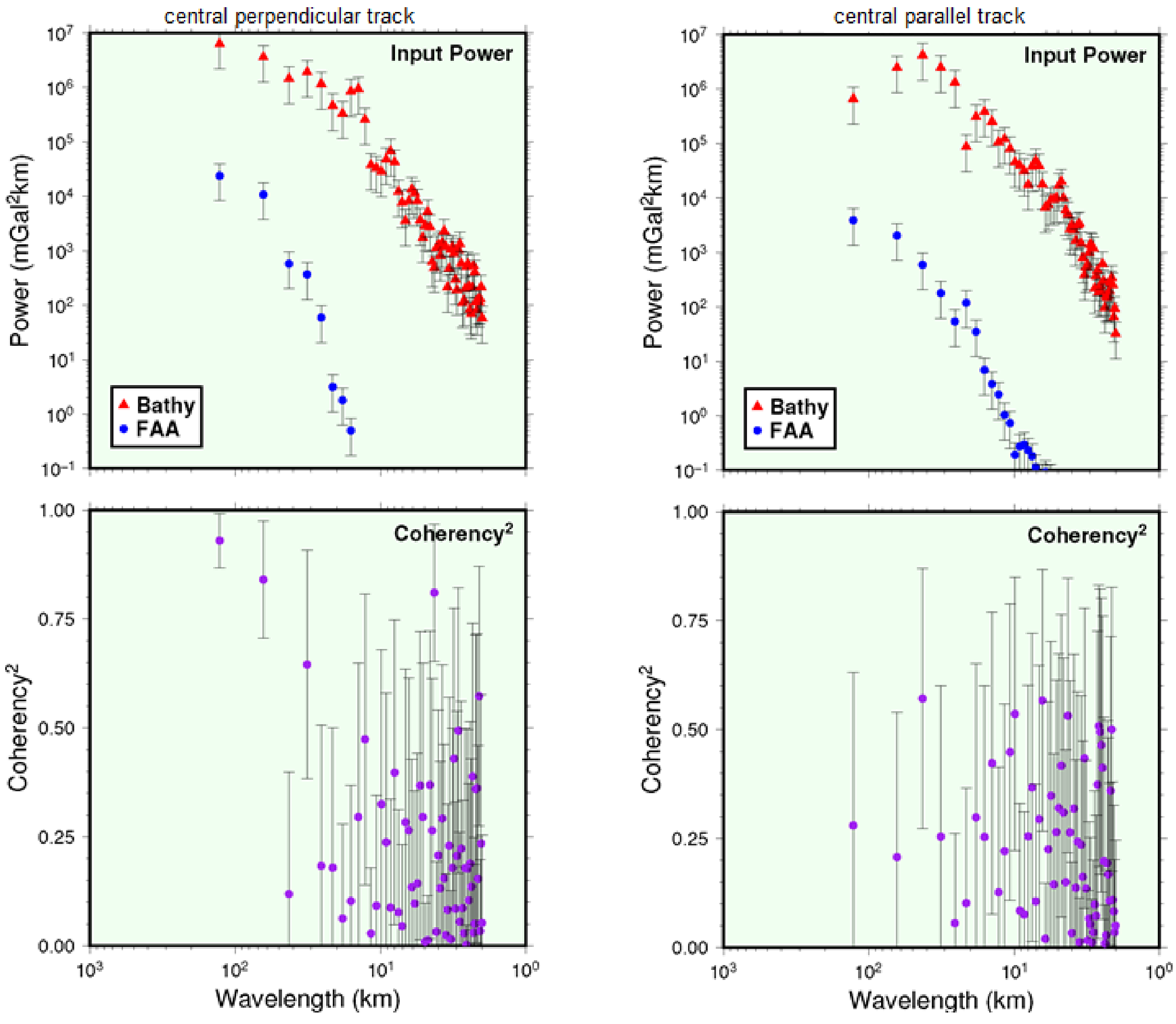

Figure 12 Power spectra from the central perpendicular and parallel tracks show limitations of the bathymetry (red) and gravity (blue) data (from FAA – Free-air anomaly)

Conclusions

The tools to calculate an adjusted gravity anomaly based on bathymetric depths and a global sediment model sediment have been completed and applied to the Gakkel Ridge area of interest. Admittance functions have been calculated. We are in the process of defining and applying a regional admittance function to provide a starting estimate of bathymetry from the free-air anomaly, which will be iteratively refined to fit the gravity anomaly adjusted to leave only the water, sediment and upper crust effects. The densities used will be the same as used in the forward gravity model (2-D Parker FFT) to calculate the Bouger anomaly. This estimate will not contain bathymetry wavelengths longer than half of the analyzed track lengths. The problem of restoring the long wavelength components is very complex. In order to simplify the problem and provide for a bounded estimate of how good the bathymetry solution can be, we will calculate statistics versus the ground-truth bathymetry after a linear best fit.

The authors believe that the currently observed data limitations, together with the natural complexity of the current area of interest, can be mitigated using the suggested approach. Inclusion of additional data sets, as noted earlier can improve the accuracy of the admittance functions, as can greater insights about the local crustal structure. Furthermore, additional areas of interest can be explored where these complexities may be lower, and present a better test case scenario for evaluation of the general approach to bathymetry calculation in these ice-covered areas of the Arctic. We continue to believe in the general validity of our approach (however complex it may be) as well as its potential applicability to other areas in the world, where high-resolution bathymetry can possibly be produced with satellite gravity, despite sediment cover, without the need of traditionally slow and expensive ship-borne surveys.

References

Brozena, J. M., Peters, M. F. and Salman, R., 1997, ‘Arctic Airborne Gravity Measurement Program’, in Segawa, J., Fujimoto, H., and Okubo, S. (eds) *Gravity, Geoid and Marine Geodesy*. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 131–138.

Childers, V.A., Bell, R.E., and Brozena, J.M., 1999, Airborne gravimetry: An investigation of filtering: Geophysics, v. 64, p. 61–69.

Cochran, J.R., Kurras, G.J., Edwards, M.H., and Coakley, B.J., 2003, The Gakkel Ridge: Bathymetry, gravity anomalies, and crustal accretion at extremely slow spreading rates: Journal of Geophysical Research: Solid Earth, v. 108.

Damiani, T.M., Youngman, M.A., and Johnson, J., 2011, GRAV-D General Airborne Gravity Data User Manual: NOAA, https://geodesy.noaa.gov/GRAV-D/data/NGS_GRAV-D_General_Airborne_Gravity_Data_User_Manual_v2.1.pdf.

Edwards, M.H., and Coakley, B.J., 2004, The SCICEX Program: Arctic Ocean investigations from a US Navy Nuclear-Powered Submarine: Arctic Research of the United States, v. 18, p. 14–14.

Jakobsson, M. et al., 2012, The International Bathymetric Chart of the Arctic Ocean (IBCAO) Version 3.0: Geophysical Research Letters, v. 39, doi:https://doi.org/10.1029/2012GL052219.

Jung, W., Brozena, J., and Peters, M., 2013, Predicting gravity and sediment thickness in Afghanistan: Geophysical Journal International, v. 192, p. 586–601.

Jung, W.-Y., and Vogt, P.R., 1992, Predicting bathymetry from Geosat-ERM and shipborne profiles in the South Atlantic Ocean: Tectonophysics, v. 210, p. 235–253, doi:10.1016/0040-1951(92)90324-Y.

King, H., 2021, Arctic Ocean Seafloor Map: Depth, Shelves, Basins, Ridges:, https://geology.com/articles/arctic-ocean-features/ (accessed March 2021).

Parker, R.L., 1973, The Rapid Calculation of Potential Anomalies: Geophysical Journal International, v. 31, p. 447–455, doi:10.1111/j.1365-246X.1973.tb06513.x.

Piskarev, A., Poselov, V., and Kaminsky, V., 2018, Geologic Structures of the Arctic Basin: Springer.

Smith, W. H. F. and Sandwell, D. T., 1997, Global Sea Floor Topography from Satellite Altimetry and Ship Depth Soundings, *Science*, 277(5334), p. 1956. doi: 10.1126/science.277.5334.1956.

Straume, E.O., Gaina, C., Medvedev, S., Hochmuth, K., Gohl, K., Whittaker, J.M., Fattah, R.A., Doornenbal, J.C., and Hopper, J.R., 2019, GlobSed: Updated Total Sediment Thickness in the World's Oceans: Geochemistry, Geophysics, Geosystems, v. 20, p. 1756–1772, doi:10.1029/2018GC008115.

Watts, A.B., 2001, Isostasy and Flexure of the Lithosphere: Cambridge University Press.

Wessel, P., Luis, J.F., Uieda, L., Scharroo, R., Wobbe, F., Smith, W.H.F., and Tian, D., 2019, The generic mapping tools version 6: Geochemistry, Geophysics, Geosystems, v. 20, p. 5556–5564.

Wu, L., 2018, Comparison of 3-D Fourier forward algorithms for gravity modelling of prismatic bodies with polynomial density distribution: Geophysical Journal International, v. 215, p. 1865–1886.

This page intentionally left blank.