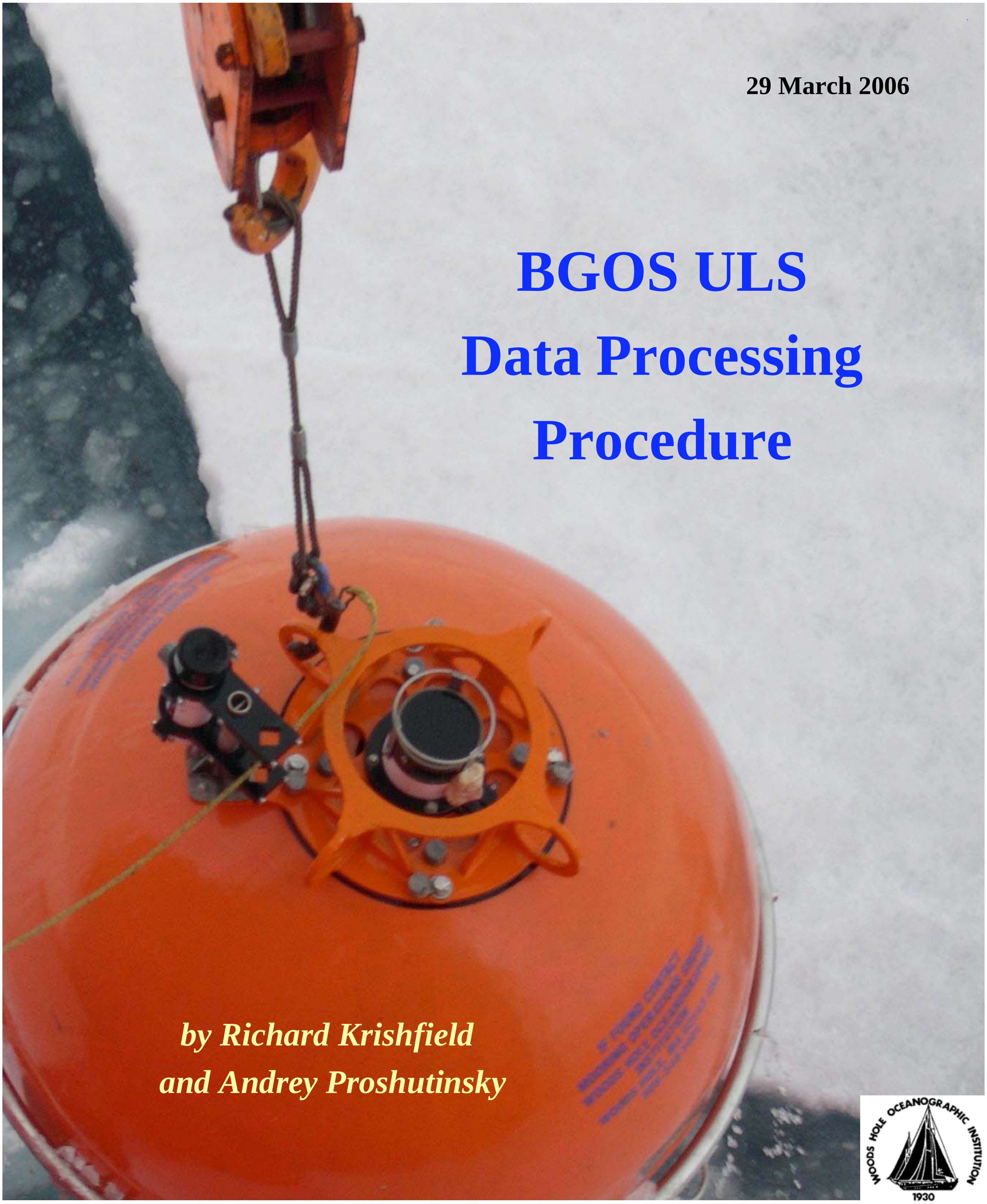

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BGOS ULS Data Processing Procedure

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Introduction

To what degree is Arctic sea ice extent decreasing? And is the sea ice thinning as well? These are questions that are being asked by researchers studying the effects of warming (natural and anthropogenic) and climate change in the far northern latitudes. Satellite visual, infrared and microwave technology has allowed for ice extent (concentration) to be observed nearly continuously since the mid-1970s, but ice thickness has proven to be more difficult to obtain remotely. As ice volume is a desirable parameter to have for climate modeling, thickness estimates (or measured drafts) are needed. Naval submarine data from the 20th century has been released and has been analyzed for thickness variations in past decades along synoptic sections (e.g. Rothrock et al., 1999; Wadhams and Davis, 2000), while more recently, upward looking sonar (ULS) have been applied to year-round moorings in the Arctic (Melling et al., 1995; Fukamachi et al., 2003) as well as Antarctic (Strass, 1998).

Since 2003, ULS were deployed beneath the Arctic ice pack on Beaufort Gyre Observing System (BGOS; http://www.whoi.edu/beaufortgyre) bottom-tethered moorings (Ostrom et al., 2004; Kemp et al., 2005). All three moorings in 2003 and 2004 were anchored in water deeper than 3500 m, but the model IPS-4 ULS (manufactured by ASL Environmental Sciences in Canada) were located between 50 and 85 m beneath the ice cover (depending on actual mooring length and deployment depth). The sampling rate of the range pings is every 2 seconds, while seawater pressure and temperature are measured every 40 seconds. Over 15 million observations are acquired for every mooring location, each year.

A directed 420 kHz beam (beamwidth 1.8 deg) samples a footprint of about 2 m from around 50 m below the bottom surface of the ice (or seawater) to determine range, from which ice draft is estimated. Draft results from corrected range minus the corrected pressure of the transducer (Figure 1). Tilt data are used to correct the range, and the pressure data are corrected for sound speed and density variations using CTD casts obtained by the Institute of Ocean Sciences in Canada at the beginning and end of each deployment (E. Carmack, F. McLaughlin, S. Zimmermann, et al.) and temperature measurements taken every pressure measurement. The stated accuracy of each acoustic range measurement is +/- 5 cm, but raw draft can be in error by as much as 1 m before corrections for atmospheric pressure and speed of sound variations are applied.

This document describes the data processing procedure used to calculate ice draft time series (and pressure, temperature and sound speed series) from the raw measurements. After implementing the processing procedure, the estimate error of the ice draft measurements is +/- 5-10 cm. Given ice velocity data, the timeseries information could be converted to a spatial distributions (Melling et al., 1995), but no ADCPs were installed on the moorings during the first two years.

Overview

Ensuring comparability to other ice draft measurements determined from similar ULS (e.g. Melling and Riedel, 1995, 1996), the processing scheme used here (Figure 2) largely follows the procedures employed by the ASL IPS Processing Toolbox (Billeness et al., 2004), except that here we developed an automated method for determining the speed of sound correction factor (beta). ASL Toolbox (version 1.02) recommended thresholds are used to remove spikes, but additional averaging of the raw range is implemented here that is not specified by ASL. The averaging windows and selected other parameters used in the processing were tuned by numerous iterations and visual inspections.

Based on the deployment configurations of the BGOS ULS, data files retrieved after each recovery of each instrument are saved in a single binary data file: ….000. Using the ALS IpsLink software and instrument specific configuration files (including calibrations), the raw files are decoded into separate ….000.BRS, ….000.PNG, ….000.PRS, and ….000.SYN files. The BRS file is for burst sampling which is not being used throughout this experiment, the PNG file is the range data, the PRS file contains the pressure, temperature and tilt data, and the SYN file is the timeclock.

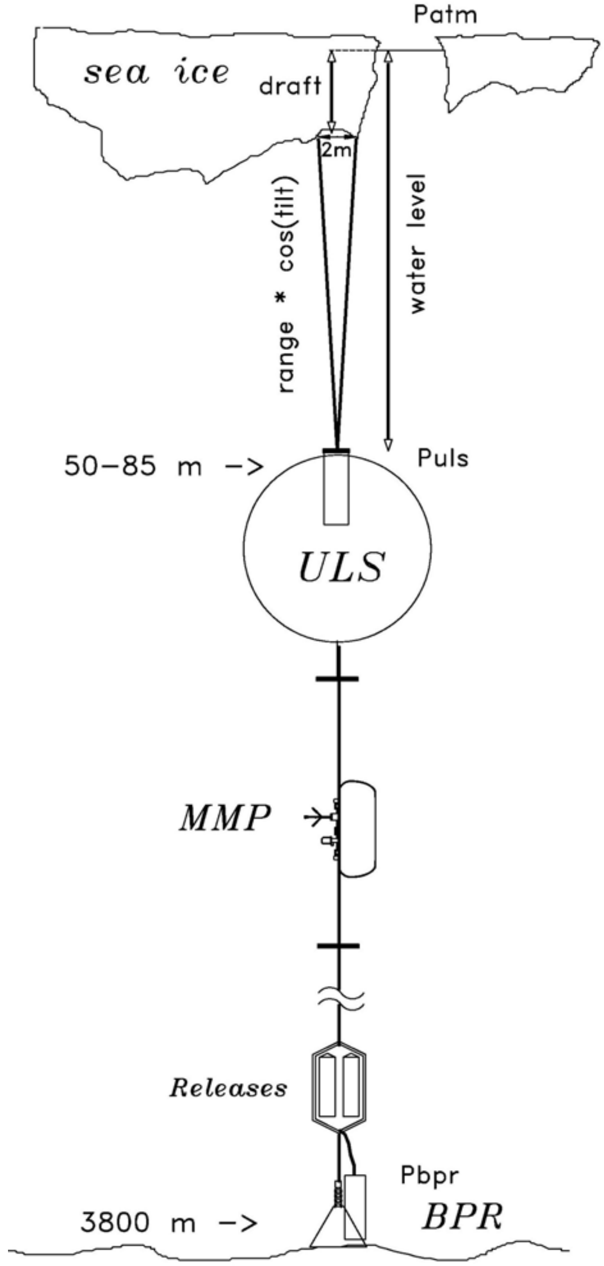

Figure 1. Schematic of BGOS moorings with ULS (and other instrument) placement, and measured and computed parameters for estimating ice draft from ULS pressure and range data.

The data processing functions and script codes described here are written to operate in the MATLAB environment. The overall processing sequence is outlined in Figure 2. The pressure, temperature, tilt data and battery voltage data (PRS and SYN files) are processed before the range data (PNG file).

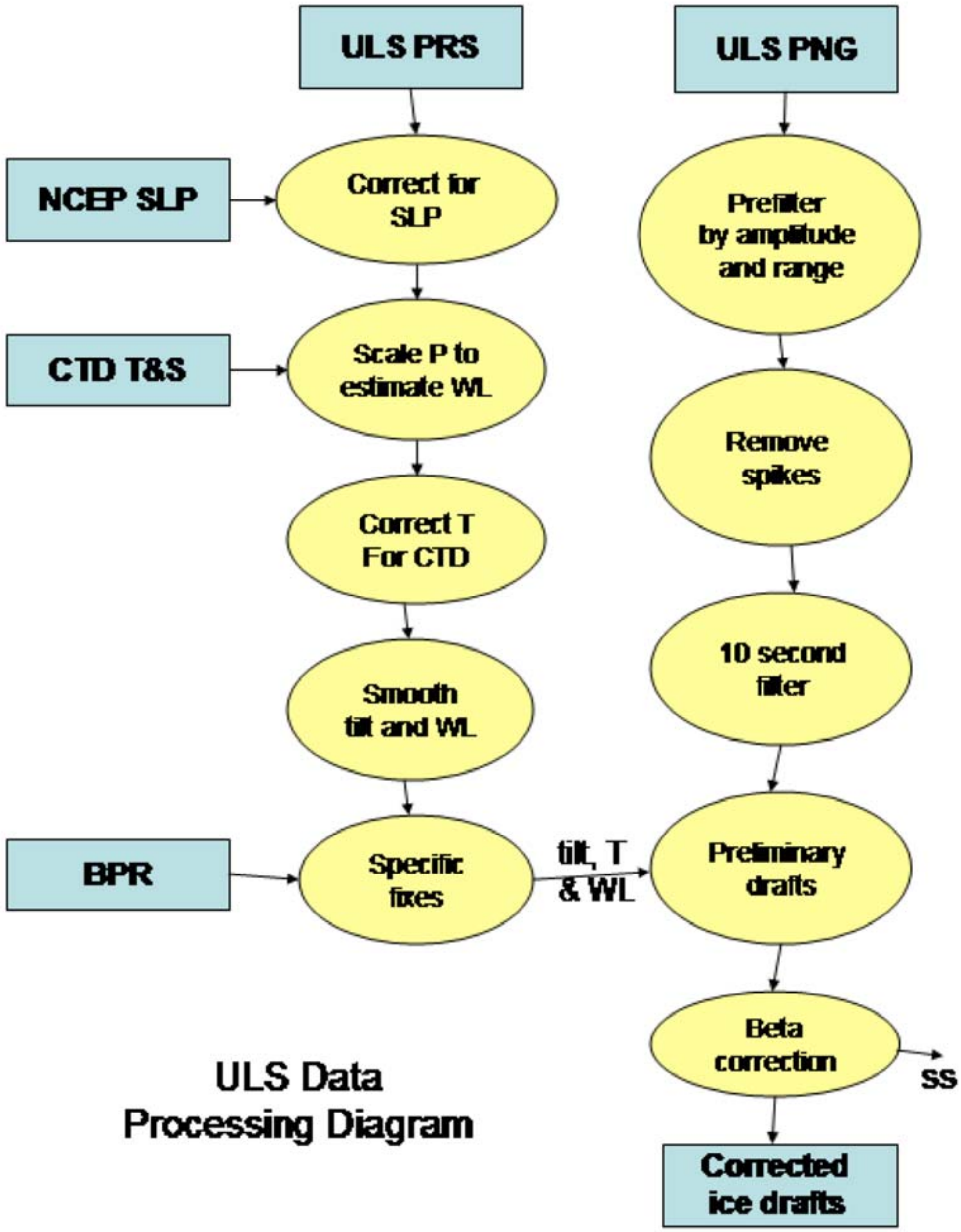

Figure 2. Block diagram of processing scheme used on BGOS ULS data.

Hydrographic profiles from CTD lowerings at the beginning and end of each year-long time series are used to correct the pressure and temperature data for determinations of water level. NCEP SLP reanalysis data is used to remove the atmospheric load (which can vary by as much as 1 m) from the pressure readings. High frequency jitter (presumably due to waves in open water conditions) is eliminated using a 20 minute running mean filter on the tilt and water level.

The raw ranges decoded using the Ipslink software are based on a sound speed of 1450 m/s (as configured for the BGOS instruments), but variations in sound speed could account for as much as 10-30 cm error in the measurement (depending on open water and ice conditions). Ranges are filtered and smoothed with a 5 point (10 second) running mean average (to eliminate wave noise and increase precision) and are adjusted for instrument tilt. Ice draft is determined from:

$$\text{Ice draft} = \text{water level} - \text{beta} * \text{range} * \cos(\text{tilt})$$

The beta correction accounts for the changes in seawater T&S properties which vary the actual speed of sound over the path of the ULS pulse, and is necessary to reduce the final error of the draft measurements to +/-5 cm. Here, an automated method was utilized that combines beta estimates based on the observed temperature and beta estimates from detectable "open water" segments to objectively average betas every 3 hours using 1.25 day windows.

After all the corrections have been applied, negative drafts are zeroed, and missing values are linearly interpolated. The output data are available in the Data section on the BGOS website (http://www.whoi.edu/beaufortgyre/data) as a time series of each 2 second ice draft determination, or as daily average ice draft statistics with daily average water temperature, water level and sound speed.

Pressure file processing

The processing steps for the raw pressure, temperature and tilt data provide calibrated smoothed time series of tilt, temperature, water level (depth from pressure and density). Specifically the major steps are:

1. Correct seawater pressure for atmospheric pressure.
2. Scale pressure using CTD data to produce water level.
3. Correct temperature bias and trend using CTD casts.
4. Smooth tilt and water level.

5. Other platform specific corrections

First all of the raw PRS data is imported into Matlab and plots are generated of the raw voltages, temperature, pressure, tiltx and tilty. Typical battery voltage decays of the alkaline packs for the BGOS deployments were from 15.5 to 12.5 V over one year. Negative pressure measurements indicate null data and are removed, as are pressures outside minimum and maximum thresholds (determined for each data set by observation). The tiltx and tilty data are combined into a single tilt magnitude. Due to the flotation holding the ULS, the magnitudes of the tilt never varied by more than degree while sampling, even during times when subsurface eddys of enhanced currents (evident from MMP data on the moorings) dragged the surface floatation deeper (as indicated by the pressure readings). Consistently across all of the moorings, comparison with bottom pressure recorder data from each same mooring seem to indicate that mooring wire stretch may account for about a 1 m decrease in measured pressure in a year, which shows up as a water level variation.

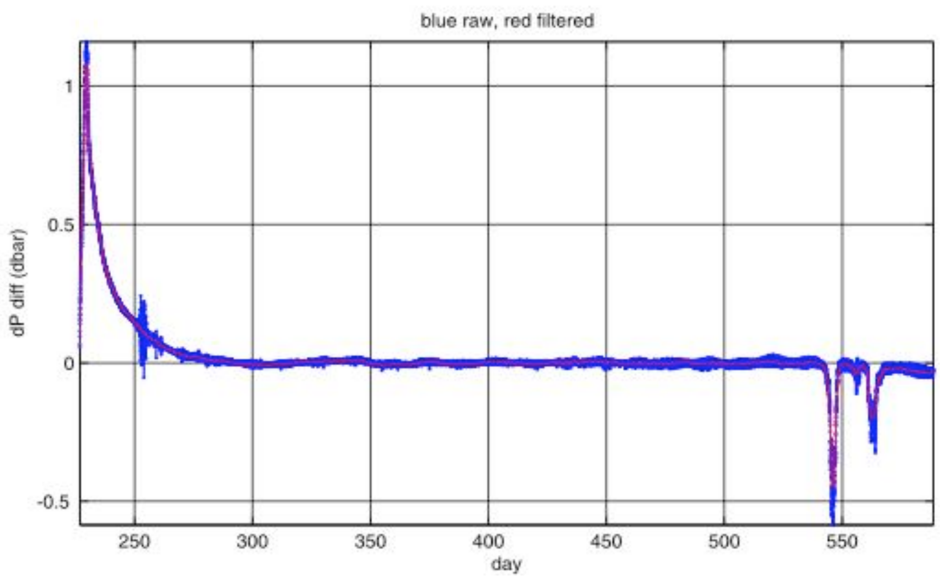

Figure 3. Large early offset correction (red line) to ULS mooring A 2003-2004 raw pressure measurements. The scatter after day 250 also shows variability associated with surface waves. The deep excursions after day 540 are due to subsurface eddys.

The atmospheric load is equal to about 10 m in the seawater pressure measurement and varies throughout the year by +/-0.5 m. NCEP reanalysis SLP estimates (http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.html) are interpolated for each time and instrument location, and subtracted from the raw pressures. The mean density of the upper ocean above the ULS at the beginning and end of each deployment are averaged for determining water level (from the hydrostatic equation) and later for sound speed calculation. The magnitude and trend of the seawater temperature at the ULS depth is also extrapolated from the annual CTD data, and used to correct bias and slope of the instrument measured temperature. A 20-minute running mean average is used to remove high frequency waves from the tilt and water level time series (especially prevalent during ice free time periods) prior to the first speed of sound correction and initial draft estimates. The occurrences of these high frequency pressure fluctuations are used during the ping file processing to identify when waves are significantly influencing the range measurements.

The pressure data from the ULS on one mooring (A: 2003-2004) exhibited a nonlinear behavior that needed to be removed by fitting the offset data gap to a 5th order polynomial (Figure 3). The timing behavior of all ULS were found to be reasonably stable (typically drifting only 10-12 minutes per year) so the only corrections to the clock were to ensure that the measurements were synchronized with UTC.

Range file processing

The range file processing converts ranges to drafts by estimating preliminary bottom temperature ice drafts, correcting for sound speed (beta) variations, and returning the positive draft data. The following steps are executed:

1. Prefiltering by range and amplitude.
2. Spike removal and filtering.
3. Preliminary draft determination.
4. Sound speed (beta) correction.
5. Final drafts.

In the PNG files, ping amplitude is decoded along with ping range. Pings with amplitudes less than 250 are removed, as are ranges outside specified minimum and maximum thresholds. This criteria removes all the pre-deployment data as well as some reflected ranges (that appear shallow in the timeseries) that were sometimes evident in the raw data. Range spikes greater than 2m (positives, negative, doubles, triples, and quadruples) are removed, and the ranges are filtered using a 5 point (10 second) running mean. For typical ice drift conditions (<10 cm/s), the averaging occurs across no more than 1 m ice, which is less than the typical footprint of the ULS.

Beta = actual sound speed / 1450. The first beta correction is estimated from the instrument temperature time series. However, in the Beaufort Sea, the upper 100 m of the water column sometimes contains several temperature maximum layers that are not well represented by the temperature at instrument depth, so we expect some deviation from reality. Salinity changes are incorporated only as straight line trends between annual CTD casts. Using these preliminary "bottom temperature" beta sound speed estimates, preliminary draft determinations were made (with corrections for water level and tilt estimated previously). With bottom temperature correction only applied to beta, the estimated drafts are estimated to be accurate to +/- 15 cm.

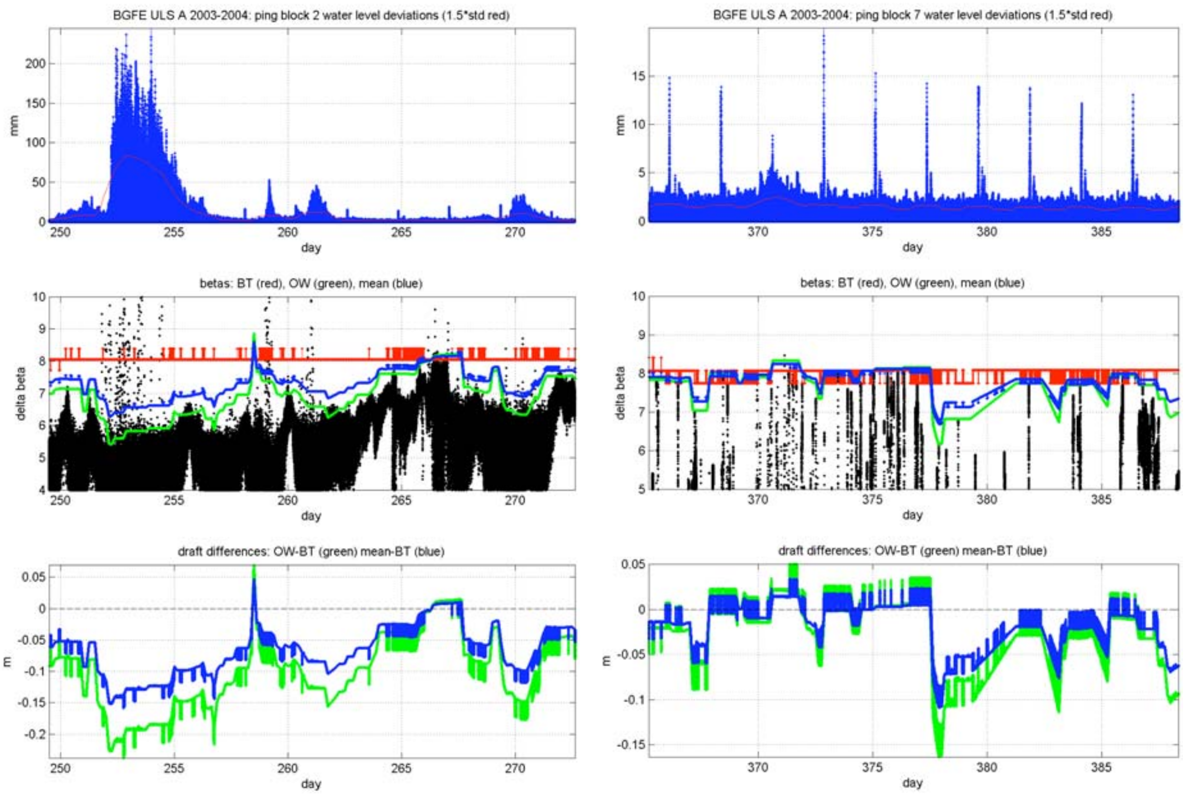

Figure 4: Water level deviations (top), delta beta (1000 * 1-beta) estimates (middle), and differences in draft (bottom) for 24 day periods from BGOS 2003-2004 mooring A ULS data during times with significant waves (left) , and during typical winter conditions (right). The regularly-spaced spikes that appear in water deviations in the top right panel are coincident with MMP profiling times. In the middle panels, the black spots indicate the preliminary betas, the red line indicates the "bottom-temperature" betas, the green line the "open-water" betas, and the blue line is the resulting weighted average. The bottom panels show the magnitude of the corrections on the ice draft determinations.

At times where open water is observed, beta can be accurately determined since the draft (=0) is known. However, difficulty occurs when the surface of the water is disturbed by waves, when long periods take place without open water leads, and when thin ice exists. Without concurrent ADCP ice drift with our BGOS range data, it is more difficult to distinguish openings in the ice from thin ice. While most other processing schemes rely on manual selection to discern ice openings, here we devised an algorithm to objectively determine "open-water" betas every 3 hours in 1.25 day windows.

"Open-water" betas are determined from the one-tenth percentile of "bottom temperature" betas between -0.1 and 0.15 m drafts. This procedure effectively chooses the near minimum sound speed which is associated with the open water (or thinnest ice). The averaging window relies on at least a few cracks or leads in the ice occurring often enough to provide opportunities to determine occasional correction points for beta. In instances where open water opportunities do not occur for several days, "open-water" betas are interpolated or extrapolated from previous betas in the time series. During periods where excessive variability associated from waves is evident in the pressure data, extra smoothing is performed while determining "open-water" betas. In general, the automated procedure typically determines betas that are within 1-2 cm of values that would be manually selected.

Final betas are computed from the weighted average of two-thirds "open-water' betas with one-third "bottom-temperature" betas, thereby including both the temperature fluctuations and "open-water" corrections. The final betas are reapplied to the range data and corrected ice draft estimates are produced. Ice drafts less than zero are forced to zero. During times of wave activity or no leads, the error in the individual draft estimates may approach +/- 10 cm (e.g. Figure 4, left panels). But most of the time, waves are not a problem and open water occurrences were frequent enough that the beta determinations yield confidence in ice draft accuracies better than +/-5 cm (Figure 4, right panels).

Statistics of the ULS range data processing for BGOS 2003-2004 are summarized in Table 1.

Table 1. Statistics of range data processing for BGOS 2003-2004 ULS data.

Mooring ID	A	B	C
Raw pings	15665479	15554699	15617639
Range limits	55-90	30-70	55-80
Pre-filtered	33486	115815	76361
Filtered	295	7955	9052
Spikes	8920	8808	14877
Multiples	194	273	514
Mean delta beta	7.75	7.24	7.60
Draft error	0.03	0.03	0.02
Negatives	7060	23894	10898
Output	15631621	15438861	15541461
Days	361.8	357.4	359.8

Output data formats

The output of the processed ULS data is available in two formats: 1) the complete 2-second ice draft time series, and 2) daily averages draft statistics, temperature, water level, and sound speed. With velocities provided from an outside source, the complete draft time series can be converted to a spatial distribution, and the features in the ice cover can be clearly discerned and described. If high resolution is not required, the daily average ice draft (and ancillary) data provide a synopsis of the results in a convenient abbreviated format. Both formats are available on the BG website (http://www.whoi.edu/beaufortgyre/data.html).

The complete draft time series are saved in separate ASCII text files for each mooring and year. The filename includes the deployment year and mooring identifier (for example **uls03a_draft.dat**). The first two lines of the file includes the experiment year, mooring location and data variable names (with units):

```
%BG 2003-2004 Mooring A: 75 00.449 N, 149 58.660 W
%date time(UTC) draft(m)
```

The remainder of the file includes all 15 million (2-second) draft estimates processed for the full year. Compressed versions of the text file are saved in **.ZIP** and **TAR.Z** formats.

Daily average draft, betas, temperature, and water level information for each mooring and year are saved in MATLAB format files (e.g. **uls03a_daily.mat**) with the following variables:

dates	date string timeseries
name	name of the mooring and dataset
yday	year day timeseries
BETA	final beta adjustment timeseries used in ice draft calculations
BTBETA	initial beta timeseries based on bottom temperature
ID	number of ice drafts binned daily every 0.1 m from 0.05 to 29.95 m
IDS	daily ice draft statistics: number, mean, std, minimum, maximum, median
OWBETA	beta timeseries determined from open water events
T	temperature timeseries (°C)
WL	water level timeseries (m)

The daily averages from the BGOS 2003-2004 mooring A, B, and C processed ULS data are plotted in Figures 5, 6, and 7.

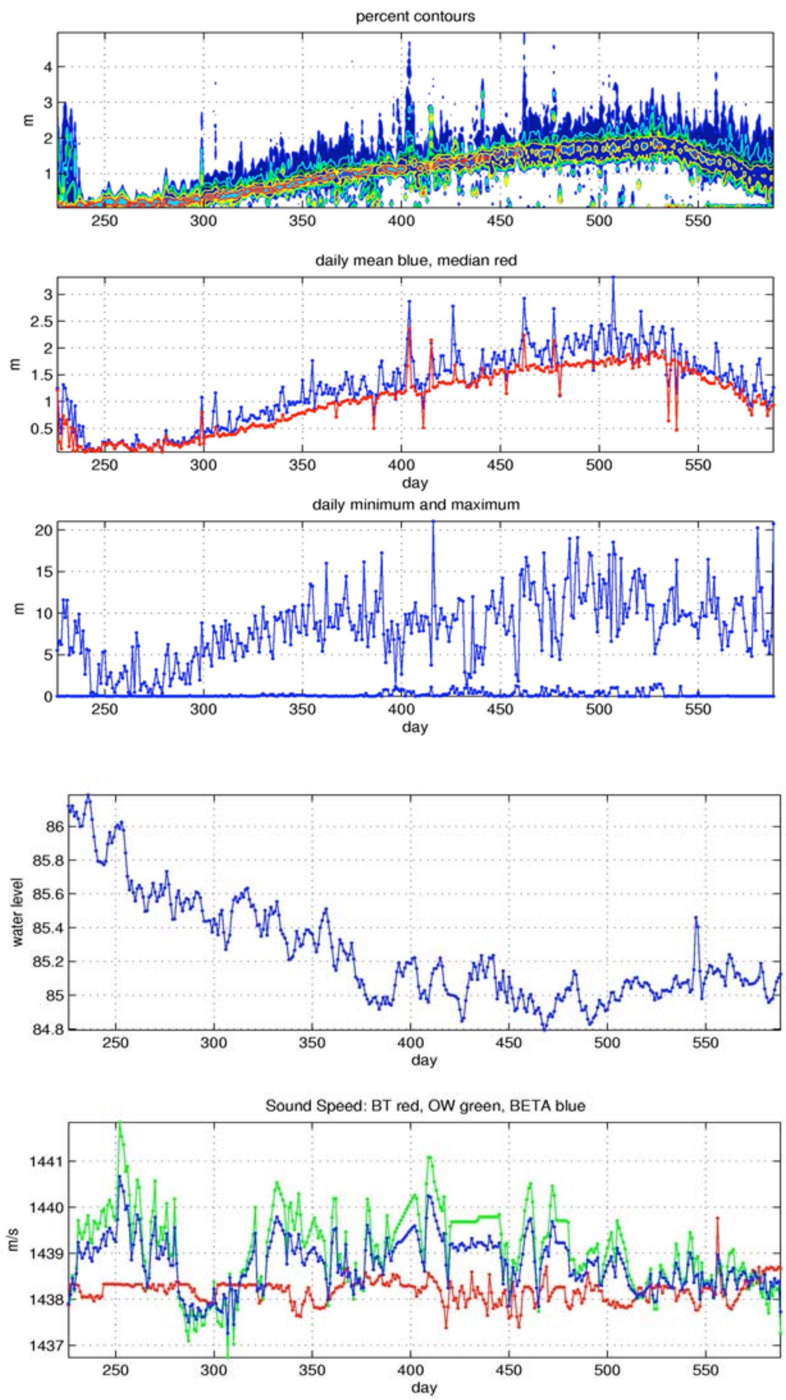

Figure 5. Daily averages from BGOS 2003-2004 mooring A processed ULS data. Upper panels: Ice draft (percent), mean and median, minimum and maximum year long time series. Lower panels: water level at instrument, and speed of sound correction (beta) used for draft calculations.

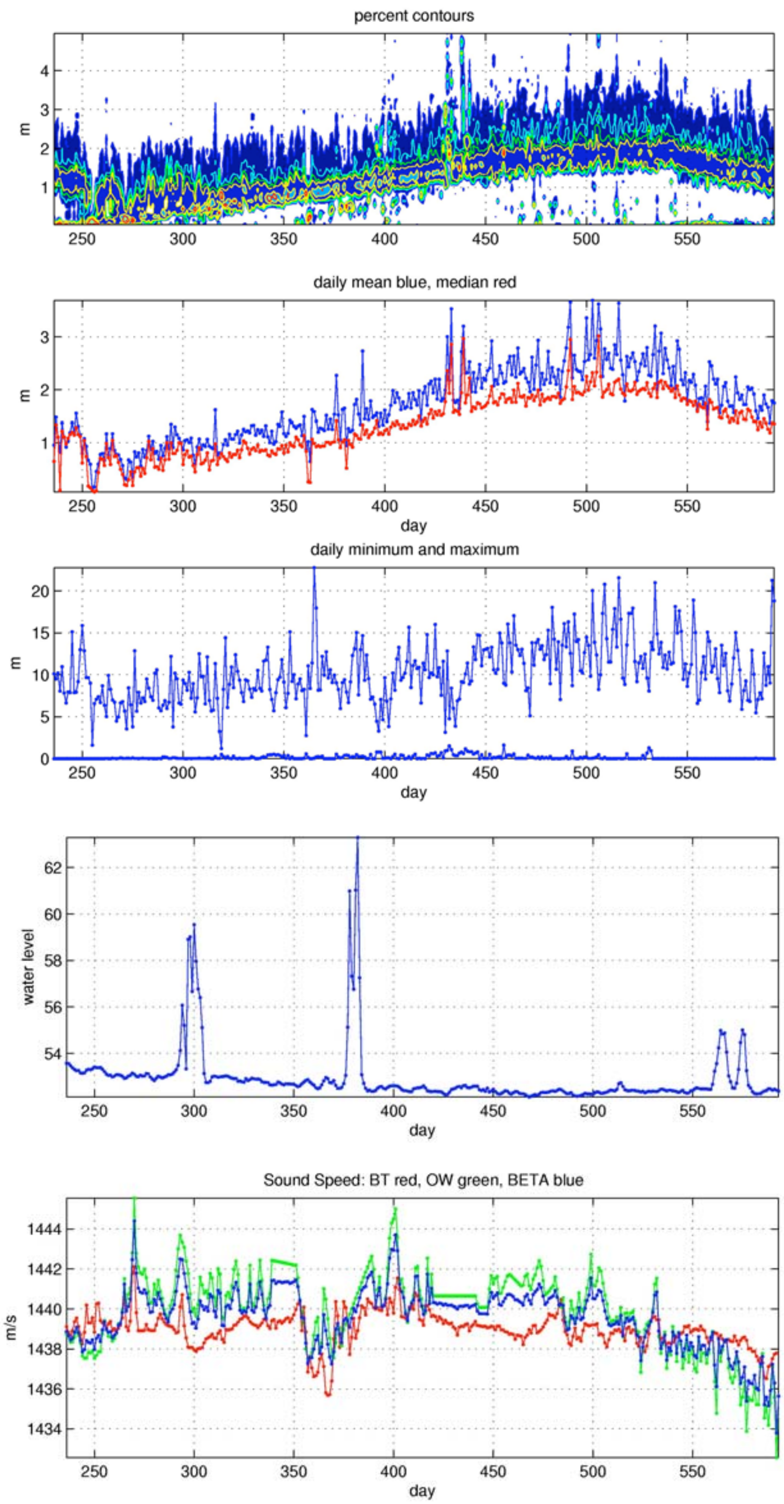

Figure 6. Daily averages from BGOS 2003-2004 mooring B processed ULS data. Upper panels: Ice draft (percent), mean and median, minimum and maximum year long time series. Lower panels: water level at instrument, and speed of sound correction (beta) used for draft calculations.

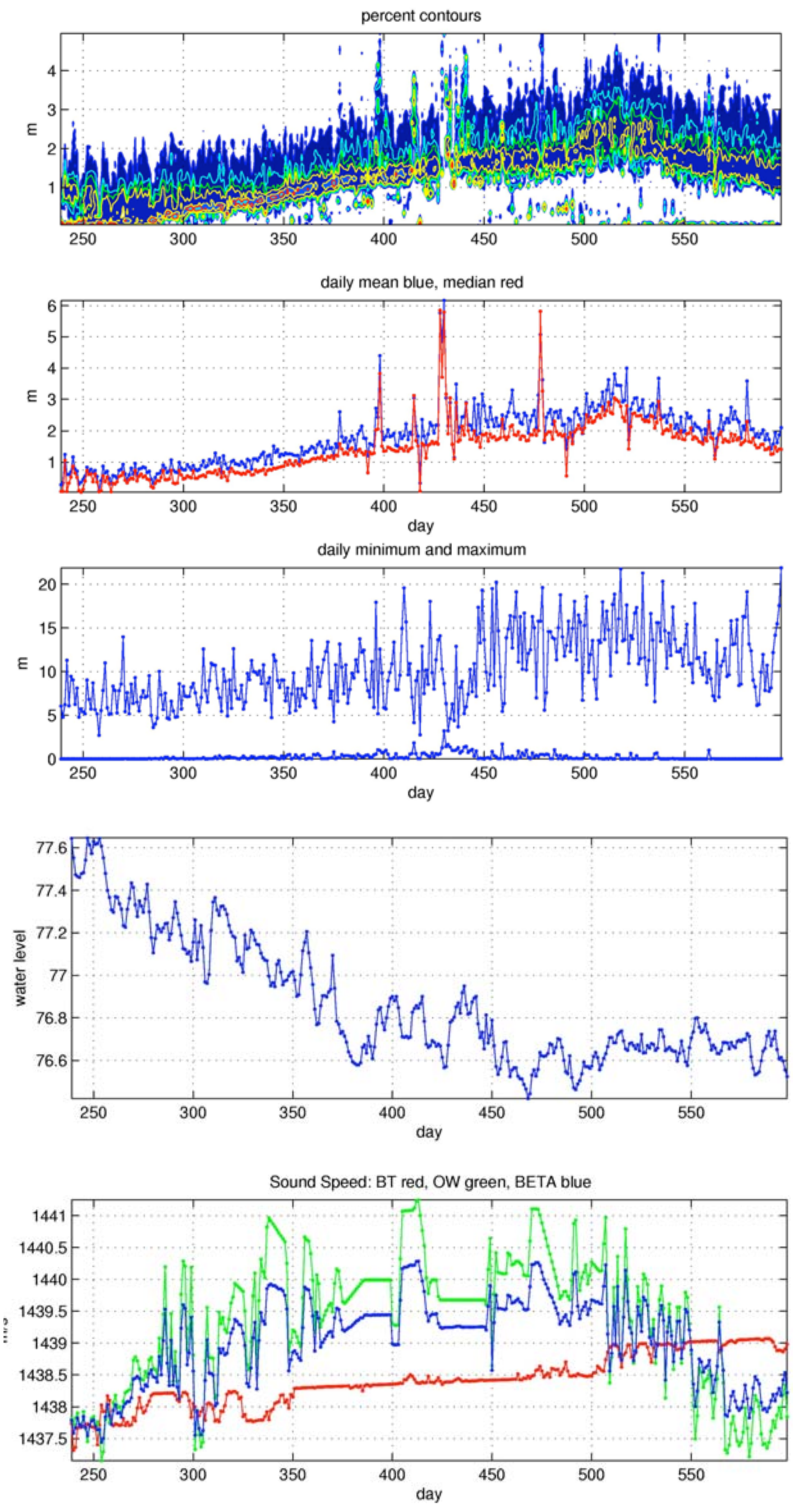

Figure 7. Daily averages from BGOS 2003-2004 mooring C processed ULS data. Upper panels: Ice draft (percent), mean and median, minimum and maximum year long time series. Lower panels: water level at instrument, and speed of sound correction (beta) used for draft calculations.

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