TUNING THE CARIS IMPLEMENTATION OF CUBE FOR PATAGONIAN WATERS

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September 2007

GEODESY AND GEOMATICS ENGINEERING
UNB

TECHNICAL REPORT
NO. 251

TUNING THE CARIS IMPLEMENTATION OF CUBE FOR PATAGONIAN WATERS

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September 2007

PREFACE

This technical report is a reproduction of a thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering in the Department of Geodesy and Geomatics Engineering, September 2007. The research was supervised by Dr. David Wells and Dr. Sue Nichols.

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Vásquez, Miguel E. (2007). *Tuning the CARIS Implementation of CUBE for Patagonian Waters.* M.Sc.E. thesis, Department of Geodesy and Geomatics Engineering Technical Report No. 251, University of New Brunswick, Fredericton, New Brunswick, Canada, 107 pp.

Dedications

To my parents for their support and continous worries.

…And for my pillar in every new challenge, my partner and friend…, my wife.

Abstract

This thesis is focused on optimizing the use of the CARIS implementation of CUBE (Combined Uncertainty and Bathymetry Estimator) for Chilean bathymetric data acquired in the Patagonian area.

The Chilean Hydrographic Office (SHOA) processes its multibeam data using interactive editing with CARIS HIPS software. To reduce the time consumed in this process and to avoid subjective decisions made by the operators, HIPS has semi-automated filters included. The latest CARIS technology uses the CUBE results for data filtering purposes. Thus the depth estimation made by the CUBE algorithm is stored in a CARIS BASE (Bathymetry with Associated Statistical Error) surface. Soundings that are inconsistent with this generated surface can be flagged as “not for use”. CUBE assumes a flat bottom in the depth estimation. The extreme seafloor morphology in Patagonian waters decreases the CUBE efficiency. A possible solution is changing its default parameters to make it more suitable for this kind of terrain and to enhance the efficiency of the CARIS filter.

TPE (Total Propagated Error) values are necessary to run CUBE. For this research, they were obtained by replacing the parameters of an existing “Device Model” within HIPS with the proper sonar information from the manuals and the manufacturer of ATLAS FANSWEEP 20 (200 kHz).

Using HIPS, two data sets acquired in the Patagonian channels were processed with CUBE default parameters and different CUBE configurations. The parameters related to the assimilation of the contributing soundings to a node, and the intervention of this process, were modified. The result of the first pass of the disambiguation engine to each configuration was observed using CARIS BASE surfaces.

The two BASE surfaces achieved at SHOA from manual subjective editing were loaded in two projects to be used for comparison purposes. The methods used for BASE surface analysis were 2D and 3D visualization. Also sub-areas were queried in order to get numerical values from different surfaces. Their discrepancies were analyzed using histograms.

Additionally, the use of the CARIS multiple and single grid resolution surfaces were tested for cleaning purposes. Single grid resolution was more effective for filtering purposes since the current version of CARIS multiple resolution produces an inappropriate seafloor representation when noise-data is present. The percentages of data rejected using the HIPS “CUBE” filter were compared between the different solutions.

Using the new configuration, named Patagonia, the efficiency of the CUBE algorithm was increased in its determination of the most likely depth. The tuned parameters showed a more realistic estimation of the depth and increased the hypothesis strength, especially in those areas affected by steep slopes and rough seafloor. The efficiency in cleaning data acquired from Patagonian waters is thus enhanced.

Resumen

Esta tesis está orientada en hacer más adecuada la implementación de CARIS CUBE (Combined Uncertainty and Bathymetry Estimator) a la data batimétrica chilena colectada en el área de la Patagonia.

El Servicio Hidrográfico Chileno (SHOA) procesa su data multihaz de acuerdo al método interactivo, usando el software CARIS HIPS. Para reducir el tiempo demandado en éste proceso y evitar las decisiones subjetivas que debe hacer el operador, HIPS ha incluido filtros semi-automáticos en su configuración. La última tecnología CARIS utiliza los resultados de CUBE para efectos de limpieza de data. Asi, la estimación de la profundidad hecha por el algoritmo es almacenada en la superficie CARIS BASE (Batimetria con Error Estatístico Asociado). Las sondas que son inconsistentes con la superficie generada son marcadas como “no para el uso”. CUBE asume fondo plano en la estimación de la profundidad. La extrema morfología del suelo marino en las aguas Patagónicas disminuye la eficiencia de CUBE. Una posible solución es cambiar sus parámetros de diseño para hacerlo mas adecuado a este tipo de terrenos y así mejorar la eficiencia del filtro de CARIS.

Los valores del Error Total Propagado (TPE) son necesarios para la utilización de CUBE. En ésta investigación, dichos valores fueron obtenidos reemplazando los parámetros existentes de otros “Modelos de Sonar” por los apropiados al ecosondas FANSWEEP 20 (200 kHz), de acuerdo a la información contenida en los manuales y a la información entregada directamente por el fabricante.

Usando HIPS, dos set de data adquiridas en los canales Patagónicos fueron computados con CUBE parámetros de diseño y por diferentes configuraciones de éste. Los parámetros relacionados con la asimilación de las sondas en la estimación del nodo y a la interrupción de este proceso fueron modificados. Los resultados de la primera pasada de desambiguación para cada configuración, fueron observados usando las superficies CARIS BASE.

Las dos superficies CARIS creadas en el SHOA derivadas de la edición subjetiva, fueron cargadas en dos projectos, para efectos de comparación. Los Métodos de visualización en 2D y 3D fueron utilizados para el análisis de las superficies BASE. Además sub areas fueron interrrogadas para obtener valores numéricos de las diferentes superficies logradas. Sus discrepancias fueron analizadas utilizando histogramas.

Adicionalmente se testearon las superficies CARIS de resolución multiple y simple para efectos de limpieza de data. CARIS resolución simple fue más efectiva debido a que CARIS multiple resolución produce una representación inapropiada del suelo marino con data ruido. Los porcentajes de la data ejectada usando el filtro de HIPS "CUBE" fueron comparados entre las diferentes soluciones.

Usando la nueva configuración denominada Patagonia la eficiencia del algoritmo CUBE fue incrementada en su decisión para determinar la profundidad mas probable. Los parámetros modificados mostraron una mejor estimación de la profundidad e incrementó la certeza en la hipótesis, especialmente en las áreas afectadas por gradiente marcada y rugosidad del suelo marino. Así la eficiencia en la limpieza de la data adquirida en las aguas patagónicas es mejorada.

Acknowledgements

My sincere gratitude to my Supervisor Dr. David Wells for his enthusiasm and guidance during my entire courses at UNB and especially in this research. Also I would like to mention Dr. Brian Calder from University of New Hampshire for his interest and support.

My gratitude also to Dr. Susan Nichols for her help and excellent advice.

Special thanks to the people from customer service at CARIS, for their time and continued support.

Thanks to the Chilean Hydrographic Office for the data and the support.

Thanks to ATLAS Germany for their support with information related to TPE computation.

And thanks to all at GGE department in UNB for these special two years that I will never forget.

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List of Symbols, Nomenclature or Abbreviations

BASE: Bathymetry with Associated Statistical Error.

CARIS: Computer Aided Resources Information System.

CUBE: Combined Uncertainty and Bathymetry Estimator.

DGPS: Differential Global Position System.

GPS: Global Position System.

HIPS & SIPS: Hydrographic Information Processing System, and Sonar Information Processing System.

HVF: HIPS Vessel File.

IHO: International Hydrographic Organization.

MBES: Multibeam echosounder System.

MB: Multibeam echosounder.

MRU: Motion Reference Unit.

SHOA: Servicio Hidrografico y Oceanografico de la Armada (Spanish), Chilean Hydrographic Office.

StdDev: Standard Deviation.

SSP: Sound Speed Profile

SURF: (acronym in German), in English: Sensor Independent Raw Data format.

THE: Total Horizontal Error (in HIPS this is called HzTPE).

TPE: Total Propagated Error.

TVE: Total Vertical Error (in HIPS this is called DpTPE).

1. INTRODUCTION

The Chilean Hydrographic Office (SHOA) is currently cleaning its bathymetric data using interactive editing. This is a time consuming task since multibeam data is used for the creation of nautical products. This chapter introduces the Chilean scenario and the objectives of this research for implementing the latest algorithm known as CUBE (Combined Uncertainty and Bathymetry Estimator) in the Chilean bathymetric data analysis procedure.

1.1 Problem Statement.

The CUBE [Calder and Mayer, 2001; Calder, 2003; Calder and Wells, 2007] algorithm generates point-wise estimates of depth from dense soundings. Applications of CUBE have become an excellent tool for bathymetric data analysis and cleaning. However, CUBE will not always make the right decision, especially if the data is corrupted by noise and if the area is affected by extreme terrain conditions. That is the case with the Chilean data. According to the nature of the seafloor and failures in bottom detection, the CUBE algorithm is not suitable with its default parameter values for this kind of scenario.

1.2 Background.

SHOA has been using the echosounders FANSWEEP 20 [ATLAS, 2002; 2003] (for areas up to 250 metres depth) and HYDROSWEEP MD 2 (for deeper sectors) to collect bathymetric data. These echosounders use electrical beamforming and interferometric techniques to produce a high-resolution seafloor representation.

In the case of the bathymetric data from the Patagonian area, SHOA faces a difficult situation, since the topography of the seafloor changes abruptly from shallow to very deep waters in just a few minutes of surveying. This seafloor is complex in its geomorphology of high mountains and extreme roughness. Also, its oceanographic aspects are very variable, making the survey a difficult task. These features produce failures in the data acquisition system (e.g., sea bottom mistracking).

Since hydrographic offices have implemented multibeam echosounder technology, the enormous amount of data available has turned the operator’s work into something extremely laborious. The advantage of having the seafloor mapped in high resolution has the disadvantage of being time consuming in the cleaning procedure. Also, the operators must deal with many subjective decisions that sometimes (depending on their expertise and dedication) could be wrong.

The Chilean Hydrographic Office is currently processing its multibeam data using interactive editing with CARIS HIPS software. This means performing data analysis through the entire area surveyed, swath-by-swath, selecting and rejecting data noticed as noise by the operators. This implies a time consuming task by SHOA to complete the cleaning process.

Reducing post-processing time is critical for any organization since it makes the hydrographic surveys less expensive. On the other hand, the data cleaning needs to guarantee safety of navigation for the relevant nautical charts. For this reason the implementation of new statistical cleaning tools in the Chilean bathymetric data cleaning processes is necessary.

Different organizations have been developing other approaches to filter bathymetry data using automated editing. NOAA COP [Herlihy, Stepka and Rulon, 1992] and the RDANK [Eeg, 1995] are methods designed to identify noise-data within a single swath. On the other hand, [Ware et al., 1991] and [Du et al., 1995] are methods designed to detect outliers within a selected subset. All of them are examples of the hydrographic desire to speed up the analysis process.

CARIS has implemented the algorithm commonly referred to as CUBE for depth estimation. Its result is then stored in the BASE (Bathymetry with Associated Statistical Error) surface, using the HIPS & SIPS software [CARIS, 2004; 2006a; 2006b]. This allows the implementation of surfaces with statistical weight and meets hydrographic standards [IHO, 1998]. Although CUBE is not a filter, a surface product derived from it can be used to select points that are judged consistent with the surface, and thereby flag all other soundings as “not for use”. This is, however, an added behavior that is entirely dependent on the implementation software for the basic CUBE algorithm (in this case CARIS HIPS). CUBE has been designed to be used with dense soundings and the default parameter settings reflect this. If for any reason the algorithm does not work properly with its default parameter settings, however, its parameters can be modified to possibly accomplish a better depth estimation and hence should result in improving the cleaning of bathymetric data.

To use the CUBE algorithm, the computation of the uncertainty associated with each sounding (vertical and horizontal) is required. The engine to accomplish that is an error model [Hare et al., 1995; Hare, 2001] built for a specific echosounder device. Although HIPS contains descriptions about a series of sonar devices already tested, ATLAS FANSWEEP 20 is not one of them. That implied the need to create a new sonar model suitable for this echosounder.

1.3 Research Objectives.

The goal of this research is to make the CARIS CUBE implementation more suitable to be used with bathymetric data collected in Patagonian waters by the Chilean Navy. Therefore the followed methods were identified:

- Compute the TPE values according to the Chilean hydrographic vessel configuration.
- Define which CUBE parameters should be refined for better depth estimation, using data affected by steep slopes and rough seafloor.
- Create several CARIS BASE surfaces to analyze the results of different CUBE configurations.
- Interpret the surfaces obtained, using histograms and visual assessment.
- Select the best approach using a traditionally-determined SHOA surface as comparison.

1.4 Objectives.

The objectives followed in this research are to:

- Study the sonar characteristics, environmental scenario and CUBE parameters' sensitivity to be changed according to the Chilean scenario.
- Set-Up (necessary work to be done before running CUBE).
- Analyse the results obtained with different CUBE configurations according to the representation of the seafloor.

1.4.1 Set-up.

Although HIPS has several device model types, it does not include FANSWEEP 20. Therefore, it was necessary to add this echosounder into the CARIS file to compute the TPE (Total Propagated Error) and thus obtain the uncertainty of each sounding.

CARIS HIPS software contains a file with the sonar parameters necessary for TPE computation. Also, HIPS highlights those sonar parameters that will be taken into account by the error model, if a particular sonar is not included on the list. Since that was the case in this research, these values were filled in, using the operator manual and by consulting the manufacturer directly [Lindlohr, 2007].

HIPS computes the TPE values, using the parameters defined in the Device Model field and the offsets of each ancillary sensor. Parameters such as distances between the sensors, their offsets, and the manufacturer's specifications for each sensor (i.e., Standard deviation) were directly entered in the HIPS Vessel file [CARIS, 2006a].

Since the ray-tracing calculation is not performed by ATLAS FANSWEEP 20, the whole data was corrected using the information obtained by the sound speed cast and offsets in the vertical axis of the transducer. Thus two new fields were created to include the transducer offsets [CARIS, 2004]. The TPE values obtained then were contrasted with values achieved by other echosounder at similar depths.

1.4.2 CUBE configuration testing.

Several CARIS surfaces were created to represent the results using different CUBE configurations. The goal was analyze the depth estimation made by CUBE through the survey area, especially in sectors with steep slopes and rough seafloor. Parameters such as Horizontal Error Scalar, Estimate Offset, Capture Distance Scale and

Capture Distance Minimum were modified and tested with a data set of 3 million soundings. The best approach, in terms of depth estimate was named CUBE Patagonia. CUBE Patagonia was later tested with a different data set of 23 million soundings to validate the experience. Also the CARIS new configurations (i.e., CUBE deep and CUBE shallow) were tested.

The SHOA surface achieved in the Hydrographic Office was used for comparison purposes. Therefore the surfaces showing the results in depth estimation obtained by CUBE default, CUBE deep, CUBE shallow and CUBE Patagonia were compared to the surface obtained by interactive editing.

Under the ideal standard the “true surface” should be used for comparison, but since this is not available, the SHOA surface (affected by subjective decisions), was considered as a “true surface”. This surface was chosen as the reference, as interactive editing was used for its generation. Independently of the time consumed in this task, the operations made by the hydrographer in the data analysis will be considered as the best estimate of the depth.

The first analysis of each solution was made using 2D and 3D visualization. Subsets of different surfaces achieved were displayed in HIPS. Using the Subset window, the different solutions can be observed from the same particular area. Thus differences in depth estimation and hypothesis strength were observed. A second analysis of different solutions was made selecting a specific area of the field sheet. The node solutions were queried and values in depth, uncertainty and hypothesis strength were exported to a spreadsheet. The biggest discrepancies in depth estimation between CUBE default and CUBE Patagonia, were analyzed using histograms and surfaces. Also the differences in the uncertainty attached to each node and its hypothesis strength were analyzed using histograms. The third analysis was conducted to determine the efficiency of each CARIS surface in terms of data rejected. The HIPS "CUBE" Filter was run separately.

1.5 Results obtained in this Thesis.

- Realistic TPE values (compared with TPE values of another echosounder at the same depth) were obtained using the information provided by the manufacturer. Also applying sound speed corrections (i.e., ray tracing) the TPE values obtained were shown to be more realistic (Page 52). These values should be treated with caution, however, since they are based on an error model that corresponds to another echosounder than the ATLAS FANSWEEP.

- By analyzing the SHOA surface (Page 60), it was observed that over-cleaning in the data (maybe produced by fatigue or inadequate operator's expertise) had occurred.

- The CARIS multiple grid resolution, independent of the depth estimation made by a different configuration of CUBE, showed surfaces being strongly corrupted by noise-data. Multiple resolution showed two undesired effects: 1) cut-off effect for these soundings outside the resolution selected, in which case they were not allowed to be considered for the depth's estimation at these nodes (Page 61); and 2) noise-data "floating" over the real surface was considered to create a grid with the resolution selected at this depth, corrupting the surface.

- HIPS CUBE deep configuration, tested using both multiple and single grid resolution, was not able to avoid the strong influence of noise-data in areas with steep slopes and rough seafloor (Page 65).

- Decreasing the parameters Estimate Offset, Capture Distance Scale and Capture Distance Minimum in CUBE setting was shown to be the best alternative solution for depth estimation (Page 78) for this particular case. Each solution achieved using CUBE was a product of the first-pass disambiguation engine. The influence of noise-data still affecting the depth estimation with default parameters in areas with steep slopes and rough seafloor was decreased. Hence, the surface generated by CARIS HIPS using the results of the new configuration, was shown to be more realistic even when it is compared with the work done at SHOA.

- CUBE Patagonia proved to be more effective against CUBE default in depth estimation, reducing up to 63% the level of uncertainty associated to each node, in areas with steep slopes and up to 56% in rough areas. Also the level of hypothesis strength was increased by 57% and 52%, respectively. In other words, the new CUBE configuration was more reliable in portraying the data compared with the result produced by CUBE Default (Page 79).

1.6 Thesis Outline.

Chapter Two describes how the performance of a multibeam echosounder is affected by the environmental conditions such as seafloor geomorphology. Also, this chapter is focused on the configuration of the echosounder FANSWEEP 20 used by the Chilean Navy, and how its data is then exported to HIPS for analysis. A knowledge of these matters is essential to identify the possible sources of sea bottom mistracking and for the settings of HIPS.

Chapter Three explains the environmental conditions that affect the performance of FANSWEEP 20 in the specific area of Patagonian channels and fjords. Since this is the area where the hydrographic vessel is normally deployed, this chapter is focused on the seafloor characteristics in which the Chilean bathymetric data is collected. The data collected in this area is used, in this research, to test the CUBE disambiguation engine efficiency.

Chapter Four addresses the different approaches used for bathymetric data analysis and cleaning. Interactive editing (still used by SHOA) and its differences with semi-automated methods are explained in this chapter. Also, the necessary background of the CUBE algorithm and associated parameters are discussed. Thus, the basis for suitably tuning CARIS CUBE implementation and the advantages of using it for bathymetric data analysis and cleaning, are established.

The methodology used in this thesis is tackled in Chapter Five. Two different surveys conducted in Patagonian waters are described. Using the information from previous chapters, the necessary set-up for Total Propagated Error computation in HIPS is performed. Several CARIS surfaces are generated. The methodology used for testing each CARIS surface and to determinate the most realistic surface is explained.

In Chapter Six the results of the surfaces produced by the operator at SHOA, and the surfaces obtained by first-pass of different CUBE configurations are shown and discussed. The discrepancies in depth estimation, and how these results then are represented by CARIS surfaces, are explained in terms of noise-data being diluted in the node estimation.

The conclusions and recommendations deduced from the results are established in Chapter Seven.

2. MULTIBEAM PRINCIPLES, DATA CHARACTERISTIC-PROCESSING AND PERFORMANCE

This chapter defines the background necessary to understand the issues related to sea bottom mistracking, which are translated into noise-data affecting the CUBE depth estimation. Since the Chilean Hydrographic Office uses FANSWEEP 20 for high-resolution bathymetric data acquisition, this chapter explains its main characteristics and how this data is then processed using CARIS HIPS software.

2.1 Multibeam echosounder background.

Multibeam echosounder systems (MBES) employ acoustic detection techniques to collect detailed data in a cross-section of the sea bottom. The transducer has the capability of generating a fan array of narrow beams, which result in acoustic travel-time measurement over a swath that varies with system type and bottom-depth typically mapping an area 2 to 14 times the water depth with each array pulse [USACE, 2004]. MBES can also be adjusted to achieve a high-resolution footprint, which gives it a capability to detect small features. On the other hand, the capability of making the swath angle variable, according to the users' needs, is translated into more (or less) coverage of the sea bottom.

Basically, multibeam data acquisition can be described as an interaction between across track swath (which "illuminates" the sea-bottom acoustically) and the reception swath (Figure 2.1), which receives the backscatter of this acoustic signal from many small sections ("footprints") across the bottom. The backscatter signal response generated after a bottom surface has been illuminated has amplitude, and phase signatures, which are dependent on the nature of the seafloor (i.e., bottom reflection and scattering), angle of incidence with respect to the bottom, and sonar characteristics.

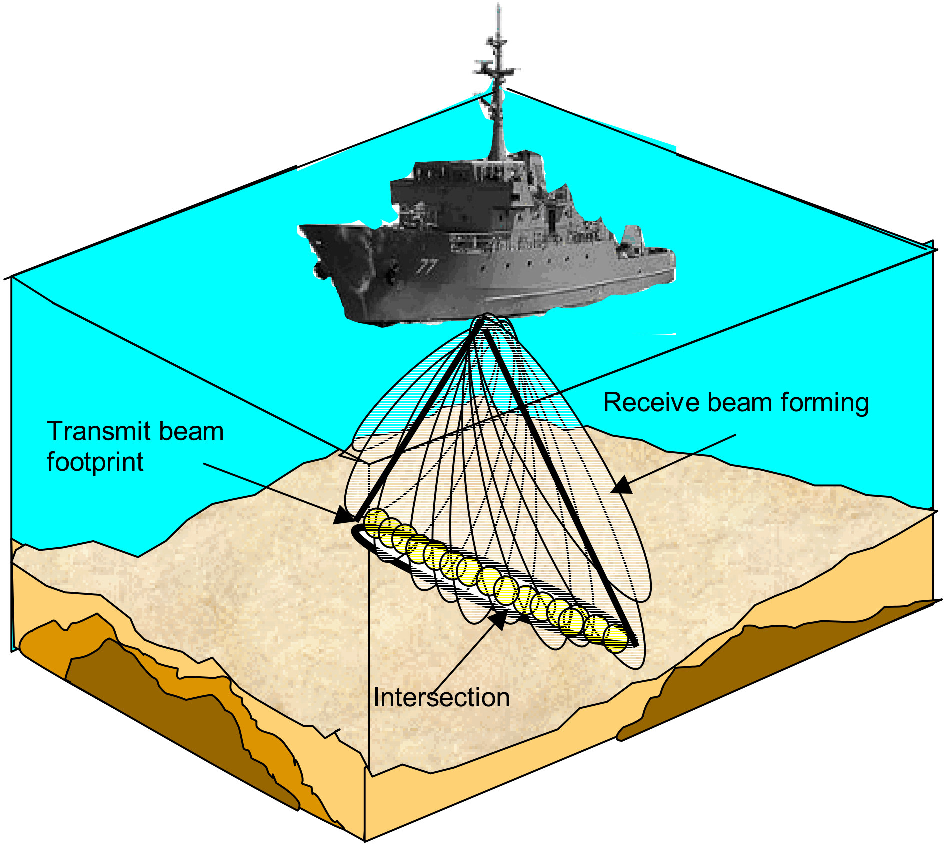


Figure 2.1: Illustration of multibeam system bottom detection. The sequence shows how a swath is generated and how the received signals are then received. The intersection between these is the resulting measurement of depth with range and bearing.

A Global Position System (GPS) signal is required to assign positions to the ship. The transducer location is required to make the proper correction and thus obtain its position. As the transducer follows the rotation of the ship, measurement of roll, pitch and heading is necessary to rotate the across-track and along-track distance for each beam with vessel attitude (Figure 2.2) and thus maintain a stable ensonification zone [ATLAS, 2006] The slant range (between the illuminated point and the receiver) is calculated taking into account the difference in time between the transmission and reception of the wave (i.e., two way travel time) and the propagation speed of that wave through the medium (i.e., sound speed in the water). To determine the corresponding vector of depth (i.e., horizontal range and depth) for a particular point illuminated by the swath, slant range is used. Finally, measurements are needed for vertical displacement of the MBES due to heave (heave sensor), tide (tide sensor) and other dynamic draft effects (i.e., models, RTK GPS).

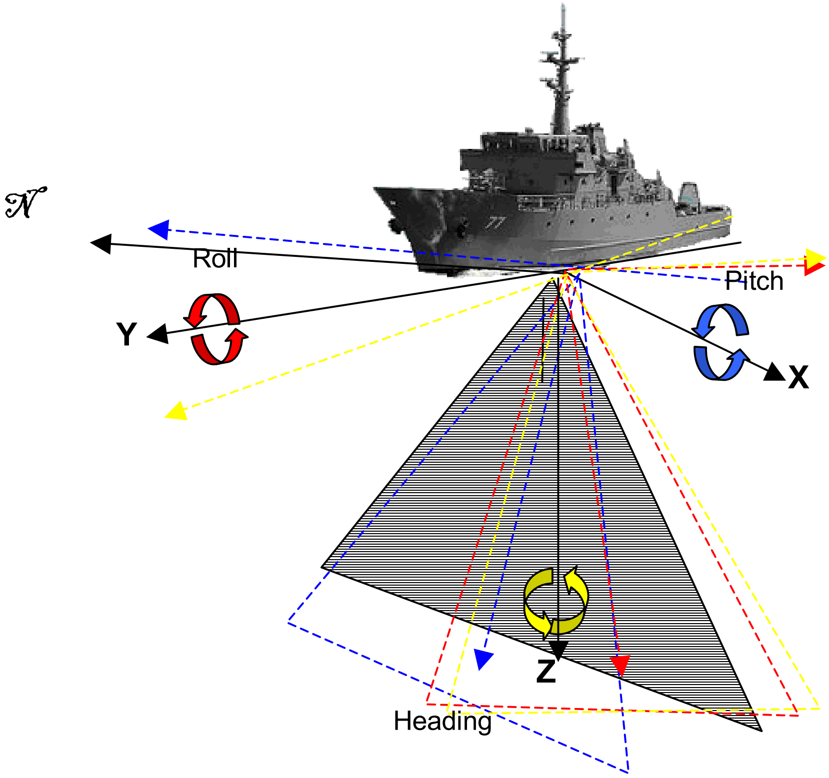


Figure 2.2: Roll, pitch and heading representation in each plane. These values are necessary for vessel motion compensation. In some systems, the corrections for roll, pitch and heading changes are applied during data processing. In other systems (e.g. Fansweep 20) roll and pitch are used in real time to maintain beamforming orthogonal to the x and y plane. This figure represents changes in beamforming without compensation.

2.2 Beamwidth, Resolution and Beam Samples.

In the across-track direction, the sampling density is controlled by the beam samples, angular sector, beam spacing and beamwidth [Hughes Clarke, 2005]. The resolution of a linear array is characterized by a set of two parameters: the angular resolution (determined by the ratio of the aperture length to the acoustic wavelength) and the range resolution (determined by the pulse bandwidth). If high-resolution data is required a narrow beam is necessary, since a narrower beamwidth yields a smaller instantaneously ensonified area. The beamwidth depends on the array aperture and it is inversely proportional to the array aperture length. So the larger the array, the narrower will be the beamwidth in the orthogonal direction to the long axis of the aperture. But since there is a physical limit to the aperture size (generally a practical manufacturing limit, or a limit on the desired near-field/far-field distances), an alternative for higher resolution is to reduce the wavelength (although this also reduces the maximum possible range), or equivalently increase the frequency of the transmissions.

The across-track resolution of the survey area is generally dependent on the number of beams per swath. Some caution is indicated, however: an echosounder that has a greater number of beams does not necessarily imply a higher resolution. A greater number of beams could work to reduce noise when they are used in oversampling, but may not mean an improvement in the resolution achieved. In the case of beams with an appropriate sampling and small beamwidth, a greater number of beams should increase the topographic resolution.

2.3 Principles of data acquisition of ATLAS FANSWEEP 20.

ATLAS Hydrographic GmbH developed FANSWEEP 10 in the late 1980s. FANSEEP 20 200 kHz, introduced in 1996, was conceived as a shallow water MBES, having a range from 0.5 metres (below the transducer) up to 250 metres, being especially suitable for coastal waters, rivers and inland waterways. Designed to work in flat-water conditions, it is capable of acquiring high quality bathymetric data with a maximum swath angle of 161° and side-scan data with a maximum aperture of 180° in parallel. The bathymetric data is compliant with IHO S-44 special order requirements for coverage of up to six times the depth [ATLAS, 2006]. Some of its applications are: hydrographic surveys, search for obstacles (e.g., wrecks), chart compilation and bathymetric investigations for research purposes.

FANSWEEP 20 applies direct compensations for roll and pitch stabilization to the whole swath, which means that beam spacing is maintained roughly consistent across and along track through the acquisition processes [Hughes Clarke, 1997]. Corrections for transducer offsets from the reference point and transducer mounting are applied. Since FANSWEEP 20 is a dual head transducer, two sets of offsets are stored in SURF format. Tidal corrections can be applied in the system in real time. Thus depth and tide are joined in the SURF format as one file.

ATLAS FANSWEEP 20 is restricted to sound speed measurement at the transducer. For sound speed corrections through the water column, the system uses the average of sound speed acquired by the launch sensor.

In the FANSWEEP 20 electronic beamforming is used to form four separate transmit beams, two to either side of the transducer. Very short transmission pulses at different acoustic frequencies are transmitted at the same time. The outer beams use a frequency slightly lower than the central beams, covering that part of the sea bottom far away from nadir. Due to the specific form and arrangement of the beam, the sound is directed to either side of the ship into the entire half-space from the vertical almost to the horizontal. The received signal is then processed to determine the beam angle, the amplitude and the Two Way Travel Time (TWTT). Each echo that is received describes a bottom element by means of the amplitude, the traveling time of the acoustic signal, and its angle relative to the normal to the receiving transducer. The angle of the received echo is measured on the basis of the phase shift by means of a large number of phase measurement units working independently of each other within the transducer [ATLAS, 2006].

Each side of the V-shaped transducer has 26 rows of individual elements distributed in two sections (responsible for transmission) and ten sections (responsible for reception). Each section produces identical very narrow beams in the bow-stern direction and the across-track detection spacing can be user modified (e.g., equal inter-beam distance spacing or equal beam-angle spacing). On line, raw data is then compensated for vessel motion, to avoid falsification or interpolations of any kind. Taking into account the fixed parameters of the ship and the sound speed through the water column, the depth and relative position (with respect to the transducer) are calculated for each individual bottom element.

In the reception process, up to 1440 bottom detection solutions are calculated independently of the transmit beam width. Additionally and completely independent of the depth measurement, FANSWEEP 20 can generate up to 4096 side-scan values per swath. These values can be stored, visualized on-line, displayed on a hard copy side-scan recorder, and geographically positioned.

ATLAS FANSWEEP 20 200 kHz allows the operator to select the resolution ratio, which will be mainly dependent on the number of samples, ping rate and sector width across track. The depth resolution is 5cm +0.2% depth [ATLAS, 2006].

Ancillary sensors are used in the conventional way. GPS is used for positioning and vessel speed, MRU and gyro for vessel motion offset, and sound speed probe (hull-mounted and dipping) for beamforming and beam tracing compensation. Tidal values can also be added in real time using a radio link between the station and the vessel. All of them are time stamped and thus are correlated to each other with the aid of acquisition time in an internal processor system.

2.4 Chilean multibeam system configuration.

SHOA has been involved in multibeam (MB) data acquisition since 1999, when ATLAS MBES and respective ancillary sensors (e.g., GPS, MRU, Gyro and SSP probes) were installed on the hydrographic vessel PSH 77 *CABRALES*. The system configuration allows acquisition of bathymetric data from 0.5 metres (below the transducer) up to 1200 metres. Thus areas with depths from 10 to 250 metres are surveyed with FANSWEEP 20 (200 kHz) and areas from 250 up to 1200 metres with HYDROSWEEP MD 2 (50 kHz). The system also has a singlebeam echosounder ATLAS DESO 25 and forward-looking sonar for hazard detection.

For vessel motion compensation ATLAS DYNABASE-CRU is designed to give roll, pitch and heave correction, while ANSCHUTZ Gyro Compass Standard 20 provides the gyro signal for generation of the ship's heading. For differential positioning the system has two Z-12 ASTECH DGPS-RTK receivers. RESON SVP-10 is used for permanent measurement of sound speed at the transducer and RESON SVP-20 for measurement of sound speed profiles.

Data acquisition and pre- and post-processing are handled with ATLAS HYDROMAP ONLINE (survey operator workstation), ATLAS HYDROMAP OFFLINE (pre/post processing workstation) and CARIS HIPS. ATLAS HYDROMAP ONLINE is the onboard system for simultaneous acquisition of bathymetry and side-scan, real-time mapping and storage of data from the multibeam echosounder (FANSWEEP 20, HYDROSWEEP MD 2 and DESO 25). Additionally, HYDROMAP ONLINE includes the necessary functions for control and operation of the FANSWEEP 20 and HYDROSWEEP MD 2. The HYDROMAP ONLINE software is installed on the survey operator workstation and on the pre/post-processing workstation (for back-up purposes). ATLAS HYDROMAP OFFLINE, in conjunction with CARIS HIPS, are the systems for managing, editing, correcting and post-processing of the data from the multibeam echosounders (ATLAS FANSWEEP 20 and HYDROSWEEP MD 2) and singlebeam echosounder (DESO 25). HYDROMAP OFFLINE is installed at the pre/post-processing workstation and allows hydrographic data verification, correction and post-processing simultaneous with the data acquisition.

The vessel is equipped with three launches for hydrographic data acquisition in shallow areas. Two of them use KNUDSEN 320MP (dual frequency) single beam echosounder and one uses DESO 17 (dual frequency) handled with HYDROMAP SUSY. The *CABRALES* also has a towed side-scan for hazard detection.

The Atlas HYDROSWEEP MD-2 provides coverage up to 8 times the water depth using a Mills Cross transducer. With a depth range from 5 to 1200 metres, this system works in deeper areas than the FANSWEEP 20. Both are hull mounted in the Chilean hydrographic vessel. The methodology for bottom detection used by the HYDROSWEEP MD-2 is basically dependent on the outer beam and inner beam region. For the inner region (0° to 30°), individual echoes are located by an iterative algorithm searching for the centre of energy (i.e., centre of mass). For the outer region (30° to 76°) echoes are located by means of the signal intersection of adjacent beams (i.e., phase measurement). The HYDROSWEEP MD-2 designed to be used in intermediate depth waters, is a system with a frequency of 50 kHz that is less accurate than the FANSWEEP 20 system in shallower waters. Its beamwidth along-track is 1.7° and in the across-track will vary from 4° (within ±30°) to 2° (outside ±30°).

2.5 Data processing of ATLAS FANSWEEP 20 in HIPS.

The format used to transfer the hydrographic data into a data processing system is ATLAS SURF (Sensor Independent Raw Data Format, in English), which contains data from a specific hydro-acoustic sensor accompanied by other sensors necessary for bathymetric computation.

CARIS HIPS reads from the ATLAS SURF format the following:

a. Vessel referenced depth: which consists of across and along track distance and depth relative to the vessel reference coordinate frame.

b. Transducer referenced depth: travel time and the angle, which are required for the sound speed correction in post-processing.

c. Vessel motion: roll, pitch, heave and heading.

d. Tide measurement. If depth is Tide corrected in real time, CARIS HIPS will split this file in two, containing depth and Tide information separately, which allows post-processing work.

e. Sound speed measurement. CARIS HIPS allows ray tracing with sound speed profiles after data acquisition (relevant in post-processing). Corrections for vessel motion need to be applied to sound speed ray tracing (i.e., heave). Roll and pitch are not applied because the angle data is already compensated. Depths, with sound speed correction applied, need to be referenced to the vessel reference point, thus transducer plate offsets need to be entered into HIPS. The sound speed correction process in HIPS will re-compute the vessel referenced across-track, along-track and depth solution [CARIS, 2004]. To re-compute the final latitude, longitude and depth for all soundings the Merge function must be applied.

If sound speed correction is not applied in HIPS (i.e., post-processing), then FANSWEEP 20 data only requires a basic set-up in the Vessel Configuration File (VCF) filled mostly by zero values. Under this circumstance, it is important to bear in mind that in the Swath section the sonar must be defined as a single head.

On the other hand, if sound speed correction will be applied after data acquisition, then it is necessary to define the sensor installation parameters to be used by the algorithm in the re-compute depth solution. In the Swath section the sonar must be defined as a dual head type configuration.

2.6 Performance of a multibeam echosounder.

In a multibeam echosounder the range of performance is a function of the attenuation, directivity, source level, spherical spreading, ambient noise and bottom backscatter strength (Equation 2.1). Thus different sources can affect the measurement, which will result in miscorrection and mistracking of the bottom detection.

$$SN=SL+BTS+DI-2TL-NL \tag{2.1}$$

Where:
SN=Signal to Noise Ratio
SL= Source Level
TL= Transmission Losses
NL= Noise Level
BTS= Backscatter Strength
DI= Directivity Index [Urick, 1983]

Within these factors, the operators can control power (SL), frequency (TL), directivity (DI), and pulse length (BTS). On the other hand, spherical spreading (TL), seabed backscatter angular response (BTS), sea-state (NL) and ship noise (NL) must be understood to minimize their unwanted effects.

Sonar performance is affected by attenuation due to sound absorption through the water column. The resulting transmission loss is comprised of two elements: spherical spreading and absorption losses [Urick, 1983]. The acoustic wave is transmitted through the water spherically. Since the wave area is increased further away from the source, the energy per unit area decays as $1/R^2$ (conservation of acoustic energy in one way), where R is the Range to target. The reduction in constant energy distributed over the surface of a growing sphere is therefore given by 20 log R (dB). Thus the total energy of an acoustic wave lost traveling through the water column (i.e., source-bottom-source) is –40 log R dB.

Attenuation, which is the energy loss due to absorption and scattering, is frequency and water temperature dependent. Its value can be estimated using an empirical relation based on observations, knowing the temperature, salinity, depth and water pH [Hughes Clarke, 2005]. Low frequency systems have better range performance since they are less susceptible to attenuation. On the other hand, high frequencies systems are strongly affected by attenuation, but they have better range and angular resolution used to discriminate small objects laying on the seafloor and the array size is more manageable.

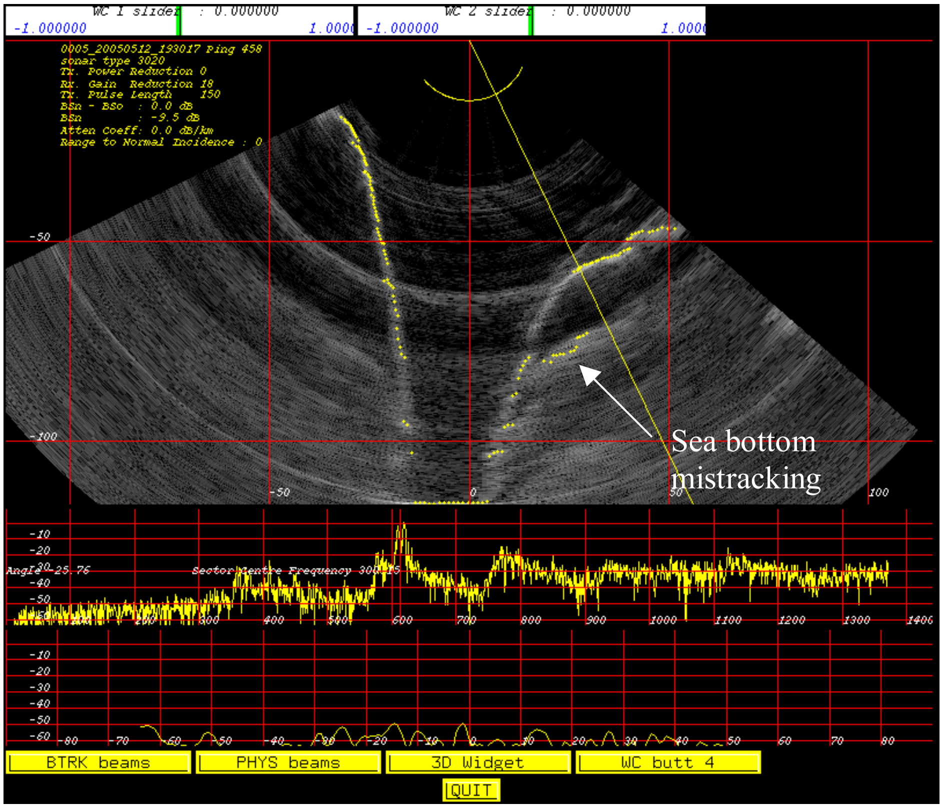
The performance of any mapping sonar is inherently limited by the local acoustic environment [Urick, 1983]. The presence of unwanted reverberation and scattering affect the capability to determine the intended target. Examples of local acoustic noises are: seismic noise, ship noise, hail, sea surface (due to wind), rain and thermal noise. Signal to noise is thus defined by the noise spectral density at the centre frequency and the receiver bandwidth. For bottom tracking, un-synchronized external noise is not an issue unless it will be comparable with the bottom return signal.

2.6.1 Sea bottom mistracking.

Under ideal conditions (benign seafloor geometry and no changes in sediment distribution), bottom tracking should be robust. Differences in sediment type and extreme changes in the seafloor morphology considerably affect the detection of the bottom however.

In extreme seabed geometry, with steep slopes and smooth surfaces, for example, sidelobe echoes can dominate. Thus the main lobe echo could be masked and presented weaker than sidelobe due to a weak reflection of the bottom. First arrivals from the sidelobe tend to produce confusion in sea bottom tracking. Although multibeam systems apply sidelobe suppression, extreme seafloor morphology could produce first arrival from sidelobe, which if also combined with a high contrast in backscatter strength will produce a higher specular return compared to the desired signal. For any MBES these situations will make the bottom detection a very complex task (Figure 2.3), in which case its data will be corrupted and the seafloor will be mistracked. Independently of the automated depth estimator (e.g., CUBE), such situations will represent difficulties to define where the true bottom was. This noise-data affecting the downhill side will be difficult for cleaning for any algorithm and require operator intervention since outliers will appear to cluster strongly in space and occur where data (representing the true depth) is poorly defined.

That scenario is a very common in Patagonian fjords where survey lines have been planned to run parallel to the shoreline. One side of the sonar faces towards high backscatter signal (from steep slope walls), while the other side of the sonar faces toward very low backscatter signal (from the flat-bottom of the fjord). The presence of high contrast in backscatter strength (25dB), between the clay and gravel (Figure 2.4), can cause the bottom detection to fail. According to the designed sidelobe level for the beamforming (~23dB) the sonar recognizes the low signal to noise level, thus beams are either rejected or mistracked where this problem occurs [Hughes Clarke, 2006a].



```
0005_20050512_193017 Ping 458
sonar type 3020
Tx. Power Reduction 0
Rx. Gain  Reduction 18
Tx. Pulse Length    150
BSn - BSo  : 0.0 dB
BSn        : -9.5 dB
Atten Coeff: 0.0 dB/km
Range to Normal Incidence : 0
```

Figure 2.3: Drowned Canyon (Lake Powell AZ). Data acquired with an EM3002 water column image. Sea bottom mistracking due to extreme seabed geometry (image from the OMG software).

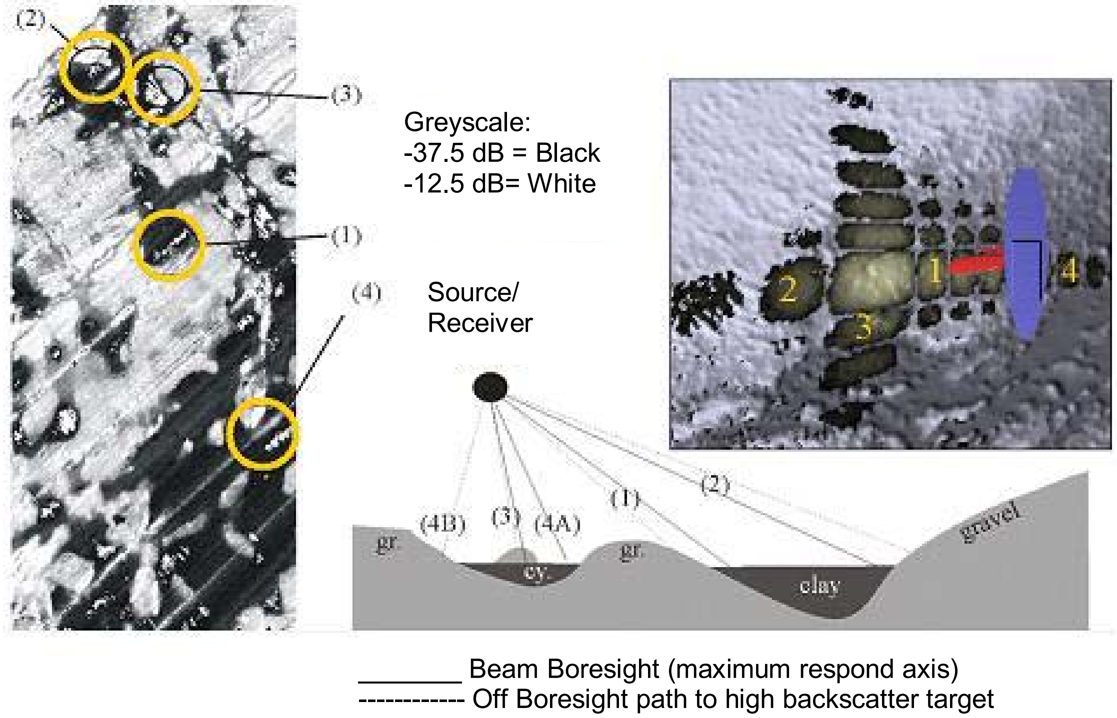


Figure 2.4: Case (1) Tracking inboard sidelobe. Not as bad, as high backscatter region is at a lower grazing angle. Case (2) Tracking outboard sidelobe period more likely, as high backscatter region is at a larger grazing angle. Case (3) Tracking high backscatter forward of the main swath in sidelobe of the transmit beam pattern. Case (4) Tracking high backscatter material in sidelobe on other side of swath. Figure and text extracted (from Hughes Clarke, [2006]).

2.6.2 Interferometric sea bottom mistracking.

The multibeam system used by the Chilean navy uses the interferometric techniques for sea bottom tracking. For an interferometric system the noise is a factor that limits the maximum range over which bathymetric data can be measured. For instance, a rough seafloor (with variable sediments type) will have a contaminated phase measurement. The noise will degrade the signal, at certain times being useless for bathymetry. Since interferometric systems use the phase measurement derived from broad receive beams to determinate the direction from the incoming signal, they cannot deal with echoes that arrive at the same time. This problem (i.e., common range ambiguity) can be observed for example in steep slopes areas, which also have another associated problem: Layover. The Layover effect (extreme case of common range ambiguity) is present in areas where the topography is steeper than the expanding waveform [Hughes Clarke, 2005]. Flat areas can also have common range ambiguity. Multipath echo ambiguity on phase signal can also produce interference in bathymetric measurements. Multiple signals coming from nadir can corrupt the phase sweep (Figure 2.5). The current technique within FANSWEEP 20 to avoid this error is to use discrete frequencies. Two different lobes are generated with slightly different frequencies, one at nadir and other for the oblique angles. Thus multiple returns are outside the bandwidth of outer lobe causing no interference. This is quite important in this thesis, since reducing noise-data will imply a better depth estimation. .

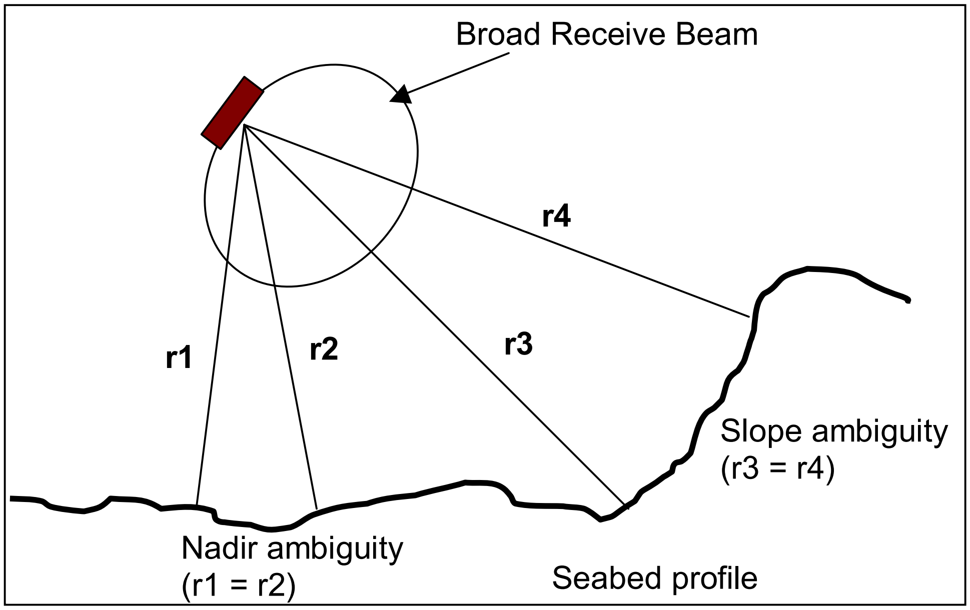


Figure 2.5: Common range ambiguity (nadir and steep slope) where different echoes arrive at the same time (from Hughes Clarke [2005]).

3. ENVIRONMENT OF THE PATAGONIAN FJORDS AND CHANNELS.

This chapter explains the variability in the seafloor geomorphology in the Patagonian region. As was explained previously, the seafloor geomorphology has a direct influence in the bathymetric data collected. Possible issues such as strong backscatter variability between different sediment types and extreme morphology are common in the Patagonian water. Consequently, the bathymetric data collected will be strongly affected by noise-data associated with sidelobe interference causing sea-bottom mistracking. Then CUBE, in some cases, will attempt to estimate the most likely depth from cluster outlier points that do not satisfy the normal properties of outliers [Calder and Smith, 2004].

3.1 Geomorphology of the Patagonian Channels and fjords.

Throughout history a series of glaciations have affected the earth (the last glaciations occurred approximately 12,000 years ago). During these periods, glaciers and sea level have changed the morphology of sea bottom on the continental shelf. Thus, the crust has been deformed by erosion plus deposition actions. Basins kilometres in length are generated by the action of glaciers (i.e., ice withdrawal) and filled up by the ocean when sea level arises.

The region between Puerto Montt and Cabo de Hornos (Figure 3.1) is subject to tectonic subduction and glacial sedimentation. The ocean has penetrated into the intermediate depression, showing a variable morphology of gulfs, channels, estuaries and fjords.

Recalling the previous chapter, the capability to detect the seafloor will depend on the backscatter strength and the seafloor morphology. If the signal reflected by the sea bottom is not strong enough to be measured by a multibeam system, the result will be a failure in data acquisition.

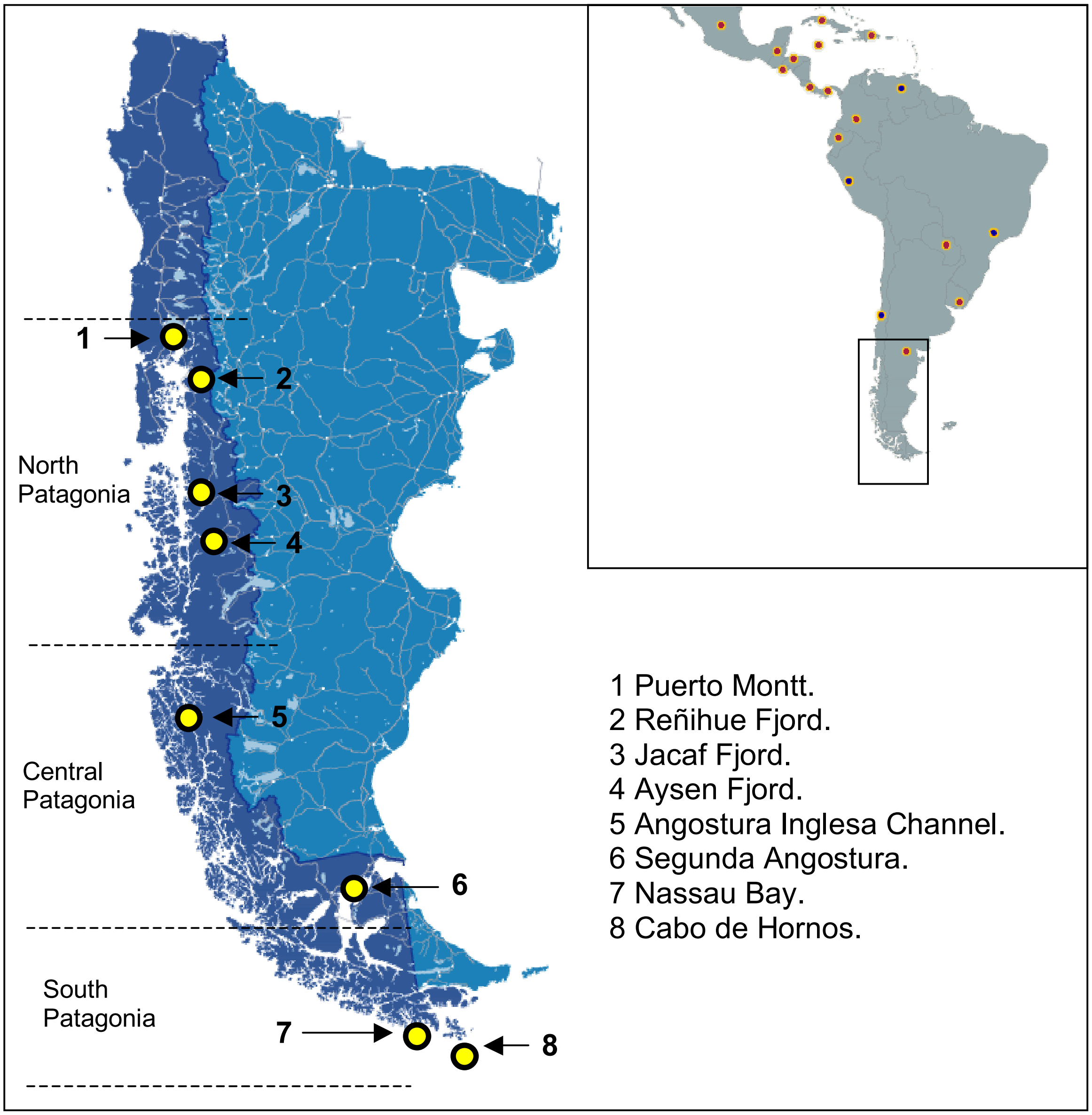


Figure 3.1: Chilean Patagonia. The seabed of fjords, channels and gulfs has been deformed and filled by the action of ice. Extreme morphology and many different sedimentation types make bottom detection a difficult task.

3.1.1 North Patagonia Area.

The geomorphology in this area can be explained mainly by differences according to the piedmont's width. Thus the fjord's depth is directly proportional to the width of this trench.

This area can be spilt into three sectors, delimited by the Jacaf Channel and the Reñihue Fjord (Figure 3.1). Their differences are regulated by the absence or presence of fjords. For example, in the north and south sectors (with presence of fjords), in general the sea bottom is very irregular. Extreme changes in depth are predominant in the fjords, where glacial deposits, such as moraines and drumlins, are observed. The basins have an accumulation of sediments (20 to 100 metres in thickness), highly stratified and acoustically weakly reflecting (Figure 3.2). On the other hand, the central area (without fjords) has a piedmont mostly intact and regular with a layer of sediments made by physical weathering action (i.e., breakdown of rocks and soils with direct atmospheric contact such as water and pressure).

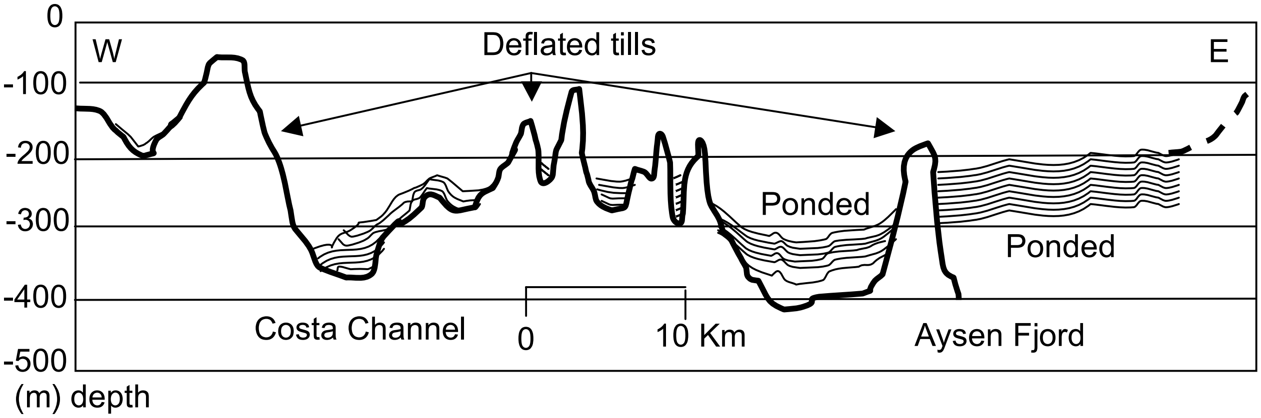


Figure 3.2: The flat bottom areas are compound by sediments with a thickness of 30 to 60 metres called Ponded (i.e. Fine-grained post glacial mud). The contrast is so strong with the high backscatter signal of deflated Tills (i.e. boulders and rock outcrop) that it can result in failures in the sea bottom tracking. From (Araya [1996]).

The fjords' basins are basically flat bottomed with sedimentation of around 30 to 60 metres of thickness and horizontally stratified (3 to 4 metres of thickness). Their constituents can be strongly, tenuously or weakly reflective. Sedimentation in this area results from pro-glacial mechanisms (i.e., fluvial glacial), deep currents and glaciomarine sedimentation (i.e., tide-water glaciers). In the Jacaf Fjord (unlike others fjords in the same area), the moraines result from ice scouring and glacial Till accumulation [Araya, 1995].

The FANSWEEP 20, as with any other MBES, has difficulties in bottom detection in these areas. Operationally it is often necessary to conduct several survey passes until one can obtain a good bottom track. High backscatter contrast between different sediment types, plus steep slopes, will make the MBES fail. The morphology, in some of these fjords, is so irregular that sea bottom tracking has no solution (Figure 3.3), and additional survey lines must be added to solve this problem.

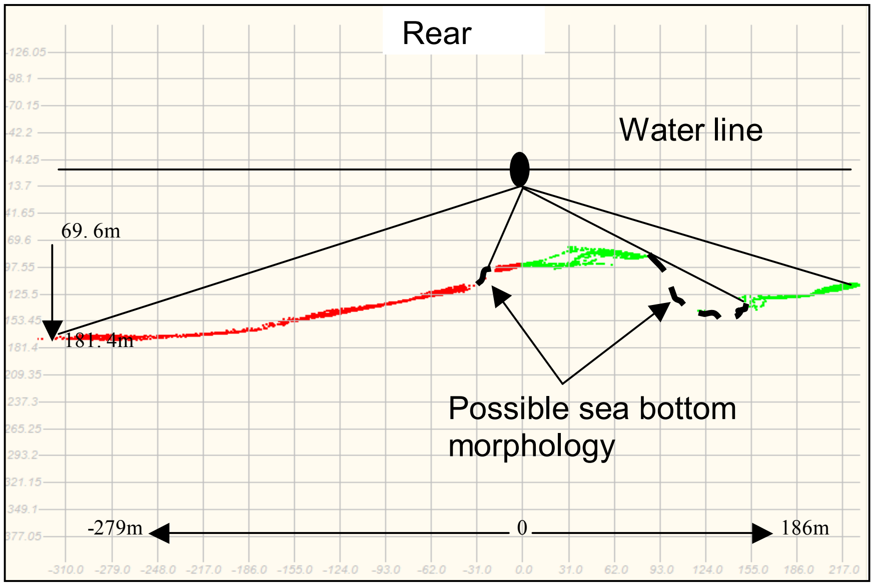


Figure 3.3: Sea bottom mistracked due to strong variability in depth. Vertical exaggeration 1:1. Data from Reñihue Fjord collected using FANSWEEP 20 (200 kHz).

3.1.2 Central Patagonian Area.

Here, unlike in the northern Patagonian area, the effects of the last glaciations are stronger. The piedmont has a very irregular structure. Both extremes (north and south) have fjords and also correspond to the wider area of the piedmont. With depths over 1000 metres, the north sector has morphology typically associated to fjords with moraines composed of diamicton.

Fjord basins, unlike the piedmont, have a more regular stratification of sediments (i.e., horizontally stratified) and associated glaciomarine effects. Their moraines also consist of diamicton, and have many categories associated with different mechanisms of formation.

The central area has no fjords and it is the narrowest sector of the intermediate depression. With depths from 50 to 200 metres, the sediments are trapped between moraines in layers of 10 to 15 metres thickness, which are acoustically weakly reflecting [Araya, 1996]. Thus, MBES operating in this region could have sea bottom mistracking due to the strong variability in backscatter signal between the walls (mostly rock compound) and the basin of the channel (fine, acoustically weakly reflecting, mud). Some of the problems found in the data acquired by the FANSWEEP 20 (Figure 3.4), could be due to this effect. Independently of its cause, this noise-data considerably affects the depth estimation made by CUBE (or by any other algorithm) Rather than the deeper, sparser true depth estimations, the dense noise-data is more probable to be selected by the disambiguation engine as the most likely solution.

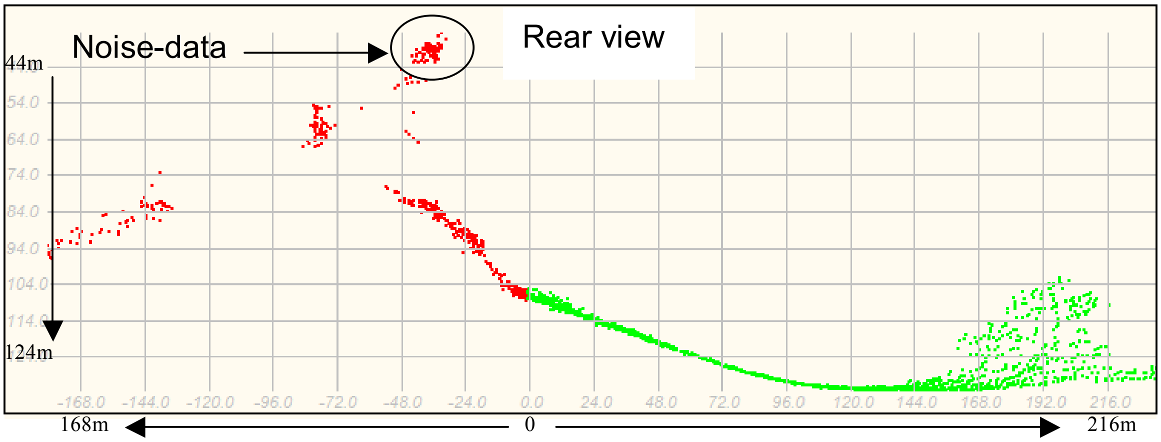


Figure 3.4: Noise-data produced by sea bottom mistracking. This dense noise-data will affect the efficiency of CUBE algorithm. Data from Reñihue Fjord collected using FANSWEEP 20.

3.1.3 South Patagonian Area.

Depth and sediment thickness are directly proportional in this area. The Piedmont lobes, fjords and wide channels (from shallowest to deepest, respectively) have a specific structure of sedimentation. The Piedmont lobes were generated by transgression (i.e., sea level rise) in the early inter-glacial period (e.g., Eastward of Segunda Angostura-Magallanes Strait) and by floating glacial ice (e.g., Nassau Bay). The sea bottom in the piedmont's lobes has a thin cover of fine sediment (e.g., gravel and mud) over a layer of thicker material.

Fjords, unlike those located in north and central area, have no large sediment stratification and do not have significant moraines in their basins. The sediments are acoustically weakly reflecting.

Sea bottom in wide channels is formed by moraines of glacial Till and basins of stratified sedimentation. The upper layer is mostly composed of sedimentation formed from outwash, on the order of 10 metres thick [Araya, 1998].

4. BATHYMETRIC DATA CLEANING

This chapter is focused on the process still used by SHOA in the data analysis and cleaning procedure (i.e., interactive editing), the CARIS HIPS alternatives to speed up this process and the theory behind CUBE and its associated parameters.

Interactive editing implies time consuming tasks and many subjective decisions. On the other hand, HIPS offers alternatives to speed up the data cleaning and help the operator to make the right decision based on statistical information from the data. Three different processes are available in CARIS HIPS to generate depth estimations: Swath Angle, Uncertainty and CUBE. The results are then stored and presented in a CARIS BASE surface.

4.1 Interactive Editing.

In this data processing method, bathymetric data acquired mainly by a multibeam echosounder is analyzed line-by-line and swath-by-swath. The survey data is downloaded into a visualization system and investigated for artifacts and outliers, which are then interactively edited [Mallace and Gee, 2004]. The high-resolution bathymetric data process can be speeded up using basic automatic filters.

In interactive editing the operator is the main decision maker in filtering outliers. The problem here is not only the time needed to clean the data after the survey, but the human intervention where the operators have to deal with subjective decisions about cleaning the whole data set. Their decisions, disregarding their skills, mostly defined by their expertise and dedication, could be wrong [Calder, 2003].

In Chile, SHOA has legal responsibility for the accuracy and reliability level of the nautical products. The current steps used by SHOA's operators involve swath filters contained in CARIS HIPS, where mainly outer beams (over 60 degrees) are cut-off due to refraction artifacts. Two methods for data editing and examination are then used: Swath editor (to process the data line-by-line), and Subset editor (to analyze the survey area in small sub-areas).

The Swath procedure involves the visualization of just one line, which is a disadvantage when it is required to see whether overlapping beams of different track lines match each other. This flaw can be rectified using Subset editor. Subset editor differs from Swath in that soundings are no longer correlated according to across-track distance (or beam number), but are now corrected for navigation, vessel heading, and other ancillary sensors. Thus each sounding has a latitude and longitude attached to it [CARIS, 2006a]. Subset mode takes a portion from the dataset where multiple tracks can be visualized at the same time. The area selected is presented in 2D and 3D making the analysis of adjacent swaths easier. Subsets can be displayed one by one until the dataset has been analyzed and marked as completed. This procedure implies revising the whole survey.

4.2 Semi-automatic method.

Semi-automatic filters have been implemented in HIPS with the aim of speeding up the cleaning process, and reserving human intervention for those areas where noise-data could not be resolved by the filters. The product achieved, a representation of the seafloor, is suitable for navigation proposes and any other environmental research.

CARIS HIPS 6.1 has different filters available for bathymetric data cleaning. The operator sets up these filters, based on knowledge of the area surveyed and Total Propagated Error model availability.

4.2.1 Filters contained in CARIS HIPS and SIPS 6.1.

HIPS contains two specialized tools designed as bathymetric data filters called Swath and TPE. CUBE, although not a filter, has been adopted by HIPS to use the surface derived from the point-wise estimates of depth that CUBE generates, to select soundings that are judged consistent with this surface, and thereby flag all other soundings as “not for use”. This is, however, an added behavior that is entirely dependent on the implementation software for the basic CUBE algorithm.

An important feature in HIPS filtering is that none of the “rejected” soundings are eliminated, just are flagged as rejected. Therefore the operator can go back and re-do the cleaning with new parameters, or merely recover these filtered soundings.

4.2.1.1 Swath Filter.

Multibeam bathymetric data can be affected by several errors that make the beams (and associated depth) less reliable. The effects of water column stratification and vessel motion misalignment are mainly seen in the outer beams. An operator may have to take a lot of time to clean these data, which are essentially corrupted through the entire surveyed area. The Swath filter has the advantage of being able to reject this type of outlier automatically. To run the filter the operator must have previous knowledge (normally attached to the data) of the area surveyed and the sonar, to set up the filter’s parameter fields; thus the bathymetric data is automatically cleaned (rejecting those soundings which fall outside the parameters selected). The parameters for filtering are: minimum and maximum depth, beam-to-beam slope, across track distance, nadir (angles and distance), quality values set by the sonar and missing neighbors.

The advantage for bathymetric data cleaning is the straightforward procedure since no TPE calculations are implied. The disadvantage of using simple filters is that they can often be mistaken about data, accepting data that should be rejected, or even worse, removing data that should be accepted. This method of filtering can be used, for example, when no suitable Device Model is contained in CARIS HIPS for a specific sonar.

4.2.1.2 HIPS Total Propagated Error (TPE) filter.

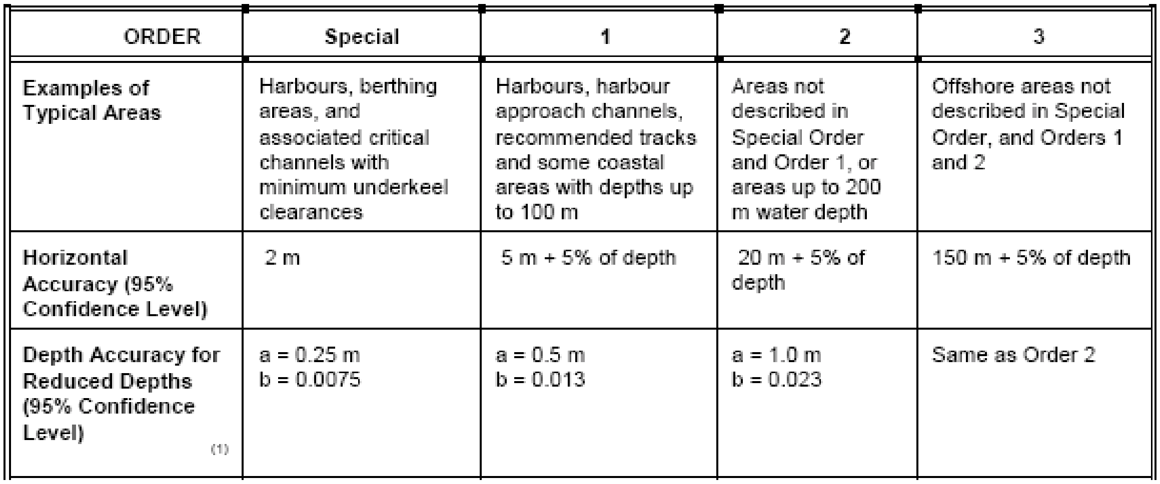
Unlike the Swath filter, the TPE filter uses the uncertainty associated with each sounding, which is calculated with the propagated error model. The error model takes into account the possible sources of uncertainty for bathymetric data, the standard deviation values pre-defined by the operator and the device model in HIPS for the specific sonar used. Once the TPE values (i.e., Horizontal TPE and Vertical TPE) are calculated for each sounding, the TPE filter can be run. The software compares the uncertainty against the limits set by the IHO standard [CARIS, 2006a] for the order of survey defined by the operator. Soundings whose TPE are outside the specifications are flagged as rejected. The limit for horizontal uncertainties are given in Table 4.1 [IHO, 1998]; the vertical uncertainty is computed by Equation 4.1.

$$\pm \sqrt{[a^2 + (b*d)^2]} \tag{4.1}$$

Where:
a = the constant depth error (sum of all constant errors).
(b * d) = the depth dependant error (sum of all depth dependant errors).
b = the factor of depth dependant.
d = depth

Using the values of (a, b) for the required survey Order in Table 4.1.

Table 4.1: Summary of minimum Standards for hydrographic surveys. (From IHO [1998]).



ORDER	Special	1	2	3
Examples of Typical Areas	Harbours, berthing areas, and associated critical channels with minimum underkeel clearances	Harbours, harbour approach channels, recommended tracks and some coastal areas with depths up to 100 m	Areas not described in Special Order and Order 1, or areas up to 200 m water depth	Offshore areas not described in Special Order, and Orders 1 and 2
Horizontal Accuracy (95% Confidence Level)	2 m	5 m + 5% of depth	20 m + 5% of depth	150 m + 5% of depth
Depth Accuracy for Reduced Depths (95% Confidence Level) (1)	a = 0.25 m b = 0.0075	a = 0.5 m b = 0.013	a = 1.0 m b = 0.023	Same as Order 2

4.2.1.3 HIPS "CUBE" filter.

The Combined Uncertainty and Bathymetry Estimator (CUBE) is an algorithm used to generate point-wise estimates of depth from dense soundings. The CARIS surface derived from the results of a CUBE pass over the data is also a powerful, semi-automated cleaning tool that can be used to increase processing efficiency [CARIS, 2006a]. The surface derived from the point-wise estimates of depth that CUBE generates (including uncertainty estimates) is used to select points that are judged consistent with the surface; all other soundings are flagged as "not for use". Thus those soundings that fall far outside of the surface product will be marked as rejected and will not be considered in further processes. One advantage of using the surface product as a filter is that the time involved in interactive editing is greatly reduced.

4.3 Bathymetry Associated with Statistical Errors (BASE) Surfaces.

A BASE Surface is a georeferenced image of a multi-attributed, weighted-mean surface. A BASE surface may contain a visual representation of horizontal and vertical uncertainty. The BASE surface meets the needs of various users. The primary focus of current survey products is chart production by creating a shoal-biased bin where shoals are exactly preserved but finer seafloor features are omitted. Other users - marine geologists, coastal zones management, fisheries habitat management, and ocean engineering - require a more detailed view of the seafloor. The BASE surface can be generated to provide for either safety of navigation or for a detailed examination of the seafloor [CARIS, 2007].

4.3.1 CARIS HIPS BASE Surfaces.

Within the HIPS workflow three different BASE surface processes are available. All of them are capable of creating smooth surfaces preserving the detailed morphology of the seafloor. However, they are quite different in terms of assigning weights to the soundings. Uncertainty and “CUBE” surfaces use TPE values and distance from the node to weight soundings. On the other hand, Swath Angle uses distance from the node and the sonar geometry.

The Chilean Hydrographic Office currently uses the Swath Angle method. Hence the only means to validate whether the survey meet the IHO S-44 specifications is by careful analysis of crossing survey lines.

According to the goal of this research, the three BASE Surfaces were analyzed to determine the most accurate method for Chilean bathymetric data cleaning. The following table (4.2) summarizes the alternatives solutions and why CARIS “CUBE” BASE surface was selected as the best solution.

Table 4.2: BASE surfaces achieved by different methodologies. These BASE surfaces can be created using CARIS HIPS 6.1, software currently used by SHOA.

CARIS BASE surface	Range weight	IHO compliant	Statistically robust estimates of depth
Swath	Yes	No	No
TPE	Yes	Yes	No
CUBE	Yes	Yes	Yes

4.4 CUBE theory and parameters associated.

CUBE was developed by Dr. Brian Calder (UNH) in an effort to process raw high-resolution bathymetric data in a semi-automatic way, avoiding subjective decisions (when possible) and processing time. Multibeam systems can determine the seafloor morphology with a high accuracy and reliability due to the contribution of many soundings in just one swath. The task is not so easy; soundings are affected by different errors, therefore we cannot determine the "true", just the most likely depth. The CUBE algorithm gets as much information as it can from the data to determine the most probable depth at any point of the survey area. Soundings are weighted and contributed to estimation nodes based on sounding uncertainty values and the distance from the node. Each incoming sounding and respective uncertainty is propagated and combined at a node, and a robust, weighted, estimated true depth is constructed. By repeating this process in a (regular) grid over the whole area of interest, a summary of the depths in the survey area is constructed.

The algorithm also has built-in checks for consistency of the data, and supports multiple potential depth reconstructions (i.e., hypotheses) at each point. The user is always provided with information on these potential reconstructions, and CUBE's estimate of their relative strengths. The goal is to provide not only objective estimates of depth, but also objective estimates of the quality of these reconstructions so that the operator has tools to decide whether to agree with the algorithm or not [Calder and Wells, 2007]. Since the CUBE algorithm can support multiple hypotheses (i.e., possible depths) at a given node (depending on the variation of the sounding data), the algorithm requires a Disambiguation method to determine which hypothesis at each node to suggest to the operator as most likely to be "correct".

CUBE's three mechanisms are: Assimilation, Intervention and Disambiguation. Assimilation (i.e., statistical assembly of incoming soundings at nodes to obtain estimated depths and depth uncertainties at each node) involves two processes: Scattering and Gathering that are important in this research. Other processes such as Reordering (designed to be the first step in CUBE processing) and Assimilation Memory Fading will not be considered in this research since they are not essential with the new version of CUBE included in HIPS.

4.4.1 Assimilation (Scattering process).

Scattering is the process of passing the information about each sounding to the surrounding nodes. This process takes into account the distance from the sounding to the node and the base uncertainty of the sounding (i.e. its TPE), and is essentially a computation of the expected propagated uncertainty of the sounding as applied to the (remote) node. CUBE has defined two parameters for this process than can be changed by the advanced user: Horiz_error_scale and Distance_exponent. Horizontal Error Scale is used to scale the horizontal uncertainty of each sounding that fell within the radius of the node's influence, to compute the node uncertainty. Distance Exponent (default value = 2) is used to control the exponential increase of the vertical uncertainty of the sounding as a function of its distance from the node.

The default value for horiz_error_scale is 2.95. If this value is decreased, the propagated uncertainty to the node will be reduced and soundings that contribute to the node could form different hypotheses. Reducing the value of horiz_error_scale increases the distance influence, reducing the certainty of the sounding (Equation 4.2).

$$\sigma_p^2 = \sigma_v^2 \left(1 + \left[\frac{dist + hes * \sigma_h}{node\_spacing} \right]^{de} \right) \tag{4.2}$$

(from Calder and Wells [2007])

Where:

σ_p = The propagated uncertainty after the translation of a sounding to a nodal point. The value is measured in standard deviation and represents the vertical uncertainty of the node (since node points are defined to be perfect at horizontal location no horizontal uncertainty is computed for the node).
σ_v and σ_h = The vertical and horizontal uncertainty attributes associated with the input sounding (at its original location).
dist = The distance from sounding location to the node.
node_spacing = The distance between nodes.
hes = The Horizontal error scale.
de = The distance exponent.

According to the CUBE users' manual, leaving the default value assigned for Horizontal Error Scale could mean that, in a steep seafloor, soundings in both shallow and deep sides of the node could appear to be compatible with the computed hypothesis (but with a significant standard deviation) instead of producing two different hypotheses.

4.4.2 Assimilation (Gathering process).

Gathering is the second process present in Assimilation, and involves which soundings will be considered to contribute to a node. The acceptance criterion is defined by the distance of those soundings from the node. Thus, soundings inside the capture radius of the node will be accepted and will have an influence in the hypothesis formulation; those outside of the radius are ignored.

Two parameters are accessible to modify the acceptance soundings criteria (i.e., distance from the node). Capture_distance_scale, controls the radius of acceptance of soundings according to the depth, and Capture_distance_minimum, defines the acceptance radius according to a minimum distance in metres from the node. Both parameters work together and have a default value defined as 5% of depth and 0.5 metres distance, respectively.

For example, at 10 metres depth, a node's depth will be estimated using the soundings that fall within a radius of 0.5 metres from the node. In much deeper waters the parameters that control the radius of acceptance will be capture_distance_scale, while for shallower areas (0 to 9 metres) the radius defined by capture_distance_minimum will be maintained independent of the depth. Thus the algorithm will take the maximum value of the two values calculated from two parameters to define the radius of acceptance according to the depth.

In some cases, increasing these parameters could smooth the surface since more soundings are used and combined to contribute to a node. CUBE uses these processes to assimilate the soundings to the nodes, but also requires other elements to select the most likely alternative or hypothesis such as the Intervention process. These parameters should be used to modulate the most suitable application of CARIS CUBE implementation in Chilean bathymetric data acquired in the Patagonian channels.

4.4.3 Intervention.

Intervention is designed to interrupt the assimilation process when incoming soundings are not statistically consistent with any of the previous depth hypotheses. The result of statistically inconsistent incoming soundings is a new hypothesis (i.e., alternative hypothesis). For example, soundings that, with their uncertainty, are within the vertical uncertainty of a given hypothesis (i.e., are statistically consistent) will contribute to the hypothesis. A statistically inconsistent sounding breaks the hypothesis construction, starting a new one. When the first sounding works through the input queue structure and the scatter and gather computations to be presented to the node, it is adopted as the first depth hypothesis. The second sounding to be presented is compared with this hypothesis. If they agree on the depth within their uncertainty limits, then the second sounding is integrated into this hypothesis; if not, it forms the basis of a second hypothesis. Subsequent soundings are treated as the second one was, except that they are compared to all hypotheses extant at the node to determine the closest match, and are compared with the closest one for potential assimilation or intervention [Calder and Wells, 2007].

The parameter used to specify the threshold for significant offset from the current estimate and thus warrant the hypotheses splitting is called by CARIS HIPS Estimate Offset, and its default value is 4. By decreasing this value, smaller depth deviations from the hypothesis will allow the production of alternative hypotheses. On the other hand, increasing this value will produce larger depth deviations to be incorporated in the same hypothesis. Whether incoming soundings will contribute to the null hypothesis or will create a new one is defined by the cumulative Bayes factor: a new hypothesis is defined when the logarithm of the corresponding sequence of Bayes factor (log Bn) is zero (Equation 4.3) indicating odds in favor of the alternate model. Since normalized differences are used, this is computed in terms of the standard Normal distribution.

$$\begin{aligned} \text{Log Bn} \propto \quad & (h^2 - 2h\left|e\right|_n) = h\,(h - 2\left|e\right|_n) = 0 \\ & h = 2\left|e\right|_n,\ h > 0 \end{aligned} \tag{4.3}$$

Where:

e_n = The normalized difference between the observation and the current depth estimate.
h = The estimate offset value.

Hence, to consider a variation outside of the 95% Confidence interval, a critical point of $\left|e_n\right| = 1.96$ was chosen, and therefore $h = 2\left|e_n\right| = 3.92$ [Calder and Wells, 2007].

The four CUBE parameters described previously are directly accessible in CARIS HIPS 6.1 when “CUBE” surface is selected. Their importance in the algorithm for the assimilation of the surrounding soundings to a node has been highlighted by HIPS in a modify command window. Due to the nature of this research (i.e., tuning the CARIS implementation of CUBE for Patagonian waters) the parameters that should be changed are those related to scattering and gathering processes (Horizontal Error Scale, Capture Distance Scale and Capture Distance Minimum). Also the parameter associated with the limitation of the vertical step of the node (Estimate Offset) could help in a better depth estimation using CUBE surface for the Chilean scenario.

4.4.4 Disambiguation Method.

The Disambiguation method is the process used by CUBE to identify the most likely depth solution when a series of hypotheses are populating the node. Since all the hypotheses are retained, the operator can override the decision if required. The disambiguation engine (automatic decision maker), has been designed with different types of methodologies or rules. Which one must be selected depends on the operator's focus in terms of reliability, processor speed and data knowledge.

In HIPS, four disambiguation rules are user-selectable. Two of them (i.e., Density and Locale) are configured to run according to their own rules completely independent of each other. The remaining two are results of either a combination of rules (i.e., Density-Locale) or using previous data (i.e., Initialization surface). So far, Density is the most commonly used rule since it is faster in calculation and more reliable. This method of disambiguation attempts to identify the best solution, taking into account the number of soundings that populated the hypotheses. Thus the hypothesis that is denser in soundings will be selected as the most reliable and hence the most suitable for depth estimation at a node.

The Locale method considers the surrounding nodes to make its decision. To do that, nodes within the radius of influence (measurement in nodes, not in metres) will be watched. If those nodes have small hypothesis strength value (i.e., are robust) their best hypothesis will be used to compute a trimmed mean value. (The trimmed mean value is computed removing the shoalest and the deepest soundings.) The remaining depths are used to compute the arithmetic mean. In the node of interest the hypothesis closest to this robustified mean value will be selected as correct.

The Density-Locale rule in HIPS is a combination of these two methodologies. It was designed to go first for Density to make the decision. If the strength value of the hypothesis selected by Density is less than the threshold assigned in density_strength_cutoff parameter, then the hypothesis selected by Density will be flagged as correct. If it is not, the algorithm will switch to the Locale rule to determine the most reliable hypothesis in the node of interest.

The Initialization surface is the last method of disambiguation in the HIPS list and it is designed to use a previous dense data set of the survey area. For this particular research Initialization surface was not used to help CUBE in the estimation of the correct hypothesis, since no suitable (previously collected) data existing for the areas of interest.

5. METHODOLOGY.

This chapter explains the methodology used for the comparison of the several BASE surfaces constructed. First the characteristics of two different surveys conducted in Patagonian waters with the same echosounder are explained. Then the considerations taken into account for TPE computation are explained. Finally how several CARIS BASE surfaces were computed is reviewed, and how they were contrasted between each other and with the surface achieved at SHOA using the software CARIS HIPS.

5.1 Survey characteristic of the selected areas.

Two areas were selected for this research. These two particular areas have a large number of sources of fresh water, sharp rock faces and different sediment types that make survey conditions difficult. The first one corresponds to a specific area of the Reñihue Fjord, which is located in the North Patagonian sector. In this area the echosounder FANSWEEP 20 200 kHz was used to search a shoal situated in the middle of the fjord. Two sound speed casts were executed (before and after the survey) and one automatic tide station was installed nearby. DGPS was used to correct the position of the vessel in real time. The number of soundings collected by the echosounder in this area was 3 million with a depth range of 11 to 245 metres. Four equally spaced tracks were planned and then modified to collect data in this area where the beam width was limited by the depth. The number of beams per ping was selected to be 600.

The bathymetric data was analyzed by an operator and treated under normal SHOA procedures for bathymetric data cleaning (i.e., interactive editing) until achieving the respective BASE surface. Since it is well known that CUBE can optimize the cleaning time against interactive editing, this research will not focus on processing time.

Once the parameters were well tested and the surface obtained was appropriate to the goal of this research, another survey with similar characteristics to the first one (in terms of nature of the seafloor and data acquisition system) was used to test the CUBE Patagonia solution. The CARIS surface, with CUBE Patagonia solution stored, was compared against the surface achieved by SHOA to validate the previous experience (Figure 5.1). The number of soundings collected in the Angostura Inglesa channel was over 71 million, but to ensure a reasonable non-interactive time (i.e., time consumed by the data processor in CARIS surface computation) a sub-area was selected. This sub-area has a total of 23 million soundings. The beam width selected allows up to 600 beams per swath. The survey was conducted to comply with the IHO specification for a survey of Order 1.

Figure 5.1: Angostura Inglesa located in the central Patagonian Area. Extreme terrain and water mass changes makes hydrographic survey a difficult task.

5.2 Total Propagated Error (TPE) Model.

Several individual error sources of MBES are propagated through the bathymetric data, affecting the depth measurement and position of each sounding. Some examples of these individual sources of error are: navigation, gyro, heave, pitch, roll, tide error, sound speed error, latency error, sensor offset error and individual sonar model characteristics [CARIS, 2006b].

The Total Propagated Error (TPE) is derived from a combination of all those errors, which are expressed as the horizontal error estimate (HzTPE) and a depth error estimate (DpTPE) for each sounding. These values are significant if the BASE surface is required and/or used as a filter to reject or accept soundings with uncertainty values that fall outside limits set by IHO standards. To compute these values, HIPS defines two different files with information about sensors: the HIPS Vessel File (HVF) and the Device Model. Other errors can be directly entered into the TPE dialogue, such as sound speed measurement error (i.e., through the entire water column and at the transducer) and tide measurement error.

HVF contains information on (a) standard deviation StdDev (obtained from the user's manuals of the individual sensors used with each MBES, or from operator's experience), (b) 3D translation offsets between Motion Reference Unit (MRU); the Navigation System (commonly refer to as GPS); and the MBES Transducers, and (c) orientation offsets (i.e., misalignments) among these sensors.

Survey characteristics are entered during the CARIS HVF set up (i.e., vessel name and date of MBES installation, type of survey and sonar features). Vessel dimension and Reference Point (RP) location are entered using the HVF vessel editor. Information about RP location is obtained from ship's offset diagram.

5.2.1 HIPS Vessel File population.

In the particular case of the Chilean data acquired using ATLAS FANSWEEP 20 200 kHz, offsets and errors for each sensor were entered with zero values in the HVF vessel editor, since compensation for transducer angles and position are executed by the system acquisition processes. The exceptions were TPE (i.e., OffSets and StdDev) and sound speed fields.

The offset values of transducers, GPS antennas and Motion Reference Unit (MRU), were obtained from the manuals and querying the data itself using CARIS dump ATLAS SURF Utility. Distance between the MRU, GPS and Transducer, were calculated using the CARIS sign convention for the vessel coordinate system (Figure 5.2) [HIPS, 2006a]. These values were then entered in the TPE Offset fields. TPE StdDev was populated according to the manufacturer's specifications for each sensor.

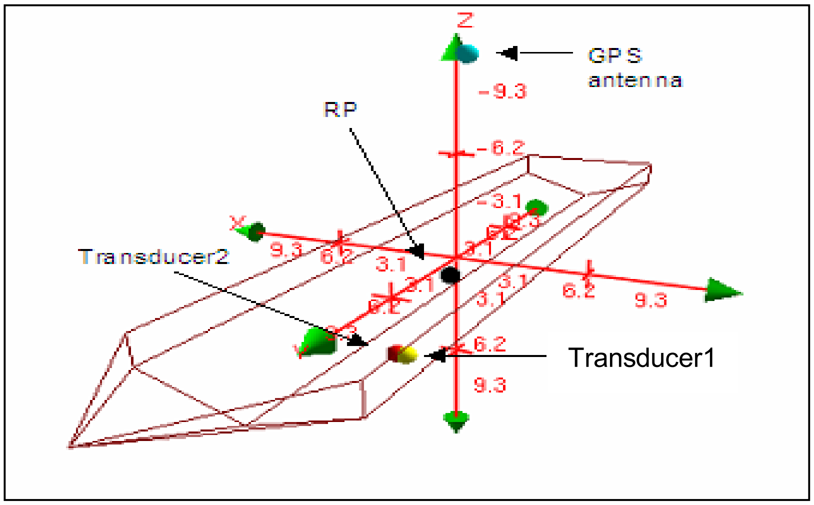


Figure 5.2: Peripherals installation parameters.

Standard deviation for sound speed (at the transducer and sound speed cast) and Tide (tide gage measurement) were directly filled in Compute TPE dialogue.

5.2.2 Sound Speed Correction.

Sound speed corrections for the entire water column (i.e., ray tracing), are not performed by ATLAS FANSWEEP 20. Instead uses the average of several examples obtained by the sound speed cast. The alternative to correct this bathymetric data (i.e., across-along track and depth solution) is to use the complete information from sound speed casts and the offsets of each transceiver plate. The result is a more realistic TPE calculation. In the HVF the difference with the basic sound speed correction is that the sonar must be defined as a two head system (swath 1 and swath 2).

HIPS allows sound speed correction in two different ways, since sound speed through the water column can be improved. The first one, and less orthodox, is using the basic sound speed correction applied by the multibeam system in data acquisition. But the most accurate and adequate method is the one that performs ray-tracing (post-processing). Hence sound speed correction through the entire water column (i.e., ray-tracing) was used to determine the TPE values and depths for this research.

The new fields (SVP1 and SVP2) in the HVF were filled with the appropriate transducer’s offsets. In this research these values were obtained from CARIS dump ATLAS SURF Utility. Roll and Yaw (Heading) fields were populated with zero value [CARIS, 2004].

5.2.3 Construction of a new Device Model.

HIPS, in CARIS\HIPS\60\System “Devicemodel.xml”, contains descriptions about a series of sonar devices tested at the University of New Hampshire (UNH). However, ATLAS FANSWEEP 20 is not one of them. That implied the need to create a new sonar model suitable for FANSWEEP 20 200 kHz. Since no authoritative Device Model is available from ATLAS, it was necessary to create an “ad hoc” Device Model, assuming that the FANSWEEP 20 Device Model would not differ significantly from the Device Model for other MBES with similar depth capabilities.

CARIS highlights the necessary values to be entered within the Device Model if an echosounder is not included on their list. This essential information must be included in the respective field. The total propagated error model in CARIS HIPS has been designed for echosounders that differ from FANSWEEP 20. For this research, a new “ad hoc” Device Model (Table 5.1) was created filling the necessary parameters in the Device Model, according to the characteristics of the FANSWEEP 20 200 kHz [ATLAS, 2006; CARIS 2007 and Lindlohr, 2007].

The Device Model, in conjunction with HVF, is required by HIPS to calculate sounding uncertainty (TPE values). The TPE values for the FANSWEEP 20, computed using the new “ad hoc” Device Model, were contrasted with TPE values obtained for another “reference” echosounder, with a well-defined Device Model, in similar depths (from 20 to 50 metres). With no authoritative Device Model properly defined and tested in HIPS for ATLAS FANSWEEP 20, the alternative used to validate the “ad hoc” TPE values in this research was statistical analysis based on the histograms of the bathymetric data achieved by both FANSWEEP 20 and the reference MBES.

However, that is not the final answer for TPE computation for this kind of echosounder. The error model developed [Hare, Godin and Mayer, 1995] is based on Simrad and RESON beamformer technology, which is different from ATLAS FANSWEEP 20. Therefore it must be understood that this approach uses an approximation of the uncertainty values (Figure 5.3) since no suitable tested model has been reported in the open literature.

Table 5.1: CARIS\HIPS\60\System “Devicemodel.xml”. An Abstract of the Device Model created for ATLAS FANSWEEP 20 200 kHz [ATLAS, 2006; CARIS 2007 and Lindlohr, 2007].

```
<SonarModel label="Atlas Fansweep 20 (200)"
key="fs202">
   <Max_Num_Beams value="600"/>
   <Operating_Frequency_1 value="200"/>
   <Operating_Frequency_2 value="0.0"/>
   <Max_Angle value="80.5"/>
   <Beam_Width_Across value="1.0"/>
   <Beam_Width_Along value="1.3"/>
   <Steering_Angle value="0.0"/>
   <Range_Sampling_Frequency
value="75000.0"/>
   <Range_Sampling_Distance value="0.01"/>
   <Min_Pulse_Length value="0.12"/>
   <Rates>….
```

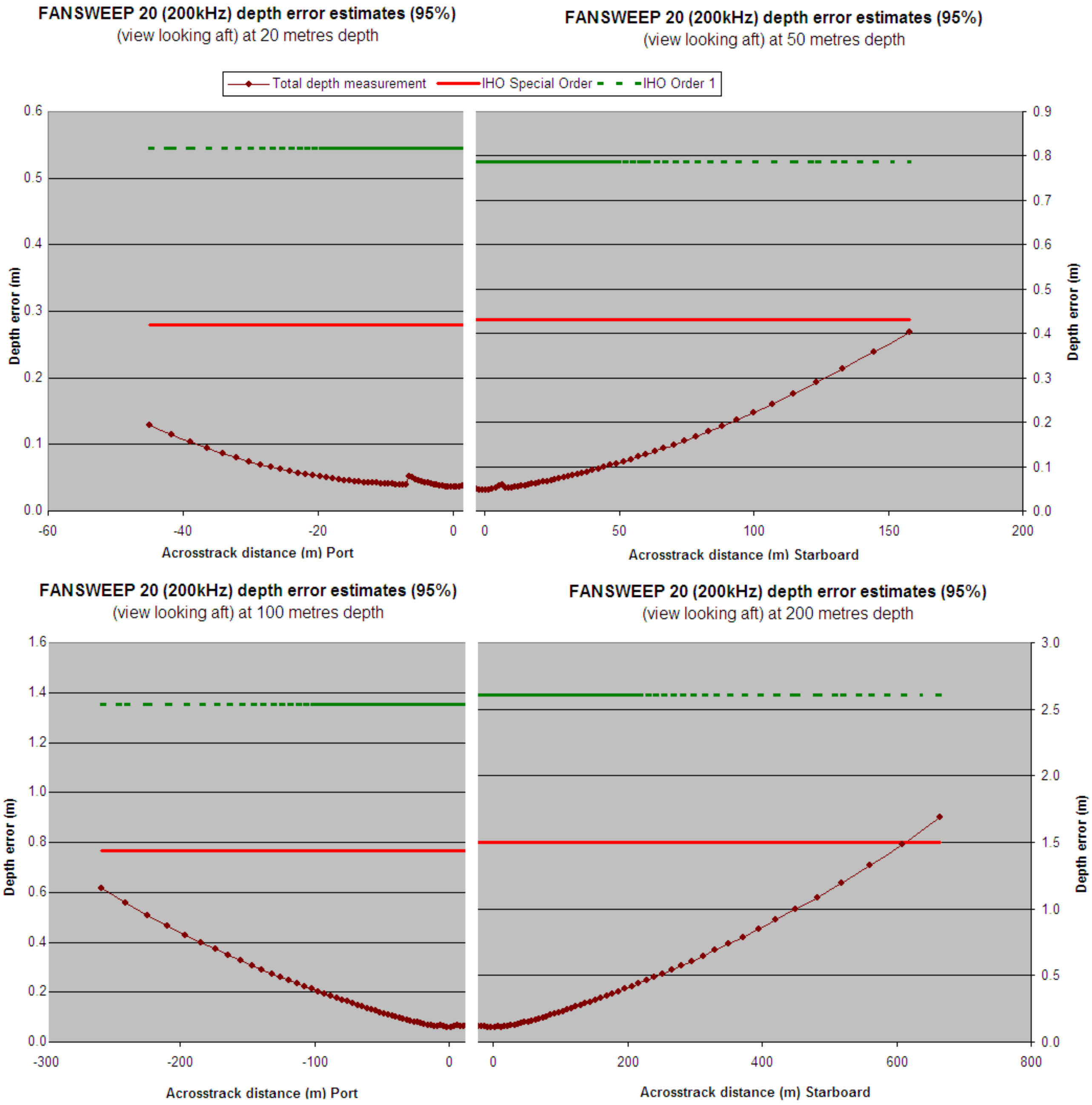


Figure 5.3: Estimates of the performance of the FANSWEEP 20 at different depths. The graphics represent the vertical uncertainty attached to each depth measurement, which increases with the operation depth and the acrosstrack distance. The model used was designed by R. Hare for a RESON SeaBat 8101, but the parameters entered correspond to the Chilean echosounder.

5.3 CARIS BASE surfaces comparison.

This section describes the procedures used in Chapter Six to compare various CARIS BASE surfaces that reflect the depth estimation made by different CUBE configurations (Figure 5.3).

5.3.1 Sources of surface to be compared.

Two areas were studied independently: Reñihue and Angostura Inglesa. For the Reñihue area, a total of 42 CARIS surfaces were compared. Different surfaces derived from the results in depth estimation made by several CUBE configurations were represented (i.e., CUBE default, HIPS CUBE new release and CUBE new configurations) and contrasted with the surface generated at SHOA. For the Angostura Inglesa area, 3 surfaces were compared. The latter corresponded to those surfaces derived from the depth estimation made by CUBE default, CUBE Patagonia and the surface created at SHOA. The Reñihue project was used for testing purposes and the Angostura Inglesa project was used to validate the CUBE Patagonia configuration in a larger area. Since both projects were analytically treated in the same way, the Reñihue project is explained in this section in detail. The Angostura Inglesa project followed the same rules for data analysis and filtering processes.

The surface produced at SHOA, using interactive editing, was downloaded in HIPS. Hydrographic raw data from the Reñihue survey was downloaded and converted for HIPS processing [CARIS, 2006a]. After the Vessel File was created, raw data converted, sound speed corrected and tides downloaded, the complete data set was merged in order to combine them in HIPS. Horizontal and vertical uncertainty attached to each sounding was obtained running the TPE computation.

A new Field Sheet called CUBE was created and added to the Reñihue project. This field sheet was populated with several CARIS BASE surfaces derived from depth estimations made by different CUBE configurations. Thus the Reñihue project has two field sheets containing: CARIS BASE surfaces (different CUBE configurations and grid resolutions) and SHOA surface.

To create BASE surfaces with the capability of maintaining the sonar resolution, multiple grid resolutions were executed. Thus the spatial resolution of the grid was split according to differences in depth. For example, for depths from 0 to 20 metres the grid resolution selectable was 0.5 metres. For depths from 20 to 80, the grid resolution was 1 metre, increasing according to the expected sonar resolution until reaching the maximum depth of the area (300 metres with a grid resolution of 5 metres).

Also surfaces with single resolution were created. Since the maximum depth found in these areas was 300 metres, a grid resolution of 5 metres was selected to gather all the information and avoid areas with holidays. The different resolution approaches (multiple and single grid resolution) are stepping stones to filter noise-data against the surfaces generated. Therefore, it must be understood that no final product should be achieved using single grid resolution in this sort of depth regime, or significant deficiencies in the characterization of the seafloor are likely.

The implementation of CUBE in the CARIS surface also implies the selection of the IHO survey Order, to delimit the propagation of a sounding's vertical uncertainty to the node. In both cases the IHO survey order selected was Order 1 [IHO, 1998].

Three of the four Disambiguation methods presented in HIPS were used: Density, Locale and Density-Locale. An Initialization surface was not used, because in both cases (i.e., Reñihue and Angostura Inglesa) the inherited data corresponds to bathymetry acquired using the single beam method, where survey lines were carried out according to the scale of the nautical chart.

Using the HIPS subset editor, several sub-areas of the surface were opened. This allowed the detailed visualization of several surfaces generated and the respective CUBE solution for depth estimation. Therefore the comparison was made using the 3D and 2D visualization tool.

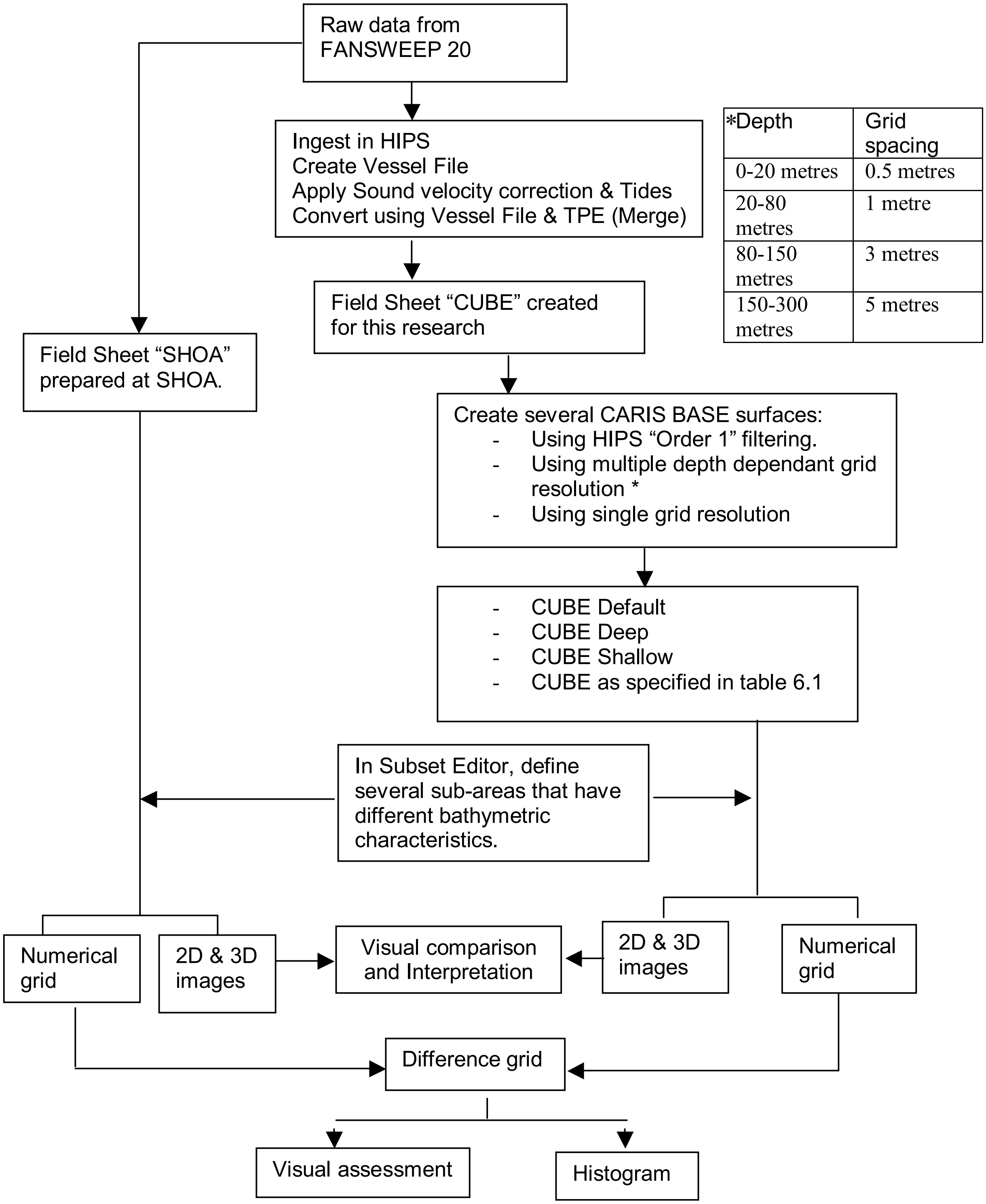
Using HIPS 3D visualization, the biggest and obvious discrepancies, visualized in surface generation as peaks were measured using the metric tool. The surfaces and corresponding measurement discrepancies were saved as images for comparison purposes. Specific areas with the obvious presence of steep slopes or roughness were selected using the HIPS subset editor tab. 3D visualization was also used to observe the x, y and z dimension of each hypothesis selected. Thus the hypothesis strength (i.e., a measure of the CUBE algorithm strength) associated with each node can be inferred. For example, small and thick cubes mean that these nodes have more than one hypothesis and therefore it will have a large strength value. Bigger and thinner cubes mean that CUBE is more “convinced” that the decision made about the data is correct. Metric comparison was obtained from the subset (hypothesis window) and analyzed using histograms.

HIPS 2D visualization tool was used to observe from the bottom view the depth differences. The 2D view allows a rough interpretation on depth difference based on the graduated scale for depth in metres and horizontal position in metres. Also the 2D visualization tool was used to identify areas with steep slopes for further analysis.

In order to get comparison metrics for the surfaces generated and to confirm the result obtained with Subset editor, another approach was executed. Specific areas of the survey were selected using field sheet editor. Then using these areas defined as reference, different surfaces were queried. Information attached to each node estimated, such as depth, uncertainty and hypothesis strength, were obtained separately and exported for data analysis. The discrepancies were plotted as surfaces and histograms to see the behaviour of the new configurations.

The whole data set was filtered using HIPS "CUBE" filter. The confidence interval of 2.0 was selected to define the threshold applied to the surface when filtering the sounding data. Therefore any sounding that deviates from the surface by more than the uncertainty value presented at 95% confidence interval was flagged as rejected [CARIS, 2007]. No manual cleaning or other filters existing in HIPS were applied. Each surface was filtered separately to avoid overlay cleaning between them. Hence, using the HIPS Query function, the whole data was interrogated in order to obtain statistical information. To determine whether the filter made the right decision rejecting clearly bad data, survey lines with noise-data were opened using the swath editor tab.

Once the results were analyzed and thus the best CUBE solution obtained, the second project named Angostura Inglesa was opened. Two field sheets were created. One contained the surface representing the CUBE default and CUBE Patagonia depth estimations, and one contained the surface achieved at SHOA. This new project was executed to validate the result obtained with CUBE Patagonia, with a new data set (with similar characteristics) but greater number of soundings. The same procedure as used with Reñihue, for data analysis, was followed with Angostura Inglesa project.



*Depth	Grid spacing
0-20 metres	0.5 metres
20-80 metres	1 metre
80-150 metres	3 metres
150-300 metres	5 metres

Figure 5.4: Procedures used in Chapter six to compare various CARIS surfaces.

6. RESULTS AND DISCUSSION

In this chapter the results obtained from different CUBE configurations and the analysis of the representation of these results against SHOA surface are explained. A total of 45 surfaces were compared between the two projects. The results obtained using the most relevant surfaces are shown. Thus SHOA BASE surface, CARIS multiple and single grid resolution surfaces with different results of CUBE new configurations, and the new release in HIPS, called CUBE deep, are described.

6.1 SHOA surface.

The surfaces achieved by SHOA in the Reñihue Fjord and the Angostura Inglesa Channel were used as reference to contrast them with the results obtained by CUBE. These surfaces were created using SHOA's current procedure to clean the bathymetric data (i.e., interactive editing). In SHOA surfaces, problems such as over-cleaning, noise-data marked as "accepted" and elimination of important features of the seafloor, were evident (Figure 6.1).

Also restrictions in the swath filter show that some noise-data can still appear as "acceptable", in which case the operator must decide to reject it. This means that any filter, independent of its relation to reality, cannot infer the true solution, just the most reliable, according to its parameter settings.

The percentage of bathymetric data rejected in the SHOA procedure for the first area selected was 10.171% (i.e., Reñihue Fjord). For the second area (i.e., Angostura Inglesa), the percentage of data rejected was 21.862%. Since these percentages are affected by some imperfections in data cleaning (which in any case affect the safety of the navigation), it was also considered in this research as one other statistical number for comparison purposes. It is necessary to bear in mind that the most important comparison parameter will be the surface created.

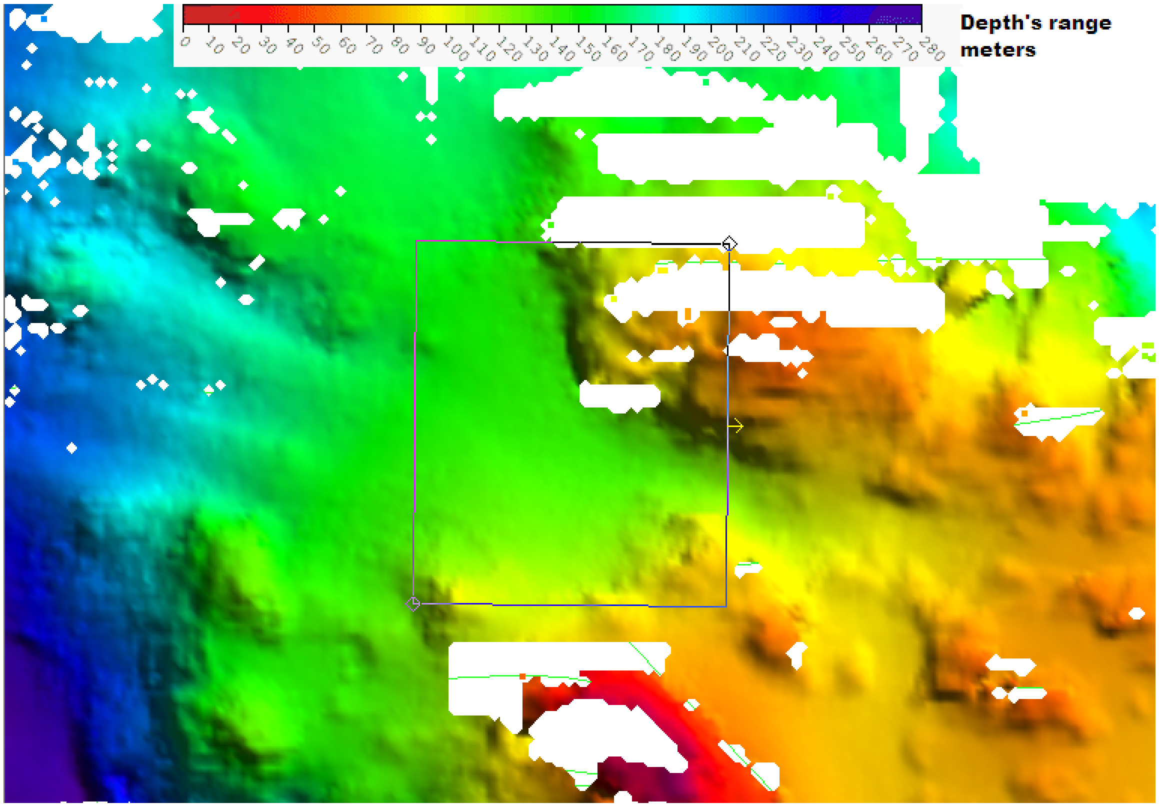


Figure 6.1: SHOA surface achieved using Swath filter and interactive editing for Reñihue Fjord. In this surface the operator was over-cleaning the area, losing some important features of the sea bottom. Independently of bathymetric data being affected by noise, the cleaning of this area was aggressive (a problem typically observed when the operator has little experience).

6.2 CARIS multiple grid resolution surfaces.

This section discusses the results obtained using CARIS surfaces multiple grid resolution and different CUBE configuration such as: default, the new release of CUBE parameters in HIPS (i.e., deep and shallow configurations), and by the new configurations created in accordance to the goal of this research (Table 6.1).

Table 6.1: Different CUBE configurations and associated surfaces.

N	Area	Configuration	GR	EO	CDS	CDM	HES	DM
1	R	SHOA	S	-	-	-	-	-
2	AI	SHOA	S	-	-	-	-	-
3	R	CUBE Default	M	4	5	0.5	2.95	D
4	R	CUBE Default	M	4	5	0.5	2.95	DL
5	R	CUBE Default	M	4	5	0.5	2.95	L
6	R	CUBE Default	S	4	5	0.5	2.95	D
7	AI	CUBE Default	S	4	5	0.5	2.95	D
8	R	CUBE Deep	M	3	20	2	2.95	D
9	R	CUBE Deep	M	3	20	2	2.95	DL
10	R	CUBE Deep	S	3	20	2	2.95	D
11	R	CUBE Shallow	M	2	4	0.4	0.5	D
12	R	CUBE Shallow	S	2	4	0.4	0.5	D
13	R	CUBE Test 1	M	4	2	0.2	2.95	DL
14	R	CUBE Test 1	M	4	2	0.2	2.95	D
15	R	CUBE Test 1	S	4	2	0.2	2.95	D
16	R	CUBE Test 2	M	4	2	0.2	0.5	D
17	R	CUBE Test 2	S	4	2	0.2	0.5	D
18	R	CUBE Test 3	M	4	5	0.5	0.5	D
19	R	CUBE Test 3	S	4	5	0.5	0.5	D
20	R	CUBE Test 4	M	3	5	0.5	2.95	D
21	R	CUBE Test 4	S	3	5	0.5	2.95	D
22	R	CUBE Test 5	M	3	2	0.2	2.95	D
23	**R**	**CUBE Test 5**	**S**	**3**	**2**	**0.2**	**2.95**	**D**
24	**AI**	**CUBE Test 5**	**S**	**3**	**2**	**0.2**	**2.95**	**D**
25	R	CUBE Test 6	M	3	2	0.2	0.5	D
26	R	CUBE Test 6	M	3	2	0.2	0.5	DL
27	R	CUBE Test 6	S	3	2	0.2	0.5	D
28	R	CUBE Test 7	M	3	5	0.5	0.5	D
29	R	CUBE Test 7	S	3	5	0.5	0.5	D
30	R	CUBE Test 8	M	5	5	0.5	2.95	D
31	R	CUBE Test 8	S	5	5	0.5	2.95	D
32	R	CUBE Test 9	M	5	2	0.2	2.95	D
33	R	CUBE Test 9	S	5	2	0.2	2.95	D
34	R	CUBE Test 10	M	5	2	0.2	0.5	D
35	R	CUBE Test 10	S	5	2	0.2	0.5	D
36	R	CUBE Test 11	M	5	5	0.5	0.5	D
37	R	CUBE Test 11	S	5	5	0.5	0.5	D
38	R	CUBE Test 12	M	4	2	0.2	3.4	D
39	R	CUBE Test 13	M	3	30	3	3	D
40	R	CUBE Test 14	M	4	30	3	3	D
41	R	CUBE Test 15	M	4	30	3	0.5	D
42	R	CUBE Test 16	S	4	20	2	2.95	D
43	R	CUBE Test 17	S	4	5	0.5	3.4	D
44	R	CUBE Test 18	S	2	2	0.2	2.95	D
45	R	CUBE Test 18	S	2	2	0.2	2.95	DL

N = Number of comparison test
R = Reñihue
AI = Angostura Inglesa
GR = Grid resolution
S = Single
M = Multiple
EO = CUBE Estimate Offset parameter value
CDS = CUBE Capture Distance Scale parameter value
CDM = CUBE Capture Distance Minimum parameter value
HES = CUBE Horizontal Error Scale parameter value

DM = CUBE Disambiguation method
D = Density
L = Locale
DL = Density-Locale

6.2.1 CUBE default configuration.

For each area, CARIS BASE surfaces were created to represent the solution obtained from CUBE Default configuration (see Table 6.1, 6 and 7). Since this research started in the period between HIPS 6.0 and the release of HIPS 6.1, the first surface created for testing purposes used a single grid resolution of 5 metres for the whole survey. The multiple grid resolution option in HIPS 6.0 did not work properly, so this option was tested using HIPS 6.1 . That was relevant in the testing of the most suitable CUBE's configuration for Chilean bathymetric data, and will be explained below.

With the release of HIPS & SIPS 6.1 the problem in the multiple resolutions option was solved and thus could be tested. Only the data set collected in the Reñihue Fjord used multiple grid resolutions. The decision to use multiple resolutions was made to maintain the resolution achieved by the multibeam echosounder, and thus detect smaller changes in seafloor morphology, which are not detectable using a larger node resolution since the surfaces are smoothed.

With smaller (depth dependant) grid resolution the probability of mapping the seafloor morphology should increase. Steep slopes and roughness present in some areas of the survey should be well mapped. For example, in an area where the density of the soundings is enough to maintain the minimum changes in morphology, the grid resolution (which may not be much different than the separation between the soundings) will work in conjunction with the CUBE assimilation parameters, gathering the necessary information for the best hypothesis estimation (Figure 6.2). Thus the node should have the required soundings to get the most likely depth. This assumption does not take into account failures in sea bottom tracking, which is translated into less sounding density and noise-data affecting the surface representation. This issue will be discussed next in the CARIS multiple resolution surface.

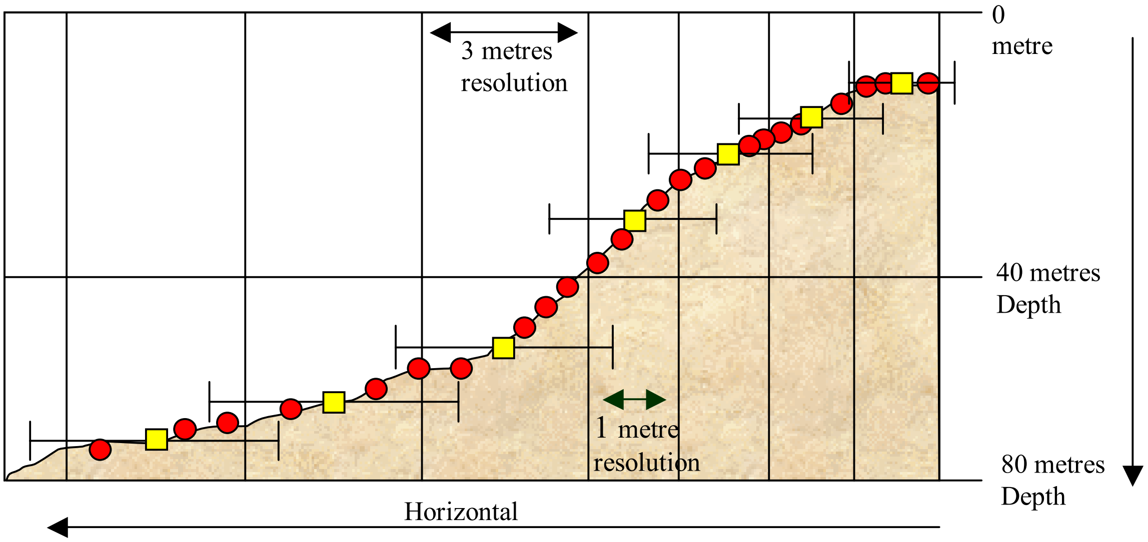


Figure 6.2: Capture Distance influence. The circles represent the soundings. The squares represent the nodes. The radius of influence is determined by Capture Distance Scale and Capture Distance Minimum Default setting (e.g., 5% of depth and 0.5 metres from the node). Differences in grid resolution are selected by the operator, which for this example is 1 metre for depth from 0 to 40 metres and 3 metres for areas deeper than 40 metres.

The result of using the CARIS multiple resolution (see Table 6.1, 3 to 5) was a surface not suitable for use for filtering purposes. This pattern was observed in areas with steep slope, roughness, or where the terrain was mostly flat.

The depth estimated using CUBE Default was tested using different disambiguation methods (see Table 6.1, 4 and 5): Density, Locale and Density-Locale rules were tested. The results in terms of depth estimation were slightly different.

6.2.2 CARIS HIPS 6.1 CUBE configurations.

HIPS 6.1 has its own configurations for deep and shallow areas, which are basically changes in the CUBE parameters previously mentioned in this research. In order to know the behavior of these configurations, named deep and shallow by HIPS, five new surfaces were created (see Table 6.1, 8 to 12). The deep configuration contains parameters that are meant to be appropriate for areas of deep water, steep slope and where small features are not expected [CARIS, 2007]. On the other hand, the shallow configuration contains parameters that are suitable for areas of critical underkeel clearance or where small features are important to be shown by the surface. Both configurations are CARIS constructs (i.e., not a CUBE recommended parameter set). Since the deep configuration is more suitable for this research, this case will be described next.

The surface generated using the results of the deep configuration (see Table 6.1, 8) were slightly better (in comparison with default) especially in those areas deeper and flatter, where also the echosounder does not show too many problems in data collection. Some peaks that are shown in the surface created using the CUBE default depth estimation (see Table 6.1, 3) for flat and deeper areas were not observed in the surface derived from CUBE deep solution. For sectors affected by steep slope, the surface generated did not have much improvement and the presence of noise in the shallower sectors still affects the construction of the surface.

CUBE Deep configuration has different settings for the assimilation parameters (i.e., Capture Distance Scale and Capture Distance Minimum) and for the Estimate Offset. The first two parameters are adjusted to “capture” soundings that are in a radius of

20% of depth or 2 metres from the node. For instance, in a depth of 100 metres the node will get surrounding soundings within a 20 metre radius.

According to these parameters in deep areas and mostly flat areas, the nodal radius of influence will be much larger than its default value, which will allow a larger contribution of the surrounding soundings in the node construction and hence a better estimation of the most likely depth. This assumption makes sense with the resolution achieved by the echosounders in deep, flat areas, where soundings are widely spread.

But this assumption is not necessary suitable for Chilean data gathered in steep slope sectors. The other parameter modified and presented in the deep configuration is Estimate Offset (EO), with a value of 3 instead of the default value of 4. Smaller EO means that the vertical step is decreased, making it more likely that alternative hypotheses will be formed at a specific node.

6.2.3 CUBE new configurations.

Since multiple resolutions can be achieved with HIPS 6.1 (see Table 6.1), several surfaces were created splitting the grid resolution according to the depth.

The main parameters of CUBE were modified, and different CARIS surfaces were created to analyze the results in depth estimation. The parameters of CUBE were modified to increase the certainty in the depth estimation. Steep slopes and roughness were the main problems in the algorithm decision, since the data located in these areas has a strong variability and high probabilities of sea bottom mistracking. Thus the algorithm must deal, in some cases, with bad data, denser in the upper layers compared with data acquired at the sea bottom.

Taking the CARIS surface with the depth estimation values achieved using CUBE default (see Table 6.1, 3) and the SHOA surfaces (see Table 6.1, 1) as reference the new surfaces created were compared.

Independent of the CUBE configurations, the results of CARIS multiple resolution were surfaces with a considerable level of noise, being affected in such a way that data cleaning may be time consuming. The surfaces created are the result of CARIS technology in which CUBE depth's estimation has been stored. The resulting surfaces are not part of the CUBE algorithm.

6.2.3.1 Changes in Capture Distance Scale and Distance parameters.

The default values of Capture Distance are based on a nominal beamwidth, and therefore expected beam density for a conventional equiangular beamformer. When using a system (as in this research) that maintains density much more stably, the Capture Distance values can be reduced.

In some cases the new CUBE configurations were more able to select the right depth estimation. These results were mostly observed in flat bottom areas, under the same spatial resolution assigned and with no bad data in the surroundings.

Some improvement was expected by decreasing Capture Distance values (Figure 6.3). In the previous configuration (i.e., CUBE default), the radius of influence is mainly determined by 5% of depth, which results in strong overlapping between the radiuses of influence from surrounding nodes. If the radius of influence is increased more soundings will be taken for assimilation purposes (which is the case of CUBE deep configuration).

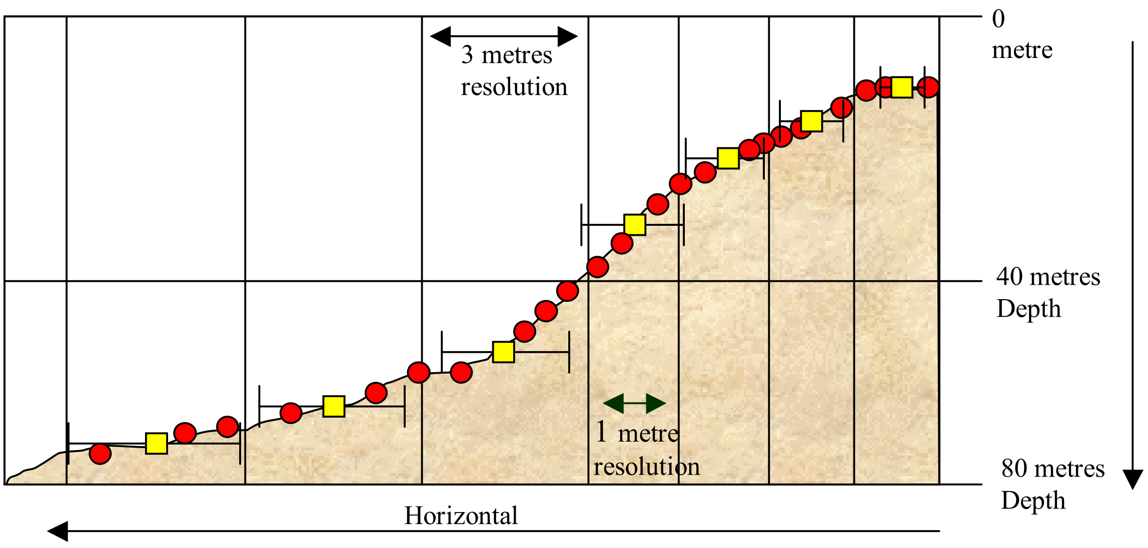


Figure 6.3: Capture Distance Scale decreased to 2% of the depth. The circles are representations of the soundings. The squares are node representations. When the radius of influence was reduced CUBE worked better for areas with steep slopes since only soundings nearer to the node are taken into account.

According to the nature of the seafloor tested in this research and the expected beam density, Capture Distance was reduced. The value adopted to reduce the Capture Distance Scale was 2% of the depth and 0.2 metres for Capture Distance Minimum (see Table 6.1, 14). For instance, the radius of influence for 120 metres depth will be 2.4 metres, for 40 metres depth 0.8 metres and for 20 metres depth only 0.4 metres.

With these smaller values, improvement was expected in surface generation, since the radius of influence was decreased and hence only surrounding soundings close to the true depth should be used in data assimilation. Fewer soundings (which also should be closer in depth measurement) will be selected to contribute to the node. Limiting that area should avoid, in some way, the interference of further-away soundings that are more suitable for estimating depths at other nodes. Again, this assumption does not take into account problems in data acquisition, such as dense noise spread over poorly covered areas.

The new configurations resulted in an increase in hypothesis strength (i.e., the value decreased), due to more soundings with similar depths contributing to the node. In other words, soundings closer in measurement contributed to the node's estimation. This means that the hypothesis selected as the most likely for depth estimation, was improved in terms of its strength.

The possible improvement in depth estimation, decreasing values of Capture Distance parameters, was not observed using the CARIS BASE surface multiple grid resolution. So far it is evident that multiple resolutions have undesired effects. Since the resolution has been selected to be split in accordance to the depth (e.g. 0 to 20 m / 0.5m, 20 to 80 m / 1m, 80 to 150 m / 4m and 150 to 300 m / 5m) the grids will be constructed taking into consideration the noise data floating over the seafloor. For instance, noise-data in a range of 20 to 80 metres depths floating over soundings at 90 metres depths have grid construction of 1 metre over a grid of 4 metres resolution. Therefore the CARIS surface took both grids independently and CUBE hypothesis construction was limited to working in these depth intervals. The assimilation of soundings, which should be controlled by Capture Distance parameters, was also controlled by the CARIS surface taking just those soundings within the same resolution range. Thus, this procedure does not take into consideration the soundings underneath the smaller grids, which in this particular case are the most suitable ones for surface generation. Hence, the multiple grid reolution surface was generated with peaks (Figure 6.4).

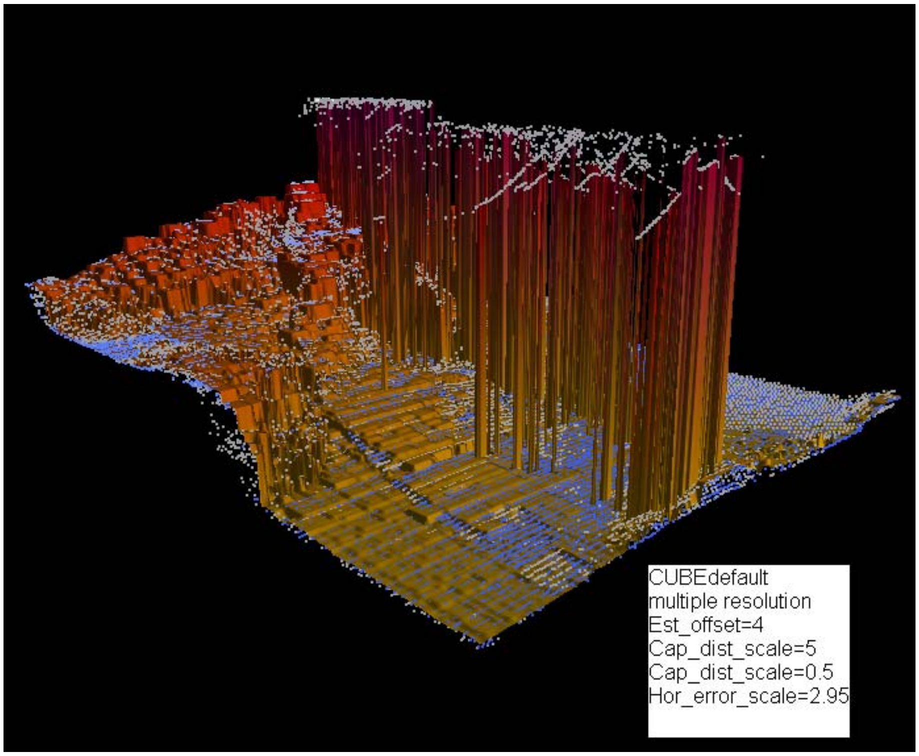

CUBEdefault
multiple resolution
Est_offset=4
Cap_dist_scale=5
Cap_dist_scale=0.5
Hor_error_scale=2.95

Figure 6.4: The effect of using multiple grid resolution, in which case bathymetric data is gathered according to their location within the depth range by the operator selected. Then in Subset editor the surface is visualized with peaks.

CARIS multiple grid resolution has an effect of cut-off for those soundings out of the edge. For example, assuming a spatial resolution (i.e., grid resolution) of 0.5 metres for depths from 0 to 20 metres, soundings out of this depth range were not allowed to contribute to the node estimation. That effect is not only applicable for data clearly located out of the range selected. It also affects the data located on the border of two different resolutions, in which case fewer soundings contributed to the node (independently of their proximity in terms of depth value and the radius of influence by certain Capture Distance values).

Due to this multiple resolution effect, the surface created shows data modeling the seafloor morphology badly. That could help to visualize wrong data in the interactive editing task, but the amount of this data is considerable. In some cases therefore it will be required to make decisions without any certainty, leading back to the use of subjective decisions, taking much time.

Another consequence of surface generation with multiple resolution was observed in the shallowest sector of Reñihue Fjord. Random noise-data in this sector is predominant due to failures in data acquisition; therefore, not too much data is available for depth estimation (Figure 6.5). These failures are seen in terms of sea bottom mistracking, which could be generated by range ambiguity error, vessel-noise and backscatter anomalies. Since the Capture Distance has been reduced (and hence the radius of influence) and multiple resolutions have been created, the shallowest sector lacks sufficient soundings to contribute to the node estimation.

The shallowest sector of Reñihue Fjord is a small piece of the whole area surveyed, and also contains the highest variability in depth. According to the differences in grid resolution the effect of cut-off has a strong influence on delimiting the number of soundings that contribute to the node. Also, since the capture distance scale corresponds to 2% of depth and capture distance minimum is 0.2 metres, the radius of influence for depths between 0 and 12 metres will have zero overlapping. Thus, the surface for this particular sector was made leaving some soundings unused (e.g., soundings that are in the center of the area closed by four nodes at the same grid resolution). These soundings could still be important for modeling the seafloor.

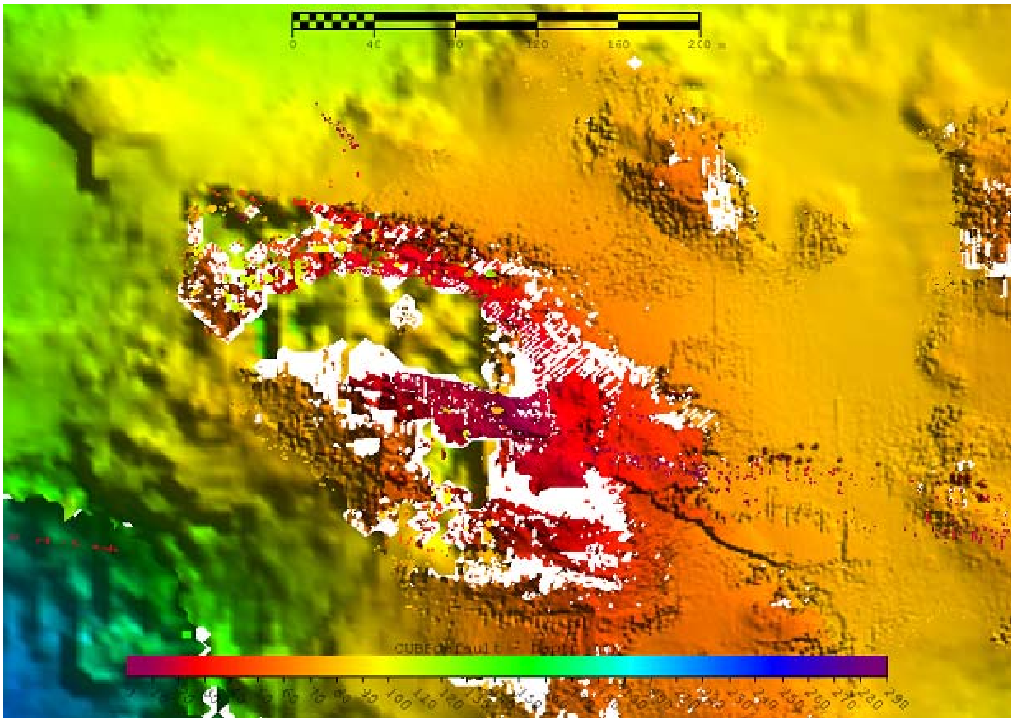


Figure 6.5: The CARIS surface generated using multiple resolution and the depth estimated by CUBE Test 1 (see Table 6.1, 14). The effect of cut-off presented in multiple resolution reduced considerably the number of soundings that contribute to a nodal depth estimation.

6.2.3.2 Changes in Horizontal Error Scale and Estimate Offset parameters.

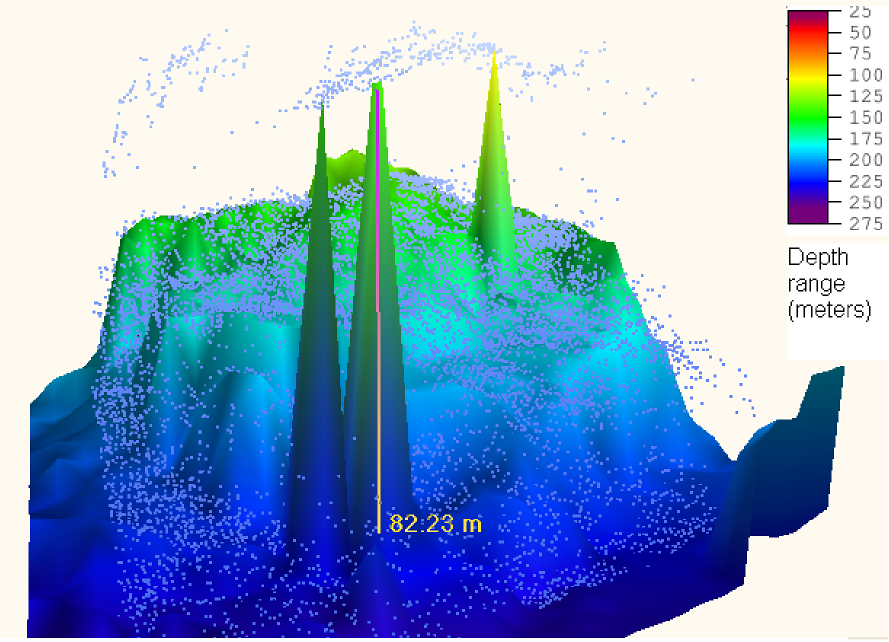
Not only reduced or increased values of Capture Distance (Scale and Minimum) were tested; other parameters, such as changes in Estimate Offset and Horizontal Error Scale values, were also tuned. Using multiple grid resolution, no large differences were observed between surface comparison. So this section will explain the results obtained using single grid resolution.

The Horizontal Error Scale was first computed according to its characteristics and probabilities to resolve some density issues. Configurations with smaller values than the default 2.95 were tested (Table 6.1, 17). The result was the hypotheses being split, increasing the number of alternative hypotheses per node. The hypothesis strength was slightly reduced or increased depending on the uncertainty associated with each incoming sounding. In some cases, soundings that were assumed by CUBE Default value as compatible to be assimilated for one hypothesis estimation were considered to be assimilated by another hypothesis in the new configuration.

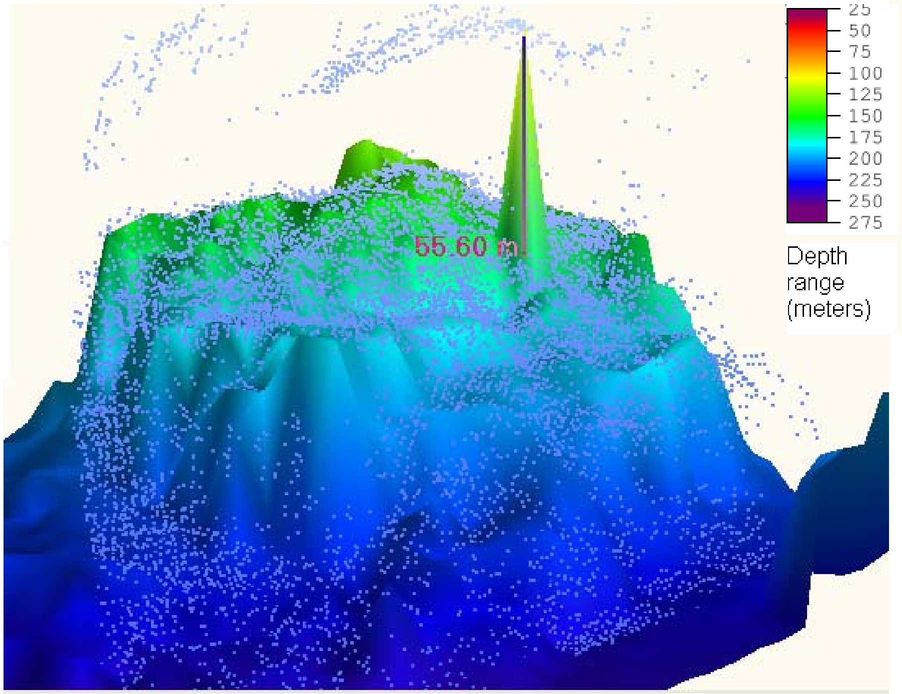
Looking for improvement in depth estimation, the Estimate Offset was slightly reduced and then increased. The default value for EO is 4. The first attempt used 3 (Table 6.1, 21). Increasing the value of the Estimate Offset allowed more variability in depth to be assimilated at the same hypothesis. Therefore, in some cases, since more depth variability was considered for node population, the noise was diluted and the right hypothesis was selected by the disambiguation method. Although an improvement was achieved, bad data can still be selected.

Making a comparison of the effect of using new values of the Estimate Offset parameter , the best approach to avoid noise data was achieved by reducing the Estimate Offset parameter to 3 (Figure 6.6).

The hypothesis count achieved by the new configuration (i.e., number of hypotheses per node) mainly increased, and the hypothesis strength showed the same behavior as previously observed with changes in horizontal error scale.



(a) CUBE default (single resolution)



(b) new configuration with Estimate Offset = 3

Figure 6.6: (a). The results of CARIS single resolution surface with Estimate Offset set to default value of 4 (Table 6.1, 6) with peaks formed due to bad data being assimilated to the node estimation. (b). The same area with Estimate Offset value of 3 (Table 6.1, 21).

6.3 CARIS single grid resolution surfaces.

A node resolution of 5 metres, independent of the depth, was selected for the whole survey area, for both Reñihue Fjord and Angostura Inglesa Channel. Selecting a single resolution in both cases avoided the problems with using multiple resolution grids.

A single grid resolution has an undesired effect in terms of seafloor representation. The resulting surface achieved with single resolution is a smoothed surface; therefore no small features (less than 5 metres for this case) can be visualized. The corresponding morphology of the seafloor is mapped with a less resolution, which in some cases would not be appropriate if special features need to be shown. In this research, the range of depth is very variable (from 20 to 300 metres). Depths are mostly more than 100 metres; therefore the percentage of data out of the smoothness consideration is predominant. Whereas shallower areas are smoothed (which could be considered a disadvantage), the shallowest sector had a better surface representation (i.e., no holidays or fewer than its equivalent CARIS multiple resolution).

The surface achieved using single resolution should not be used for the final product. In this research it is only being tested as a means to remove the worst of the noise before processing for multiple resolution bands in the final stage.

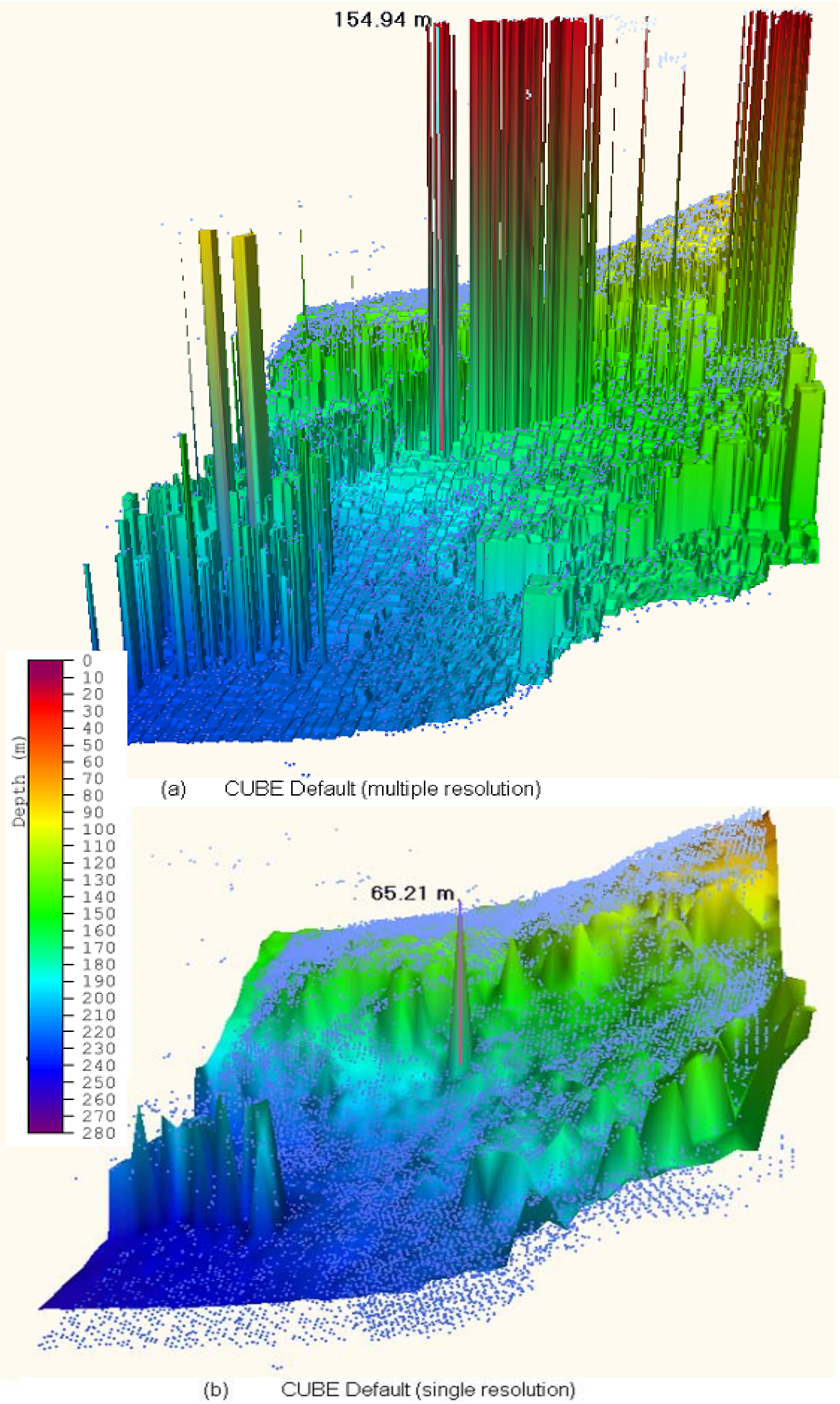
6.3.1 CUBE Default configuration.

Since CUBE Default (see Table 6.1, 6) has Capture Distance Scale value of 5% of the depths, the overlapping between the radiuses of influence is considerable for areas with more than 100 metres in depth. On the other hand, for areas with less than 50 metres depth the radius of influence will be smaller than 2.5 metres.

The grid resolution selected was 5 metres independently of depth variability. Thus the inappropriate seafloor representation produced by CARIS multiple resolution (when noise-data is present) was avoided. All the soundings within the radius of influence can be considered by CUBE for depth estimation and no external issues should alter these results. Therefore noise-data is considered by the algorithm as an alternative hypothesis, which being statistically contrasted with the other hypotheses was selected as inconsistent by the disambiguation method. In that way the noise is mostly diluted.

The advantage of noise being diluted is balanced by the disadvantage of less strength in the hypothesis selected. The principle of more data being gathered has to do with the depth variability, which in some cases (particularly in areas with strong depth changes) will create several hypotheses, decreasing the certainty of the hypotheses selected by the algorithm as the most likely one.

The surface generated by CARIS single grid resolution proved to be more realistic than the surfaces created using multiple grid resolution (Figure 6.7 a and b). Based on this fact, the next stage was creating surfaces with single grid resolution that could represent changes in the depth estimation made by different CUBE configurations. Having a new configuration with a more realistic depth estimation compared with CARIS CUBE default implementation, will allow the capability to use its product for filtering purposes. Hence the efficiency in data cleaning for data acquired in Patagonian waters should be increased.



(a) CUBE Default (multiple resolution)

(b) CUBE Default (single resolution)

Figure 6.7: (a) Inappropriate seafloor representation produced by CARIS multiple resolution when noise-data is present. (b) CARIS single resolution surface representing the values in depth estimation made by CUBE Default. The surface is smoothed since is using a grid resolution of 5 metres for the whole area. Picks can still be observed specially in those areas with steep slopes.

6.3.2 CUBE new configurations.

Several CARIS surfaces representing the estimation of the depth according to the new CUBE configurations were created and compared to: a) the surface with CUBE default results and b) the SHOA surface. The noise-data located in the upper layer (which still affect the depth estimation) was isolated until a better result was obtained.

Parameters such as: Capture Distance (Scale and Minimum), Estimate Offset and Horizontal Error Scale were tuned. The disambiguation method used for all of the new surfaces generated was Density.

Taking into account the result obtained with CARIS single resolution surface, a node resolution of 5 metres was selected. The new surfaces representing the estimated depth values from different settings of CUBE parameters were more realistic. The exception was some peaks located in steep slopes and roughness areas. Those peaks were the product of noise-data being assimilated by the node and selected by the disambiguation method as the most statistically consistent. This does not mean that there is not a more realistic solution, just that the disambiguation engine chose the wrong one.

The results in all the surfaces represented the depth estimated by different configurations of Estimate Offset and Horizontal Error Scale parameters, but the same values for Capture Distance Scale and Minimum (i.e., 2% and 0.2 metres) were surfaces mostly similar to the surface achieved by SHOA. Changes in Horizontal Error Scale did not show too many differences in the surface constructed. The most obvious changes achieved by changing Horizontal Error Scale value were visualized in deeper and flat bottom areas, but none of them were significant in terms of improvement of the depth estimation. In areas with steep slopes and roughness, the scale of their changes could be considered as insignificant. On the other hand, Estimate Offset modifications sometimes allowed a better representation of the seafloor morphology, avoiding surrounding bad data. Thus, Capture Distance (Scale and Minimum) and Estimate Offset were mainly relevant for the most suitable CARIS implementation of CUBE for Patagonian waters.

6.3.2.1 CUBE Patagonia.

Using the CUBE default configuration, data far away from the node is used to gather the necessary information to estimate the depth at this point. The latter does not take into account the morphology of the seafloor. Also dense noise-data floating in the upper layers can result in the disambiguation engine deciding to use it at the best depth estimation instead of the data laying on the seafloor. According to this, Capture Distance Scale, Capture Distance minimum and Estimate Offset parameters were decreased. The values used to set up the new “CUBE Patagonia” configuration were: 2% of depth (Capture Distance Scale), 0.2 metres from the node (Capture Distance Minimum) and 3 for Estimate Offset (Table 6.1, 23).

The CUBE Patagonia configuration has, as a result, a more realistic depth estimation (Figure 6.8), where dense noise-data affecting the performance of the disambiguation engine has no (or little) effect in this process. Also the average of the hypothesis strength was increased (Figure 6.9).

Since Capture Distance has been reduced, in some cases no data could be assimilated due to some density issues. That is, the surface representing the results of CUBE Patagonia contains a few holidays.

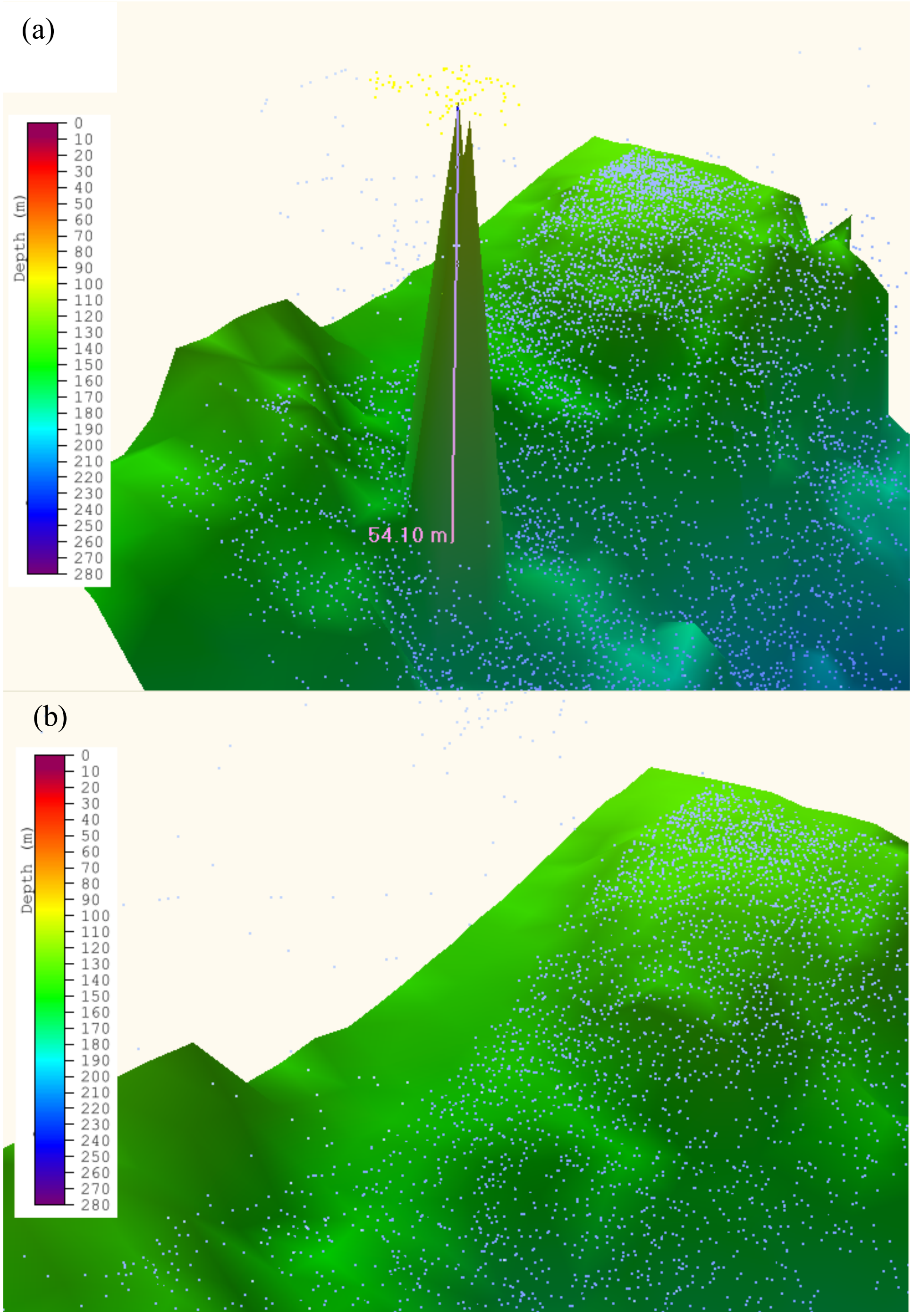


Figure 6.8: (a). Subset of the surface using the CUBE Default configuration results in bad data being assimilated and interpreted by the algorithm as the most likely depth. (b). Using the CUBE Patagonia configuration, the disambiguation engine has selected a depth estimation more realistic for this particular node.

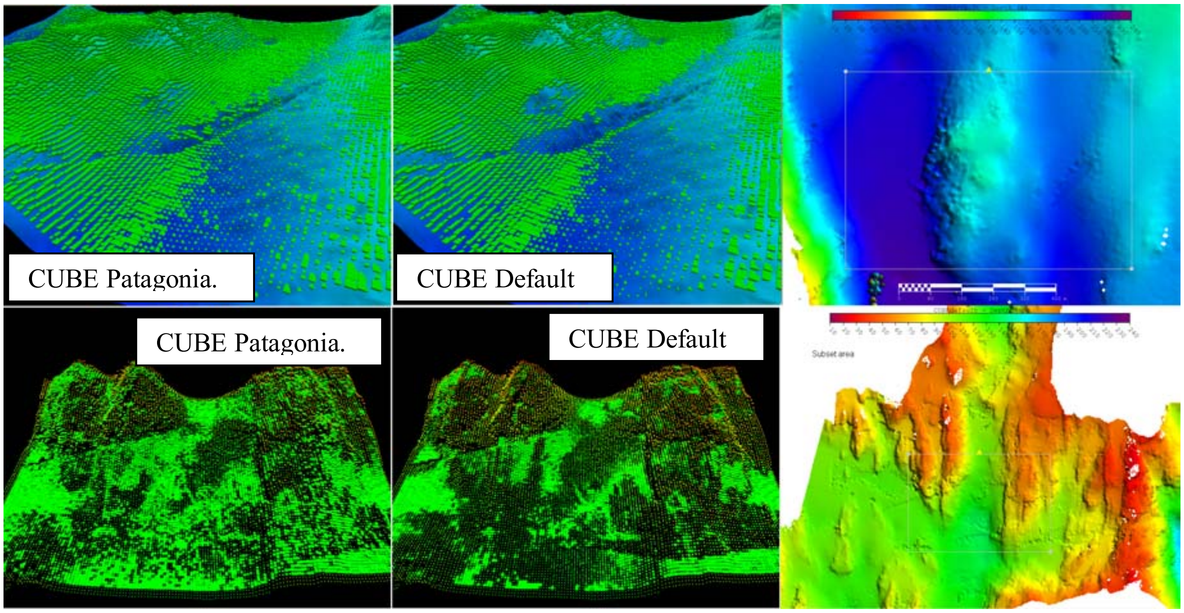


Figure 6.9: Comparison between surfaces representing differences in the hypothesis strength by CUBE default and CUBE Patagonia, in areas with steep slopes and rough seafloor. Left top: CUBE Patagonia. Center top: CUBE Default. Right top: Subset of the selected area. Left bottom: CUBE Patagonia (hypothesis strength) Center bottom: CUBE Default (hypothesis strength). Right bottom: Subset of the selected area. In these figures the hypothesis strengths have been increased with the new configuration.

Comparing the depth estimations made by CUBE Patagonia and represented in the CARIS surface against the result obtained at SHOA, differences are observed in areas where the operator cleaning was aggressive (i.e., considerable amount of data being rejected without any consideration) or imprecise, leaving some noise-data (Figure 6.10). These imperfections in data editing are precisely what this thesis is attempting to avoid.

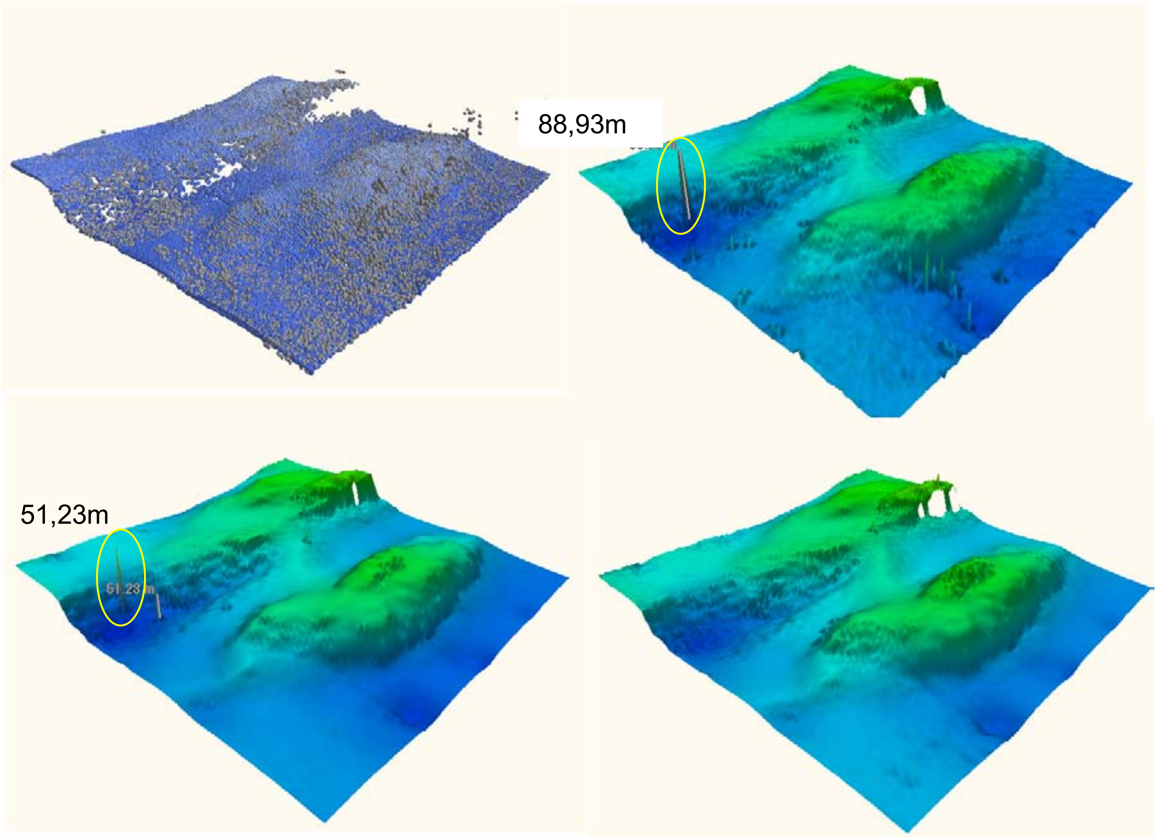


Figure 6.10: Top left. The whole bathymetric data for a specific Subset in HIPS. Top right. SHOA result achieved by interactive editing. Bottom left. Depth estimation made by CUBE Default and represented in CARIS surface. Bottom right. Depth estimation made by CUBE Patagonia and represented in CARIS surface.

The results obtained using the second approach explained in Chapter Five section 5.3.1, show that CUBE Patagonia was better able to dilute noise-data from the upper layers. Both surfaces (CUBE default and CUBE Patagonia), in general have a similar result in terms of depth estimation. CUBE Patagonia was less affected by noise-data than CUBE default. Hence the depth estimation was more realistic and importantly, more efficient because it will not be necessary to go back in and edit many hypotheses or much data. CUBE Patagonia proved to be more effective against CUBE Default in depth estimation, reducing up to 63% the level of uncertainty associated to each node, in areas with steep slopes and up to 56% in rough areas. Also the level of hypothesis strength was increased in a percentage of 57% and 52%, respectively. In other words, the new CUBE configuration was more reliable in portraying the depth estimation compared with the CUBE Default.

Since CUBE parameters have been tuned to assess a more realistic depth estimation using Chilean bathymetric data acquired in Patagonian channel, the next stage was to use the application of the product of CUBE Patagonia for filtering purposes. The result was noise-data being flagged as rejected.

Making a comparison with the data rejected by the operator at SHOA against the data rejected by CARIS “CUBE” filter, it can be observed that those rejected based on the product of CUBE Patagonia comprised mostly of all the noise-data.

6.4 Summary of results.

1. SHOA surfaces have several issues such as over-cleaning and noise-data still affecting it.
2. CARIS multiple grid resolution did not work properly for surface generation with noise-data floating in the upper layers. Hence it could not be used for data filtering .
3. CARIS single grid resolution allowed CUBE to use the whole data, within its radius of influence, for the assimilation process. Hence a surface product for filtering purposes was achieved.
4. The disambiguation engine using CUBE default and especially with HIPS CUBE deep configurations was not able to determine the right hypothesis in areas with steep slope and affected by noise-data.
5. CUBE Patagonia was more realistic in the depth estimation. Parameters that were decreased, such as Capture Distance Minimum, Capture Distance Scale and Estimate Offset, helped the disambiguation engine to select the most likely depth in areas with steep slope, rough seafloor and affected by dense noise-data floating in upper layers.
6. The efficiency of the HIPS "CUBE" filter was increased using the product surface derived from the results of CUBE Patagonia.

7. CONCLUSIONS AND RECOMMENDATIONS

This chapter describes the conclusions and recommendations attached to each result obtained. Having in mind the objectives and the goal of this research, recommendations for future work are also described.

7.1 Conclusions.

The CUBE default configuration is not suitable for data affected by steep slopes and rough seafloor; intervention is necessary to adapt the algorithm to this kind of terrain. Several CUBE parameters can be modified. How to select the appropriate parameter setting for a better estimation of the surface is assessed according to the resulting data features. Hence knowledge of the system used is necessary and the specific characteristics of the survey area should be well understood by the operator.

Since CUBE has been designed to get all the possible information from the bathymetric data collected, any failure in the sea bottom tracking due to noise or mistracking will have a direct influence in the depth estimation. Areas with complex survey conditions such as strong variability in the seafloor geomorphology, have more likelihood of data corruption. The density of this data will regulate the CUBE performance and hence the CARIS surface generation.

CUBE assumes a flat seafloor in the assimilation process. Parameters such as Capture Distance Scale and Capture Distance Minimum define which data will contribute to the node estimation. Decreasing their default values allow a more realistic seafloor representation for areas where steep slopes and roughness are predominant. In areas with steep slopes, decreasing the assimilation parameters avoids gathering soundings far away from the node. Thus, the node estimation uncertainty should decrease, if the data assimilated is also similar in magnitude (depth and uncertainty).

In CUBE the intervention process is ruled by the Estimate Offset. Decreasing this value, allows the production of alternative hypothesis from smaller depth deviations. For bathymetric data affected by noise in the upper layer, slightly decreasing this parameter could result in the more realistic surface representation. Decreasing the CUBE Estimate Offset parameter, restricts the contribution of soundings at each hypothesis estimation. Hence noise-data, randomly distributed in the upper layer and within the radius of influence for the node estimation, will generate several hypotheses. Weighting these hypotheses against the null hypothesis, the algorithm should have the necessary information to select the most likely depth solution from the null hypothesis. Obviously this assumption will not be valid when noise-data is denser than the true data, in which case reducing Capture Distance parameters should help in the selection of the most likely depth.

The new release of CUBE in HIPS 6.1 (i.e., deep configuration) is fundamentally inappropriate to be used in areas with steep slopes. The value assigned for Capture Distance parameters in this configuration increase the radius of influence. With a steep seafloor, the node will capture soundings within a radius of 20% of the depth or 2 metres from the node, which is significant when the morphology of the seafloor is so extreme that several soundings with different magnitudes are found.

HIPS 6.1 in CARIS BASE surface generation allows the splitting of the grid resolution according to the depth. CARIS multiple grid resolution should not be used for filtering purposes if noise-data is still present through the data set. CARIS/HIPS implementation of multiple grid resolution, on which CUBE algorithm can be used, is flawed due to its implementation. This is independent of CUBE algorithm, and is not part of the standard CUBE distribution. The base distribution does have a multiple resolution mode, but it uses spatial masks to decide where each resolution level should be used.

CARIS single grid resolution allows CUBE to use the whole data within its radius of influence to compute the depth estimation for the nodes. Therefore noise-data will be weighted with real data in which case the disambiguation method will decide correctly.

The performance of HIPS "CUBE" filter will be strongly governed by the surface generated. Therefore, a more realistic CUBE depth estimation will imply better filtering. Tuning the CUBE parameters should allow a more realistic depth estimation in those cases with non-ideal conditions (i.e., locally flat bottom and no mistracking). Thus the product obtained from CUBE results should be able to reduce considerably the time consumed and the subjective decisions in data cleaning.

7.2 Recommendations to SHOA.

Following the results of this thesis, the CARIS CUBE implementation has been enhanced to be used with multibeam data from the Patagonian waters. CUBE should be soon included within the SHOA data analysis and cleaning procedures. The advantage to have a surface objectively estimated and its relative strength will be translated in a better estimation of the surface currently generated by SHOA. That is not only applicable for data analysis made in the office, but also could help to visualize the data onboard. Thus IHO S-44 non-compliant data or data inconsistent with the bathymetry solution could be re-collected before leaving the survey area.

Interactive editing needs to be helped with computer-assisted hydrographic processing. Despite expertise and dedication, the operators may still make inappropriate decisions rejecting or selecting data. Advances in data cleaning tools allow having a better representation of the seafloor, but since the filter is based on mathematical processes, the resulting model is just a simplified description of it. Hence a combination of interactive editing and semi-automated filters must be carried out.

The procedure to use the CARIS implementation of CUBE with Chilean data should include the uses of other filters such as Swath and TPE contained in HIPS. Thus the amount of noise-data will be reduced, and the CUBE's performance should be increased. Furthermore, using the surface product for filtering purposes, single grid resolution should be run. Operator interactive work should focus on areas where the disambiguation engine could not select the right hypothesis.

After depth estimation (in specific cases) has been re-validated by the operator, CUBE must be run again – this time to fulfill its main purpose of "telling the truth about the data". The final surface product should be achieved with the highest resolution available; therefore multiple resolution should be used in this run, to insure that echosounder resolution will be maintained. Since now the survey is treated in terms of the BASE surface achieved, SHOA should work to define the requirement for grid accuracy and grid resolution instead of be limited to the sounding accuracy.

Total Propagated Error computation in this research was achieved using an existing error model already tested for other type of echosounder (i.e. SIMRAD). Newer versions of the ATLAS online software, includes the TPE computation. This information can be directly addressed by the operator in HIPS, in which case no Device Model and

HVF is required [Beaman, 2007]. However some suitable level of caution should be considered, since the uncertainty model apparently in use with ATLAS system has not been reported in the open literature. Therefore the performance of this system can only be inferred.

This research was focused on the implementation of CUBE algorithm into SHOA's workflow in order to get the most reliable tool currently available for depth estimation and hence to use the surface product for filtering purposes. The challenge was not only to create the setting up for CUBE computations, but also to make the CARIS implementation of CUBE more suitable for irregular terrain always present in the Patagonian channel areas. The result was a new configuration that estimates the depth more realistically for this scenario.

7.3 Recommendations to CARIS.

Since CARIS multiple resolution (HIPS 6.1) is strongly affected by noise-data, some restrictions should be recommended to the users to avoid the use of the BASE surface as a filter. This application should be reviewed and enhanced to work in conjunction with CUBE. For example, the base distribution of CUBE does have a multiple resolution mode, but it uses spatial masks to decide whether each resolution level should be used, avoiding specifically the problem found in this research. CARIS has recently pointed out [Collins, 2007] that multiple resolution it was initially constructed in HIPS on a vertical basis instead of an area basis. That means, it was essentially implemented as a visualization tool, in the sense that once all data (over a large range of depths) was cleaned, the multiple resolution surface could be used to construct a "seamless" type surface, so that all data could be viewed as a single surface.

CARIS intends future implementation of a better seamless (multi-resolution) surface that can be used the same way as the single resolution [Collins, 2007].

The CARIS CUBE deep configuration should not be used in areas with steep slope. Its radius of influence (4 times the default configuration) gathers information from soundings far away from the node, in which case these soundings are not representatives for depth estimation at that node. It is suggested this configuration be reviewed and its use be clarified in the command window.

7.4 Recommendation to ATLAS.

Validation and publication of uncertainty models (Device Models) for ATLAS MBES is strongly recommended. Thus, estimations of the performance of these systems could be studied and visualized before the survey. In that way the operators could infer the expected performance of the MBES in a specific scenario.

7.5 Suggestions for future work.

Calder [Calder, 2007] has suggested other approaches to steep slopes issue, which consist of either: (a) applying CUBE normal to the prevalent slope, or (b) run CUBE to determine local slope (between nodes) and then apply these slopes in a second CUBE run. These would require more extensive modifications to the application of CUBE, than does the simpler parameter-modification approach taken here.

The fourth disambiguation method existing in HIPS (initialization surface) could be used to help CUBE in the estimation of the node. An initialization surface could be used to provide another source in the process to determine which hypothesis is the most likely for depth estimation. Thus changes in depth from current data could be contrasted with data previously gathered, which should increase the strength in the disambiguation engine. Another approach could be followed using a median binned depth estimate to form an effective initialization surface. The idea is to then use the BASE surface created to turn on the slope correction in CUBE.

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APPENDIX A

Ancillary sensors of the ATLAS FANSWEEP 20

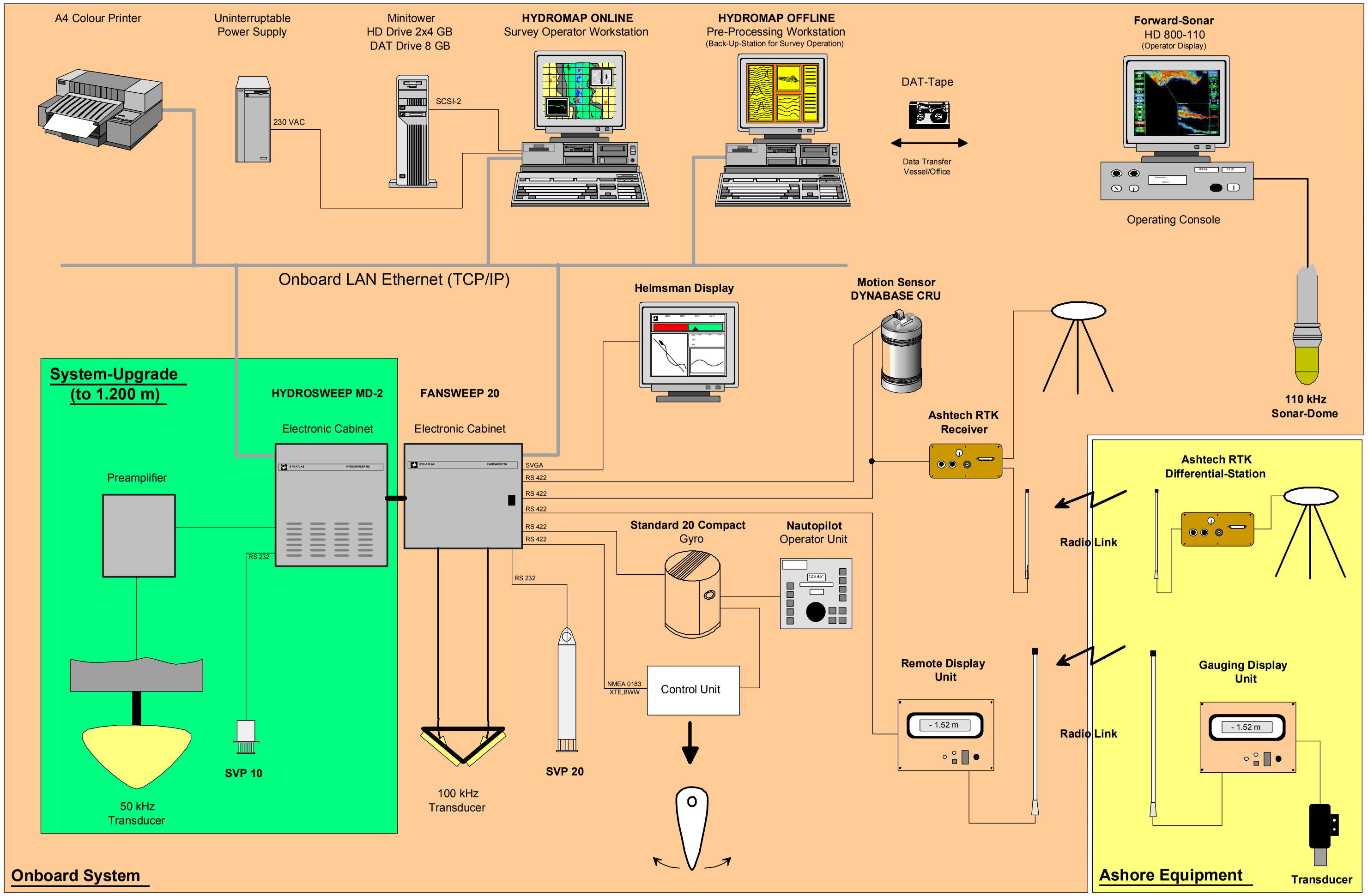


Figure A-1. Chilean multibeam configuration onboard of the Hydrographic vessel *CABRALES*.

APPENDIX B

Device model for ATLAS FANSWEEP 20 (200 kHz)

```
<SonarModel label="Atlas Fansweep 20 (200)" key="fs202">
  <Max_Num_Beams value="600"/>
  <Operating_Frequency_1 value="200"/>
  <Operating_Frequency_2 value="0.0"/>
  <Max_Angle value="80.5"/>
  <Beam_Width_Across value="1.0"/>
  <Beam_Width_Along value="1.3"/>
  <Steering_Angle value="0.0"/>
  <Range_Sampling_Frequency value="75000.0"/>
  <Range_Sampling_Distance value="0.01"/>
  <Min_Pulse_Length value="0.12"/>
  <Rates>
   <Repetition value="10"/>
   <Bathy value="10"/>
   <Attitude value="10"/>
   <Imagery value="0"/>
  </Rates>
  <Density>
   <Bathy value="1"/>
   <Attitude value="1"/>
   <Imagery value="0"/>
  </Density>
  <DeviceProperties>
   <Multibeam value="Yes"/>
   <SideScan value="No"/>
   <Towed value="No"/>
   <Calibrated value="No"/>
   <DualFrequency value="No"/>
   <HasAccuracy value="No"/>
   <Steered value="Yes"/>
   <Splithead value="Yes"/>
   <Bathymetric value="Yes"/>
   <Imagery value="No"/>
   <Attitude value="Yes"/>
  </DeviceProperties>
 </SonarModel>
```

APPENDIX C

DUMP ATLAS SURF Utility.

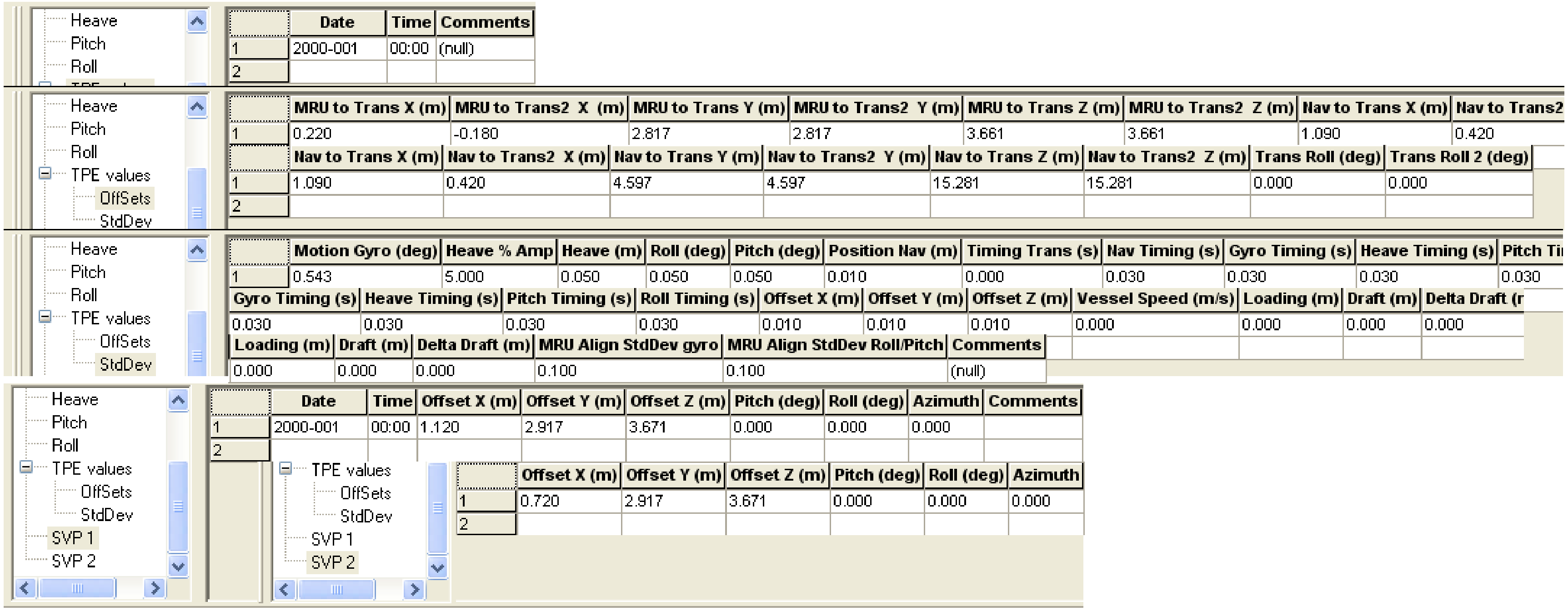
```
CARIS - dump Atlas SURF utility               Linked 31-Mar-2006

SURF Global Data:
    Name Of Ship   : 'CabralesFS'
    Type Of Sounder: 'F'
                     Data has high frequency
    Name Of Sounder: 'FS20'
    Number Of Soundings: 1909
    Number Of Beams    : 400
    Number Of Side-scan: 0
    Transducer (1) Depth:  3.671  Ahead:  2.917  Across:  1.120
    Transducer (2) Depth:  3.671  Ahead:  2.917  Across:  0.720
    Start Time Of Profile  2005-09-23  02:09:58
    Region of profile:    42S  72W
    Ellipsoid  'WGS84'
    Projection 'Mercator'
    SemiMajorAxis:  6378137.000  Flattening: 0.0033528107
    Flags 00000801  CP_TIDE_CORRECTED
    Offsets H:  0.00  R(P):  0.00  R(S):  0.00  P(F):  0.00  P(A):
0.00
    PosRef East: -72.7500520 deg  North: -42.4460368 deg
    Planned Start X/Y:  0.00000034 -0.00000032, Stop: 0.00020863 -
0.00016291
    Original Start X/Y: 0.00000034 -0.00000032, Stop: 0.00020863 -
0.00016291
    Original Start/Stop distance:   4509.324,  Time:   1198.642
  Modified  Start  X/Y:  0.00000034  -0.00000032,  Stop:  0.00020863  -
0.00016291
    Modified Start/Stop distance:   4509.324

SURF Statistics
    Min/Max Northing: -0.74098601 -0.74082341, Easting: -1.26972760 -
1.26925550
    Min/Max Speed:  2.80   6.18
    Min/Max Roll:  -3.510  3.093
    Min/Max Pitch: -1.291 -0.385
    Min/Max Heave: -0.153  0.134
    Min/Max Beam Position Star:  -400.789 433.723
    Min/Max Beam Position Ahead:  -2.240   2.489
    Min/Max Depth:   35.040  268.626

Number Of Positionsensors      : 2
    Sensor Nr. 0 = 'INTEGRATED NAV'  Ahead:  -1.68  Across:   0.03
Hgt:  11.61
    Sensor Nr. 1 = 'GPS'  Ahead:  -1.68  Across:   0.03  Hgt:  11.61

Number Of SoundvelocityProfiles: 1
Number Of Events               : 40
    Event Nr. 0 time       2.04 sec ''
    Event Nr. 1 time      32.00 sec ''
    Event Nr. 2 time      62.05 sec '>Òíx'
    Event Nr. 3 time      92.02 sec ''
    Event Nr. 4 time     122.11 sec 'ng'
```

```
    Event Nr. 5 time     152.03 sec '[ç_@'
    Event Nr. 6 time     182.05 sec ''
    Event Nr. 7 time     212.01 sec ''
    Event Nr. 8 time     242.03 sec ''
    Event Nr. 9 time     272.05 sec ''
    Event Nr.10 time     302.06 sec ')Çy¦AĐÌÙP‹•□'
    Event Nr.11 time     332.00 sec '¬õé6'
    Event Nr.12 time     362.03 sec ''
    Event Nr.13 time     392.04 sec ''
    Event Nr.14 time     422.11 sec 'AĐÌÙnŽ¸R'
    Event Nr.15 time     452.05 sec ''
    Event Nr.16 time     482.04 sec 'X
`B'
    Event Nr.17 time     512.07 sec ''
    Event Nr.18 time     542.05 sec ''
    Event Nr.19 time     572.00 sec ''
    Event Nr.20 time     602.02 sec ''
    Event Nr.21 time     632.00 sec ''
    Event Nr.22 time     661.99 sec ''
    Event Nr.23 time     691.99 sec '#□p¤'
    Event Nr.24 time     722.03 sec ''
    Event Nr.25 time     752.08 sec ''
    Event Nr.26 time     782.05 sec ''
    Event Nr.27 time     811.97 sec ''
    Event Nr.28 time     842.11 sec '@U,Ž(_NIAĐÌÙf å`'
    Event Nr.29 time     872.07 sec 'DCAST'
    Event Nr.30 time     902.09 sec '²µç¿'
    Event Nr.31 time     932.03 sec ''
    Event Nr.32 time     962.03 sec '2‹Æ¨AĐÌÙ2‹çm'
    Event Nr.33 time     992.09 sec '?|í‘'
    Event Nr.34 time    1022.15 sec ''
    Event Nr.35 time    1052.06 sec ''
    Event Nr.36 time    1082.04 sec ''
    Event Nr.37 time    1112.03 sec '¿ôP_Ãgöë'
    Event Nr.38 time    1142.00 sec '(íø?'
    Event Nr.39 time    1172.05 sec '2Pô¿Œ™éq°µç¿¿¼^¹_½ù?_„²,G.ù?'
Number Of Polygonelements      : 0


Sound velocity profile. Number of entries: 19
Label: C_PROFILES   Time: 0.000000
    0.50  1493.50
   14.90  1493.50
   16.10  1493.30
   17.90  1493.20
   23.30  1493.10
   25.70  1492.90
   29.90  1492.90
   31.10  1492.70
   34.70  1492.60
   36.50  1492.30
   38.30  1491.90
   43.70  1491.10
   51.50  1491.00
   53.30  1490.80
```

```
   58.60  1490.70
   60.40  1490.60
   64.00  1490.60
  100.00  1491.30
  107.60  1490.80


Sounding Nr 1   Profiletime: '02:09:58.603'  RelWay: 0.000000
No side-scan data
  Heading: 139.52 deg Heave: -0.04 m Roll: -0.61 deg Pitch: -1.08 deg
  cKeel: 1488.000  cMean: 1491.599  tide:  0.000
  SoundingFlag: 00000000
  Fullfan
  CenterPos East: -72.7500324 deg  North: -42.4460550 deg  Spd:  5.92
001  Depth:    0.00 Alg:    0.00 Acr:    0.00  E: -72.7500324d  N: -
42.4460550d F: 2401
    Heading on receive: 139.43  Heave: -0.04
    Angle:  -63.435  TravelTime:  0.000000
002  Depth:    0.00 Alg:    0.00 Acr:    0.00  E: -72.7500324d  N: -
42.4460550d F: 2401
    Heading on receive: 139.43  Heave: -0.04
    Angle:  -63.320  TravelTime:  0.000000
```

APPENDIX D

HVF population.



	Date	Time	Comments
1	2000-001	00:00	(null)
2			

	MRU to Trans X (m)	MRU to Trans2 X (m)	MRU to Trans Y (m)	MRU to Trans2 Y (m)	MRU to Trans Z (m)	MRU to Trans2 Z (m)	Nav to Trans X (m)	Nav to Trans2
1	0.220	-0.180	2.817	2.817	3.661	3.661	1.090	0.420

	Nav to Trans X (m)	Nav to Trans2 X (m)	Nav to Trans Y (m)	Nav to Trans2 Y (m)	Nav to Trans Z (m)	Nav to Trans2 Z (m)	Trans Roll (deg)	Trans Roll 2 (deg)
1	1.090	0.420	4.597	4.597	15.281	15.281	0.000	0.000
2								

	Motion Gyro (deg)	Heave % Amp	Heave (m)	Roll (deg)	Pitch (deg)	Position Nav (m)	Timing Trans (s)	Nav Timing (s)	Gyro Timing (s)	Heave Timing (s)	Pitch Ti
1	0.543	5.000	0.050	0.050	0.050	0.010	0.000	0.030	0.030	0.030	0.030

Gyro Timing (s)	Heave Timing (s)	Pitch Timing (s)	Roll Timing (s)	Offset X (m)	Offset Y (m)	Offset Z (m)	Vessel Speed (m/s)	Loading (m)	Draft (m)	Delta Draft (r
0.030	0.030	0.030	0.030	0.010	0.010	0.010	0.000	0.000	0.000	0.000

Loading (m)	Draft (m)	Delta Draft (m)	MRU Align StdDev gyro	MRU Align StdDev Roll/Pitch	Comments
0.000	0.000	0.000	0.100	0.100	(null)

	Date	Time	Offset X (m)	Offset Y (m)	Offset Z (m)	Pitch (deg)	Roll (deg)	Azimuth	Comments
1	2000-001	00:00	1.120	2.917	3.671	0.000	0.000	0.000	
2									

	Offset X (m)	Offset Y (m)	Offset Z (m)	Pitch (deg)	Roll (deg)	Azimuth
1	0.720	2.917	3.671	0.000	0.000	0.000
2						

Configuration of TPE values (Offsets and Standard Deviation field), for the echosounder FANSWEEP 20 200 kHz hull mounted in the Hydrographic vessel. Values obtained from the manuals of each device and interrogating the data itself using CARIS dump ATLAS SURF Utility. [CARIS, 2006a]

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