AALBORG UNIVERSITY

MASTER'S PROGRAMME IN SURVEYING,
PLANNING AND LAND MANAGEMENT WITH
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Analyzing the possibility of using satellite-derived bathymetry in Greenland

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Synopsis:
This master thesis is written at the Geodatastyrelsen (Danish Geodata agency). In order to analyze the possibility of using the satellite-derived bathymetry in Greenland. The test is mainly comparing SDB and multibeam data. The multibeam data is got from Geodatastyrelsen. Likewise, the SDB data is processed and delivered by EOMAP. There are two main test areas, which are called Sisimiut and Anders-olsen-sund. The test shows in Sisimiut, the RMSE is 1.5m in terms of MBE and SDB 10m , and the Pearson R is calculated as 0.19. In Anders-olsen-sund, the RMSE is 2.0m, and Pearson R is 0.68 basis on MBE and SDB 2m data. The RMSE is 1.5m, and Pearson R is 0.63 according to the result of MBE and SDB 10m data. If integrating the SDB charts into charts, the SDB products can meet the ZOC Category C level in accordance with the test.

Preface

This project is made by Yanmin Wang, on the 4^{nd} semester of the Master's Program in Surveying, Planning and Land Management with specialization in Surveying and Mapping.

The project is made during the spring semester of 2019 and delivered on the 7^{th} of June 2019. The project has a strong relation with the previous report 'Status and Improvement on Hydrographic Survey in Greenland', which was made during the last semester(autumn semester of 2019). From the last internship in GST, I gained more interest on the new hydrographic method. Therefore, the new report is created and based on the previous knowledge and experience.

On behalf of myself, I would like to give thanks to Karsten Jensen for useful feedback and guidance during the project period. And I appreciate Yvonne Morville Petersen who having me again in GST. What's more, many thanks for Philip Sigaard Christiansen who gives me a lot of inspiration when doing the test and writing the report.

Reading guide

The used literature is cited by [author, year] in the text where the source is used. The literature sources are listed alphabetically in the reference section. When the citation in the text is placed before the full stop the cited source is only related to that one sentence. When the citation is placed right after the full stop the source is related to the previous paragraph.

Figures and tables are numbered by two numbers: x.y, where x is the current chapter and y is the number of the figure/table in that chapter.

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CHAPTER 1

Introduction

Satellite-derived bathymetry(SDB) is a technique that estimating the water depth from the satellite imagery. The technique is to use the satellite imagery, and the imagery contains a lot of information in every pixel. After the processing of the imagery, SDB can provide and build a model of the seafloor. The principle is that there is a physical relationship between the measured light signal and the water column depth. SDB is getting more and more popular nowadays, because it has a lot of advantages compared to the other surveying methods, like the multibeam, single beam, airborne laser system, and airborne electromagnetic systems. The primary advantage is that it offers the ability to measure a rapid and remote area at between 5-10 times less costs than most traditional methods.[EOMAP, 2014] The other advantages can be it also has up-to-date satellite imagery data ,and the data can deliver bathymetric information with high horizontal resolution. Right now, different satellites can be used, like Sentinel, Worldview, and Landsat. In Europe, the Sentinel-2 images can be freely downloaded from the Internet, and it can be used for research use.

In Denmark, the hydrographic survey is done by the Danish Geodata agency; they are also in charge of the Greenland water. Right now, the multibeam system is most widely used in Greenland. The multibeam system is a sonar system. The system maps the sea bed with a high resolution. The problem is that it takes a lot of time to measure the water depth, and it also reasonably pricey. In Greenland, due to a lot of reasons like bad weather and short survey season, it is a risky task to do the survey. Plus, in Greenland, the nautical charts has not been fully fulfilled. Therefore, it is difficult to survey in Greenland area. It is somehow dangerous to send the surveying boat into an unsurveyed area, because the water depth cannot be determined. In that case, the SDB might be another solution to solve the problem, which also means it could be for the reconnaissance use. Reviewing the lecture [EOMAP, 2014] on the internet, it is worth to say that the SDB can be safely used in the water where is less than 30m.

In the beginning, in order to get a brief knowledge into the hydrographic survey, and to know how are the different survey methods used. The problem for a preliminary investigation is formulated as follows:

Different hydrographic survey methods

The problem is investigated in chapter 2. Answering the problem formulated above should enable the formulation of a problem statement in chapter 3.

CHAPTER 2

Preliminary problem analysis

In this chapter we will investigate the problem statement from chapter 1:

Different hydrographic survey methods

The earth is 71 percent covered by the water, even though the people all live on the land, the water area makes an important place among the human's activities. In order to have a clear idea about how the seabed looks and what is going on in the ocean, the hydrographic survey is a fundamental step when people want to understand the water area. Therefore, it is worthwhile to have a look at what are the different hydrographic survey methods, and the principle behind it.

In this chapter, first of all, the acoustic systems(single beam and multibeam) will be introduced. As a good method to measure the water depth, the acoustic systems play essential roles in the Danish hydrographic survey. In the meantime, there are other techniques which can also be supplementary methods for bathymetry. For example, the airborne laser system and airborne electromagnetic system are good options. Plus, the satellite imagery can also give information about the water depth. [International hydrographic Bureau, 2005] In the following, the introduction of these non-acoustic systems will be described as well.

2.1 Single beam echo sounders

In order to learn how does the multibeam echo sounders work, the knowledge of the single beam echo sounders is indispensable. What's more, the single beam technique still remains in the world. The principle of the single beam can be seen in figure 2.1. An echo sounder works by the pulse generator, and then it transmits acoustic energy. The acoustic energy travels through the water; when it hits the seabed, it will return to the transducer. So the distance from the pulse generator to the seabed can be calculated by the following formula [International hydrographic Bureau, 2005]:

$$Z_m = \frac{1}{2} \cdot t \cdot \bar{c}$$

where Z_m is the measured depth,

t is the time interval between the sound transmission and echo reception

$\bar{c}$ is the mean sound velocity in the water column.

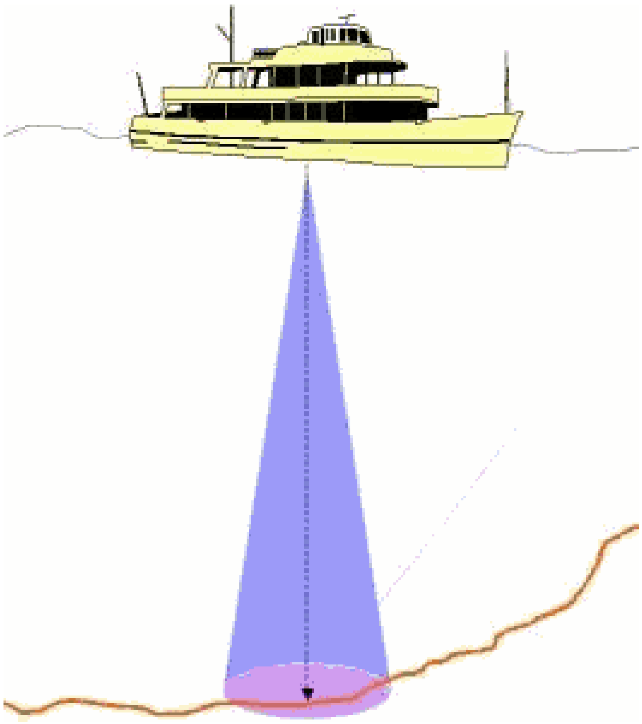

Figure 2.1: *the single beam echo sounder*

As we can see from the formula, the water depth is influenced by the sound velocity. Besides, the temperature, salinity, pressure, and density are the main factors for sound velocity variation. In practice, the survey ship unusually equips with Underway SV system which can directly measure the sound velocity through the water. SV is short for sound velocity. The look of the Underway SV can be seen from the figure 2.2. The principle of Underway SV is quite similar to the depth measurement conducted by the echo sounders. The system has a transducer which can emit a sound, and a reflector can reflect the sound. If the distance between the transducer and reflector is known, and the time interval from the transducer to the reflector is known. These two numbers can calculate the sound velocity.

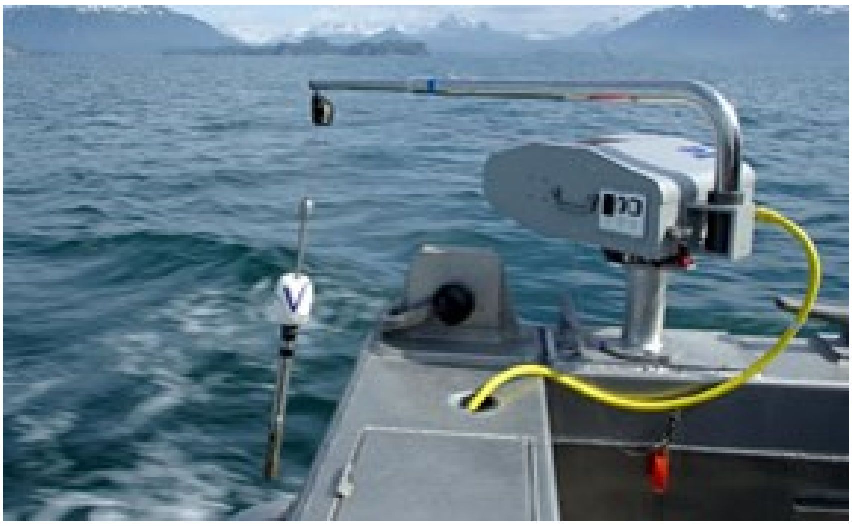

Figure 2.2: *The look of Underway SV*

2.2 Multibeam

In the present, in most sea mapping areas, multibeam is usually the most common survey instrument. Multibeam sonar is a technique that can map more than one locations in the seabed, and provides higher resolution. The principle of the multibeam is quite similar to the single beam. Instead of just one pulse, the transducer of the multibeam can transmit a fan-shaped area, and when the pulse directly hits the seabed, it will return to the receiver. The time interval and sound velocity can calculate the depth. The multibeam can give a wide swath of the seabed. Figure 2.4 is a display of the multibeam technique. It is worthwhile to note that the coverage of the seabed is strongly associated with the sea depth and multibeam opening angle. For example, a multibeam with a maximum angle of 120°, and if the water depth is 100m in the survey line, as a consequence, the coverage on the seabed could be ($3.4 \cdot 100$m) 340m. [International hydrographic Bureau, 2005] Figure 2.3 is a display of the example.

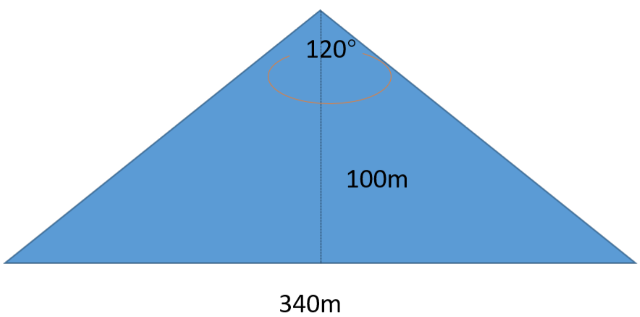

Figure 2.3: *The example of sea bed coverage*

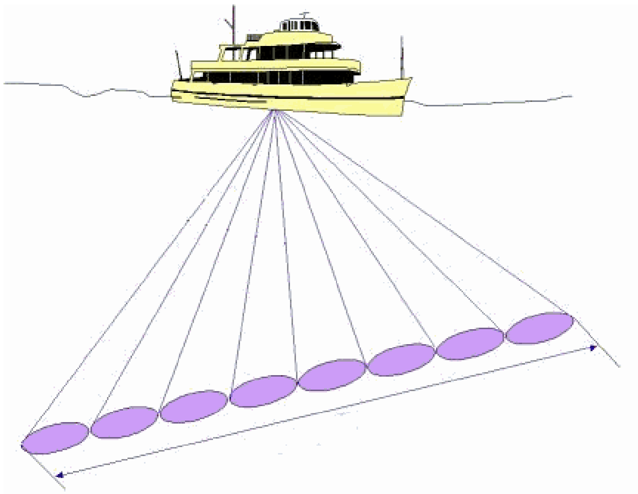

Figure 2.4: *the multibeam echo sounders*

2.3 Airborne laser system

The hydrographic airborne laser system is an alternative to survey with acoustic systems in shallow water. In general, the principle is the system which is mounted on an aircraft can emit laser pulses, and record the time interval when the pulses both from the sea surface and sea bottom. In that way, the measured time difference can be converted into the distance. In practice, there are two frequencies of the light mainly used for the bathymetry which are the blue-green beam and the infrared beam. When the system emits laser pulses, the part of the energy(Infrared beam) will be reflected by the sea surface, and the blue-green beam will be transmitted to the water, and part of the energy will be reflected to the aircraft and recorded. Using the accurate speed of the light and the time difference, the depth of the water can be calculated. It is worth to mention is that the transparency of seawater will make a big influence. The quantity of material suspended might make the light cannot get through the water and reach the water bottom.

2.4 Airborne electromagnetic systems

In the beginning, the airborne electromagnetic system technology is used for detecting the ore bodies which are buried beneath a conductive ground. Later, this technique is also used for mapping seawater depth. The principle is that the system transmits magnetic dipole source to generate a primary magnetic field that inducing currents in the ground, then the currents will create a secondary magnetic field. Assuming horizontal layers, signal processing in time or frequency domain can be used to measure the water depth. [Vrbancich, 2004]

2.5 Remote sensing

This section presents the water depth estimated from the satellite imagery, which is also called satellite-derived bathymetry(SDB). The technique is to use the satellite imagery, and the imagery can deliver information in every pixel. After the processing of the imagery, SDB can provide and build a model of the seafloor. The principle is that there is a physical relationship between the measured light signal and the water column depth. It uses some sophisticated algorithms and which can help to determine the water depth. [EOMAP, 2014] However, before using the satellite imagery technique, it needs to know somehow depth information(materials, salinity) in this area to 'tune' the satellite information into getting accurate depths. Figure 2.5 shows the brief idea of remote sensing.

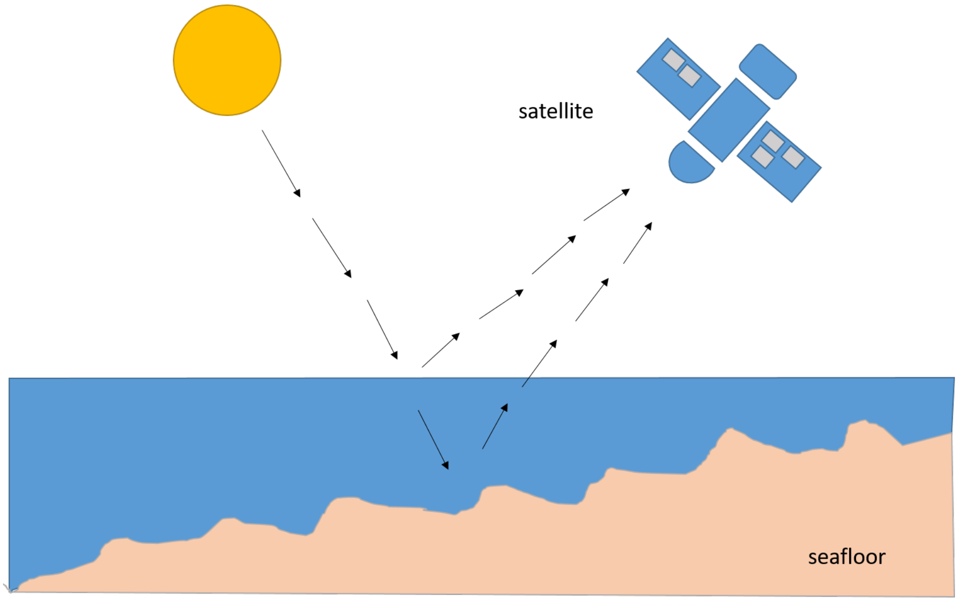

Figure 2.5: *Illustration of the path of the sunlight signal which being measured by satellite sensor*

2.6 Summary

In this chapter, the ideas of the echo sounder technique have been introduced. And it is worth to note that the single beam echo does have some limitations when it is used for measuring the water depth. For example, it takes a lot of time in order to make a large number of measurements. Because in the single beam technique, it will only tell you the ocean depth where the boat is located. In other ways, it is making a one-at-a-time measurement at many locations. As for multibeam, it is the most common technique has been used in the both Danish and Greenland water area, it can give high resolution of the seabed.

What's more, the introduction of the non-acoustic systems has been presented. Even though the techniques have been invented and developed for at least 40 years, all the systems have both some capabilities and limitations in the bathymetry. As for the airborne laser system, it gives good coverage and performs better in extreme water conditions of the salinity and temperature than acoustic system' performance. However, the laser system is very sensitive to the suspended material. If the water is not clear enough, it may not give the right result. Concerning the airborne electromagnetic system, due to the low frequencies, it has the capability to detect the water depth more than 100 meters, while it cannot perform well when the water depths are less than 100 meters. Regarding the satellite-derived bathymetry, it can cover the global water area and gives more information than water depth, but the SDB techniques can only be applied to shallow water areas(under 30 m).

All in all, different surveying methods may be used in a different situation; it is worth to make a test between them. Right now, in Greenland, the multibeam technique has been widely used, but the safety of navigation is still a major disadvantage of it. Investigating different method techniques, which might give an idea can other technology be used in Greenland. Considering the SDB can be used in the shallow water, while in some shallow areas, the survey boat can not navigate there. And the SDB data can be accessible in the GST office. Eventually the test will be basing on comparing the multibeam data and the SDB data in the same selected areas. The test will be introduced and presented in chapter 6.

CHAPTER 3

Problem Statement

From last chapter 2, all the hydrographic survey method has been introduced. As one of the most modern techniques: satellite-derived bathymetry(SDB), it has a lot of advantages such as low-cost expense, high resolution, and real-time data. Right now, there are a lot of challenges when doing hydrographic surveying in Greenland. The survey season is very short due to high latitude geography. What's more the weather in Greenland is often shifting, Besides, some of the icebergs are melting now, and the rest of the icebergs are floating by the wind. In that case, a lot of ice will be formed as a new ice block somewhere, which will make the navigation of the ship much harder. Considering all these factors, it is worth to study can SDB be used in Greenland. Consequently, the main problem statement has been formed in the following:

Can SDB be an alternative method when doing the hydrographic survey in Greenland

In order to answer this problem statement, it arises several sub-questions:

- How does the satellite-derived bathymetry work
- how water depth influences the error of SDB
- What is SDB accuracy in Greenland and can it be an alternative method

In the next chapter the procedure of how to answer the problem statement and the sub-questions will be explained. The structure of the report will be described as well.

Chapter 4 Method

In this chapter, the method for answering the problem statement is described. This implies an outline of the structure and the the flow of the report. In the meantime, a description of each chapter will be presented as well. The problem statement has already been formed in chapter 2 as:

Can SDB be an alternative method when doing hydrographic survey in Greenland

In order to answer this problem statement, it arises several sub-questions:

- How does the satellite-derived bathymetry work
- how water depth influences the error of SDB
- What is SDB accuracy in Greenland and can it be an alternative method

The first question will be answered in chapter 5. The overall principle of SDB and what are the potential uses of it are both illustrated in the chapter. Chapter 6 will discuss the second and third sub-questions. It will give an idea on how the water depth makes an impact on the error of SDB, and what is the accuracy of SDB in Greenland. The analysis of the possibility of using SDB in Greenland will also be discussed. The detailed structure of this report can be viewed in figure 4.1. Section 4.1 will outline the method for 'Satellite derived bathymetry technique'. Then the method for 'test' will be introduced in section 4.2.

4.1 Satellite derived bathymetry(chapter 5)

In chapter 5, the basic principle of satellite derived bathymetry will be presented. Then two algorithms about deriving the water depth from the satellite observations will be discussed as well. In order to analyze if SDB can be used in hydrographic survey, there is a section that will illustrate the potential use of SDB. ALL the text will base on the online literature and the workshop by EOMAP in GST.

4.2 Test(chapter 6)

The test is mainly about the comparison between satellite derived bathymetry and multibeam technology. The purpose is to answer the main problem statement :

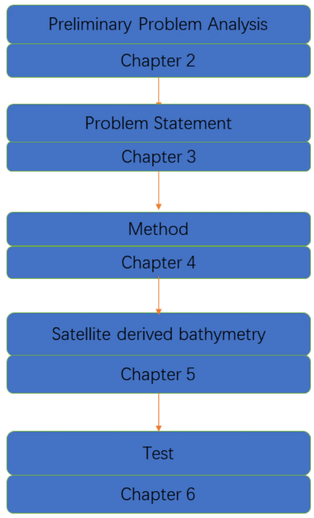

Figure 4.1: *The structure of report*

Can SDB be an alternative method when doing the hydrographic survey in Greenland.

In chapter 6, it will describe how the test is designed and performed. The outline of the data sets will be illustrated. To visualize and process both SDB data and multibeam data will be implemented in the QGIS software. QGIS is an Open Source Geographic Information System, which can process these two data sets freely. The multibeam data were retrieved from Geodatastyrelsen(Danish Geodata Agency), and the 10m resolution satellite data was got from Sentinel-2 observations, the 2m resolution satellite data was got from worldview-2 observations. All the data-processing part of satellite image was delivered by EOMAP company.

The main problem is how to compare the multibeam data(vector), and SDB data(raster). The first step is importing multibeam data(xyz file) into QGIS. Then set the multibeam data as the shapefile. Afterward, converting the vector data to raster is by using' Rasterize(vector to raster)' function in QGIS. There is another way around, using Point Sampling tool can collect raster values from multiple layers at specified sampling points. These two methods can both make these two data sets as the same format and compare with it.

After getting the data from both SDB and multibeam at the same point, the analysis of data sets will emphasis on the two indexes, which are the root mean square error(RMSE) and Pearson correlation coefficient(R).

The root mean square error(RMSE) is usually used for measuring the difference between two data sets(Predicted values and observations). The value could be calculated by the following formula:

$$RMSE = \sqrt{\frac{\sum_{t=1}^{n}(\hat{y}_t - y_t)^2}{n}}$$

where $\hat{y}_t$ is the predicted value,

y_t is each observation

n is the number of the observations.

The Pearson correlation coefficient is to measure whether the two data sets are on one line.

The value could be calculated by the following formula:

$$R = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i - \bar{Y})}^2}$$

where X_i is the each predicted value,

Y_i is the each observation value,

$\bar{X}$ is the mean value of predicted value,

$\bar{Y}$ is the mean value of Observations.

The calculation of these two indexes will be carried out in Matlab. The script of calculation can be seen in the digital appendix. In order to compare the SDB and multibeam data, the test will be shown in both scatter chart and curve chart. The terrain profile plugin in QGIS can make a line in the map, then the raster value from multiple layers will be generated.

Another test will emphasis on how water depth influence on the error of SDB. The error of SDB is the deviation between water depth derived from SDB and water depth derived from the multibeam. The category of water depth range will be decided by general water depth in the test area.

CHAPTER 5

Satellite derived bathymetry

From chapter 2, all different hydrographic survey methods have been discussed. Because the test is mainly about the SDB and multibeam data, it is necessary to get a handle of the knowledge of each technique. The principle of multibeam echo sounders has already been well illustrated from section 2.2. In this chapter, the more detailed physical principle of SDB model will be exhibited.

5.1 How does SDB work

The first concept of satellite derived bathymetry was created since the 1970s.[Véronique Jégat, 2016] Later with the development of sensors, software, and newly algorithm, the SDB can be gradually put into used in the hydrographic survey at a production level. The principle of SDB can be seen from figure 5.1. As it is shown from the picture, the energy from the sun will be collected by the satellite sensor at the end. However the energy recorded in sensor is divided into four components, which are the bottom radiance L_b, the subsurface volumetric radiance L_s , the surface radiance L_s, and the atmospheric path radiance L_A. So the radiance which is registered in the sensor(L_{TOA}) is including these four radiance, the formula can be written as formula [Chybicki, 2017]:

$$L_{TOA} = L_B + L_V + L_S + L_A$$

L_B is the result of sun energy reflecting from the sea bed, it has information about the water depth. L_V the subsurface volumetric radiance is the result of energy reflecting in the water by organic/inorganic constituents, which can be sediment and chlorophyll. The surface radiance L_S is the result of the energy reflected from the water surface. Plus, the atmosphere path radiance L_A is the result of energy reflected from the atmosphere. There are two most popular algorithms can obtain the water depth from the total radiance. The main goal is to remove the atmosphere radiance L_A and surface radiance L_S, and try to minimize the effect by subsurface volumetric radiance L_V. The general idea is that the bottom radiance is could be close to zero when the water is extremely deep. So the overall radiance is combined only with atmosphere path radiance, surface radiance and subsurface volumetric radiance in deep water. After correction of atmosphere and sunglint, the subsurface volumetric radiance could be calculated. While the subsurface volumetric radiance and atmosphere absorption in shallow water could be assumed as same as these in adjacent deep water. So after correction of sunglint, the bottom radiance in shallow water could be calculated by the overall radiance which is recorded by the satellite sensor. It is also needed to be known that, the energy from sun only penetrate water up to 30m at most. There are several bands got from the satellite can be used to determine the water depth. The blue light(440 to 540 nm), as a basic band for SDB, can penetrate water up to 30m in optimal condition. Then the green light (500 to 600 nm) can penetrate at maximum 15m, and red light (600 to 700 nm) can reach to 5m. The near infrared (700 to 800 nm) only can penetrate up to 0.5m. [Chybicki, 2017]

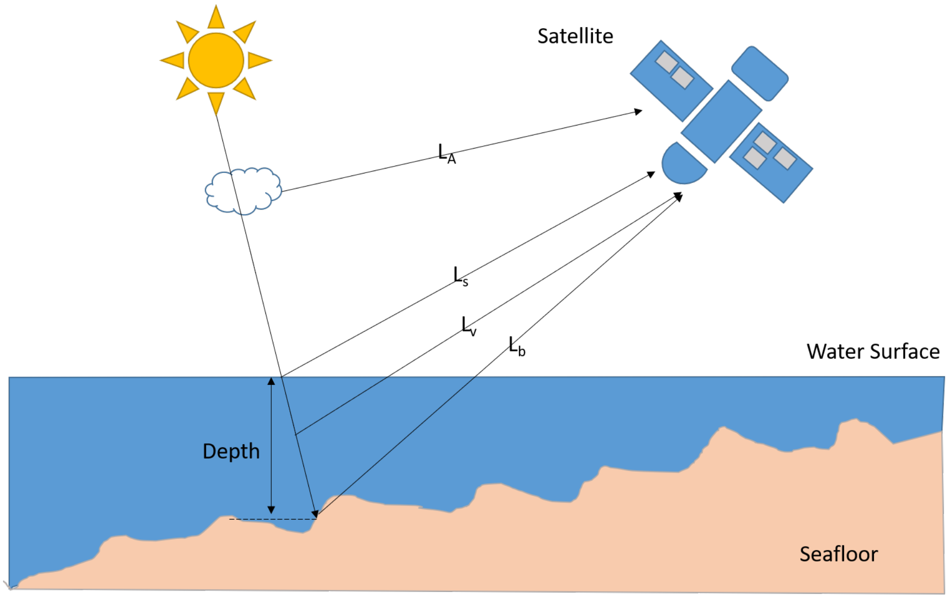

Figure 5.1: *Physical principle of SDB*

For the sake of getting the SDB product, the satellite images need to be pre-processed. It includes land-water-cloud detection, which is distinguishing different types of area. Then the radiometric correction is necessary; it includes top-of-air radiance, sunglint correction, and atmosphere correction. [Najhan Md Saida & Hasanb, 2017] Plus, the radiometric analysis is important as well. This step will use both tidal data and bathymetry data. The flow chart of SDB production can be viewed from figure 5.2.

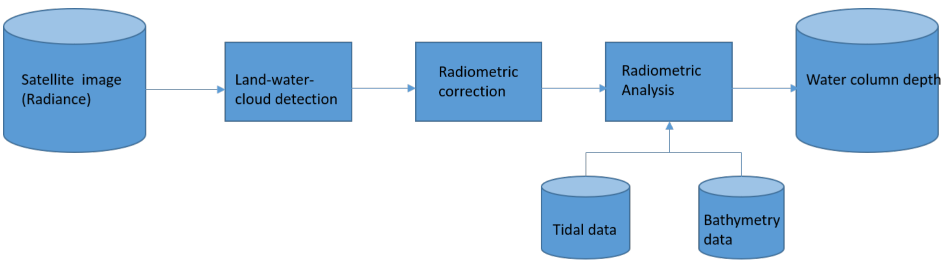

Figure 5.2: *The flow chart of SDB production*

There are two popular algorithm models stumpf [Stumpf, 2003] and Lyzenga [R. Lyzenga, 1981] can obtain water depth from satellite observations. The explain of models will be illustrated in the following.

5.1.1 Stumpf model (Log-Ratio Model)

The first model was developed by stumpf in 2003. The fundamental idea is that different band has a different level of water body's absorption. And the different level of absorption from bands can create a ratio between bands. At the same time, the ratio will change when the water depth changes. By analyzing the ratio between bands, the water depth could be calculated from it. The equation describes the Stumpf model can be seen in the following:

$$Z = m_1 \frac{ln(nL(\lambda_i))}{ln(nL(\lambda_j))} - m_0$$

where n,m_1,m_0 are the constant coefficients for the model

$L(\lambda_i)$, $L(\lambda_j)$ are the radiance for spectral λ_i and λ_j

Z is the estimated water depth

5.1.2 Lyzenga Model (Log-Linear Model)

The second model was first introduced in 1978. The equation can be seen as follows; it makes a linear correlation between the water depth and corrected remote sensing radiance of spectral bands.

$$Z = \alpha_0 + \sum_{i=1}^{N} \alpha_i ln[L(\lambda_i) - L_\infty(\lambda_i)]$$

where $\alpha_i (i = 0, 1, 2....i)$ are the constant coefficients, N is the number of spectral bands

$L(\lambda_i)$ is the remote sensing radiance after atmospheric and sunglint corrections for spectral band λ_i

$L_\infty(\lambda_i)$ is the deep-water radiance for spectral band λ_i

5.2 Potential use of SDB

Compared to traditional survey methods like multibeam, SDB cannot reach the same accuracy as multibeam. Additionally, optical remote sensing is limited to water clarity and weather, so the SDB can only apply in shallow water. Regardless of these limitations, the SDB still has a lot of advantages. For example, the survey can be conducted in a remote area by SDB. And SDB costs less and takes less time than traditional survey methods. Nowadays, SDB products have been more and more used world widely. The most common use of SDB is for survey reconnaissance and planning. [Véronique Jégat, 2016] The potential use of SDB can be put into four phases during the hydrographic survey. They are planning phase, survey phase, chart integration, and frequent monitoring. It can be seen from the figure 5.3

5.2.1 Planning phase

In the beginning, SDB can be used as a tool to identify the charts which are out of date or the old method which is not meet with modern standard. In that case, the next survey plan can add to the poor quality area. In other words, the SDB

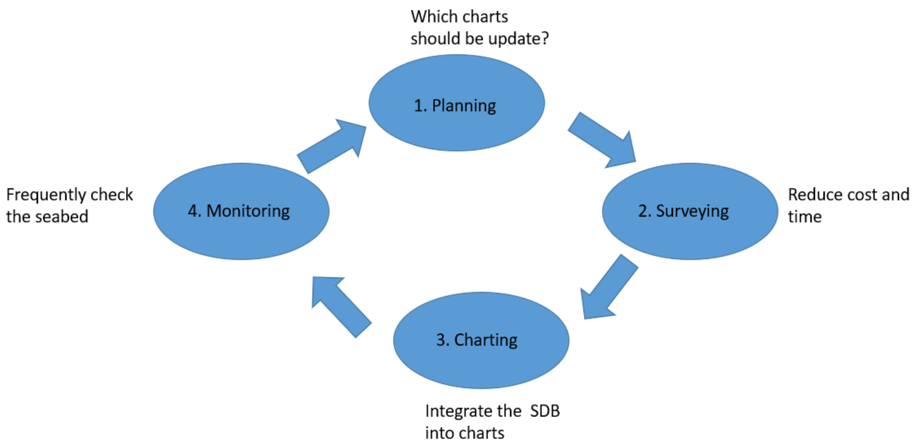

Figure 5.3: *SDB can be used in four phases*

can help to plan survey routes more efficient. Especially in Greenland, there are some sea areas have not been surveyed or were surveyed a long time ago. The SDB can be a supplementary tool, and it can tell the possibility of updating in this area. Moreover, the SDB can reduce the risk for the safety of navigation.

5.2.2 Survey phase

In the survey phase, the SDB can be used to identify potential hazards for survey ships. The SDB also can provide an understanding of sea bed in the survey area. When the water is too shallow for the survey ship, the SDB can fill 'white gaps' near to the shore, the area where the survey ships cannot navigate through.

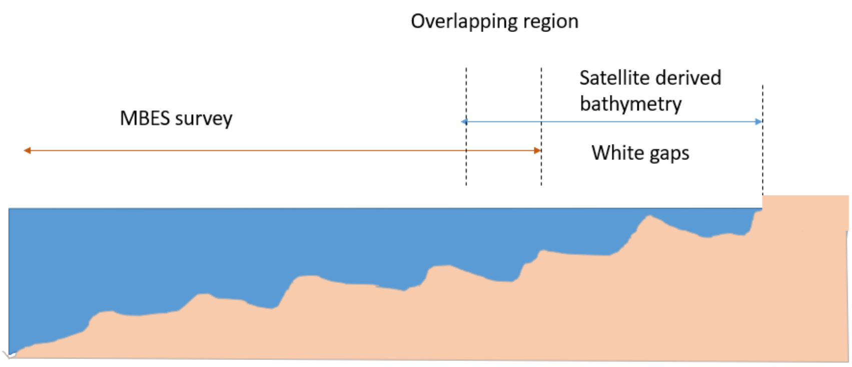

Figure 5.4: *SDB used in the 'white gap'*

5.2.3 Chart integration

In the production of nautical charts, there are some countries that have already integrated SDB into their charts. For example, France first produced SDCs(Satellite derived chart) in Raroia. Later, SDCs has also been used in the South West India ocean, Myanmar, Thailand and etc. [IHO, 2012] The example of different satellite derived charts can be seen in the appendix A There is worth to mention that hydrographers still need to keep aware of the limits of SDB when using SDCs, due to the lower accuracy of water depth.

5.2.4 Frequent monitoring

SDB can be a tool for frequent chart assessment, seabed change detection, and survey reconnaissance. Likewise, SDB is an environmental friendly technique, which will not harm the local ecosystem. Usually, it takes a lot of years to resurvey same area in Greenland, SDB can provide the change of water depth in real time if necessary.

CHAPTER 6

Test

In this chapter, the test is mainly about comparing SDB and multibeam data. By analyzing and comparing two resolution satellite images and multibeam echo sounders data, which will give people an idea that can SDB be used in the hydrographic survey and is it suitable for nautical charts in Greenland. The results will be evaluated in terms of the depth error estimation, spatial distribution, and overall quality.

6.1 Preparation of the multibeam data

The multibeam data is in xyz format, which contains longitude, latitude, and water depth. The data is got from Geodatastyrelsen(Danish Geodata Agency). The coordinate system is in World Geodetic System 1984. The data is mainly situated in two areas; one is called Sisimiut, which is situated in West Greenland, facing the Davis Strait, located about 320km north of Nuuk. The position of the Sisimiut can be seen from figure 6.1 . Another area is called Anders-olsen-sund, which is situated south of the Sisimiut, the position of it can be seen from figure 6.2. The selected area could be seen in a more detail way from the old nautical charts figure 6.3 and figure 6.4.

Figure 6.1: *Sisimiut*

Figure 6.2: *Anders-olsen-sund*

6.2 Preparation of the SDB data

GST has ordered the SDB data from a company called EOMAP. EOMAP is the leading global service provider of satellite-derived aquatic information in

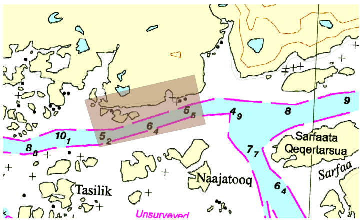

Figure 6.3: *Clip of the chart in Sisimiut*

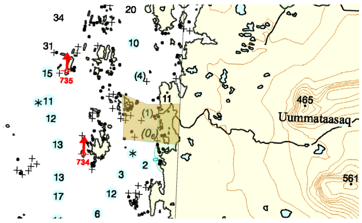

Figure 6.4: *Clip of the chart in Anders-olsen-sund*

maritime and inland waters. The high resolution (2m) SDB data is from the worldview-2 satellite, one of the most advanced civilian imagery satellites. The low resolution(10m) SDB data is from the Sentinel-2 satellite, which is a land monitoring constellation of two satellites that provide optical imagery. The EOMAP processed the raw satellite imagery of Greenland and made into a new satellite product which contains the water depth. The company also made an uncertainty value based on each pixel. The uncertainty is given in LE90 (linear error, 90% confidence interval).

6.3 Software for processing data

In order to investigate and visualize the SDB data, the choice of the software should be made. After considering different software, the 'QGIS' was chosen for analyzing. QGIS is an Open Source Geographic Information System. Initially, it was to provide a GIS data viewer; later it also gives people the possibility to edit and analyze the geospatial data. There are several reasons for choosing QGIS to test SDB data.

- Accessible in the GST office
- Easy to visualize geospatial data
- A straightforward users manual
- Compatible for different data formats

6.4 Results

The first chosen area is called Sisimiut. In order to compare the SDB data and multibeam data, there should be some overlap between different data sets. However, it shows no overlap between the SDB 2m and multibeam data. The test will only emphasis on the SDB 10m and multibeam data in Sisimiut area. There are around 3000 points which can be seen from figure 6.5. The root mean square error was calculated RMSE=1.5m. Meanwhile, the Pearson correlation coefficient was R=0.19. It can be seen that it does not have a strong relation between SDB 10m and multibeam data. And it is worth to mention that when the points have the same water depth derived by SDB 10m, it has multiple water depth derived from the multibeam. The reason behind it is because the resolution of SDB 10m data is bigger than multibeam 5m data. In other words, one pixel of SDB data covers 4 times areas than that of multibeam data. From figure 6.5, it seems that the points are randomly separated. When at the same location, the depth derived from SDB 10m is 3 meters, but the depth derived from MBE can reach to 7 meters. However, it also happens the other way around, when the depth of the point derived from MBE is low, but the depth of the point derived from SDB 10m is relatively deep. The average difference between 10m resolution SDB and MBES is around 1 meters

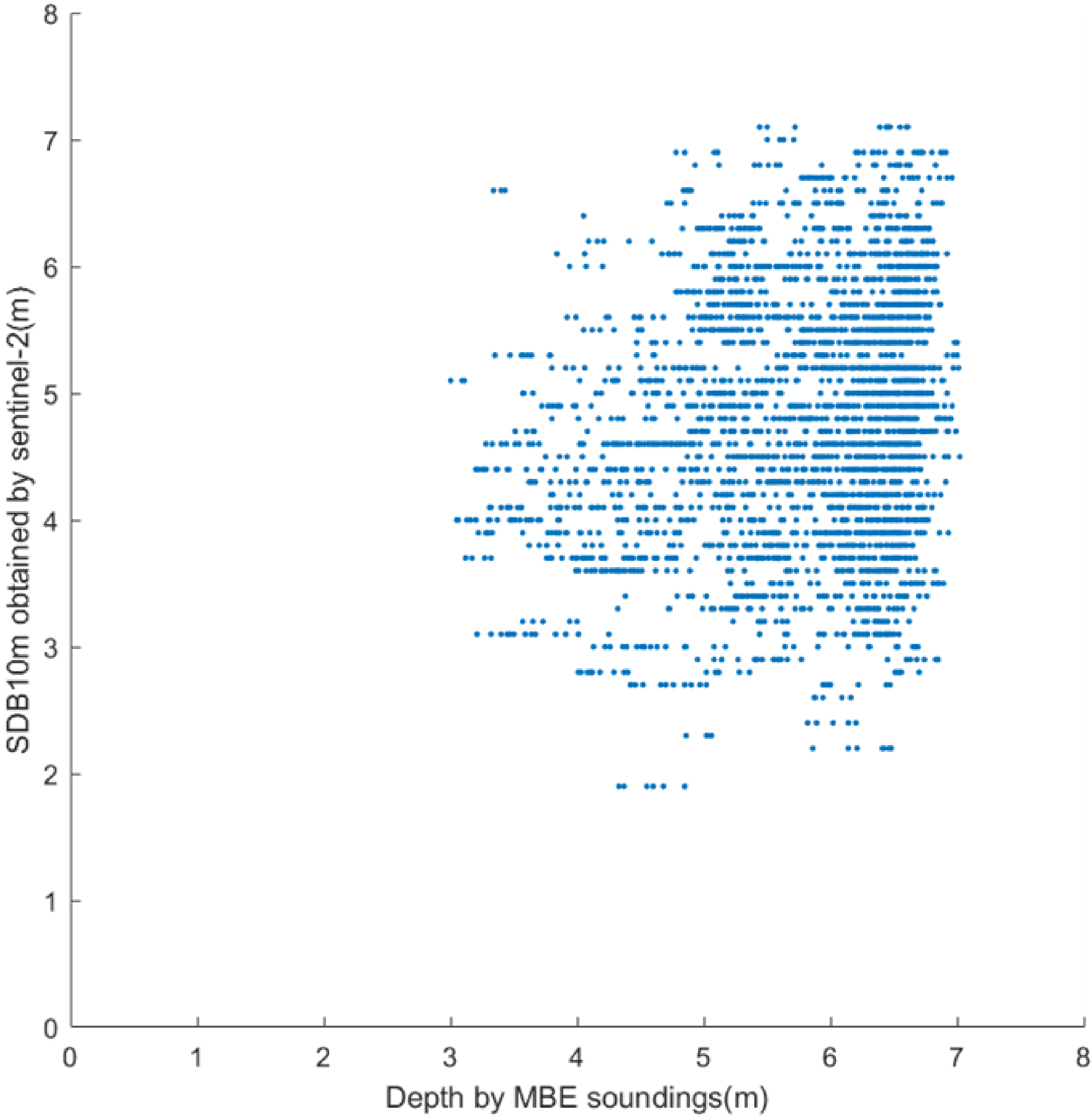

Figure 6.5: *Scatter plot of results obtained by 10m resolution SDB vs depths obtained by MBE in Sisimiut*

The figure 6.6 shows the Raster graph of Multibeam 5m in Sisimiut. The coordinates of the selected area can be seen from table 6.1. The color map shows the water depth range is from 2m to 10m. From the color of pixels, it can be seen the water depth of the selected area is around 4 to 6 meters. There are some blank pixels in the figure, which means the information of some pixels is missing.

Coordinates	Sissimiut		Anders-olsen-sund	
	Em	Nm	Em	Nm
Lower left corner u	635699.1	7442157.5	648145.1	7365838.1
Upper right corner	635786.4	7442225.3	648241.3	7365912.9

Table 6.1: *Coordinates of selected areas in Sisimiut and Anders-olsen-sund*

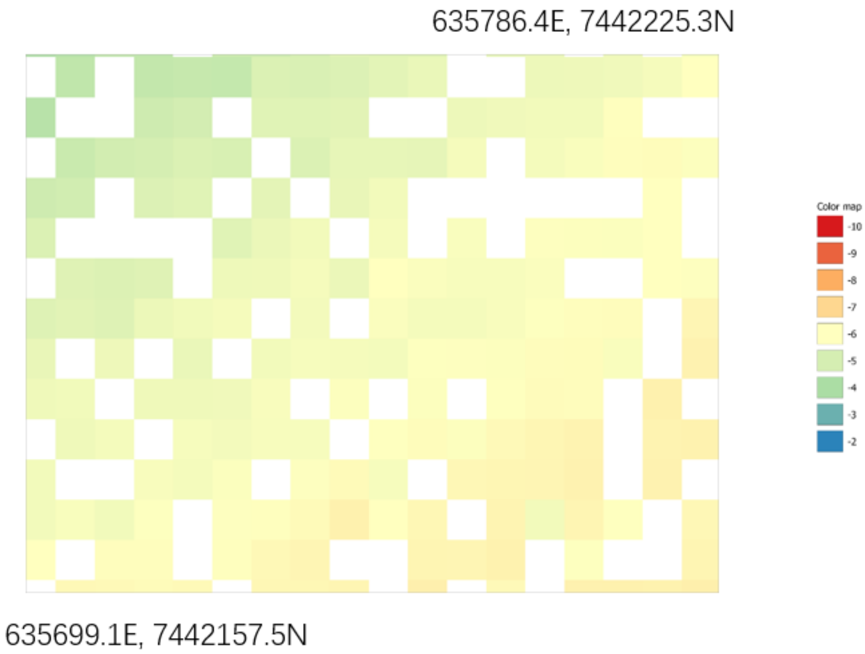

Figure 6.6: *Raster graph of MBE 5m in Sisimiut*

The figure 6.7 shows the raster graph of SDB10M in Sisimiut. The water depth of the same selected area is ranging from 2 to 7 meters. Comparing to the raster graph of multibeam 5m, the changes of the sea bottom is more significant in SDB 10m.

In order to give a more vivid illustration of what is the water depth difference between SDB 10m and multibeam 5m data. The show of the water depth difference can be seen from figure 6.8. The resolution of it is 5m. The color map shows the water depth difference is from 4m to -5m. When the figure is positive(the color of the pixel is green or blue), it means the water depth derived from SDB 10m is higher. Otherwise, when the figure is negative(the color of the pixel is orange or red), it means the water depth derived from multibeam is higher. The biggest difference is around 4m.

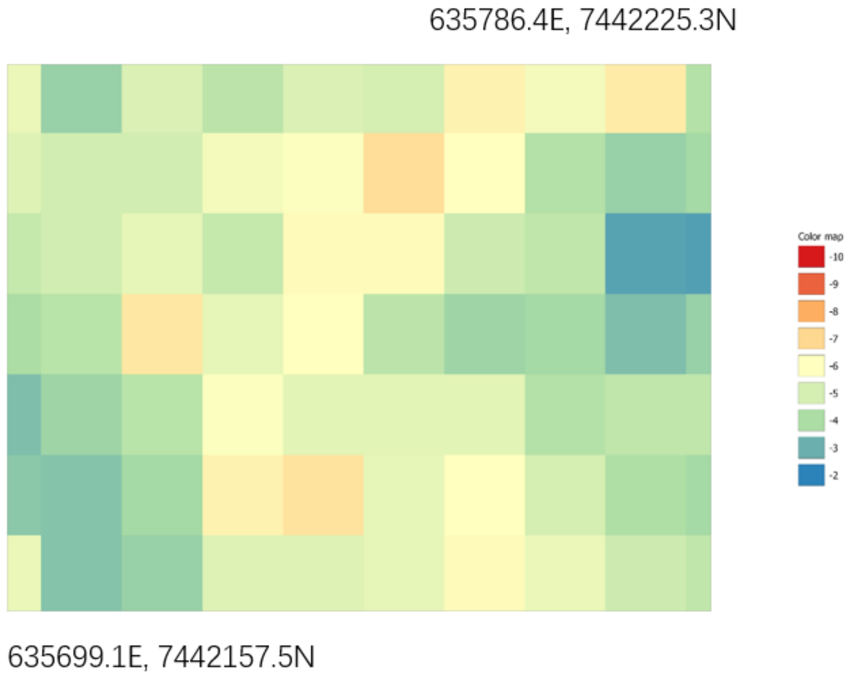

Figure 6.7: *Raster graph of SDB 10m in Sisimiut*

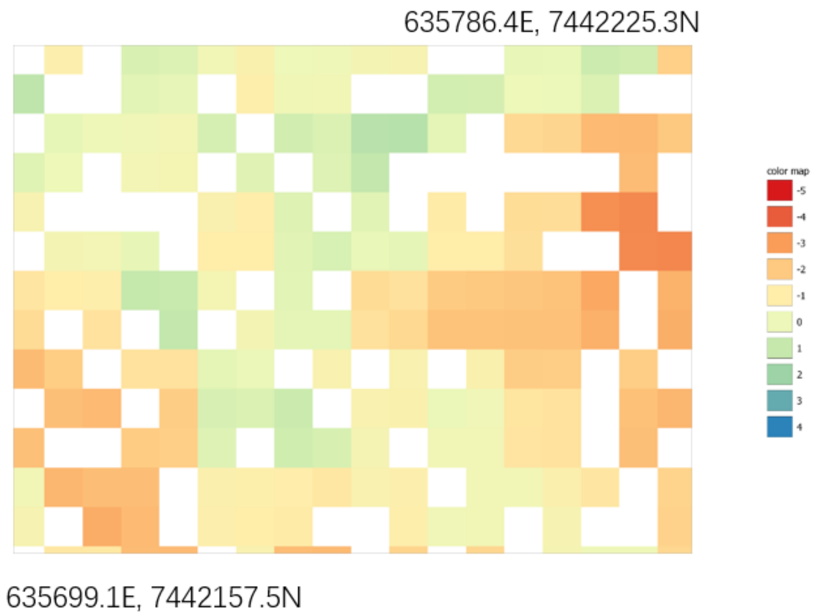

Figure 6.8: *Water depth difference in Sisimiut area of 10m SDB*

Finding the same line in the selected area, which can stimulate how a survey ship navigates in this area. The chosen line can be seen in figure 6.9. It originates from the left upper corner and ends at the right upper corner. The distance of the selected line is 350 meters long.

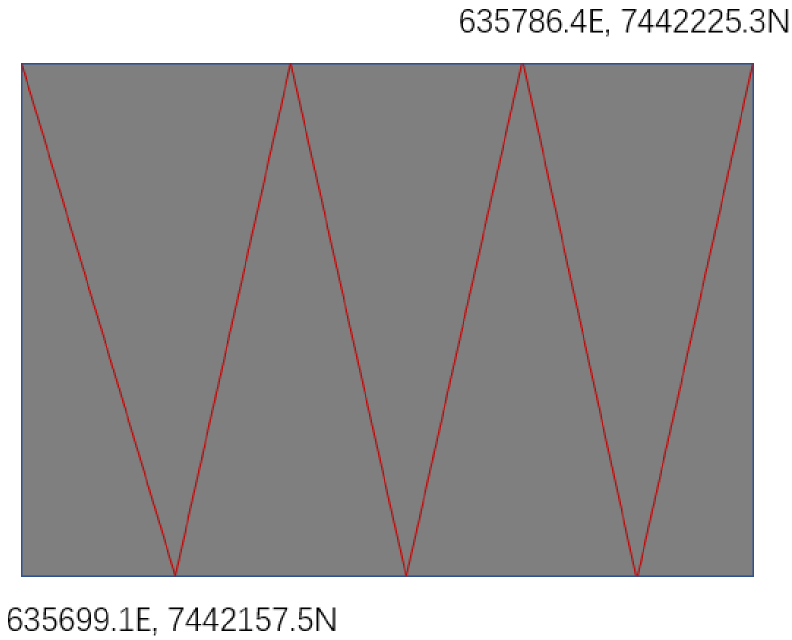

Figure 6.9: *The selected line in Sisimiut*

Figure 6.10 illustrates the water depth difference in the same selected line. The red line in the figure represents the MBE 5m data, and the blue line is SDB 10m data. As we can see, the water depth derived from MBE 5m(red line) in this line is more steady, the water depth is ranging from 4 to 6 meters. However, the water depth derived from SDB 10m(blue line) changes a lot more than MBE 5m. The biggest water depth difference can reach to almost 3 meters when the point is at 330m far away from the beginning.

Figure 6.10: *Comparison of SDB 10m and MBE derived bathymetry in Sisimiut*

For the purpose of analyzing how water depth influences the error of SDB, there is an additional test is made. The test is mainly to explain how the water depth can affect the SDB error, and the SDB error is the deviation between depths derived from SDB and multibeam. There are around 3000 points in the Sisimiut area which are selected. The water depth is divided into five categories, which are 3m to 4m, 4m to 5m, 5m to 6m, 6m to 7m and 7m to 8m. From figure 6.11, which could be seen that the most points are around 6 to 7 meters deep. The points which are situated in 3-4 m deep and 7-8m account a small part.

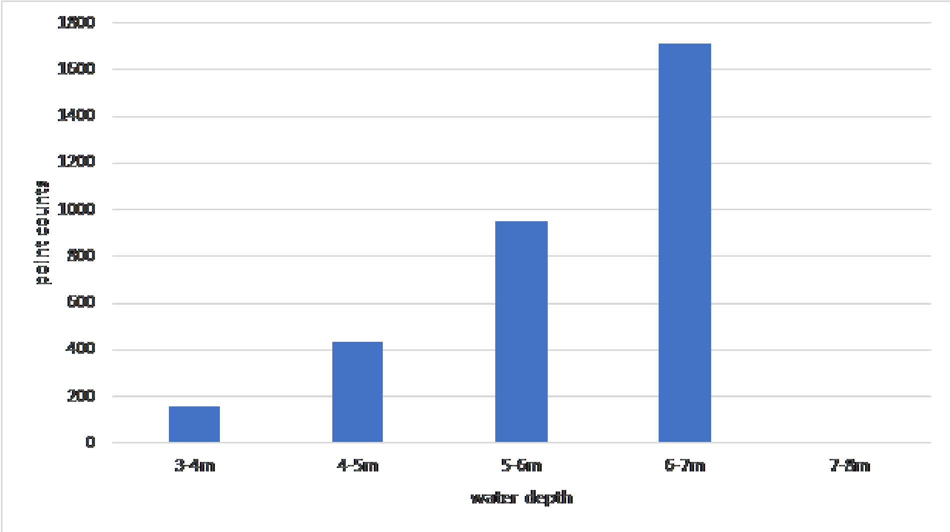

Figure 6.11: *MBE sounding counts in Sisimiut*

Figure 6.12 shows how the SDB error change with different water depth. The red line is the SDB 10m data. As we can see, in terms of SDB 10m data, the SDB error arises when the water depth gets higher, especially the water depth is around 4 to 8 meters. Then the smallest error is when the water depth is about 3 to 6 meters. The most significant error can reach to around 2 meters when the water depth is approximately 7 to 8 meters.

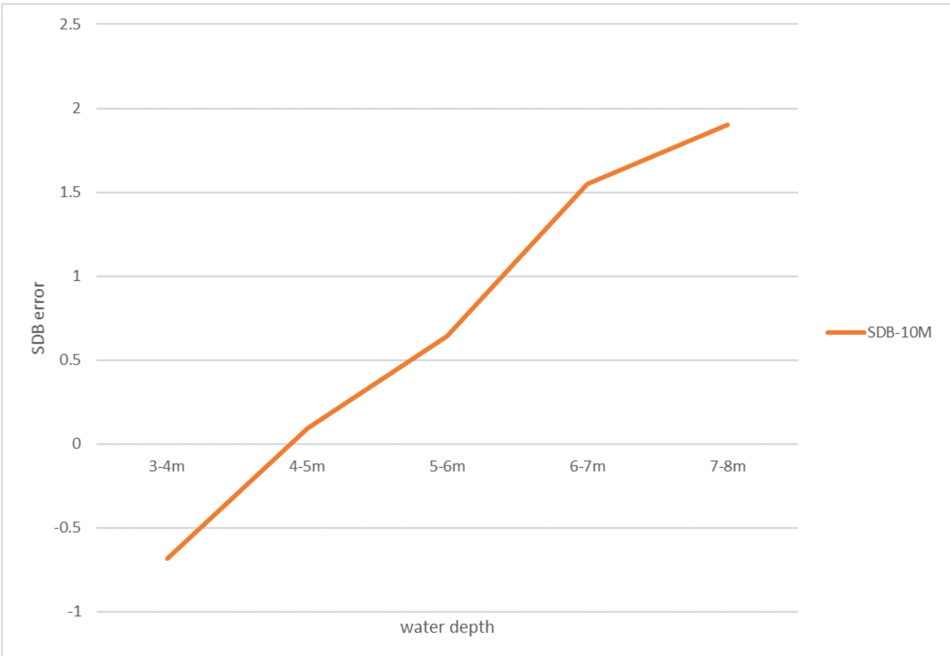

Figure 6.12: *SDB error in Sisimiut*

The second test area is called Anders-olsen-sund. There are around 450 points selected in the same area, the points which are both providing water depth information from SDB and MBES. Figure 6.13 shows the results obtained by 2m resolution SDB vs depths obtained by MBES. The root mean square error was calculated RMSE=2.0m. Besides, the Pearson correlation coefficient was R=0.68. The presented results show there is a strong relation between SDB data and MBES data, whereas at the same point, the depths derived from worldview-2 are higher than the depth got from MBES. Especially when the water depth is in deeper ranges like 3-5 meters. The average difference between 2m resolution SDB and MBES is around 1.8 meters.

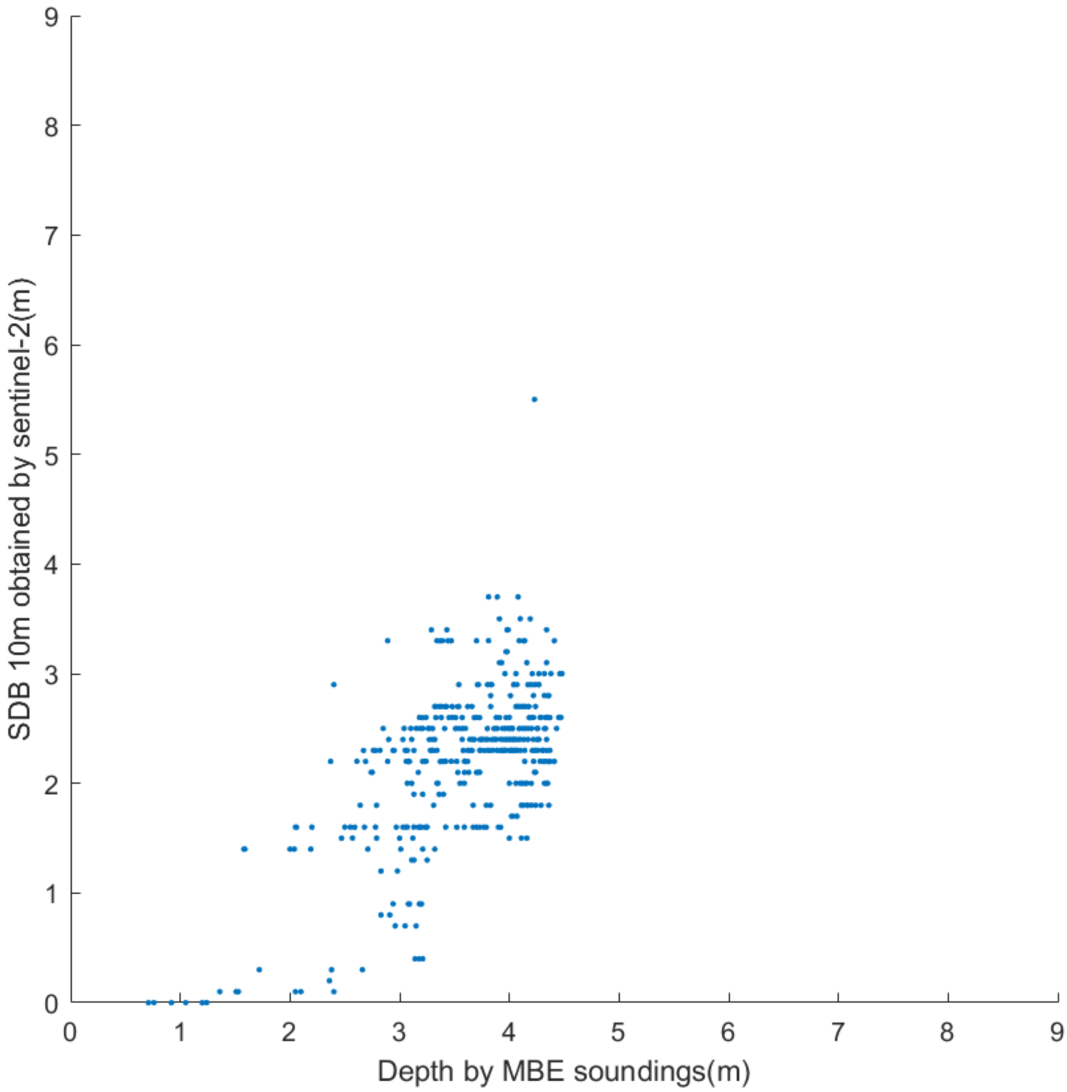

Figure 6.13: *Scatter plot of results obtained by 2m resolution SDB vs depths obtained by MBE in Anders-olsen-sund*

Figure 6.14 shows the results obtained by 10m resolution SDB vs depths obtained by MBES. The root mean square error RMSE=1.5m. Plus, the Pearson correlation R=0.63. In that case, it also shows there is a strong relation between these two data sets. It should be noted that the depths derived from SDB 10m are lower than the depth got from MBES. The average difference between 10m resolution SDB and MBES is around 1.37 meters. The difference gets higher when the water depth is around 1-3 meters.

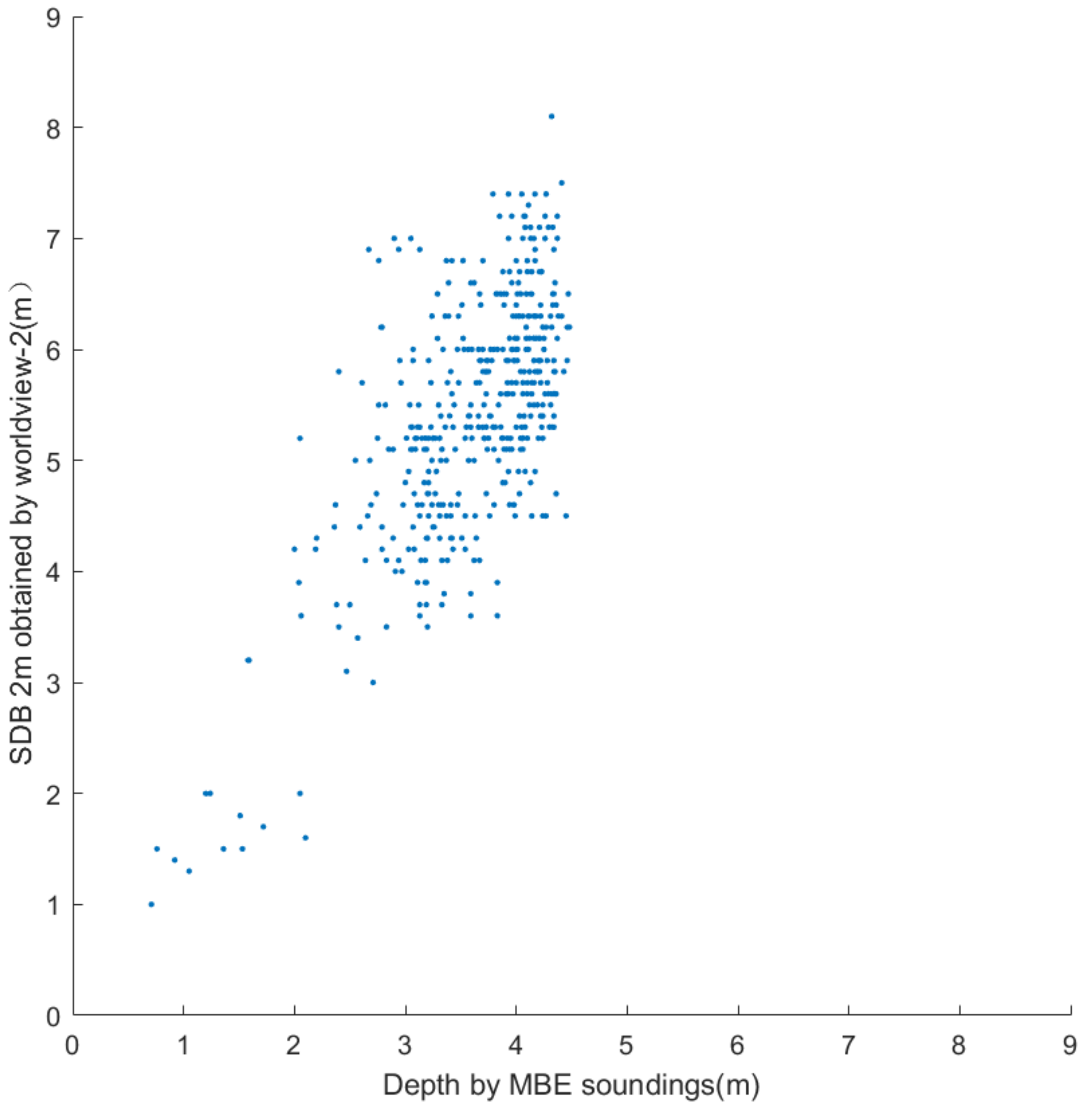

Figure 6.14: *Scatter plot of results obtained by 10m resolution SDB vs depths obtained by MBE in Anders-olsen-sund*

So as to give a clear visual inspection of the sea bottom, Figure 6.15, 6.16 and 6.17 show the raster figure from the same selected area in terms of SDB2m, SDB10m and MBE5m. Each figure somehow gives the water depth, which can be easily noticed by the human eyes. The data is presented as coloured pixels, and the depth is ranging from 0 to 8 meters. It is worth to mention that different resolution of data means different pixel size, for example, SDB 2m figure has much more pixels, which give more detailed water depth than Multibeam 5m and SDB 10m data. The blank pixel represents there is no data in that area. The SDB 2m and multibeam 5m data are both missing some information in a few pixels.

It can be observed that the different corresponding depth maps give not exact same water depth information. In the SDB 2m figure, the water depth is more or less ranging from 5 to 8 meters. However, in the SDB 10m figure, the water depth is from 2 to 5 meters. The multibeam data is regarded as the actual value. In the multibeam 5m figure, the water depth is from 2 to 4 meters. From visualizing this selected area, the SDB 10m figure and multibeam 5m figure give a small difference in representing the water depth. Although, the SDB 2m figure provides a much higher water depth information. The visual inspection makes people can quickly tell the difference from the different data sets, and the difference between each raster figure cannot be ignorable.

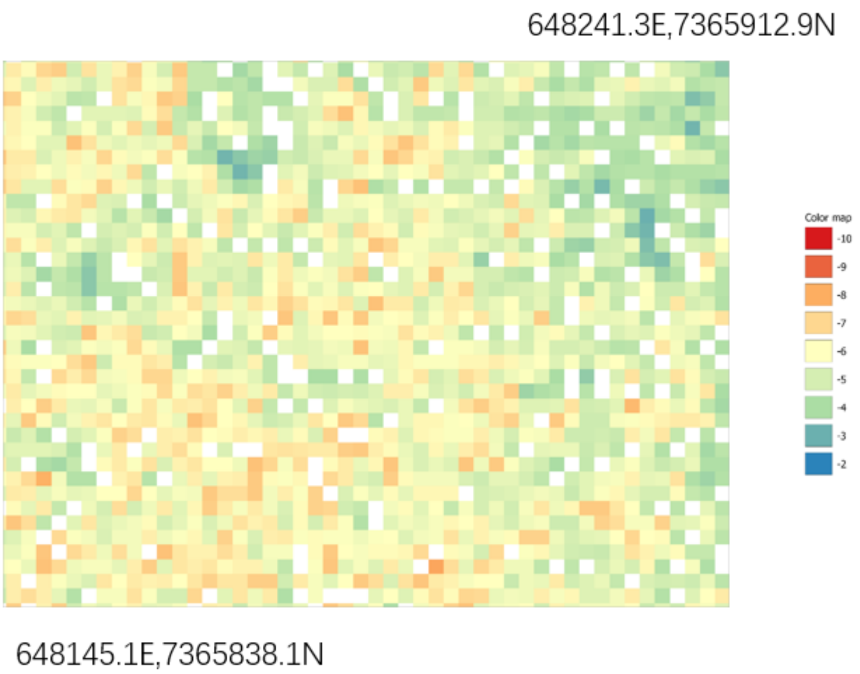

Figure 6.15: *Raster graph of SDB 2m in Anders-olsen-sund*

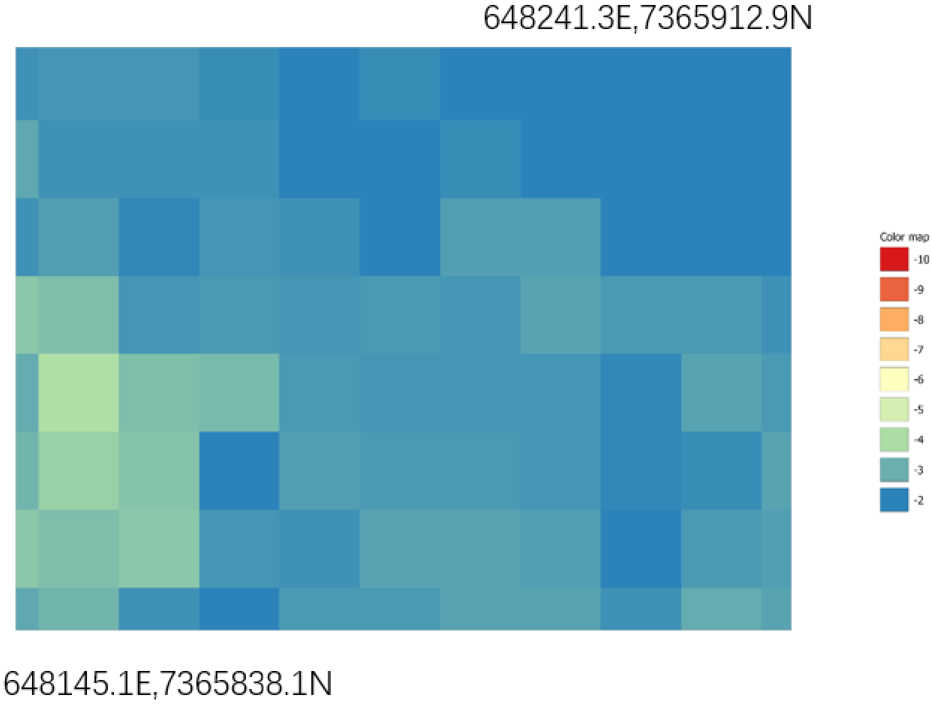

Figure 6.16: *Raster graph of SDB 10m in Anders-olsen-sund*

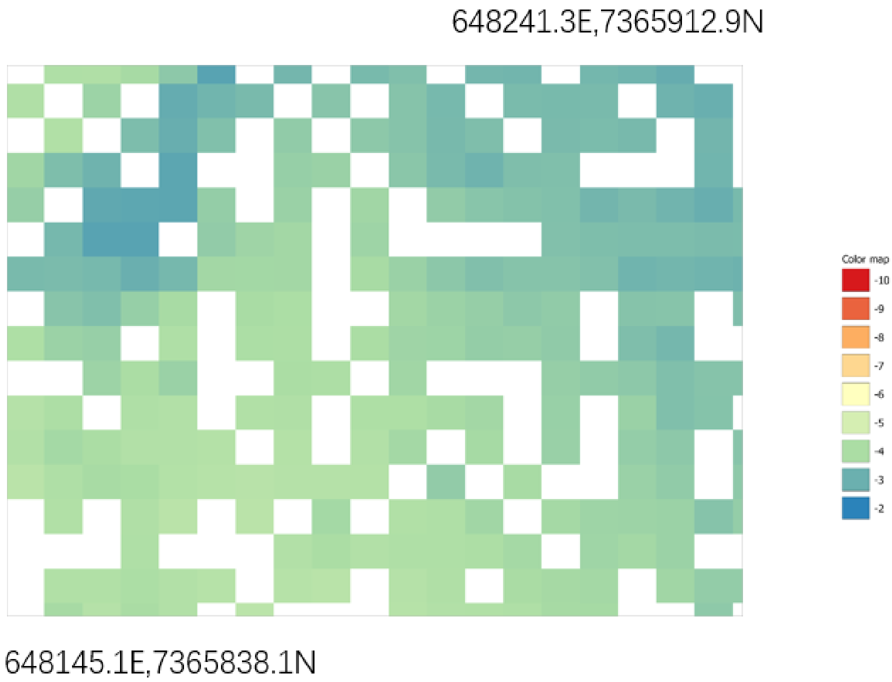

Figure 6.17: *Raster graph of MBE 5m in Anders-olsen-sund*

With the aim of showing the water depth difference in a detailed way. Figure 6.18 shows the water depth difference in Ander-olsen-sund area in terms of SDB 2m data. As we can see, all the pixels are almost green or blue, which means the water depth derived from SDB 2m is deeper than the water depth derived from MBE 5m. The biggest deviation can reach to 4 meters.

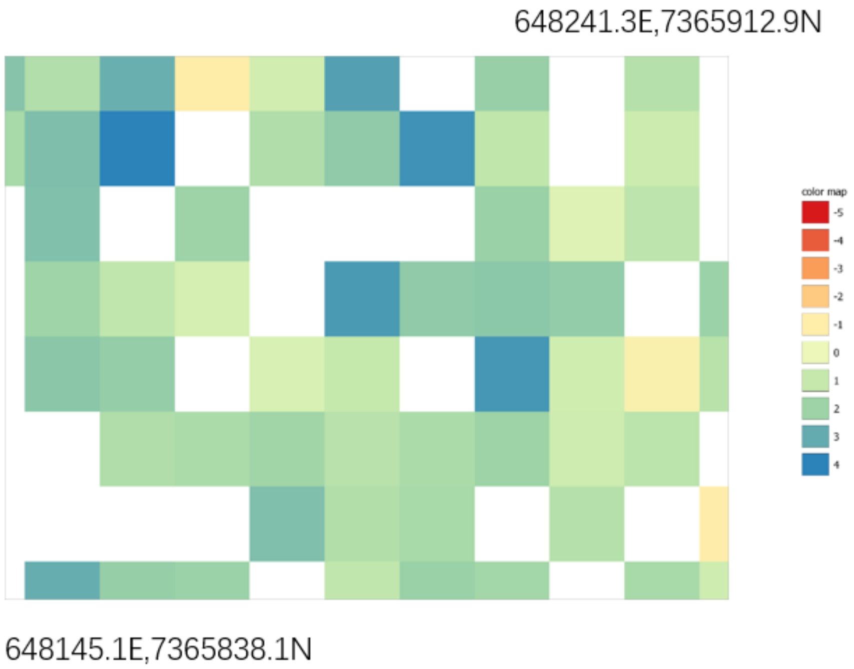

Figure 6.18: *Water depth difference in Anders-olsen-sund area of 2m SDB*

Figure 6.19 shows the water depth difference in Ander-olsen-sund area in terms of SDB 10 data. Almost every pixel is in orange or yellow. It can be concluded that the water depth derived from SDB 10m is lower than the water depth derived from MBE 5m.

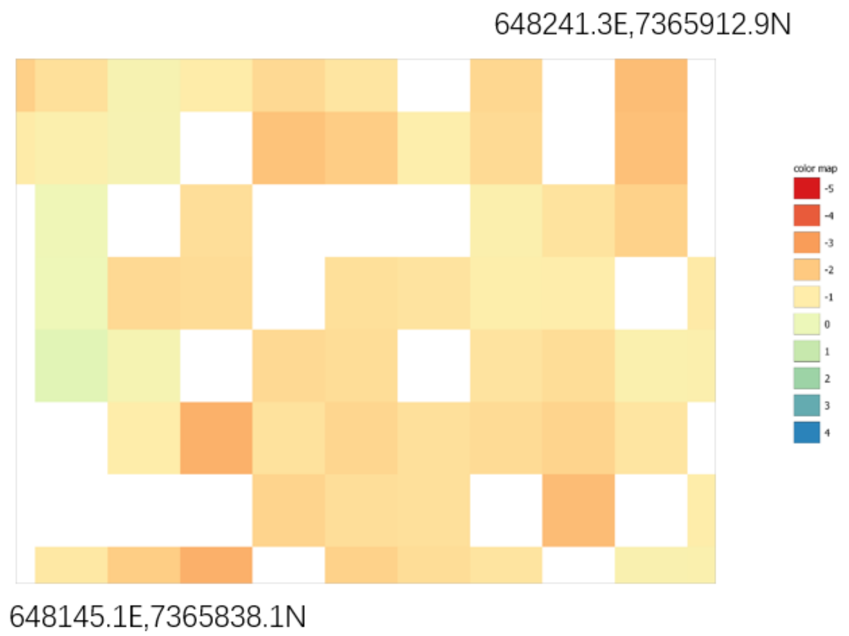

Figure 6.19: *Water depth difference in Anders-olsen-sund area of 10m SDB*

There is also a similar line has been chosen in Ander-olsen-sund area. The chosen line can be seen from figure 6.20. The distance of the selected line is around 450 meters long.

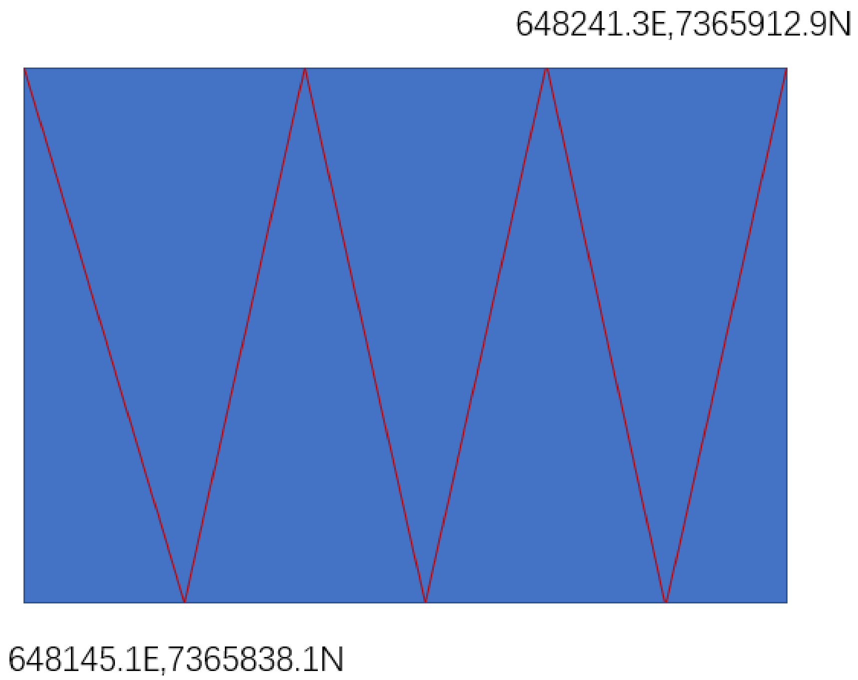

Figure 6.20: *The selected line in Anders*

Figure 6.21 shows that water depths derived from SDB 2m, SDB 10m and MBE

5m. The red line in the figure represents the MBE 5m data, and the blue line is SDB 10m data, the green line serves as SDB 2m data. As it vividly is shown, the depths derived from the MBES are situated between SDB 2m and SDB 10m, which also means the SDB 2m depicts the water depth is higher than MBES, then the SDB 10m follows. The depths derived from SDB 2m are mostly around 5-7m high, and the depths obtained from multibeam are approximately 3-4 meters. What's more, the depths derived from SDB 10m are roughly 1-3 meters. It could be safely concluded that there is a water depth difference between SDB2m, SDB10m, and multibeam data. It also means when using SDB data for acquiring the water depth, the uncertainty of each water depth should be considered.

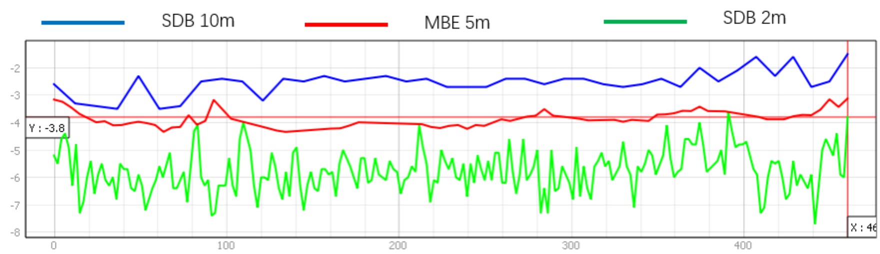

Figure 6.21: *Comparison of SDB 2m, SDB 10m and MBE derived bathymetry in Anders-olsen-sund*

The same test about analyzing how the water depth can affect the SDB error has also been made, and the SDB error is the deviation between depths derived from SDB and multibeam. There are around 1600 points in the Anders area which are selected. The water depth is divided into seven categories, which are 1m to 2m, 2m to 3m, 4m to 5m, 5m to 6m, 6m to 7m and 7m to 8m. From figure 6.22, which could be seen that the most points are around 3 to 4 meters deep. The points which are situated in 1-2 m deep and 7-8m account a small part.

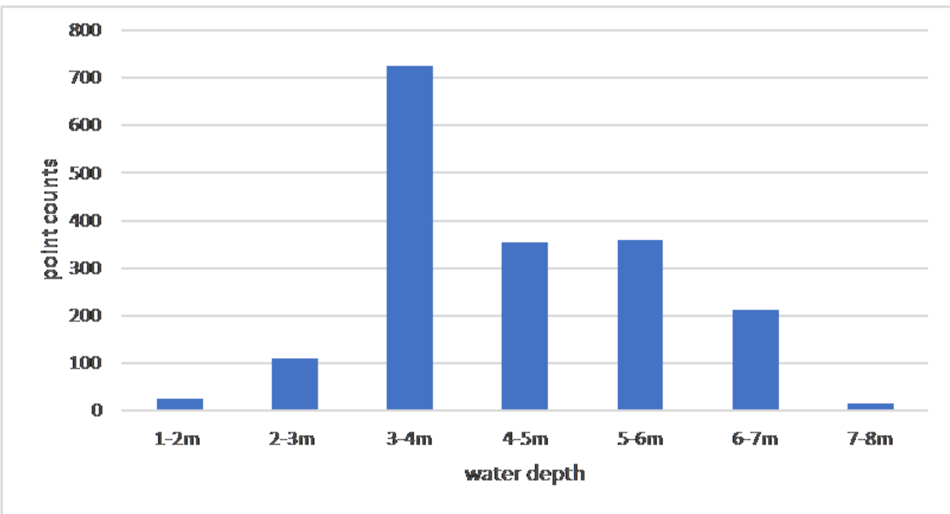

Figure 6.22: *MBE sounding counts in Anders-olsen-sund*

Figure 6.23 shows how the SDB error change with different water depth. The blue line is SDB 2m data, and the red line is the SDB 10m data. As we can see, in terms of SDB 10m data, the SDB error arises when the water depth gets higher. The most significant error can reach to around 3 meters when the water depth is approximately 7 to 8 meters. On the other hand, regarding the SDB 2m data, the SDB error gets higher when the water depth is around 1-3 meters. Then the SDB error drops from 2m to zero, when the water depth gets deeper and deeper. It could be noticed that, when the water depth is around 5-8 meters, the SDB 2m data can provide a more accurate result, which is close to the multibeam data.

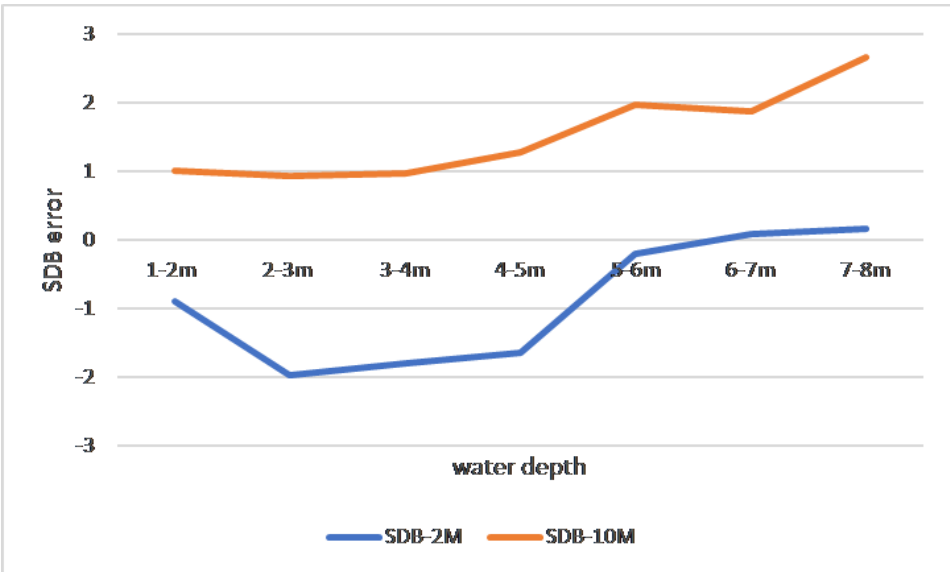

Figure 6.23: *SDB error in Anders-olsen-sund*

Category Zone of Confidence (CATZOC) values are assigned to geographical areas to indicate whether data meets a minimum set of criteria for the position, depth accuracy and seafloor coverage. The Zone of Confidence (ZOC) value is dependent on the positional and depth accuracy of the survey. [white paper, 2017] The above test has shows the vertical depth accuracy can reach to 2-3 meters when the water depth is around 7-8 meters. According to figure 6.24, category C can be fulfilled with SDB. It also means, if applying the SDB data into charts, the category C need to be informed on the charts, due to low depth accuracy.

ZOC [1]	Position Accuracy [2]	Depth Accuracy [3]	Seafloor Coverage	Typical Survey Characteristics [5]
A1	± 5 m + 5% depth	=0.50 + 1%d Depth (m) / Accuracy (m) 10 / ± 0.6 30 / ± 0.8 100 / ± 1.5 1000 / ± 10.5	Full area search undertaken. Significant seafloor features detected [4] and depths measured.	Controlled, systematic survey [6] high position and depth accuracy achieved using DGPS or a minimum three high quality lines of position (LOP) and a multibeam, channel or mechanical sweep system.
A2	± 20 m	= 1.00 + 2%d Depth (m) / Accuracy (m) 10 / ± 1.2 30 / ± 1.6 100 / ± 3.0 1000 / ± 21.0	Full area search undertaken. Significant seafloor features detected [4] and depths measured.	Controlled, systematic survey [6] achieving position and depth accuracy less than ZOC A1 and using a modern survey echosounder [7] and a sonar or mechanical sweep system.
B	± 50 m	= 1.00 + 2%d Depth (m) / Accuracy (m) 10 / ± 1.2 30 / ± 1.6 100 / ± 3.0 1000 / ± 21.0	Full area search not achieved; uncharted features, hazardous to surface navigation are not expected but may exist.	Controlled, systematic survey achieving similar depth but lesser position accuracies than ZOC A2, using a modern survey echosounder [5], but no sonar or mechanical sweep system.
C	± 500 m	= 2.00 + 5%d Depth (m) / Accuracy (m) 10 / ± 2.5 30 / ± 3.5 100 / ± 7.0 1000 / ± 52.0	Full area search not achieved, depth anomalies may be expected.	Low accuracy survey or data collected on an opportunity basis such as soundings on passage.
D	*Worse than ZOC C*	Worse than ZOC C	Full search not achieved, large depth anomalies expected.	Poor quality data or data that cannot be quality assessed due to lack of information.
U	Unassessed - The quality of the bathymetric data has yet to be assessed			

Figure 6.24: *Zones of confidence(ZOC) table*

6.5 Summary

In this chapter, the test between SDB 2m, SDB 10m, and MBE 5m data have been presented. The results can be seen from the table 6.2. There are two main test areas, which are called Sisimiut and Anders-olsen-sund. In Sisimiut area, the test is only focused on the SDB 10m data and MBE 5m data. The RMSE is calculated as 1.5m, and Pearson correlation coefficient is calculated as R=0.19. The R is near to 0; it seems that there is not a significant relation between MBE and SDB 10m data. By reviewing the water depth difference, the depth derived from SDB 10m is deeper than depth derived from MBE 5m when the water depth is 3 to 5 meters, but when the water depth is around 5 to 7 meters, the depth derived from SDB 10m is more shallow, according to figure 6.12. SDB 10m depicts the sea bottom more changeable, even though the real sea bottom is more stable. The SDB error arises when the water depth gets higher, especially the water depth is around 4 to 8 meters.

In Anders-olsen-sund area, the test mainly studies on both SDB 10m and SDB 2m data when comparing with MBE 5m data. The RMSE and Pearson correlation coefficient R calculated by SDB 10m are close to these numbers derived from SDB 2m. The R is near to 1; it proved that these two data sets are correlated. When the water depth derived from MBE is deeper, the water depth derived from SDB will

Areas	Test Name	RMSE	Pearson R	Points	Average difference
Sisimiut	MBE-SDB10m	1.5m	0.19	3000	1m
Anders-olsen-sund	MBE-SDB2m	2.0m	0.68	450	1.8m
	MBE-SDB10m	1.5m	0.63		1.37m

Table 6.2: *The results from the test*

get deeper as well. By reviewing figure 6.18, figure 6.19 and figure 6.21, the water depth derived from SDB 2m is deepest, the water depth derived from SDB 10m is lowest. The average water depth derived from MBE is around 1m deeper than water depth derived from SDB 10m data. In the meantime, the average water depth derived from MBE is around 1m lower than water depth derived from SDB 2m data. In terms of SDB 10m data, the SDB error complies with the previous finding in Sisimiut, the SDB error arises when the water depth gets higher, especially the water depth is around 4 to 8 meters. Regarding the SDB 2m data, the SDB error gets higher when the water depth arises in the range of 1 to 5 meters. Then the SDB error declines when the water depth arises up to 8 meters.

The depth accuracy is not good enough in some points or area. When considering put water depth derived from SDB into nautical charts, the plus text in the charts needs to be informed for navigators. For example, it should be noted that the water depth is derived from SDB and the ZOC Category is reach to C level. In terms of RMSE value, the value from this test is similar to results obtained by other authors. 'Eastern Sabah' [Najhan Md Saida & Hasanb, 2017] ,'South Baltic' [Chybicki, 2017] and 'Diamond Head'[D. R. Lyzenga & Tanis, 2006].

CHAPTER 7

Conclusion

This paper compares multibeam data and SDB data(10m resolution and 2m resolution) of the same area in Greenland. The test is basing on two regions, Sisimiut and Anders-olsen-sund. The 10m resolution SDB data is from Sentinel-2 and 2m resolution SDB data is from Worldview-2. The processing of the raw satellite image is carried out by EOMAP company. The multibeam data is in 5m resolution and acquired from Geodatastyrelsen(Danish Geodata Agency). In Sisimiut area, the test is only focused on the SDB 10m data and MBE 5m data. The RMSE is calculated as 1.5m, and Pearson correlation coefficient is calculated as R=0.19. The low Pearson correlation number implies there is not a great relation between SDB 10m data and MBE 5m data. The most significant error can reach to around 2 meters when the water depth is approximately 7 to 8 meters. The SDB error arises when the water depth gets higher, especially the water depth is around 4 to 8 meters.

In Anders-olsen-sund area, the RMSE and Pearson correlation coefficient R calculated by SDB 10m are close to these numbers derived from SDB 2m. The RMSE and R are near to 1. It implies the SDB data has a strong relation between multibeam data. The average difference between 2m resolution SDB and MBES is around 1.8 meters. The average difference between 10m resolution SDB and MBES is around 1.37 meters. The SDB error complies with the previous finding in Sisimiut in terms of 10m SDB data, the SDB error arises when the water depth gets higher, especially the water depth is around 4 to 8 meters. Regarding the SDB 2m data, the SDB error gets higher when the water depth arises in the range of 1 to 5 meters. Then the SDB error declines when the water depth arises up to 8 meters.

The big water depth difference is maybe from several reasons. The first reason perhaps are the water turbidity and the effects of light attenuation, because Greenland is in high latitude area. The second reason is that when EOMAP company calculated the water depth from the satellite image, they did not use the tide gauge from the GST. The GST has its tide gauge in these two areas, which can collect the tide information. It is assumed that using better tide data can improve the SDB products.

However, from the results, the SDB data is not very accurate compared to multibeam data. The SDB still can be used in several situations. For example, in the survey phase, the SDB can be used to identify potential hazards for survey ships. The SDB also can provide an understanding of sea bed in the survey area. When the water is too shallow for the survey ship, the SDB can fill 'white gaps' near to the shore, the area where the survey ships cannot navigate through. If integrating the SDB charts into charts, the SDB products can meet the ZOC Category C level according to the test.

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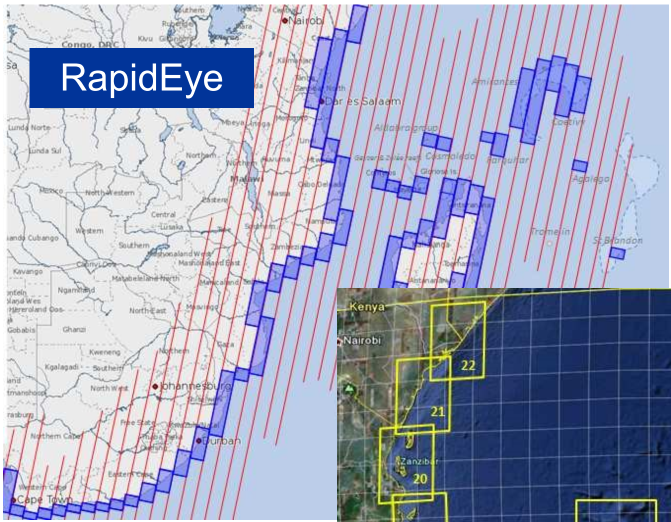
Appendices

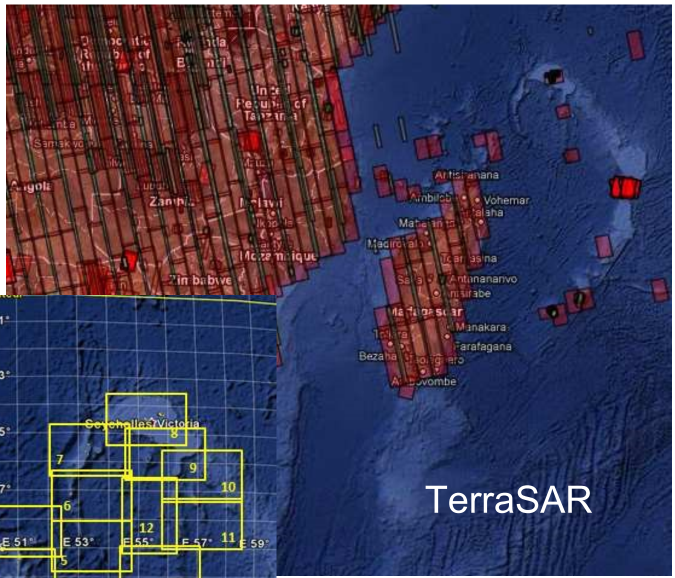
APPENDIX A

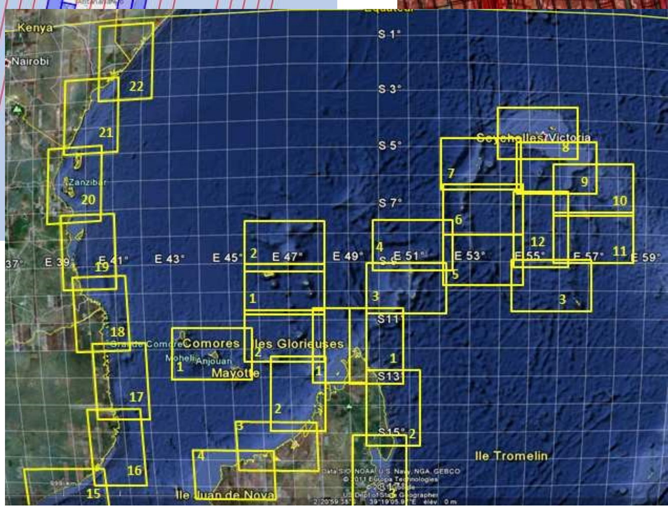
Satellite derived charts

In this appendix, the different nautical charts will be presented. These charts are all the examples which used the SDB technique. These charts are from International Holographic Office. [IHO, 2012]

South West Indian Ocean



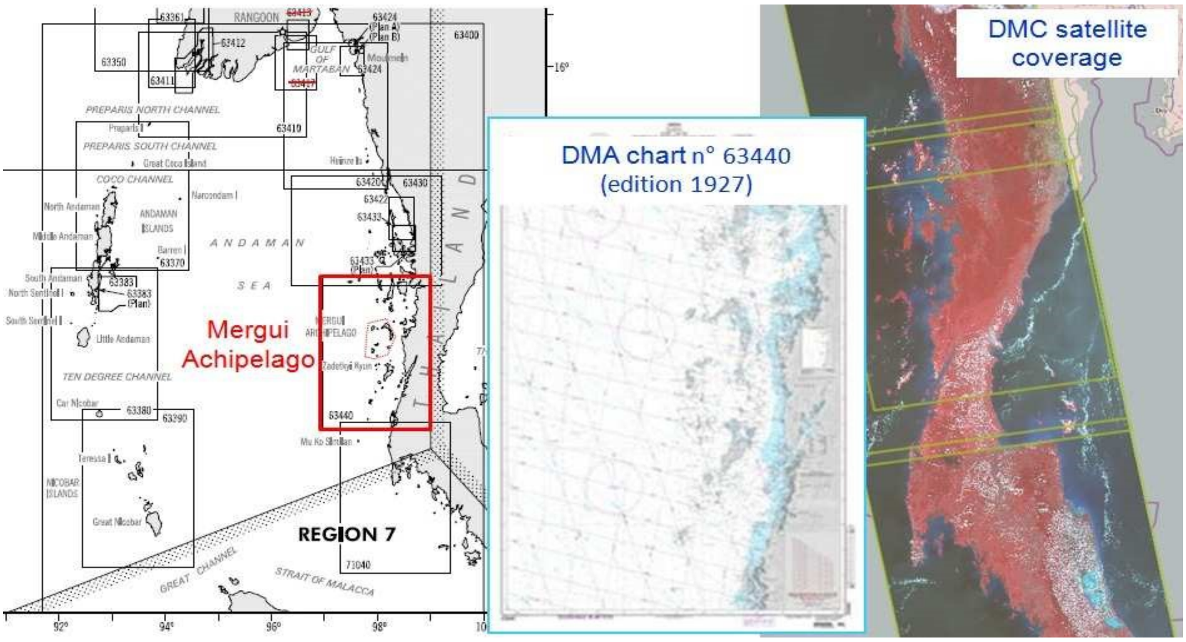




With special thanks to
Pierre Mouscardes
Consulting

Myanmar and Thailand ICZM

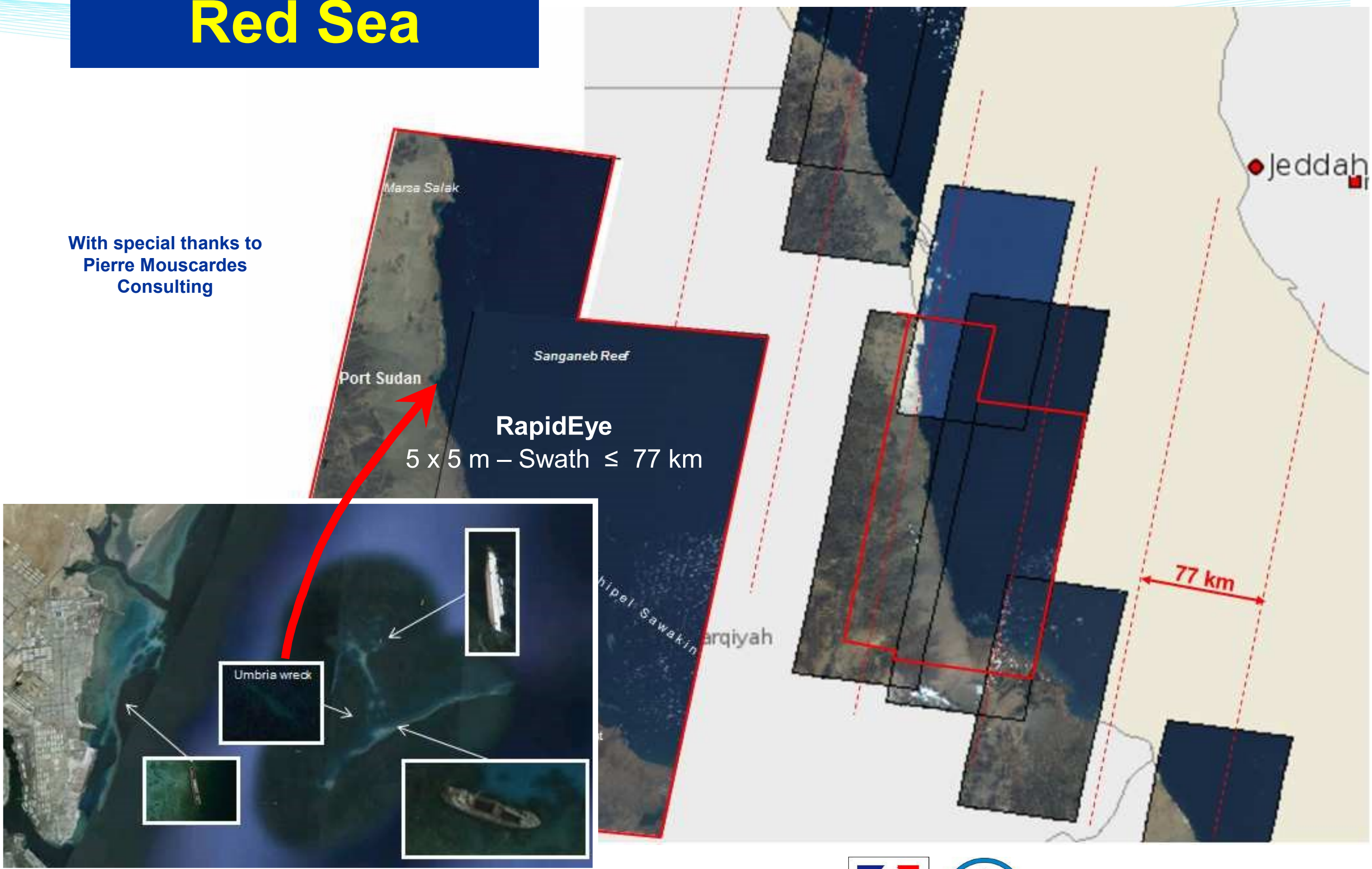
A tourist heaven, the Mergui archipelago comprises 800 islands and covers a 36 000 sq. km uncharted area and a National Park



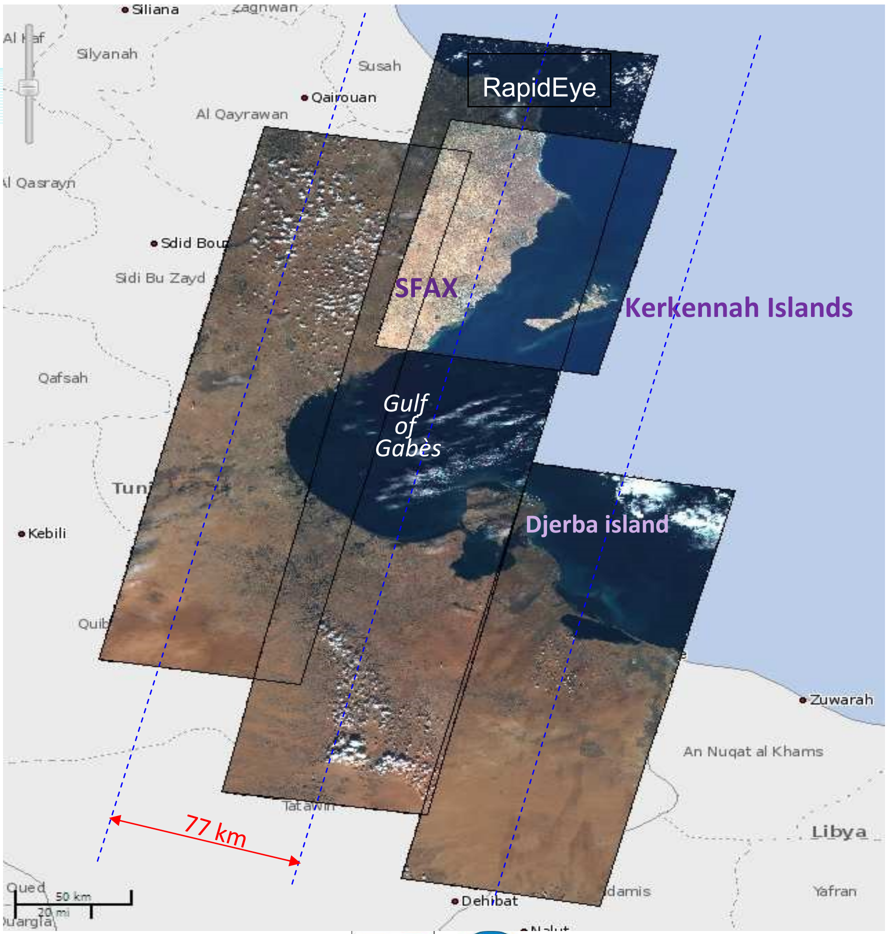
With special thanks to Pierre Mouscardes Consulting

Red Sea

With special thanks to
Pierre Mouscardes
Consulting



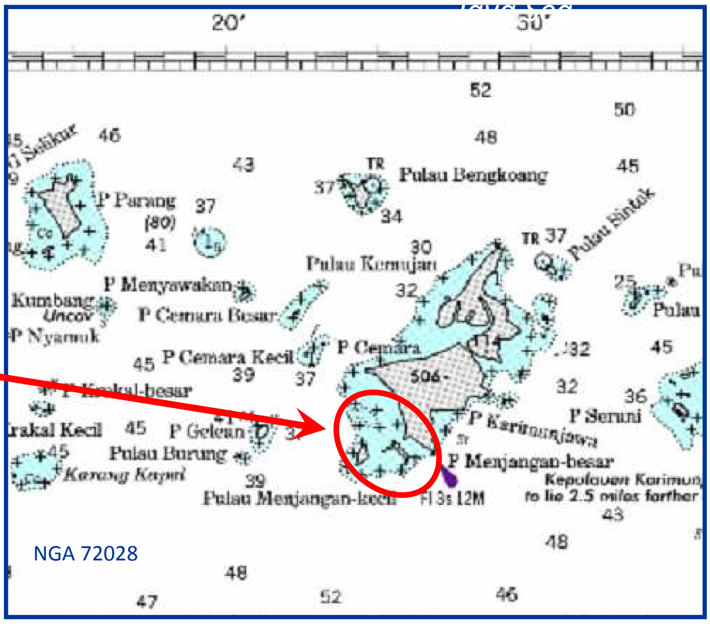
Mediterranean



Updating of some Maghreb old charts is considered as a possible component of the future Southern Mediterranean Marine Highway

With special thanks to Pierre Mouscardes Consulting

Indonesia



With special thanks to
Pierre Mouscardes Consulting

APPENDIX B

Digital appendix

In this appendix, the folder structure of the digital appendix is illustrated. The 'folder tree' below is an index of the digital appendix. The content is described in the sections and subsections of this chapter.

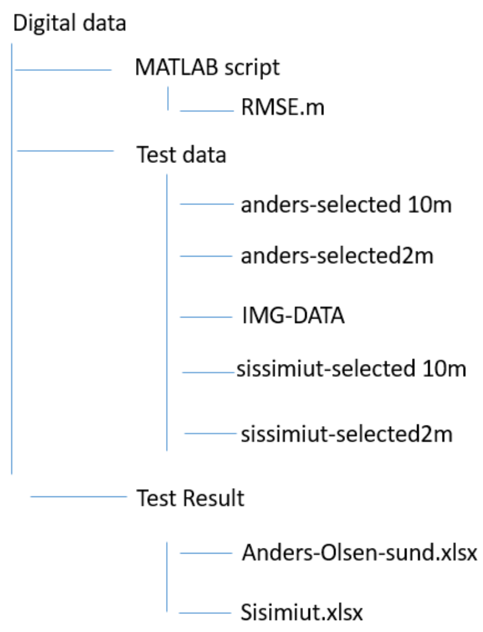


Figure B.1: *Folder tree*

B.0.1 MATLAB script

In the MATLAB script folder, it contains the script for computing the Root Mean Square Error(RMSE). The computation of Pearson correlation coefficient R can be calculated by type R = corrcoef(A,B) in MATLAB.

B.0.2 Test data

In the test data folder, the raw satellite image data can be found in IMG-DATA, it includes 14 bands. And the ander-select 10m includes 10m resolution SDB in Anders-olsen-sund area. The ander-select 2m includes 2m resolution SDB in Anders-olsen-sund area. The Sissimiut-select 2m includes 2m resolution SDB in Sisimiut area. The Sissimiut-select 10m includes 10m resolution SDB in Sisimiut area.

As for the multibeam data, according to the aggrement with the GST, it will not upload into the digital appendix. But, the computation can be found in the Test result.

B.0.3 Test result

The Anders-Olsen-sund.xlsx and Sisimiut.xlsx includes all the result in the test chapter, and the calculation also can be found there.