Aalto University
School of Science
Degree programme in Engineering Physics and Mathematics

Estimating the protection provided by islands against anti-ship missiles

Bachelor's Thesis
September 3, 2019

Johannes Mäkinen

Aalto University
School of Science

Aalto University, P.O. BOX 11000, 00076 AALTO
www.aalto.fi

Abstract of bachelor's thesis

Author Johannes Mäkinen	
Title of thesis Estimating the protection provided by islands against anti-ship missiles	
Degree programme Engineering Physics and Mathematics	
Major Mathematics and Systems Sciences	**Code of major** SCI3029
Supervisor Prof. Ahti Salo	
Thesis advisor(s) M.Sc. Juho Roponen	
Date 03.09.2019	**Number of pages** 24+2 **Language** English

Abstract

The purpose of this thesis is to develop a method for estimating the protection provided by islands against anti-ship missiles. These missiles pose a threat to the safety of the military equipment and personnel on board navies' ships operating in coastal areas. Especially during a resupply mission, ships are susceptible to missile strikes as they are almost immobilized. Thus, finding a reliable way of estimating the protection islands provide for ships can decrease casualties during war time.

The method merges the information of the possible locations of the ships to elevation data and calculates the protections for these locations and the routes between them. At the start of this thesis, the objective and the limitations of the method are defined. After this, parameters are selected and the method is implemented. The method is then tested and its results are validated using locations and elevation data from within the Finnish Archipelago Sea. Sensitivity analyses are performed to examine how the parameter values affect the processing time and the computational results.

The method appears to be an accurate and a computationally efficient way for finding the safest location for a ship to be in a coastal area. The method can also estimate the protections between the locations, making it a viable way of determining a safe route to the resupply location. The method is implemented so that it is easy to modify the parameters for various situations where different ships and missiles are used. Thus, the method can be used for not only the area presented in this thesis, but also for other coastal areas.

Keywords protection, navy, ship, coastal, warfare, anti-ship missile

Aalto-yliopisto
Perustieteiden
korkeakoulu

Aalto-yliopisto, PL 11000, 00076 AALTO
www.aalto.fi

Tekniikan kandidaatintyön tiivistelmä

Tekijä Johannes Mäkinen

Työn nimi Saarten suojavaikutuksen arviointi meritorjuntaohjuksia vastaan

Koulutusohjelma Teknillinen fysiikka ja matematiikka

Pääaine Matematiikka ja systeemitieteet **Pääaineen koodi** SCI3029

Vastuuopettaja Prof. Ahti Salo

Työn ohjaaja(t) DI Juho Roponen

Päivämäärä 03.09.2019 **Sivumäärä** 24+2 **Kieli** Englanti

Tiivistelmä

Tämän kandidaatintyön tarkoituksena on kehittää menetelmä, jolla voidaan arvioida saarten suojavaikutus meritorjuntaohjuksia vastaan. Kyseiset ohjukset ovat rannikkoalueilla merkittävä uhka merivoimien aluksille ja henkilöstölle. Alukset ovat alttiita ohjusiskuille erityisesti täydennystehtävän aikana, sillä silloin alukset ovat ankkuroituja eivätkä pysty tekemään väistöliikkeitä. Siksi, saarten aluksille tarjoaman suojan luotettava arviointi voi pienentää tappioita sota-aikana.

Menetelmä yhdistää aluksien mahdolliset sijainnit korkeusdataan ja laskee tämän avulla sijaintien ja niiden välisten reittien suojaisuudet. Tutkielman alussa määritellään menetelmän tavoitteet sekä rajoitukset. Tämän jälkeen valitaan parametrit ja implementoidaan itse menetelmä. Tämän jälkeen menetelmää testataan ja sen tulokset validoidaan käyttämällä esimerkkinä Suomen Saaristomeren aluetta. Herkkyysanalyyseilla tarkastellaan, miten parametrien arvot vaikuttavat algoritmin laskenta-aikaan sekä lopullisiin tuloksiin.

Kehitetty menetelmä näyttää olevan tarkka ja laskennallisesti tehokas keino löytää suojaisimmat paikat alukselle rannikkoalueella. Sillä voidaan myös arvioida yksittäisten paikkojen välisetkin suojaisuudet, jolloin suojaisin reitti täydennyspaikalle voidaan määrittää. Menetelmässä parametrien arvoja on helppo muuttaa eri tilanteisiin, joissa on käytössä erilaisia aluksia ja ohjustyyppejä. Menetelmä ei ole rajoittunut vain Suomen lähisaaristoon, vaan sitä voidaan käyttää myös muilla rannikkoalueilla.

Avainsanat suojaisuus, merivoimat, alus, rannikko, sodankäynti, meritorjuntaohjus

Contents

1 Introduction

While the modern naval and coastal warfare has advanced steadily throughout the years, there have been recent technological breakthroughs that affect the safety of ships and boats during time of war. In particular, anti-ship cruise missiles that are almost impossible to detect in time to counter them. The current radars and anti-ship missile defense systems may fail to intercept missiles due to their supersonic speeds in their last stage of approach (Lewis, 2015). This is a threat to the ships' safety especially during resupplying. During a resupply ships cannot move and thus making them easy to find with air surveillance. In protecting the ships against threats such as these, the surrounding terrain matters. Thus, using the islands in close proximity of the ships is an important way of shielding them from possible threats.

Research on naval warfare has been the interest of militaries around the world for a long time and countries need to be planning ahead of time to combat the threats from the sea effectively (Vego, 2015). There have been studies on the ships' capabilities to detect the missiles launched at them as Gripenwaldt (2011) discussed in his study for the Finnish National Defense University. His study helps to understand how the missiles are detected and how fast and close to the surface of the sea they need to be moving to be undetectable. There have also been studies on how the anti-ship missiles have become more accurate and destructive (Schulte, 1994). Although missiles have been studied extensively, hardly any research has been done to analytically define to what extent scattered landmasses around the ships' supply missions give cover from them.

The objective of this thesis is to develop a method to calculate how much protection islands provide for specific locations. The method is used for precalculated locations in the Finnish Archipelago Sea to illustrate its effectiveness in real-world situations.

The methods of calculation and parameter selections are discussed in Section 2. The method is applied to a predetermined dataset and the results are presented with sensitivity analysis of the parameters in Section 3.

2 Methods

The advancement of warfare technology involves new challenges and threats to military personnel and equipment. There has been considerable progress in the types of missiles used to destroy countries' naval and coastal ships in combat situations in the littoral areas. New ways of analyzing the dangers due to these threats are needed to decrease the casualties that would be caused by this type of warfare. This thesis is part of a larger study done at Aalto University. The objective of this larger study is to develop and assess uses of adversarial risk analysis for estimating weapons systems effectiveness and to enhance military combat modelling tools (Roponen and Salo, 2015).

The objective of this thesis is to develop and implement a method for calculating the safest locations for resupplying a military ship, based on the natural terrain in the area of operations as protection against the missiles. The terrain will not only give cover for the ships, but it also forces the attacker to consider alternative approaches for missile strikes. These approaches could include relocating the attacker's equipment to find a different location to launch the missiles or to use missiles that are easier to intercept. These new tactics can then consequently make the attacker vulnerable to counterattacks.

2.1 Parameter selection

To reduce processing time and to obtain a viable solution for real-world situations, we make assumptions on the missiles and the ship's defense capability. For example, how far can the ship detect the incoming missiles with its radars and thereafter intercept them before impact? Also, what kind of an island is an adequate cover from missiles? Thus, the elevation and the shape of the island need to be examined.

Three parameter values have to be defined before calculating the protections for vertices and edges. First, the radius R of the area surrounding the vertex; only within this area are the islands considered as cover from missiles. Second, the elevation requirement E for an island to be able to protect from low flying anti-ship missiles. Third, the number of sectors S that the area is divided around the vertex simplifies the calculation to take into consideration only the directions from which the missiles can hit the target, not how much cover there is in the radial direction. Figure 1 shows a vertex in the middle and the surrounding area with radius R. The area is divided into eight sectors and there are some elements of islands inside it with elevation above E.

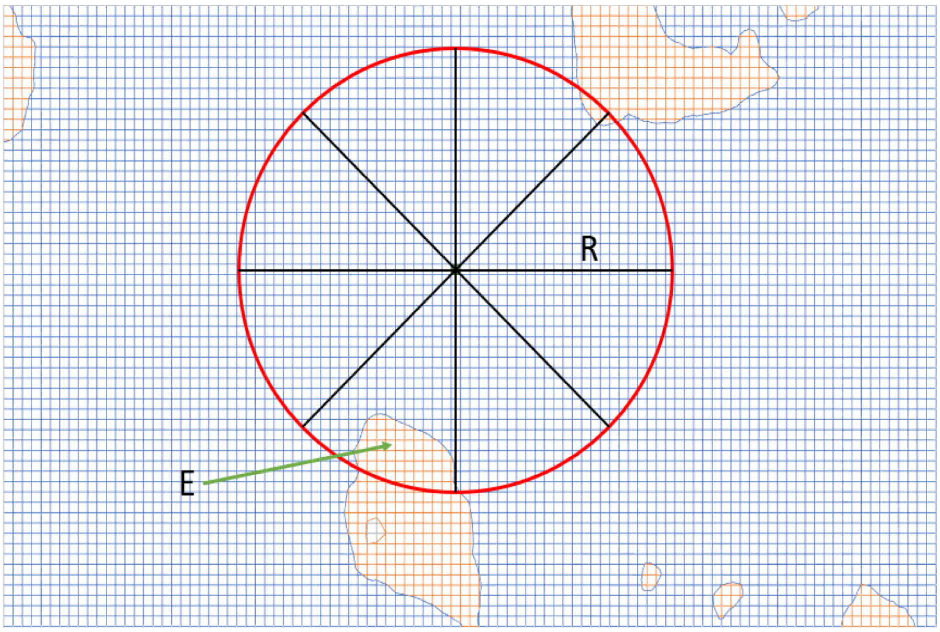

Figure 1: Parameters R and E illustrated.

Gripenwaldt (2011) suggests that if a missile is using the sea skimming technique for its approach to the target, it is very unlikely that the radars will notice it in time for countermeasures. This means that the missile is flying close to the surface and is therefore below the radar horizon. Therefore, to provide meaningful cover, the island has to be large enough to obstruct the missile's flightpath. Only those parts of the islands that are over the required elevation E from the sea level, are thus considered in calculating the protection.

Only the parts of the islands that are within a decided radius R from the ship will be considered as a protection against incoming missiles. This is due to different models and types of ships with different kinds of radars and missile interception systems. The incoming missile could be flying 5 meters above the sea level until it encounters an island and then flies over it and returns back under the radar. The missiles can maneuver during their flight, and thus the radius needs to be chosen so that the missiles cannot significantly change their direction of approach within the radius. Using the radius as a parameter, a suitable protection can be calculated for multiple different types of ships, missiles and missile intercept systems.

The area surrounding the ship will be divided into equal sectors, the number of which is a model parameter in this calculation. These sectors represent the simplified directions of possible threats. If there are multiple elements of islands in the same direction, the protection is the same as if there was only one element in that direction. This is due to the assumption that the missiles are equipped with contact fuzes (Morosow, 1964), which will detonate them on impact no matter how thick the obstacle is. There are also proximity fuzes which are mostly used for moving targets as they detonate not by hitting the target but by being close to it. However, in this thesis the islands would still block the flightpath of the missile regardless of the fuze type.

Although Rantanen (2016) and Rosti (2007) suggest that there are modern missile types that can maneuver around the islands using the Terrain Contour Matching navigation system (Golden, 1980) in combination with the Digitized Scene-Mapping Area Correlator (Carr and Sobek, 1980), the types of missiles that can dodge an island in very tight angles used in this thesis are quite rare. Thus, this type of ability is not considered explicitly, but it is dealt with by using the sectors as an approximation of the directions together with the radius and elevation requirements to make it highly unlikely a missile could hit the target.

Fourth optional parameter α, is the ability to delimit the directions that are assumed dangerous. This parameter consists of two angles, which delimit the threatening directions. This parameter is used as the directions may not be equally unsafe. With enough knowledge about the enemy's location, some directions can be dismissed as safe and others considered as dangerous. This means that by providing two angles, the calculation will assume that everything that is not between them is safe.

2.2 Method for calculation

The method for calculating the protection provided by the islands near a ship's location consists of two parts. First, it is necessary to determine the actual end locations of the ship where it can resupply in the archipelago. These locations can be represented by vertices on a graph. Second, the edges connecting these vertices define the route which the ship takes from the starting point to the resupply location. Thus, every location is a vertex which is connected to another vertex with an edge between them. This ensures that all the locations with an incoming edge can be accessed by the ship.

2.2.1 Vertices

The first task of the calculation is to determine the location of the vertex in the area and to collect the nearby elevation data for processing. The elevation data consists of rasterized data or data in some other grid-like format, which is readily available for this thesis.

The area surrounding the vertex can be separated into k grid elements that can be processed individually. Specifically, the element $i \in 1, ..., k$, with radius $r_i \leq R$ and an elevation $e_i \geq E$ provides protection for the vertex. R and E are the radius and elevation parameters as discussed in Section 2.1. Polar coordinates can be used to divide the surrounding area into n sectors. Each sector S_j, $j \in 1, .., n$ will be either protected by the islands or not.

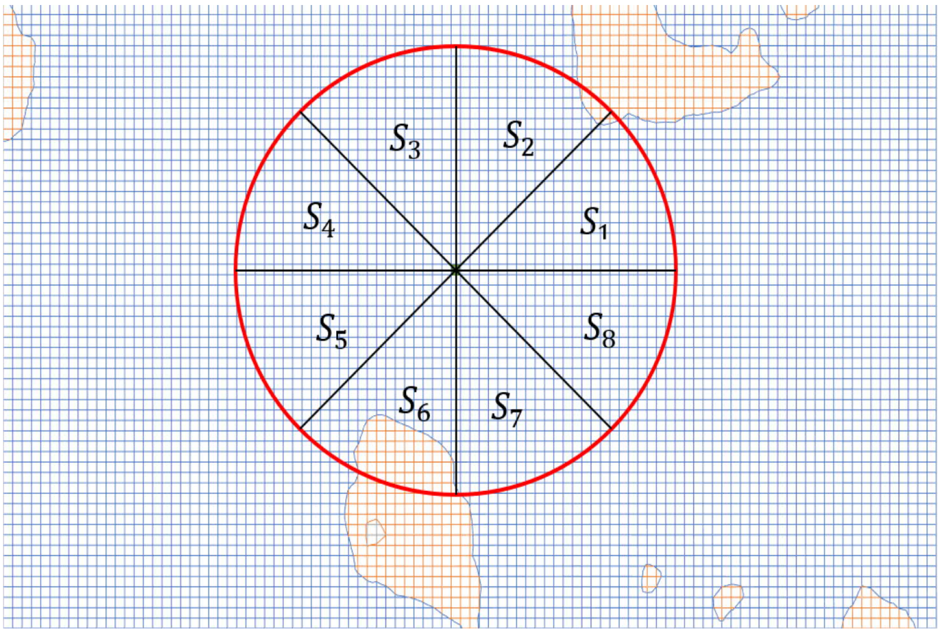

Figure 2: Sectors in the area around a vertex illustrated.

Figure 2 shows the nearby area of a vertex in a surface plot. The blue area is at sea level and the orange areas indicate islands. Here it can be seen that the islands are made of multiple grid elements. The area that consists of the inside of the red circle with the vertex in the middle is divided into eight sectors. The division into eight sectors is done only for purpose of illustration, in reality the number of sectors will be much larger.

The first phase of the method is to go through the area and determine the positions of the islands with relation to the vertex. Towards this end, the Cartesian coordinates of the original data are mapped to polar coordinates. This is done by inspecting the elements within radius $r_i \leq R$ from the vertex with an elevation $e_i \geq E$. When an element with sufficient r_i and e_i are found, it is given a polar coordinate representation (r_i, φ_i) in relation to the vertex in the middle of the area as demonstrated by Figure 3. This represents the direction which is protected by an element of some island.

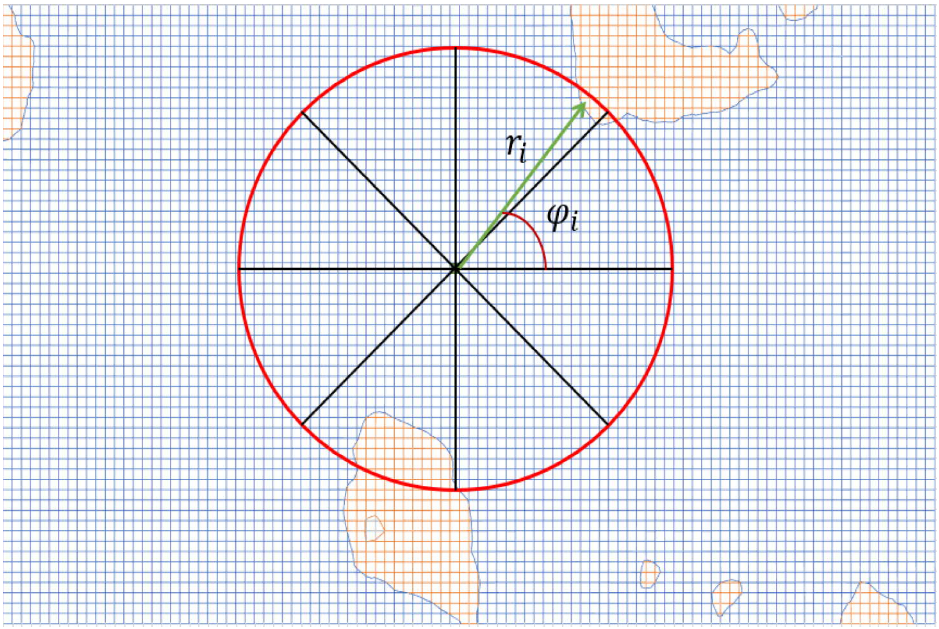

Figure 3: Element within the area with polar coordinates (r_i, φ_i).

With the angle φ_i, the direction can be compared to sectors S. If the angle φ_i is between the angles that delimit sector S_j, then the sector S_j is protected, i.e.,

$$p_j = \begin{cases} \frac{360°}{n}, & \text{sector } S_j \text{ is protected.} \\ 0, & \text{otherwise.} \end{cases} \tag{1}$$

If the direction of sector S_j has already been calculated and p_j is not zero, the calculation can proceed to the next sufficient element. Otherwise, that direction of sector S_j is marked as calculated by assigning p_j by equation (1). Figure 3 shows that the polar coordinate is closest to sector S_2, which is thus protected and p_2 will be assigned as described above.

The sector specific variables p_j in (1) are used to calculate the final protection. The variable gives the protected angle in relation to the whole area. By processing all the sufficient elements in the area and updating the variables p_j, the aggregated protection for the vertex can be calculated as

$$P_v = \sum_{j=1}^{n} p_j. \tag{2}$$

Equation (2) shows how the final protection P_v for a vertex is calculated using the variables p_j in equation (1). P_v indicates how large the protection is considering all directions. The unit of the result is degrees (°). If the protection is precisely 0°, the vertex has no elements of islands with sufficient radius and elevation surrounding it. On the other hand, if the protection is 360°, the island is completely surrounded by islands that give sufficient cover.

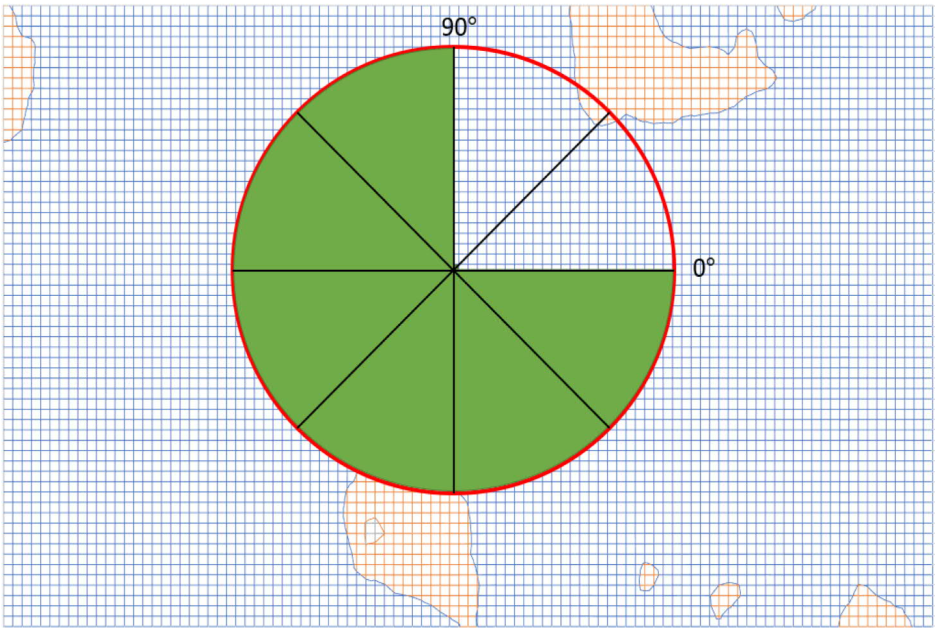

Figure 4: The use of parameter α illustrated.

Figure 4 shows the use of the optional parameter α, which is a tuple with two positive values in between 0 and 360. In this illustration α is given values [0 90], which corresponds to a dangerous sector starting from 0° and extending to 90°. Using this sector, the variables p_j in (1) are marked as usual, but all the other sectors outside the dangerous sector are automatically considered as protected. The automatically protected sectors are shown as green in Figure 4.

2.2.2 Edges

The edges between the vertices represent the route which a ship can traverse. Therefore, estimating the safest way from one point to another is an important aspect of the ships operational planning. The protection for the edges connecting the vertices could be calculated in various ways, of which many would be too slow or inaccurate. Therefore, the priority is finding an efficient and robust method for the calculation.

The edges are protected almost from the same directions than the vertices they are connected to. Also, the distances between the vertices are usually short due to narrow passages between the islands and shallow waters. This is especially the case in archipelagos for which this method is intended. Thus, the protection of an edge can be simplified as the mean of the two vertices it is connected to. This simplification is justified as long as the edges are short compared to the radius R, because then the protection of nearby islands is already taken into consideration. This method gives reasonable results and is fast enough for real-world use. Specifically, the protection P_e, defined as

$$P_e = \frac{P_{v_1} + P_{v_2}}{2}, \tag{3}$$

is the protection of an individual edge, where v_1 and v_2 are two vertices that are connected by the edge for which the protection is calculated. With these estimated protections, the safest route to the resupply location could be determined. For example, by using the estimates as weighs in a graph and finding the optimal route from one vertex to another.

3 Results

3.1 Data

There are two main data sources. The geographical elevation data, also called Digital Elevation Model 10 or DEM10, is provided by the National Land Survey of Finland (2019) in a grid form, in which one element of the grid represents a square with a side length of 10 meters. Every element is a number of three decimal precision that represents the average elevation from the sea level in that particular square area. The accuracy of the elevation data is 1.4 meters on average. The DEM10 data used in this thesis is from the area of the Finnish Archipelago Sea, and it is originally separated in grids the size of 1200x2400.

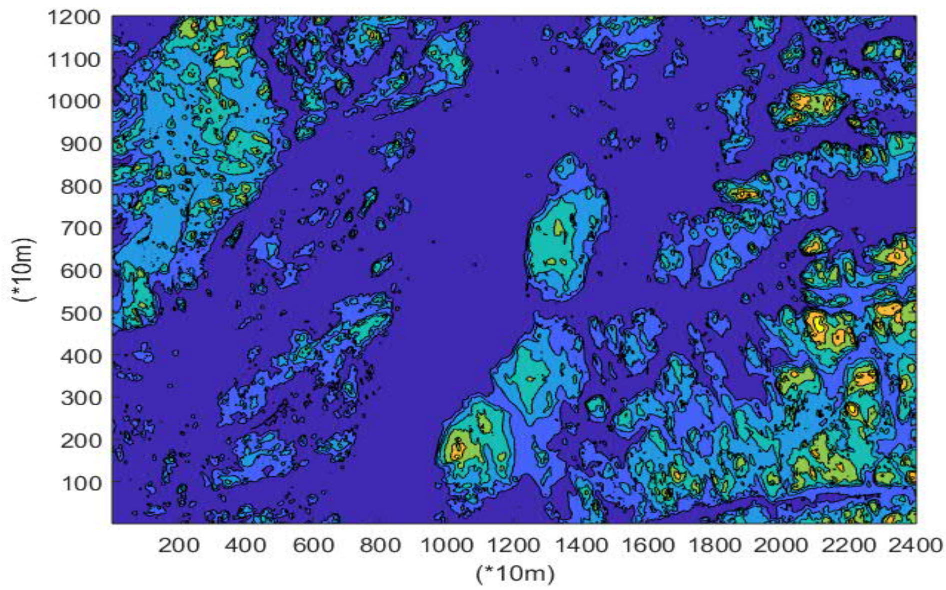

Figure 5: Contour Plot of one DEM10 data grid.

Figure 5 represents one of the 63 grids of the DEM10 data. It shows that the islands are detected due to their elevation from the sea level. The figure illustrates a problem that if the points for which the protection needs to be calculated are on or near the boundaries of the map, there is no information from the adjacent grids.

One approach for this problem is to take the point, the grid that it is on and the surrounding grids for each separate calculation. This method however is not efficient enough as the number of points is very large and it would be too slow to process the data. Thus, the whole geographical data will be 63 of these grids, which will be merged together to form a 10800x16800 grid covering the whole area. After the merge, a small portion of the full data matrix can be sliced and the results can be calculated for that area only. This is an efficient and a reliable solution.

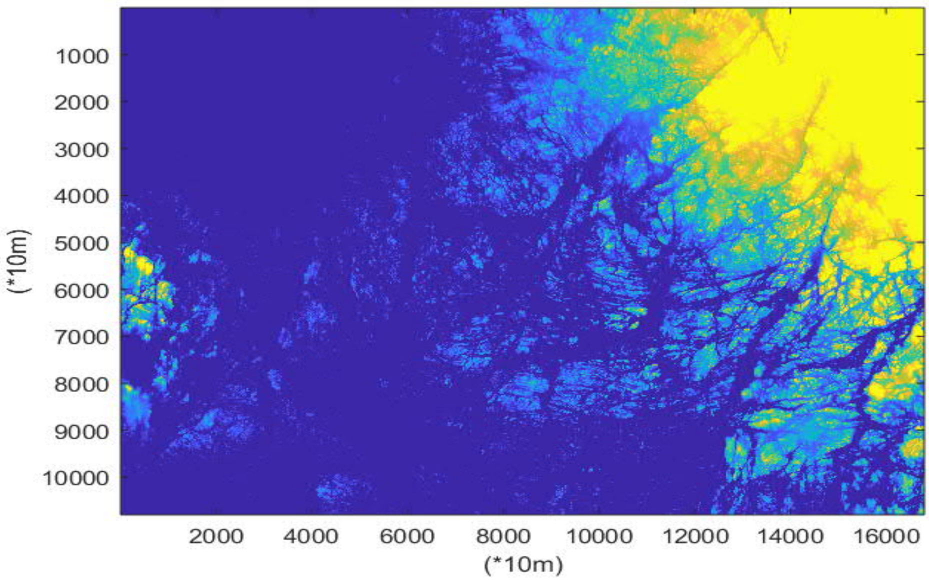

Figure 6: The Archipelago Sea southwest of Turku, Finland.

Figure 6 shows the whole area of the Archipelago Sea in the southwestern corner of Finland. It is created by joining the data grids into one large matrix and visualizing it as an image with MATLAB.

The DEM10 data is defined in the ETRS-TM35FIN -coordinate system, which is the recommended system in Finland by Advisory Committee on Information Management in Public Administration (JUHTA, 2016). This is convenient as the second source of data is from a tool for locating possible supplypoints for ships implemented by Olander (2018) in his Bachelor's thesis. The tool gives a set of points in the same coordinate system, and thus it is easy to merge the data sources.

3.2 Computational results

The method of Section 2 can be used to calculate the protection for all of the possible supplypoints and edges between them in the Archipelago Sea. For this calculation, parameters will be adapted to the missile named 3M-54 Kalibr or SS-N-27 Sizzler, which is a considerable threat to ships due to its supersonic speeds and low flying approaches. Capaccio (2007) suggests that this missile is able to penetrate the US Navy's missile defense systems.

The radius R used in this calculation is 1000 meters. This is justified by the fact that a 3M-54 Kalibr missile has a terminal velocity of Mach 3 or about 1 km/s during its last stage of approach (Berger et al., 2016). At this speed it has only one second of time to adjust its course inside the area the radius creates. This is taken to be a large enough of a radius to make it unlikely that the missile can hit the target by going over or around the island surrounding the ship's location, because it does not have the time to change its direction.

The elevation requirement E for the elements of the islands is set to 5 meters, as it is believed that a sea skimming missile like the 3M-54 Kalibr could be flying just a few meters above sea level (Dudeja and Kalsey, 2000). Also, most of the missile boats used by the Finnish Navy in the archipelago are about 5 meters above the sea level. This can be seen from Figure 7, where the measurement of 51 meters in length is provided by The Finnish Navy (2016), from which the other measurements are estimated.

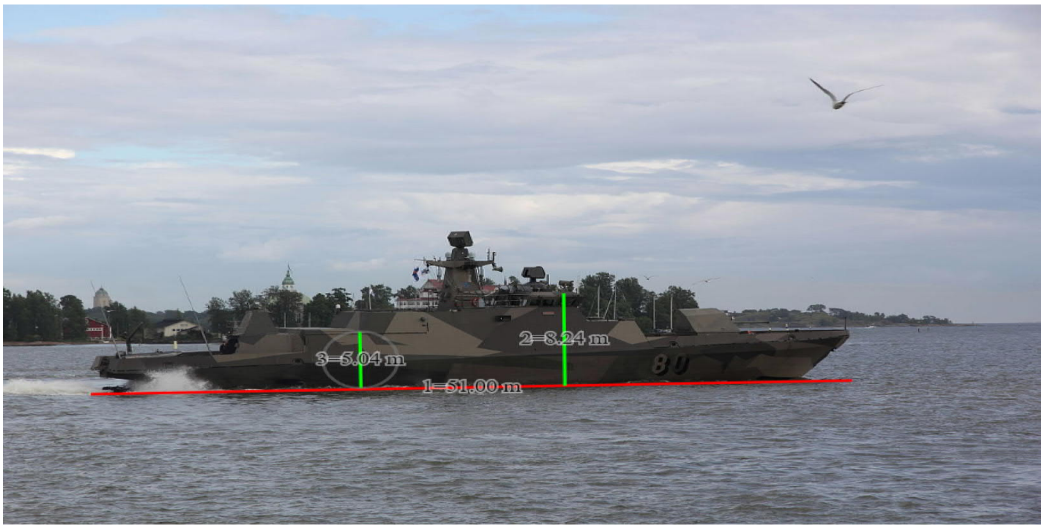

Figure 7: Hamina-class missile boat in Helsinki by Wikipedia Commons user MKFI (2015)

The 5-meter requirement gives the calculation a good baseline for low flying missiles because the exact flying altitude of these missiles is classified information and can vary in different circumstances. This parameter is not absolute and should be adjusted for the ships and missiles used.

The number of sectors needs to be chosen carefully, because considering too few sectors would overestimate the protection an element of an island can provide. The elements in the data used are 10x10 -meter squares and therefore the arc of a sector has to be under 10 meters for the calculation to be accurate. Otherwise a small island could theoretically give protection to a much larger sector than it actually covers. From this, the number of sectors can be calculated using the perimeter of the area $2\pi R$. An estimation of the arc being a straight line is done here to simplify the calculation. Thus, the minimum number of sectors can be calculated from

$$nSectors \geq \frac{2\pi R}{10}. \tag{4}$$

Using the equation (4), denominator of 10 meters for the 10x10 -meter data and the radius $R = 1000$ meters, the area around the ship's location should be divided into 628.3 sectors. For simplification, an estimate of 630 sectors will be used. This division should give precise enough estimates for the protected directions. The number of sectors is kept at the minimum level as with more sectors the computational time could increase with no substantial effect on the results, as seen in Section 3.3.

After these parameters have been given as inputs, the results can be computed and visualized.

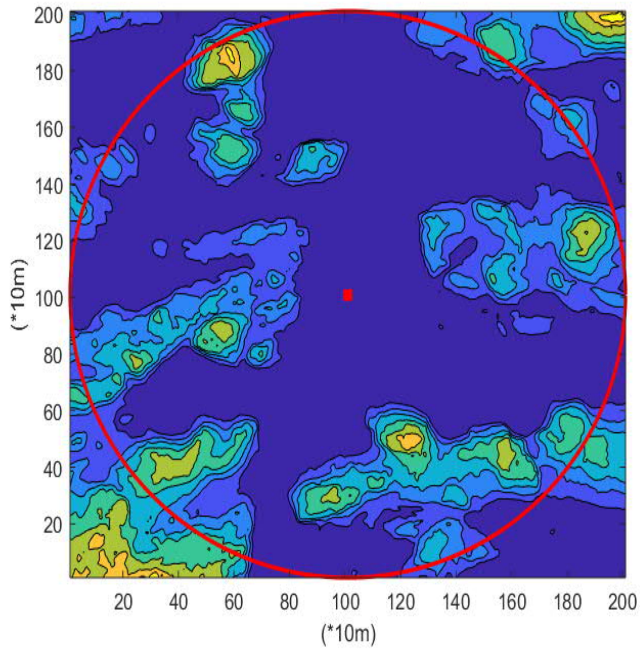

Figure 8: Surroundings of possible supplypoint #17992.

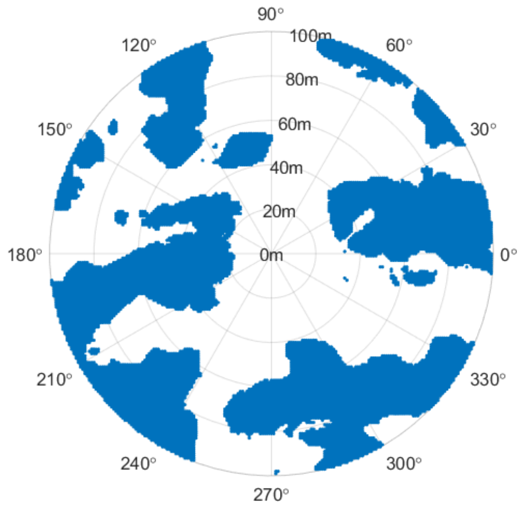

Figure 9: Surroundings of supplypoint #17992 in a polar plot.

Figure 8 shows a contour plot of the possible supplypoint with index #17992 marked as a red box in the center of the plot and its surrounding islands. The circle around the point is the area with radius $R = 1000$m, where within the sufficient elements of islands are searched. The possible supplypoint in the figure has the coordinates (6677995N, 238516E) in the ETRS-TM35FIN -coordinate system. As the radius is 1 kilometer and the grid points are 10 meters in size, this figure represents an area of 4km^2 and the circle within it is 3.14km^2 in surface area. This figure shows that the location is heavily surrounded by islands from almost all directions and could be a good supplypoint.

Figure 9 plots the surrounding area of the supplypoint #17992 in polar coordinates. Comparing it to Figure 8, a resemblance can be easily seen. Thus, the information on the islands around the location is preserved and transformed correctly into polar coordinates. For illustration purposes, the division of the area into sectors is not considered in this figure and all of the sufficient elements of islands are taken into consideration. This can be observed by the fact that the whole islands are drawn in the figure. As in, with a specific angle, there are multiple elements of islands with different radii in the plot. Therefore, not only the direction of the island is considered, but also the length in the radial direction. This is only done to visualize the method, but as in Section 2 it was described, only the direction matters for the calculation.

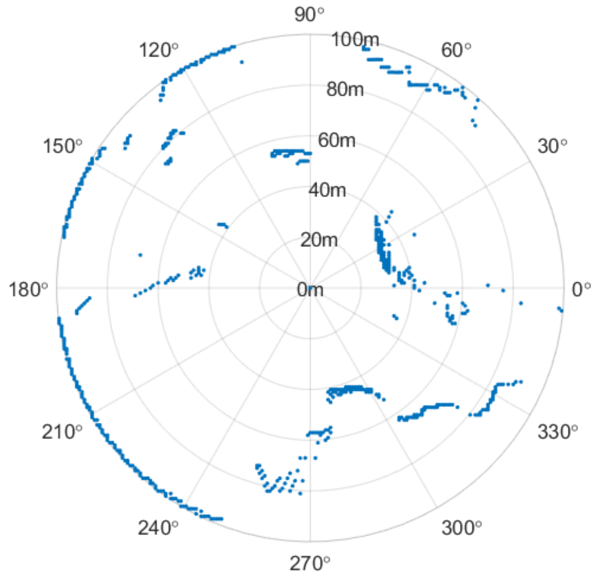

Figure 10: Surroundings of supplypoint #17992 in a simplified polar plot.

Figure 10 is another plot of the surrounding area of the supplypoint #17992 in polar coordinates. In this plot, the division of the area into sectors is not dismissed and the method is used as intended. This figure shows that only some parts of the islands are plotted. This is due to the method taking only one of the elements in the direction of the sector into the calculation. Thus, there will be no two elements with same angle in this figure.

The method starts naively from the top left corner of the area and iterates through the data column by column. This causes the plot in Figure 10 to be more scattered on the left side of the plot and more coherent on the right side. This is due to the method taking the first sufficient elements in the sector because it does not matter if there are multiple sufficient elements in the same sector, as discussed in Section 2.1. Therefore, on the left side, the elements seen are the furthest elements of the islands from the supplypoint. Consequently, the right side contains only elements that are the closest points of the islands in relation to the supplypoint in the center. This will usually cause the plot to show more detailed outlines of the islands on the right side.

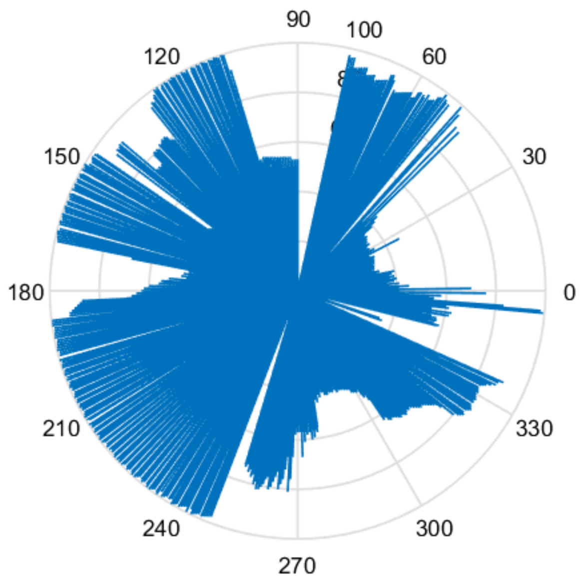

Figure 11: Sectors protected around point #17992 in a polar plot. Units on the outer circle are degrees (°) and the distance from the origin is measured in meters (m).

Figure 11 visualizes the sectors which are protected by islands. This figure shows how the elements in Figure 10 fall into different sectors and give cover for the possible supplypoint in the middle. These sectors are then used to estimate the protection as described in Section 2.2.

The method is implemented so that the results of the calculation are saved into an ASCII file, where every point and the edges between the points are given a protection estimate. The estimated protection of the possible supplypoint #17992 shown in figures 8, 9, 10 and 11 is about 332.57° rounded to two decimal digits. Based on this information, the point can be compared to other points and a decision about the best possible supply location can be done.

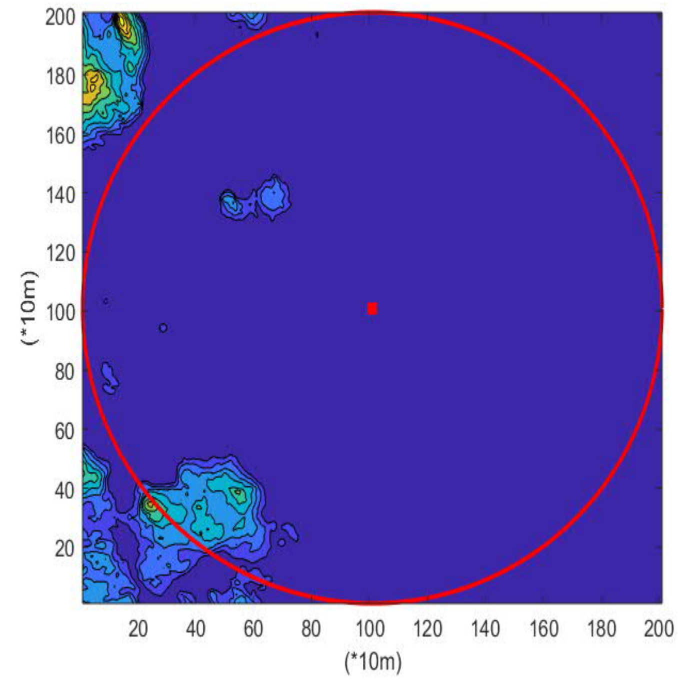

Figure 12: Surrounding area of possible supplypoint #31538.

Figure 12 is a contour plot of another possible supplypoint with index #31538. The point is marked with a red square in the middle and the area within radius R is marked with a red circle. This figure shows that not all points are equally protected as the number of islands nearby varies as a function of the direction in the archipelago. The left side of the area is to some extent covered by islands, but some of them are beyond the reach of the area within the radius used in this calculation. There are no islands on the right side of the area. This suggests that this possible supplypoint would be a poor choice for ships looking for protection.

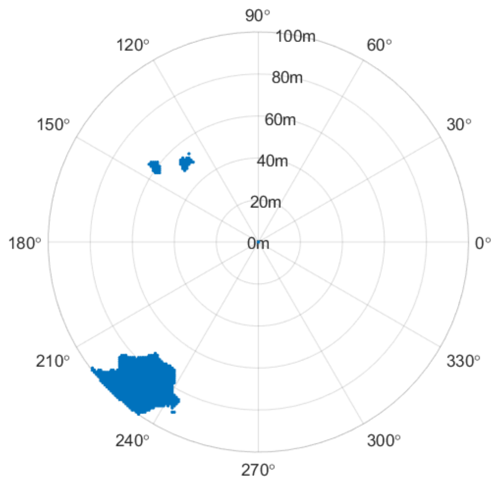

Figure 13: Polar plot of point #31538.

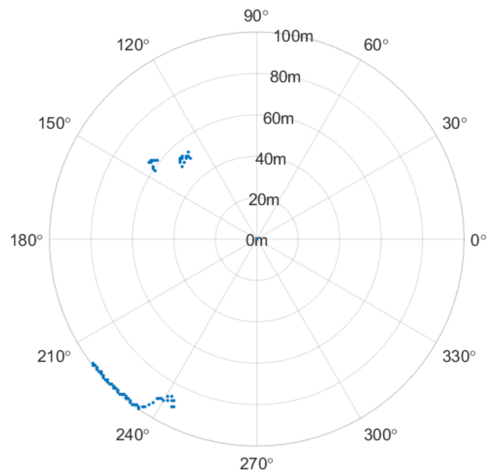

Figure 14: Simplified polar plot of point #31538.

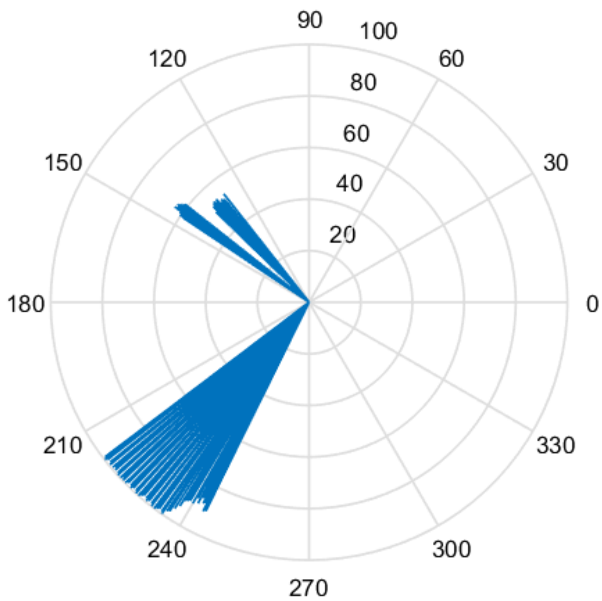

Figure 15: Sectors protected around point #31538 in a polar plot. Units on the outer circle are degrees (°) and the distance from the origin is measured in meters (m).

As with the supplypoint #17992, the polar plots can be applied for the point #31538. Figure 13 shows the polar plot for this point without the division into sectors and the Figure 14 with the sectors considered. Figure 15 represents the sectors which are protected. With the figures it is easy to compare and see how the method progresses from the upper left corner of the area column by column and simplifies the calculation by keeping only the important directional information. Ultimately, only those sectors that are protected are used to calculate the protection. The estimated protection of this point is only 39.43°, making it a much worse location for a supply mission than the point #17992 in Figure 8.

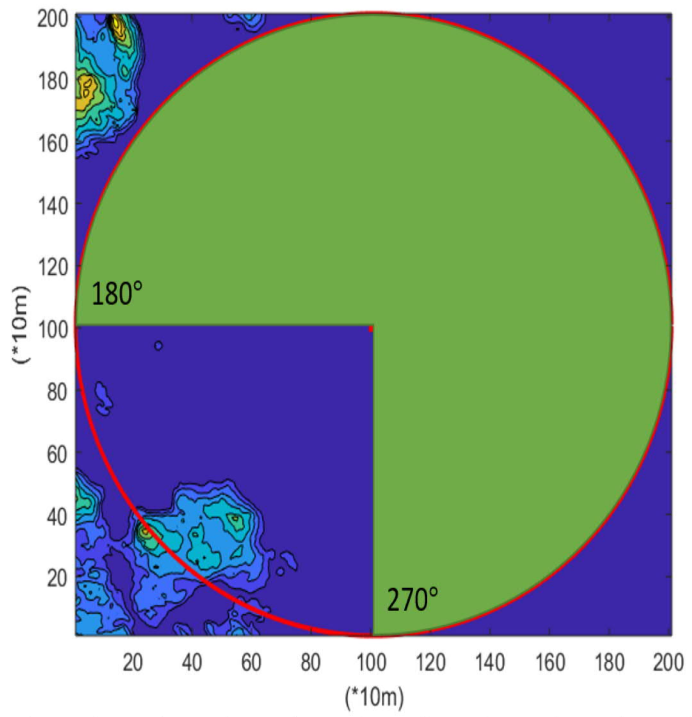

Figure 16: Point #31538 with parameter α used.

Figure 16 represents the usage of the optional parameter α with values [180 270]. The figure shows the dangerous sector given by α as normal contour plot and the safe sector which is colored green. The angle of the green safe sector is 270°. This means that the total protection for this point is calculated by adding the protection provided by islands within the dangerous sector to 270°. This leads to a result of 298.29°. This seems accurate by comparing it to the previous result of 39.43° for this same point in Figure 12.

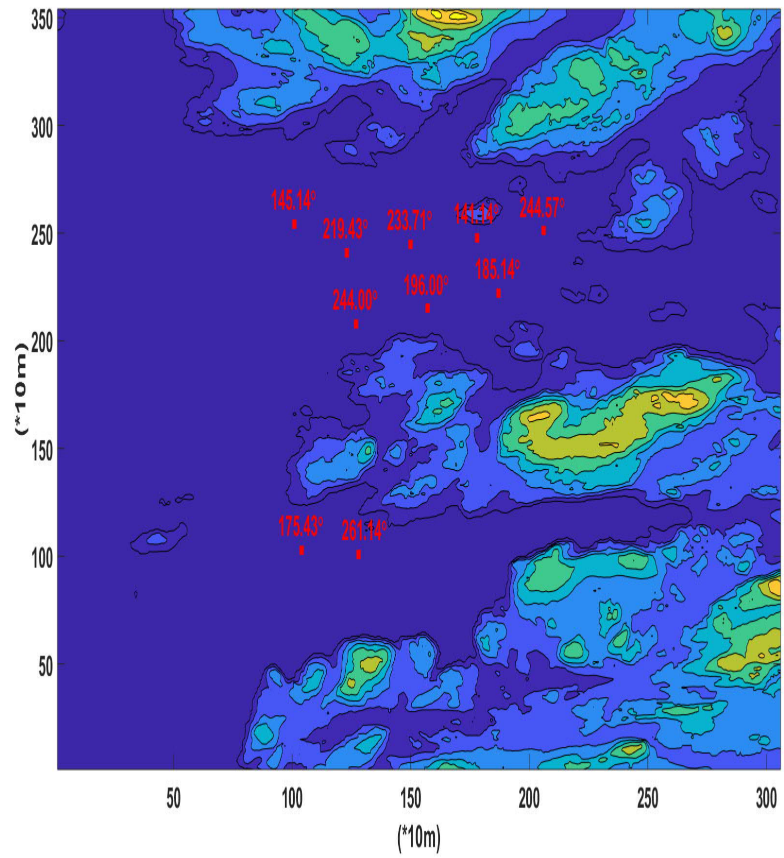

Figure 17: Multiple points and their protection estimates above them.

Figure 17 shows 10 points close to each other. The estimated protections of these points are marked above each one. From this it can be seen how the protection increases the more sufficient elements of islands there are within the radius used in the calculation.

Once the protections for the points have been estimated, the protections of the edges can also be calculated.

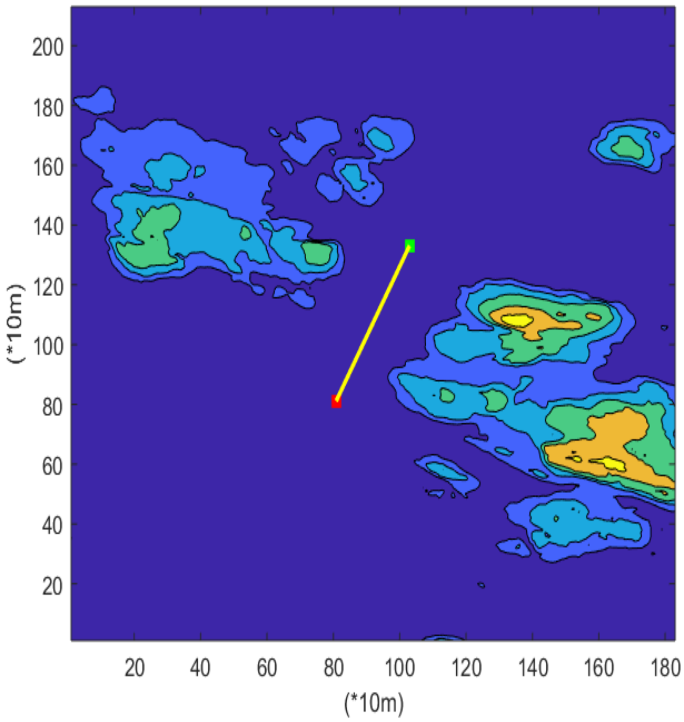

Figure 18: The edge between points #13121 as a red square and #13123 as a green square.

In Figure 18, there is an edge between two possible supplypoints and their surrounding area. The protections for the points #13121 and #13123 in two decimal digit precision are 196.00° and 225.71° respectively. Thus, using the mean of these protections as an estimate for the protection of the edge as in equation (3) in Section 2.2.2, a result of 210.86° is achieved. This result seems reasonable, because the edge does not have much protection from the northeast or southwest directions, but is protected from other directions.

3.3 Sensitivity analysis

The parameter values in Section 2.1 influence the computing time of the method and the estimated protections of supplypoints and edges. There were 34,967 points and 188,216 edges within the 18,144 km^2 area used in this analysis.

Table 1: Computing times with different parameter values.

R \ E	5 m	10 m	15 m	*nSectors*
1 km	5.12 min	4.13 min	3.36 min	530
	5.76 min	4.67 min	3.94 min	630
	7.10 min	5.52 min	4.79 min	730
1.5 km	12.64 min	9.18 min	7.74 min	845
	13.67 min	10.33 min	8.28 min	945
	14.71 min	12.17 min	9.74 min	1045
2 km	27.89 min	18.72 min	15.04 min	1160
	28.14 min	20.31 min	16.60 min	1260
	30.93 min	22.10 min	17.08 min	1360

Table 1 lists the processing times of the method on different sets of parameters. Radii R used were 1, 1.5 and 2 kilometers and the elevation requirements E were 5, 10 and 15 meters. The number of sectors $nSectors$ was calculated using the equation (4) for different radii. The middle ones, i.e., 630, 945 and 1260 sectors, are the minimum numbers of sectors for the corresponding radii for accurate results. The number of sectors is also examined in the range ± 100, to see how it affects the computing times and results.

Table 1 suggets that the radius R is the biggest factor on the computing time. This is due to the significant increase in the area which needs to be processed around each supplypoint. With a radius of 1 kilometer, the area surrounding the point to be processed is 3.14 km^2, and with a radius of 2 kilometers the area becomes 12.57 km^2. Thus, the area increases by the power of two with relation to the radius.

The elevation requirement is the next most important parameter, because the method can dismiss many steps if the element is not of sufficient height. In Table 1 it can be seen how changing from 5-meter requirement to 15 meters with a radius of 2 kilometer allows the results to be computed in half the time.

The number of sectors increases the computation time slightly. With a radius of 1000 meters and a height requirement of 15 meters, the time would increase about 20% by using 730 sectors instead of 630. This is not a significant delay, and therefore it would be preferable to use at least the minimum number of sectors calculated from equation (4).

Not only does the parameter selection have an effect on the time it takes to run the method, it also affects the results. In this thesis, the baseline results were calculated with a radius of 1000 meters, 5 meters elevation requirement and 630 sectors as in Section 3.2. Determining the sensitivity of the method to parameter variation can be done by comparing the baseline to results with different parameters. The difference in the results can be calculated for both the possible supplypoints and the edges between them from

$$Diff = \frac{\sum(Result_{new} - Baseline)}{N}. \tag{5}$$

The average difference between the results with other parameters to the baseline results is calculated by (5), where N is the number of points or edges in the whole area. The $Baseline$ and $Result_{new}$ variables are arrays of results with the baseline parameters and with different parameters respectively. This gives an estimate of how much the results differ per point or edge compared to the baseline.

Table 2: Differences in protection per point.

R \ E	5 m	10 m	15 m	*nSectors*
1 km	0.98°	-26.31°	-44.21°	530
	0.00°	-26.97°	-44.63°	630
	-0.81°	-27.52°	-44.99°	730
1.5 km	30.67°	-4.23°	-29.07°	845
	29.89°	-4.81°	-29.47°	945
	29.18°	-5.32°	-29.83°	1045
2 km	55.24°	15.23°	-15.02°	1160
	54.60°	14.74°	-15.38°	1260
	54.03°	14.28°	-15.71°	1360

Table 2 shows the effect of parameter selection on the results considering only the points and not the edges. The baseline results are in boldface to distinguish them from the other results. Comparing the differences, it can be seen that the radius R affects the results much more than the other parameters. This can be explained by the fact that the larger the radius, the more islands there can be to protect the point. Thus, too large of a radius will in most cases result in overestimated protections. This consequently implies that the parameter selection for the radius needs to be planned carefully for different ships and their missile defense systems.

Table 2 shows how the elevation of the island affects the results. By increasing the elevation requirement, the results will give lower estimations of protections. This is predictable behavior as there are less elements that are able to cover the point.

In Table 2, the results are almost the same for using different numbers of sectors. In this calculation, the number of sectors were only 100 sectors apart from each other, thus the differences are not large. Although, comparing a calculation with 10 sectors versus 1000 sectors gives a more significant difference in results, but using 10 sectors would require the radius to be under 16 meters, as equation (4) shows, which is not viable in reality. Taking into consideration the low computing time increases from Table 1 and the slight gain in accuracy, it might be preferable to use at least the minimum number of sectors given by equation (4) for the calculations.

Table 2 is calculated only from the protections of the possible supplypoints but the same can be done for the edges.

Table 3: Differences in protection per edge.

R \ E	5 m	10 m	15 m	*nSectors*
1 km	0.79°	-21.64°	-36.20°	530
	0.00°	-22.17°	-36.53°	630
	-0.67°	-22.61°	-36.83°	730
1.5 km	30.54°	-0.21°	-22.06°	845
	29.87°	-0.70°	-22.39°	945
	29.27°	-1.14°	-22.70°	1045
2 km	56.50°	19.77°	-8.05°	1160
	55.93°	19.33°	-8.37°	1260
	55.42°	18.92°	-8.67°	1360

Table 3 lists the effect the parameters have on the results considering the edges between the points, indicating similar effects as Table 2. Although, the differences per edge are less drastic because the protections for edges are calculated as the average of two points.

4 Conclusions

In this thesis, a method for estimating the protection provided by islands against specific enemy threats was developed and implemented. The focus was on the possible low flying anti-ship missiles which could penetrate the defenses of a ship. The selection of the parameters used in the calculation were based on assumptions on the types of ships and missiles likely to be used in modern warfare. The original method was developed for a small dataset for testing purposes, and it was then expanded for the actual data used in this thesis. Once the method was implemented and the data had been processed to a suitable form, the calculation was tested. The results of this calculation were then examined and verified by visualization.

The results appear plausible and the method works as intended. The method is quite flexible as it can be applied with different parameters depending on the ships and anti-missile systems used. Also, the method will calculate estimates for the protections on any dataset with elevation data and predetermined points with some simple modifications. The computation times are low enough, so that the method is viable in most real-world situations.

Although the method is usable in most cases, it is still dependent on the user's choices for the parameters. Thus, the method is not a general solution for the problem. The data used in Section 3 has elevation data with a resolution of 10x10 -meters with an average accuracy of 1.4 meters. This could be improved by using data with smaller elements, like the DEM2 (2x2 -meter elements) data, which was not available at the time this thesis was done. Also, the method does not explicitly consider how maneuverable the missiles are, as it is done by using appropriate estimates of the radius R. This can cause small inaccuracies in the final protection estimates.

The method could be improved in both accuracy and computing time. By obtaining more specific information about the ships and missiles, the parameters could be optimized for every calculation run to produce fast and exact results. The maneuverability of a ship in the coastal area should be studied more and the ship's ability to evade the missiles could be taken into consideration in the calculation. Also, alternative approaches for calculating the protection for the edges could be examined. Lastly, field studies and further analysis could be carried out to verify the results and to give insight into the effects that islands have on the ship protection.

References

Berger, Z., Davis, K., and Romero, A. (2016). Addressing the Air and Ballistic Missile Threat to Europe. https://missiledefenseadvocacy.org/wp-content/uploads/2016/06/Europe-report-for-roundtable.pdf. Accessed 20.06.2019.

Capaccio, T. (2007). Navy Lacks Plan to Defend Against 'Sizzler' Missile . https://web.archive.org/web/20071119102801/http://www.bloomberg.com/apps/news?pid=20601070&sid=a5LkaU0wj714&refer=home. Accessed 20.06.2019.

Carr, J. R. and Sobek, J. S. (1980). Digital Scene Matching Area Correlator (DSMAC). *Image Processing for Missile Guidance*. volume 238, pages 36–41. International Society for Optics and Photonics.

Dudeja, J. and Kalsey, G. (2000). Shipborne laser beam weapon system for defence against cruise missiles. *Defence Science Journal*, 50(2):231–239.

Golden, J. P. (1980). Terrain Contour Matching (TERCOM): a Cruise Missile Guidance Aid. *Image Processing for Missile Guidance*. volume 238, pages 10–19. International Society for Optics and Photonics.

Gripenwaldt, C.-M. (2011). Surface ship's ability to detect an incoming anti-ship missile. (in Finnish: Pinta-aluksen kyky havaita kohti ammuttu meritorjuntaohjus), Finnish National Defense University.

JUHTA (2016). JHS 197 EUREF-FIN -coordinate systems, the variations related to them and division of map sheets, (in Finnish: JHS 197 EUREF-FIN -koordinaattijärjestelmät, niihin liittyvät muunnokset ja karttalehtijako). http://docs.jhs-suositukset.fi/jhs-suositukset/JHS197/JHS197.html. Accessed 10.06.2019.

Lewis, J. (2015). Sokov on Russian Cruise Missiles. https://www.armscontrolwonk.com/archive/207801/sokov-on-russian-cruise-missiles/. Accessed 11.07.2019.

Morosow, K. (1964). Naval Air Defense of Ships. Technical report, Foreign Technology Div Wright-Patterson AFB OH.

National Land Survey of Finland (2019). File Service of Open Data. https://tiedostopalvelu.maanmittauslaitos.fi/tp/kartta?lang=en. Accessed 09.06.2019.

Olander, L. (2018). Generating a Navigation Graph for Coastal Waters. Bachelor's Thesis, Aalto University, School of Science.

http://sal.aalto.fi/publications/pdf-files/tola19_public.pdf. Accessed 20.8.2019.

Rantanen, A. (2016). Applicability of anti-ship cruise missile's radar- and infrared targeting system in Finnish coastal areas, (in Finnish: Meritorjuntaohjuksen tutka-ja infrapunahakupään soveltuvuus Suomen rannikon toimintaympäristöön). Master's thesis, Finnish Defence University.

Roponen, J. and Salo, A. (2015). Adversarial risk analysis for enhancing combat simulation models. *Journal of Military Studies*, 6(2):82–103. https://www.degruyter.com/downloadpdf/j/jms.2015.6.issue-2/jms-2016-0200/jms-2016-0200.pdf, Accessed: 21.08.2019.

Rosti, R. (2007). Use and development of western cruise missiles in recent wars, (in Finnish: Länsimaisten risteilyohjusten kehitys ja käyttö viimeaikaisissa sodissa). Master's thesis, Finnish Defence University.

Schulte, J. C. (1994). *An Analysis of the Historical Effectiveness of Antiship Cruise Missiles in Littoral Warfare*. PhD thesis, Monterey, California. Naval Postgraduate School.

The Finnish Navy (2016). Equipment description on Hamina-class missile boat. https://merivoimat.fi/documents/1951215/2015876/Hamina-luokka/382e53b8-0ac0-4bfd-8031-f9cf4c65a620/Hamina-luokka.pdf. Accessed 06.08.2019.

Vego, M. (2015). On Littoral Warfare. *Naval War College Review*, 68(2):30–68.

Wikipedia Commons user MKFI (2015). Missile Boat Hamina leaving Helsinki south harbour during Finnish Navy 2015 anniversary. https://commons.wikimedia.org/wiki/File:Hamina_Merivoimien_vuosip%C3%A4iv%C3%A4_2015_07.JPG. Accessed 13.08.2019.