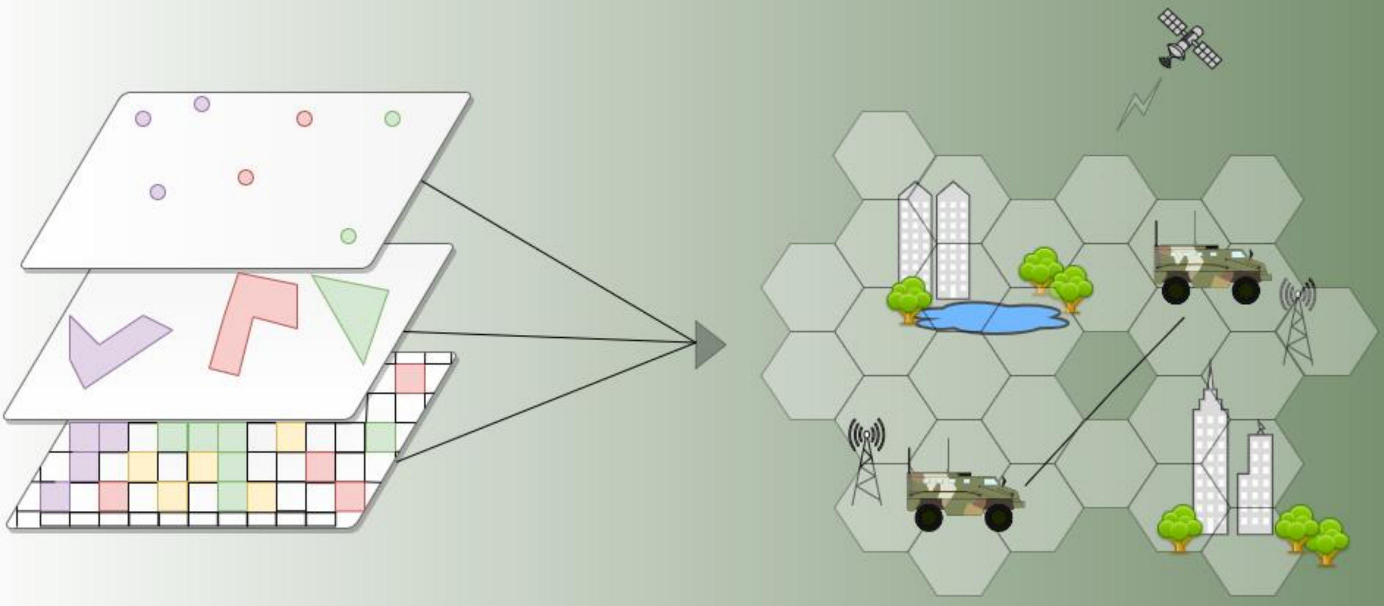
MSc thesis in Geomatics for the Built Environment

Modelling a military scene using a Discrete Global Grid System

Theodoros Papakostas

June 2022



TU Delft

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Abstract

Nowadays, the military stakeholders take advantage of the various geospatial infrastructure and technology while exploiting the wide use and distribution of geographic data, to model military scenes and/or conduct geospatial analysis for military operational scenarios. While a host of technology is offered, in potential joint military operations or joint civil-military operations, several difficulties elapse in geospatial communication, due to different Coordinate Reference Systems (CRS), non-conforming resources, different data formats and different areas of responsibility perception between the stakeholders. The multidisciplinary geospatial communication, data integration and a common modelling geospatial framework is integral for the accurate and fruitful modelling of a military scene assisting in joint operations. Discrete Global Grid Systems (DGGS), while not being a new concept, recently emerged in the geospatial community with various distributed implementations, as a framework to integrate, analyze and manage geospatial data.

This thesis attempts to apply a DGGS, using an existing distributed implementation, to integrate different format, two dimensional and elevation geospatial datasets, coming from military and civilian stakeholders, to identify the potential of this approach for military scene modelling. The different approaches of quantization of the datasets are explored for their efficiency, quality and the ability to assist in performing geospatial military analysis, while according APIs are developed for the DGGS conversion. Given the model of the military scene the research tackles the geovisualisation alternatives and a case study is also conducted for a military geospatial operation (ranging) using the DGGS approach.

The results show the promising potential of the DGGS approach to model military scenes, providing a uniform area based framework, encapsulating the different qualitative and quantitative military information, offering strong connectivity and hierarchy relations and increasing the qualitative spatial perception and multidisciplinary geospatial communication. The datasets' DGGS conversion showed advanced integration, segmentation, aggregation and visualization capabilities, also exploiting the 3rd dimension data. Uniform storage through the DGGS integration can be realized in a database, facilitating the distribution of military data. A DGGS can also support common military geospatial operations (i.e. ranging). However, the quality of the results is highly dependent of the original data accuracy/spatial uncertainty and the demanded precision requirements of the scene's coverage. In parallel, due to the fact that this technology is still emerging and dynamically optimized, it is not mature yet to handle high precision requirements and be treated as a frame with high positioning accuracy for high scale military scene coverages.

Acknowledgements

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Acronyms

DEM	digital elevation model
IT	Information Technology
GIS	Geographical Information System
CMI	Civil-Military Interaction
CIMIC	Civil-military cooperation
CRS	Coordinate Reference System
DGGS	Discrete Global Grid System
DGG	Discrete Global Grid
NATO	North Atlantic Treaty Organization
WGS84	World Geodetic System 84
SFC	Space Filling Curve
OGC	Open Geospatial Consortium
C3I	Command Control Communication System
MSL	Mean Sea Level
DIGEST	Digital Geographic Information Exchange Standard
AO	Area of operations
DGIWG	Defence Geospatial Information Working Group
ISO	International Organization for Standardization
STANAG	Standardization Agreement
NSO	NATO Standardization Office
AJP	Allied Joint Publication
MGRS	Military Grid Reference System
UTM	Universal Transverse Mercator
JGSWG	Joint Geospatial Standards Working Group
API	Application Programming Interface
EMODnet	European Marine Observation and Data Network
UI	User Interface
HTTP	Hypertext Transfer Protocol
ETRS89	European Terrestrial Reference System 1989
EPSG	European Petroleum Survey Group
COP	Common Operational Picture
SA	Situational Awareness

1. Introduction

In the recent years, apart from the widespread use of Information Technology (IT) in the military environments, the military stakeholders also focus in exploiting the benefits of the various geospatial infrastructure and Geographic Information Systems (GIS). The evolution of conventional maps, navigation infrastructure, space partitioning, through the use of such systems, highly improves the technical capabilities, to harness the most out of spatial information which is of great importance for military operations.

The military parties across the world are focusing on the modernization of the military scene modelling. While the term military is conventionally referring to the uniformed stakeholders of the air force, navy and army, the term defense enmeshes all the parties involved in peace-keeping missions (civil sector, private sector, politics, countries, treaties)(Swann, 1999). Concerning this, apart from the standalone military interest actions, the military also engages in situations where close partnership with the civil party is required, such as first response activities, disaster management, hybrid threats and interoperability provision in cross-border crises.

Depending on the need of the situation, a high level of collaboration is needed, requiring effective Civil-Military Interaction (CMI)(Cusumano and Corbe, 2017), to exploit the different resources and model a military scene. Civil-military cooperation (CIMIC) stands as a joint function in the military structure (NATO/OTAN, 2018a), aiming to maintain cooperation with non-military actors within an area of operations (NATO/OTAN, 2018a). Concerning the geospatial applications, the military frequently operates within areas of coverage. An area of coverage is a ground area, usually a scene, within a planned amount of time, as a part of a Mission Plan (NATOTerm).

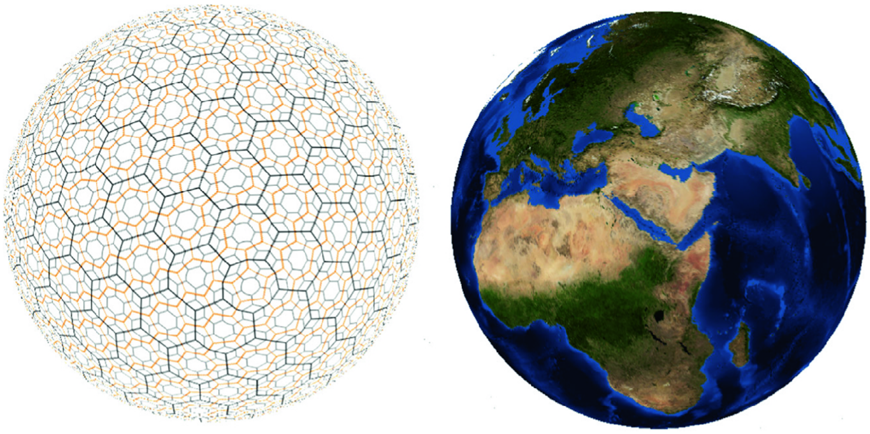


Figure 1.1.: Global-Grid-Systems-ISEA3H-DGGS-W640, image taken from (Alderson et al., 2019)

In military scenes, embedded to the area of coverage concept, the space partitioning is an important aspect, as a base framework for operations. The military divides the spaces of operations into several non-overlapping regions, also forming strong spatial relations. In potential joint operations, several difficulties in geospatial communication elapse, due to different Coordinate Reference Systems (CRS), outdated/non-conforming resources, different data formats, different area of responsibility perception and need of updates, processing, and data integration. Likewise, those difficulties emerge in military combined operations (air – ground – sea), designating the demand of an integrated system to analyze geospatial data.

The military would foster utilizing multiple types of datasets (vector,raster) provided by civil parties and/or, disseminated across the military components, to achieve the integrated modelling of a military scene. An approach of a Discrete Global Grid System (DGGS) could be applied for this purpose, also assisting on setting a model for geospatial analysis, reinforcing the current military GIS infrastructure.

DGGS are used in several scientific and commercial systems in the recent years (Lu et al., 2012). Mainly, they are utilised as frameworks for information and data and differ from the conventional CRSs that are originally designed for navigation purposes (Purss, 2017). A Discrete Global Grid(DGG) is a spatial structure that comprises a set of regions that partition the surface of the Earth (Sahr et al., 2003). A Discrete Global Grid System (DGGS) comprises different resolution grids (DGG) and forms a hierarchical tessellation of regions/cells used to fit the Earth’s surface (Zhou et al., 2020). Multiple examples of the use of DGGS exist, in spatial data management (large-scale), desicion making and analysis (Wang et al., 2021).

1.1. Research Objectives

This thesis attempts to apply a DGG system and integrate different datasets (vector, raster) of military interest, to demonstrate the integration and storage procedure and identify the potential of this approach to model a military scene. The research attempts to justify for the beneficial use of a DGGS, in comparison with the existing approaches in the military. Based on an existing DGGS implementation that will be used, the research will gauge the different data quantization approaches for the different datasets and explore their limitations. In parallel, the geospatial insight potential and the visualisation possibilities of the integrated datasets will be explored.

The **main research question** that this thesis attempts to address is: To what extent can a Discrete Global Grid System assist in modelling military scenes in one integrated way?

This research aims to study the potential of applying a DGG system and integrating different datasets (vector, raster) to model a military scene. To achieve this, the following sub-questions are relevant:

Subquestion(s):

1) What are the benefits of using a DGGS when modeling a military scene, in comparison with the current state of the art?

2) How to achieve integration and storage of different format geodatasets of military interest (vector, raster) using a DGGS?

3) How to use a database, exploiting different format DGGS indexed datasets for geospatial analysis of a military scene?

4) What are the different visualisation alternatives of DGGS indexed datasets assisting in military analysis?

1.2. Research scope

This research will mainly be focused on the procedure of converting and storing different datasets using a DGGS framework to model a military scene, utilizing an existing implementation. The different approaches of quantization will be explored and gauged for efficiency and quality as well as the ability to assist in performing geospatial military analysis. In parallel, given the data of the case study, the research will attempt to tackle different ways of visualising the integrated datasets to show the potential of the DGGS in geovisualisation of a military scene. A case study is also conducted using the integrated model, carrying out a military geospatial operation (ranging). This research is focusing in the European region geographic extent and the current geospatial standards of NATO and european NATO members.

1.3. Outline

The body of this thesis consists of the introduction followed by five main chapters. Chapter 2 looks at the theoretical background and related research pertaining to this thesis. The basic theoretical aspects and concepts concerning the Discrete Global Grid Systems (DGGS), the existing implementations as well as the Open Geospatial Consortium's (OGC) abstract specification are discussed. Following, the chapter discusses about military geospatial applications and the use of Geographic Information Systems (GIS) and geospatial data in the military as well as the current military geospatial standards pertaining to the scope of the research.

The overview of the methodology used to address the research objectives of this thesis is provided in Chapter 3. The different steps of the methodology are conceptually explained. The implementation of the methodology is provided in further detail in Chapter 4. Chapter 5, presents the results of the methodolody along with analysis over them, addressing the research objectives.

Finally, Chapter 6, provides the conclusions of this thesis. The research questions are reviewed, in order to determine the level of fulfillment of the objectives, followed by a discussion over the limitations of the methodology's approach. Finally, recommendations for future research over the topic as well as future work based on the results' analysis are discussed.

2. Theoretical background and Related research

On this chapter the relevant theoretical background and related work that this thesis is based on, will be presented. Focus is given in the following main topics: Discrete Global Grid Systems, OGC DGGS specifications, Military geospatial applications, current military geospatial standards.

2.1. Discrete Global Grid Systems (DGGS)

2.1.1. Overview

A Discrete Global Grid(DGG) is a spatial structure that comprises a set of regions that partition the surface of the Earth (Sahr et al., 2003). In the set of non-empty regions, each region or region-point of the grid is called a cell, represented by a unique identifier (Goodchild, 2006). A Discrete Global Grid System (DGGS) comprises different resolution grids, i.e. discrete global grids (DGG) and forms a hierarchical tessellation of regions/cells used to fit the Earth's surface (Zhou et al., 2020). Each cell of a grid is recursively partitioned, forming a series of Discrete Global Grids in multiple levels of granularity (Sahr, 2008).

They can be used as a common global reference frame for the storage, analysis, visualisation of geospatial data. Mainly, they are utilised as frameworks for information and data and differ from the conventional Coordinate Reference Systems(CRS) that are originally designed for navigation purposes (Purss, 2017). Each cell can be related with values or data objects and/or other cells (in the case of a hierarchical DGGS) (Sahr et al., 2003). Each cell refers to a subset of cells and in parallel, each identifier provides information regarding the hierarchy and structure logic. In the recent years, DGGS were proposed for various geospatial applications, such as data fusion and integration, spatial databases, vector/raster location representation among others. In addition, DGGS are also proposed as a spatial data model for the support of the Digital Earth vision (Hojati et al., 2022).

DGGS are described as polyhedral reference systems on the surface of a base polyhedron's circumscribed ellipsoid (Purss, 2017). The main components are a base polyhedron, a polyhedron orientation, a space partitioning method (subdivision shape), a refinement ratio and an inverse projection method. The applied base polyhedron location and orientation is defined in geocentric coordinates. An ellipsoidal Earth model is chosen an its initial equal area tessellation is achieved by scaling a unit polyhedron (Figure 2.1) (Purss, 2017).

The most usual grids that are used for 2D representations, are using a standard datum, like the World Geodetic System (WGS84). Each cell's unique identifier can be used for spatial indexing purposes, geocoding or geodatabases. Each cell's underlying geometry as well as the topological relationships with the neighboring cells, can be exploited defining globally

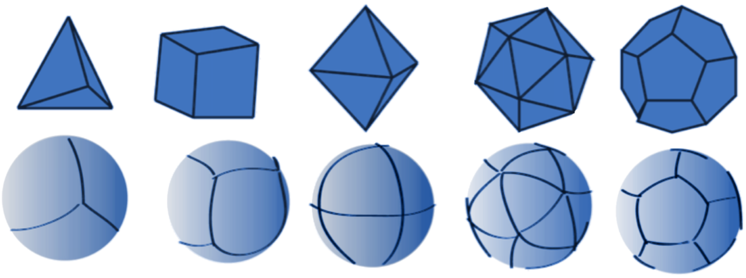


Figure 2.1.: (Top) Regular polyhedra. (Bottom) Their corresponding initial equal area tessellation: tetrahedron, cube, octahedron, icosahedron and dodecahedron (platonic solids), image taken from Purss (2017).

unique cell identifiers at any resolution (Purss, 2017). The identifier is most of the times spatial index, referring to only one cell of discrete global grid by the spatial hierarchy. The equal area partitioning attribute, theoretically represents the surface of the Earth uniformly, ensuring the equal probability of each cell contributing in an analysis, at multiple resolutions (Purss et al., 2019).

The regular polyhedron's planar faces subdivision shape can be a variety of shapes, such as triangle, quadrilateral, hexagon (Figure 2.2), pentagon and rhombus. Each of them having specific pros and cons. For instance, hexagons suffer from incongruity, being unable to perfectly decompose a parent hexagon to smaller child hexagons. Square shapes are not appropriate to use on triangle faced polyhedrons (icosahedron), while triangles at continuous resolutions struggle from non-uniform orientation (Sahr et al., 2003).

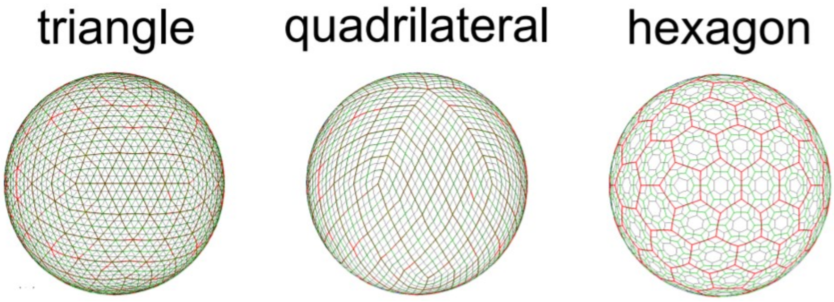


Figure 2.2.: Different DGGSs' planar faces subdivision shapes (Sahr et al., 2003)

For cell navigation, the referencing method can be either a space-filling curve (SFC) or a hierarchical-based index, depending on the implementation. In many DGG Systems, there is an explicit structure ordering cells on a path uniquely traversing all cells in the different resolutions. This path in most implementations is a space-filling curve (SFC). Space-filling curves (SFCs) provide an efficient method for spatial indexing of a n-dimensional space into a one dimensional representation (Uher et al., 2019). Using an SFC the location of each cell is explicitly defined, constructing a unique cell-id. The path defines thus a spatial axis, while the cell-id, is related with the cell's coordinates, cell size/ resolution (Purss et al., 2019).

Several SFCs exist and have been used in various geospatial indexing cases (Figure 2.3). In the DGGS context not all SFCs are suitable for every occasion. The area subdivision approach (space partitioning) method is highly relevant. Morton or Hilbert space filling curves can be used for indexing and clustering of a rhombus based DGGS, being quadrant recursive orderings (Sirdeshmukh et al., 2019). Rhombuses retain same size, orientation and shape in each DGGS resolution (White, 2000). A triangle or a hexagon have more complex geometries comparing to a rhombus (Baia et al., 2005). A Gosper space-filling curve (Gosper fractal), can be used in a hexagon based DGGS, retaining the hexagonal grid's benefits and providing hierarchical and efficient indexing (Uher et al., 2019).

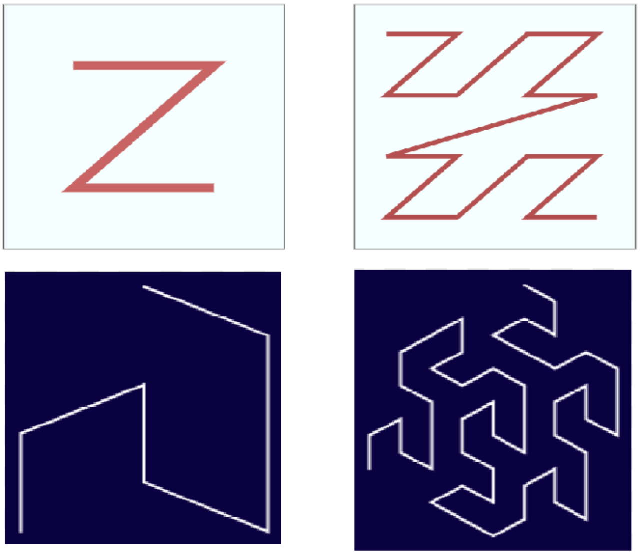


Figure 2.3.: Morton (Z-order) curve (TOP) and Gosper curve (BOTTOM) : iterations 1,2

2.1.2. Existing implementations of DGGS

Several DGGS implementations have elapsed in recent years, offering platforms for DGGS cell generation, along with various native functions to perform basic indexing operations, analysis, dataset integration and others. Details over the base polyhedron used, the indexing methods, the supported resolutions as well as their open source designation are given in Table 2.1.

- **PYXIS** Global Grid System, is a commercial DGGS implementation:
    - based on the ISEA Aperture 3 Hexagon Discrete Global Grid System (ISEA3H DGGS) (Sahr et al., 2003),
    - uses the inverse Icosahedral Snyder Equal Area (ISEA) Projection (Snyder, 1992)
    - is promoting the DGGS technology and also is a part of creating the OGC DGGS standard (`https://www.globalgridsystems.com/`).
- **DGGRID** is an open source software program for creating and manipulating Discrete Global Grids:

  - provided by the Department of Computer Science of Southern Oregon University (Southern Terra Cognita Laboratory) (`https://www.discreteglobalgrids.org/`).
- **H3** is an open source library of a Hexagonal hierarchical geospatial indexing system:
  - offered by Uber (`https://h3geo.org/`).
- **rHEALPix** is an open source web service, DGGS implementation:
  - based on Gibb's rHEALPix DGGS, Bowater and Stefanakis (2019); Gibb (2016).
- **Geogrid** is an open source library:
  - providing methods for the generation and handling the ISEA3H DGGS using the Inverse Snyder Equal-Area Projection (ISEA) (Mocnik, 2019) (`https://github.com/giscience/geogrid`).
- **S2 Grid System**, part of the "S2 Geometry Library", is an open source implementation:
  - developed by Google
  - offering a hierarchical index system based on cube projection (`http://s2geometry.io/`).

	base polyhedron	indexing method	resolution	Open source
PYXIS Global Grid System	Icosahedron	Hierarchy based	mm2	NA
DGGRID	Icosahedron	Hierarchy based	cm2	+
H3	Icosahedron	Hierarchy based	m2	+
rHEALPix	Cube	Hierarchy based	m2	+
Geogrid	Icosahedron	Identifier schema using coordinate pairs	NA	+
S2 Grid System	Cube	Hierarchy based	cm2	+

Table 2.1.: DGGS implementations and properties

The aforementioned DGGS implementations, support various operations, regarding the manipulation of their provided DGGS. Most importantly, all the implementations support cell addresses - geographic coordinate pairs conversions and cell size determination. Moreover, all the implementations except PYXIS support cell centroid and boundary determination. PYXIS, H3, S2 support hierarchy and neighbourhood navigation, whereas the rest do not support cell navigation. Hierarchy navigation pertains to finding parents, children in the different resolutions while neighbourhood pertains to finding neighbouring cells in a given level. PYXIS supports data query, when having an integrated model with multiple attributes, while H3 and S2 need to be integrated in a .geojson format or other environments such as kepler.gl (`https://kepler.gl/`) to perform data queries. Each implementation also supports other operations that can be studied in their documentations.

2.1.3. Open Geospatial Consortium(OGC) Abstract Specification

The OGC specifications (`https://docs.ogc.org/`) has already started developing standards for the DGGS frameworks (Purss, 2017). The Abstract Specification is the provider of the conceptual foundation regarding most of the OGC specification development projects. This is critical for the connectivity and communication of the various DGGS infrastructures. Thus, (`https://docs.ogc.org/as/15-104r5/15-104r5.html`) is the document specifying the core of an OGC Discrete Global Grid System Abstract Specification.

Open
Geospatial
Consortium

Figure 2.4.: Open Geospatial Consortium (OGC)

As stated in the document, the conventional geospatial standards suffer from the non uniform preservation of bearings, angular lengths and area at the same time. Either small well fit local planar grids or global grids preserving bearings and angular lengths are utilised, with the cost of area distortions. Specifically, conventional spatial reference systems rely on grids built from projected Cartesian or ellipsoidal coordinate axes. Planar grids are based on planar geometry (projections) and not the curved geometry of the sphere or ellipsoid. Properties of this approach well fit at local scales, however in the case of curved surfaces, distance and area preservation properties start failing while moving away in larger regions of interest. The Abstract Specification offers the DGGS specification for area preserving reference frames/systems. In the meantime, those systems respect the accuracy and presicion of geospatial data scaling from local to global as well as use the Earth's surface model as a fundamental factor (Purss, 2017).

Explicitly, the Abstract Specification is defining :

1. ”A concise definition of the term Discrete Global Grid System as an earth centered spatial reference system comprised of spatial units of equal area;”

2. ”The essential characteristics of a conformant DGGS; and,”

3. ”The core functional algorithms required to support the operation of a conformant DGGS.”

, (Purss, 2017).

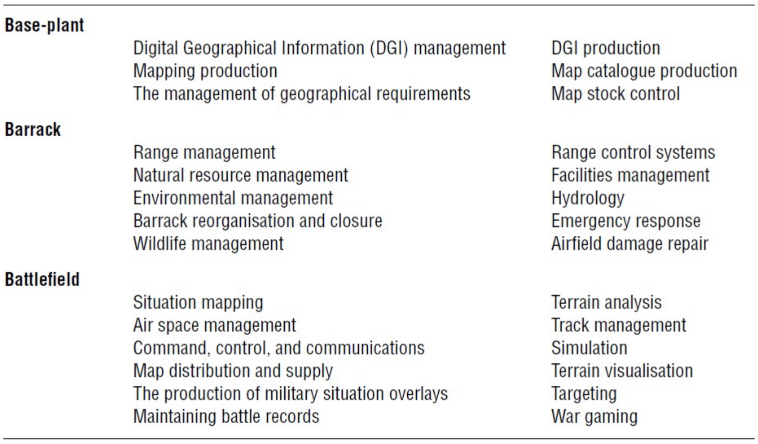
The DGGS Core Data model Overview is described in detail, comprising two main components : the reference frame elements and the functional algorith elements. The latter consists of the basic DGGS operations (quantization, algebraic, interoperability) (Purss, 2017) (Figure 2.11).

2.2. Military geospatial applications

2.2.1. GIS in military

Nowadays, the vast majority of the military around the world takes advantage of the GIS technology for various operational applications. Geographic Information Systems are of a great significance for a military mission, offering the capability to create, analyse, visualise and query geospatial data (Swann, 1999), boosting the decision making processes, in military operations.

Geospatial data handling and analysis plays a major role for military operations, giving commanders the capability to assess and execute data-driven analyses, exploiting the digital capabilities of the new era (Satyanarayana et al., 2022). GIS is used for various military applications that can be divided into three main categories: Base-plant, Barrack and Battlefield applications, summarised in Figure 2.5.

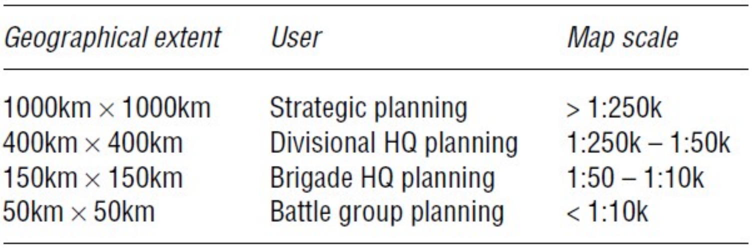


Base-plant		
	Digital Geographical Information (DGI) management	DGI production
	Mapping production	Map catalogue production
	The management of geographical requirements	Map stock control
Barrack		
	Range management	Range control systems
	Natural resource management	Facilities management
	Environmental management	Hydrology
	Barrack reorganisation and closure	Emergency response
	Wildlife management	Airfield damage repair
Battlefield		
	Situation mapping	Terrain analysis
	Air space management	Track management
	Command, control, and communications	Simulation
	Map distribution and supply	Terrain visualisation
	The production of military situation overlays	Targeting
	Maintaining battle records	War gaming

Figure 2.5.: Major Military applications engaging GIS and geospatial data use. Table taken from (Swann, 1999)

GIS is used in those various applications either standalone (Geographical Military Services) or attached in Command, Control, Communication, Intelligence Systems (C3I). Some C3I systems are already in service. Such GIS powered 3CI systems tend to use a geographical client-service architecture. A lower-end GIS is embedded on the C3I system, while the high-end GIS functionality is maintained and operated by geographical specialists, managing the background geospatial data and providing a managed depiction of the terrain (Swann, 1999). The use of geographical data within military operations, designates the need of explicit standardization and maintenance to enhance interoperability. In parallel, the military always demands for updated, high level, various scale/resolution digital geodata/geoproducts, most in wide areas of coverage (Swann, 1999). Some indicative levels are shown in Figure 2.6.

Commercial GIS software is also nowadays developed and used with digital databases providing military - oriented geospatial products (Fleming et al., 2009). An example of such a software is ESRI's ArcGIS - A Defence (`https://www.esri.com/en-us/industries/defense/overview`). The military was also striving for the implementation of geospatial - topographic



Geographical extent	*User*	*Map scale*
1000km × 1000km	Strategic planning	> 1:250k
400km × 400km	Divisional HQ planning	1:250k – 1:50k
150km × 150km	Brigade HQ planning	1:50 – 1:10k
50km × 50km	Battle group planning	< 1:10k

Figure 2.6.: Indicative military map scale requirements. Table taken from (Swann, 1999)

data exploitation systems, since the past decades (PEUQUET and BACASTOW, 1991). Frequently, the military parties turn to commercial off-the-the-shelf solutions, for cost issues (Swann, 1999), bringing up issues regarding the standards conformity between the military and the commercial data structures and data formats.

The capability to depict updated military data in regional security environments is of great importance for a military leader, greatly assisting in warfighting assessment and desicion making (Fleming et al., 2009). A host of different geospatial data are utilised and need to be integrated to have a high level data driven analysis (Figure 2.7).

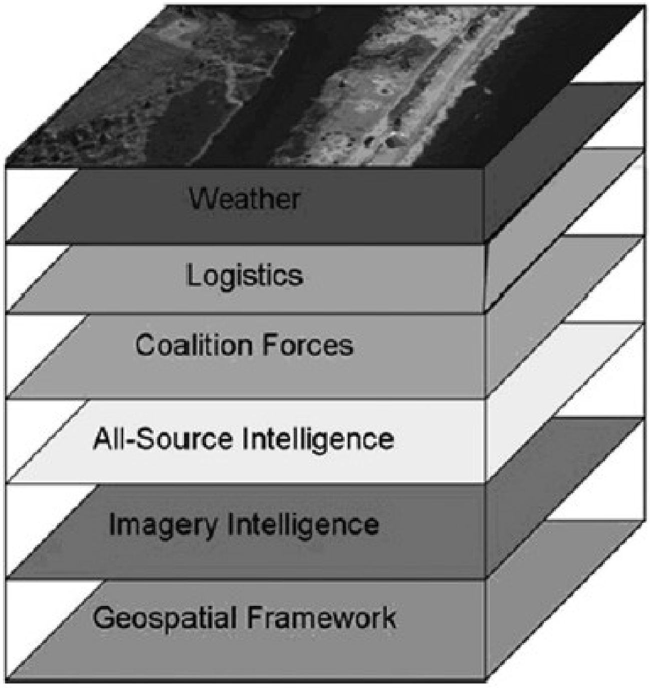


Figure 2.7.: Geospatial data fusion on the modern battlefield, image taken from (Fleming et al., 2009), (NIMA, 2003)

In combined forces (air - ground - navy) military operational scenarios, the multidisciplinary communication, data integration, data standardization and common geospatial framework is of great significance. Such a scenario may need to combine terrain evaluation with air and naval operations in an integrated approach (Satyanarayana et al., 2022). Joint forces (combined Ground, Air, Navy) would foster using integrated systems allowing the execution of required tasks. While operating in an integrated way, a "Common Operational Picture" (COP) can be given for operational and tactical commander service, offering commanders a uniform and accurate intelligence over a scene (Bekele, 2019). The Common Operational Picture (COP), in a military context is viewed as a "centralised information display system" and also related to Situational Awareness (SA), (Steen-Tveit and Erik Munkvold, 2021), which is of great importance for a military scene. Coordinating joint service operations, calls for a single datum framework. While the naval operations utilise a vertical datum based on high water mark, the ground forces operate on Mean Sea Level (MSL) datums and the air force is focused on obstruction heights above the ground (Satyanarayana et al., 2022). Apart from the standalone military interest actions, the military also engages in situations where close partnership with the civil party is required, such as first response activities, disaster management, hybrid threats and interoperability provision in cross-border crises. Such situations, require effective Civil-Military Interaction (CMI)(Cusumano and Corbe, 2017), to exploit the different resources and model a military scene. Civil-military cooperation (CIMIC) stands as a joint function in the military structure (NATO/OTAN, 2018a), aiming to maintain cooperation with non-military actors within an area of operations (NATO/OTAN, 2018a). In parallel, in treaty situations, burden sharing distributes the production across the allied nations and is also an important aspect, regarding the exchange of geospatial products and services (Swann, 1999). A common framework and common standards are essential. Regarding the standards, the work of creating and maintaining an exchange standard for digital geographical information is handled by the Digital Geographical Information Working Group, with the former exchange standard known as Digital Geographic Information Exchange Standard (DIGEST) (Swann, 1999).

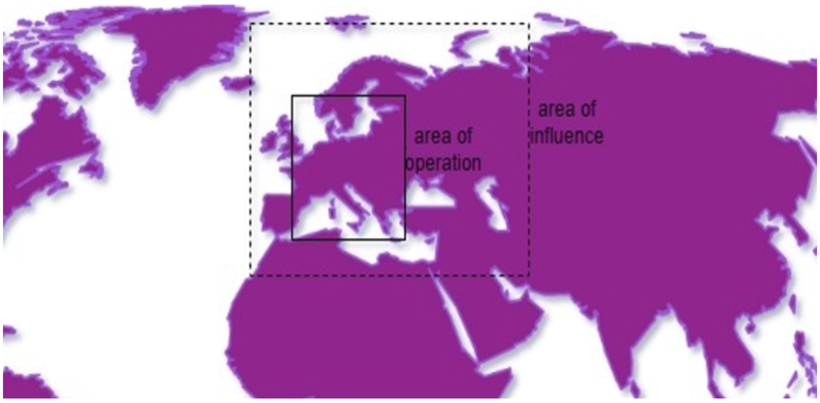


Figure 2.8.: Area of operations (AO), area of influence

Either in military joint operations, or in joint civil - military cooperative operations, the area designation and classification is an important aspect. An area of operations, is "an area within a joint operations area defined by the joint force commander for conducting tactical level operations" (NATOTerm), while the area of influence is "the area in which a commander can directly affect operations" (NATOTerm) (Figure 2.8). Concerning the geospatial applications, the military frequently operates within areas of coverage. An area of coverage is a ground area, usually a scene, within a planned amount of time, as a part of a Mission Plan (NATOTerm). The area of interest for a given level of command, is " the area of concern to a commander relative to the objectives of current or planned operations, and which includes the commander's areas of influence, operations or responsibility, and areas adjacent thereto" (NATOTerm). The importance of the area classification as well as the insight of the adjacent areas is designated. For a military scenario multiple data sources need to be integrated to have a high level data driven analysis assisting in decision making on areas of operations. In many strategic and tactic decisions of military and civil fields, spatial localisation is turning into a serious subject (esri, 1998). Sometimes, due to the fact that GISs are based on quantitative spatial models (using either vector or raster models), they can be indeterminate or ambiguous, for an exhausting spatial analysis of a military scene (Kettani and Maamar, 2000). Vector and raster models, being metric, do not support connectivity between objects in a scene and can be inadequate (Kettani and Maamar, 2000). Apart from neighbourhood relation a connectivity relation is really important. A more qualitative spatial model based on human spatial reasoning would provide useful insight (Kettani and Maamar, 2000), also harnessing the quantitative models' associated information.

2.2.2. Current military geospatial standards

This section aims in depicting the current military geospatial standards that exist in the countries/regions of scope, specifically, the European region and the North Atlantic Treaty Organisation (NATO) members. The free exchange of digital geographical data the last decades, has achieved strong international standards (Swann, 1999). In some aspects, the international defence standards for digital geospatial data can be be superior to the civilian equivalents (Swann, 1999).

The work of standardization of geographical data is undertaken by the Defence Geospatial Information Working Group (DGIWG) (Figure 2.9), formerly known as Digital Geographical Information Working Group, on behalf of the NATO Geographic Committee. The DGIWG (`https://www.dgiwg.org/`), as stated, is the multinational body established by the defence organizations of respective nations. Its main objective is the guidance and recommendations on its membership regarding the standardization of geospatial data, products and services. The DGIWG supports the NATO requirements and other alliances and those have been identified to address explicit operational scenarios. Existing international standards are utilised by DGIWG's standards where practical, including the abstract standards for geographic information by the International Organization for Standardization (ISO) (ISO TC/211), as well as, geospatial web services standards given by the Open Geospatial Consortium (OGC). Those standards are profiled and extended to serve defence requirements, allowing provision of common standard based solutions to enhance interoperability in coalition networks of nations.

As aforementioned, given by the working group, a widely used exchange standard is the Digital Geographic Information Exchange Standard (DIGEST), initially supporting efficient exchange of Digital Geographic Information among nations, data producers/users and over time distributing data products directly to military end users. DIGEST as a framework addresses various types of data: Imagery(raster data), boundary data(vector) and matrix data(elevation) and also handle capabilities for different encodings of the same data content. This standard is no longer maintained by DGIWG, but is still documented in their website since legacy systems that are still operating are based on this. For the DGIWG, technically, a key objective is ensuring the standards it provides fit to the largest practical degree, to the NATO geospatial requirements and are adopted by NATO.

Figure 2.9.: Defence Geospatial Information Working Group

In NATO the standardization protocols and agreements are given by STANAGs. A Standardization Agreement (STANAG) defines the procedures, conditions, processes and others for common military or technical procedures between the members of the alliance. A STANAG is a " standardization document that specifies the agreement of member nations to implement a standard, in whole or in part, with or without reservation, in order to meet an interoperability requirement" (NATOTerm). STANAGs are published in English and French by the NATO Standardization Office (NSO) in Brussels (`https://nso.nato.int/nso/home/main/home`) (Figure 2.10).

(a)

(b)

Figure 2.10.: (a) Northern Atlantic Treaty Organization - (b) NATO Standardization Office

Regarding the geospatial standards, several STANAGs and promulgated documents exist in the NSO, however not a lot are non - classified. An Allied Joint Doctrine (AJP) for civil-military cooperation is given in (NATO/OTAN, 2018a). STANAG 2211 is referring to geodetic datums, projections, grids and grid references throughout the NATO (NATO/OTAN, 2016), establishing the U.S. Department of Defense World Geodetic System 1984 (WGS84) as the standard geodetic system for geospatial information used by NATO. Except raster, geospatial information should use geographic coordinates (latitude, longitude), in decimal degrees (WGS84 ellipsoid). Raster data and products should be stored in the projected CRS for their use and display, as long as it is based on WGS84 or equivalent (NATO/OTAN, 2016). Explicit specifications for the rasters are given in a Standards related document (AGeoP), regarding the GeoTIFF raster format specification in a NATO environment (NATO/OTAN, 2018c). Regarding the position reporting by NATO ground units and ground combat operational forces, the Military Grid Reference System (MGRS), based on the WGS84 and the Universal Transverse Mercator (UTM) coordinate system, is the preferred method (NATO/OTAN, 2016). The MGRS is the geocoordinate standard used by NATO for locating points on Earth. It is used as geocode for the entire Earth. In STANAG 2586, specifications over the NATO geospatial metadata profile are given (, NSO), supervised by the Joint Geospatial Standards Working Group (JGSWG), which relates to the DGIWG. In STANAG 2592, the framework for coherent digital/printed geospatial products meeting the operational requirements from strategic to tactical across all branches, is given (NATO/OTAN, 2018b). This NATO geospatial information framework is aiming to support all operational domains(Joint, Land, Maritime and Air) requiring geospatial information. Similarly, in STANAG 6523, the Defence geospatial Web Services standardization ensuring inter connectivity over NATO and nation members, is given (NATO/OTAN, 2020).

2.3. Related research

In recent years, various researches were conducted signifying the potential of the Discrete Global Grid Systems (DGGS) use in the geospatial domain. Several DGGS platforms have emerged and are maintained, offering the implementation of DGGS operations defined by the Open Geospatial Consortium (OGC) Abstract Specification (Purss, 2017). The following literature are resourceful aiming to sustain the topic and explore applications of data integration using a Discrete Global Grid System.

2.3.1. Geospatial operations of Discrete Global Grid Systems

Li and Stefanakis (2020), compare Discrete Global Grid System and traditional GIS operations. The paper aims to serve as a reference for the development of future DGGS operations. It explores and tests existing proposed DGGS implementations. The geospatial operations they provide are evaluated, based on the essential operations defined by the Open Geospatial Consortium (OGC) Abstract Specification, and other potential operations to be provided by a DGGS. Those operations are compared with the traditional GIS operations to gain insight over various aspects such as database techniques, data visualisation, pre-processing, manipulation and spatial analysis among others.

2.3.2. Use of a Discrete Global Grid system in geospatial applications

Recently, the DGG system is utilised for several geospatial applications making use of the different existing state-of-the-art DGGS implementations. Researches often use different approaches concerning the intermediate pre-processing, for the integration of different types of datasets in a DGGS framework.

Rawson et al. (2021) propose the use of the Discrete Global Grid System (DGGS) as a structure to integrate various maritime datasets predicting the occurrence of ship groundings. The

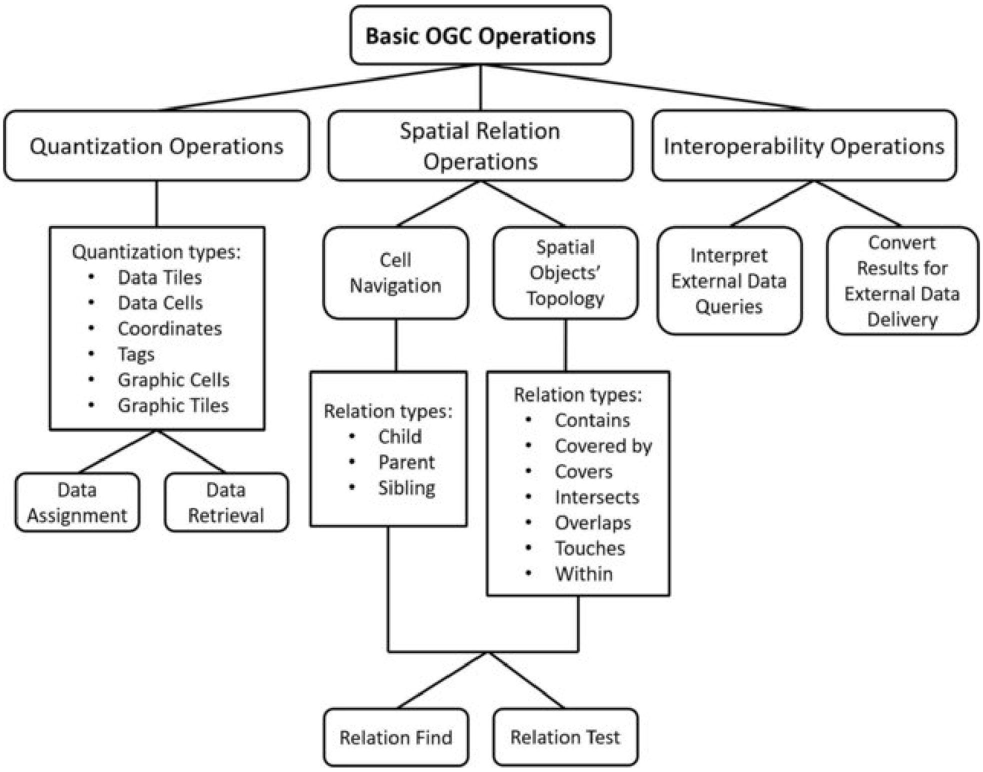


Figure 2.11.: Basic DGGS operations required by the OGC Abstract Specification. Image taken from Li and Stefanakis (2020)

research demonstrates the advantages and efficiency of the DGGS structure, using an existing implementation for the generation and manipulation of the common DGGS framework applied. Vessel traffic, bathymetric, metocean, infrastructure and other maritime datasets are integrated using the DGGS framework, whereas a spatial maritime risk model is developed to predict the occurrence of ship groundings.

Bousquin (2021) explores the use of a geospatial framework based on an hexagonal Discrete Global Grid System (**DGGS!**) on a coastal area. This research explores two different DGGS implementations; H3 (`https://h3geo.org/`) and dggridR (`https://www.discreteglobalgrids.org/software/`) which are compared in terms of data aggregation to scales from other existing frameworks and data integration across different frameworks, among others. While the research finds dggridR more flexible and simple in scale matching and using smaller units, H3 is found to have better performance in neighbour recognition and more efficient in moving scales.

Raposo (2019), in an early-stage project, builds on previous flow visualisation methods, while utilizing the DGGS properties, offering the hierarchical tessellation upon which the flow matrices for origin and destination can be stored and following, visualised. A suite of flow visualisation techniques is developed utilising an existing open source platform to render the products.

Robertson et al. (2020), introduce a new environmental analytic data model and analytics system (IDEAS), an integrated discrete environmental analysis system. This is build to develop a DGGS based GIS fitting large scale environmental analysis and modelling. The study shows the feasibility of the DGGS based GIS within a relational database environment and the outperformance of this system, in common GIS operations using conventional geospatial data types. Furthermore, a case study is conducted using the aforementioned DGGS based system, into wildfire modelling, demonstrating the potential for data integration and big data analytics. The study indicates the potential of DGGS systems in solving geospatial data analytics problems, offering a uniform representation for efficient algoriths to be built on.

3. Methodology

This chapter provides the methodology upon which the research objectives are addressed. The main stages of the methodology are depicted in a flowchart in Figure 3.1. Those stages can be divided in the following : data preparation (collection and pre-processing), data quantization, data integration and storage. Those stages are discussed in the following sections.

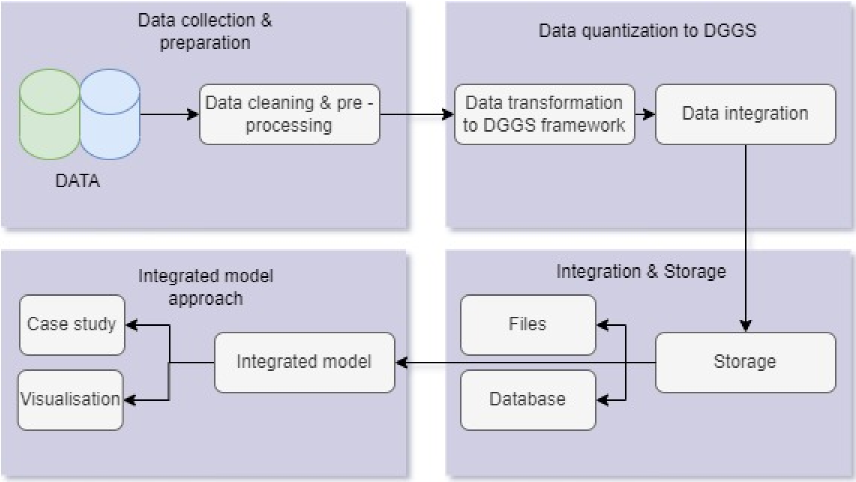


Figure 3.1.: Brief flowchart of the methodology

3.1. Data preparation

3.1.1. Data collection

In order to demonstrate the procedure of integrating different data formats and storing them under the same DDGS framework for a military scene, the first stage of the methodology involves collecting the according data. Non classified military data is relatively hard to find and also not common to be openly distributed. The data that were used for this research were openly available datasets of military interest and civil interest. This choice was made to be analogous to a military joint operation where datasets provided by both civil and military stakeholders, are integrated for the scope of the operation. In parallel, within the scope of the research (European region), datasets where chosen to represent both ground and maritime areas, as an analogous of an in-military joint operation. Elevation information is also selected to be integrated under the common framework offering height info and detail over the third dimension. Specifically, vector and raster datasets are used, being the most common and potentially interoperable data formats, both in civilian and geospatial military environments.

Regarding the vector data, maritime military (military naval areas) and civil ground data are used. The civil ground data refer to transport networks and specifically all the civil airports in Europe, a point vector dataset. The maritime military datasets consist of one point vector dataset and one polygon vector dataset. For the elevation values, a raster dataset containing gridded elevation data, for the research area is utilised. Further details regarding the datasets are given in the following chapter.

3.1.2. Data pre-processing

Aiming to reach a product, of an integrated model containing the fusion of the different data sources, coming in different geospatial formats, the data must be first manipulated. With focus on working according to the current military geospatial standards, the datasets are first-if needed- transformed in the WGS84 Coordinate Reference System, being the standard geodetic system for geospatial information used by NATO. In parallel, the DGGS framework that is utilised is the WGS84 system, guaranteeing the CRS conformity of the different data sources. Following, regarding the data pre-processing and cleaning, each vector dataset's attributes are examined and a basic framework of attributes for the integrated model is chosen. Basic attributes containing military interest qualitative and quantitative info are selected. The remaining attributes are cleaned, preserving the most relevant subset of attributes and also filtering the data from unwanted null values or other irrelevant information. Their geometry is preserved to be used in the following steps for performing the quantization operation and translating the datasets' information into the DGGS framework.

3.2. Data quantization

Given a DGGS specification, the quantization is the process of digitally assigning data values sampled from other data sources to the DGGS cells (Purss, 2017). Quantization methods to transform raw data to DGGS cells are not limited by the OGC. Regarding the different raw spatial datasets coming from multiple sources, different approaches should be used to translate them into DGGS cells (Li and Stefanakis, 2020).

Given the datasets used in this research, namely vector and raster datasets, the quantization procedures differ. In particular, for each different data format used and according to each dataset's geometry traits, different application programming interfaces (APIs) are developed, aiming to reform the datasets in a new DGGS framework (Figure 3.3) .

Regarding the vector datasets, two different are chosen in terms of geometry traits: point vector datasets and a polygon vector dataset (shapefiles). Different pre-processing is applied and several quantization strategies are tested in order to compare the differences and test the limitations that potentially exist when integrating them under a DGGS framework, to model the military scene of the research.

Concerning the point datasets, referring to military interest locations/observations, accompanied with the Coordinate Reference System (CRS) metadata, the quantization strategy is direct. The existing implementation's native indexing operations and the longitude, latitude properties of the dataset are used, while guaranteeing the correct CRS establishment. In this

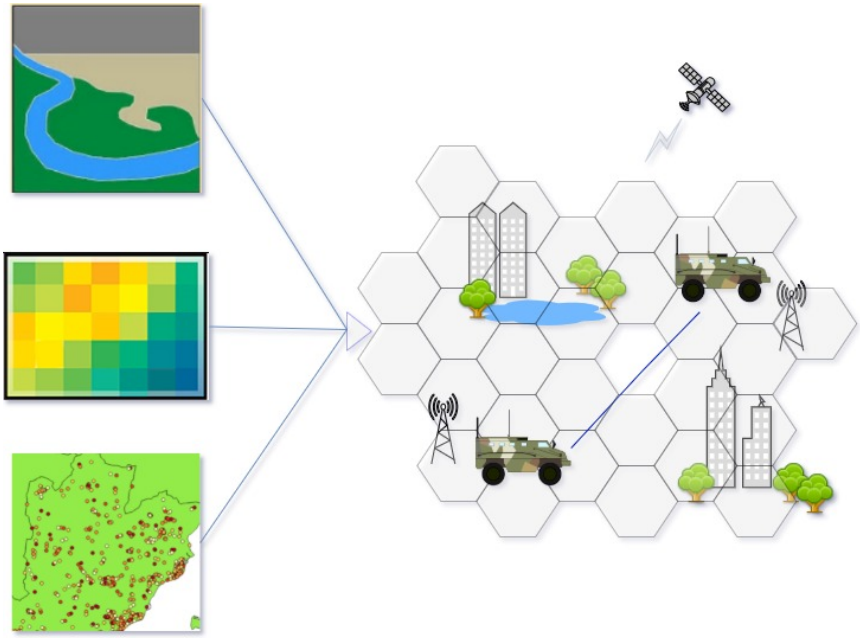


Figure 3.2.: Integration of different data formats under a DGGS framework, modelling a military scene: geo-features are assigned to the corresponding DGGS cell after a quantization operation, while the DGGS offers a common modelling framework based on a common CRS.

case, that potentially the DGGS cells represent data cells, the spatial observations are assigned to individual cells based on their geometry (Purss, 2017). An aggregation operation (data binning) is also developed and applied in different resolutions visualising the different resolution results to gain spatial insight refering to the military scene of the research. Further details over those actions are given in the following chapter.

The polygon dataset is more complicated, regarding the strategy of quantization that can be followed. Two different approaches were followed in the pre-proccessing stage, to integrate their geometry/values under the designated DGGS framework. Based on the selected resolution and different quantization strategy, the results differ. Two different approaches were tested, regarding the polygons. On the one hand, each polygon's centroid was sampled and then using the conventional method, indexed in the DGGS framework. On the other hand, utilising the existing implementation's (`https://h3geo.org/`) native functions, the polygons and the area they cover without overlap, is partitioned and indexed into the according DGGS cells of a specific resolution. This is relevant with a hierarchical cell rasterization that is used to store vector features in a DGGS using for instance, quadtrees for the approximation of geo-features refining a quad cell recursively (Mahdavi-Amiri et al., 2016);(Sahr, 2008). Each approach yields different results, with relevant distortions and differences that are appearing per different resolution. The results are tested for data quality, geometric measurement, topology validity. In parallel, aiming to yield the integrated model of the military scene, the optimal resolution is selected based on the data accuracy, dataset geometric coherence, visual capability and storage efficiency. Their potential and limitations in geospatial analysis for the military, through visualising the different results is tested. Those steps are discussed in greater detail in the following chapter.

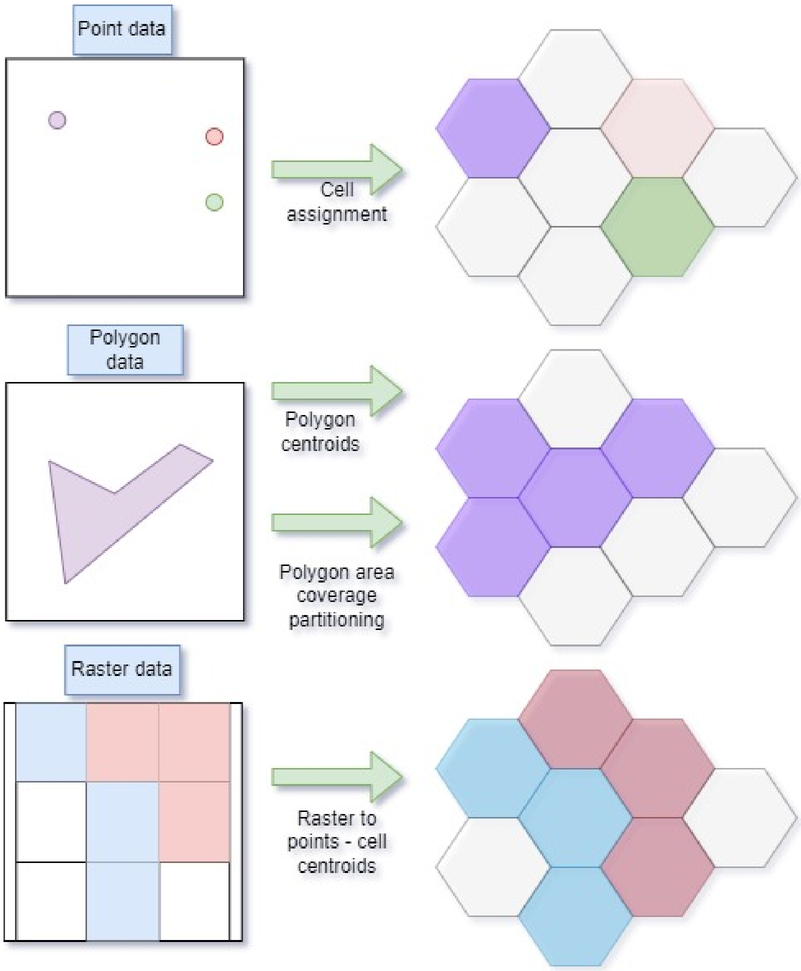


Figure 3.3.: Approaches to assign different geospatial data to corresponding DGGS cells

Regarding the raster datasets, the process is relative to resampling the original raster to the corresponding DGGS cells (Li and Stefanakis, 2020). Specifically, the cell centroids of a raster stand for a reference which is directly assigned to a corresponding DGGS cell based on its locations. Based on the different approaches and resolutions, each DGG cell can contain either the direct original raster value or an aggregated value from different original raster cells (Rawson et al., 2021), accompanied with the corresponding limitations or potential distortions. Referring to the selection the basic quantization resolution, according to Robertson et al. (2020), the nearest to the original cell size can be applied for the raster datasets, while for the vector datasets it should be selected according to the accuracy of the original data.

After the pre-processing of the raw data and the quantization operation, the conversion to the DGGS has a certain impact. Based on the original data models there are various ways of assessing the data quality after this conversion. For instance, the raster conversion data quality can be investigated through comparison of the a-priori DGGS conversion values with the a-posteriori ones, of a set of sample points(i.e via Root Mean Square error method) (Li and Stefanakis, 2020). Regarding the vector spatial data, when converted to the designated DGGS model, the data quality is assessed through the points' position displacement and the polygon features' geometry coherence (Li and Stefanakis, 2020). Testing the different approaches and resolution results, the potential limitations are evaluated by storing and visualising the integrated data. The military scene model either separately (for each different dataset) or as an integrated model, is exported and stored after quantization/integration both in files and in a database.

3.3. Data integration and storage

As previously mentioned, the process of the primary datasets' quantization is carried out using an existing implementation, and utilising the DGGS framework offered, along with some native functions. Specifically, H3, (`https://h3geo.org/`), the hexagonal hierarchical geospatial indexing system library is used. The main details and properties of this tool are discussed in the following chapter along with the advantages offered by the hexagonal partitioning method.

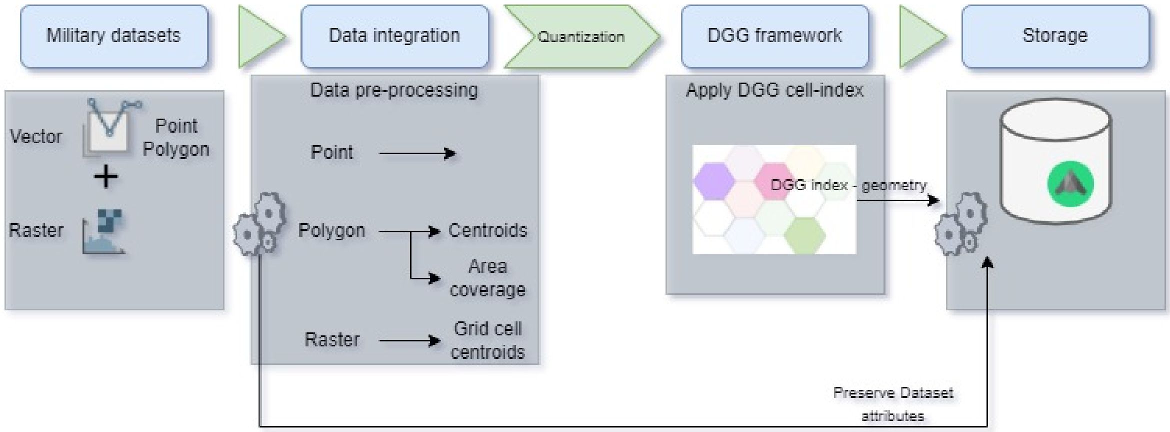


Figure 3.4.: Data integration and storage flowchart

In the context of storing the integrated data of military purpose under the common framework, the data are stored in files offering the capability to preserve the datasets' attributes to conduct further analysis, apart from only saving the DGGS index and geometry of each data entry. In parallel, a database is also used for the storage. This venture is aiming to demonstrate the procedure of storing and updating spatial data coming from multiple civil sources and in various formats, in a military purpose database. Collecting geospatial data sources of various types from published services and fusing them in a coherent format containing metadata and spatial/non-spatial information, to transform them in a fashion ready for spatial analysis, is needed to designate the accessibility and interoperability of databases (Peterson and Shatz, 2019).

The DGGS application offers to solve various problems of fusing data across distributed data sources and exchanging geodata of various data formats (Li and Stefanakis, 2020). After the

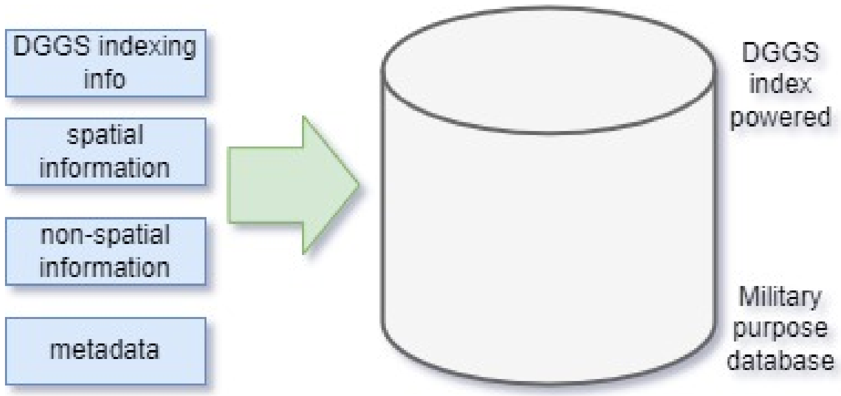


Figure 3.5.: Different format data accompanied with the DGGS index passed in the military purpose database

integration of the raw spatial datasets in the DGGS framework, the indexing and observations/values, along with the additional attributes (spatial/non-spatial) that accompany them, will be stored in the database (Figure 3.5). Preserving the datasets' attributes while using the DGGS indexing, aims to minimize the data loss and preserve the metadata and quality as much as possible. In parallel, the DGGS cell indexing mechanism, offers robust spatial positioning as well as hierarchical/neighboring cell navigation (Li and Stefanakis, 2020). Furthermore, according to Hojati and Robertson (2020), in-database spatial analysis using a DGGS framework has yielded a flexible architecture to be applied on massive data analysis, which would be purposeful for military scene concepts.

The use of a database aims to identify the potential of a military DGGS powered database, in terms of efficiency, dynamic storage of integrated different data sources and interoperability between civil-military parties. In parallel, the database is used to gauge the results as a product to gain insight and perform geospatial analysis for military purposes, utilising the integrated spatial datasets. After integration, the database offers an environment of the integrated model containing data from all the available resources, to efficiently query, update and perform analysis having a common framework and data that are spatially relevant and connected. The visualisation possibilities of the integrated datasets is also explored, using open standard geospatial data interchange format files (i.e. geoJson files) in multiple visualisation platforms. The visual results are depicted in the following chapters.

3.4. Military case study

Given the integrated model, containing the qualitative and quantitative values from the different data sources, a military case study is formed. The integrated model that not only contains civil - military area designation information, but also contains elevation information, over the terrain of the research region of scope, is utilised, to perform a ranging operation of military interest. The integrated model, modelled in a specific resolution under the common DGGS framework, enmeshes information about the military 'Firing Areas' and their locations, as well as, about the locations of the civil airports in the European union. The ranging operation is concerning, the query to locate and designate the civil airports domains (areas in the DGGS framework) , that would be potentially affected of a missile firing of 250km range (Figure 3.6). The case study is conducted, utilising the DGGS native functions and operations, as well as the hierarchy and neighbourhood spatial indexing, as an analogous to a range/radius search, aiming to designate the DGGS indexing potential in such geospatial military operations. Following, an additional demonstration of a potential missile trajectory given in DGGS terms is done, in a 2D approach as well as in an approach exploiting the 3rd dimension's info contained in the integrated model.

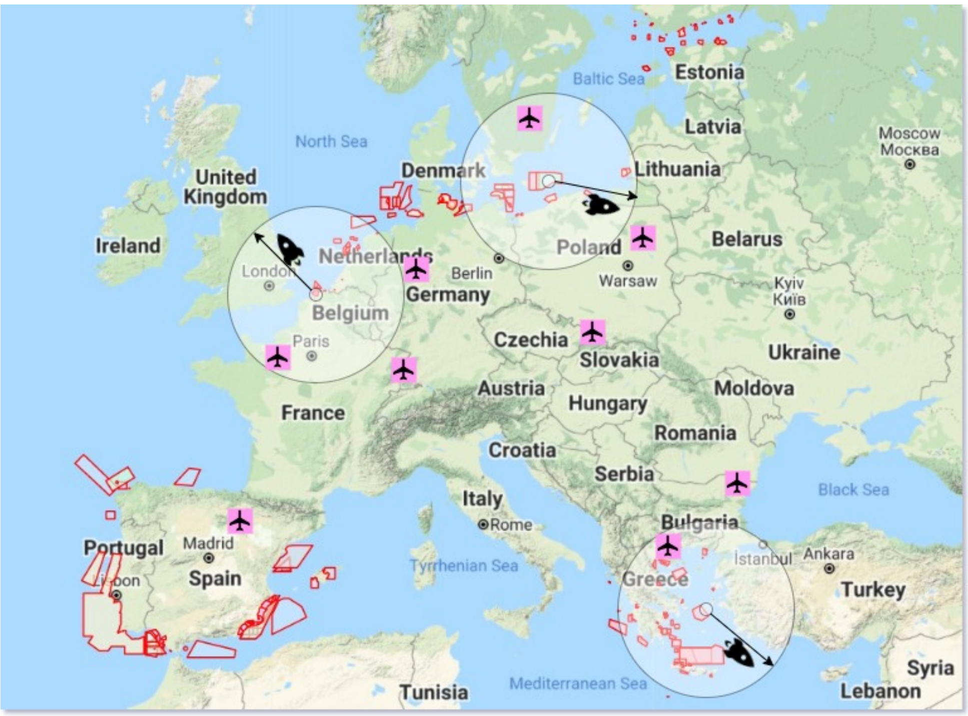


Figure 3.6.: Military case study - Missile ranges from Firing areas to detect potentially affected civilian airport domains

4. Implementation

In this chapter, the main steps followed to implement the methodology are presented. First, information about the datasets that were used are given, along with details regarding the DGGS framework used to integrate those datasets. Following, some programming details regarding the implementation are given, and a description of cleaning, pre-processing steps. Then, the different APIs developed concerning the datasets' quantization are described, along with details regarding their integration and storage. Finally, the case study conducted using the integrated model is presented.

4.1. Datasets

Both military non classified and civil open source geospatial datasets are used. The datasets mainly represent geospatial data concerning the European region (scope of the research), representing both ground and maritime areas. In parallel, elevation data regarding the terrain is also given by a raster dataset containing gridded elevation data. Two point vector datasets are used. One dataset concerning military interest entries and one containing civil interest entries. The polygon vector dataset is concerning military interest entries. Specifically, the military datasets are containing maritime(offshore) military areas, characterised by a certain designation (for example: 'Firing Area'), across the European region, created by the European Marine Observation and Data Network (EMODnet). The datasets contain polygons and/or points. Those military datasets are primarily given in a shapefile format. The other vector dataset, which contains non-military ground data, refers to civilian transport networks and specifically all the civil airports in Europe, a point vector dataset. Provided by Eurostat Geographical Information and Maps (`https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/transport-networks`), in a shapefile format, covering the European region and containing info about the airport locations, names and several other attributes. Details over the vector datasets are given in Table 4.1 . The raster dataset that is used, containing a world digital elevation model is the ETOPO5. This dataset was generated from a digital database of land and sea-floor elevations on a 5-minute latitude/longitude grid, with a varying resolution 5min to 1 degree in different parts of the world. For the scope of the research, the dataset is cropped and isolated in the European region geographic extent and is provided by the European Environment Agency (`https://www.eea.europa.eu/data-and-maps/data/world-digital-elevation-model-etopo5`).

Dataset	Format	Geometry	Geographic Coverage	Number of features
EU Offshore Military Areas	shapefile/vector	point	Europe	36
EU Offshore Military Areas	shapefile/vector	polygon	Europe	227
EU transport networks (Airports)	shapefile/vector	point	Europe	2847

Table 4.1.: Details over the vector datasets

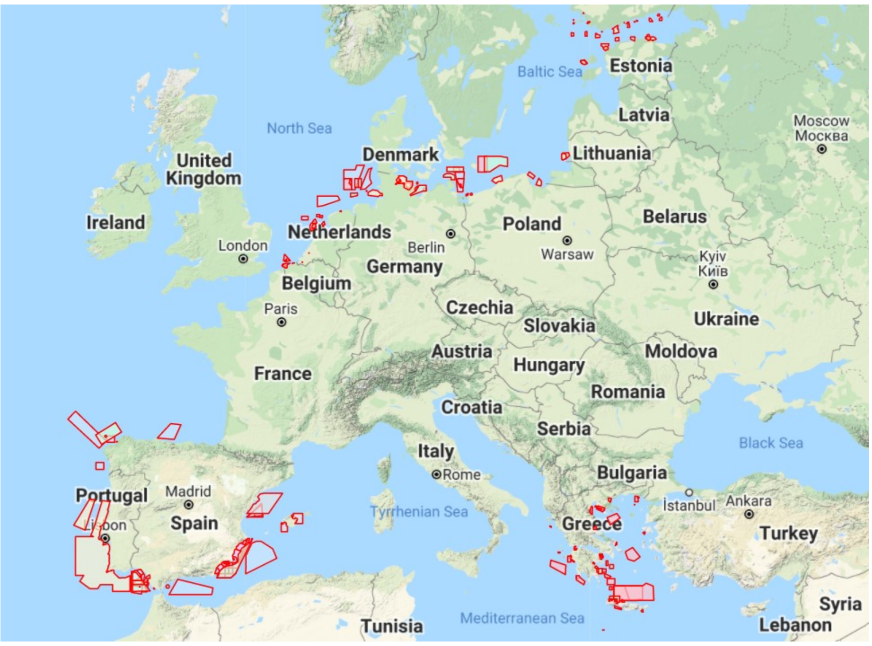


Figure 4.1.: Offshore military areas in EU, source : `https://ows.emodnet-humanactivities.eu/geonetwork/srv/api/records/579e4a3b-95e4-48c6-8352-914ebae0ae1d`

Figure 4.2.: Geographic extent - EU , source : `https://ows.emodnet-humanactivities.eu/geonetwork/srv/api/records/579e4a3b-95e4-48c6-8352-914ebae0ae1d`

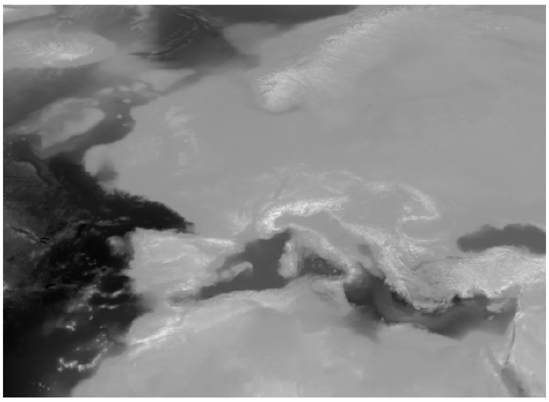


Figure 4.3.: ETOPO5 gridded elevation, cropped to the geographic extent of the European region

Source:https://www.eea.europa.eu/data-and-maps/data/world-digital-elevation-model-etopo5

H3 resolution	Average area of hexagon (km2)	Average Hexagon Edge length(km)	No of unique indexes
0	4,250,546.8477000	1,107.712591000	122
1	607,220.9782429	418.676005500	842
2	86,745.8540347	158.244655800	5,882
3	12,392.2648621	59.810857940	41,162
4	1,770.3235517	22.606379400	288,122
5	252.9033645	8.544408276	2,016,842
...	...	...	...
15	0.0000009	0.000509713	569,707,381,193,162

Table 4.2.: Abstract of h3 resolution table

4.2. Discrete Global Grid System framework

The Discrete Global Grid System framework that was utilised to transform and integrate the datasets is the H3 Hexagonal hierarchical geospatial indexing system, provided by Uber. This geospatial indexing system partitions the world into hexagonal cells and is open source under the Apache 2 license `https://h3geo.org/`. The H3 library that was used, specifically using its Python binding, is implementing the H3 Grid system. Functions are included for longitude/latitude to cell conversion, finding the center of cell, finding geometry boundary of cells (hexagonal), finding neighbours among others, that were used in the implementation of the different APIs to transform the different format geodatasets to this framework. The H3 is a hierarchical geospatial index, offering 16 resolutions (0-15), while the finest resolution (15) is down to a square meter. In the context of this research, the capabilities of this system were used to join disparate data sets (formats). An abstract overview of the resolutions is provided in Table 4.2. The full resolution table can be found in `https://h3geo.org/docs/core-library/restable`.

The hexagonal shape of the grid offers various benefits for geospatial modelling, such as for the analysis of movement between the cells of a model. In comparison with a triangular or a rectangular subdivision shape, the hexagon has the benefit of having exactly 6 neighbours that are also equidistant. A triangle has 12 neighbours with different distances while a rectangle has 8 neighbours with different distances (Figure 4.4) . In parallel, hexagons have the beneficial property of expanding neighbour rings, approximating circles (radiuses) (Figure 4.5). Furthermore, the hexagonal shape is more optimal that a rectangle in space-filling situations such as filling a polygon with hexagons, having smaller margins of error, which is important for this research. On the other hand, the incongruity of hexagons must be stated, as a parent hexagon cannot be perfectly decomposed to smaller child hexagons.

H3 is a discrete global grid system offering a multi-precision hexagonal tiling of the sphere with hierarchical indexes. A sphere-circumscribed icosahedron is used as the base polyhedron, while the coordinate reference system (CRS) is spherical coordinates with WGS84 / EPSG:4326. Using WGS84 data with this framework is common. In parallel, this CRS is also the one used by the current NATO geospatial standards (NATO/OTAN, 2016), and is the main framework of the military scene model of this research. The grid is formed on the icosahedron creating higher precision resolution grids recursively. However, the sphere/icosahedron cannot be tiled completely with hexagons. Each resolution of an icosahedral hexagon grind contains 12 pentagons at every resolution, having one pentagon in the center of each of the icosahedron vertices. The indices of H3 are defined via hexadecimal format (16-bits, 16 resolutions) having the capability to determine the cell resolution by checking the id of the cell.

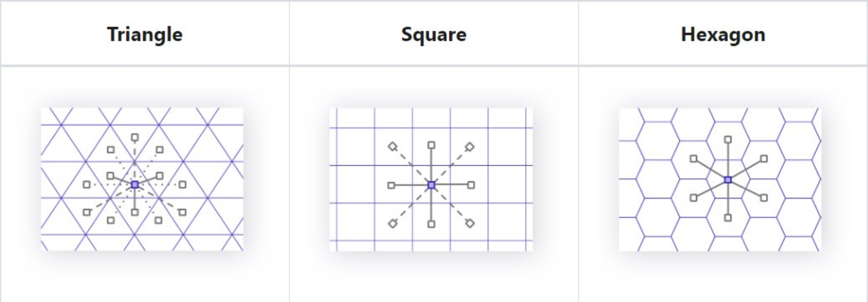


Figure 4.4.: Different shape subdivisions neighbours and distances - source: `https://h3geo.org/docs/highlights/aggregation`

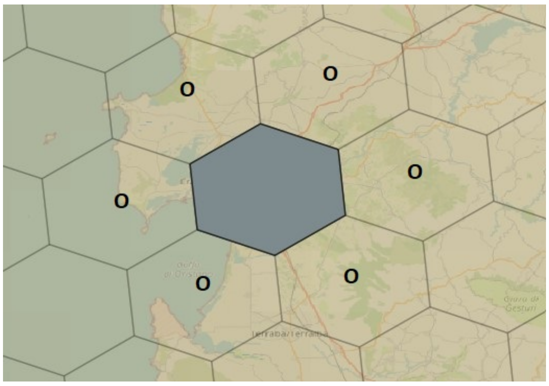


Figure 4.5.: A hexagon with its 6 neighbours - ring 1

4.3. Programming details

All tests and implementations of the methodology were carried out using a Windows 10, Intel Core i7-10510U CPU, having a speed of 1.8-2.3 GHz, 12 GB RAM on a 64-bit operating system. The methodology steps were mainly implemented using Python as the main scripting language. A PostgreSQL database was used for the storage of the integrated DGGS indexed datasets as well as for querying capabilities. The datasets used, were also loaded in their primary state/format in QGis for visualisation and monitoring purposes. QGis was also used for CRS transformations of the primary datasets and/or to export different formats of the datasets to further manipulate them in Python.

For the preparation of the data before manipulating and integrating them under the common framework Python was used both with scripts and notebooks. The h3 library's python binding along with its relevant methods was used for the data quantization within the different APIs for the different data formats. The datasets after conversion were stored locally in files and in the PostgreSQL database. A connection with the database was also established using the *psycopg* library (Federico Di Gregorio), giving the capability to perform queries executed in Python and also loading external files into the database and manipulating the database's tables.

After the data pre-processing and integration in the DGGS framework the resulting transformed datasets were stored locally in pandas dataframes (Wes McKinney, 2010). Several operations of joining and grouping were performed using pandas, exploiting the indexing unique ids of the transformed datasets that were also stored in .csv files locally apart from the database, for the easy distribution and use of them in other platforms. For the raster pre-processing and implementation of the quantization API, *rasterio* was used for raster manipulation purposes (Gillies et al., 2013–).

Specifically, the integrated datasets stored in .csv files and further transformed in pandas dataframes were loaded in the kepler.gl (`https://kepler.gl/`) tool for visualisation and querying purposes. Furthermore, pydeck (`https://deckgl.readthedocs.io/en/latest/`), the python binding of deck.gl (`https://deck.gl/`) was also used for visualisation purposes, giving a dataframe input and visualising the integrated model locally in .hmtl files. In the same context, follium (`https://python-visualization.github.io/folium/`), was also used for visualisation purposes, using the python created dataframe data and visualising them locally using .html files in leaflet.js maps background. Moreover, the different APIs are exporting .geojson files stored locally, that are used to visualise and/or query,analyse the integrated datasets when imported in GIS softwares like QGis or FME. Another tool used to visualise the integrated datasets on the Globe, importing .geosjon locally stored files, was globe.gl (`https://globe.gl/`), a UI component that uses ThreeJS/WebGL. In order to use this component/web application an Apache Tomcat 9.0.45 server was set locally, used as the HTTP server to visualise the datasets on the globe on the localhost. The use of this tool was done using Javascript language and by reformating the .html files for visualisation.

4.4. Data cleaning and pre-processing

Data cleaning and pre-processing was conducted using both manual and semi-automatic steps. For the different data formats that were used (point vector, polygon vector, raster)

country	type	lng	lat
		geometry	

Table 4.3.: Point datasets attribute structure

country	type	status	area	coast_dist	’attributes’
’type’	Polygon	’coordinates’	[...]		’geometry’

Table 4.4.: Polygon dataset attribute structure in .geojson file

different cleaning and pre-processing steps were made according to their specific particularities. In order to integrate and index the different datasets under the used DGGS framework the most important aspect is the geometry of each. Following, the according attribute values that are selected to represent the data entry indexed in DGGS framework. A main structure of attributes is selected for the integrated model and aiming to fullfil this, the most important attributes containing military interest qualitative and quantitative info are selected.

Regarding the point vector datasets, given in shapefiles,they were first imported in QGis, and then exported in .csv files, preserving their geometry (longitude, latitude values). The military offshore areas dataset was given in the WGS84 CRS (EPSG:4326) which is also the project’s CRS. The civilian airports dataset was given in the ETRS89 CRS (EPSG:4258) and thus, a coordinate reference system transformation of its geometry to the WGS84 CRS was primarily conducted. The quantitative/qualitative attributes that were selected and passed in the .csv were: ’lng’,’lat’ for their geometry and ’country’,’type’. The ’country’ attribute is enclosing the country they correspond to whereas the ’type’ attribute differs per dataset. For the military dataset, the ’type’ attribute refers to the value that corresponds to the military use type of this area (ex. ’Firing Area’). For the civilian airports, the type attribute encloses the official name of the airport, for designating the airport location and use. This structure (Table 4.3) is then used as an input for the point-to-DGGS transformation. The rest attributes were removed while in parallel, degenerate or missing values were cleaned.

Regarding the polygon vector dataset, that is also given in a shapefile format, a different approach is carried out due the different geometry comparing to the point vector datasets. While the point datasets, can easily be quantized using their longitude and latitude values, in a polygon vector dataset, the full polygon geometry should be preserved, to be processed and following quantized. The dataset is again imported in QGis, but then exported in a .geojson file, preserving the geometry (polygon coordinates) as well as the selected attributes. The quantitative/qualitative attributes that were selected and passed in the .geojson file apart from the ’geometry’ were: ’country’,’type’,’status’,’area’,’coast dist’. Attributes ’country’ and ’type’ have the same context with the point datasets, while ’status’ is referring to a military area’s condition/state designation(Active, Inactive or Unknown). Attributes ’area’ and ’coast dist’ refer to the float values (if present in the dataset) of the area and distance from coast, as the dataset represents offshore military areas. This structure (Table 4.4) of the .geojson file is then used as an input for the polygon-to-DGGS transformation. The rest attributes were removed while in parallel, degenerate or missing values were cleaned.

Regarding the military offshore areas, coming from both data sources (point and polygon dataset), a distribution of the military areas use for both the polygon and point datasets is demonstrated in the graph(Figure 4.6).

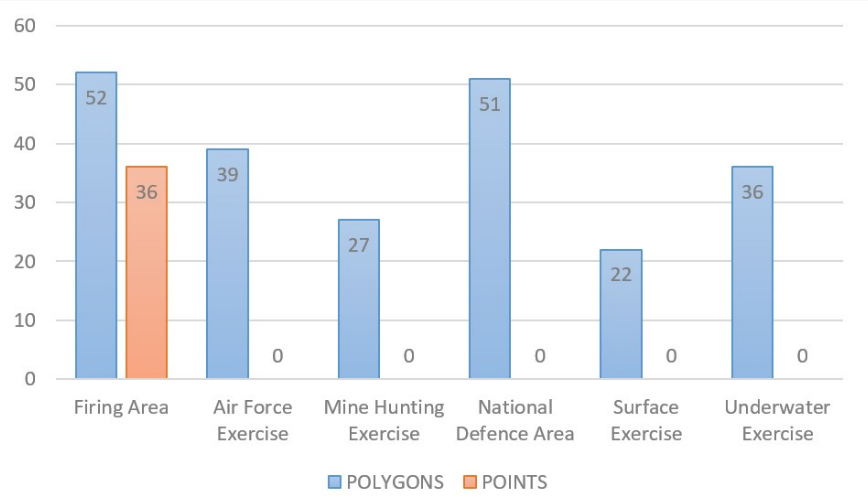


Figure 4.6.: Military offshore areas uses distribution for both point and polygon vector datasets

The raster dataset (ETOPO5), World digital elevation model, was first imported in QGis, as a GeoTiff raster. This dataset is given in a projected CRS based on Clarke - 1866 ellipsoid. First, it is transformed into the project's CRS (WGS84) complying with the current military geospatial standards. Then, it is cropped to the European region's geographic extent. For convenience, in the borders, parts of North Africa and Western Asia are also included. In that state, it is ready to be used an input to the raster-to-DGGS transformation, to be indexed under the common DGGS framework.

4.5. Data quantization APIs

In order to convert the different geospatial data formats into the according indexed DGGS framework used (using H3), different APIs were implemented according to the type of the data format. Specifically, a point-to-DGGS and and a polygon-to-DGGS for the vector datasets and a raster-to-DGGS for the raster elevation dataset. Those APIs convert a given specific data format file, to the according DGGS indexed entries, preserving the attribute structure of each dataset, for a given resolution of the used DGGS framework on demand. In parallel, aggregation capabilities over the quantization operations are supported. For this reason, the data model attribute structure is enriched with an extra attribute 'value', used to store the aggregated sum of uses per resolution. The results can be exported on demand in .csv files for analysis-extra manipulation and in .geojson files offering visualisation capabilities in external softwares and/or querying capabilities. The individual different data format results are then fused into the integrated model, using the final attribute data model structure.

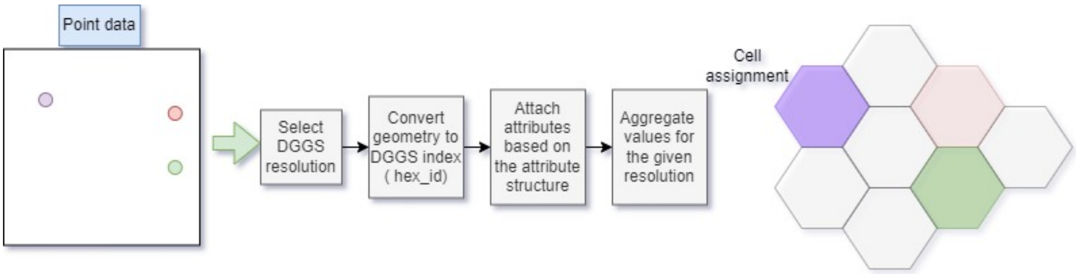


Figure 4.7.: Vector point data conversion/quantization flowchart

4.5.1. Points to DGGS

Regarding the point vector datasets conversion the API is using the .csv input having the pre-processed data model attribute structure. The file is loaded in a pandas dataframe to exploit the different column values. A user defined resolution is selected, and then using the geometry of each data entry ('lat','lng' attributes) the data entry is converted/quantized to the according DGGS index id. This operation is carried using the native indexing method of the h3 implementation *geo to h3*, taking as input the geographic coordinates (longitude, latitude) of each point and the selected uniform resolution. The indexing id is stored in a new column called 'hex id'. From now on, the primary geometry is neglected, while the 'hex id' attribute, includes information about the geometry of the hexagon in the given resolution, the resolution, the parent/children hierarchical links as well as the neighbour cells. The remaining attributes are preserved and attached in the dataframe. Then, an aggregation operation is conducted, grouping by the 'hex id' attribute, counting the number of different uses ('type' attribute) per hexagon. The 'value' attribute, is used to store the sum of different uses (aggregated value). The qualitative information of the different types, is stored in the 'type' attribute as a semicolon delimited string. Each cell/object is stored using the 'hex id' attribute as a key-value pair, while all the attributes refer to the specific cell/object they belong to. The resulting DGGS converted dataset can be exported as a .csv file to be used as a dataframe for extra analysis, or to be loaded in the database. The capability to export a .geojson file is also supported. The attributes are preserved, while the 'geometry' column in the .geojson format is given using the native method of the h3 implementation *h3 to geo boundary*. This method given a 'hex id', returns the geometry of the polygon (hexagon) in a .geojson format in the according resolution.

4.5.2. Polygons to DGGS

The conversion of polygon vector datasets into the DGGS framework is different and more complicated from the point data. The geometry of polygons is more complex and a different strategy must be followed. In the beginning, two approaches were intended to be applied. However, the first approach that referred to first modelling each polygon's centroid and then quantizing using this entry, was tested and decided not to be applied. The reason is, that this approach is heavily error prone, as factors like the selected resolution, the polygon geometry complexity have a high effect. Modelling the polygon's centroid can give satisfactory results only in cases the selected resolution and the dataset's scale/spatial uncertainty are

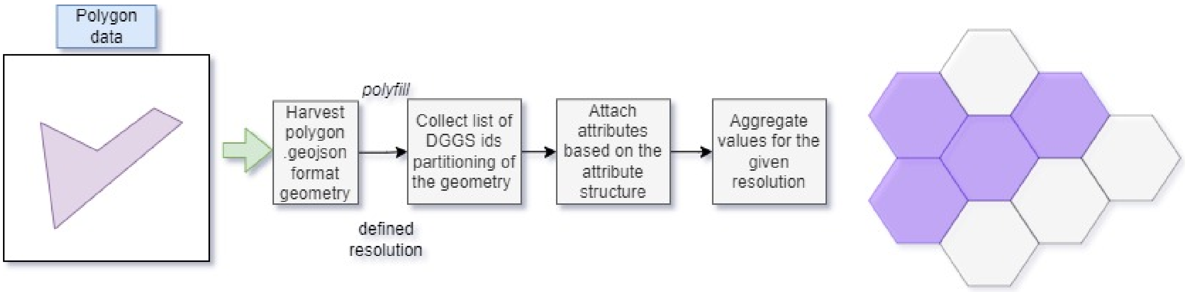


Figure 4.8.: Vector polygon data conversion/quantization flowchart

close. In most cases, important proportion of the polygon's geometry is not partitioned in the according DGGS framework yielding poor quality results.

The API to model polygon datasets and convert them into the selected DGGS framework, works by partitioning the area that each polygon covers and yields the according DGGS cells included in this partition. This operation is conducted, using the native method of the h3 implementation *polyfill*. This method takes as input a given .geojson format data structure and fills it with hexagons that are contained by the .geojson format data structure. The containment is determined by the centroids of the cells. If the centers of the provided hexagons are within the given polygon, then the hexagons are returned. A partitioning of the .geojson format, where polygons cover an area without overlap, results a DGGS grid partitioning of hexagons where the cells cover the same area without overlap approximately. The method is called giving also as input the resolution on demand, which is relative to the quality of the resulting partitioning.

To convert polygon vector data into the DGGS model, first the .geojson format file is given as input and loaded into the API's function. Then for every feature (polygon), the geometry attribute is used and passed into the *polyfill* method for a defined resolution. The DGGS ids returned by the method that form the partitioning of the each polygon are then stored in the 'hex id' attribute. The properties are attached in every DGGS id and the geometry of every hexagon ('hex id') is also retrieved through the native method of the h3 implementation *h3 to geo boundary* in a .geojson data structure format. In case of duplicates, due to the nature of the datasets (overlapping polygon areas), the values are aggregated, grouping by the 'hex id' attribute in the given resolution. The different information is stored again using the 'value' attribute (aggregated value), while the 'type' attribute is used to store the different type uses designation in a semicolon delimited string. The function returns a new .geojson file containing the converted hexagons of the primary dataset (both their ids and geometry) as well as the relevant properties attached to them. Moreover, the API offers the capability to also return a .csv file flattening the .geojson file's attributes and neglecting the geometry for memory efficiency, that can be also used as a dataframe for several operations as well as to be loaded in the database.

4.5.3. Raster to DGGS

Regarding the raster dataset, in this case containing elevation values, the pre-processed raster GeoTiff file is given as an input for the API. Then, the Tiff format is translated into a XYZ dataframe using *rasterio* and *xarray*, storing the longitude, latitude and elevation value from

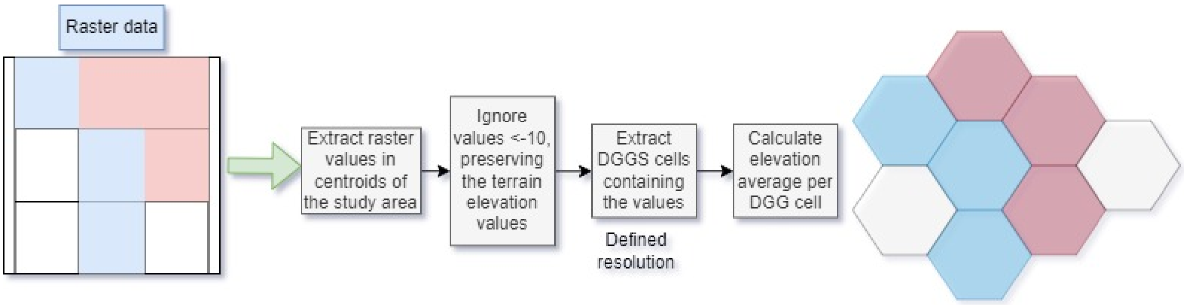


Figure 4.9.: Raster data conversion/quantization flowchart

the raster entries. Following, aiming to preserve the terrain values of the study area (European region), the 'sea' values are ignored, setting a threshold and ignoring the values below -10 meters. In that way, values are present even in borderline situations, such as the Netherlands (having a vast amount of values below 0 meters) and still characterised as ground/terrain values. Converting raster data into the according DGGS grid, the raster's resolution selection is important to select the DGGS cell resolution, to form a continuous partitioning of the terrain representation. Most of the times, the finest DGGS resolution that can be used, in order to avoid gaps and empty areas is analogous to the primary raster dataset's resolution, also maintaining the proper elevation values. For higher resolutions, values can be aggregated using the hierarchical indexing of the DGGS framework. Then, after a resolution is selected, the DGGS cells containing the points/values are found. Following, the elevation average is calculated per DGGS cell (hexagon) in the given resolution (aggregation) and stored as the 'elevation' attribute. The converted dataset is exported in a .csv file containing the 'hex id' and 'elevation' attributes. The capability to export a .geosjon containing the geometry of the DGGS cells is also supported. The geometry is again given using the 'hex id' DGGS cell id and the method *h3 to geo boundary*.

4.6. Integration and Storage

The different DGGS converted geodatasets were stored both in files (.csv and .geojson) and in the PostgreSQL database created for this purpose. Different resolutions were exported for testing and conversion quality assessment, however in the current implementation multi-resolution representations were not stored explicitly in files or in the database. For visualisation purposes, different resolutions stored in files were used in the same representations.

Aiming to yield an integrated model, containing the fusion of all the different data formats converted into the DGGS framework a uniform resolution has to be decided. In most cases, in order to have sufficient and decent quantization results of a spatial dataset, the selected resolution must be analogous with the scale/spatial uncertainty of the input dataset. In parallel, apart from the individual optimal resolution, the selected resolution must be appropriate to fullfil the fusion of all the participant datasets. For this case, while the point and the polygon vector datasets allow for a relatively high accuracy, thus a high resolution into the DGGS framework, the DGGS converted raster elevation resolution is proportionate with the primary raster resolution. Through error and trial, visual inspection and testing, in order to have a continuous terrain elevation representation without gaps, based on the raster data

hex id	country	status	type	area	coast dist	elevation	value

Table 4.5.: Integrated model attribute structure

resolution, resolution 5 in the DGGS framework (H3 grid) was selected to be the uniform resolution for the integrated model. The according resolutions of the different datasets are computed on demand through aggregation if needed. In resolution 5 (Table 4.2), each DGGS cell (hexagon) has an average hexagon area of 252.9033645 km2 and an average hexagon edge length of 8.544408276 km while having 2,016,842 unique hexagon indices. This resolution was used for the integrated model, stored in individual files and in the database.

The different DGGS converted data formats were loaded and stored in the database, establishing a database connection through the *psycopg* library. First, different tables were created for each different data format (point vector, polygon vector, raster), having the previously defined data model attribute structure. Then, for the given resolution (=5), the according generated .csv files were used to populate the tables copying their values to the according tables (*copy from* command).

The integration of the different DGGS converted data formats, is done exploiting the same underlying DGGS framework those data are attached to. Using the 'hex id' attribute the integration is done by merging the attributes of the different datasets grouping by this index. In this way, multi-source information is integrated under the same DGGS framework in the uniform resolution that was selected (=5). The integration is done in the database, using PostgreSQL commands, as a more straightforward approach and the integrated model is stored in a new table, that was first created (Figure 4.10), setting the final data model attribute structure (Table 4.5).

```
CREATE TABLE integ AS (
        SELECT DISTINCT hex_id, string_agg(country,';') country, min(status) status,
    string_agg(type,';') as type,
min(area) area, min(coast_dist) coast_dist, min(elevation) elevation,sum(value) as
    value
FROM ppr GROUP BY hex_id ORDER BY value
)
```

In parallel, a function *get logs* was also developed to conduct queries in scripting environment through the established connection with *psycopg*. In that way the integrated model is stored in the database allowing dynamic update, retrieval and querying capabilities and in parallel, it can be exploited in the scripting environment for conducting further analysis using extra geospatial tools and the DGGS framework's native hierarchical and neighbourhood capabilities. The 'hex id' used as a primary key in all the tables, contains info regarding the geometry, resolution, hierarchy and neighborhood, and in this context allows the efficient storage, neglecting the geometry of the integrated datasets. The integrated model can be exported in a .csv file to be used for analysis and/or be converted to other data formats (.geojson, restoring the geometry) for visualisation purposes.

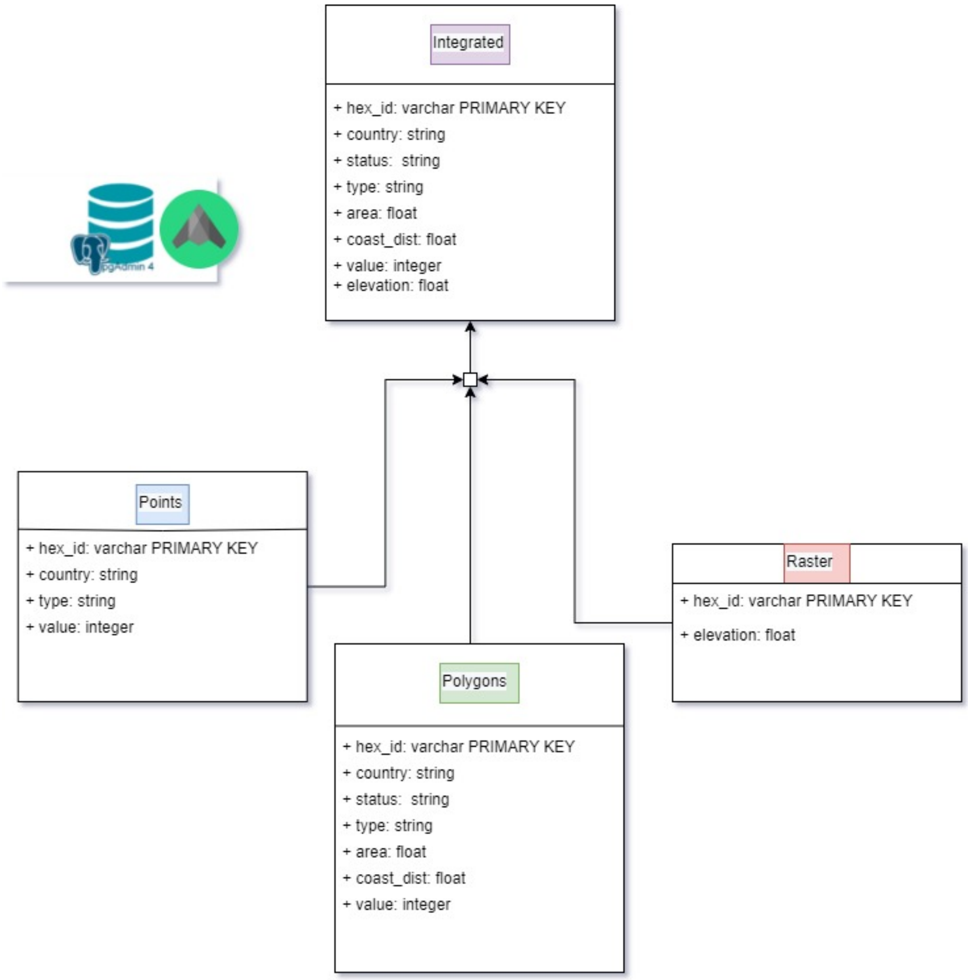


Figure 4.10.: PostgreSQL Database tables architecture

4.7. Military case study

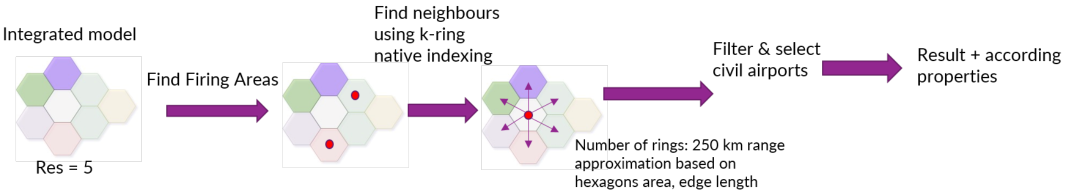


Figure 4.11.: Case study's flowchart

The integrated model that contains qualitative and quantitative values yielded from the different data formats, was used to conduct a military case study. Civil/Military area designation along with elevation information of the terrain of the study area (European region) are included in the model. It is used to perform a military interest ranging operation, while modelled in a uniform resolution (resolution 5), under the common DGGS framework. The case study, is regarding the ranging operation, querying to locate and point out the civil airport domains (areas in the DGGS framework in the analysis uniform resolution) that are potentially affected by a missile firing of a 250 km range. The case study is carried out, using only the integrated model and DGGS indexing and querying capabilities, without the use of geometric operations. The spatial indexing of the DGGS framework and the neighbourhood capabilities are exploited to yield the result. The ranging operation, being analogous to a range/radius search exploits the information of the integrated model to point out the results, using the approximated DGGS indexed geo-features of the different data sources, avoiding expensive geospatial operations.

A function is developed in Python, to conduct the case study giving the integrated model as an input. The input is given in a .csv format neglecting the geometry attribute, taking advantage of the geocoding and indexing capabilities of the 'hex id' attribute. This index can be used for retrieving the geometry, resolution, hierarchy if needed. The integrated model is loaded in a pandas dataframe. First, for every entry in the model, a lookup operation is carried out to find the 'Firing Areas' appearing in the model, stored in the 'type' attribute. From now on, using those 'hex id' values that correspond to the 'Firing Areas' of the integrated model, an approximation is made to find an analogous radius of 250km in the integrated model, in the uniform resolution. Given that the area subdivision of the used DGGS is a hexagonal shape, as aforementioned hexagons have neighbors that are equidistant. In that way, the analysis of movement is simplified exploiting the property of hexagons to expand rings of neighbors approximating circles/radiuses. Using the native method provided by the DGGS framework used (h3) , *k-ring*, for grid traversal, the radius is translated into a number of rings traversal on the hexagonal grid. This method produces indices within a k distance (k rings) of the origin index. 0-ring is the origin index, ring-1 is the origin index plus all its neighbouring indices and so on.

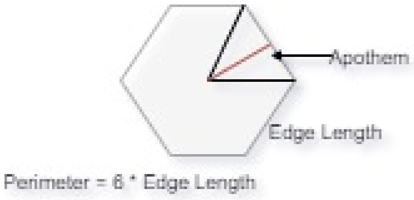


Figure 4.12.: Hexagon's geometric properties

Using the uniform resolution properties, the edge length of an average 8.54 km, and the hexagonal geometric properties (Figure 4.12), through calculations and error-trial, an analogous of a 15-ring range is found to be an optimal fit for an approximation of 250 km range, in the case study area. Back in the implementation flow, while having the indexes of the 'Firing Areas', those are applied as origin indices in *k-ring* operation of 15 rings, producing indices within this distance of the origin index. Then, for every neighbour, of each origin index the indices' attributes are retrieved and filtered to select the indices containing civil airports, either individual or aggregated in the uniform resolution (more than one). The result can be stored locally either in files preserving the rest information of the integrated model, or can be further used for extra querying or analysis. The results were exported in a .csv format to be used for visualisation purposes. The study can be further expanded, for providing the trajectory of a missile given as an input the start(base) and end(target) locations of the missile firing. The generated line's geometry can be quantized through an API and yield the sequence of DGGS cells of the military scene that describe the trajectory of the missile in a 2D projected approach. In the meantime, the same procedure can be done using native methods of the implementation, specifically using the *h3 line* method, that takes as input a starting and an ending DGGS index ('hex id') in a given resolution, returning the line of indices between them including the inputs. The line is drawn on the grid space and may not exactly correspond to arcs or Cartesian lines, introducing a distortion, however, given the uniform modelling resolution of the scene and the areal partitioning of the scene, this precision loss is acceptable. In parallel, the reverse is also available, using the method *h3 to line*, that takes as input a sequence of DGGS indexed cells and returns the line geometry in WGS84 coordinates as an sfc(simple feature) linestring geometry. In the meantime, for more accurate 2D trajectory DGGS cell sequences a finer modelling resolution can be selected on demand, based on the military scenario's positional accuracy requirements. Enriching the attribute structure model of the scene with an extra attribute used to store height values (apart from the terrain), the 2D trajectory can be augmented in a 2.5D approach, by quantizing a trajectory's prediction (X,Y,Z) values and passing them to the integrated model in the uniform resolution. The trajectory's sequence can be stored as a key/value pair of the participant DGGS cell indices with their according trajectory height values, similar with the terrain's 'elevation' values.

5. Results and analysis

This chapter is presenting the results and analysis. First, the different data format conversion results yielded by the quantization through the according APIs are presented. Several visualisations of the results are depicted, while after, an assessment over the quality of the conversions and the results is made. In addition, the integrated model results after the fusion of the different geospatial datasets is presented along with different visualisation approaches and analysis over the model and its potential use in a military application. Last, the results are of the conducted military case study using the integrated model of the military scene are presented and analysed.

5.1. Different data formats conversion results

Using the different developed APIs for the according data formats (point vector, polygon vector, raster), the mixed (military and civil) geospatial datasets were converted to a uniform global geospatial framework. Through this conversion, the use of a uniform geospatial framework was established, having the same CRS under the current military geospatial standards, to model the military scene of the research scope (study area - European region). The OGC abstract specification reports that a standard DGGS implementation should guarantee the transformation of cell addresses to other CRSs and vice versa. Different data formats transformed into the WGS84 system (EPSG:4326) used by NATO and in the region of scope, can be used and translated to this DGGS framework. This framework offers a multi-precision tiling of the globe, having a hierarchical architecture of linear indexes for data organization. Using the DGGS approach to manipulate data, various advantages are offered. The DGGS framework has the capability to approximate geo-features coming from the different data sources, as points, polygons or raster data and avoiding expensive geospatial operations using geometric calculations such as intersections, spatial joins and others. In parallel, offering multi-resolution tiling that is also hierarchically indexed can be used efficiently for data binning, aggregation operations and depending on the resolution structure, has satisfactory scaling behavior. Through the APIs, using the DGGS implementation (H3) the target shape of each different format gets coordinates, resolution and an indexing operation, transformed into the according cell of the DGGS. The basic operation that is carried out is the quantization operation. Through the quantization, sampled data values from the different sources are assigned into the according DGGS cells.

Different resolutions were exported for testing and conversion quality assessment and for testing the visualisation insight potential for a military approach. Multi-resolution representations were not explicitly stored in this implementation. However, individual resolution results are used for visualisation purposes (Figures 5.2, 5.3, 5.4).

For the point datasets of the military scene, due to the nature of their geometry, a classification of the point values based on their qualitative and quantitative attributes is not clear. For a military scene, that the area designation and classification is important, the insight of the analysis through visualisation or conduction of other type of analysis, would be beneficial as area-wise or regional scope. Using the DGGS framework, the behaviour of the grid representing the according point values binned into it in a specific resolution can be analysed. The DGGS application for the point datasets, offers a powerful aggregation capability, offering discrete grids of the modelled military scene representing the data insights of the points attached to them. This also offers a much more concrete visual insight when visualised, for military analysis of the scene. In parallel, aggregating in the DGGS framework is a more efficient approach and less computationally expensive from classifying point datasets, as distances for neighbouring points must be computed and classified to different groups. Of course, we cannot disregard the point datasets' precision importance and granularity aspects, however, given the different military analysis scales/map scales, an according resolution of the DGGS can be selected to perform analysis on. The finest representation for point spatial data, is yielded through quantization of the data at the DGGS framework resolution that best approximates the input's spatial uncertainty. Point vector data come with varying scales and positional uncertainties in conventional geographic data manipulation environments. Generally, given point vector datasets and the nature of DGGS, the extent of the modelling resolution cells can be used to model the extent of the original positional uncertainty, assisting in efficient storage of this factor. The margin of error after quantization in a specific resolution lies within the boundaries of the according resolution DGGS cell, based on the original spatial uncertainty (Figure 5.1). Moreover, point data representing data values to model a military scene, are only linked through their CRS and only if they share a common CRS. After conversion to the uniform DGGS framework the point data, translated into DGGS cells in a specific resolution are topologically related and are also geocoded and indexed offering hierarchical and neighbourhood relations.

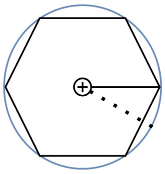


Figure 5.1.: The original positional uncertainty of point data can be used to define the modelling resolution under the DGGS framework

The same applies also for polygon vector datasets, that are converted through the DGGS quantization to a common framework to represent the military scene uniformly. This uniformity, in defined resolutions based on the scale of the analysis, eases the cooperation between the different military corpses (ground, air, navy) in joint operations, as it offers a common framework and CRS based on the NATO standards, to exploit their different data sources. However, the more complex geometries of the polygon vector data do not always yield optimal conversions to sufficiently represent the inputs. Here, the scale and spatial accuracy of the datasets are also relevant to reach an optimal representation of an area, in a DGGS cell partitioning. In the case of the polygons, the API using *polyfill*, fills the entire boundary of the input polygons in a specific resolution. The optimal fit resolution can be found and used through error and trial, however, to proceed to a military scene integrated model of a potentially coarser resolution, that resolution is used. Moreover, polygons, even though giving satisfactory and precise visual insight for a scene on a map, may reveal unwelcome, excessive information. On a military scene, multiple polygon data coming from different sources and in different standards, may have overlapping geometries that refer to the same region/area (Fig-

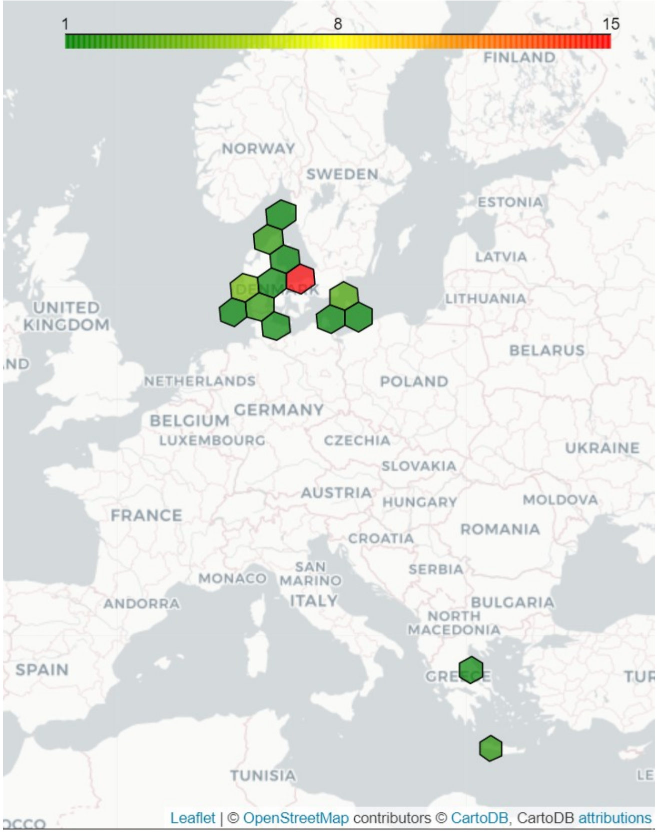


Figure 5.2.: Choropleth map with color gradient of the aggregated offshore military areas in the military scene of scope (DGGS resolution 3) - Background Leaflet/Openstreetmap

ure 5.5). This is also the case given the polygon dataset used in this research. Several offshore military areas were overlapping in same region having same or different area designation types. This is fixed both in the visual and in the computational aspect, as after conversion the DGGS resulting partitionings of the polygon areas are uniform, under the same framework and redundant information is removed. Duplicates are also fixed through aggregation on the same target cells of the DGGS framework. Furthermore, polygon manipulation and DGGS conversion is an important capability for a military commander operating on a military scene, as geo-fencing operations can be conducted on the fly. A geofence, a virtual perimeter for a real-world geographic area, can be generated. Then, using a polygon-to-DGGS conversion in a given resolution, that yields the DGGS cell partitioning, linking those generated data with already existing DGGS key/value pairs of polygons and other formats information regarding the military scene. Interactive maps in resolutions on demand are exported, offering also a tooltip capability, providing insight for the qualititative and quantitative information of each enmeshed DGGS cell geometry (Figure 5.6).

Raster datasets, are also a really important tool in the modelling of military scenes, as they form a continuous partition of the research area that they refer to (military scene). In this case, the raster utilised for the study area of scope (European region), contains values over the elevation of the terrain. Various raster values can be used apart from elevation, such as

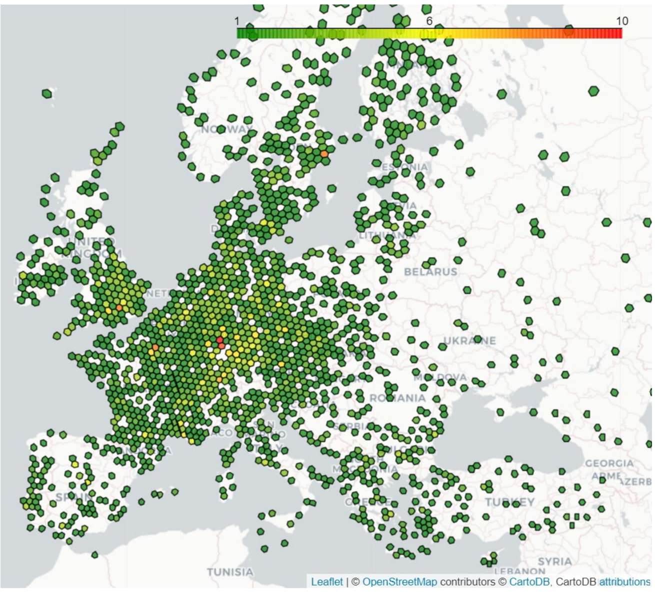


Figure 5.3.: Choropleth map with color gradient of the aggregated european civilian airports in the military scene of scope (DGGS resolution 4) - Background Leaflet/Openstreetmap

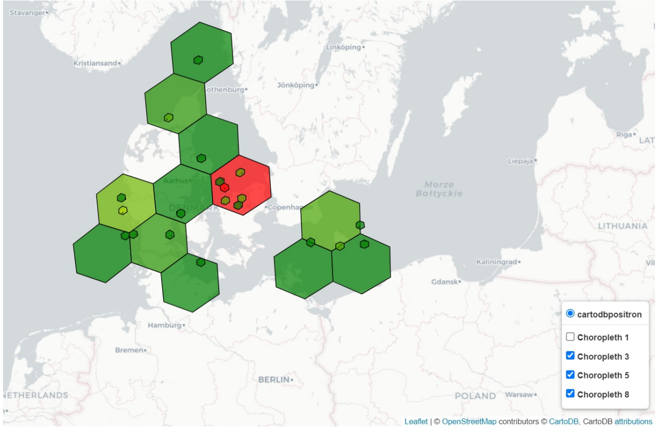


Figure 5.4.: Interactive Choropleth map with color gradient of the aggregated offshore military areas in part of the military scene of scope (DGGS resolutions 3-5-8), user can switch on/off the different resolution visualisations - Background Leaflet/Openstreetmap

color, intensity values in ground rasters or vessel density values in raster representing offshore areas, for military analysis. In addition, in the recent years the military makes use of satellite as well as drone imagery for purposes of field data collection (also GPS-powered), aerial/satellite reconnaissance. Apart from the one-off conversion of such imagery into the DGGS framework, representing each pixel in the raster as a DGGS cell based on the estimation of the modelling resolution according to the original raster resolution the are also other capabilities. Image processing for multi-spectral imagery can also be conducted before converting the raster data into the DGGS framework. Various well known indices for remote sensing (i.e. NDVI index), can be calculated given the underlying geometries of the DGGS

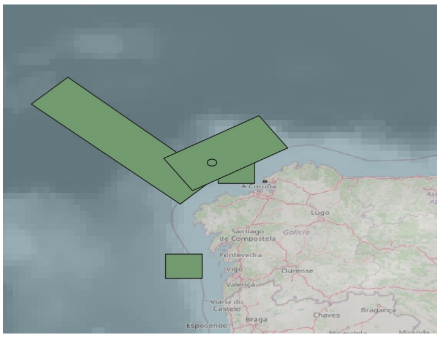
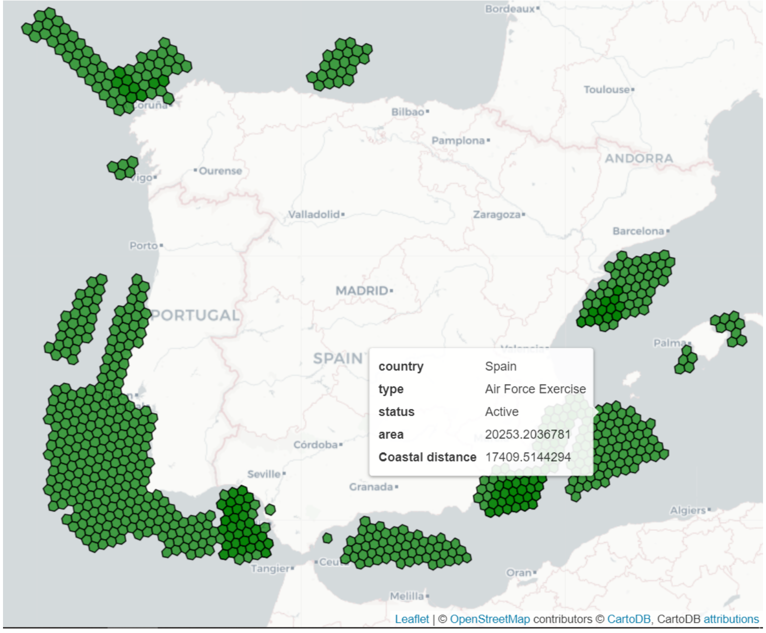


Figure 5.5.: Overlapping polygon vector offshore military areas in part of the military scene



country	Spain
type	Air Force Exercise
status	Active
area	20253.2036781
Coastal distance	17409.5144294

Figure 5.6.: Interactive map of the aggregated offshore military areas in part, Tooltip capability provided - Background Leaflet/Openstreetmap

cells grid of a scene, assisting in the characterisation of unknown areas. For large areas of coverage, the nature of the original satellite imagery may yield distortions while we move towards high latitude areas. In that context, the equal area nature of the DGGS framework can assist in disregarding those distortions, via the selection of an optimal modelling resolution.

For the scope of the research, the european region's terrain elevation values were preserved, while ignoring the values in offshore areas. By error and trial and using the raster primary resolution the quantization resolution is selected (resolution =5), to guarantee a continuous terrain representation, in the DGGS framework (Figure 5.7). In resolutions lower than then selected, gap areas appear. The DGGS model exported offers a terrain representation of the research scene, as key/value pairs of the indexing id and according elevation value. The value resampling method is always based on the nature of the data and application. In the case of the DGGS indexed cell elevation values of the terrain, a mean value is used. This strategy can also be changed based on the potential operation/application that the DGGS indexed raster will be used for modelling/analysing a military scene. Coarser resolution results can be yielded through aggregation/resampling across the new cell sizes as an analogous to a raster resampling. For the visualisation of large raster DGGS converted datasets the hexagon geometries in the applied resolutions is carried out using vector cells, introducing performance issues in rendering, for gradually incremented number of features. This is also an issue, for military scenes that form a wide area of coverage and high resolution rasters can be used for partitioning the scene. In such cases, the DGGS framework aggregation capabilities can assist in efficiency, offering a trade-off of sacrificing the data quality/precision in designated areas and offering rendering and analysis efficiency. In parallel, the use of a DGGS framework for terrain data storage and representation, can be realised through hierarchical storage, using the hierarchy of the DGGS framework (Dutton).

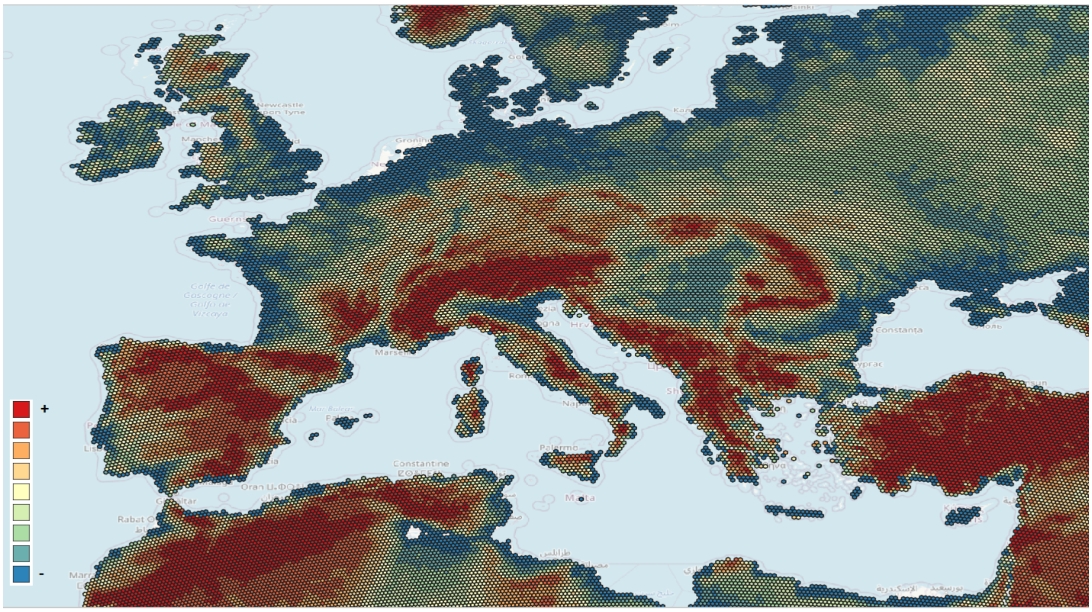


Figure 5.7.: Aggregated elevation value map of the military scene of scope (color gradient), in the DGGS framework (resolution 5)

5.2. Conversion quality

The conversion quality of the different datasets, to the applied DGGS framework is highly relevant with the spatial uncertainty and spatial resolution of the primary datasets. A trade-off between geometric coherence of the converted datasets and efficiency using the DGGS spatial indexing is introduced when having to integrate different data sources of different spatial uncertainties and geometric attributes. Several sources can provide different accuracy datasets to model a military scene and for each specific scenario, depending on the coverage of an operation different resolutions might be used to fuse the different sources and getting a satisfactory result.

Regarding the point datasets, vector points are the most precise and granular data formats, having a geometry providing the (X,Y) in a projected CRS or (longitude, latitude) in a geodesic CRS. The finest resolution(0) could be used for modelling the points, however, taking into consideration the study region and exploiting the aggregation properties of the implementation, a coarser resolution fits better. Moreover, in situations of large datasets, for efficiency and visualisation simplification, spatial aggregation into bin regions, grouping the complex point data would be optimal. Using the geocoding of the DGGS cell indices and neglecting the geometry attribute also provides efficiency in storage (Table 5.1). The primary datasets consisted of the military offshore areas (2 KB, 36 features) and the civilian airports (112 KB , 2846 features), point vector datasets in a .csv entry. The required storage space augments going into finer resolutions.

DGGS resolution	Military offshore areas		Civilian airports	
	.csv	.geojson	.csv	.geojson
1	0.8	2	46	63
2	0.9	2.9	48.8	110
3	1	5	58.5	271
4	1	7	78.7	607
5	1.15	7.82	93.3	850

Table 5.1.: Different DGGS resolution storage spaces of the military scene's point vector datasets (units: KBs)

Regarding the polygon DGGS converted dataset, the scale of the entry areas is an important factor to define the optimal modelling resolution. In addition, the area of coverage of the military scene is also important defining the satisfactory level of detail the polygonal areas can be converted into the uniform DGGS framework of a potential military scenario. The polygon data conversion can be evaluated by the level of geometric fidelity/coherence between the a-priori area and the a-posteriori DGGS partition in the different resolutions. The different hexagon areas per resolution can be accessed dynamically, using the DGGS implementation's native methods while in parallel the average hexagon lengths and areas are provided in the DGGS specification's resolution table. Depending on the military scene, the balance between accuracy around the polygon edges to be filled and the amount of memory and processing required, an optimal resolution can be selected (Figure 5.8). Again the geometry can be neglected, however , a polygon area entry can yield several polygonal DGGS cells forming its partition, employing larger amount of storage space. On the other hand, for a military scene analysis the segmentation of a polygonal area would be beneficial, as the area will no longer be treated as an individual feature and several sub-regions could be used in analysis on demand. In parallel, each sub-region will still be attached to the uniform DGGS framework and topological links will be offered not only for the primary polygonal area but also for different geometric features (with their according qualitative and quantitative values) attached to the same model. In the case of the military scene of the research, due to the large area of coverage in a regional level (Europe) and aiming to have an integrated model of uniform accuracy/resolution, resolution 5 was selected as aforementioned. In the selected resolution, the primary polygon .geojson dataset is 635 KB with 227 features while the converted to DGGS .geojson is 628 KB with 1559 features, showing a storage balance. In the DGGS converted polygon dataset the geometries of the features are simpler, while duplicates/overlaps are settled. A conversion to the next finer resolution (=6) yields a much more storage dependent .geosjon file of 4.3 MB, consisting of a lot more DGGS cell geometries.

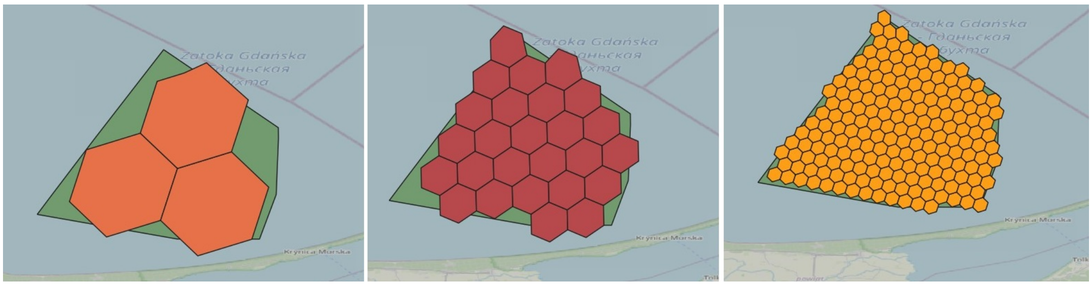


Figure 5.8.: DGGS cell partitions of an offshore military polygonal area in different resolutions (5-6-7)

Regarding the raster dataset having elevation values, as aforementioned, the resolution of the quantization into the DGGS framework is selected as the nearest one to the primary original raster's resolution. In parallel, given the military scene study area (European region) the resolution was selected to optimally approximate the European region's shape and represent ground elevation values, not including offshore areas with elevation values. The selected uniform resolution (=5) (Figure 5.7), yields a total of 53751 features (DGGS cells) with aggregated (mean sampling method per cell) elevation values of the military scene. The formed partition offers a continuous terrain with elevation values as key/value pairs in every according DGGS cell area. This approach is a 2.5D (two-and-a-half dimensional or pseudo-3D) Digital Elevation model (DEM), simulating the appearance of the scene being three-dimensional, in a 2D graphical projection. In other words, in the continuous terrain formed by the partition of DGGS cells of the scene, each location (DGGS cell area) is assigned to only one height h. This is similar to a raster digital elevation model, using a different shape subdivision (hexagonal in this case). The more accurate and high resolution the original raster is given, the more accurate and realistic the military scene elevation model based on the DGGS will be, forming finer DGGS cells of small average hexagon areas. Resolution 4, being coarser does not yield optimal geometric results, as it distorts the military scene's ground shape, striving to larger area DGGS cells. In parallel, the aggregation up-sampling to this resolution was avoided to have as much accurate as possible elevation values in the smallest DGGS cell areas possible. Striving to the finer resolution (=6), being also closer to the original raster's resolution, the conversion yields gap areas not containing elevation values, due to the different space filling of the hexagonal shape DGGS and the original raster's rectangular projected structure (Figure 5.10). In parallel, while the resolution 5 result yields a 1.3 MB .csv file of 53751 DGGS cells, the resolution 6 result yields a 4.6 MB file of 205848 DGGS cells, consuming more storage while not offering a continuous terrain representation of the military scene. The pure raster conversion timings are satisfactory given an original cleaned raster (excluding offshore regions) of 218542 cell data values (Figure 5.9), which is an important factor for handling large datasets as rasters and converting them into the DGGS framework.

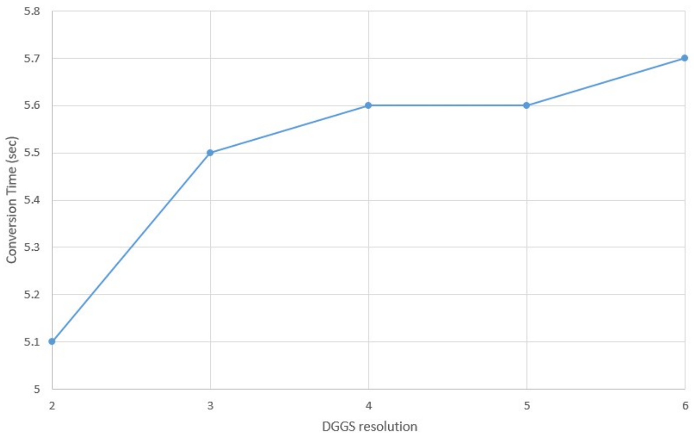


Figure 5.9.: Raster DGGS conversion timings per different resolutions

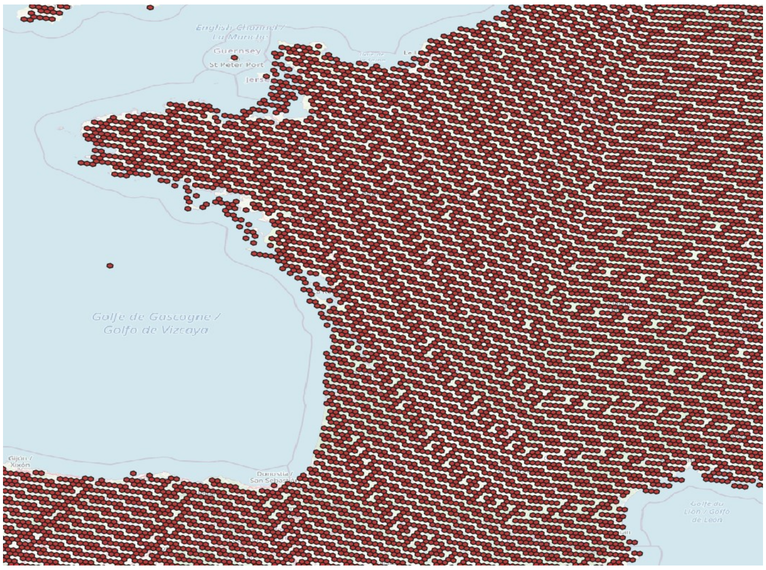


Figure 5.10.: Elevation value DGGS cells in part of the military scene of scope, (resolution 6)

5.3. Integrated model

The different data formats from different sources of the military scene are integrated under the uniform DGGS framework, into the final integrated model. In this case, both vector (point and polygon) and raster formats (offering elevation values over the scene) are utilised. The different formats came from different stakeholders. While the military offshore areas come from various Navy corpses of NATO within the EU, the raster elevation dataset and the transport network dataset come from civilian, hybrid stakeholders. The datasets deploy different standards, different CRSs and are offered in different resolutions/scales, not subserving the geospatial cooperation and communication between the stakeholders. This scene can be compared with a joint civilian - military operation scene, modelled to perform geospatial analysis over an operational scenario, exploiting the different datasets from the multiple stakeholders.

The integrated model is stored in the military purpose database and is also exported in a .csv file for distribution to other platforms and/or conversion to other formats including the geometry, for visualisation and analysis purposes. Visual interpretations of the military scene model are available in Github, in the following repository: (`https://github.com/tpapakostas/Military_scene_model`). The final integrated model, represents the military scene of scope (European region), and contains both qualitative and quantitative values characterising the different equal area DGGS cells. The model exported in a .csv file, integrated in resolution 5 of the DGGS framework is employing 1.71 MB of storage space containing 55184 features, in the given final attribute structure model. Geometry is not included exploiting the indexing mechanism of the DGGS framework. The original primary datasets used to construct this model are employing approximately 1.6 MB offering a storage balance, in case the integrated model should be stored locally for analysis. The final model is slightly larger, however the DGGS framework can be used for simple operations on source without having to store the integrated datasets. Eitherway, the integrated model is stored in the database as a whole and individually per converted dataset, offering a centralised geospatial data manipulation capability, regarding the military scene.

Given the integrated model of the military scene, the operational area, is now modelled uniformly, under a common geospatial framework, using the same CRS according to the military standards and segmented in equal domains/DGGS cells that can equally contribute in a potential analysis of the scene. The different datasets used and integrated into the military scene, are no longer discrete datasets as vector and raster datasets that do not support straightforward connectivity between objects in the scene. As parts of the integrated model, they are parts of a unified topologically linked model of the scene. The DGGS capabilities offer hierarchical and neighbourhood connectivity between the model's cells. In parallel, the areal segmentation offered, is an important aspect, given the importance of the area designation in military scenes and military geospatial operations. Utilising geospatial data from different sources, in joint military operations or in joint civilian - military operations is made easier using this uniform DGGS model, augmenting the cooperation and communication between the stakeholders. All the engaged geospatial datasets are now represented as a continuous geography of the modelled scene in contrast with the different discrete thematic original datasets.

In the military scene of research the 2D datasets used represent both ground and offshore areas, while the raster dataset, provides elevation values, striving for a 2.5D approach representation of the scene in a continuous manner. The military scene of scope is visualised under the 2.5D approach (two-and-a-half dimensional or pseudo-3D), using a 2D graphical projection to simulate a three-dimensional appearance. Specifically, the 2.5D model, offers third dimension information (elevation values) in discrete areas (elevation value of each DGGS cell). Third dimension elevation values are modelled on the center of each DGGS cell and represent a uniform elevation for each DGGS cell. The finer the DGGS resolution, the better quality this DGGS 2.5D digital elevation model will be (Figure 5.11). The elevation values of the military scene, refer to the ground terrain geometric heights per DGGS cell (hexagon) in the WGS84 CRS, as modelled to fit the military standards, in the uniform modelling resolution of the scene. A realistic and interactive representation of the scene is given by extruding the DGGS cells' geometries according to their elevation values (Figure 5.12), offering intuitive understanding of the terrain of the scene and potentially assisting in decision making. In parallel, tooltip capabilities offer extra visual insight for the military scene's dynamic state, offering also the indexing ids info along with the integrated numerical and categorical info from each integrated dataset, both in ground and offshore areas (Figure 5.13).

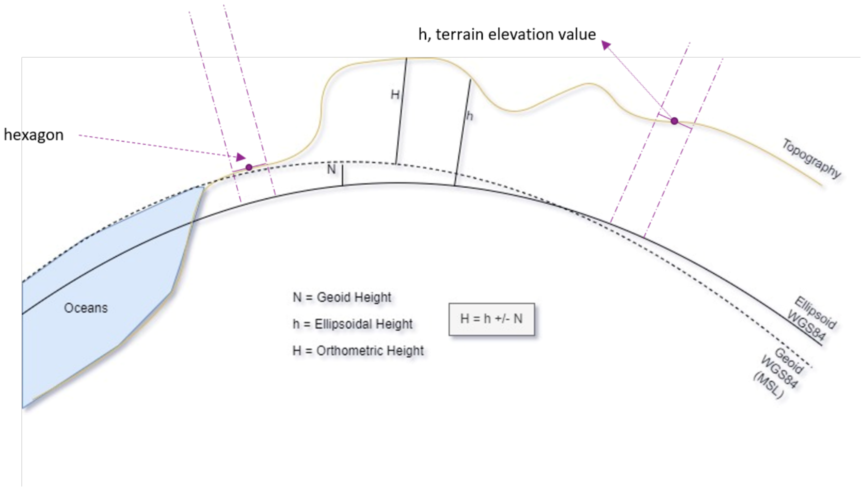


Figure 5.11.: Horizontal alignment view - 2.5D approach of the integrated model, terrain elevation values

In the military scene, modelled using the DGGS framework, the topology is defined in the cell navigation objects, using the referencing method of the DGGS structure. The hierarchical based DGGS cell indices ('hex id' stored in the integrated model) carry information allowing navigation between hierarchical links (parent - child resolutions) as well as neighbourhood links (neighbouring cells). Given the hexagonal partitioning of the applied DGGS, the uniform adjacency property is also an important aspect, for spatial movement analysis of the military scene. In parallel, the different DGGS cells include the fused information from the multiple resources, relevant with the scene. Geospatial operations such as radius look-ups, intersections, containment, overlaps for military operational scenarios can be carried out using the DGGS framework's connectivity of the cells in the military area. A trade-off is introduced here, regarding the spatial accuracy of the operations, after the quantization of the geometric spatial objects into the DGGS framework. The quality of the results is highly relevant with the accuracy of the original spatial data and the selected modelling resolution into the DGGS. The DGGS application must be wisely used to fulfill the military scenario's accuracy requirements for a defined area of coverage. Moreover, terrain analysis can be conducted using the integrated model of the scene, utilising the height information by developing algorithms based on the adjacency of the DGGS cells, that are hexagons in this case.

Furthermore, the visual representation as well as the efficiency in calculation and storage is augmented through the spatial aggregation of the different data sources into bin regions of the military scene. This also allows for classification and categorisation of the different com-

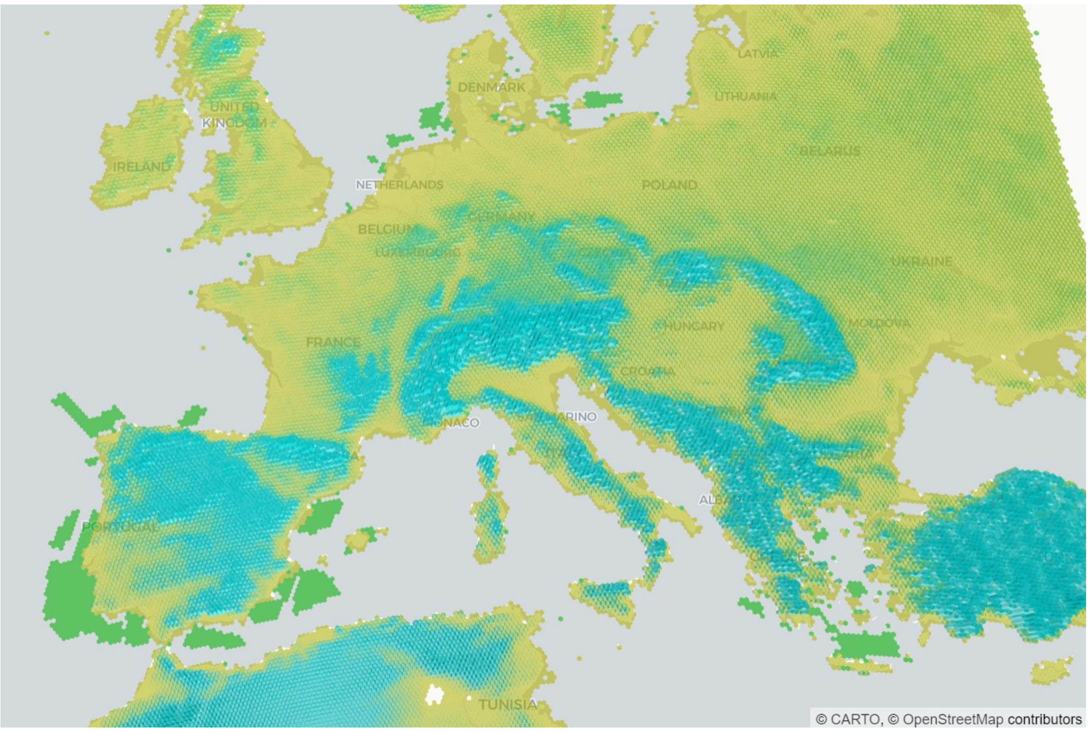
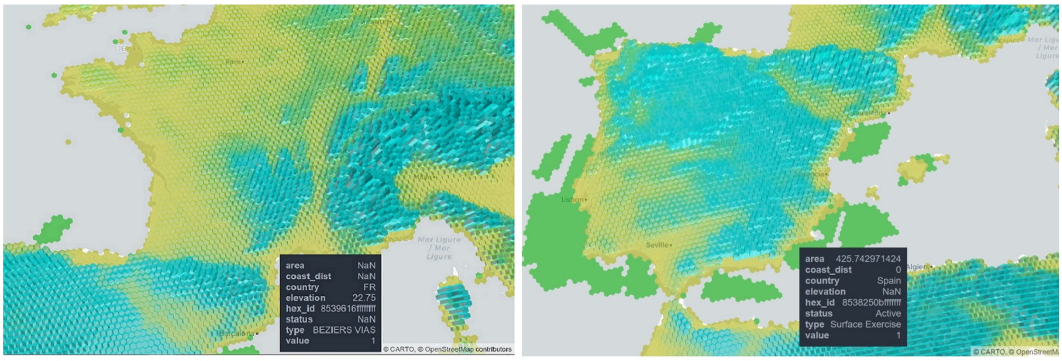


Figure 5.12.: Interactive realistic 2.5D representation of the military scene, Integrated model - Background CARTO/Openstreetmap, visualised using *pydeck*



area	NaN
coast_dist	NaN
country	FR
elevation	22.75
hex_id	8539616ffffffff
status	NaN
type	BEZIERS VIAS
value	1

area	425.742971424
coast_dist	0
country	Spain
elevation	NaN
hex_id	8538250bfffffff
status	Active
type	Surface Exercise
value	1

Figure 5.13.: Tooltip capabilities in ground and offshore areas of the military scene - Interactive realistic 2.5D representation, Integrated model - Background CARTO/Openstreetmap, visualised using *pydeck*

plex data (military and non military) engaging in the integrated model. While the variable resolution is reduced for certain datasets, the complexity in calculations is also reduced for feature creation, transformation, extraction and selection through the different DGGS cells modelling the military scene. For polygon primary data, as aforementioned, the segmentation of the original data into the military scene, offers the capability to exploit the different modelled sub-regions enriched with categorical and numerical values in analysis, instead of using the discrete geometric properties of the primary polygon. In parallel, if the DGGS cells of the integrated military scene model are treated as a set, a Dijkstra's shortest path algorithm can be used, computing the shortest path (given the appropriate constraints for each DGGS cell) the different centroids of the military scene grid (Purss et al., 2019).

The integrated model of the military scene is also stored in the database. Through this, efficient storage is allowed neglecting the geometric properties and relying on the enriched information provided by the DGGS indexing. The different converted datasets are stored both individually and integrated into the database. Each data entry in the integrated model stored as a table in the database, follows the defined attribute data structure architecture (Figure 5.14). Loading the point vector DGGS converted datasets into the database takes 123ms. The DGGS indexed polygons take 61ms while the DGGS indexed raster data takes 533ms. The selection query yielding the integrated model based on the different DGGS converted different tables, takes 916ms, while creating the integrated model's table based on this selection takes 868ms. Generally, the nature of the datasets as well as the limited amount of records does not allow for drawing satisfactory conclusions over the performance of the data that were converted into the database. The integrated model was also exported as a .csv file and loaded into the database as a new table, taking 580ms, offering a fast storage of the 55184 feature integrated model of the scene. Queries based on the integrated model converted into the database are fast, also due to the simplicity of the data model. All attributes are integrated to one record with their according hexagon id. This yields a lot of empty values for specific attributes. Through database normalisation, exploiting the relational model of the different format DGGS converted stored in the database, data redundancy can be reduced. For instance, in a potential query linking polygon DGGS converted data with elevation values given in the raster elevation DGGS converted data, the join can be executed on demand for explicitly defined attributes, avoiding null/empty values. The extra integration into an integrated model, can be avoided, performing spatial analyses and operations using the individual tables with the different DGGS converted datasets, exploiting the unique identifiers of each data entry that explicitly refers to a unique geographic region (DGGS cell). It should be mentioned, that the complete pipeline offering the result of non-DGGS raw data conversion to DGGS up until reaching a visualisation is conducted in individual steps, hence the many ad hoc file conversions. First, is the DGGS conversion of the data referring to the military scene of research, using a uniform modelling resolution via APIs and exploring the different output files' properties. Second, the storage in common data structures (files) and in the database, given a custom attribute data model. Then, the current distributed visualisation alternatives are explored, mostly based on vector representations, commonly used in military geospatial applications to sustain the interoperability. This venture, depending on the modelling resolution, shows performance/rendering issues proportional to the quantity of features and respective attributes that are visualised. For instance, using the digital globe representation in *globegl*, shows performance issues when rendering increasing resolution features of the scene.

	hex_id character varying	country text	status text	type text	area double precision	coast_dist double precision	elevation double precision	value bigint
1	851f06abfffffff	Germany	Unknown	National Defense Area;Firing Area	506.796527807	0	-7	2

Figure 5.14.: In-database integrated model's table data entry, PostgreSQL database

The DGGS indexed entries of the integrated model stored in the database, provide a centralised storage architecture of the military scene. The military scene's categorical, numerical values and location indexing is stored in the database, avoiding redundant storage of geometry. The scene is stored as a uniform model, under the same framework and contains the info coming from different formats and different sources. In cases of different formats and different standards, in-database table communication and communication with other databases containing other military data is inefficient, while now data distribution can be enhanced by using DGGS indexed models or by converting data to DGGS indexed models. In the meantime, the capability to update, retrieve, edit, delete data entries regarding the military scene is offered. Querying capabilities of data can become more efficient based on the locations, utilising the indexing mechanism of the DGGS model of the scene. Common database techniques can be applied using the integrated model, without the need of spatial extensions to manipulate the different format spatial data. A military commander, can perform queries based on the various values of the integrated model, either in-database or using a connection with other platforms, to gain insight about the scene and/or conduct test cases or analysis scenarios, to assist in desicion making. In addition, the centralised database allows for dynamic enrichment of the military scene's model, through for instance, geofencing or reverse geocoding of geospatial data converted into the uniform DGGS framework. Those data can come from various stakeholders, as open source geospatial data, public/private provided data or geospatial data coming from military geodatabases and/or military datasets.

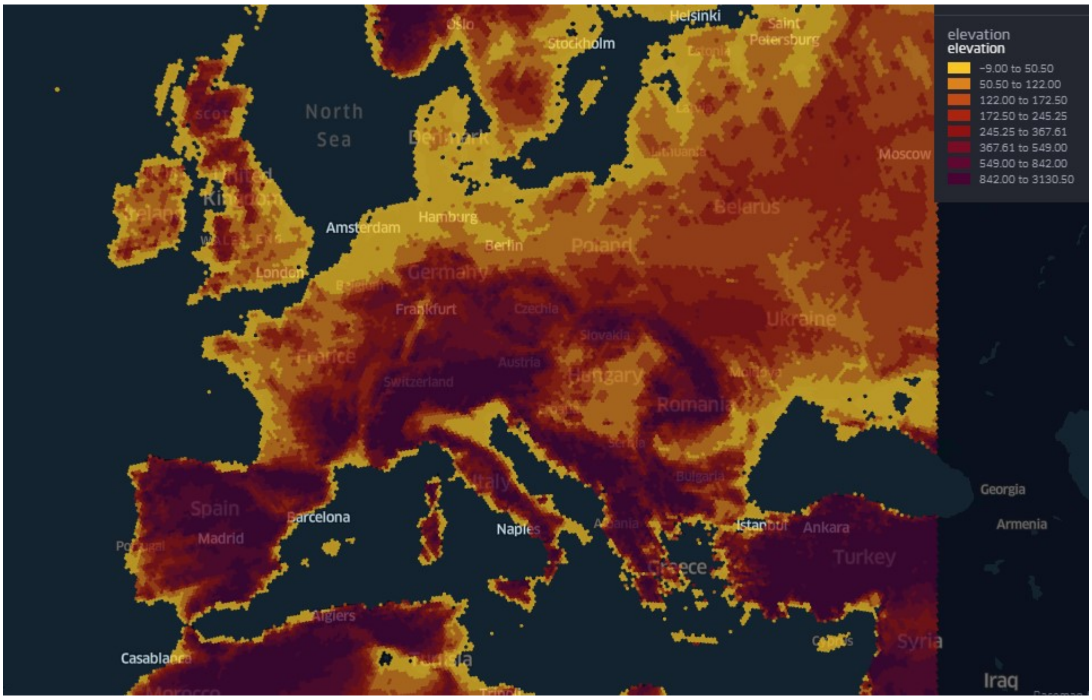


Figure 5.15.: Choropleth map of the military scene (Integrated model) based on the elevation values of the DGGS cells - generated in *keplergl*

Apart from the database, the integrated model can be stored in .csv files for efficient storage neglecting the geometry and allowing satisfactory dissemination to other platforms and systems. Converting the model of the scene to formats encoding also geometry structures (i.e. a .geosjon) format, also containing the relevant attributes of each DGGS cell, can be beneficial for using the military scene model in external commercial and/or open source platforms. The model can be loaded in commercial/open source GIS platforms (QGis, FME) or online tools/ web components, harnessing the variety of visualisation, data query and filtering capabilities, for gaining geospatial insight and conducting analyses of the military scene on demand. Given the military scene, a choropleth map based on the elevation values of each DGGS cell of the military scene is generated in *keplergl* (Figure 5.15). In a different scenario, the military commander can request for the civilian airport locations of the scene in a specific region (i.e. France) (Figure 5.16). The according DGGS cells also contain several other attribute regarding the scene that can be further used and either way, tooltip capabilities can enlighten the user regarding specific details. Different background base maps can be used per case. Apart from using 2D projected base map backgrounds, the integrated model of the military scene can also be superimposed on a digital globe (Figure 5.17), using the *globegl* web component via a .geojson format, encapsulating the DGGS cell geometries.

hex_id 853963b3fffffff
country FR
status
type LEZIGNAN-CORBIERES
area
elevation 78.8

Figure 5.16.: Civilian airport locations in France, sub-region of the military scene, aggregated in the uniform resolution, tooltip capabilities (Satellite map background) - generated in *keplergl*

When modelling military scenes, the DGGS structure is offered as a useful geospatial framework, having an underlying CRS and a global nature set of discrete cells, for the integration, analysis and manipulation of geospatial military data. Upon a certain level of granularity, given the existing distributed implementations' offered resolutions, DGGS can serve as a reference frame, offering a discrete area based cell grid. Given the underlying CRS, if the data used are modelled in the finest possible resolution based on their spatial uncertainty the DGGS area cells can sufficiently encapsulate the positional information of the used data as a reference frame. Each cell represents a discrete area and a point (DGGS cell centroid). In

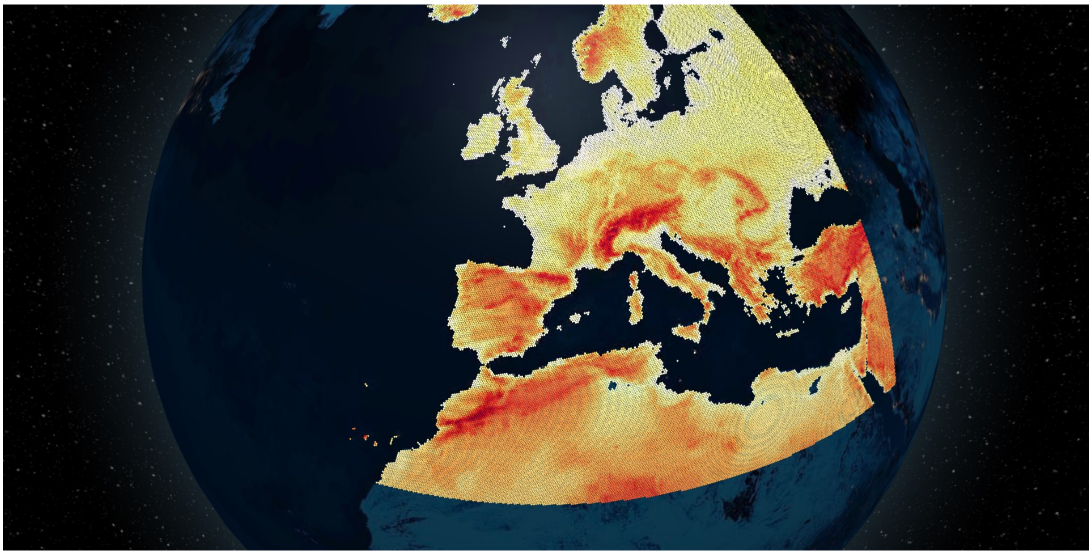


Figure 5.17.: Color gradient visualisation based on elevation values of the integrated model on a digital globe - generated in *globegl*

this research, the used implementation is offering a finest resolution of below 1m2 area cell, covering the globe with a grid of (less than 1m2) hexagonal area cells. Given the nature of DGGS the selected modelling resolution can serve as the unit of accuracy/spatial uncertainty of the modelled geodata representing locations. For example, given a GPS observation point, which is widely used in military operations, having a spatial uncertainty of 1-5m, it can be correctly modelled into the finest resolution. This is also plausible with different geodata formats (polygons, raster), encapsulating observation positional uncertainty. For military large or medium coverage operations, the submeter margin of error displacement is considered to be insignificant and will not vitally affect a potential analysis outcome. This venture is also appropriate for elevation information, as shown in this research, using the DGGS framework and offering a 2.5D approach based on the underlying CRS, offering the vertical datum's properties. Similarly, subterrain height values can also be modelled given this approach.

However, the DGGS discrete nature, being a set of discrete cells across the globe cannot supersede the conventional data models level of detail and accuracy. The quantization of data into the DGGS framework yields precision and geometric errors, making it still inappropriate to serve as a reference frame. This framework though can be powerful for the integration of the different data models, offering geospatial analysis tools and capabilities and also serves as a promising cartographic and visualisation mechanism with varying resolutions and a global uniform nature. For varying area of coverage military scenes, the DGGS nature, being equal area based and global assists in reducing distortions. Treating each different DGGS cell as a local reference frame for demanding submeter resolutions, still cannot be used neglecting the original coordinates due to orientation definition problems. However, the DGGS cell index can still be used as a geocoding tag, fusing the original data with a uniform DGGS framework. Exploiting the hierarchical structure and the neighborhood connectivity offered by the DGGS, a military scene can be represented as a congruent geography, enriched with the different spatial observations and offering distance calculations between locations in both absolute and logical ways. Modelling the geodata according to their respective spatial uncertainties in a specific resolution, absolute distances can be calculated. Such distances are calculated as haversin distances between two locations (cell centroids) modelled in according DGGS cells, based on the globe surface given the undelying geocentric CRS used. The error in the calculations can be acceptable given the original spatial uncertainty and the military operational accuracy requirements. In parallel, for military geospatial analyses, requiring the engagement of concepts like vicinity, neighbourhood, spatial movement (i.e. movement analysis, military ranging operations, movement of troops/militia/artillery), the distance between two locations can also be interpreted as a ring-distance between two DGGS cells in a specific resolution, signifying connceptual proximity based on the military scenario's constraints by setting logical and numerical thresholds. In that context, the military case study conducted, treats a 250km distance as a 15-ring distance in a specific resolution of the modelled military scene. Further, as a geospatial aggregation mechanism, given each time the military scenario accuracy requirements, the DGGS framework can be a robust analysis and visualisation tool for military SA of a scene.

Additionally, exploiting the DGGS framework's nature, several area characterisation operations over the military scene can be carried out. The DGGS cell's connectivity links can be exploited to yield buffer zones or exclusion zones in regions of the scene on demand, as well as territory borders or operational and influence area definitions. The DGGS integrated model, can also be used for point location and navigation purposes as an analogous to MGRS, the geocoordinate standard currently used by NATO. MGRS is offering geocodes of a 1m precision level at best, while the utilised DGGS framework of this research, offers DGGS cell indices with an area of less than 1 m2, for a coordinate pair modelled in the finest resolution. The MGRS offers a variety of 7 different precision levels, while most of the different operating DGGS offer a wider variety of modelling resolutions. Moreover, enriching the attribute structure model according to extra location enriched military data (i.e. military infrastructure locations, state), the monitoring of military infrastructure of the scene can be possible, modelled into the uniform framework. Further, the integrated model can be exploited by military geospatial specialists, offering a uniform data structure representing the military scene, as a geospatial background embedded to a C3I system, encapsulating multiple qualitative and quantitative data reinforced with strong spatial connectivity links. In that way, the C3I operating system can be reinforced with multilevel data over a scene assisting for more precise, data driven decision and support applications. An integrated model of a scene offered in a DGGS framework and exploiting this data structure's nature also enhances the concept of common operational picture (COP), as a "centralized information display system", as well as a model of the scene to conduct analysis on. Through this integration, the cooperation and geospatial communication in joint military or joint civil military operations can be enhanced and their individual intelligence capabilities can be equally exploited, augmenting the SA over a scene.

5.4. Military case study results

The military case study attempts to imitate a military joint intelligence operation integrating Ground, Air and Navy Forces at a designated area of coverage and a common area of operations. As an operational geospatial application, the multidisciplinary communication, data integration, data standardization and common geospatial framework is of great significance. In the military scene of scope, the different pieces of geospatial information come from different stakeholders. The military offshore areas come from various Navy corpses of NATO within the EU. The raster elevation dataset and the transport network dataset come from civilian, hybrid stakeholders, also signyfying the potential engagement of civilian, non military data and intelligence. The datasets deploy different standards, different CRSs and are offered in different resolutions/scales, not subserving the geospatial cooperation and communication between the stakeholders. The operational scenario refers to the detection of potential civilian airports that can be potentially affected from a missile firing of 250km range as a first analysis phase. After that, given the integrated model of the scene using the DGGS approach, the scene's model can be exploited to yield potential missile trajectories predictions on demand, in the region of scope, offering the uniform framework for the cooperation of the engaging stakeholders.

The ranging operation refers to the detection of the civilian airport domains (parts of the DGGS model of the scene), that are potentially affected from a missile firing of 250km range. The case study was conducted only using the DGGS framework capabilities of the integrated model of the military scene, trying to avoid potentially expensive geometric calculations to perform the same operation. Such operations would include haversine distance calculations, geometry intersection/overlap tests and would need different approaches for each different geometry type. Instead, the case study performs the radius lookup of the ranging, approximating circles as k-rings of neighboring DGGS cells, using the uniform DGGS framework of the military scene, as described in the implementation chapter. For a similar case study in higher resolution/scale, depending on the available data accuracy, the model is expected to have a similar behavior, given the available modelling resolutions offered by the implementation. For instance, having a high resolution raster with elevation values and high accuracy polygon and point vector data over a smaller subregion of the scene the case study operations could be executed similarly. In parallel, exploiting the DGGS multi-resolution nature, aggregation could be executed on demand yielding coarser DGGS cells in less important regions of a larger coverage and the finest modelling resolution can be applied in the important subregions of the target areas. The approach given in this model can serve as a Digital Terrain model and also be exploited for modelling subterrain values or bathymetric values in defined resolutions, but is not fully 3D. It cannot serve as a Digital Surface model offering information over buildings and artificial obstructions for analysis. Such obstructions can only be drapped in visualisation environments over the DGGS cell grids for visualisation purposes.

The case study takes approximately 6 minutes of runtime, while the capability to export the results on a .csv file for further use takes an extra second. The runtime is not considered to be optimal for a real time scenario, however is acceptable, in cases of preliminary analysis.The case study's results show that out of the total 198 DGGS cell areas designated as 'Firing Areas' in the military scene, a total number of 495 DGGS cell areas, are potentially affected by a missile firing of 250km range. Conceptually, flattening the aggregated civilian airport locations of the integrated model, a total of 533 civilian European airports are potentially affected, being the 18,7 per cent of the total civilian airports (2847) engaging in the military scene. The results can be visualised and further analysed in a GIS platform (i.e. QGis) (Figure 5.18), as well as fused into the interactive realistic 2.5D representation of the military scene, providing tooltip capabilities (Figure 5.19), offering an intuitive representation for the analysis of the military scene, based on the data driven results.

Most of the potentially affected areas are close to coastal areas of the scene, due to the fact that the 'Firing Areas' of the integrated model, are located in offshore designated military zones. Those results show that a 250km range missile cannot decisively approach locations deep in the mainland of the military scene (European region), given of course the available military data utilised in this research. Furthermore, according to the geographic locations of

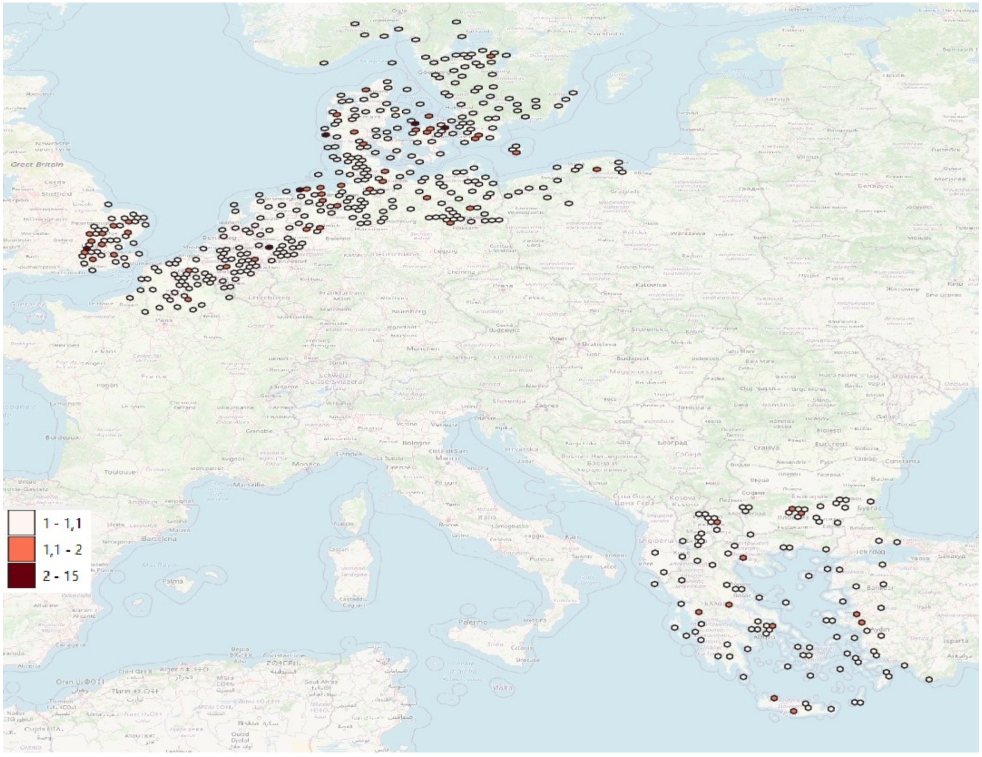
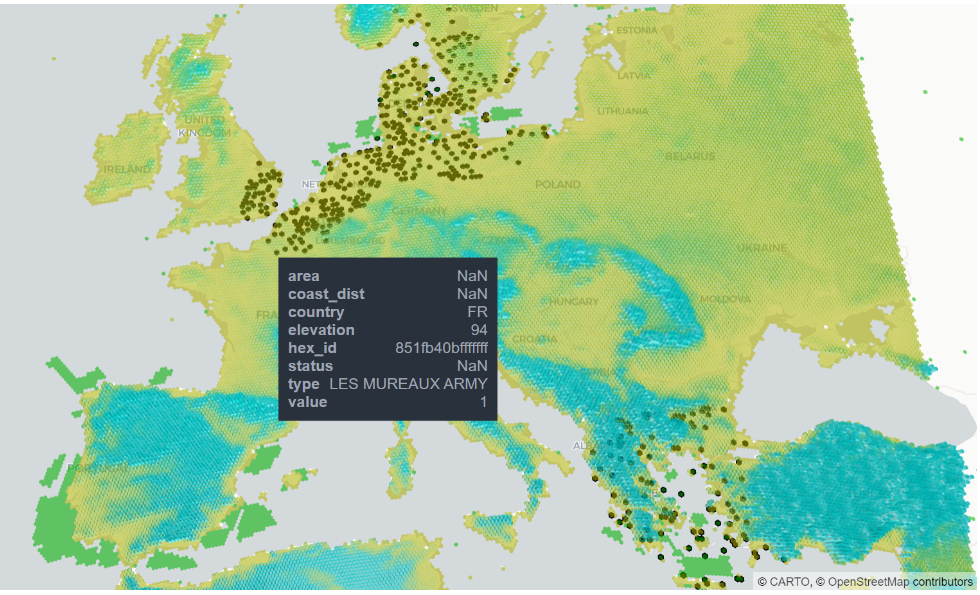


Figure 5.18.: Potentially affected DGGS cell areas containing civilian airports, within a 250km range of a missile firing coming from the 'Firing Areas' of the military scene, (color gradient based on the aggregated total number of airports) - visualised in QGis on an OpenStreetmap background

the 'Firing Areas', the missile firing affected locations are mainly distributed in two different zones. On the one hand, the Aegean sea affecting multiple civilian airports in Greece, Turkey, and southern Balkans.

On the other hand, in a wide area of both the North and Baltic sea, affecting civilian airports in the northwest parts of France, northern parts of Belgium, Netherlands, Germany, the whole Denmark, northern parts of Poland and southern parts of Norway and Sweden. While the approach of the case study, introduces a precision distortion on location distances and is depending on an approximation, given the area coverage of the scene and the area-oriented importance of the locations, this does not pose a great significance. The margin of error, potentially causing the miss of individual DGGS cell values, can be backed up by augmenting the number of k-rings of neighboring cells in the lookup.

The DGGS approach for modelling this scene, offers the analysis of the scenario without the use of GIS technologies and only exploiting the framework's spatial properties. In parallel, the military scene is modelled as a congruent geography, not in discrete thematic layers, while the geospatial data that are used are integrated under the common framework. This framework also gives the commander of the joint scenario a "common operational picture"(COP), unifying the standards and data models, to conduct the analysis for operational and tactical commander service, combining the individual intelligence capabilities of each stakeholder



area	NaN
coast_dist	NaN
country	FR
elevation	94
hex_id	851fb40bfffffff
status	NaN
type	LES MUREAUX ARMY
value	1

Figure 5.19.: Potentially affected DGGS cell areas containing civilian airports, within a 250km range of a missile firing coming from the 'Firing Areas' of the military scene, fused into the interactive realistic 2.5D representation of the military scene, tooltip capability provided - Background CARTO/Openstreetmap, visualised using pydeck

and increasing the data driven SA over the military scene. The distance ranging perception is improved as the common operational area is explicitly defined. In parallel, the detection of potential targets or exclusion regions is improved, given the scene's DGGS model centralised data retrieval and display system. As a product of the integration of the data and intelligence, this would potentially increase speed and efficiency of operational tasks and decision making.

Expanding the case study, as explained in the implementation chapter, given a trajectory prediction model equation describing the (X or longitude, Y or latitude, Z or geometric height) values across a trajectory line, the trajectory can be generated as a sequence of DGGS cells of the integrated model. Coordinate pair values (longitude,latitude) in the WGS84 CRS, being the current standard used in NATO, can be sampled to create a line geometry, giving as an input the start (base) and end (target) locations. Then, this geometry can be quantized through an API into the framework's uniform resolution, yielding the sequence of DGGS cells that describe the trajectory, in a 2D projected approach. Moreover, the cell sequence of a line between two DGGS cells of the scene as an analogous to a trajectory, can be given using the native methods of the DGGS framework. The input (start (base) and end (target) locations) should be given as DGGS indices of the scene. In the case coordinate pairs are provided, those should be first geocoded into the desirable resolution, conventionally (Figure 5.20).

In order to strive for a 2.5D approach of a trajectory, exploiting the integrated model of the scene, the attribute structure model of the scene should be enriched with an extra attribute, offered for the storage of height values of the trajectory. In that manner, the trajectory equation values can be fully exploited (X,Y,Z) and quantized into the uniform resolution of the model. The sequence of DGGS cells describing the trajectory, can be stored as a key/value pair set, associating the height values data objects with the corresponding DGGS cell indices.

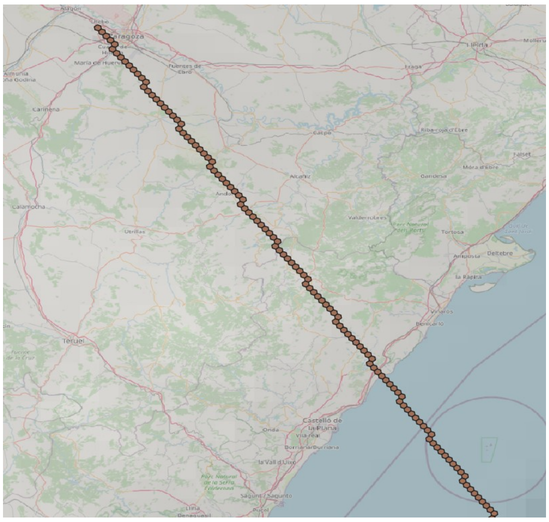


Figure 5.20.: A 2D trajectory expressed as a DGGS cell sequence of the integrated model

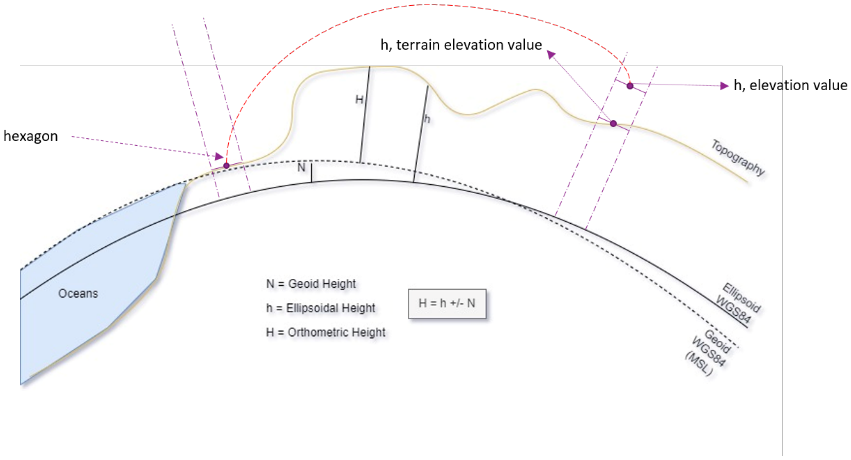


Figure 5.21.: Horizontal alignment view - 2.5D approach of the integrated model, terrain and trajectory elevation values

The terrain elevation values are modelled on the center of each DGGS cell and represent a uniform elevation for each DGGS cell as geometric heights in the WGS84 CRS. The trajectory's elevation values can be stored as absolute geometric heights in WGS84 CRS, or relevant to the terrain geometric heights in each according DGGS cell.

For such a class of operations, the capability to perform analysis and predict potential results for the outcome of actions is important for military applications. The centralised system of the scene through the DGGS integration augments the cooperation and operational tempo when a joint action should be made, based on the predicted alternatives. Furthermore, the analysis results can be realistically visualised, offering the intuitive representation of the common operational area of coverage. A potential trajectory though, modelled as a sequence of DGGS cell locations, is more that a geometric aspect. Every part (DGGS cell) of the trajectory, modelled in a defined resolution based on the scenario's requirements carries the according semantic, qualitative and quantitative information of the locations it crosses. This can also be exploited for attaching extra constraints to a potential trajectory analysis. For example, based on the cell's sequence, buffer zones as well as area exclusions can be yielded on the fly. Given the 2.5D approach based on the elevation data provided in the integrated model, extra constraints can be taken into consideration, complying with military or civil authority aerial/air traffic safety regulations. In addition, the use of the uniform framework, can help reduce incidents of wrong target locations incidents and also the risk of friendly fire, that may arise in demanding multinational in-treaty operations due to bad geospatial communication or lack of accurate timely update.

Generally, the military stakeholders in geospatial operational scenarios, turn to commercial off-the-shelf solutions for geospatial analysis and visualisation and also rely on C3I systems with embedded geospatial frameworks for the integration of the geospatial data and multidisciplinary communication. These technologies rely on military scene modelling based on thematic layers (feature models) or other data models that are well standardised and maintained throughout the years. However, there is the need of extra integration in-software as well as pre-processing procedures to fuse the different data under an integrated modelling environment for analysis. The DGGS approach can be offered as a data structure-framework to facilitate the geospatial data integration and fusion of multidisciplinary standards, augmenting cooperation. As a multi resolution data structure it can be important for modelling and analysing continuous military geographic phenomena under a uniform, global, area based framework. It also shows potential in interactive and intuitive visualisation of military scenes, adding strong connectivity relations between the different geospatial objects of the scenes. Further, it can serve as a geocoordinate standard, with superior performance to the current existing used by NATO (MGRS) for locating points on Earth. However, it cannot seamlessly be treated as a reference frame, due to finest resolution constraints. Given the case study results, it appears to be useful for large areas of coverage, but not mature yet for submeter accuracy, making it not appropriate for military scenes engaging level of detail for military construction or positioning networks. In parallel, as the DGGS concept is still emerging and dynamically optimized, it is still difficult to construct a full architecture pipeline for its use in a military geospatial intelligence environment, respecting underlying military patterns and standards and still cannot compete in efficiency and performance with the established commercially maintained GIS tools.

6. Conclusion

The conclusions of the analysis are presented on this chapter. An overview of this research is presented and the research questions are reviewed, aiming to determine the objectives' level of fulfilment. Then, the limitations of the research are discussed. Finally, recommendations over future work regarding the topic of this research are provided.

6.1. Research overview

The aim of this thesis was to apply a DGG system and integrate different geospatial datasets (vector, raster) of military/civilian interest, to demonstrate the integration and storage procedure and identify the potential of this approach to model a military scene. The research attempted to justify the beneficial use of a DGGS, in comparison with the existing approaches in the military. Based on an existing DGGS implementation that was used, the research gauged the different data quantization approaches for the different datasets and explored their limitations. Moreover, a case study regarding a common military operation (ranging) was conducted, utilising the DGGS integrated model of a military scene and its relevant properties. In parallel, the geospatial insight potential and the visualisation possibilities of the DGGS integrated datasets were explored. A main research question was defined, followed by four sub-questions. Following, those research questions are reviewed.

The **main research question** that this thesis is addressing is:

To what extent can a Discrete Global Grid System assist in modelling military scenes in one integrated way?

The research has shown that using a Discrete Global Grid System approach to model a military scene in one integrated way is promising. A DGGS can provide a uniform area based framework, encapsulating different qualitative and quantitative information regarding a military scene, offering strong connectivity and hierarchy relations and increasing the qualitative spatial perception. Using a DGGS to model a military scene, showed advanced different format data integration, segmentation, aggregation and visualisation capabilities. Information regarding the 3rd dimension can also be exploited using a DGGS approach for modelling a military scene in one integrated way. Uniform storage through the DGGS integration can be realized in a database. A DGGS can also support common military geospatial operations(i.e. ranging) in an integrated model of a scene, also offering navigation and geocoding capabilities. However, the use of a DGGS integrating different format geospatial datasets to model a scene should be made with prudence, as the quality of the results is highly dependent of the original data accuracy/spatial uncertainty and the demanded precision requirements of the scene's coverage. In parallel, the current distributed DGGS implementations are not mature yet to support high spatial accuracy results and geometric calculations/operations, also given the DGGS nature.

Subquestions:

1) What are the benefits of using a DGGS when modeling a military scene, in comparison with the current state of the art?

The research has shown, that the use of a DGGS, can provide a uniform framework, representing the surface of the earth, fixed in certain resolution levels, also fitting the current geospatial standards of scope. The uniformity can assist in combined military or joint civil/military operations augmenting geospatial communication and cooperation.

In parallel, the DGGS use offers advanced integration capabilities of vector, raster data formats being the most common and interoperable in military geospatial operations. In that way, geospatial information concerning a military scene can be modelled as a continuous representation, opposite to discrete thematic layers. Moreover, the DGGS can support aggregation, segmentation and data binning of spatial info, in areas/regions of fixed locations and resolution, to facilitate the monitoring and analysis of continuous military interest observations.

The nature of DGGS, in a DGGS modelled scene, provides strong cell connectivity links between the DGGS cells, offering information regarding the hierarchy of resolutions (parent, child relations) and vicinity (neighbourhood relations). The cell traversal across the scene's regions/cells is facilitated using the DGGS indexing mechanism. Those properties combined with the areal subdivision in fixed resolutions, augment the qualitative perception of the military scene. For military scenarios, where the area importance aspect is designated, the DGGS use is practical, striving for a more qualitative spatial modelling approach, providing connectivity relations between the different regions/objects of the military scene.

The research shows that the DGGS use, contributes in the efficient storage of point vector datasets, neglecting the geometry. Regarding the polygon vector and raster datasets, the DGGS offers a storage balance up to a given uniform resolution conversion. In parallel, using a DGGS integrated model of a military scene, analogous to common military geospatial operations (ranging), can be carried out, via DGGS native methods (radius lookup, approximating circles as k-rings of neighboring DGGS cells) and avoiding intermediate geometric operations and calculations.

The DGGS framework can also be exploited in a military scene, for navigational and geocoding purposes, as an analogous of the current geocoordinate standard MGRS. The DGGS approach offers a wider variety of modelling resolutions, a similar finest precision level, while also having the capability to associate multiple spatial information with a grid reference (DGGS cell, point, region) of a military scene.

Additionally, the research shows that modelling elevation values given in a raster, can provide a 2.5D approach digital elevation model of the scene, similar to a raster DEM, forming a continuous terrain representation, where each engaging DGGS cell area is associated with a uniform height value, in a fixed resolution. The data structure does not prevent further enrichment of each region cell with extra data values, assisting in modelling the scene in one integrated way.

2) How to achieve integration and storage of different format geodatasets of military interest (vector, raster) using a DGGS?

As specified by the OGC, quantization operations are part of the basic operations that the distributed DGGS implementations should support. As shown in this research, different APIs can be created for different data formats (vector point, vector polygon, raster), utilising different quantization strategies to convert the original data values to the according DGGS cells. For the military scene, given the importance of area designation, each DGGS cell represents a region in a fixed resolution and spatial data coming from the original datasets are assigned to the according cells based on their geometry. The developed APIs support the conversion of the different data formats (point, polygon, raster) to the DGGS framework, for a user defined resolution also offering aggregation, data-binning and file storage export capabilities.

The selected uniform resolution is selected to fit the military scene's area of coverage compromising the original datasets' accuracy and spatial uncertainty. Based on the original datasets' specifications a custom attribute structure model is defined, harvesting the military-important qualitative and quantitative data values. The DGGS indexed datasets can be stored both in local files (using their geometry on demand) or in a database neglecting their geometry. Further integration is accomplished, fusing the different DGGS converted datasets, into an integrated uniform model of the military scene, exploiting the DGGS cell spatial indexing properties. This operation can be conducted both in-database and in other platforms. The resulting integrated model of the military scene, offers a continuous representation containing qualitative and quantitative data provided by the original different format datasets.

3) How to use a database, exploiting different format DGGS indexed datasets for geospatial analysis of a military scene?

As shown in this research the different format DGGS indexed datasets can be stored in a database, exploiting a predefined custom attribute structure model containing their military-important qualitative and quantitative data values regarding the military scene. Through the database, an integrated model can be uniformly stored representing the scene.

Traditional database techniques (i.e. selection, update, retrieval, edit, delete) can be applied using the integrated model, without the need of spatial extensions to manipulate the different format spatial data for analysis. The spatial indexing property of the DGGS, can also be utilised via connecting the database with external platforms to conduct more complex geospatial analysis.

In parallel, data distribution, in-database table communication and communication with other databases containing military spatial data can be enhanced by using DGGS indexed models or by converting data to DGGS indexed models. Moreover, storing an integrated model of a military scene in a database, provides a centralised architecture, allowing the dynamic enrichment of the scene with data of different formats converted into the DGGS framework, to enhance data-driven desicion making over the military scene.

4) What are the different visualisation alternatives of DGGS indexed datasets assisting in military analysis?

DGGS indexed datasets modelling the military scene, can be exploited in different data formats, securing (.geojson) or neglecting (.csv) their geometries. The different datasets can be used either separately or uniformly representing an integrated model of the scene.

Models can be used in external commercial and/or open source platforms. Commercial/Open source GIS platforms can utilise the models harnessing the variety of visualisation, data query and filtering capabilities they provide, offering 2D projected visualisation of the geometries representing a scene, to assist in military analysis, providing geospatial insight. Such capabilities are also offered in open source web tools and locally stored graphic libraries offering a variety of visualisations and background maps. The relevant attributes of each DGGS cell can be attached and filtered/highlighted on demand, offering comprehension of the effect of the various information to assist in decision making in a military scenario. Apart from using 2D projections, integrated models can also be superimposed in digital earth models providing a more exhaustive representation of the scene's coverage onto the surface of the Earth. Tooltip capabilities also augment the visual insight for the military scene's dynamic state.

In parallel, making use of the elevation values of an integrated model, the 2.5D (two-and-a-half dimensional or pseudo-3D) approach can be practically visualised, in platforms allowing 2D graphical projections of scenes to simulate the appearance of being three-dimensional, by extruding the DGGS geometries given their uniform elevation. Such terrain visualisations can be an alternative of pure terrain analysis for military, offering an intuitive representation of the scene's terrain, reinforced with various qualitative and quantitative information also attached to each region, assisting in decision making.

6.2. Limitations

Despite the fact that this research demonstrates the promising potential of a DGGS application to model a military scene in one integrated way, the approach has a number of limitations that are outlined below.

First, is the lack of pure military geospatial data, being relatively hard to find and also not common to be openly distributed. Pure military spatial and non-spatial data would be more insightful to fully assimilate the military structure and patterns used in military scene modelling. Instead, openly available datasets of military and civil interest were used, approximating and compromising the military important information they provide to fit a military scene modelling scenario.

Second, a certain part of the methodology is dealing with the preliminary data cleaning, reformatting and pre-processing. Data cleaning is often manual and based on assumptions, possibly removing certain data entries that could take part in the analysis. In parallel, the basic attribute structure model representing the integrated model of the military scene, is customised based on the preliminary datasets' properties. In certain parts, the procedure requests for user intervention before setting the preliminary datasets to a ready- for-conversion/analysis fashion.

Third, the approach presented in this research refers to a uniform modelling resolution of the different data formats into a DGGS integrated model of the military scene. An assumption is made, selecting a uniform resolution to best fit the military scene of the study, while compromising the original finer spatial accuracy of certain datasets. In any case, the modelling quality of the DGGS integrated military scene is highly dependent on the original integrated datasets' spatial uncertainty and the area of coverage/scale requirements of the military scene scenario.

Additionally, regarding the pipeline's performance, the different APIs implementations performing the quantization of the different format data into the DGGS framework, call for optimization, to be capable of handling diverse datasets in a more automated manner and minimizing the user intervention where this is applicable. Furthermore, the military case study's runtimes, do not appear to be optimal for real time or close to real time analysis and optimization should be considered.

6.3. Recommendations and future work

Being part of the discussion, several recommendations for similar research regarding the modelling of a military scene utilising a Discrete Global Grid System are provided.

Firstly, given the increasing wide use of DGGS in the geospatial domain in research and commercial applications, and the recent DGGS Absract Specification developed by the Open Geospatial Consortium (OGC), DGGS datasets seem that will be in wide use in the future. The profiling and extension of DGGS standards to fit military/defence requirements, should be considered by stakeholders engaging in military geospatial standardization.

Secondly, a more comprehensive approach should be considered, forming a research where strictly military geospatial data and conventional military standards and patterns should be used for modelling a military scene using a DGGS. In the meantime, pure military performance assessment models should be used to offer more insightful military-oriented conclusions.

Third, a more exhaustive research is recommended on computational strength and storage efficiency of the DGGS application, modelling a military scene where multiple large datasets are utilised, conducting big data analysis for continuous observations of military phenomena.

Additionally, the DGGS data structure nature, offering strong hierarchical,cell connectivity properties and fixed area based grids is appropriate to apply machine learning algorithms. A research on the use of machine learning through the DGGS framework in a wargaming/prediction modelling scenario of a military scene would be practical.

During this research, based on the methodology and analysis of the results, several other research directions came up on this topic that can be addressed for future work.

- Application of different data formats:
  The research topic can be reinforced, fusing extra different geospatial formats or formats with different specifications to model a military scene. A more fruitful modelling approach would be possible, modelling point cloud datasets and vector line datasets, testing their quantization approaches, limitations and contribution in an integrated model of the military scene.
- Multi-resolution approach and optimization :
  Taking advantage of the DGGS hierarchical nature, an approach of a multi-resolution analysis for a military scene would be practical. In that way, the different integrated datasets would be modelled using a more precise approach based on their original accuracy and spatial uncertainty, assessing their conversion quality more concretely. Further, the research should also focus in bypassing certain approximations and offering (semi-)automatic ways of modelling the scene based on the variable area of coverage and scale/precision requirements.
- Profiling of conventional spatial analysis algorithms for military operations using a DGGS:
  Given that in most distributed DGGS platforms, certain capabilities are still under research and construction, various conventional spatial algorithms can be redefined in a DGGS context, taking into consideration the different space subdivisions(hexagonal,

rectangular, triangular, rhombus). For military important aspects such as terrain analysis, geology, topography, hydrology, meteorology, spatial algorithms can be reformulated and assessed to assimilate the impact of using a DGGS.

- Different area subdivision approach:
  This research is using a hexagonal DGGS and works on the according cell adjacency and geometric properties of this subdivision. A future research utilising implementations offering different space subdivisions (rectangular, triangular, rhombus) and testing their different pros and cons, would potentially help in determining the optimal area subdivision when modelling a military scene using a DGGS.

A. Datasets information

This appendix provides additional information regarding the datasets used to carry out the case study of this research. In order to model the military scene of the case study, both military non classified and civil open source geospatial datasets are used. All the datasets are openly available. In Table A.1, an overview is provided including metadata and links to the datasets.

Dataset name	Description	Coverage	Provider	Version	Source
EU offshore military areas (points)	EMODnet human activities, Military areas	Europe	EMODnet	1/2/21	(1)
EU offshore military areas (polygons)	EMODnet human activities, Military areas	Europe	EMODnet	1/2/21	(2)
EU transport networks (airports)	European geodata, transport networks	Europe	Eurostat	1/12/13	(3)
ETOPO5	World digital elevation model	World	European Environment Agency	28/6/16	(4)

Table A.1.: Overview of the used datasets

(1) `https://ows.emodnet-humanactivities.eu/geonetwork/srv/api/records/579e4a3b-95e4-48c6-8352-914ebae0ae1d`

(2) `https://ows.emodnet-humanactivities.eu/geonetwork/srv/api/records/579e4a3b-95e4-48c6-8352-914ebae0ae1d`

(3) `https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/transport-networks`

(4) `https://www.eea.europa.eu/data-and-maps/data/world-digital-elevation-model-etopo5`

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Colophon

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