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# Photogrammetric Underwater and UAS Surveys of Archeological Sites: The Case Study of the Roman Columns of Porto Cesareo


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*Dedicated to the noble women of my homeland*

*who bravely shine in the front line of the*

***Woman Life Freedom***

*movement*

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# Summary

This thesis delves into the exploration and documentation of **Underwater Cultural Heritage (UCH)** with the help of **Photogrammetric Techniques** and **Unmanned Aerial Systems (UAS)**. Focusing on the captivating case study of the **Roman Columns of Porto Cesareo (Le),** this research encompasses theoretical and practical dimensions to enhance our understanding of underwater archaeological site surveying and preservation.

The initial chapters of this study elucidate the significance of underwater cultural heritage and the transformative role of photogrammetry as a non-invasive, precise method for **Surveying Submerged Archaeological Sites**. Additionally, it delves into the specialized domain of underwater photogrammetry, shedding light on the unique challenges and methodologies involved in capturing accurate data in the aquatic environment.

Furthermore, the thesis meticulously examines the shipwreck of the Roman Columns of Porto Cesareo, a submerged historical treasure in the south of Italy in the waters of the Ionian Sea. Through a comprehensive site survey using advanced UAS and photogrammetric techniques, valuable data was amassed. Subsequent data processing via software such as Agisoft Metashape facilitated the creation of detailed 3D models and visual reconstructions.

This research adds to the field of **Heritage Documentation** by showcasing the effectiveness of photogrammetric methods in capturing intricate details of underwater archaeological structures. By leveraging the survey output and subsequent data processing, comprehensive documentation of the Roman Columns was achieved. The outcomes underscore the potential of integrating modern technology into underwater archaeology, emphasizing the importance of precise **Data Acquisition** and its applications in **Cultural Heritage Preservation**.

In conclusion, the research exemplifies the synergy between cutting-edge technology and archeological preservation, providing insights into the potential for advancing underwater archaeology through photogrammetric and UAS techniques. The case study of the Roman Columns of Porto Cesareo serves as a testament to the value of such methodologies in unraveling submerged historical narratives and ensuring their conservation for future generations.

*"There's nothing like a shipwreck to spark the imagination of everyone who was not on that specific ship."*

Jon Stewart

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With deep gratitude,
Sara

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# Chapter 1

# Introduction

This research is dedicated to the application of geomatics for the precise metric documentation of cultural heritage (CH), with a specific emphasis on underwater cultural heritage (UCH). Unlike other forms of cultural heritage, UCH faces unique challenges, including limited visibility and a commitment to in situ preservation, which can lead to its lesser recognition. To address this issue, the International Committee on Underwater Cultural Heritage (ICUCH), a part of the International Scientific Committees of ICOMOS (International Council on Monuments and Sites), plays a crucial role in advocating for the importance and protection of UCH.

ICUCH's efforts encompass a multifaceted approach, including research and documentation, fostering international cooperation, formulating comprehensive guidelines and best practices, providing professional training, conducting extensive public outreach initiatives, advocating for legal frameworks, global monitoring of UCH's status, and promoting responsible diving and tourism practices. Collaborative partnerships with governments and international entities are pivotal in ensuring the legal protection of submerged sites and artifacts. Furthermore, ICUCH engages in comprehensive public outreach activities to educate and inform the broader population about the profound significance of underwater cultural heritage.

In essence, ICUCH assumes a vital and responsible role in preserving these invaluable historical and archaeological assets, securing their enduring legacy for future generations. This mission stems from the imperative of fostering an enlightened understanding of the paramount importance of underwater cultural heritage and the critical necessity for its vigilant safeguarding.

The preservation and conservation of Underwater Cultural Heritage (UCH) sites in their original locations are central principles of the UNESCO Convention on the Protection of Underwater Cultural Heritage. This approach ensures the preservation of the contextual authenticity and integrity of underwater cultural heritage sites. While most documented shipwrecks in the Mediterranean are found in waters shallower than 50 meters, ongoing technological advancements and increased interest in technical diving and deep-water exploration suggest a notable shift in this trend.

Projects such as Puglia Seascapes and UnderwaterMuse, coordinated by the Puglia Region, aim to enhance our understanding of underwater cultural heritage in the Marine Protected Areas of Porto Cesareo and Torre Guaceto in Apulia. These projects investigate various archaeological sites, including the remnants of cargo and artifacts from different historical periods. Utilizing archaeological and geoarchaeological data, along with 3D modeling techniques like photogrammetry and underwater videos, these projects have developed a methodological and technological protocol known as Puglia Seascapes VR. This software offers immersive scenarios through advanced 3D modeling and interactive videos, enabling viewers to experience and emotionally connect with ancient maritime landscapes and the formation of underwater contexts. It provides an innovative approach for both the general public and scholars to explore new environments and reinterpret the history of ancient Italy.

Approximately 17 to 18 centuries ago, a ship arrived off the coast of Porto Cesareo, carrying a valuable cargo of marble. This cargo consisted of five massive columns, each measuring nearly 9 meters in length and with diameters ranging from 85 to 97 cm. These columns were crafted from Cipollino marble sourced from Karistos on the island of Evia.

The marble trade, an ancient practice, gained significant importance during the Roman era, especially in the Imperial period. By the 1st century AD, there was a structured system for collecting and using marble, involving imperial ownership of quarries and private contractors. Private ship owners typically delivered marble to Rome and other significant cities in the Roman Empire by sea. While some marble-laden ships were quite large, the Torre Chianca ship, for instance, was of a more standard "medium" size, around 80–100 tons. The substantial size of the five columns suggests they were intended for important, likely public construction projects. Cipollino marble was a common choice for civil structures.

In June 2021, a mission involving participants from the Polytechnic of Turin, including professors Filiberto Chiabrando and Andrea Lingua, doctoral student Alessio Calantropio, technician Paolo Maschio, and Professor Rita Auriemma from the University of Salento, conducted various operations related to the cargo. These operations included photographic documentation, target placement and measurement, and 3D photogrammetry. The use of 3D reconstruction provided valuable insights into the cargo's positioning, surpassing traditional two-dimensional surveys.

The implementation of an app in this context added significant value. It allowed for the reconstruction and simulation of events leading to the formation of the archaeological site, suggesting that a storm likely propelled the ship toward the shore, grounding it instead of sinking it. The heavy cargo and potential hull damage may have exacerbated this situation. Notably, sea levels have risen over time due to geological changes affecting both the sea and the land.

Within the realm of geomatics, numerous tools and techniques are available to address various needs. In this context, the focus was directed toward image-based solutions, specifically photogrammetry. These approaches are well-suited for addressing research requirements due to their inherent qualities: flexibility, cost-effectiveness, adaptability to diverse situations, and their capacity to cater to the distinct demands of various archaeological research areas.

In summary, this thesis endeavors to contribute to an advanced understanding of geomatics theory with a specific focus on photogrammetry, particularly underwater photogrammetry. By examining the achievements in Porto Cesareo and the comprehensive documentation process of the Roman Columns of Porto Cesareo, this research aims to underscore the multifaceted utility of underwater surveys. These surveys encompass diverse objectives, ranging from the discovery and preservation of submerged sites and artifacts to their ongoing monitoring. As time progresses, certain artifact categories are susceptible to degradation. Systematic surveys, such as the one in our case study, conducted at regular intervals, facilitate effective monitoring and enable the assessment of the need for preservation and restoration interventions, especially vital for vulnerable shipwrecks susceptible to deterioration.

Chapter2

# Underwater Heritage

## 1) Underwater Heritage

The subaquatic repository of cultural and natural heritage, concealed beneath the world's seabeds, stands as a prized asset, attracting a multitude of visitors. This allure emanates from the enigmatic aura surrounding these submerged cultural and natural treasures, coupled with the intricate symbiosis between historical artifacts and marine ecosystems.

Notwithstanding the burgeoning fascination with Underwater Cultural Heritage (UCH), the formidable challenges encountered in accessing and experiencing underwater archaeological and historical assets are conspicuous. Consequently, there is an imperative need for pioneering solutions aimed at enhancing public awareness and knowledge concerning these profoundly significant and emergent subjects. Cultural Heritage (CH) represents a pivotal facet of our historical narrative, serving as a reflection of the socio-cultural evolution of human civilizations through the annals of time. Individuals and tourists seeking to explore novel realms and diverse cultures invariably seek out museums and Visitor Centers as primary sources of indispensable information. Concurrently, the demand from users for augmented value and innovative services, in conjunction with the desire to engage with subaqueous assets, continues to burgeon. Nevertheless, there persist substantial impediments to the comprehensive enjoyment and comprehension of these submerged wonders.[1]

An appreciation of shifts in landscapes is essential to the comprehension of human endeavors. The establishment of ports and the coastal urbanization process, along with the transformation of coastal topographies, constitute salient junctures in the annals of human settlement evolution. Coastal geoarchaeological research endeavors to scrutinize these archaeological vestiges, even though the inexorable rise in sea levels over centuries and millennia has submerged the majority of them.

This cutting-edge data confers invaluable insights into the ramifications of climate change on human societies and its attendant social repercussions. A very important part of protecting underwater archaeological sites is putting together the results of geological and geomorphological studies, geophysical and geomatic surveys, and archaeological investigations. Simultaneously, it affords the means to manage these submerged vestiges as

[1] Fabio Bruno and others, 'Digital Technologies for the Sustainable Development of the Accessible Underwater Cultural Heritage Sites', *Journal of Marine Science and Engineering*, 8.11 (2020), 955 <https://doi.org/10.3390/jmse8110955>.

tangible testimony to the profound impact of ongoing climate change on ancient habitations and coastal transformations.[2]

The central aim of this chapter is to expound on the myriad threats and challenges that confront underwater heritage. Additionally, it delves into the international and regional legal and policy frameworks that have thus far been deployed to safeguard these submerged treasures.

Fig 2-1) Egyptian Underwater Cultural Heritage
Discovered by Institute European d'Archeologie Sous-Marine (IEASM)

## 2) Threats and Challenges

**(Environmental and Urbanization Effects on Underwater Cultural Heritage)**

Within aquatic environments, an array of challenges emerge, demanding vigilant acknowledgment and, where feasible, amelioration. These challenges may be broadly categorized into two distinct groups: environmental threats, primarily associated with climate fluctuations, and inadvertent human actions, notably exacerbated by the encroachment of urbanization. Regrettably, a prevailing concern is the often irrevocable and enduring nature of these repercussions, with certain instances culminating in the irremediable degradation or complete annihilation of precious heritage assets. Simultaneously, the imperative to accord precedence to the safeguarding of designated World Heritage sites frequently assumes paramount importance, thereby compounding the financial and resource-oriented dilemmas confronting heritage custodians entrusted with the preservation of other imperiled regions.[3]

[2] Gaia Mattei and others, 'Sensing the Submerged Landscape of Nisida Roman Harbour in the Gulf of Naples from Integrated Measurements on a USV', *Water*, 10.11 (2018), 1686 <https://doi.org/10.3390/w10111686>.

[3] Hakan Öniz, 'UNDERWATER CULTURAL HERITAGE AT RISK: PROBLEMS RELATED TO URBANIZATION', in *Heritage at Risk: Special Edition 2020: Heritage Under Water at Risk: Threats, Challenges and Solutions* (International Council on Monuments and Sites, 2020).

## 2-1) Environmental Effects

Numerous overarching themes extend beyond the conventional purview of archaeologists and cultural heritage stewards, encompassing critical concerns that transcend customary boundaries. Notably, these encompass the far-reaching implications of climate change and the imperative for the conservation of marine ecosystems. The Seventeen United Nations Sustainable Development Goals (UN 2020a), as articulated within SDG 13 (Climate Action) and SDG 14 (Life Below Water), underscore the pressing urgency and profound significance of these multifaceted threats.

UNESCO, cognizant of the intricate interplay between environmental dynamics and underwater cultural heritage sites, elucidates the precarious nexus. UNESCO aptly notes, "Environmental changes, such as climate change, heightened erosion, and alterations in oceanic currents, pose substantial threats to underwater cultural heritage sites. Paradoxically, submerged cultural heritage sites provide invaluable insights into historical climatic fluctuations that once reverberated through the lives of our forebears. Today, the specter of tsunamis, coastal erosion, and rising water temperatures looms ominously over these submerged cultural treasures" (UNESCO 2020).

In the ensuing discourse, we shall expound upon the multifaceted impact of climate change upon underwater cultural heritage (UCH).[4]

Key documents like the 1992 United Nations Framework Convention on Climate Change, the 1998 Kyoto Protocol, and the 2015 Paris Accord highlight the global community's extreme concern over climate change. These seminal accords collectively resonate with a global narrative that accentuates the exigency for a transformative paradigm shift in human conduct, with a primary focus on curtailing carbon emissions and embracing renewable energy sources such as wind and solar power. Notably, in 1988, the United Nations Environment Program (UNEP) and the World Meteorological Organization (WMO) jointly established the Intergovernmental Panel on Climate Change (IPCC). Since its inception in 1990, the IPCC has diligently published a series of comprehensive scientific assessments pertaining to climate change. Ongoing alterations in coastal topographies and fluctuations in inland water bodies, driven by the vicissitudes of climate change, increasingly unveil long-submerged relics such as ancient shipwrecks, coastal settlements, and time-honored artifacts.

Intriguingly, climate change, in tandem with its secondary consequences, can yield unexpected serendipities in the realm of cultural discovery. Noteworthy among these instances is the revelation of the Bronze Age timber circle known as 'Seahenge 4,' situated along the Norfolk coast and discovered in 1998. This remarkable archaeological find, located within the intertidal zone, owed its unearthing to the inexorable forces of coastal erosion, exemplifying how climate-induced transformations may inadvertently unveil hitherto unknown cultural sites.[5]

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[4] Albert Hafner, Christopher J. Underwood, 'INTRODUCTION TO THE IMPACT OF CLIMATE CHANGE ON UNDERWATER CULTURAL HERITAGE AND THE DECADE OF OCEAN SCIENCE FOR SUSTAINABLE DEVELOPMENT 2021–2030', in *Heritage at Risk: Special Edition 2020: Heritage Under Water at Risk: Threats, Challenges and Solutions* (International Council on Monuments and Sites, 2020).

[5] Albert Hafner, Christopher J. Underwood.

Fig 2-2) The Timber Circle at Holme-Next-the-Sea in Norfolk, England

## 2-1-1) Rising Sea Temperatures and Ice-Melt

Elevated sea temperatures precipitate thermal expansion within the oceanic domain, expediting the process of ice melt. The United Kingdom's Marine Monitoring and Assessment Strategy underscores an anticipated surge in sea levels, ranging from 12 to 76 centimeters, over the course of the twenty-first century. As polar ice continues to recede, it unveils fresh frontiers for exploration, affording individuals the opportunity to seek out, uncover, and examine locales that were hitherto deemed inaccessible due to their formidable nature. Nevertheless, the public dissemination of information pertaining to these underwater heritage sites raises concerns about potential forays marked by unreliable objectives, thereby posing a risk to their preservation. Furthermore, the retreat of mountain glaciers, a corollary of shifting climate patterns, exerts a transformative influence on river dynamics, lake ecosystems, and, in turn, the condition of submerged heritage assets.[6]

Fig 2-3) Muir Glacier and Inlet, Late 19th Century (Left) and 2005 (Right)

[6] Albert Hafner, Christopher J. Underwood.

## 2-1-2) Sea Level Rise and Ocean Processes

Moreover, the escalating consequences of rising sea levels in regions lacking adequate tidal defenses usher in a surfeit of challenges for Underwater Cultural Heritage (UCH). These challenges encompass heightened susceptibility to inundation, culminating in greater inaccessibility to these submerged treasures. This, in turn, engenders escalated conservation expenditures and diminishes their allure as tourist destinations. It is an undeniable reality that the lion's share of available funding and support is invariably allocated to the preservation of renowned heritage sites, which hold immense cultural and economic significance. Yet, this focus on well-established sites inadvertently relegates lesser-known or yet-to-be-discovered sites, which may hold equivalent historical and cultural import, to the periphery of attention. These understated heritage sites merit commensurate consideration and resources to ensure their preservation and propagation for future generations.[7]

Fig 2-4) Unique Medieval Scotland Bridge,
Hidden Beneath the Waters of the River Teviot for Centuries

## 2-1-3) Ocean Acidification

In addition to a suite of environmental perils, ocean acidification has engendered apprehensions pertaining to the accelerated corrosion of metal shipwrecks and the augmented erosion of submerged stone structures. An equally disconcerting facet resides in the presence of fuel oil or other deleterious cargo within a substantial proportion of wartime shipwrecks, signifying a significant hazard to Underwater Cultural Heritage (UCH). The quantities of fuel oil preserved within these submerged relics are estimated to range between 2.5 and 20 million tons. When acidification and other ocean processes happen together, they might make the gradual breakdown of these submerged "rusting time bombs" worse, which could lead to a lot of fuel leaking into the oceans.[8]

[7] Albert Hafner, Christopher J. Underwood.
[8] Albert Hafner, Christopher J. Underwood.

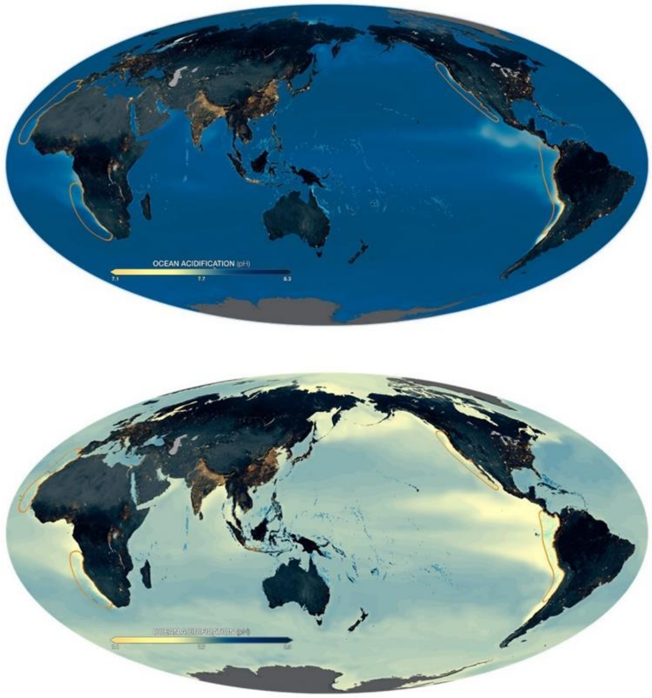


Fig 2-5) Pre-Industrial pH Levels (Up)
Predicted pH Levels for 2100 (Down)

## 2-1-4) Economic Adaptation to Low Carbon Economies

The interplay between "heritage preservation" and the imperative of "climate action" can become further strained, particularly in light of the ongoing shift toward low-carbon economies and the presence of fragile legislative frameworks. This complicated situation could get worse if there aren't enough or the right kinds of assessments or if new, eco-friendly structures are built near the coast, which could put nearby Underwater Cultural Heritage (UCH) sites at risk.[9]

## 2-1-5) Practicalities for the Work of Underwater Marine Archaeologists

Engaging in activities within the marine environment entails practical considerations. Rising sea levels, strong water currents, and tidal fluctuations all work together to create an environment with inherent limitations and constrained operational windows for experts. Consequently, the implementation of remote methodologies and technological devices becomes imperative. Moreover, the heightened turbidity in this milieu results in reduced visibility, a condition that proves unsatisfactory both for archaeologists and the broader audience seeking to engage with underwater heritage sites.[10]

[9] Albert Hafner, Christopher J. Underwood.
[10] Albert Hafner, Christopher J. Underwood.

## 2-2) URBANIZATION EFFECTS

Throughout human history, the intricate relationship between civilization and the sea has remained deeply intertwined, a connection that has become even more pronounced in contemporary times. Regrettably, this symbiotic bond has emerged as a potent source of challenges for the marine environment, transcending to encompass broader implications for national and cultural heritage, particularly within coastal regions. The evolution of significant social and cultural civilizations in these coastal areas has unfolded across centuries, coinciding with the parallel growth of trade and commercial activities. Consequently, coastal regions have emerged as coveted locales for habitation, resulting in urban sprawl, surges in population, the imperative for extensive infrastructure development, and concurrent industrialization, collectively exerting heightened pressures on global water resources and their surrounding ecosystems.

Amidst these dynamics, a multitude of archaeological remnants concealed beneath coastal waters or strewn along the shorelines have been lost to the annals of time. These submerged archaeological treasures represent a veritable repository of historical records and invaluable data. It is incumbent upon us to recognize the intrinsic worth of these fragile assets, considering them not merely as scientific resources but also as entities deserving of widespread accessibility, to the greatest extent feasible, while also safeguarding them for future generations.[11]

### 2-2-1) Direct Impact of Urbanization on Coastal and Underwater Cultural Heritage

With the burgeoning coastal population, urbanization of shorelines and land reclamation initiatives have proliferated, instigating profound transformations in the coastal topography of numerous regions. The rationales behind coastal and land reclamation are manifold and diverse, encompassing an array of motives. These encompass endeavors aimed at enhancing and enlarging settlements, industrialization ventures, the promotion of tourism, the development of hotels and commercial complexes, the establishment of recreational spaces such as parks and beaches, the construction of coastal infrastructure such as roads, piers, harbors, and breakwaters, the creation of themed sea tourism hubs, underwater hotels, artificial reef structures, artificial islands, the facilitation of transportation through airports, and the facilitation of the global transport of natural resources including natural gas, oil, and water via pipelines. Additionally, these initiatives extend to waste disposal from industrial zones and the dredging of ports, reflecting the wide-ranging scope of such endeavors.

Economic opportunities have increased the intrinsic value of coastal land in urban areas, contributing to the allure of coastal living on a global scale. This, in turn, has precipitated a surge in land reclamation undertakings across the world.

Regrettably, archaeologists, museums, cultural heritage experts, municipal authorities, and national public institutions face these challenges on a global scale. In many instances, cultural heritage bears the brunt of this contest, with an indeterminate number of cultural sites succumbing beneath the weight of these sprawling structures. The extent of the loss remains immeasurable.[12]

[11] Hakan Öniz.
[12] Hakan Öniz.

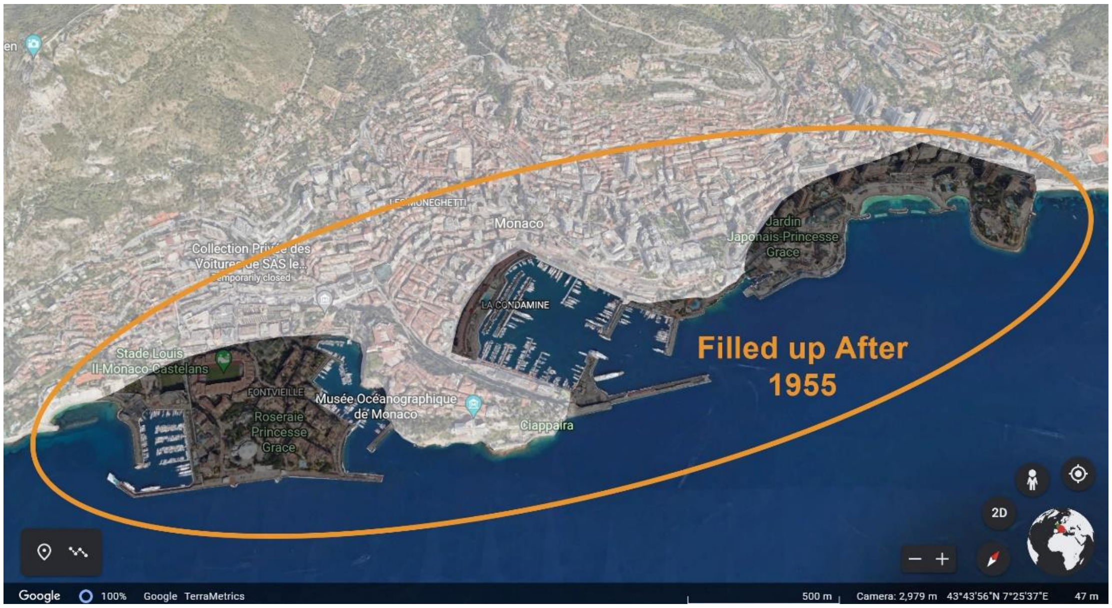


Fig 2-6) Fontvieille Stadium, Monaco:
The Difference in the Country's Coastline between 1955 and 2022

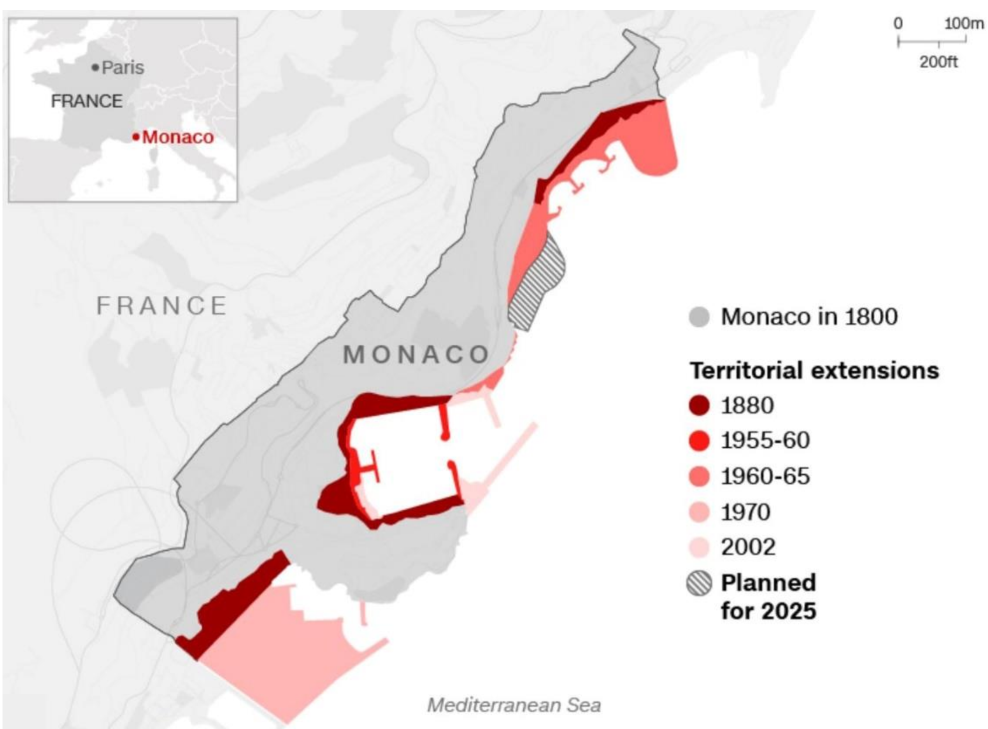


Fig 2-7) Land Reclamation in Monaco

## 2-2-2) Indirect Effects of Urbanization

### 2-2-2-1) Scuba Diving

Since its inception in the 1940s, the self-contained underwater breathing apparatus (SCUBA) has experienced remarkable global proliferation, particularly over the past three decades. The surge in its user base, notably among recreational divers, has concurrently exerted a substantial and growing impact on Underwater Cultural Heritage.

The escalating interaction between various cultural groups raises concerns, primarily centered on the lack of awareness among divers regarding the concept of non-intrusion, a pivotal factor in preserving the scientific integrity of UCH. Divers often fail to distinguish between world heritage sites and the fictional portrayals of pirate shipwrecks commonly depicted in the cinematic industry. Notably, archaeological shipwrecks typically do not yield sensational finds like skulls, sailcloths, or "traces of pirates in action. Divers motivated by the pursuit of valuable artifacts may inadvertently damage shipwrecks resting on the seabed, which are predominantly composed of deteriorating wooden structures ensconced in marine vegetation.

Another significant concern revolves around recreational diving inadvertently promoting visits to shipwrecks and archaeological sites worldwide, often marketed as "archaeological dives" by commercial tourism-focused diving centers. Usually, divers rather than archaeologists or cultural heritage experts plan and oversee these programs and training, oblivious to the intrinsic value of submerged sites. Consequently, these programs pose a new and unforeseen threat to UCH, which has endured for millennia.

In light of these challenges, it is imperative that divers shift their focus towards reporting underwater artifacts encountered during their explorations rather than engaging in potentially destructive "archaeological dives. Given that water covers about 70% of the Earth's surface, the vast majority of UCH sites are still unexplored. The passion of hundreds of thousands of divers for the underwater realm can be harnessed as a valuable scientific resource. It is now evident that their fascination with the submerged world can be transformed into a scientific endeavor.

One promising avenue involves the implementation of comprehensive training programs designed to instruct divers in the principles of UCH preservation rather than disturbance. Such initiatives hold the potential to be a brilliant and mutually beneficial strategy for the conservation of these historically significant underwater sites.[13]

Fig 2-8) Divers Accidentally Stumble, Upon Nazi Enigma Machine in Baltic Sea

[13] Hakan Öniz.

**2-2-2-2) Fishing**

A significant portion of our sustenance is derived from marine, lake, and river sources, but it is essential to acknowledge that both traditional and modern fishing methodologies pose substantial risks to Underwater Cultural Heritage (UCH). Numerous fishing practices involve deploying nets or equipment into the water column or onto the seabed and subsequently retrieving them along with the catch. However, these methods carry the inherent risk of snagging on seabed features such as rock outcrops, shipwrecks, or other heritage assets. Such snagging incidents not only jeopardize the safety of vessels and crew but have, regrettably, led to fatalities in some instances, even in recent years.

Paradoxically, the very features that increase the risk of snagging also serve as attractive habitats for marine life, drawing fish to seek refuge or sustenance in their proximity. Consequently, fishermen frequently target these features, striving to operate their equipment as closely as possible to enhance their catches while exercising caution to avoid entanglement. Notably, several of the most historically significant wrecks designated under the Protection of Wrecks Act of 1973 were initially discovered when fishing gear snagged on them, prompting subsequent investigations by divers to ascertain the cause of the snag.

In some regions, the use of explosives for fishing purposes inflicts irreversible damage to cultural artifacts. It is imperative to raise awareness and foster cooperation among anglers to establish a foundational step toward safeguarding UCH. Restricting or prohibiting angling activities in areas where cultural artifacts are frequently ensnared in fishing nets should not be considered until comprehensive scientific surveys have been conducted. Moreover, the practice of explosive fishing should be unequivocally banned, given not only its grave risk to UCH but also its profound adverse environmental repercussions.

The establishment of fish farms, both at sea and on land, involves the utilization of construction materials for pools and fish-feeding systems, which can significantly impact the flora and fauna of the seafloor and potentially cause harm to archaeologically sensitive regions. Consequently, it is incumbent upon archaeologists to conduct thorough assessments of proposed fish farm locations to ensure the preservation of cultural heritage remains unharmed.[14]

Fig 2-9) Aerial View of Fish Farm, Coast of Greece

[14] Hakan Öniz.

**2-2-2-3) Anchoring**

Ports constitute the foremost architectural elements that contribute to the enrichment of coastal cities, many of which boast a history spanning several centuries. Consequently, contemporary vessels predominantly anchor in the same locations as their historical counterparts. Numerous instances illustrating this historical continuity were unearthed during underwater research conducted along the Antalya coast between 2000 and 2020. Disturbingly, some modern anchorages have been directly established above the remnants of shipwrecks that succumbed to storms, thereby posing a formidable threat to Underwater Cultural Heritage (UCH).

It is imperative to acknowledge that, in the absence of a comprehensive warning system indicating the presence of these submerged relics, attributing potential harm to archaeological sites solely to ship captains is an inequitable proposition. A judicious approach necessitates either prohibiting anchoring in the vicinity of noteworthy shipwreck sites or relocating such sites based on the findings of archaeological investigations. Alternatively, the deployment of fixed mooring anchors and buoyancy systems for vessel anchorage should be considered. Collaborating with underwater archaeologists to identify suitable locations for these mooring anchors is essential to ensuring the protection of these archaeologically sensitive sites.[15]

Fig 2-10) Naples, an Important Port of Italy

[15] Hakan Öniz.

### 2-2-2-4) Marine Accidents and War

Marine winds and currents have historically posed significant threats to maritime vessels, often leading to shipwrecks caused by collisions with shoreline reefs, entrapment in shallow waters, or collisions with rocky outcrops. It is plausible that these natural forces may have been the primary contributing factors to previous shipwrecks.

Furthermore, in the contemporary context, the dive tourism industry sometimes intentionally scuttles vessels and adds additional objects to enhance their appeal to tourists. This practice may result in similar adverse impacts on underwater heritage.

The ravages of war exert a similar influence on underwater heritage as they do on terrestrial structures. During the World Wars, numerous ports of historical significance, such as Piraeus, which has served as a vital maritime link between Athens and the global community for over two millennia, were subjected to bombings, resulting in the loss of a substantial quantity of undocumented cultural heritage. Additionally, military exercises that employ live ordnance often employ uninhabited islands as target areas, which is an important consideration given that these islands possess a significant cultural heritage.[16]

Fig 2-11) The Turret of a Japanese Kawanishi H8K Emily Flying Boat Lies on the Sea Floor along the Maritime Heritage Trail

[16] Hakan Öniz.

**2-2-2-5) Dredging**

Human interventions yield a myriad of repercussions, including the submergence of numerous ancient settlements due to river damming, resulting in the creation of artificial lakes. Another direct consequence impacting Underwater Cultural Heritage (UCH) is the extraction of marine aggregates from seas, lakes, and rivers. These marine aggregates serve as fundamental materials in two vital industries: the casting and molding of metals as well as construction.

In the process of extracting aggregates from marine environments, operators of dredging equipment often operate without awareness of the potential presence of archaeological objects or sites. Consequently, proactive archaeological investigations are imperative in these areas to prevent any inadvertent harm to UCH resulting from dredging activities. In cases where archaeological sites are suspected, the practice of dredging should be strictly prohibited and rerouted to safer locations.[17]

Fig 2-12) Dredging Project in Galveston, Texas

In the past two decades, there has been a growing recognition of the profound impact of climate change on the preservation of cultural heritage. This acknowledgment found tangible expression in initiatives such as the European Union's Horizon 2020 project, "Mitigation of Climate Change Impacts and Natural Hazards on Sites, Structures, and Artifacts of Cultural Heritage," which ran from 2016 to 2019. While more recent attention has been directed towards the broader examination of climate change's implications, with a particular focus on maritime environments, it is essential to underscore that the effects of climate change on Underwater Cultural Heritage (UCH) were previously underestimated.

The confluence of urban expansion and extensive industrialization has emerged as a pivotal and multifaceted factor impacting UCH, with consequences that are often unintended but nonetheless significant. The ongoing trajectory threatens the integrity of thousands of irreplaceable heritage sites and valuable submerged resources, poised for daily destruction unless more resolute measures are adopted.

In this context, international validation and the cultivation of widespread awareness surrounding the significance of UCH assume paramount importance, akin to other analogous situations. The preservation and protection of UCH hinge on collective efforts involving governments and non-governmental organizations, both of which must take proactive steps to fulfill these crucial objectives.[18]

[17] Hakan Öniz.
[18] Hakan Öniz.

## 3) Legal and Policy Perspectives

The conservation of underwater cultural heritage holds a prominent position within the framework of international heritage law. This domain is subject to the jurisdiction of multiple legal frameworks, including salvage law, the United Nations Convention on the Law of the Sea, and the UNESCO Convention on the Protection of Underwater Cultural Heritage. By examining the evolution of norms and regulations in this context, one can discern a significant historical narrative that elucidates the intricate interplay between human activities and the maritime realm. It is worth noting that the UNESCO Convention on the Protection of Underwater Cultural Heritage owes its existence, in part, to the invaluable scientific insights provided by experts in the field of underwater archaeology.

ICOMOS officials have devoted considerable effort to lend their support to UNESCO treaties, underpinned by a robust scientific foundation. People still don't know enough about underwater cultural heritage compared to other types of historical heritage. This is because underwater cultural heritage is harder to see than other types of heritage and needs special in-situ conservation measures. Consequently, ICOMOS endeavors diligently to augment awareness pertaining to the unique character of underwater cultural heritage and the profound importance of its conservation and preservation for the benefit of future generations.[19]

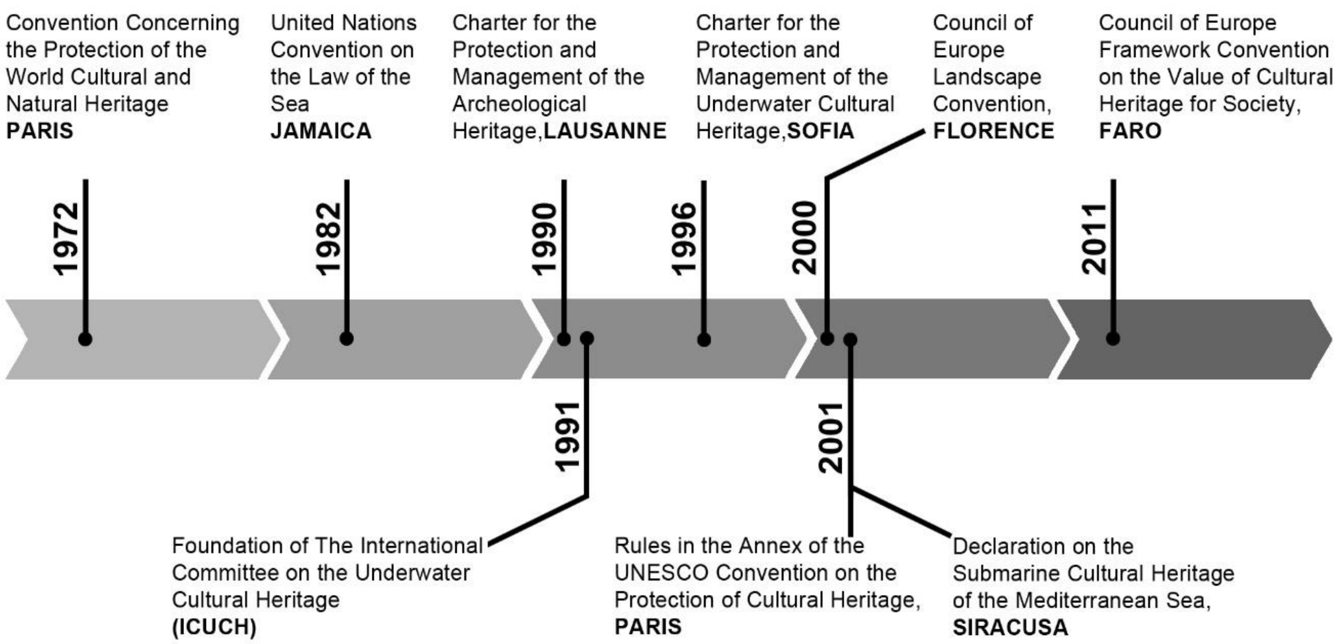


Fig 2-13) Underwater Cultural Heritage Legalization

[19] Mariano J. Aznar, 'CULTURAL HERITAGE: ITS INTERNATIONAL LEGAL PROTECTION', in *Heritage at Risk: Special Edition 2020: Heritage Under Water at Risk: Threats, Challenges and Solutions* (International Council on Monuments and Sites, 2020).

## 3-1) 1982: United Nations Convention on the Law of the Sea

**(Law of the Sea Convention / Law of the Sea Convention) - UNCLOS III**

The United Nations Convention on the Law of the Sea, which was officially opened for signature in Montego Bay, Jamaica, on December 10, 1982, and subsequently entered into force on November 14, 1994, holds binding status for 154 states, in addition to the European Community (as of July 24, 2008). This pivotal convention is widely recognized as the "constitution of the oceans" and represents an unparalleled and as-yet-unmatched endeavor in the codification and progressive development of international law.[20]

Grounded in General Assembly Resolution 2749 (XXV) of December 17, 1970, the Convention serves as a foundational framework for the continued evolution of specific aspects within the domain of the Law of the Sea. Its comprehensive scope encompasses more than 400 articles and nine integral annexes, constituting the most expansive and detailed outcome of codification efforts ever undertaken and successfully completed by member states under the auspices of the United Nations.

The Convention delineates that the seabed and ocean floor, along with their subsoil, are positioned beyond the purview of national jurisdiction, constituting what is commonly referred to as "the area." The provisions outlined in General Assembly Resolution 2749 (XXV) of December 17, 1970, support the idea that the resources therein are part of humanity's shared heritage.

Crucially, the Convention expressly prohibits any state from asserting sovereignty or sovereign rights over these areas, mandating that their utilization be solely for peaceful purposes. Furthermore, it stipulates that exploration and exploitation of these resources must transpire within the framework of an "international regime," supported by an "appropriate international machinery. This international regime is to be established through a universally agreed-upon international treaty of comprehensive scope.[21]

## 3-2) 1990: Charter for the Protection and Management of the Archaeological Heritage **(Approved by the 9th General Assembly in Lausanne – ICOMOS)**

Following the pivotal advancements brought about by the 'Venice Charter' in 1966, which significantly advanced the cause of global archaeological sites, the subsequent establishment of the 'ICAHM' (ICOMOS International Committee on Archaeological Heritage Management) marked a pivotal milestone in furthering the safeguarding of such heritage.[22]

The '1990 Charter' provides a comprehensive definition of 'archaeological heritage,' encompassing all aspects of material heritage for which archaeological methodologies serve as the primary source of information. This all-encompassing definition includes the entirety of human vestiges, including places associated with various facets of

[20] The Third United Nations Conference on the Law of the Sea, *United Nations Convention on the Law of the Sea*, 1982.

[21] 'United Nations Convention on the Law of the Sea - Main Page' <https://legal.un.org/avl/ha/uncls/uncls.html> [accessed 18 May 2022].

[22] International Committee for the Management of Archaeological Heritage (ICAHM), *Charter for the Protection and Management of the Archaeological Heritage*, 1990.

human activity, abandoned structures, and a diverse array of remnants, along with all portable cultural artifacts affiliated with these contexts.[23]

The protection of this invaluable heritage transcends the application of archaeological techniques alone, necessitating a broader foundation of professional and scientific knowledge and expertise. Consequently, it underscores the imperative for effective collaboration among experts from diverse disciplines. This collaborative approach extends to encompass government authorities, academic researchers, both private and public enterprises, and the broader public.

Key elements covered by the Charter include delineating the responsibilities of public authorities and legislators and establishing fundamental principles governing the professional execution of processes such as inventorying, surveying, excavation, documentation, research, maintenance, conservation, preservation, reconstruction, information dissemination, presentation, public access, and utilization of heritage assets. Furthermore, it outlines the qualification criteria for professionals engaged in the protection and preservation of archaeological heritage.[24]

## 3-3) 1991: Foundation of the International Committee on the Underwater Cultural Heritage (ICUCH)

The 'International Committee on Underwater Cultural Heritage (ICUCH)' constitutes one of the specialized international scientific committees operating under the umbrella of the 'International Council on Monuments and Sites (ICOMOS). Established in 1991, its primary mission revolves around fostering international collaboration for the safeguarding and management of underwater cultural heritage. Additionally, it serves as an advisory body to ICOMOS on matters pertaining to underwater cultural heritage across the global spectrum.

Comprising ICOMOS members and an array of international experts specializing in underwater cultural heritage, the committee has grown to include nearly 60 members hailing from 47 countries, spanning UNESCO's five geographical regions, which encompass Africa, the Arab States, Asia and the Pacific, Europe, and North America, as well as Latin America and the Caribbean.

ICUCH is engaged in a diverse array of activities, including the promotion of ethical stewardship of underwater cultural heritage, with a strong emphasis on prioritizing in situ preservation as the foremost approach. It actively supports scientific research encompassing both non-disturbance and disturbance-related activities. Furthermore, the committee encourages the public presentation of underwater cultural heritage and fosters public engagement in its preservation efforts. A central tenet of its mission involves elevating the visibility of the world's underwater cultural heritage and enhancing public awareness regarding its existence and intrinsic value.

ICUCH plays an instrumental role in promoting ethical practices in the field of underwater cultural heritage by facilitating the development of national and regional cooperation initiatives, programs, and legislative frameworks. It advocates for an inclusive approach to addressing underwater cultural heritage matters and extends its support

[23] 'The Venice Charter - International Council on Monuments and Sites' <https://www.icomos.org/en/participer/179-articles-en-francais/ressources/charters-and-standards/157-the-venice-charter> [accessed 27 April 2023].

[24] International Committee for the Management of Archaeological Heritage (ICAHM).

to educational and capacity-building initiatives geared towards enhancing the management, research, protection, conservation, and dissemination of underwater cultural heritage knowledge. The committee also functions as an information hub, providing critical insights to governments, the general public, and political organizations concerning the protection and preservation of underwater cultural heritage.[25]

## 3-4) 1996: Charter for the Protection and Management of the Archaeological Heritage **(Approved by the 11th General Assembly in Sofia, Bulgaria – ICOMOS)**

The purpose of this Charter is to advocate for the preservation and effective management of underwater cultural heritage across a spectrum of aquatic environments, encompassing inland and inshore waters, shallow seas, and the depths of the oceans. It is meticulously tailored to address the distinctive attributes and intricate circumstances associated with cultural heritage submerged beneath water, serving as a complementary framework to the ICOMOS Charter for the Protection and Management of Archaeological Heritage, 1990.

Within this Charter, 'Underwater Cultural Heritage' is defined as a subset of 'archaeological heritage' that is situated underwater, having either been discovered in its submerged context or previously extracted from the aquatic environment. This heritage holds international significance by virtue of its intrinsic nature, encompassing submerged structures, sites, wrecks, and their contextual surroundings. It is pertinent to note that a substantial portion of such heritage is located within international waters, often marking the locations where ships have been lost in remote maritime expanses.

Underwater cultural heritage faces multifaceted threats, including those arising from construction activities that modify shorelines and seabeds or disrupt the natural flow of currents, sediment, and pollutants. Insensitive exploitation of both living and non-living resources, as well as inappropriate forms of access and the incremental impact of souvenir removal, also pose significant risks.

One of the principal objectives of this Charter is to facilitate the prompt and efficient deployment of advanced archaeological expertise in addressing threats to underwater cultural heritage. Furthermore, it endeavors to ensure that the goals, methodologies, and expected outcomes of all investigations are rendered explicit and transparent to all stakeholders involved in these endeavors.[26]

## 3-5) 2000: Council of Europe Landscape Convention ( Florence Convention)

**Amended by the 2016 Protocol**

The overarching objective of the Convention is to foster the adoption of comprehensive policies and measures by public authorities operating at local, regional, national, and international tiers for the preservation, management, and strategic planning of landscapes across Europe. These encompass all landscapes, whether characterized as exceptional or commonplace, as they collectively contribute to defining the quality of the living environment for

[25] Hakan Öniz.

[26] The General Conference of the United Nations Educational, Scientific and Cultural Organization, *Convention on the Protection of the Underwater Cultural Heritage*, 2001.

individuals. The Convention delineates a flexible framework to accommodate the diverse attributes of landscapes, warranting a spectrum of interventions that span from rigorous conservation to protective measures, effective management, improvement, and even the active creation of landscapes.

To advance this agenda, the Convention introduces a series of legal and financial mechanisms, both at the national and international scales, with the primary aim of shaping coherent 'landscape policies.' Furthermore, it advocates for heightened synergy between local and central authorities and promotes cross-border collaboration in the realm of landscape preservation. The Convention offers a range of tailored solutions that member states can employ, taking into account their specific requirements and contextual nuances.

The oversight and monitoring of the Convention's implementation will fall under the purview of the Council of Europe's intergovernmental committees, ensuring its effective execution and adherence across member states.[27]

## 3-6) 2001: Rules in the Annex of the UNESCO Convention on the Protection of Cultural Heritage ( UNESCO 2001 Convention)

Threats to underwater cultural heritage (UCH), such as treasure hunting, looting, and commercial exploitation, persist as significant challenges. The rapid industrialization of coastal regions has ushered in remarkable developments but also heightened the availability of marine resources, consequently exposing UCH to environmental degradation. Despite its profound importance and distinctiveness, UCH often grapples with inadequate legislative support due to its unique characteristics and submerged location.

The adoption of the Convention stemmed from a recognition of the imperative to codify and progressively enhance regulations pertaining to the safeguarding and preservation of underwater cultural heritage. This imperative aligns with established international norms and practices, including the principles outlined in the UNESCO Convention on the Means of Prohibiting and Preventing the Illicit Import, Export, and Transfer of Ownership of Cultural Property of November 14, 1970, the UNESCO Convention for the Protection of the World Cultural and Natural Heritage of November 16, 1972, as well as the United Nations Convention on the Law of the Sea of December 10, 1982.[28]

## 3-7) 2001: Siracusa Declaration on the Submarine Cultural Heritage of the Mediterranean Sea ( Siracusa Declaration)

During the International Conference titled "Means for the Protection and Touristic Promotion of the Marine Cultural Heritage in the Mediterranean," which convened in Palermo and Siracusa, Italy, from March 8th to 10th, 2001, experts from several Mediterranean-bordering countries came together. Their collective concern stemmed from the realization that the underwater cultural heritage in this region faced threats arising from uncontrolled exploration and appropriation activities that disregarded the imperatives of preservation and research. The increasing commercialization of newly discovered artifacts and the harm caused by various other marine activities exacerbated

[27] The Committee of Ministers of the Council of Europe, *Council of Europe Landscape Convention*, 2000.
[28] The General Conference of the United Nations Educational, Scientific and Cultural Organization.

these worries. The participants, acting in their personal capacities, formulated the Siracusa Declaration on the Submarine Cultural Heritage of the Mediterranean Sea.
The declaration advocates for the implementation of 'Legal and Financial Measures' at both the national and international levels, with the goal of shaping comprehensive 'Landscape Policies. It emphasizes the importance of fostering collaboration among authorities at all levels, including the facilitation of cross-border cooperation in the realm of landscape protection. The declaration further presents a spectrum of options that member countries can choose from, tailoring their approach to suit their unique needs. Oversight of the implementation process will be entrusted to the intergovernmental committees of the Council of Europe.
In addition, the text introduces the establishment of the 'Council of Europe Landscape Award,' designed to commend regional governments and non-governmental organizations that have exhibited exceptional commitment to supportive policies pertaining to underwater cultural heritage.[29]

### 3-8) 2011: Council of Europe Framework Convention on the Value of Cultural Heritage for Society (Faro Convention)

The Faro Convention underscores the vital intersection between heritage, human rights, and democracy. It underscores the significance of heritage within the context of communities and society, prompting a broader appreciation of its multifaceted dimensions. Within the Convention's framework, there is a call to acknowledge that cultural heritage objects and sites derive their importance not from their intrinsic qualities but rather from the meanings, uses, and values that individuals and societies attribute to them.
This convention operates as a 'framework convention,' delineating key issues, overarching objectives, and potential areas of engagement. Importantly, it does not impose binding obligations; instead, it allows each 'State Party' the autonomy to select the most suitable method of implementation from a range of suggested approaches.[30]

## 4) Marine Protected Areas (MPA)

A protected area is a well-defined geographic space, officially acknowledged and designated through legal or other highly effective mechanisms, with the primary objective of ensuring the sustained conservation of natural elements along with their associated ecosystem services and cultural significance.[31]

[29] Università di Milano"Bicocca" (Dipartimento Giuridico delle Istituzioni Nazionali ed Europee), Regione Siciliana (Assesorato dei Beni Culturali ed Ambientali e della Pubblica Istruzione), and Università degli Studi di Palermo, Facoltà di Economia (Istituto di Diritto del Lavoro e della Navigazione), *Siracusa Declaration on the Submarine Cultural Heritage of the Mediterranean Sea*, 2001.
[30] Council of Europe, Directorate of Democratic Governance, DG II, Managing Diversity Division, *Framework Convention on the Value of Culturale Heritage for Society*, 2015.
[31] Nigel Dudley, *Guidelines for Applying Protected Area Management Categories* (IUCN, 2008) <https://doi.org/10.2305/IUCN.CH.2008.PAPS.2.en>.

To enhance the precision of this definition, it is essential to delve deeper into specific phrases, as outlined in the 'Guidelines for Applying the IUCN Protected Area Management Categories to Marine Protected Areas:[32]

***Clearly defined:*** This implies a spatial area with explicitly outlined and agreed-upon boundaries. Riverbanks and other physical characteristics that may change over time, as well as managerial measures like designated no-take zones, may establish these boundaries.

***Geographical space:*** encompasses terrestrial, inland aquatic, marine, coastal, or a combination thereof. Recognizing that space has three dimensions, it can include restrictions on airspace or water depth, protecting the seabed while allowing certain activities in the water above.

***Recognized:*** Indicates that protection may result from a variety of governance arrangements, whether declared by people or sanctioned by the state, but these areas should be officially recognized in some manner, including listing in the World Database on Protected Areas (WDPA).

***Dedicated:*** signifies a binding commitment to long-term conservation through various means, such as international agreements, national laws, customary practices, NGO commitments, private trusts, or corporate policies.

***Managed:*** This implies active measures to conserve the natural values for which the protected area was established. Management can involve leaving the area untouched if this approach best serves conservation objectives.

***Legal or other effective means:*** It encompasses formal legal recognition, either through statutory civil law or international agreements, as well as effective, non-gazetted mechanisms like traditional community rules or NGO policies that ensure protection.

***To achieve:*** signifies the need for a level of effectiveness, introducing a new aspect to the definition to address the requests of protected area managers. While categorization remains objective, management effectiveness will progressively become a critical criterion for identification and recognition, as recorded in the WDPA.

***Long-term:*** emphasizes that protected areas should be managed perpetually, emphasizing a commitment to sustained, rather than short-term or temporary, conservation strategies.

***Conservation:*** Within this context, conservation pertains to the in situ preservation of ecosystems, natural habitats, and viable species populations in their native environments. It also includes domesticated or cultivated species within their customary surroundings, where they have developed distinct attributes.

***Nature:*** In this context, nature exclusively refers to biodiversity, encompassing genetic, species, and ecosystem levels, and may also encompass geodiversity, landform characteristics, and broader natural values.

Associated ecosystem services: This signifies ecosystem services linked to but not conflicting with the primary goal of nature conservation. These services can encompass provisioning (e.g., food and water), regulation (e.g., flood control), support (e.g., soil formation), and cultural (e.g., recreational) services.

[32] Jon Day and others, *Guidelines for Applying the IUCN Protected Area Management Categories to Marine Protected Areas* (IUCN, 2019) <https://portals.iucn.org/library/node/48887> [accessed 21 May 2022].

***Cultural values:*** encompass values that do not compromise conservation objectives. These values may include those contributing to conservation outcomes (e.g., traditional management practices benefiting key species) and those facing their own threats.[33]

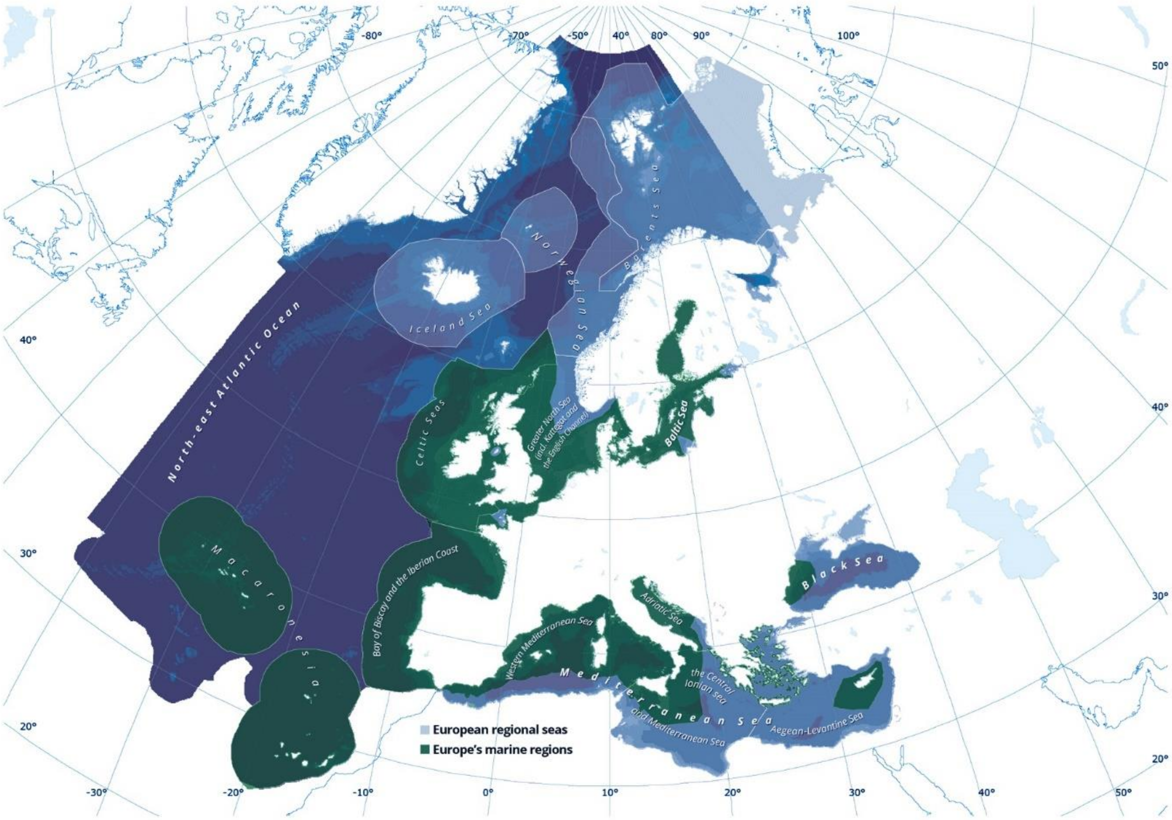


Fig 2-14) Europe's regional seas are defined as shown on the map.
Marine waters of EU Member States make up the assessment areas used to calculate the coverage of MPA network

[33] Day and others.

## 4-1) The MPA Policies

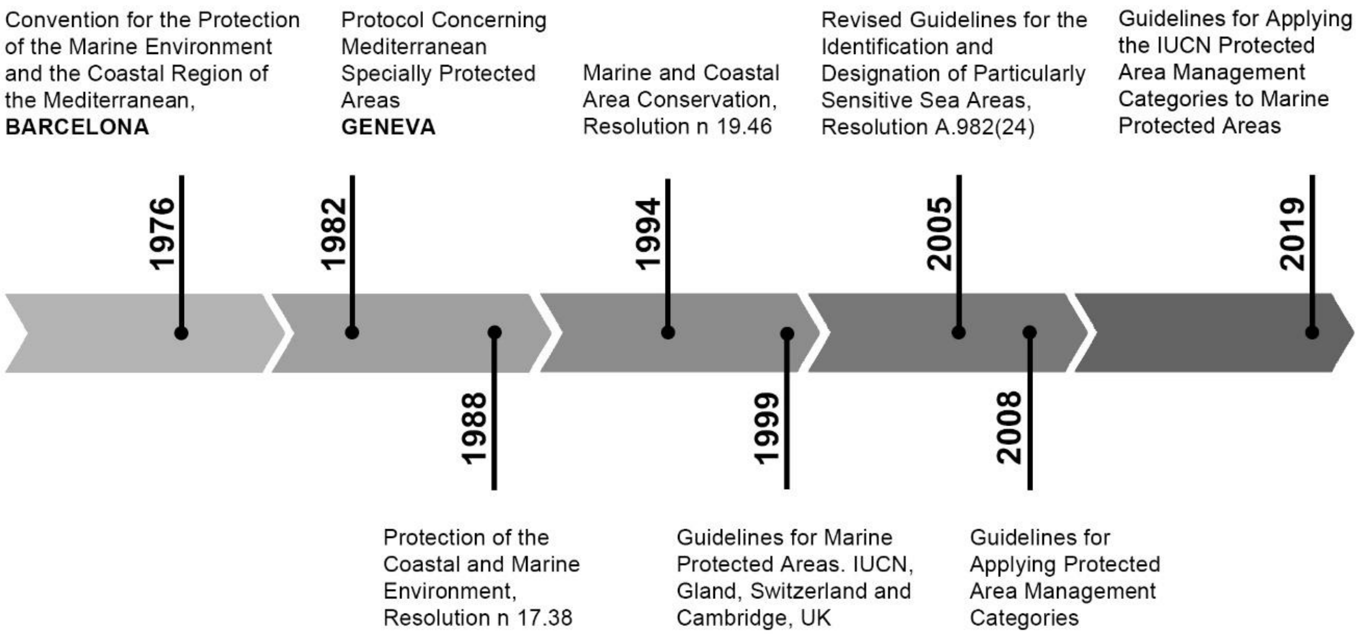


Fig 2-15) MPA Legalization

### 4-1-1) 1976: Convention for the Protection of the Mediterranean Sea Agaist Pollution (Barcelona Convention) - United Nations

Considering the distinctive characteristics and susceptibility of the Mediterranean region, the signatory parties to the treaty prioritized a phased approach to address environmental concerns. This approach focused initially on reducing pollutants and subsequently on safeguarding and restoring the marine ecosystem.

The parties to the treaty committed to implementing a comprehensive set of measures aimed at preventing and mitigating pollution in the Mediterranean. These measures encompass the following:

**Pollution Prevention:** Parties pledged to undertake all necessary measures to prevent and mitigate pollution in the Mediterranean arising from various sources, including:

- Dumping of waste from ships and aircraft
- Discharges from ships
- Pollution resulting from seabed and subsoil exploration and exploitation
- Discharges from rivers, coastal facilities, and other land-based sources within their territories.

**Cooperative Actions:** The signatory parties agreed to collaborate in a series of cooperative efforts, including:

- Implementing measures to address pollution emergencies, regardless of their origin,
- Establishing comprehensive programs for monitoring pollution in the Mediterranean area
- Supporting scientific and technical research activities related to all forms of marine pollution.
- Developing procedures for determining liability and providing compensation for damages arising from violations of the Convention and its Protocols.

These commitments collectively aim to address the various facets of pollution and environmental degradation within the Mediterranean region, reflecting a shared dedication to protecting this unique and ecologically sensitive area.[34]

### 4-1-2) 1982: Protocol Concerning Mediterranean Specially Protected Areas

On April 3, 1982, in Geneva, the Protocol Relating to Specially Protected Areas in the Mediterranean Sea was signed. The signatory parties to this protocol were also parties to the 'Convention for the Protection of the Mediterranean Sea against Pollution, adopted in Barcelona on February 16, 1976. Recognizing the environmental challenges faced by the 'Mediterranean Sea Area' due to intensified human activities in the region, they reached a consensus on several critical issues.

In doing so, they took into consideration the unique hydrographic and ecological characteristics of the Mediterranean Sea Area. Their shared commitment emphasized the paramount importance of preserving and, where feasible, enhancing the condition of the natural resources, natural sites, and cultural heritage within the Mediterranean Sea region.[35]

### 4-1-3) 1988: Protection of the Coastal and Marine Environment (Resolution n 17.38)

According to this declaration, the expanse of the sea and seabed exceeds that of the world's landmasses by over two and a half times. Regrettably, less than 1% of this vast marine territory is presently protected, highlighting a substantial disparity in marine environmental conservation when compared to terrestrial areas. It is recognized that the immense diversity of marine and estuarine ecosystems, encompassing a wide array of animals, plants, and communities, holds pivotal significance within self-sustaining systems at local, regional, national, and international scales. These ecosystems constitute an integral component of the world's natural and cultural heritage.[36]

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[34] IUCN, *Convention for the Protection of the Mediterranean Sea against Pollution*, 1976 <https://www.ecolex.org/details/treaty/convention-for-the-protection-of-the-mediterranean-sea-against-pollution-tre-000543/?q=Convention+for+the+Protection+of+the+Marine+Environment+and+the+Coastal+Region+of+the+Mediterranean+1976&type=legislation&xdate_min=&xdate_max=> [accessed 11 May 2022].

[35] 'No. 24079. Protocol Concerning Mediterranean Specially Protected Areas. Concluded at Geneva on 3 April 1982', in *Treaty Series 1858*, by United Nations, United Nations Treaty Series (UN, 2001), pp. 448–448 <https://doi.org/10.18356/969b5995-en-fr>.

[36] IUCN, *Protection of the Coastal and Marine Environment, GA 1988 RES 038 (17.38)*, 1988 <https://www.ecolex.org/details/literature/protection-of-the-coastal-and-marine-environment-mon-092246/?q=Protection+of+the+coastal+and+marine+environment> [accessed 11 May 2022].

Concerningly, certain areas have already suffered severe degradation due to direct or indirect human activities, and the rate of such degradation is rapidly escalating. While acknowledging the continued welfare of communities traditionally reliant on marine areas, it is imperative that the responsible stewardship of living and non-living coastal and deep ocean resources, as well as the seabed, become a shared national and international responsibility. This stewardship is vital to ensuring their preservation and judicious utilization for the immediate and lasting benefit and enjoyment of both present and future generations.[37]

In this regard, the International Union for Conservation of Nature (IUCN) has outlined a comprehensive objective for a global network of Marine Protected Areas (MPAs), as articulated in its General Assembly Resolutions. The goal is "to provide for the protection, restoration, wise use, understanding, and enjoyment of the marine heritage of the world in perpetuity through the creation of a global, representative system of marine protected areas and through the management, in accordance with the principles of the World Conservation Strategy, of human activities that use or affect the marine environment. The subsequent sections of the declaration elucidate the mechanics and principles underpinning the establishment and operation of this network.[38]

### 4-1-4) 1994: Marine and Coastal Area Conservation (Resolution n 19.46)

Recognizing the global imperative of integrated management for coastal and marine environments, the 19th Session of the General Assembly of the World Conservation Union, convened in Buenos Aires, Argentina, extends an invitation to governments, international organizations, and the non-governmental sector. The purpose of this invitation is to address the following key objectives:

***Priority to Conservation Programs:*** Emphasizing the need to accord priority to the initiation and support of conservation programs aimed at achieving integrated management of coastal lands, waters, shallow seas, and marine environments These programs should be designed to meet the sustainable requirements of nations, regions, and the global community over the long term.

***Inclusivity in Development Strategies:*** Advocate for the active involvement of all levels and pertinent governmental agencies, local communities, non-governmental organizations, related industries, and other relevant stakeholders in the formulation of strategies and the execution of programs.

***Respect for Indigenous and Local Involvement:*** Encourage coastal nations, especially in situations where the indigenous and traditional use of the sea is implicated, to incorporate indigenous and local populations as partners in discussions and significant steps concerning the planning, development, management, and maintenance of these areas.

***Capacity Building and Resource Provision:*** Allocate resources to foster capacity-building efforts within each coastal nation and among regional communities of nations that share common waters. This support is intended to

[37] IUCN, *Protection of the Coastal and Marine Environment, GA 1988 RES 038 (17.38)*.

[38] *Guidelines For Marine Protected Areas*, ed. by Graeme Kelleher and Adrian Phillips (IUCN Publications Services Unit, 219c Huntingdon Road, Cambridge CB3 ODL, United Kingdom: IUCN, Gland, Switzerland and Cambridge, UK, 1999) <https://doi.org/10.2305/IUCN.CH.1999.PAG.3.en>.

facilitate the development and implementation of sustainable integrated management for coastal, shallow sea, and marine environments and resources.

***Global Networks for Capacity Enhancement:*** Foster the establishment of effective global networks aimed at peer support to enhance management capacity and training. These networks should promote extensive sharing of experience, research findings, and technical knowledge among nations and regions within the global community. The overarching goal is to advance integrated management of coastal, shallow sea, and marine environments and resources in the pursuit of sustainable development.

***Responsibility Allocation and Conflict Resolution:*** Define and designate responsibilities and mechanisms for marine conservation and for resolving conflicts related to resource utilization.

***Marine Protected Areas:*** Encourage coastal nations to establish representative systems of marine protected areas under their national legislation, encompassing areas with wilderness designation.

***International Mechanisms for Protected Areas:*** Promote, within suitable international frameworks, the establishment of protected areas, including those designated as wilderness, in regions extending beyond the confines of national jurisdiction.

This invitation underscores the commitment to collective action and international cooperation to address the complex challenges posed by coastal and marine environmental management.[39]

## 4-1-5) 1999: Guidelines for Marine Protected Areas

**Gland, Switzerland and Cambridge, UK - 'IUCN'**

Marine Protected Areas (MPAs) constitute a vital component of global initiatives aimed at conserving the Earth's marine heritage and sustaining the fundamental life-support systems. They also play a pivotal role in ensuring the ecologically sustainable utilization of living marine resources. The establishment of a comprehensive system of MPAs is of utmost urgency to safeguard biodiversity and facilitate the restoration of ocean productivity.

The objective of these Guidelines is to provide countries with valuable assistance in the development of MPA systems, which are integral to the integrated management of their coastal and marine territories and integral to their sustainable development goals. MPAs serve as instrumental tools in realizing the three fundamental objectives of conserving living resources as articulated in the World Conservation Strategy (IUCN, 1980). These objectives encompass the preservation of essential ecological processes and life support systems, the safeguarding of genetic diversity, and the promotion of sustainable utilization of species and ecosystems.

These Guidelines offer a comprehensive framework, spanning the entire spectrum from the initial planning phases to actual implementation. While they do not delve into the minutiae of day-to-day MPA management operations, they nonetheless furnish critical guidance to natural resource managers across all levels, whether engaged in environmental conservation or the sustainable management of marine resources. The guidelines are also invaluable resources for policymakers, planners, and on-the-ground managers.

[39] IUCN, *Marine and Coastal Area Conservation , GA 1994 REC 046 (19.46)*, 1994 <https://portals.iucn.org/library/node/43915> [accessed 11 May 2022].

It is imperative to note that these guidelines supersede the previous IUCN guidelines issued in 1991. They form part of a collection of contemporary documents pertaining to MPAs, developed by the International Union for Conservation of Nature's World Commission on Protected Areas (WCPA).

The establishment of MPAs aligns with the obligations outlined in international agreements such as the United Nations Convention on the Law of the Sea (UNCLOS) and the Convention on Biological Diversity (CBD). Despite these commitments, the presence of large, effectively managed MPAs remained infrequent, rendering the existing network woefully inadequate. The hope is that these guidelines, formulated by IUCN, will facilitate the creation and effective management of MPAs on a global scale, thereby expediting progress and success. In this regard, governments are urged to earnestly adopt and implement the various international conventions and IUCN resolutions related to MPAs that they have embraced.

Furthermore, active participation from local communities and non-governmental organizations is strongly encouraged throughout this process. International entities, including UNESCO, UNEP, UNDP, the World Bank, the Global Environmental Facility, WWF, and IUCN, are called upon to lend their essential support and encouragement to bolster this endeavor.[40]

### 4-1-6) 2005: Revised Guidelines for the Identification and Designation of Particularly Sensitive Sea Area (PSSAs) - IMO

This document offers comprehensive guidance on the designation of Particularly Sensitive Sea Areas (PSSAs). The International Maritime Organization (IMO) has endorsed the Resolution, which is a crucial tool for improving global maritime safety, reducing pollution, and addressing various issues relating to international marine shipping.

The designation of a PSSA is warranted when a specific area boasts recognized ecological, socioeconomic, or scientific attributes that render it susceptible to potential harm from international shipping activities. The IMO must endorse or enact an accompanying protective measure at the time of designating a PSSA. This protective measure is essential to thwart, mitigate, or eliminate identified threats or vulnerabilities. Moreover, these protective measures must align with the prerequisites stipulated within the relevant legal instrument that establishes such measures.

It is important to protect areas that are important for biodiversity conservation and other areas that have high scientific, cultural, historical, or archaeological value. This is emphasized in many international and regional agreements. These instruments oblige signatories to shield these sensitive areas against damage or degradation arising from shipping activities.

The overarching purpose of these Guidelines is threefold:

- To furnish guidance to IMO Member Governments concerning the formulation and submission of applications for PSSA designation.
- To ensure that the process incorporates a comprehensive consideration of all interests, encompassing those of the coastal state and flag state, as well as the environmental and shipping communities. Relevant

[40] Kelleher and Phillips.

scientific, technical, economic, and environmental data pertaining to the region at risk of harm from international shipping activities and the accompanying protective measures intended to mitigate such risks should serve as the foundation for this scrutiny.

- To establish a framework for the evaluation of these applications within the IMO.

The process of identifying and designating a PSSA, along with the adoption of associated protective measures, necessitates a meticulous assessment of several factors. These include the unique characteristics of the proposed area, its susceptibility to harm stemming from international shipping activities, and the feasibility of implementing protective measures within the purview of the IMO's competencies to avert, lessen, or nullify the risks associated with these shipping activities.[41]

### 4-1-7) 2008: Guidelines for Applying Protected Area Management Categories - 'IUCN'

The IUCN's Protected Areas Management Categories, which categorize protected areas based on their management objectives, have gained widespread recognition as the standard for delineating, documenting, and classifying protected areas. These categories enjoy acknowledgment from prominent international organizations like the United Nations, in addition to numerous national governments. Consequently, there is a growing trend toward integrating these categories into governmental legislation.

In light of this, these guidelines endeavor to offer maximum clarity concerning the interpretation and implementation of these Categories. They aim to elucidate the definition of each Category and provide insights into its application within specific biomes and management paradigms.[42]

### 4-1-8) 2019: Guidelines for Applying the 'IUCN' Protected Area Managemenet Categories to Marine Protected Areas - 'IUCN'

The development of this second edition of the guidelines stemmed, in part, from a recognition of the widespread misapplication of the categories pertaining to Marine Protected Areas (MPAs). It's important to note that marine management and sustainable fisheries management, while pivotal aspects of effective ocean governance, differ from the domain of protected area management, where the principal emphasis lies on the conservation of natural ecosystems.

The primary objective of these supplementary guidelines is to enhance precision and uniformity in the assignment and reporting of IUCN categories when employed in the context of marine and coastal protected areas. These supplementary guidelines are designed to facilitate the effective application of IUCN categories across all types of MPAs, as well as in situations involving the marine segments of adjacent terrestrial protected areas, contingent upon the fulfillment of the IUCN's defined criteria for a protected area.[43]

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[41] *The Legal Order of the Oceans: Basic Documents on Law of the Sea*, ed. by Vaughan Lowe and Stefan Talmon (Bloomsbury Publishing Plc, 2009) <https://doi.org/10.5040/9781509955572>.

[42] Dudley.

[43] Day and others.

## Chapter 3

# The Theory of Geomatics

## 1) Survey and Geomatics

### 1-1) Aims and Definitions

Surveying science is a field that deals with the precise determination of the location, elevation, distance, and angles of natural and constructed structures found on or below the Earth's surface. It is an essential part of various industries such as construction, engineering, urban planning, and resource management. Surveyors use specialized instruments and techniques to capture and record data, which can be presented in different forms such as maps, plans, charts, or digital models. The science of surveying also involves the development and application of advanced technologies such as remote sensing, geographic information systems (GIS), and Global Positioning System (GPS) technology to enhance the accuracy and efficiency of surveying processes. Surveying science has been essential in the growth and development of many industries, and it continues to progress with new advancements and innovations.

The term "geomatics" was coined in the early 1980s at Laval University in Canada. It was based on the notion that electronic computing's expanding capabilities were transforming surveying and representation sciences. This computerized design, such as video diagrams, could be used to effectively analyze massive amounts of data.[1] Geomatics is a term that is fairly recent in origin and was first used in Canada before it spread to Australia and eventually to the UK.

Improving the images acquired during surveying, or in other words, making them more up-to-date, up-market, and simultaneously in an advanced collaboration with the latest technologies, plus making the surveying programs more prevalent among academic enthusiasts, were the main reasons to apply the changes.[2]

Geomatics is the mathematical study of the Earth and its related phenomena, relationships, and processes. This term, derived from the words ***"geo"*** (meaning "Earth") and ***"metrics"*** (from mathematics), refers to the discipline

[1] Mario Gomarasca, 'Basics of Geomatics', *Applied Geomatics*, 2 (2010), 137–46 <https://doi.org/10.1007/s12518-010-0029-6>.
[2] 'Should We Replace the Word "Geomatics"?' <https://www.gim-international.com/content/article/should-we-replace-the-word-geomatics> [accessed 14 April 2023].

of geospatial technology or geomatics engineering, which entails the collection, storage, processing, and distribution of spatially referenced or geographic information. Geomatics is crucial in the planning and monitoring of social, economic, and technological processes.

Today's surveyors' abilities and knowledge have expanded significantly, allowing them to apply their equipment and expertise, as well as their understanding of the exactitude and relative precision of measurements from various origins, to a wide range of fields that extend beyond the traditional domains of surveying and mapping.[3]

Geomatics is a field of study that focuses on the collection, analysis, interpretation, and management of geographic data. It involves the use of various technologies, including tools and techniques used in land surveying, remote sensing (LiDAR, UAV), cartography, geographic information systems (GIS), global navigation satellite systems (GPS, GLONASS, Galileo, and Compass), photogrammetry, geography, and related forms of Earth mapping.

Geomatics is an interdisciplinary field that combines various disciplines, such as surveying, geography, cartography, computer science, and engineering, to provide insights into the spatial aspects of different phenomena. Its applications are widespread and can be found in land use planning, environmental management, disaster management, transportation, urban planning, and natural resource management fields, as well as the cultural heritage management.

The goal is to create a thorough comprehension of the spatial relationships between different objects, features, and phenomena in the natural and built environment. This data can be used to make informed decisions and solve complex spatial data management and analysis problems.

Scientific activities related to Earth observations, data collection, and analysis have grown significantly over the decades, beginning with traditional surveying methods. Ground surveying, global satellite positioning systems, traditional and digital photogrammetry, and multispectral remote sensing from airplanes and satellites are now included in this expansion, with varying levels of geometric, spectral, radiometric, and temporal resolution. Despite these advancements, there is still a lack of understanding about how to properly use all of the available tools.[4]

Luckily thanks to modern equipment and technology, there is currently a significant opportunity to save manpower and money in the field of data collection and analysis processes.

[3] 'Should We Replace the Word "Geomatics"?'

[4] Gomarasca.

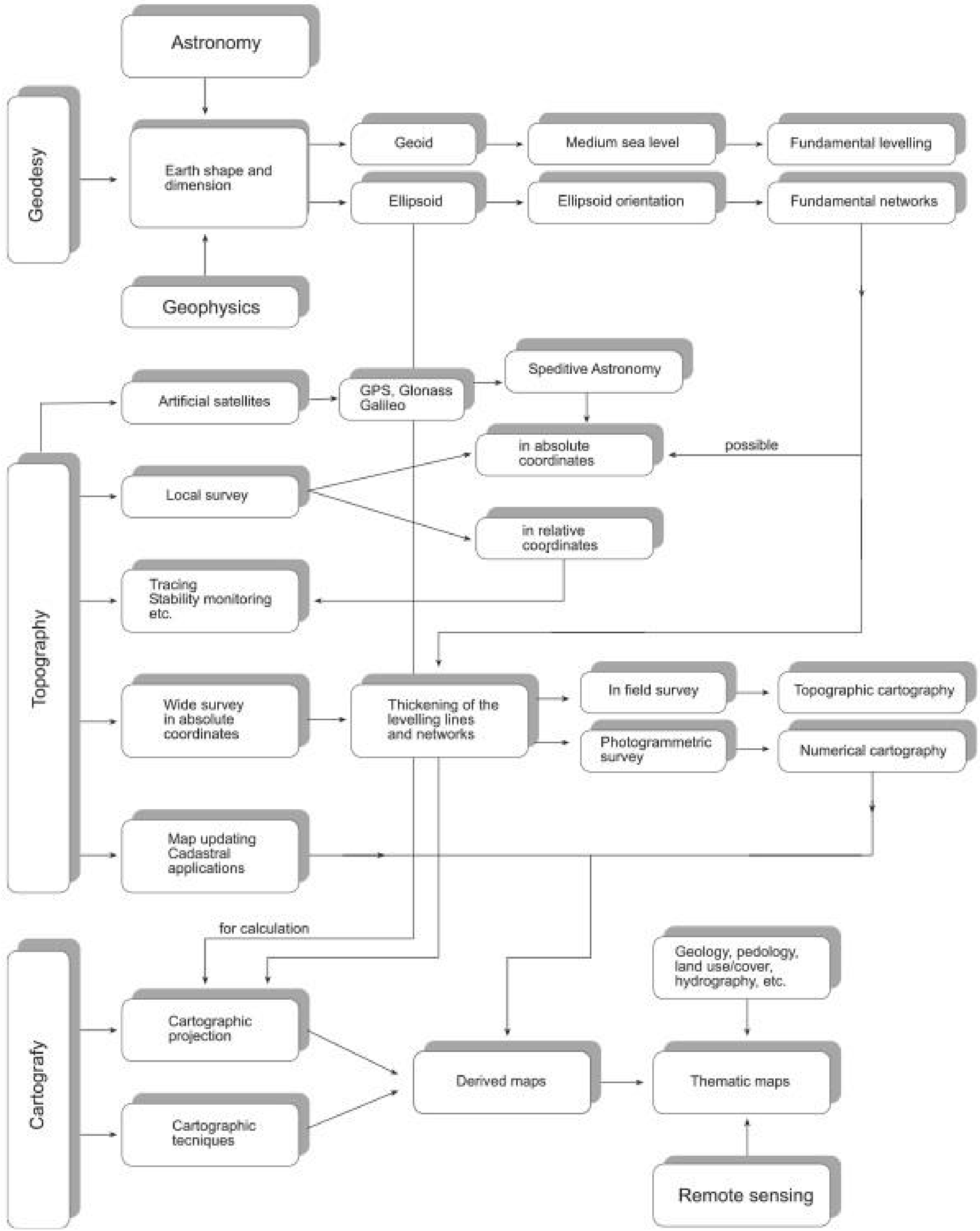


Fig 3-1) Relationship Among the Most Relevant Elements of Geomatics[5]

[5] Gomarasca.

## 1-2) Geomatics and 3D Digitization in Cultural Heritage

A review of recent developments in the field of documentation reveals that geomatic surveyors are becoming increasingly aware of the benefits that these techniques can provide in protecting heritage sites. The diverse range of methods developed and continuously improved by research in this field can now be classified as geomatics for preservation of cultural heritage.[6]

Therefore, Geomatics plays a crucial role in enhancing our understanding of an asset. It generates validated documentation concerning its geometric shape and various specific spatially-referenced topics. *"In all works of preservation, restoration or excavation, there should always be precise documentation in the form of analytical and critical reports, illustrated with drawings and photographs."*[7]

In the past, it was challenging to differentiate between measuring and interpreting a building, and the timing of these operations was often unclear. However, modern technologies have made it possible to perform on-site operations much more quickly. Therefore, minimal assumptions are necessary beforehand, and the interpretive phase can systematically follow the measurement stage. Geomatics has made it possible to bring heritage sites into the laboratory at present, providing experts with a range of new possibilities that cannot be achieved easily in the field.[8]

The conventional approach to surveying and measuring historical architecture is a slow and time-consuming process that has several limitations. This involves taking photographs and using manual tape methods to gather data, which is then manually transferred into engineering drawings in AutoCAD. Although 2-dimensional drawings can provide some support in reconstructing historical architecture, they are limited and cannot fully capture a truly 3-dimensional model. Advanced techniques are necessary to support the preservation and conservation of cultural heritage. Digitizing historical cultural architecture has become an international trend in preservation as traditional tools and methods of surveying and probing are ineffective and inefficient in supporting preservation procedures.[9]

Nowadays, advanced 3D measurement methods with high accuracy are commonly employed in industrial production and quality control to ensure precise inspection of objects. However, the potential of these techniques for surface monitoring is not limited to industrial use only. In the field of cultural heritage, a thorough and trustworthy spatial representation of surfaces is often beneficial and can bring about fresh opportunities for preserving, analyzing, or displaying objects.[10]

The availability of digital collections of 3D data has led to a fundamental change in the Cultural Heritage field, allowing for more effective communication of information about scenes or objects that have intrinsic 3D

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[6] Grazia Tucci and Valentina Bonora, 'Geomatics and Management of At-Risk Cultural Heritage', *Rendiconti Lincei*, 26.1 (2015), 105–14 <https://doi.org/10.1007/s12210-015-0427-0>.

[7] 'The Venice Charter - International Council on Monuments and Sites' <https://www.icomos.org/en/participer/179-articles-en-francais/ressources/charters-and-standards/157-the-venice-charter> [accessed 27 April 2023].

[8] Tucci and Bonora.

[9] *Digital Heritage: Third International Conference, EuroMed 2010, Lemessos, Cyprus, November 8-13, 2010. Proceedings*, ed. by Marinos Ioannides and others, Lecture Notes in Computer Science (Berlin, Heidelberg: Springer, 2010), <https://doi.org/10.1007/978-3-642-16873-4>.

[10] Ioannides and others, .

characteristics. 3D models are a powerful tool, particularly for archaeological and architectural applications, as they provide a more objective and reliable way to simulate reality. Furthermore, 3D models can be used as a visualization container or interface between different types of information, and can be organized according to semantic rules to ease data retrieval. Building Information Model (BIM) was created to describe building components with respect to their geometry, topology, and semantic information. Overall, 3D models offer a new way to access and exchange knowledge, leading to the recognition of connections and enlarging possibilities for interpretation and analysis of the past.[11]

## 1-3) Development of Geomatics

Over the years, various approaches to processing and interpreting data collected from different sensors have been proposed and tested in the geomatics community. The researchers aimed to strike the best balance between available resources, speed, accuracy, and ultimately linking the data and products for management, analysis, and evaluation. However, the most common practice remains the visual interpretation of spatial data, which requires manual work from multiple operators, making it time-consuming. Nowadays, researchers are focused on providing spatial data at a larger scale and reducing operational time by optimizing the workflow using standards and guidelines. This goal is achievable through the development of image-based and range-based solutions (air and ground) and the availability of modern, low-cost sensors.[12]

One of the main developments is mobile mapping systems (MMS), consisting of digital imaging or ranging devices, positioning or georeferencing devices, and computer systems. Initially, digital frame cameras or action cameras were used as imaging sensors, and ad hoc detection solutions were developed by configuring these devices with multiple camera networks. The field of research around 360-degree panoramic cameras has greatly benefited from these developments. With the introduction of Google Street View in 2007, the exponential growth of MMS began, making it the standard for documenting urban areas. The market for 360-degree cameras and MMS development have mutually benefited from their parallel growth.[13]

Range-based techniques follow a similar development path to these systems. Initially, traditional terrestrial laser scanners were adapted to the needs arising from their use in moving vehicles. After that, specific solutions were predicted and developed.[14] Regardless of the sensor(s) used in MMS, researchers face two major challenges: georeferencing the acquired data and synchronization. Global Positioning System (GPS) and Global Navigation Satellite System (GNSS) receivers were the first sensors used to georeference data obtained from other devices. For relative positioning, usually, an inertial measurement unit (IMU) or a distance measuring instrument (DMI) is

[11] Ioannides and others, .

[12] A. Calantropio and others, 'USE AND EVALUATION OF A SHORT RANGE SMALL QUADCOPTER AND A PORTABLE IMAGING LASER FOR BUILT HERITAGE 3D DOCUMENTATION', *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII–1 (2018), 71–78 <https://doi.org/10.5194/isprs-archives-XLII-1-71-2018>.

[13] *Advances in Mobile Mapping Technology*, ed. by C. Vincent Tao Li Jonathan (London: CRC Press, 2007) <https://doi.org/10.4324/9780203961872>.

[14] Gordon Petrie, 'Mobile Mapping Systems: An Introduction to the Technology', *Geoinformatics*, 13 (2010), 32–43.

used. One of the most difficult aspects of these systems is synchronizing and processing all the data collected simultaneously by platforms equipped with several devices.[15] The miniaturization of sensors and electronic components and research in this sector have created new scenarios in recent years. The exponential growth and development of unmanned aerial vehicles (UAVs), coupled with newly available sensors, have led to their successful deployment. The portability of MMS allows it to extend its deployment to other applications, such as indoor mapping.[16]

Moreover, the intersection of geomatics with other disciplines is generating fresh insights. For example, the fusion of geomatics and robotics has led to the development of mobile mapping systems that utilize simultaneous localization and mapping (SLAM) based on the homonymous algorithm.[17]

However, this paper will only focus on investigating an image-based methodology, particularly the capabilities arising from the utilization of GNSS and UAVs for documenting sunken vessels in the southern region of Italy.

[15] Lorenzo Teppati Losè, 'Geomatics Support to the Metric Documentation of the Archaeological Heritage. Tests and Validations on the Use of Low-Cost, Rapid, Image-Based Sensors and Systems.' (Politecnico di Torino, 2019).
[16] C.M. Ellum and N. El-Sheimy, 'Land-Based Integrated Systems for Mapping and Gis Applications', *Survey Review*, 36.283 (2002), 323–39 <https://doi.org/10.1179/sre.2002.36.283.323>.
[17] 'SLAM for Dummies: A Tutorial Approach to Simultaneous Localization and Mapping | BibSonomy' <https://www.bibsonomy.org/bibtex/10a62a970431f4e75c58328ba15d20557/b.bruns> [accessed 11 May 2023].

## 2) GNSS

The basic concept of GNSS (Figure 1) consists of various phases to determine time and position for end-user applications. The first phase consists of GNSS satellites orbiting the Earth with precise knowledge of their orbital periods and times, which ground control stations can modify as necessary. In the next phase, the satellites regularly broadcast their time and position, and the GNSS radio signals pass through the atmospheric layers to reach user equipment. Then to receive signals from multiple satellites using the GNSS user equipment, retrieve the transmitted information for each satellite, and determine the release time.

Following this, the GNSS user equipment uses the data retrieved to determine the time and position. Finally, in the last phase, the calculated position and time are provided to the end-user application for use in various contexts, such as navigation and mapping.[18]

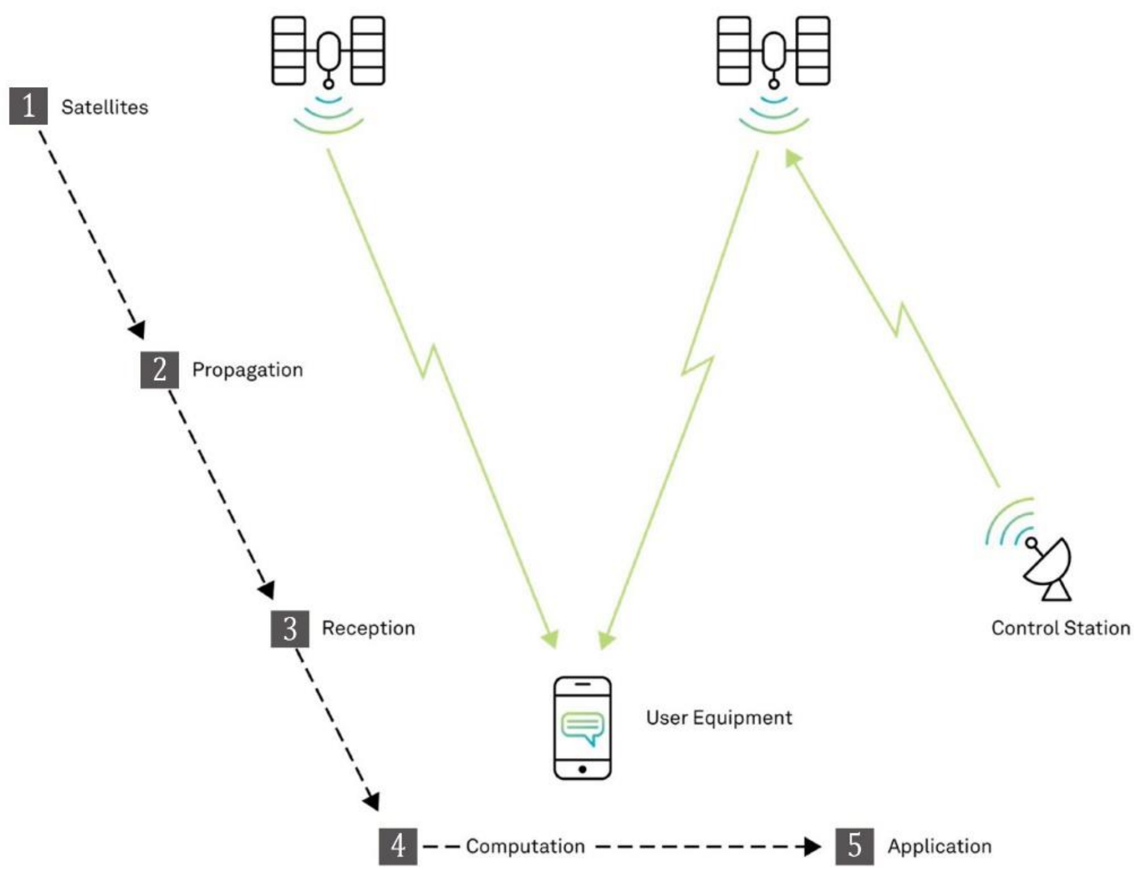


Fig 3-2) Basic GNSS[19]

[18] 'An Introduction to GNSS - NovAtel', *calameo.com* <https://www.calameo.com/read/0019157965c9cf7056211> [accessed 12 May 2023].
[19] 'An Introduction to GNSS - NovAtel'.

## 2-1) Satellites

Throughout history, Earth's surface points have evolved from distant objects to celestial navigation. The space age introduced precise positioning and navigation systems, such as optical and radio techniques. Transit, the US Navy Navigation Satellite System, was the most successful satellite-based positioning system, allowing receiver positions to be inferred from satellite orbit shifts. Transit measured the Doppler shift of the satellite signal during a full pass, enabling two-dimensional position-fix accuracies of several tens of meters.

In the modern era, Global Navigation Satellite System (GNSS) constellations, including GPS, GLONASS, Galileo, and BeiDou, offer accuracy, redundancy, and availability. GNSS signals are secure and jamming-resistant, but errors can accumulate over time. Satellites have finite lifespans and are occasionally replaced to improve signals and synchronization.[20]

## 2-2) Propagation

GNSS signals travel through space and several atmospheric layers before reaching Earth, with the satellite range calculated by multiplying the time to the receiver by light speed. The ionosphere and troposphere affect GPS signal transmission, with the frequency-dependent ionosphere and local temperature, pressure, and humidity affecting GPS. Advanced techniques track direct signals.[21]

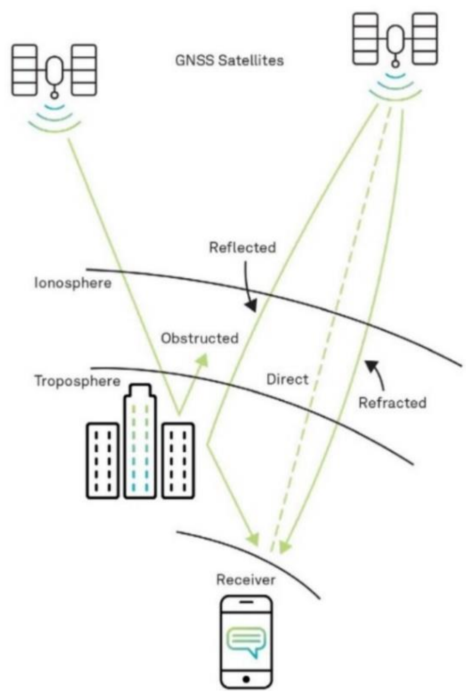


Fig 3-3) Basic GNSS GNSS Signal Propagation[22]

[20] 'An Introduction to GNSS - NovAtel'.
[21] 'An Introduction to GNSS - NovAtel'.
[22] 'An Introduction to GNSS - NovAtel'.

## 2-3) Reception

GNSS receivers need at least four satellites to accurately determine position and time. More satellites can improve the positioning solution, but computing power may limit their use. A line of sight is needed for tracking satellites. Selecting a GNSS antenna involves considering constellation and signal frequencies, antenna gain, element gain, beamwidth, and wave gain.[23]

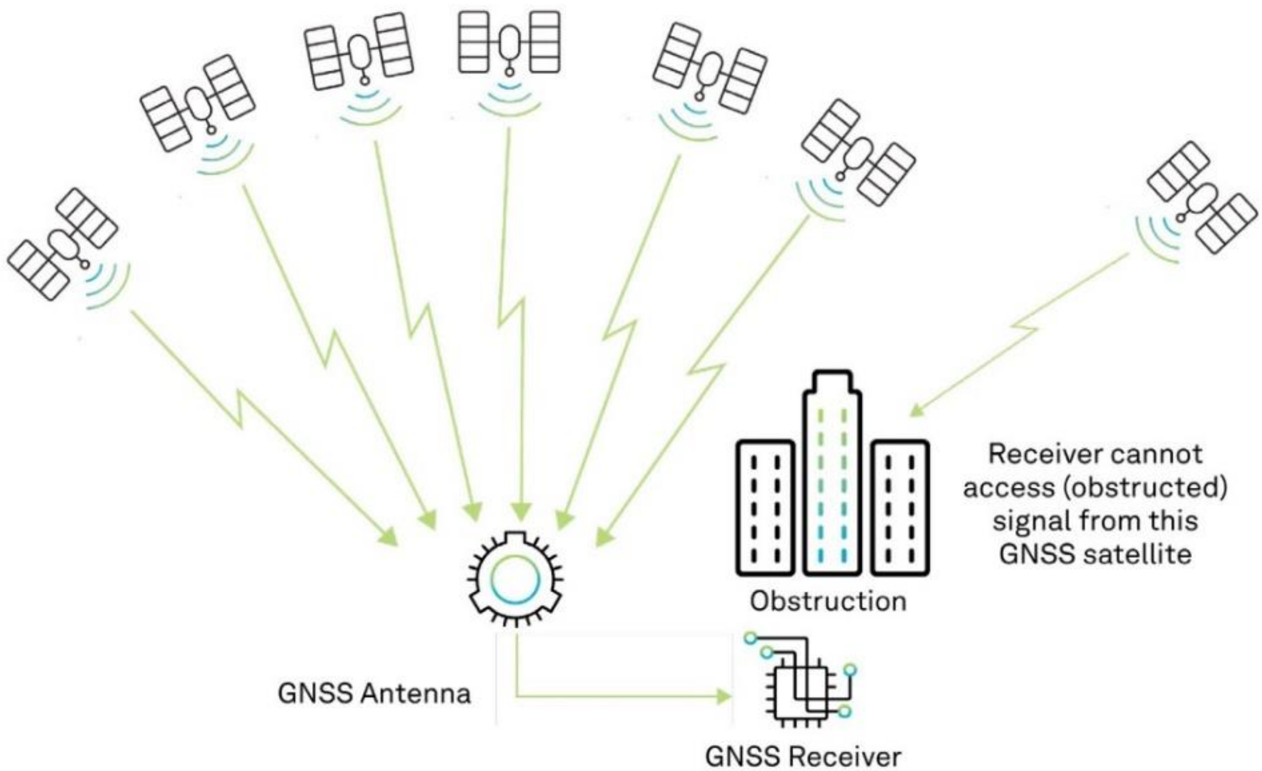


Fig 3-4) GNSS Reception[24]

## 2-4) Computation

GNSS positioning requires at least four satellites and their ranges. The receiver determines propagation time using trilateration. Four ranges are needed due to range errors from receive clocks. Understanding errors is crucial for accurate position measurements.[25]

[23] 'An Introduction to GNSS - NovAtel'.
[24] 'An Introduction to GNSS - NovAtel'.
[25] 'An Introduction to GNSS - NovAtel'.

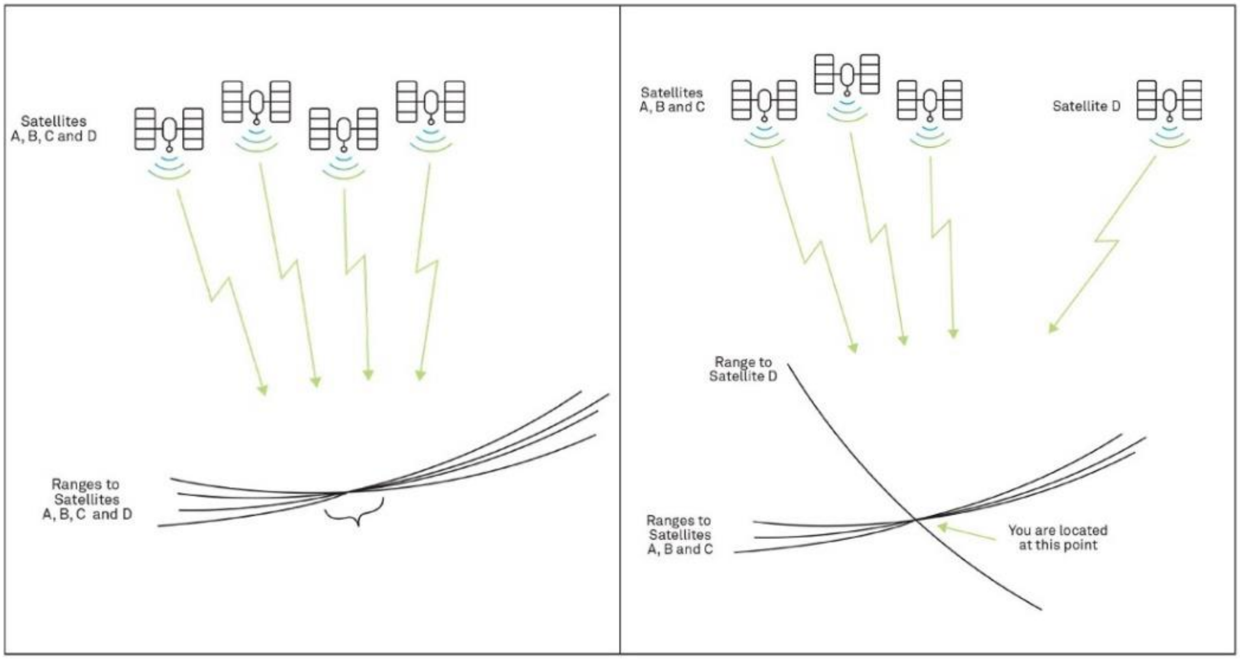


Fig 3-5) Position Is Not Easy to Determine Accurately When the Satellites Are Angularly Grouped Together(Left) Improved Satellite Angular Separation Lead to Better Achievable Position Accuracy (Right)[26]

## 2-5) Application

The GNSS technology market, worth billions, uses GNSS equations to compute position and time, with applications ranging from navigation tools to military and autonomous systems. Combining GNSS with inertial technology enhances precision and dependability.

The application of GNSS in geomatics and cultural heritage methods of documentation will be discussed in the following.[27]

[26] ‘An Introduction to GNSS - NovAtel’.

[27] ‘An Introduction to GNSS - NovAtel’.

# 3) Photogrammetry

## 3-1) Definition, History and Evolution

Accurate 3D measurements hold a vital role in numerous fields, spanning manufacturing, engineering, biology, medical science, architecture, archaeology, and forensics. While various specialized tools and techniques exist for such measurements, they often come with limitations. Photogrammetry, on the other hand, stands out for its versatility, from mapping with space cameras to measuring microtopography on human skin. Once confined to geomatics and surveying, it has now become readily accessible to engineers and professionals seeking precise 3D measurements of complex objects. The essence of photogrammetry lies in its image-based approach, where 3D measurements are derived from 2D images using mathematical models.[28]

The term "photogrammetry" originates from the Greek words ***"phos"*** (light), ***"gramma"*** (symbol or drawing), and ***"meterin"*** (measurement), reflecting its essence as the art of measuring and interpreting images to determine an object's shape and location. Several factors contribute to the effectiveness of photogrammetry, including its relative affordability, speed, flexibility, and ease of implementation compared to other geomatics techniques. This approach, rooted in projective geometry and perspective camera models, has been considered innovative since its inception.[29]

Photogrammetry boasts numerous advantages, such as the capacity to collect extensive data at varying scales and resolutions. It offers highly accurate mapping with objectivity, repeatability, and verifiability, ensuring consistent overall precision. Furthermore, photogrammetry delivers detailed and precise 3D reconstructions, enriched with texture data for enhanced comprehension. The captured data, marked by high resolution and detail, is geo-referenced to common reference systems and includes valuable metadata. Its cost-effectiveness and efficiency make it a preferred choice across a wide range of applications.[30]

However, photogrammetry does have its drawbacks, primarily the requirement for medium-to-high-end software and hardware as well as the need for traditional field survey measurements, which can extend project timelines. Nonetheless, advancements in digital photogrammetry have largely overcome these issues, thanks to the computational power of modern computers and the availability of off-the-shelf cameras that offer enhanced solutions. Research efforts have focused on reducing field measurement time and optimizing the process under different strategies. Photogrammetry's sensitivity to environmental conditions, due to inherent sensor characteristics, is another consideration, where illumination and light conditions during acquisition can significantly affect image quality and subsequent photogrammetric processes.[31]

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[28] T. Luhmann and others, *Close Range Photogrammetry: Principles, Techniques and Applications / T. Luhmann, S. Robson, S. Kyle and I. Harley*, 1.th ed. (Dunbeath (UK): Whittles, 2006).
[29] T Schenk, 'Introduction to Photogrammetry'.
[30] John Fryer, *Applications of 3D Measurement from Images* (Dunbeath, UNITED KINGDOM: Whittles Publishing Ltd, 2007) <http://ebookcentral.proquest.com/lib/polito-ebooks/detail.action?docID=3417316> [accessed 24 April 2023].
[31] Fryer.

The evolution of photogrammetry closely aligns with broader advancements in science and technology. Its four main phases correlate with innovations in photography, aviation, computers, and electronics. Interestingly, photogrammetry's history parallels that of photography, with its early applications primarily in close-range architectural measurement rather than topographical mapping.

French military officer Laussedat began experimenting with photogrammetry in 1849, shortly after photography's invention, using a lucida camera. German architect Meydenbauer created photogrammetric cameras and methods to measure façades, thus coining the term "photogrammetry. Notably, Meydenbauer compiled a significant archive of metric images of architectural monuments between 1885 and 1909. This archival tradition persists today in various countries to preserve cultural heritage.

In the 19th century, inventors like Porro, Paganini, and Koppe contributed to the development of the phototheodolite, a combination of the camera and theodolite. Plane table photogrammetry, based on intersecting rays, suited architectural subjects but posed challenges to topographic mapping. Still, some topographic mapping occurred in the latter part of the 19th century, focusing on inaccessible or challenging-to-reach objects.[32]

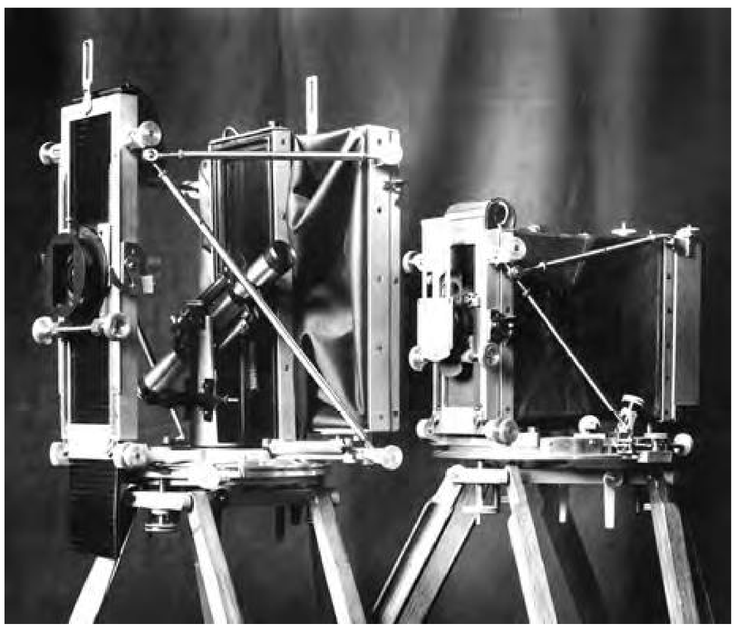

Fig 3-6) Metric Cameras by Meydenbauer (ca. 1890)[33]

The turn of the 19th century saw a significant breakthrough with the development of stereoscopic measurement. The stereoscope, invented in the 1830s, laid the foundation. In 1893, Stolze's discovery of the floating measuring mark in Germany marked a milestone. Pulfrich, Fourcade, and others developed stereo-comparators, allowing

[32] Luhmann and others.
[33] Luhmann and others.

simultaneous measurement mark placement on two photos. Numerical computation's successful integration in the 20th century, despite initial skepticism, marked a significant phase in photogrammetry.
The rapid rise of aviation has unlocked new possibilities for photogrammetry. Aerial photography enabled comprehensive Earth mapping. Stereoscopy's application to complex surfaces emerged, although economic advantages were not always evident.[34]

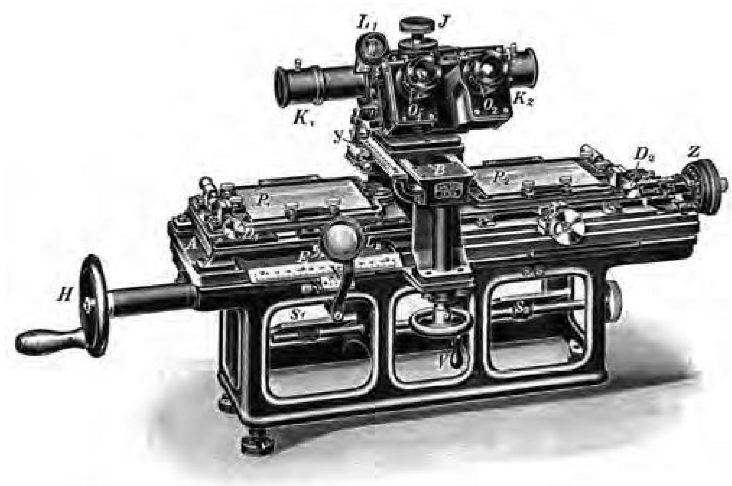


Fig 3-7) Pulfrich’s Stereocomparator (Zeiss, 1901)[35]

By 1930, the Stereoplanigraph C5 was in production, allowing oblique and convergent photography. Wild stereometric cameras, consisting of two identical metric cameras fixed to a rigid base, emerged in 1933. Glass plates initially provided a flat image surface, but film with mechanical film-flattening devices became more prevalent in the 1950s.
The 1950s saw a significant shift towards analytical photogrammetry, with digital computers facilitating photogrammetric triangulation. Numerical methods enabled unparalleled accuracy and flexibility, along with error detection and statistical insights. Analytical stereo plotters and triangulation programs adapted to close-range work.[36]
Analytical photogrammetric triangulation is a method that involves the simultaneous orientation of all photographs and taking all interrelations into account, using numerical data to determine point location. The first stereocomparator designed for use with aerial photographs was the Cambridge Stereocomparator, designed in 1937. By 1955, there were five stereo comparators on the market, and mono-comparators designed for use with aerial photographs also appeared. The method of photogrammetric triangulation, also known as bundle adjustment, is crucial for close-range photogrammetry. Schmid and Brown's papers in the late 1950s established the foundation

[34] Luhmann and others.
[35] Luhmann and others.
[36] Luhmann and others.

for block adjustment. Various bundle adjustment programs were created for air surveys, including Ackermann et al.'s and Brown's programs. In the 1980s, many programs designed specifically for close-range work emerged.
Bundle adjustment is extremely important in close-range photogrammetry as it places no restrictions on camera positions or orientations, and there is no need to limit the imaging system to central projection. Additionally, the method allows the parameters of the interior orientation of all cameras to be included as unknowns in the solution. The direct calibration of cameras focused on near objects is often more challenging than that of cameras focused on distant objects. This is because the geometry of non-topographical work is frequently far from ideal, requiring more precise inner orientation. Previously, indirect, numerical methods were suggested to overcome this difficulty, but bundle adjustment now eliminates this concern. It is no longer necessary to use metric cameras for high-precision work since virtually any camera can be used. Calibration through bundle adjustment is also known as "self-calibration."
The use of traditional stereophotogrammetry has decreased at close ranges, and multi-photo analysis systems have been widely used for architectural and accident recording. Many special cameras, such as modified professional photographic cameras with an in-built réseau (an array of engraved crosses on a glass plate that appears on each image), have been developed for photogrammetric use. Opto-electronic image sensors have increased dramatically since the mid-1980s, and digital photogrammetry procedures are becoming more common. Video cameras, analytical plotters, and closed procedures for simultaneous multi-image processing were also developed for photogrammetry.[37]


Fig 3-8) Rolleiflex SLX (ca. 1980) Semi-Metric Camera[38]

Scanning cameras with high resolutions have been developed to record static objects, while electronic theodolites have been equipped with video cameras to record directions to targets. Digital cameras with high resolutions have been available since the 1990s and have expanded photogrammetric measurement technology in the industrial field. Online photogrammetric systems are becoming increasingly popular, and coded targets allow for the automatic

[37] Luhmann and others.
[38] Luhmann and others.

identification and assignment of object features and image sequence orientation. Pattern projection methods combined with photogrammetric techniques have made surface measurements of large objects possible.

Interactive digital stereo systems, like Leica/Helava DSP and Zeiss PHODIS, have been around since the late 1980s, with Kern DSP-1 being introduced in 1988. Nowadays, they are becoming more popular than analytical plotters. However, they are not commonly used for close-range photogrammetry. For such purposes, graphical multi-image processing systems are more significant as they offer a CAD environment for processing various image configurations, like PHIDIAS from Phocad. Moreover, user-friendly and inexpensive software packages like PhotoModeler from EOS, ImageModeler from REALVIZ, and iWitness from PhotoMetrix allow the creation of virtual 3D models from digital images without the need for extensive knowledge of photogrammetry.

One trend in close-range photogrammetry is the integration or embedding of photogrammetric components into application-oriented hybrid systems. These hybrid systems include links to other software packages like 3D CAD systems, databases, quality control systems, navigation systems, and visualization systems. Another trend is the use of computer vision methods like projective geometry or pattern recognition to provide rapid solutions without high accuracy demands. Close-range photogrammetry is a well-established 3D measuring technique that is widely used in interdisciplinary fields. It is expected to continue its development well into the future.[39]

In summary, for many years, photogrammetry has been evolving, and this process is still going on today. Four phases based on *Kondratiev cycles*[40] can be used to trace the development of photogrammetry. These cycles, which are connected to the creation, uptake, development, and downturn of new technology, are characterized by alternating phases of growth and decline. The first stage, which started in the middle of the 19th century, was primarily used to produce topographic maps. The development of airplanes and the spread of stereoscopy defined the second phase. The creation and advancement of computers, which resulted in an analytical and numerical approach to photogrammetry, marked the beginning of the third phase, which lasted until the middle of the 20th century. Photogrammetry then faced the next phase called "digital photogrammetry," which is characterized by the digitalization of both the photogrammetric and image acquisition processes.[41]

Photogrammetry is currently in a phase known as "artificial photogrammetry,"In the realm of computer vision and object recognition, the process involves extracting distinctive attributes or features from an image to establish a unique description of an object's characteristics. These descriptions, initially derived from a reference or training image, serve as the basis for identifying the same object within a test image that may contain multiple objects.

Ensuring the robustness and reliability of this recognition process is paramount. It demands that the features extracted from the reference image remain discernible even when confronted with variations in scale, noise levels, and illumination conditions. Typically, these distinctive points are strategically positioned in high-contrast regions of the image, such as object outlines, where they are more likely to maintain their integrity under diverse conditions.

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[39] Luhmann and others.

[40] S. N. Solomou, 'Kondratieff Cycles', in *The New Palgrave Dictionary of Economics: Volume 1 – 8*, ed. by Steven N. Durlauf and Lawrence E. Blume (London: Palgrave Macmillan UK, 2008), pp. 3470–75 <https://doi.org/10.1007/978-1-349-58802-2_899>.

[41] Luhmann and others.

Equally crucial is the requirement that the relative spatial relationships between these distinctive features within the original scene remain consistent across similar images. For instance, if we consider the corners of a door distinctive features, they should continue to serve as reliable identifiers irrespective of the door's position. Conversely, if features along the door's contour were included, the recognition process might falter depending on whether the door is open or closed.

Furthermore, features located within articulated or flexible objects tend to encounter difficulties when changes in their internal geometry occur between two images in the processing pipeline. Nevertheless, certain techniques, such as Scale-Invariant Feature Transform (SIFT), have been devised to mitigate the impact of errors arising from localized variations, enhancing the reliability of object recognition in various scenarios.[42]

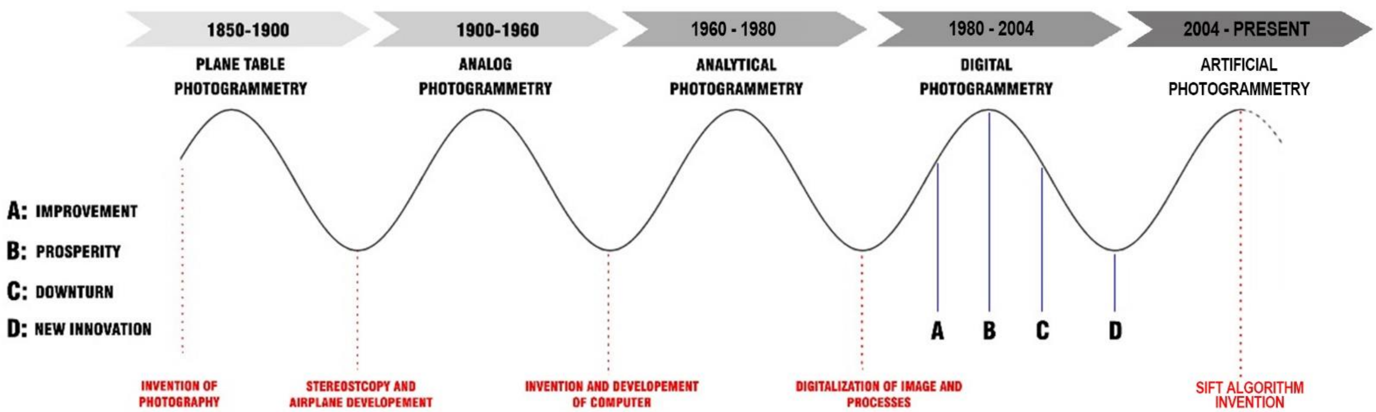


Fig 3-9) Representation of the Cycles of Evolution of Photogrammetry Based on the Long Waves' Theory of Krondatiev[43]
***(Edited by Adding the Next Evolutions in Recent Years)***

## 3-2) Geometrical Fundaments and Digital Photogrammetry

It was mentioned that photogrammetry is the process of making precise measurements and drawings from images. It involves capturing overlapping photographs of a subject from multiple positions to replicate the images captured by each eye and create a 3D image. The surface of the object can be considered a collection of points, which can be defined numerically by obtaining their three-dimensional coordinates. The accuracy of this representation depends on the surface's irregularity and the level of precision required, which determine the number of points needed. By measuring the shape, size, position, and orientation of an object, we can obtain the coordinates of individual points in 3D space.

To use a photograph for measurement, a standard photograph is inadequate due to the errors inherent in it. Firstly, standard photographs have perspective projections that can result in scale or displacement errors when the subject

[42] Nayma Martín Amaro and others, 'Trends in Photogrammetry and Its Integration with Artificial Intelligence', in *Artificial Intelligence in Project Management and Making Decisions*, ed. by Pedro Y. Piñero Pérez, Rafael E. Bello Pérez, and Janusz Kacprzyk, Studies in Computational Intelligence (Cham: Springer International Publishing, 2022), pp. 417–31 <https://doi.org/10.1007/978-3-030-97269-1_23>.
[43] Lorenzo Teppati Losè.

has depth or the camera is tilted relative to the facade. Secondly, standard cameras can exhibit lens and film distortion. Photogrammetry overcomes these issues by utilizing specially made "metric" cameras that minimize lens distortion and contain a mechanism to ensure film flatness. In addition, these cameras have fiducial marks, which are small reference points in the negative plane that appear in the image and enable subsequent correction of any film distortion that may occur.[44]

A camera is used in photogrammetry to project an object point onto an image plane using the fundamental mathematical model of 3D perspective projection. This model is based on the idea that a 3D object is back-projected onto a 2D image during image formation. The camera model, which is an abstraction of a real camera, aims to simulate the relationship between the locations of image points and the associated bundle of viewing rays. Physically, modern cameras are similar to the first ever made cameras, but thanks to technological advancements, they now have lenses that need to be modeled because they alter the electromagnetic radiation the camera can record.

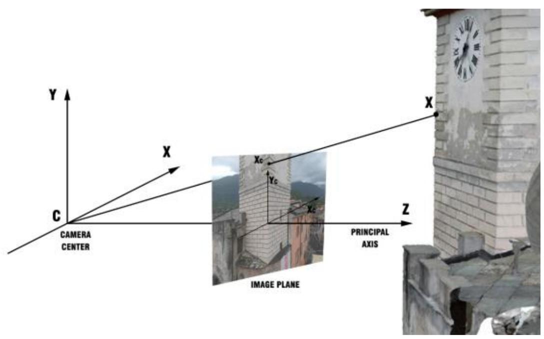


Fig 3-10) Scheme of the Ideal 3D Perspective Projection Based on the Pinhole Camera Model[45]

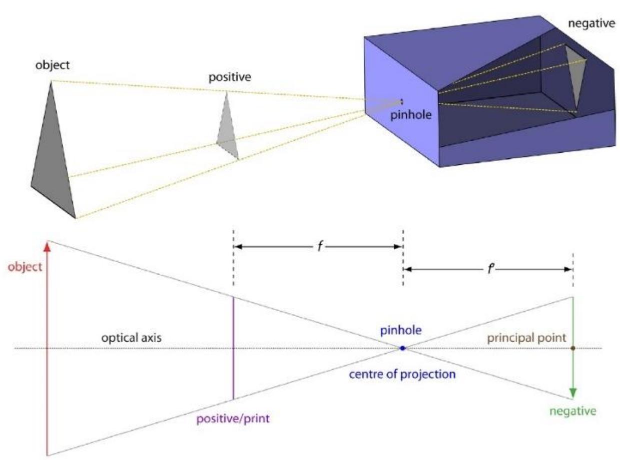


Fig 3-11) Pinhole Camera Model and Geometry of Image Formation in These Types of Cameras[46]

[44] A. L. Allan, *Principles of Geospatial Surveying* <https://blackwells.co.uk/bookshop/product/Principles-of-Geospatial-Surveying-by-A-L-Allan/9781420073461> [accessed 18 March 2022].
[45] Lorenzo Teppati Losè.
[46] 'Basics of Photography for Cultural Heritage Imaging' <https://biblio.ugent.be/publication/8050621> [accessed 2 May 2023].

The pinhole camera model serves as the structural foundation for the camera system. In this model, electromagnetic radiation passes through a tiny hole and the image is formed inverted on the box surfaces opposite the hole. A pinhole camera should have no lenses at all. Since lenses alter the electromagnetic radiation that the camera records, they introduce a new component that must be accounted for in the camera system's modeling.

### 3-2-1) 3D Reconstruction

The 3D reconstruction problem involves determining the position of an object point and reconstructing the geometry of a scene based on the recognition of corresponding points. The approaches to solving this problem depend on prior knowledge of the camera setup. Four main approaches are described:

***1. Euclidean 3D reconstruction:*** requires knowledge of the intrinsic and extrinsic parameters of the cameras and assumes that the relative position of the cameras is known.
***2. Metric 3D reconstruction:*** assumes that the cameras are calibrated, but the distances between them are unknown.
***3. Affine 3D reconstruction:*** uses the theory of vanishing points to create a system of affinity equations for scene reconstruction and does not require knowledge of camera calibration.
***4. Projective 3D reconstruction:*** assumes no prior knowledge of the camera configuration or scene and relies on image correspondences and projective transformation.

These four approaches are described for a standard two-view configuration, and subsequent sections will address traditional stereo and SfM approaches.[47]

### 3-2-2) Traditional Stereoscopic Image Survey

In photogrammetry, it is necessary for every point in a scene to be visible in at least two images, with a B/H ratio (relation of the stereoscopic base and the distance to the area of interest) between 1/2 and 1/6 for accurate depth measurement. Stereoscopic image surveying was previously done manually or with software tools that required a small area of overlap between images, with a "normal" stereoscopic configuration for visualization of stereoscopic pairs. This configuration is simple to implement from an aerial viewpoint for low-relief landscapes but more complex for terrestrial image surveying due to challenges such as complex structures and hidden areas. On the other hand, in image reconstruction, a set of two images recorded from different viewpoints can reconstruct a scene without prior knowledge, with tie points identified manually or using a feature-based approach to provide a robust connection between images. The relative orientation of the cameras can be obtained up to the scale factor, which derives all 3D corresponding points between images and the relative pose of the two cameras in a local coordinate system.

[47] Lorenzo Teppati Losè.

The traditional two-step solution involves applying these constraints and transforming the scene system into a global object coordinate system using reference points.[48]

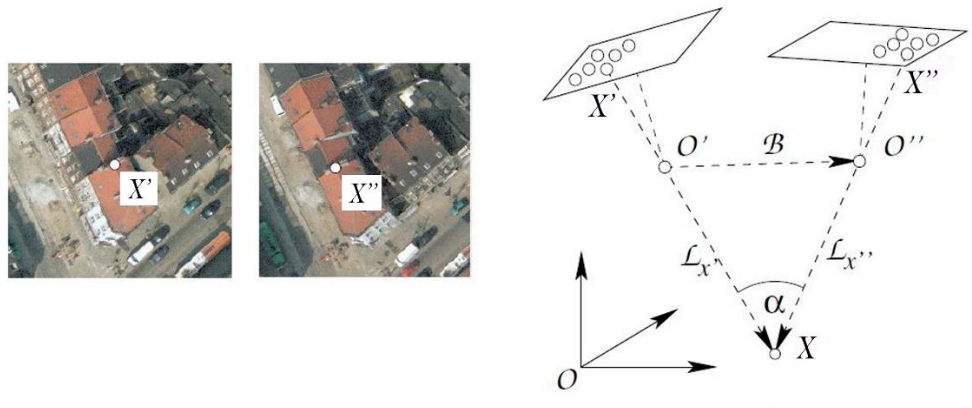


Fig 3-12) Example of a Stereo-Configuration:
X' and X'' Are the Two Corresponding Point of the Object Point X.
$L_{X'}$ and $L_{X''}$ Are the Image Rays from the Projection Centres O' and O'' (That Forms the Baseline B)[49]

## 3-2-3) Structure from Motion (SfM), Innovative Approach

A structure-from-motion (SfM) approach is essential when capturing images from a moving camera. In SfM, the relative positions of the camera and the 3D reconstruction of the scene are obtained simultaneously. Typically, the scene is assumed to be stationary with no moving objects, and this approach can be divided into two parts:

- The correspondence problem
- Camera motion and 3D reconstruction problems

If there are moving objects in the scene, the issue of segmentation can add to the previously mentioned issues. Both of these problems can be solved using two different approaches, one more traditional and the other more recently developed and widely used today.
In the first approach, the basis matrix is computed by matching at least eight features between different modes, which allows 3D reconstruction of the scene image. To upgrade the fundamental matrix and perform a 3D metric

[48] 'Specific Requirements for the 3D Digitization of Outstanding Sites - 3D Modeling of Buildings - Wiley Online Library'.
[49] 'Photogrammetric Computer Vision – Statistics, Geometry, Orientation and Reconstruction. By Wolfgang Förstner and Bernhard P. Wrobel. Springer International Publishing, 2016. ISBN 978-3-319-11549-8. 816 Pages with 59 Colour Figures. Price: £44·99 Hardback; £35·99 eBook. - Gerke - 2017 - The Photogrammetric Record - Wiley Online Library' <https://onlinelibrary.wiley.com/doi/full/10.1111/phor.12187> [accessed 3 May 2023].

reconstruction, the internal and external parameters of the camera must be known. Various approaches are available to solve this task, and self-calibration is the most common among operators.

A pioneering approach to SfM is the Bundle Block Adjustment (BBA) method, which was derived from the photogrammetry community and is now widely used in computer vision. Thomas Lohmann defines BBA as "a method for simultaneous numerical fit."

of an unlimited number of spatially distributed images (bundles of rays). It makes use of photogrammetric observations (measured image points), survey observations, and an object coordinate system."[50]

In this approach, the tie points are used to integrate the images into a global model, which allows a 3D reconstruction of the surface of the object. The global object coordinate system can be connected to the global model using several reference points. It is important to note that all corresponding image rays must intersect continuously at the corresponding object point. The success of regularization techniques lies in the fact that all necessary parameters (coordinates of the 3D object, image orientation parameters, additional parameters, and statistical information on accuracy and reliability) are estimated simultaneously, providing a "strong geometry for a dense, high accuracy measurement network"[51].

Moreover, the development of the BBA is closely linked to the increase in the computing power of computers.

Considering all these factors, BBA can be thought of as a combination of known elements of photogrammetric and geodetic triangulation, spatial extraction, and camera calibration. The challenges of this approach lie in the number of unknowns in the system of equations, the approximation of the unknown values, and the detection and elimination of gross errors. BBA is an iterative process that redefines camera parameters and 3D structure across the bundle of rays to minimize reflection errors. Reproduction errors can be defined as the Euclidean distance between an image feature and its reprojection in the image plane, given its calculated position and camera positions.[52]

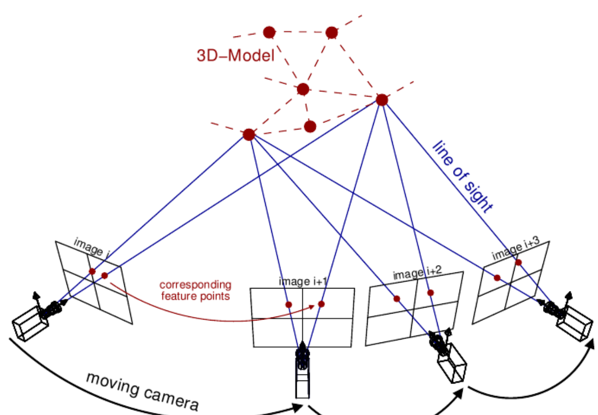


Fig 3-13) SfM Triangulation Pipeline[53]

[50] Luhmann and others.
[51] Luhmann and others.
[52] Lorenzo Teppati Losè.
[53] 'Structure from Motion (SfM) — Theia Vision Library' <http://theia-sfm.org/sfm.html#chapter-sfm> [accessed 31 May 2023].

## 3-3) The Photogrammetric Workflow

To make it easier to comprehend the abstract definition and to better understand the intricate field of photogrammetry, we will utilize a systems approach, as shown in Fig 3-14), the input involves acquiring trustworthy data via electromagnetic radiation pattern recording, mainly in photographic image form. In contrast, the output includes photogrammetric products produced inside the black box, the mechanics of which we will explore during this course.[54]

But to be more precise, photogrammetry is a five-step process that includes acquisition, pre-processing, processing, validation, and delivery. The acquisition phase is critical as it involves capturing images in the field, and any issues during this phase can affect subsequent phases. Pre-processing involves image enhancements and corrections, while the processing phase includes orientation (Tie Points extraction), dense matching, point cloud generation, and other product derivations.

Before final product delivery, it is essential to assess the quality of the photogrammetric process, which can be evaluated using statistical parameters such as accuracy, precision, noise, bias, and ground sample distance (GSD). The resulting photogrammetric products can be grouped into four categories: point clouds, meshes, DTM/DSM, and orthoimages.[55]

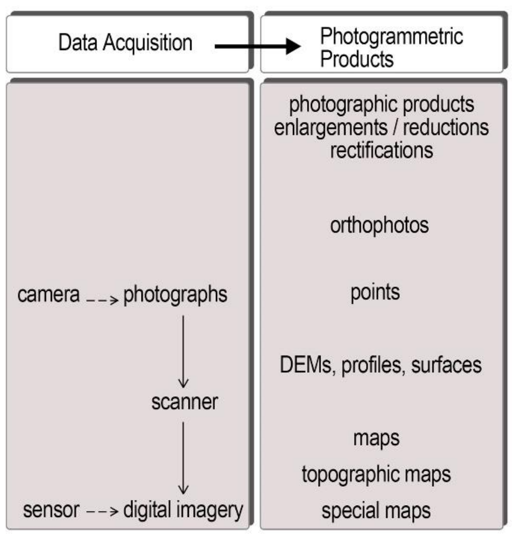


Fig 3-14) Photogrammetry Portrayed as Systems Approach.
The Input Is Usually Referred to as ***Data Acquisition***, the Output Comprises ***Photogrammetric Products***[56]

### 3-3-1) Data Acquisition

Acquiring reliable information about the properties of surfaces and objects is a crucial aspect of data acquisition in photogrammetry. This process relies heavily on the images captured in the field, and it is essential to follow certain

[54] Schenk.
[55] Lorenzo Teppati Losè.
[56] Schenk.

principles and guidelines to achieve optimal results. One of the main aspects of ensuring high-quality images is selecting the correct photographic setup for the camera, which includes proper exposure, sharpness, radiometry, and focusing. Experienced operators must consider all these factors and use the available equipment to its full potential, while also ensuring consistent colors and focus per subset of images to ensure precise determination of the geometric characteristics affecting the model by photogrammetry. Ultimately, the goal is to obtain high-quality images that allow for the precise determination of geometric characteristics affecting the model by photogrammetry.[57]

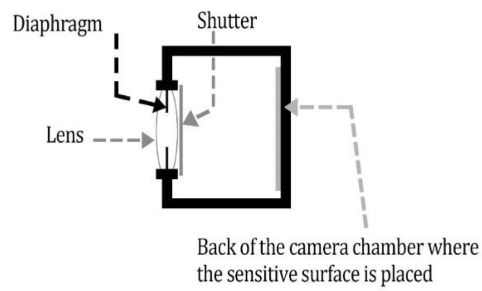


Fig 3-15) Simplified Diagram of A Camera[58]

Following camera setup, it is critical to ensure that the acquisition geometry is correctly projected, and several guidelines must be followed for this purpose.

1. Camera parameters such as the color profile and zoom setting should remain fixed throughout the acquisition process to prevent any variation in the I.O. parameters of the camera.
2. With the help of a tripod, you can improve image quality in low light conditions or indoor acquisitions.
3. It is advisable to obtain diffuse illumination for artificial light and avoid punctual light sources. Additionally, outdoor acquisitions should be made when there are no incident sun rays to avoid different illumination areas and shadows.
4. To capture each part of the object, it is necessary to take at least two to three images to achieve good coverage of the whole part of the item.
5. The base-to-depth ratio (B/D ratio) is also crucial in determining the distance between camera stations and the object-to-camera distance. A smaller base between camera stations leads to a vast coverage overlay between images, but it is necessary to consider the incidence of rays from multiple cameras. The optimal

[57] 'Specific Requirements for the 3D Digitization of Outstanding Sites - 3D Modeling of Buildings - Wiley Online Library' <https://onlinelibrary.wiley.com/doi/abs/10.1002/9781118648889.ch1> [accessed 2 May 2023].
[58] 'Specific Requirements for the 3D Digitization of Outstanding Sites - 3D Modeling of Buildings - Wiley Online Library'.

convergent angle between images should be ensured, striking a balance between these two requirements. As a result, the network geometry of the acquisition is a critical component, and several factors, such as network accuracy, the number of images recorded for a point, and the correctness of the retrieved object coordinates, influence the acquisition's success.

6. To solve the scale ambiguity during the process, it is essential to insert metrical references on the scene before the acquisition, such as georeferenced control points (GCPs) or known distances like scale bars of precisely known length.

7. It is advisable to store images in an organized archive and associate them with their location on the field.[59]

In general, the information obtained remotely can be categorized into four groups:

- ***Geometric Information,*** pertains to the spatial position and shape of objects and is the most critical source of information in photogrammetry.
- ***Physical Information,*** refers to properties of electromagnetic radiation, such as radiant energy, wavelength, and polarization.
- ***Semantic Information,*** deals with the meaning of an image and is typically derived by interpreting the recorded data.
- ***Temporal Information,*** relates to changes in an object over time and is usually obtained by comparing multiple images captured at different times.[60]

### 3-3-2) Camera Calibration

Camera calibration has always been a crucial aspect of the photogrammetric process. However, its significance has increased with the proliferation of consumer-grade non-metric cameras. This is because obtaining mathematical parameterization to account for deviations from collinearity is uncommon and rare for users, as these parameters are not typically provided by camera producers. Extracting reliable and precise metric information is vital in the photogrammetric workflow. The problem's centrality holds for both computer vision and photogrammetry experts.

A camera is considered calibrated when its principal distance (focal length), principal point offset, and lens distortion parameters are known. These parameters are crucial for solving the collinearity equations.

Within the photogrammetric community, two main approaches are employed for camera calibration, each utilizing a different camera model:

***Perspective Projection Model:*** derives from collinearity equations and incorporates the modeling of all deviations from collinearity. At least five-point correspondences are required in a multi-image network. The parameters are approximated through a least-squares bundle adjustment. It represents a fundamental framework in photogrammetry, rooted in the collinearity equations that govern the relationship between object points, image

[59] Lorenzo Teppati Losè.

[60] Schenk.

points, and the projection center. This model serves as the basis for capturing and accounting for all deviations from collinearity, making it a robust and versatile tool in the field of geomatics.

To effectively apply the Perspective Projection Model, a multi-image network necessitates a minimum of five-point correspondences. These correspondences establish the tie between object points in the real world and their corresponding image points within the acquired images. It is through these correspondences that the model can be calibrated and fine-tuned to ensure accurate spatial reconstructions.

The process of parameter estimation within the Perspective Projection Model is typically carried out using a least-squares bundle adjustment. This mathematical optimization technique iteratively refines the model parameters to minimize the discrepancies between the observed image points and their predicted positions based on the model's equations. Through this adjustment process, the model adapts to the specific characteristics of the image data, compensating for factors such as lens distortion, camera orientation, and other sources of measurement error.

In summary, this camera model offers a comprehensive framework for capturing and accommodating deviations from collinearity in geospatial data. When it comes to photogrammetry and geomatics, this model is very important for getting accurate and reliable measurements of space because it uses least-squares bundle adjustment and at least five-point correspondences.

***Projective Model:*** represents a critical framework within the field of photogrammetry, offering a versatile approach to addressing complex scenarios by considering various parameters, including variable and unknown focal lengths. This model plays a pivotal role in accommodating a range of camera configurations and is particularly useful when dealing with challenging geometric setups.

For efficient use, it necessitates a minimum of six to eight-point correspondences. These correspondences establish the relationship between object points in the real world and their corresponding image points captured by the camera system. By having an adequate number of correspondences, the model can accurately estimate essential and fundamental matrices, which are crucial for describing the geometric transformations between image points and the associated epipolar lines.

One of the notable strengths of the Projective Model is its ability to handle variable and unknown focal lengths. This feature makes it highly adaptable to scenarios where camera parameters may vary or are not precisely known. The model can estimate these focal lengths during the calibration process, resulting in a more robust and accurate representation of the camera's behavior.

Additionally, this model provides a solid foundation for addressing challenges related to perspective distortions, lens imperfections, and other optical aberrations that can affect the imaging process. By considering these factors, it enhances the model's capability to accurately project object points onto the image plane, yielding precise spatial measurements.

To sum up, the Projective Model is an effective technique in photogrammetry that can handle focus lengths that are variable or unknown but requires a minimum of six to eight point correspondences for calibration. Because of its adaptability and capacity to handle intricate camera setups, it is a fundamental framework for precisely representing and comprehending object geometry in the context of mapping and geospatial data processing.[61]

There are also additional criteria for classifying camera calibration approaches:

***Implicit vs. explicit models:*** Implicit and explicit. Implicit calibration involves calibrating a camera system without explicitly calculating its physical parameters, focusing on the relative relationships between image points. This is useful for historical imagery or situations where explicit parameters are challenging or impractical. Explicit calibration, on the other hand, involves computing and refining the camera's physical parameters, capturing calibration images of known targets, and analyzing patterns to determine critical parameters. Both methods are used in various domains, with implicit calibration excelling in relative geometric relationships and motion analysis, while explicit calibration is essential for absolute accuracy in measurements or image rectification.[62]

***Methods using 3D rather than planar point arrays:*** These methods are employed in both computer vision and photogrammetry.

***Point-based vs. line-based methods:*** Point-based methods are more commonly used in photogrammetry, except for plumbline calibration, which is a line-based method.[63]

Another classification can be made based on the technique used for parameter estimation and optimization:

***Linear Techniques:*** These techniques are simple and fast but cannot handle lens distortion. They require a control point array with known coordinates.

***Non-linear Techniques:*** These techniques involve accurate modeling of the camera's internal orientation and lens distortion using an iterative least-squares estimation process. The extended collinearity equation model, which forms the basis of self-calibration, is part of these techniques.

***Combined Linear and Non-linear Techniques:*** This approach utilizes linear techniques to estimate initial parameter values and employs a non-linear approach for iterative refinement.[64]

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[61] Lorenzo Teppati Losè.

[62] Guo-Qing Wei and Song De Ma, 'Implicit and Explicit Camera Calibration: Theory and Experiments', *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 16.5 (1994), 469–80 <https://doi.org/10.1109/34.291450>.

[63] Fabio Remondino and Clive Fraser, 'Digital Camera Calibration Methods: Considerations and Comparisons', *Ine. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.*, 36 (2005).

[64] Lorenzo Teppati Losè.

## 3-4) Photogrammetric Products

If adequate metric control is implemented throughout the processing stages of terrestrial and aerial photogrammetry, various products can be generated based on the survey requirements. Generally, the photogrammetric method yields 3D object coordinates that can be utilized to derive additional products. The sections that follow give a brief overview of the main products made possible by photogrammetric records and then assess their applicability to archaeological contexts.

### 3-4-1) Point Cloud Derived from Dense Matching

It becomes possible to digitally reconstruct a scene using iterative processes or dense matching techniques if the camera orientation parameters are known, either through a priori calibration or self-calibration techniques. For carrying out the dense image-matching step, there are currently both open-source and commercial algorithms available.

Whatever the chosen approach, the process usually results in a dense or sparse point cloud that describes the salient characteristics of the object of interest. To maintain the object's key features while avoiding having too many points in flat areas, it is crucial to take the density of points into account in relation to the object's geometry.[65]

### 3-4-2) Mesh

Once the point cloud is generated, it is possible to obtain another product known as a polygon model, which can be in the form of a mesh network or a triangular Irregular Network (TIN). The polygon model serves various purposes, such as enhancing object visualization and enabling texturing. The process of mesh generation is typically divided into sub-steps that can be completed in different sequences depending on the source data.

In the case of a sparse point cloud as the source data, the mesh is commonly created through an iterative approach. This involves initially constructing lines, followed by polygons, and ultimately surfaces. Conversely, when dealing with a dense and unstructured point cloud, a specific process, such as the Delaunay method, becomes necessary. In this scenario, the 3D points are projected onto a plane or another basic surface, followed by a search for the shortest point-to-point matches. Potential triangles are generated based on these correspondences, and the resulting triangles are subsequently projected back into 3D space and verified for topological consistency.

The steps involved in generating a mesh from an unstructured point cloud typically include merging the 2.5D point clouds to minimize overlapping regions and create a uniform 3D cloud with full resolution. Meshing using a more advanced approach than the Delaunay method is required.

[65] Fabio Remondino and others, 'State of the Art in High Density Image Matching', *The Photogrammetric Record*, 29.146 (2014), 144–66 <https://doi.org/10.1111/phor.12063>.

Two primary approaches can be followed:

- interpolating a surface that generates an excess of triangles and subsequently removing triangles that are not connected to the surface;
- approximating surfaces, often resulting in a triangulation of a best-fit function based on the raw 3D points.[66]

### 3-4-3) DEM / DSM / DTM

Digital elevation models (DEMs), digital surface models (DSMs), and digital terrain models (DTMs) are commonly used terms for describing surface representations. A DEM establishes the relationship between z values and x and y coordinates, encompassing both DSM and DTM. DTM specifically refers to the bare terrain, while DSM represents the complete terrain with all its features.

These models can be obtained through traditional methods such as fieldwork, the digitization of existing data, or the use of satellite images. They can also be directly derived from precomputed point clouds using various techniques.

In a specific study, DSMs and DTMs were generated from point clouds obtained through an image-based approach employing mathematical models.

A DEM can be structured as:

- a grid layout where elevation is recorded at grid nodes or
- as a Triangular Irregular Network (TIN) where points are interconnected to form non-overlapping triangles, enabling the creation of accurate surface representations.[67]

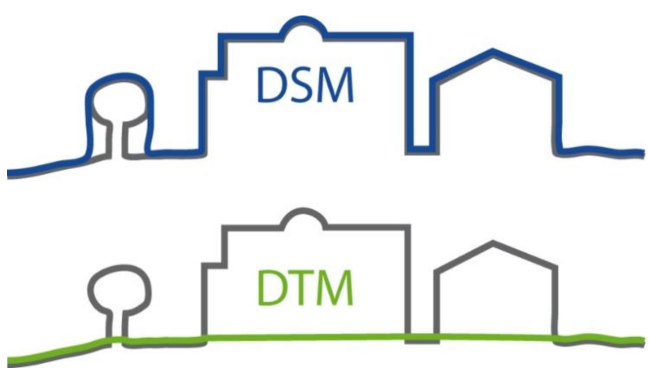


Fig 3-16) Schematic Representation of DSM and DTM Features[68]

[66] Matt Berger Claudio T. Silva and others, 'An End-to- End Framework for Evaluating Surface Reconstruction.', *Scientific Computing and Imaging Institute University of Utah Salt Lake City, UT 84112 USA*, 2011.
[67] Lorenzo Teppati Losè.
[68] Paolo Corradeghini, 'DTM vs DSM vs DEM', *3dmetrica*, 2017 <https://3dmetrica.it/dtm-dsm-dem/> [accessed 16 May 2023].

### 3-4-4) Orthoimages

An orthophoto is a geospatial representation of terrain that adheres to metric accuracy standards comparable to traditional topographic maps. Unlike topographic maps, orthophotos incorporate additional detailed information derived from aerial photography, faithfully portraying both natural and human-altered landscapes without the need for conventional cartographic codes or symbology typically employed in digital map production.

Orthophotos are designed to be comprehensible and interpretable by individuals without specialized technical expertise, in contrast to digital maps, which often require a specific skill set for accurate interpretation. The geometrical precision of orthophotos is achieved through an orthogonal projection process, where each pixel from an aerial image is transformed onto a cartographic plane, thereby converting the original perspective view, as seen in aerial photographs, into an equivalent metrically precise image. This transformation allows for the measurement of angles and distances, following a known scale factor, and facilitates coordinate readings on orthophotos, much like traditional maps.

Orthophotos find extensive utility in various land planning applications, including infrastructure development and land use monitoring, among others. However, in urban contexts characterized by complex terrains with numerous discontinuities and concealed areas, certain challenges may arise when utilizing commercial software. Therefore, the creation of an accurate and rigorous orthophoto in such settings often necessitates the implementation of specialized procedures to ensure precision and fidelity in the final product.[69]

A DTM that only correctly describes the ground and not existing buildings can cause incorrect positions in the base and roof. In the case of a building also described by the DTM, point Q is represented correctly but lost due to traditional ortoprojection.

To generate a rigorous orthophoto of a discontinuous surface,

- the correct description of the surface,and
- the availability of images representing all object details

are required. Precautions must be taken to avoid doubling images, such as obtaining point Q0 from image IQ and point P0 from image IP.

[69] Andrea Biasion, Sergio Dequal, and Andrea LINGUA, 'A New Procedure for the Automatic Production of True Orthophotos', *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 35 (2004).

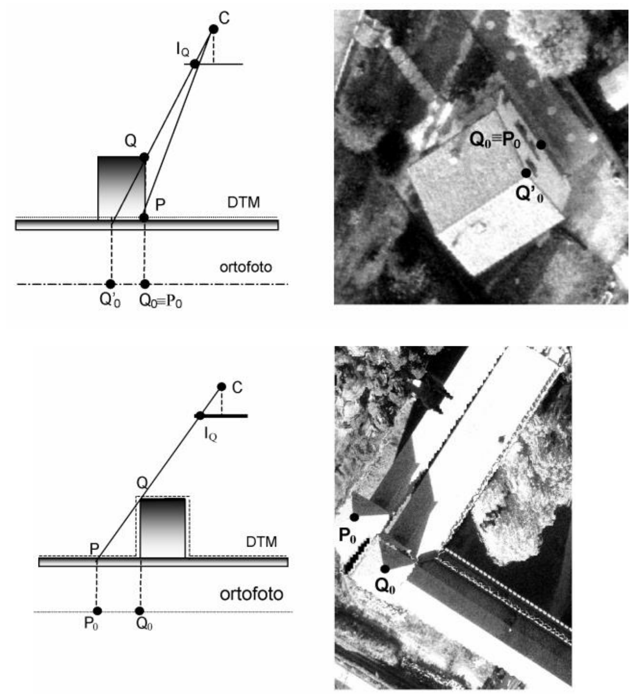


Fig 3-17) Orthoprojection with an Erroneous Description (Up)
Orthoprojection with Hidden Areas (Down)

On the other hand, to create a complete true orthophoto of a discontinuous surface, two data sets are needed:

- digital images with known orientation parameters,
- a description of the surface using a traditional DTM,
- a digital surface model (DSM), or a dense DTM (DDTM).

The latter is the cheapest and simplest solution, requiring no expensive stereoplotting or complex database management software. This type of cartography is becoming more common in local municipality administrations, urban development instruments, and Geographical Information Systems. A 3D digital map describes territory and buildings in a tridimensional space, containing all the information needed to generate a DDTM.

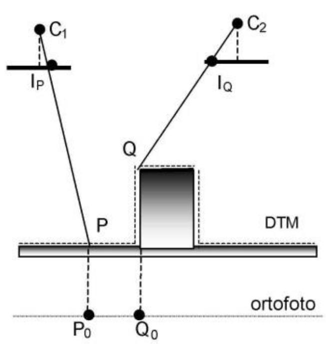


Fig 3-18) True Ortoprojection From Multiple Images

The generation of a comprehensive and accurate orthophoto for fragmented terrain necessitates the utilization of two primary datasets:

***1.*** A collection of digital images endowed with well-documented interior and exterior orientation parameters, derived either through aerial triangulation or direct methodologies incorporating GPS/INS sensors This dataset ensures extensive photographic coverage of the target area.

***2.*** A precise representation of the terrain surface is obtainable through one of the following means:

- A conventional Digital Terrain Model (DTM), supplemented with breaklines where necessary
- A Digital Surface Model (DSM) containing detailed surface geometric attributes is managed through sophisticated database structures.
- A Dense Digital Terrain Model (DDTM), often the most cost-effective and straightforward option, obviating the need for costly stereoplotting, intricate editing processes, or complex database management software. DDTMs can be readily acquired using contemporary instruments such as laser scanners or, alternatively, derived through interpolation from existing 3D digital maps when available.

This type of cartography has gained popularity within local municipal administrations, serving as a foundational map for urban development initiatives and as the geometric basis for Geographical Information Systems (GIS). A 3D digital map provides a comprehensive depiction of the terrain and structures within a three-dimensional space, encompassing all essential information required to generate the corresponding DDTM. Specifically:

- Areas devoid of structures are represented by elevation points and contour lines.
- Individual regions are delineated by points with known 3D coordinates, with linear features such as streets, bridges, and railways described through arcs and nodes, each with precise X, Y, and Z coordinates.
- Structures, in the form of volumetric entities with uniform heights, are represented by a central height point. This approach enables a comparison of volumetric entities with parallelepiped shapes, where the building perimeter serves as the base, extruding vertically from the ground to the specified height.[70]

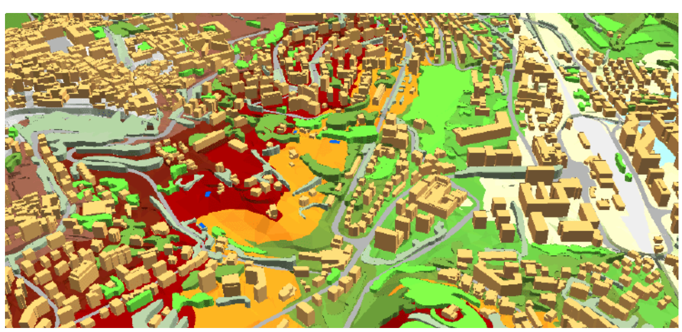

Fig 3-19) An Example of 3D Digital Cartography

[70] Biasion, Dequal, and LINGUA.

An innovative approach to generating true orthophotos was proposed in 1996, primarily tailored for urban environments. The methodology relied on a Digital Surface Model (DSM) managed within a relational database. It involved a meticulous classification of all images into either terrain or building surfaces, followed by a phased orthophoto production process wherein the terrain and roof components were treated separately. The outcomes of these procedures were subsequently integrated into a unified digital orthophoto. Any concealed or obscured areas were rectified by overlaying orthophotos generated from alternate images.

This proposed solution seeks to streamline and enhance this approach. The requisite input data for producing a true orthophoto comprises a Dense Digital Terrain Model (DDTM) as previously described, along with a series of oriented images containing radiometric descriptions of all the points intended for orthoprojection. The objectives of this methodology are twofold: first, to uphold full automation, thereby ensuring performance levels commensurate with conventional orthoprojection software; and second, to circumvent the aforementioned issues that have been previously emphasized.

Consider the object depicted in Fig 3-20). In perspective images, higher points correspond to lower points, necessitating a workflow that proceeds from the highest to the lowest point. The procedure commences at point R. The most optimal grayscale value for this point is found in the image with the projection center nearest to it (designated as image I1). To prevent image duplication, a "flag image" is created, wherein each pixel records the height used for orthoprojection of the corresponding pixel in the original image. Consequently, the pixel representing point R in I1 is inhibited from further use. Point R has also been recorded in I2, and for the same reason, the corresponding pixel for point R in I2 is likewise inhibited. The procedure ortho-projects point S using analogous criteria (point S will only be recorded in I1).

As the procedure progresses to orthoproject point P, it seeks the pixel on I1 that was previously employed for point R. The flag image prevents a second use of this pixel because the recorded height is higher than that of point P. Subsequently, the procedure searches for the grayscale (or color) value in I2. Since the corresponding pixel is not inhibited, the orthoprojection of point P is feasible. When the procedure advances to orthoproject point Q, the initial attempt is to utilize the corresponding pixel in I1. However, this pixel has already been assigned to point S, and the "flag image" thus precludes reading its radiometric value. The secondary attempt involves utilizing the corresponding pixel in I2, but this too has been inhibited as it contains the grayscale (or color) value of point R. In this instance, with no additional images accessible, defining the orthoprojection of point Q becomes unfeasible.

This straightforward example encompasses all conceivable scenarios in the context of true orthophoto projection.

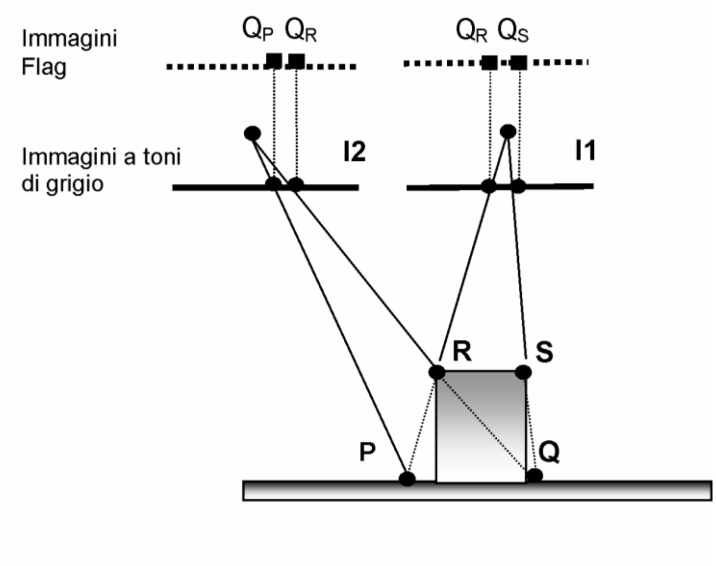


Fig 3-20) Ortoprojection Procedure Scheme

The key enhancements of these softwares since their initial release in 2001 include:

- ***Dividing Orthophoto into Smaller Windows:*** To reduce computational demands, particularly for large-format orthophoto production, the software now subdivides the final orthophoto image into smaller windows. Notably, even a color orthophoto for a standard 1:2000 scale map, with a pixel size of 20 cm (approximately 300 dpi), can reach around 24 megabytes (2300x3400 pixels).
- ***Efficient Orthoprojection Procedure:*** The software has implemented an orthoprojection procedure that selectively extracts the relevant sections from available images within each window. This strategic approach minimizes the loading operations associated with the initial digital images, with a maximum of six images considered in optimal scenarios.
- ***Customizable Orthophoto Box:*** Users now have the flexibility to define the orthophoto's boundaries based on standard map sizes. By specifying the reference scale and sheet, the software automatically calculates the necessary orthophoto boundaries for the orthoprojection phase, creating an enclosed rectangle. Any areas beyond the cartographic dimensions are assigned a white color (RGB 255, 255, 255) in the final orthophoto.
- ***Georeferenced Digital Image Output:*** The software generates georeferenced digital images that seamlessly integrate with Geographic Information Systems (GIS), enhancing the utility and compatibility of the output.
- ***Redesigned User Interface:*** The user interface has undergone a comprehensive redesign.

These enhancements collectively improve the efficiency, usability, and applicability in the field of orthophoto generation by using these type of softwares, such as Agisoft Metashape.[71]

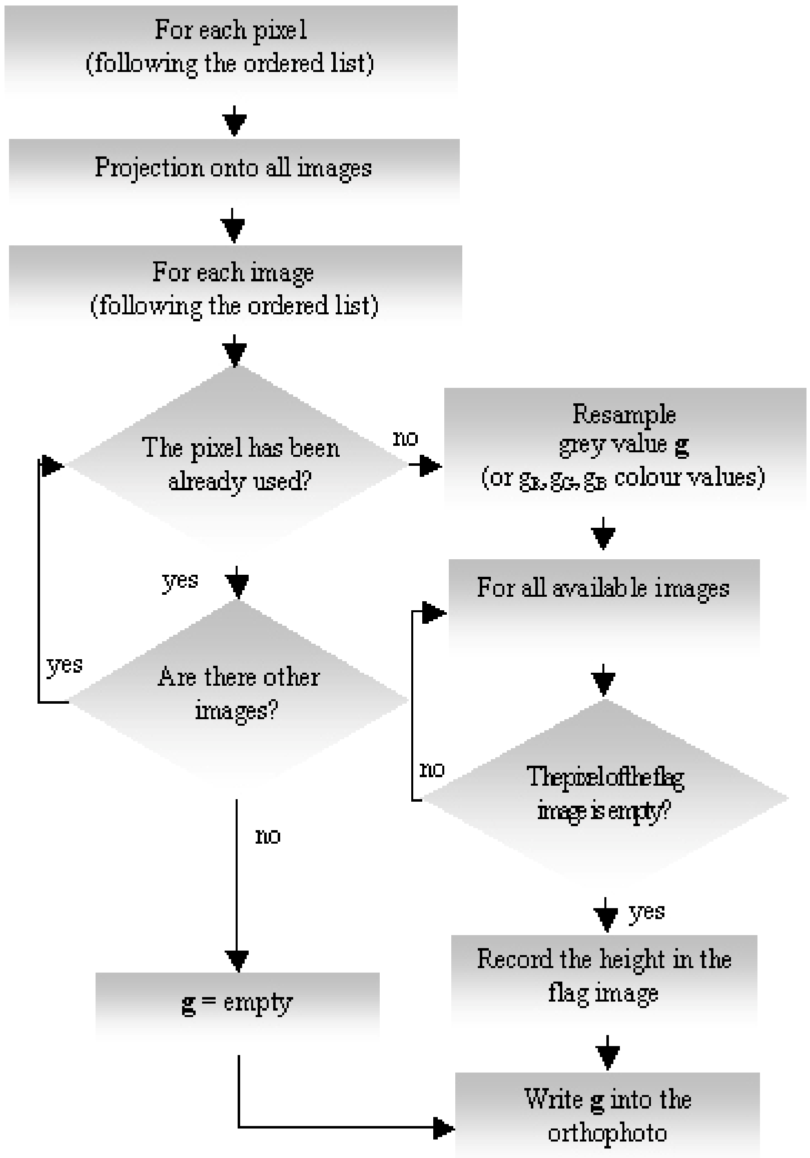


Fig 3-21) Flow-Chart of the Basic Software Functions to Generate Orthophoto

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[71] Biasion, Dequal, and LINGUA.

# 4) Unmanned Aerial Vehicle: UAVs

The Unmanned Aerial Vehicles (UAVs), also known as drones or remotely piloted aircraft (RPAs), have undergone significant evolution and revolutionized various fields, including military, civilian, and geomatics applications. Initially developed for military purposes, UAVs served as versatile platforms for training, reconnaissance missions, surveillance, mapping, and warfare actions. However, their potential for mapping applications was quickly recognized. The development of UAVs can be traced back to the utilization of various flying vehicles for aerial observation, including balloons, kites, rockets, and even birds, during the latter half of the 19th century.[72]

The early history of aerial imaging involved capturing aerial images using these unconventional flying platforms. However, with the invention of airplanes and the rapid progress of manned airborne photography, these early endeavors took a backseat for several decades. Aerial photography from airplanes became an indispensable tool in military operations, starting with the historic first flight in 1903. Technological advancements in the late 20th century reignited the exploration of remote-controlled aerial platforms, leading to remarkable growth rates and progress within the UAV sector.[73]

In geomatics, UAVs have experienced tremendous success by offering new possibilities for close-range aerial applications and providing a cost-effective alternative to traditional manned photogrammetry. These motorized aerial vehicles operate autonomously without a human pilot on board, enabling precise positioning, orientation tracking, and direct geo-referencing of sensors. UAV photogrammetry combines aerial and terrestrial techniques to generate digital surface models and orthoimages, delivering valuable solutions for heritage documentation and rapid response applications. The significance and potential of UAVs in remote sensing are evident in the growing market for UAVs.[74]

However, ongoing research is necessary to address challenges related to regulations, data processing, and accuracy. Despite limitations, UAVs have proven to be highly capable sources of imaging data, pushing the boundaries of traditional surveying methods and shaping the future of aerial remote sensing and mapping. While the integration of UAVs with automated photogrammetric software has made data acquisition more accessible, it still requires expert supervision for accurate results. UAVs have successfully been deployed in archaeology and cultural heritage projects for high-quality image data acquisition, facilitating the generation of orthoimages, DSMs,

[72] Piero Boccardo and others, 'UAV Deployment Exercise for Mapping Purposes: Evaluation of Emergency Response Applications', *Sensors*, 15.7 (2015), 15717–37 <https://doi.org/10.3390/s150715717>.

[73] I. Colomina and P. Molina, 'Unmanned Aerial Systems for Photogrammetry and Remote Sensing: A Review', *ISPRS Journal of Photogrammetry and Remote Sensing*, 92 (2014), 79–97 <https://doi.org/10.1016/j.isprsjprs.2014.02.013>.

[74] M. Bolognesi and others, 'Testing the Low-Cost Rpas Potential in 3d Cultural Heritage Reconstruction', in *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences* (Gottingen, Germany: Copernicus GmbH, 2015), XL, 229–35 <https://doi.org/10.5194/isprsarchives-XL-5-W4-229-2015>.

and 3D models. Close-range photogrammetry using light RPAS has made significant advancements, providing a cost-effective alternative for producing accurate 3D models.[75]

UAVs are extensively used for metric surveys, large-scale documentation, reconnaissance, surveillance, and mapping of natural hazards. They are classified based on specifications and offer a rapid and cost-effective means of data acquisition compared to piloted aerial vehicles. The consolidation of inventories of miniature sensors for civil applications remains a challenge due to the constantly evolving nature of UAV technology. With their versatility, efficiency, and accessibility, UAVs have revolutionized data acquisition, opening up new possibilities for remote sensing, mapping, and documentation in various domains.[76]

Drone miniaturization has been facilitated by advances in electronic components, lightweight materials, and increased computing power, making them more accessible and affordable. The technological components that comprise a typical civilian drone have greatly benefited from advances made in the last decade, including reducing the size of the high-performance video cameras that have become commonplace on quadcopter drones.[77]

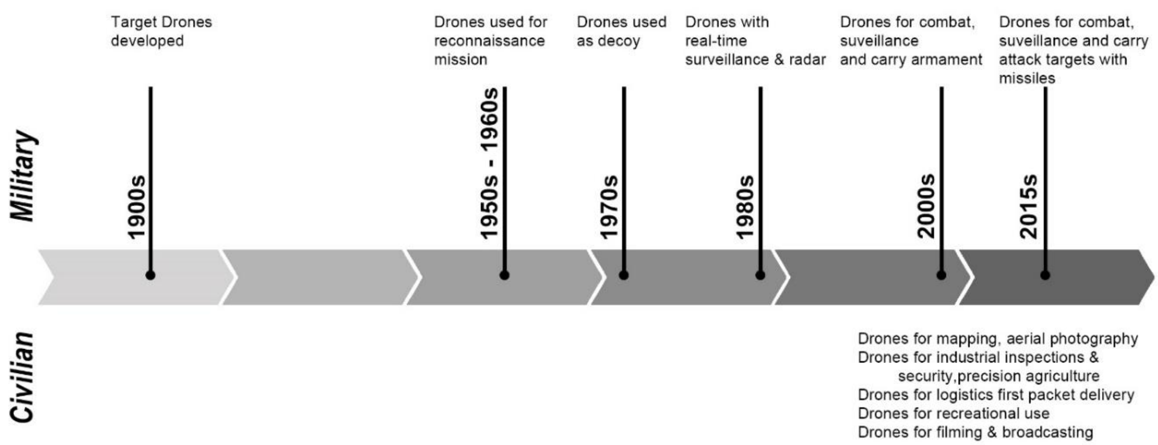



Fig 3-22) Timeline of Military and Civilian Evolution of UAVs Use[78]

## 4-1) Frameworks and Regulations

Drones, as mentioned previously, have become increasingly popular in civilian applications in recent years, which led to a need for regulations to ensure the safety of drone flights.

[75] A. Georgopoulos and others, ‘EVALUATING UNMANNED AERIAL PLATFORMS FOR CULTURAL HERITAGE LARGE SCALE MAPPING’, *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLI-B5 (2016), 355–62 <https://doi.org/10.5194/isprs-archives-XLI-B5-355-2016>.

[76] Filiberto Chiabrando and Andrea Maria Lingua, ‘Archaeological Site Monitoring: UAV Photogrammetry Can Be an Answer’ <https://core.ac.uk/works/4833819> [accessed 16 May 2023].

[77] Ferran Giones and Alexander Brem, ‘From Toys to Tools: The Co-Evolution of Technological and Entrepreneurial Developments in the Drone Industry’, *Business Horizons*, 60.6 (2017), 875–84 <https://doi.org/10.1016/j.bushor.2017.08.001>.

[78] Giones and Brem.

NATO and Eurocontrol began working together since 1999 to develop rules for UAV platforms and flights. However, the lack of a unified standard has led to a patchwork of regulations in different countries.
In order to address this issue, the European Union has proposed three "roadmaps" on research and development, complementary measures and safety rules for drones, which will be completed in 2028. The primary goals of UAV regulations are to:

- Increase the reliability of UAV platforms
- Emphasize the importance of UAV safety certifications
- Ensure public safety

The EU's roadmaps for UAV regulations are a significant step forward in ensuring the safe and responsible use of drones in civilian applications. It will harmonize the regulations across the EU, and provide clear guidance for drone operators and manufacturers.
The use of drones is expected to continue to grow in the coming years. As the number of drones in the sky increases, it is essential to have clear and comprehensive regulations in place to ensure the safety of all users.[79]

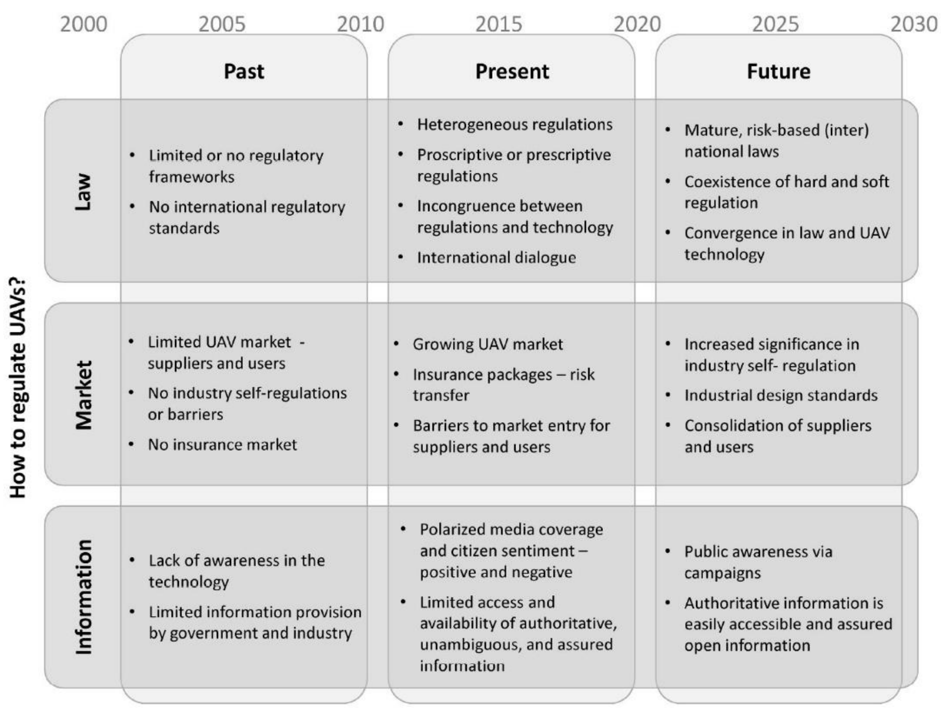



Fig 3-23) Consolidated overview of past, present and future developments distinguished according to main regulatory mechanism law, market and information[80]

[79] Francesco Nex and Fabio Remondino, 'UAV for 3D Mapping Applications: A Review', *Applied Geomatics*, 6.1 (2014), 1–15 <https://doi.org/10.1007/s12518-013-0120-x>.
[80] Claudia Stöcker and others, 'Review of the Current State of UAV Regulations', *Remote Sensing*, 9.5 (2017), 459 <https://doi.org/10.3390/rs9050459>.

## 4-2) UAVs' Applications in Geomatics

The field of geomatics is experiencing an increasing use of drones to collect, measure and analyze geographic data. UAVs are no longer just another remote sensing platform but are pushing boundaries and inspiring new applications.

Drones offer a wide range of data collection capabilities, including images, videos, and LiDAR data. These capabilities are used in various sectors such as agriculture, forestry, archaeology, architecture, environmental monitoring, emergency management, and traffic monitoring. On the other hand they also use in the fields of firefighting, rescue operations, energy sector monitoring, agriculture, fishing activities, Earth observation, remote sensing, and other communication and dissemination.[81]

Drones have already revolutionized remote sensing and led to the development of innovative methods and applications in various fields. To fully exploit the enormous potential of UAVs in geomatics and other industries, special attention must be paid to their integration and safe operation in the airspace to ensure their continuous evolution.[82]

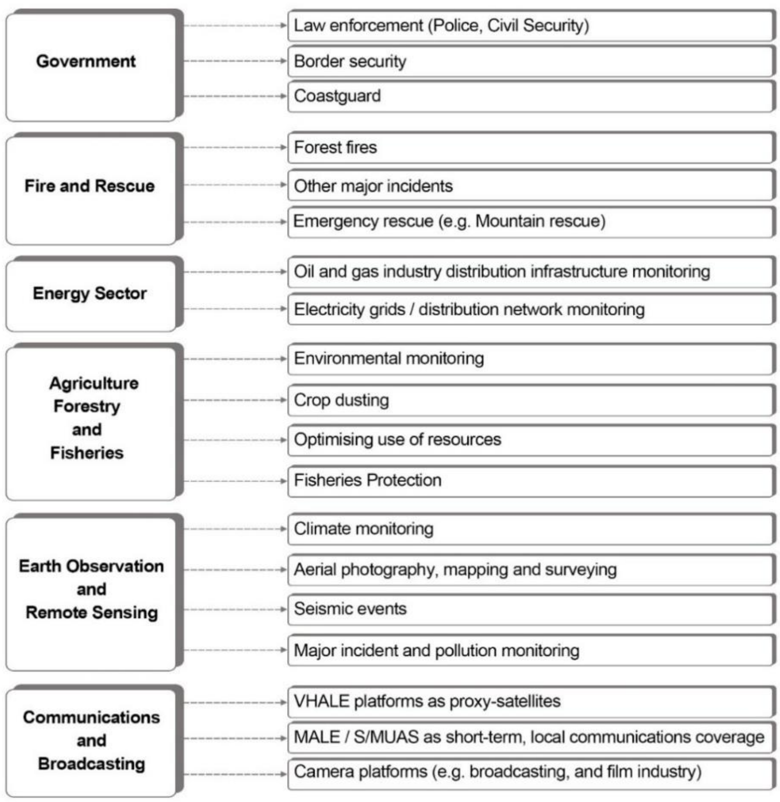



Fig 3-24) List of UAVs' Applications[83]

[81] 'Official Publication No. 56 (2009) | EuroSDR' <http://www.eurosdr.net/publications/official-publication-no-56-2009> [accessed 16 May 2023].

[82] Nex and Remondino.

[83] 'Study Analysing the Current Activities in the Field of UVA (Unmanned Aerial Vehicle) - Conducted by Frost and Sullivan for the European Commission, DG Enterprise and Indu' <https://home-

### 4-2-1) UAVs Deployment in the Field of Heritage Documentation

In recent years, the use of drones in the field of cultural heritage has gained significant momentum. Due to their affordability, adaptability, ability to collect high-resolution data, and capacity to acquire dense point clouds, UAVs are now a viable option for cultural heritage projects. Drones offer a valuable solution by capturing images from elevated positions and providing a more comprehensive view of buildings and their surroundings. In addition, they enable material analysis, identification, detailed documentation, and photography of the entire city. The integration of thermal imaging cameras and infrared thermography produces crucial spatial and spectral data for the comprehensive interpretation and analysis of cultural heritage objects.

Significant progress has been made in the use of drones for the documentation of archaeological sites, with the first documented use of sealed flasks for this purpose dating back to the 1960s. RGB orthophotos, DEMs, and 3D models are now widely utilized for the observation of archaeological sites, documentary excavations, the recording of Ancient Greek sites, the recording of burial mounds, the combination of drones with ground systems for monuments and architecture, and the production of precise archaeological cultural heritage models.[84]

## 4-3) UAVs Project Workflow

Typically, the UAV deployment process consists of five main steps: flight planning, ground control point (GCP) planning and measurement, image acquisition, photogrammetric processing, and delivery of the product.

However, there are additional tasks that must be completed before the acquisition phase. These include the maintenance and upgrade of the system as well as the management of all administrative documents for the flight permit. It is essential to pay attention to these details to ensure the safe completion of the acquisition process.[85]

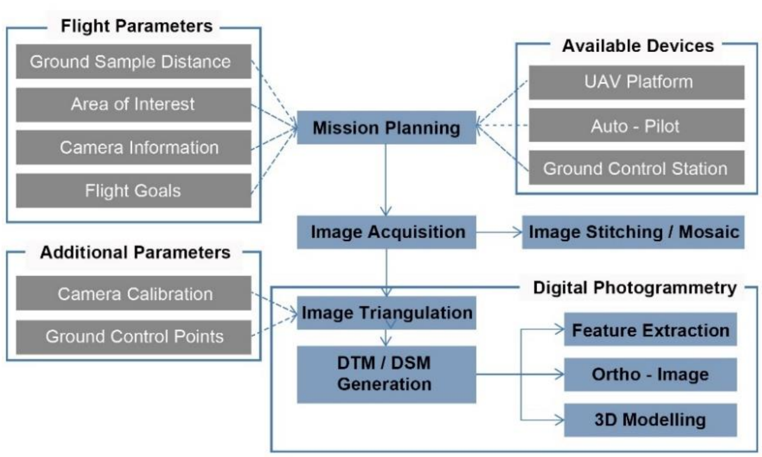



Fig 3-25) Typical Acquisition and Processing Pipeline for UAV Images[86]

affairs.ec.europa.eu/pages/document/study-analysing-current-activities-field-uva-unmanned-aerial-vehicle-conducted-frost-and-sullivan_en> [accessed 25 May 2023].

[84] Armagan Gulec Korumaz and others, *UAV SYSTEMS FOR DOCUMENTATION OF CULTURAL HERITAGE*, 2014.

[85] Lorenzo Teppati Losè.

[86] Nex and Remondino.

## 4-3-1) Flight Planning for UAVs and Data Acquisition

Flight planning for UAVs has been developed for various applications, including the military, robotics, computer vision, and artificial intelligence. Research focuses on flight maneuvers like flips and rolls, collision avoidance, automated target tracking, and "follow me" modes. Local 3D environments with known static and passive mobile obstacles enable local path planners to produce fast collision-free trajectories. Point navigation is a standard tool for M- and L-class UAV systems, allowing autonomous flight based on defined points in a global coordinate system. Integrating photogrammetric flights into UAV path planning requires mission planning software with additional functions, such as photogrammetric aerial flight planning tools.[87]

In 2004, a GIS-based flight planning system that includes parameters like altitude, aircraft position, and viewing angle for UAV flight planning was developed. UAVs operate in a transition between aerial and terrestrial photogrammetry, requiring different flight tools for data acquisition. The mission planning process typically employs specialized software in a laboratory setting to gather information about the area of interest, desired ground sample distance (GSD), and intrinsic camera parameters. Autonomous flight uses GNSS/INS navigation devices for takeoff, navigation, and landing, and an autopilot facilitates executing a flight according to planned parameters and enables communication with the platform. Inertial sensors can be cost-effective for navigation in low-cost UAVs, but their accuracy may not be sufficient for direct georeferencing.[88]

Advanced sensors based on single- or double-frequency positioning can improve positioning accuracy, but their high cost limits their widespread use in low-cost solutions. Ground Control Stations (GCS) monitor autonomous platforms during the flight, providing real-time flight data. Choosing the right devices, including the platform, autopilot, and GCS, is crucial for ensuring the quality and reliability of the final results. Low-level control tasks involve achieving flight, stabilizing the UAV, and following a designated flight path. Attitude control focuses on flight stabilization and tracking the desired heading, while position control facilitates trajectory following.

Low-cost platforms with advanced controllers, and error-model-based model-predictive control, have shown promising results. UAV control tasks involve maintaining stable hovering, rejecting disturbances, and following desired trajectories. High-level flight planning focuses on mission and path planning, including obstacle avoidance, enabling autonomous flight based on predefined mission plans. Path planning involves determining optimal flight paths using receding horizon planning or model predictive control techniques. Challenges in high-level planning include computational demands exceeding low-cost UAVs' capabilities, obstacle avoidance complexities, and airspace integration efforts.[89]

Adaptations or onboard implementations of path-planning methods may be required to overcome computational limitations. Proper formalization and consideration of computational limitations are essential for effective mission

[87] Henri Eisenbeiß, *UAV Photogrammetry*, Mitteilungen / Institut Für Geodäsie Und Photogrammetrie an Der Eidgenössischen Technischen Hochschule Zürich, 105 (Zürich: ETH, Inst. für Geodäsie und Photogrammetrie, 2009).

[88] Nex and Remondino.

[89] Koppany Mathe and Lucian Busoniu, 'Vision and Control for UAVs: A Survey of General Methods and of Inexpensive Platforms for Infrastructure Inspection', 2015, 14887–916 <https://doi.org/10.3390/s150714887>.

planning. By integrating control and planning techniques, UAVs can achieve autonomous flight and accomplish specific missions with improved efficiency and safety.

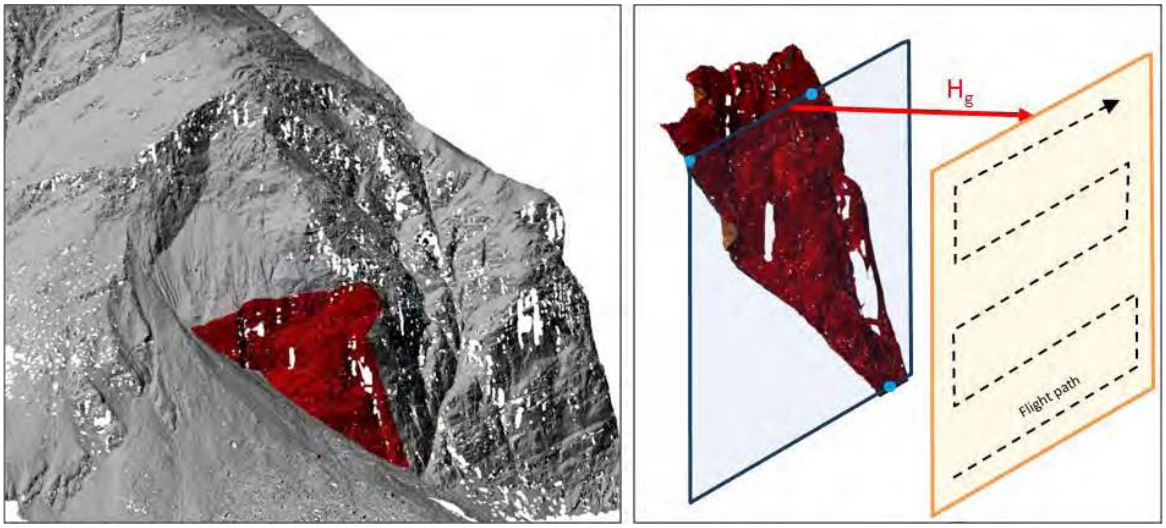



Fig 3-26) Left: Example for a 3D Case Showing the Existing DSM

Right: Fitted Plane for the Area of Interest and A Parallel Plane with A Distance $H_g$ to the Fitted Plane[90]

## 4-4) Georeferencing Strategies and GCPs

Among the various phases of the photogrammetric pipeline, one of the most time-consuming processes, both in field acquisition and data processing, is georeferencing and scaling the model. Three primary strategies can be employed to accomplish this task:

- Direct georeferencing
- Use of GCPs
- Dataset co-registration

***Direct georeferencing,*** becomes feasible by knowing camera positions and utilizing GPS/GNSS sensors mounted on aerial platforms. Two main techniques are real-time kinematics (RTK) and post-processed kinematics (PPK). RTK involves real-time correction of satellite data, while PPK is performed in a separate phase. In RTK, the aerial platform's GNSS is connected to a base station where global coordinates are embedded in the Exchangeable Image File Format (Exif) metadata. PPK employs two GNSS receivers, one on the platform and the other as a ground station, recording raw data and processing it with dedicated solutions.

[90] Eisenbeiß.

***Use of GCPs,*** are widely used but are time-consuming and resource-intensive. Traditional approaches employ pre-coded markers and natural features, meticulously projecting and establishing control points. Factors such as the number, position, and size of the targets need to be considered, along with altitude, lighting conditions, and surface color. If natural or man-made features are chosen, the same level of attention described for the targets must be applied, ensuring their recognizability in the acquired images. After selecting and positioning the points, the measurement phase is carried out using conventional topographic techniques such as Total Station (TS) or GNSS. The choice of techniques depends on the area's configuration, size, available time, and desired accuracy. TS provides better measurement accuracy but requires more time in the field. GNSS techniques cover larger areas in a shorter time but they sacrifice some accuracy. The positioning and measurement of control points are critical phases in this process.

***Dataset Co-registration*** is a third approach for scaling and georeferencing data collected in the field. This method is designed to monitor dynamic scenes and reduce the reliance on GCPs, necessitating manual operator intervention. It involves using a reference epoch as a base to register slave epochs.

Further tests will be conducted to standardize flight planning for the multitemporal approach in archaeological excavation documentation. New strategies for co-registering and validating the multitemporal dataset will be experimented with, such as setting up fixed materialized points around the excavation for processing and metric control of the results. Masks within the photogrammetric software during processing can exclude areas that have undergone modifications and enhance the processing phase. These strategies can yield appreciable results but are undoubtedly time-consuming.[91]

[91] Lorenzo Teppati Losè.

# Chapter 4

# Underwater Photogrammetry

## 1) Underwater Photogrammetry

Photogrammetry has played a pivotal role in the documentation of underwater archaeology for several decades. Its initial application dates back to the 1960s and 1970s, when the first stereo-pair cameras were employed, adapting aerial surveying techniques to the challenging underwater environment. While this approach significantly reduced the time required for documentation and provided high accuracy in recording, measuring, and interpreting photographic images, it also presented certain operational constraints. These included the necessity for parallel optical axes to ensure stereovision, demanding a high level of technical expertise, cumbersome equipment like double cameras mounted on metal structures, and extensive manual processing efforts to yield relatively limited measurements.[1]

In recent years, the imperative to produce detailed and precise three-dimensional mappings, coupled with the advantages of affordability, expediency, and ease of execution, has led to the application of image-based techniques and digital photogrammetry in underwater archaeological site documentation. Numerous experimental projects in 3D modeling of underwater features now employ consumer-grade cameras and specialized software for highly automated data processing. This calibration and measurement approach is widely recognized as a powerful and accessible tool for non-destructive archaeology worldwide. Notably, it offers the advantage of on-site validation of feature-matching results.[2]

Multi-image photogrammetry currently stands as a capable technique for mapping and reconstructing the shape and geometry of fully submerged objects. It has transformed underwater photogrammetry from a highly technical and costly process into a considerably more robust and accessible tool.

The creation of dense and accurate 3D models offers myriad opportunities for the interpretation and presentation of underwater archaeological sites. It provides highly realistic documentation, characterized by "high fidelity"

[1] George F. Bass, '1970_Archaeology Under Water', 1966 <https://www.academia.edu/34248126/1970_Archaeology_Under_Water> [accessed 31 May 2023].

[2] John McCarthy and Jonathan Benjamin, 'Multi-Image Photogrammetry for Underwater Archaeological Site Recording: An Accessible, Diver-Based Approach', *Journal of Maritime Archaeology*, 9.1 (2014), 95–114 <https://doi.org/10.1007/s11457-014-9127-7>.

models, and a recording that can be consulted to obtain precise measurements. This capability allows for virtual "return" visits to the site, even in challenging access conditions, to verify various data points such as measurements, shapes, colors, and locations. Furthermore, 3D models have the potential to enable the public to explore underwater archaeological sites as if they were in dry suits, as demonstrated in ongoing research.[3]

## 2) Water Environments Limitations and Challenges

Underwater photogrammetry entails a multitude of intricacies and obstacles arising from the distinctive attributes of the submerged environment. Key challenges in the realm of underwater photogrammetry encompass:

- ***Refraction Effects:*** Light's passage from one medium, typically air, to another, notably water, induces refraction, leading to deviations in the trajectories of light rays. This phenomenon introduces distortions and displacements in underwater imagery, posing significant hurdles to precise measurements and reconstructions.
- ***Limited Visibility:*** Underwater visibility frequently faces constraints due to factors such as suspended particles, sedimentation, and the presence of algae. Impaired visibility gives rise to indistinct and noisy images, thereby impeding the extraction of accurate 3D data.
- ***Water Turbidity:*** The presence of suspended particles and sediments in water contributes to turbidity, which scatters and absorbs light. This exacerbates the degradation of underwater image quality and exerts an adverse influence on the precision of photogrammetric measurements.
- ***Color and Lighting Variations:*** Water exhibits selective absorption of different light wavelengths, leading to color alterations in underwater images. Additionally, the intensity and direction of natural illumination undergo rapid alterations with changing depths and surface conditions, affecting image consistency and quality.
- ***Calibration Complexities:*** Achieving accurate calibration of underwater cameras and equipment is essential to compensate for the distortions introduced by refraction and water-related properties. Calibration in an underwater context is often intricate and time-intensive.
- ***Image Noise:*** The presence of water introduces noise and artifacts into images, complicating the identification and correspondence of matching points essential for precise 3D reconstruction.
- ***Depth-Dependent Variations:*** Photogrammetry relies on the assumption of a fixed focal length, which can pose challenges when capturing objects at varying depths underwater. Depth variations can lead to scale and perspective distortions in the reconstructed models.

[3] M. Ballarin and others, 'UNDERWATER PHOTOGRAMMETRY: POTENTIALITIES AND PROBLEMS RESULTS OF THE BENCHMARK SESSION OF THE 2019 SIFET CONGRESS', *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLIII-B2-2020 (2020), 925–31 <https://doi.org/10.5194/isprs-archives-XLIII-B2-2020-925-2020>.

- ***Water Movement:*** Underwater environments are subject to waves, currents, and turbulence, which can introduce motion blur and instability into captured images. This phenomenon hinders the acquisition of sharp and clear photographic data for photogrammetric analysis.
- ***Equipment Reliability:*** Underwater photogrammetry necessitates specialized, waterproof, and pressure-resistant cameras and equipment. Ensuring the reliability and functionality of such equipment can present logistical complexities.
- ***Data Integration:*** The amalgamation of data from diverse underwater images to construct a coherent 3D model is intricate. Each image may exhibit distinct lighting conditions, depths, and perspectives, necessitating meticulous integration.
- ***Environmental Challenges:*** Conducting underwater photogrammetry often entails working in demanding and unpredictable environments. These may encompass challenges such as saltwater corrosion, strong underwater currents, and limited visibility, posing safety risks to both divers and equipment.[4]

For accurate and reliable photogrammetric results in underwater settings, you need a mix of specialized techniques, exact calibration procedures, and flexible methods to deal with these issues.

# 3) Applications of Geomatics Technology to Marine Archaeology

Underwater cultural heritage (UCH) assets, such as shipwrecks and architectural structures, present diverse shapes and sizes that require varying levels of detail in their investigation. To address these complexities, specialized high-resolution sensors like underwater laser scanners and digital cameras are well-suited for detailed 3D recording but may be limited when surveying expansive underwater areas. For mapping extensive seafloor regions and detecting shipwrecks, ship-mounted multibeam echosounders (MBES) emerge as the preferred solution. Accurate geo-referencing is essential for archaeological studies, with airborne or ship-mounted surveys relying on GNSS-INS systems for precise positioning. Mobile systems like remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) leverage simultaneous localization and mapping (SLAM) and acoustic positioning for navigation and orientation. Reference measurements play a crucial role in photogrammetry and can be obtained through calibration or traditional surveying techniques.

Underwater surveys are classified as shallow or deep based on their depth relative to divers or vessels. Achieving success in underwater archaeological projects hinges on a collaborative approach between maritime archaeology and underwater surveying experts. Adopting a coarse-to-fine strategy is a common practice where an initial survey provides adequate spatial resolution for the entire area, followed by a detailed examination of particular points of interest.

Georeferencing underwater cultural heritage (UCH) sites presents unique challenges, particularly at depths exceeding 3 meters. GPS receivers with large poles can be employed on land for precise geolocation, but buoys

[4] Ballarin and others.

are discouraged in deeper waters due to the influence of currents and waves. Long-baseline acoustic positioning systems offer centimeter-level accuracy, but their high cost renders them impractical for most archaeological purposes.

Establishing an underwater network of control points is a challenging task, and increasing depth makes it more challenging to choose, stabilize, and measure control points. Conventional land-based methods are often ineffective due to harsh underwater conditions, limited downtime, poor visibility, and communication challenges.

Underwater 3D reconstruction using Structure from Motion (SfM) offers speed, ease of use, and versatility but faces limitations and challenges due to environmental and IT factors.[5]

## 3-1) Camera Calibration

Camera calibration is a crucial procedure in underwater photogrammetry, allowing for the accurate determination of object positions and dimensions within the image space. While the classification of this process as a pre-processing step remains debatable, its significance cannot be understated. It is essential to consider the implications of camera housings and the aquatic environment to achieve reliable results. Maintaining a consistent focal length throughout the camera calibration and image orientation phases is paramount. Employing separate calibration certificates for each camera is also necessary to ensure accuracy. Additionally, strategically positioning scale bars or markers within the scene is crucial for reference and scale estimation. When feasible, undertaking pre-calibration protocols in both terrestrial and aquatic settings helps compensate for distortions arising from the ambient conditions. Furthermore, it is advisable to maintain a fixed camera position during the rasterization and object acquisition stages to preserve the integrity of external camera functionalities.[6]

Various methods and strategies exist for calibrating digital cameras. Commonly available photogrammetric software utilizing computer vision algorithms allows for self-calibration of the camera. This approach can lead to accuracy improvements of up to threefold compared to situations where no camera calibration is performed. (This self-calibration method has proven effective even with non-metric and non-conventional low-cost photogrammetric sensors.)[7]

Camera calibration is subject to the laws of physics and requires corrections to the collinearity equation. When dealing with flat or domed ports, aligning the center of projection with the center of the dome is crucial to eliminating refraction. However, achieving this alignment can be challenging unless the camera and housing are integrated as

[5] Dimitrios Skarlatos and Panagiotis Agrafiotis, 'Image-Based Underwater 3D Reconstruction for Cultural Heritage: From Image Collection to 3D. Critical Steps and Considerations', in *Visual Computing for Cultural Heritage*, ed. by Fotis Liarokapis and others, Springer Series on Cultural Computing (Cham: Springer International Publishing, 2020), pp. 141–58 <https://doi.org/10.1007/978-3-030-37191-3_8>.

[6] A. Calantropio and others, 'IMAGE PRE-PROCESSING STRATEGIES FOR ENHANCING PHOTOGRAMMETRIC 3D RECONSTRUCTION OF UNDERWATER SHIPWRECK DATASETS', *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLIII-B2-2020 (2020), 941–48 <https://doi.org/10.5194/isprs-archives-XLIII-B2-2020-941-2020>.

[7] Evan Kovacsc Alessio Calantropio, 'PRE- AND SELF-CALIBRATION OF UNDERWATER CAMERAS FOR PHOTOGRAMMETRIC DOCUMENTATION OF ARCHAEOLOGICAL SITES', *Editorial Universitat Politècnica de València*, 2021 <https://doi.org/10.4995/arqueologica9.2021.13259>.

a single unit. Deviations within 1 cm of the two centers can be compensated by combining the central and tangential distortion parameters in the calibration model. In cases where misalignment occurs between the camera and the dome or planar port, a comprehensive physical model is necessary, taking into account factors such as glass thickness.[8]

The underwater environment presents a significant challenge in terms of chromatic aberration, resulting in the distortion of pixels. To mitigate these distortions, it is essential to ensure compatibility between the color channel used for calibration and the one used for 3D reconstruction. In underwater structure from motion (SfM), selecting a specific color channel for alignment and 3D reconstruction while using color images for texture instead of single-channel images is recommended. While post-processing techniques can address chromatic aberration, correcting refractive aberration in close-range imaging is a depth-dependent 3D problem.

Wide-angle lenses introduce considerations such as light absorption and vignetting effects, primarily in the realm of radiometry rather than geometric aspects. Underwater strobes can be effective over short distances, but they may impact image sharpness, clarity, and the performance of feature finders. Floating particle backscatter and strobe misalignment can have a negative impact on feature detection, texturing, and orthoimage generation.[9]

While pre-calibration is commonly used in data acquisition situations, particularly in archaeology, a robust self-calibration procedure can still yield significant gains in survey accuracy. Properly performed self-calibration leads to lower reprojection errors, which is especially crucial in underwater environments due to additional distortions caused by the varying refractive indexes of water and air, as well as the geometric characteristics of flat or dome ports that may be utilized.[10]

[8] Skarlatos and Agrafiotis.

[9] Skarlatos and Agrafiotis.

[10] Alessio Calantropio.

Chapter 5

# Photogrammetry in Selected UCH

## 1) Historical and Geographical Context

The Porto Cesareo Marine Protected Area (MPA) represents a remarkable coastal expanse situated within the Apulia region of Italy, nestled along the eastern shores of the Ionian Sea. Initiated through a formal decree issued by the Ministry of the Environment on December 12, 1997, this location stands as an exceptional testament to its distinct character. Encompassing an expansive domain spanning 16,654 hectares, the Porto Cesareo MPA garners distinction as the third-largest among Italy's collection of 29 Marine Protected Areas.

Extending across a coastal stretch of 32 kilometres, the MPA envelops the territorial perimeters of Porto Cesareo and Nardò within the province of Lecce. Punta Prosciutto to the north and Torre Inserraglio to the south flank it, blending sandy expanses and low-lying rocky shorelines adorned with islets and formations. The precinct of the MPA harbours a multitude of invaluable environmental and archaeological assets intertwined with a diverse spectrum of human endeavours, thus collectively accentuating its profound significance.[1]

The municipalities of Porto Cesareo and Nardò, which are located within the Reserve's boundaries, in collaboration with the Province of Lecce, have elevated the MPA to the status of a State Marine Reserve under the control of the Consortium. The MPA is demarcated into two Zone A sectors, two Zone B sectors, and a single Zone C sector. Particularly notable is the Porto Cesareo MPA's distinction as the sole State Marine Reserve in the Salento region. Despite its considerable magnitude, the Porto Cesareo MPA distinguishes itself as one of the select Marine Protected Areas to have undergone comprehensive seabed cartography. Employing sophisticated methodologies and technological tools such as geoacoustic systems and remotely operated vehicles (ROVs), meticulous data was amassed regarding habitat classification, distribution, and extent. This survey unveiled more than 15 distinct habitats within the MPA's seafloor, exemplifying a remarkable representation of Mediterranean marine ecosystems. In 2011, the Porto Cesareo MPA was duly incorporated into the roster of Specially Protected Areas of Mediterranean Importance (ASPIM) under the designation IT08. The discernible presence of prominent Posidonia oceanica,

[1] Assistenza Tecnica Clio, 'Amp Porto Cesareo - Area Marina Protetta', 2023 <http://www.ampportocesareo.it/ente/a-m-p> [accessed 13 June 2023].

Coralligeno, and Submerged Caves came to light, underscoring the environmental value intrinsic to these habitats and warranting protective measures.[2]

Within the precincts of the MPA, three marine Sites of Community Importance (SCI) have been designated, contributing substantively to collaborative environmental safeguarding and cooperation spanning neighbouring jurisdictions. The Porto Cesareo MPA further features as an integral component of the proposed "North Ionian" PEACE PARKS initiative, encompassing the Torre Guaceto Reserve along with coastal expanses in Albania and Greece.[3]


Fig 5-1) The Situation of the Study Area in Apulia, Southeast Italy, with the Locations Cited in the Text

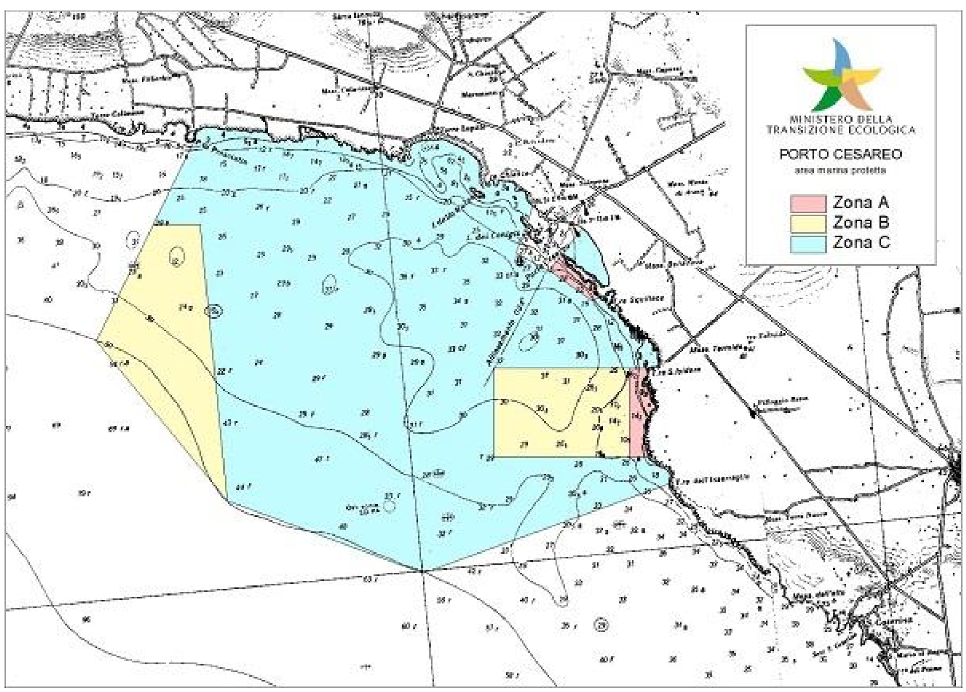



Fig 5-2) The Limits of the MPA of Porto Cesareo and Its Special Protection Subareas (A, B,C)

[2] 'Auriemma et al. 2nd Dive in Blue Growth'.

[3] Clio.

## 2) Case Study

Beneath the serene waters of Porto Cesareo lies a captivating tapestry of historical treasures, embodying the rich legacy of human existence across epochs. Beyond its renowned sun-soaked beaches and crystalline seas, this coastal haven unfolds a narrative steeped in time. Mycenaean ceramic artifacts that attest to ancient Greek trade exchanges reveal echoes of a Bronze Age settlement within the Scala di Furno peninsula. Meanwhile, near the Chianca Tower's inlet, Roman columns fashioned from cipollini marble grace the seabed, their origins dating back to the 2nd century AD. An enduring reminder of a shipwreck's enigmatic tale safeguards the remnants of a Greek vessel's cargo—relics that met their fate in the embrace of the sea during ancient voyages and were recently brought to life through a captivating drone portrayal by Emiliano Peluso.[4]

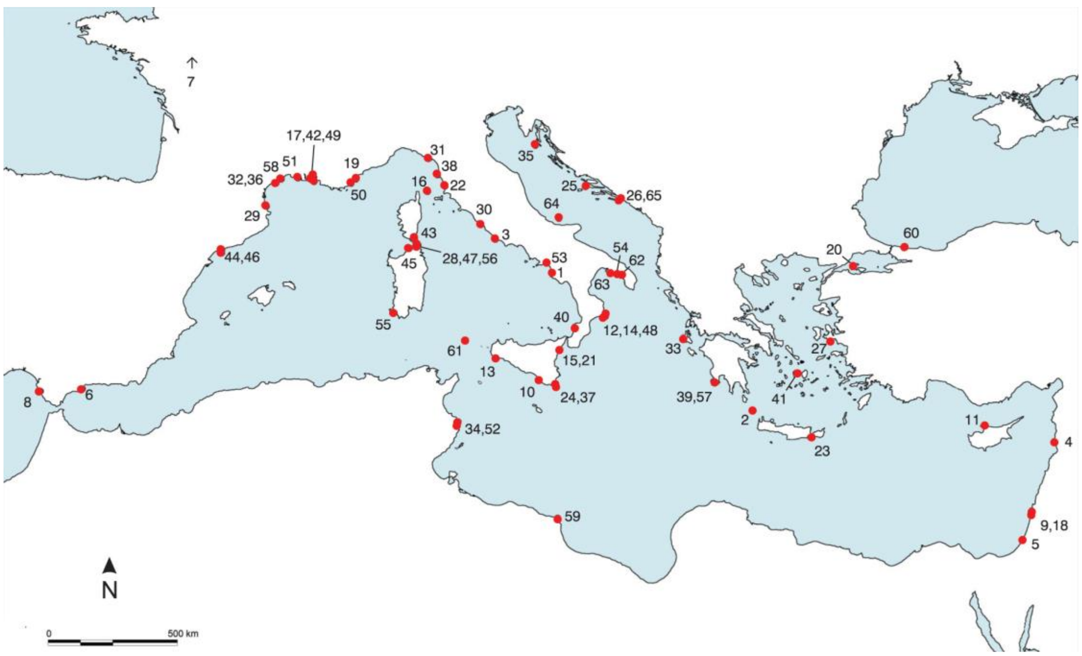



Fig 5-3) Map of Distribution of Shipwrecks with Marble/Stone Cargos[5]

These five monolithic Roman columns rest 4.5–5 meters below the water's surface near the Torre Chianca inlet and merely 80 meters from the shoreline, providing an intimate link to ancient Roman craftsmanship. Crafted from cipollini marble, their imposing statures, ranging around 9 meters in height with diameters spanning from 70

[4] 'Porto Cesareo, il drone svela le colonne romane inabissate da duemila anni', 2019 <https://www.ilmessaggero.it/italia/porto_cesareo_colonne_romane-4396179.html> [accessed 10 September 2023].

[5] Katarína Čekovská and others, 'Population Genetic Diversity of Two Marine Gobies (Gobiiformes: Gobiidae) from the North-Eastern Atlantic and the Mediterranean Sea', *Journal of Marine Science and Engineering*, 8.10 (2020), 792 <https://doi.org/10.3390/jmse8100792>.

centimeters to one meter, narrate a tale of resilience against the ravages of time and turbulent waters. They reveal themselves both as submerged artifacts and ethereal sculptures when viewed from above the sea.[6]

Fig 5-4) Shipwreck of the Columns Porto Cesareo (Le)

Originating from the Karystos quarries of Euboea's southern reaches, these columns, marked by their rudimentary grooves, endured the ages and are now adorned with marine life. While the passage of time has eroded the wreck that housed them, these columns persist as stoic sentinels. This submerged wonder invites exploration, whether reached via a leisurely maritime voyage or an 80-meter coastal swim from the nearby inlet. It is a realm accessible not only to seasoned divers but also to enthusiasts equipped with nothing more than masks and fins, offering a glimpse into an enchanting world beneath the waves.[7]

Fig 5-5) Shipwreck of the Columns Porto Cesareo (Le)

The case study of the Porto Cesareo Marine Protected Area (MPA), situated in southern Italy, serves as a focal point of investigation. Over the last decade, numerous on-site surveys have been conducted by various teams, contributing to an extensive body of research. These surveys have formed the basis for in-depth studies that shed

[6] 'Articolo:UnderwaterMuse e Le Nuove Frontiere Dell'archeologia Subacquea', *Università Ca' Foscari Venezia*, 2021 <http://unive.it/pag/14024/?tx_news_pi1%5Bnews%5D=11364> [accessed 12 September 2023].
[7] 'The Underwater Archaeology of Salento. Preliminary Report on Recent Research in the Adriatic and Ionian Seas' <https://iris.unisalento.it/handle/11587/499807> [accessed 12 September 2023].

light on the region's historical significance. Notably, these efforts have led to the discovery of diverse ancient historical traces, enriching our understanding of the area's history. The site has revealed a wealth of cultural heritage, both on land and underwater, providing valuable insights into the past. One of the study's central focuses is on the underwater columns, showcasing the relevance of these submerged architectural elements.[8]


Fig 5-6) Porto Cesareo MPA (Le). Snorkeling Tour of Underwater Trails

[8] C Alfonso and others, 'Ancient Coastal Landscape of the Marine Protected Area of Porto Cesareo (Lecce, Italy): Recent Research', *Underwater Technology*, 30.4 (2012), 207–15 <https://doi.org/10.3723/ut.30.207>.


Fig 5-7) Shipwreck of the Columns Porto Cesareo (Le) Location: Google Map (Up); Google Earth (Down)

Part of the UnderwaterMuse project, conducted in June 2021, involved the participation of the Polytechnic of Turin, professors Filiberto Chiabrando and Andrea Lingua, doctoral student Alessio Calantropio, and technician Paolo Maschio. Additionally, Professor Rita Auriemma from the University of Salento collaborated on this project. The actions were conducted in two distinct locations, one of which was the designated marine conservation area of Porto Cesareo. It is worth underscoring that the author of this document did not participate directly in the on-site surveys. Instead, the author leveraged the acquired data for the ensuing stages of the study, thanks to Professor Filiberto Chiabrando and Alessio Calantropio[9], my supervisor and co-supervisor, respectively.

Fig 5-8) Underwater Surveying of Shipwreck of the Columns Porto Cesareo (Le)

[9] CALANTROPIO, ALESSIO, 'Geomatic Techniques for the Documentation of the Underwater Cultural Heritage' <https://iris.polito.it/handle/11583/2978503%20as%20Calantropio,%20A.%20(2023).%20Geomatic%20techniques%20for%20the%20documentation%20of%20the%20Underwater%20Cultural%20Heritage.> [accessed 10 September 2023].

## 3) Data Acquisition

The inception of crafting precise three-dimensional models via multi-image photogrammetry mandates the acquisition of top-tier photographs. Optimal results pivot on the selection of an apt camera and accompanying gear to secure the capture of vivid, faithfully hued images. While archaeologists are presented with an array of feasible options, the pinnacle of success lies in the caliber of chosen equipment. An exploration by Zhukovsky delves into the intricacies of underwater photography. The gamut of intricacies encompasses optical distortions induced by water and camera interaction, optical interference arising from mobile elements such as aquatic life or suspended particles (backscatter), diminished visibility, and inadequate illumination that reshapes color perception. Given the evident chromatic degradation with depth and the prevalent subdued light conditions underwater, the inclusion of strobe lights emerges as a requisite. A configuration of two strobe lights strategically poised with extended articulated arms emerges as the most efficacious and adaptable setup for multi-image photogrammetry.

Ensuring a robust interlinkage between the site plan and a well-grounded coordinate network constitutes a cardinal aspect of photogrammetry. This alignment not only rectifies scale and inherent distortions within photogrammetry models but also fashions a contextual accord with archaeological vestiges. A salient hallmark of Agisoft Metashape is its dispensation of the necessity for camera pre-calibration. While calibrated methodologies might find relevance in certain scenarios, Metashape is endowed with automated lens calibration capabilities, thus proficiently simulating lens distortions through its integrated camera model. The approved calibration target within Metashape employs a chessboard pattern on an LCD screen. Alternatively, a printed chessboard pattern can suffice, provided it retains evenness and square-cell symmetry. This calibration regimen encompasses an exhaustive estimate of the complete camera calibration matrix, encompassing non-linear distortion coefficients.

Invariably, distortions ensue as an inescapable constituent, necessitating the careful arrangement of control points. A concurrent rationale underpinning the establishment of these points is anchoring models within a congruous coordinate framework. Absent such mooring, models are adrift within uncharted three-dimensional realms. Prudent integration of coordinates into the reconstructed models is pivotal for the seamless import and export of referenced computer graphic files, facilitating unobstructed workflows across diverse mapping software platforms. Furthermore, the processing and rendering capacities of Agisoft Metashape are tethered to hardware confines, thereby imposing limits on the scale of models processed in solitary batches. A judicious workaround entails the merging of partial 3D models or those crafted via distinct software, contingent on the allocation of spatial references. The infusion of coordinates into models and orthophotos initiates an automated fusion process, culminating in the unlocking of exported files in their intended orientations. This clears the path for amalgamating surveys spanning divergent epochs, simplifying the tracking of excavation progress.[10]

[10] P. Agrafiotis and others, 'THE EFFECT OF UNDERWATER IMAGERY RADIOMETRY ON 3DRECONSTRUCTION AND ORTHOIMAGERY', *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-2/W3 (2017), 25–31 <https://doi.org/10.5194/isprs-archives-XLII-2-W3-25-2017>.

Fig 5-9) Underwater Control Points

Fig 5-10) Measurement Points on the Ground

In order to manipulate tridimensional models and project orthophotos with precision and security, the establishment of a localized coordinate framework is indispensable. A multitude of methods exists for constructing a three-dimensional control point network. However, our discourse here centers on our endeavors to establish localized coordinates across terrestrial and aquatic domains, guided by rudimentary surveying principles foundational to archaeological contexts.

The survey encompassed a methodological framework reliant on different tools, sequenced across discrete phases as delineated below:

- ***Preliminary Analyses:***

This foundational stage served to orchestrate the ensuing work processes. Prior to the underwater survey, meticulous site inspections were conducted, serving to engender a comprehensive comprehension of the environment and to discern potential critical nuances. Concurrently, meteorological forecasts were scrutinized, ensuring optimal water conditions. This assessment, pivotal in selecting the requisite instrumentation, streamlined subsequent operations.

- ***Target Positioning and Measurement:***

The process of target positioning adhered closely to directives proffered by knowledgeable archaeologists well-acquainted with the survey's focal subject matter. The operationalization of this facet entailed the utilization of the Leica GS18 GNSS RTK Rover, endowed with an extendable pole spanning up to 5 meters. The complex challenges of the survey, such as the movement of the sea surface, the currents on the seabed, and the length of the pole, led to the choice of this equipment, which includes an IMU sensor that can correct pole tilt. This configuration conferred heightened precision by mitigating disturbances. However, measuring targets brought forth certain complexities. A diver positioned on the seabed proximate to the measurement point was tasked with ensuring the precise placement of the pole's tip, while a secondary operator on the surface received hand signals to maintain pole verticality, keeping the receiver above water. Concomitantly, this surface operator communicated to a third counterpart on the boat, who executed measurements through the controller. The equipment's size and weight during underwater transit increased operational complexity in addition to the intricate coordination. The bottom operator was further burdened with the responsibility of avoiding target displacement and water turbidity, safeguarding subsequent survey phases.

- ***Photogrammetric Survey:***

This phase culminated in the photogrammetric survey, employing the collated data to construct an accurate visual representation of the underwater terrain.

By delineating the survey into these distinct phases and employing a meticulous selection of tools, the research aimed to achieve robust and dependable outcomes, even in the face of formidable operational challenges.

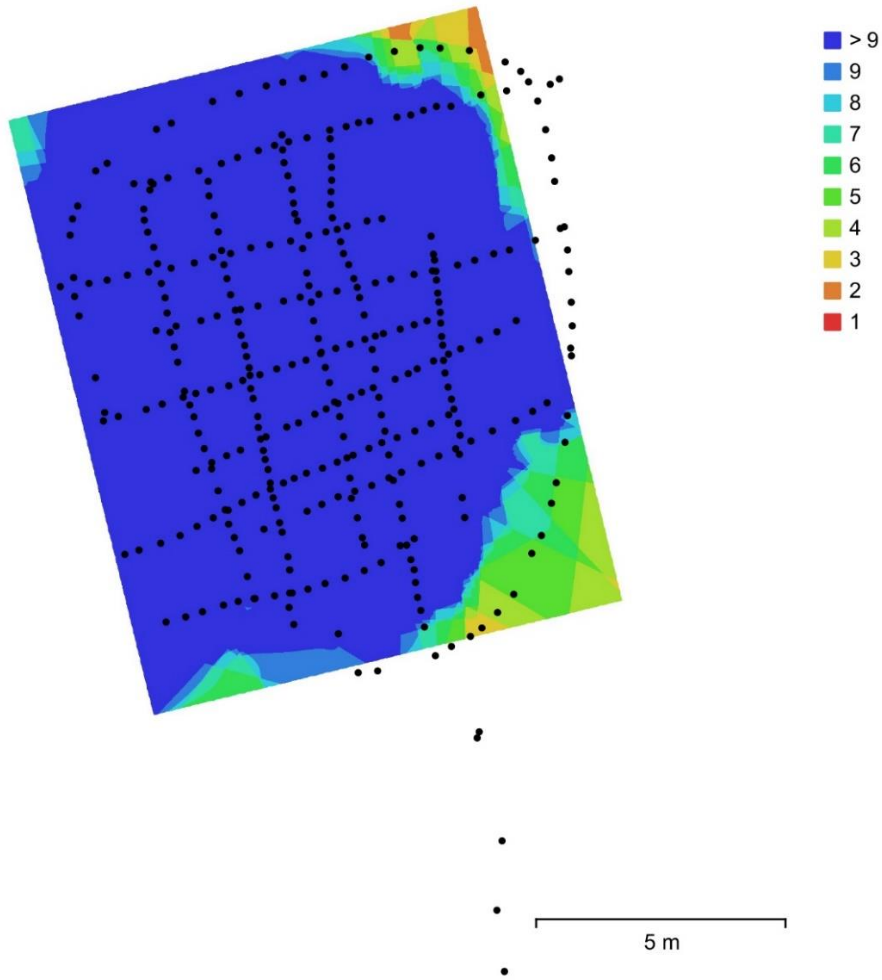
## 3-1) Photogrammetric Survey

To investigate the submerged component, the study adopted photogrammetric methodologies, leveraging three distinct camera systems—namely, two Olympus TG-6s and a Nikon Coolpix AW130 (To produce final results, just acquired images by camera Olympus TG-6s have been used). The employment of this trio of devices necessitated the involvement of two distinct teams, operating on separate days and employing differing equipment configurations. The rationale behind this diversity in equipment usage is rooted in the unique attributes inherent to each device, as delineated subsequently, which inherently influence the data acquisition outcomes.


Fig 5-11) Right: Nikon Coolpix AW130; Left: Olympus TG-6;

| | Olympus TG-6 |
|---|---|
| **Camera Type** | Compact |
| **Image Sensor** | 1/2.33 inch CMOS |
| **Objective** | With x4 optical zoom |
| **Focal Length** | 4.5-18.0 mm |
| **Focus Method** | Tracking autofocus of the contrast |
| **Image Size in Pixels** | 4000x3000 |
| **ISO sensitivity** | 100-12800 |

Table 5-1) Camera Olympus TG-6 Characteristics




Camera locations and image overlap.

| | | | |
|---|---|---|---|
| Number of images: | 376 | Camera stations: | 352 |
| Flying altitude: | 2.24 m | Tie points: | 453,118 |
| Ground resolution: | 0.521 mm/pix | Projections: | 1,151,298 |
| Coverage area: | 119 m² | Reprojection error: | 1.09 pix |

| Camera Model | Resolution | Focal Length | Pixel Size | Precalibrated |
|---|---|---|---|---|
| TG-6 (4.5mm) | 4000 x 3000 | 4.5 mm | 1.53 x 1.53 μm | No |

Fig 5-12) Underwater Survey Data

Concurrently with the underwater survey, an airborne drone reconnaissance was conducted to establish a contextual framework for the investigated artefacts in relation to the coastal landscape. The initial stage involved the utilisation of a Dji Phantom 4 unmanned aerial vehicle (UAV), which was chosen due to its distinct technical features, as described below:

| **Drone (Dji Phantom 4)** | |
|---|---|
| Maximum rate of climb | 6 m/s |
| Maximum descent speed | 4 m/s |
| Weight | 1388 gr |
| Battery capacity | 6000 MAH (30 minute flight) |
| Maximum tilt angle | 27° |

Table 5-2) Drone Dji Phantom 4 Characteristics

| **Camera** | |
|---|---|
| Image sensor | 1/2.3 inch |
| Objective | FOV 94° 20 mm |
| ISO sensitivity | 100-3200 (video) 100-1600 (foto) |
| Image size in pixels | 4000x3000 |
| Pixel size | 1.5 micron |
| Focal distance | 4.56 mm |

Table 5-3) Fotocamera Characteristics

Fig 5-13) Left: Drone; Right: Fotocamera

Similarly, an array of markers was meticulously positioned across the terrain, ensuring uniform distribution. These markers underwent comprehensive surveying via the Leica GS18 GNSS RTK rover to facilitate the georeferencing of photogrammetric data. The distinct topographic circumstances near the shoreline introduce various challenges to this form of mapping. Notable challenges encompass the continual motion of the water, which restricts the utilisation of substantial portions of image frames for alignment purposes, as well as the luminous reflection of sunlight upon the sea's surface, causing glare that hampers the drone's ability to capture images of optimal clarity and precision.

Upon the subsequent analysis and processing of the acquired dataset, an orthophoto emerged depicting the submerged site. The water's clarity and the shallow depth of the site make this depiction possible.


Fig 5-14) Orthophoto Produced Depicting the Submerged Site

# 4) Data Processing

This section provides a comprehensive overview of the collected underwater data and the subsequent processing steps undertaken to achieve the desired outcomes. It also highlights the significant challenges encountered during the process and the approaches used to address them. The data processing was carried out using the Agisoft Metashape software, which facilitated a seamless workflow encompassing the generation of point clouds and orthophotos from the acquired images.

As previously elucidated, the camera Olympus TG-6s was deployed, yielding the following image quantities:

- Operator 1 using the Olympus TG-6 captured 376 shots,

The images were captured in both RAW and JPEG formats. The dual-format choice was influenced not by survey-related needs but by the requirement to conduct color analyses using uncompressed RAW data, known for its higher quality. The image acquisition occurred in a nadiral orientation, employing cross-sweeping techniques to achieve an approximate longitudinal overlap of 80% and a transversal overlap of 60%. Oblique images were selectively integrated at specific points to enhance software alignment precision.

Attaining high-quality photos was pivotal, with optimal focus and minimized inter-frame discrepancies being key considerations.

Prior to dataset elaboration, preliminary field operations were undertaken. A chessboard pattern was strategically positioned as a backdrop, followed by the capture of multiple shots. Subsequently, these images were imported into Agisoft Metashape, wherein a masking procedure was implemented to eliminate surrounding sand, thereby minimizing potential errors.


Fig 5-15) Checkerboard Used for Chamber Calibration

This meticulous approach facilitated the storage of parameters essential for camera calibration adjustments.The calibration parameters—f, k1, k2, k3, cx, cy, p1, p2, b1, and b2—are coefficients automatically calculated by the software to be applied to the project while maintaining segregation based on camera type. Following camera calibration, the alignment of photos was executed.

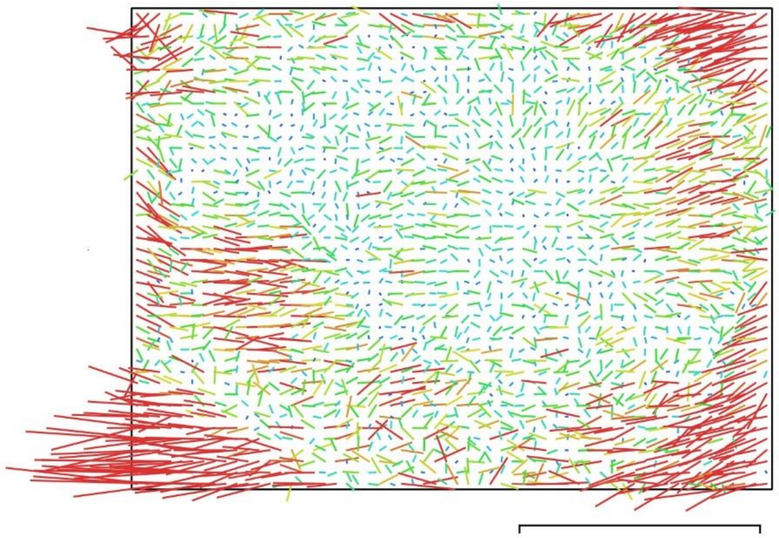



Fig 5-16) Image Residuals for Camera TG-6 (4.5mm)

**TG-6 (4.5mm)**

376 images

| Type | Resolution | Focal Length | Pixel Size |
|---|---|---|---|
| **Frame** | **4000 x 3000** | **4.5 mm** | **1.53 x 1.53 µm** |

| | Value | Error | F | Cx | Cy | B1 | B2 | K1 | K2 | K3 | P1 | P2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| F | **3940.46** | 0.25 | 1.00 | 0.14 | -0.14 | -0.52 | 0.20 | 0.08 | 0.17 | -0.10 | 0.07 | -0.13 |
| Cx | **-4.5248** | 0.16 | | 1.00 | -0.08 | 0.01 | 0.26 | 0.04 | -0.00 | 0.00 | 0.90 | -0.04 |
| Cy | **0.894257** | 0.16 | | | 1.00 | -0.11 | -0.05 | -0.03 | -0.02 | 0.00 | -0.03 | 0.88 |
| B1 | **-3.42216** | 0.085 | | | | 1.00 | -0.02 | -0.10 | -0.01 | -0.02 | 0.04 | 0.02 |
| B2 | **-0.296661** | 0.078 | | | | | 1.00 | 0.05 | -0.00 | 0.01 | 0.10 | 0.02 |
| K1 | **0.412261** | 0.00024 | | | | | | 1.00 | -0.91 | 0.87 | 0.03 | -0.04 |
| K2 | **0.12233** | 0.0018 | | | | | | | 1.00 | -0.98 | -0.01 | -0.01 |
| K3 | **0.326789** | 0.0042 | | | | | | | | 1.00 | 0.01 | 0.00 |
| P1 | **0.00312849** | 2.9e-05 | | | | | | | | | 1.00 | -0.02 |
| P2 | **-0.000341553** | 3.1e-05 | | | | | | | | | | 1.00 |

Table 5-4) Calibration Coefficients and Correlation Matrix

After several iterations, a decision was made to employ medium-precision alignment due to the observation that attempting higher precision led to errors resulting from points moving over time or not coinciding. Satisfactory results were achieved, aligning 352 out of 376 images, identifying 453,118 of 489,975 homologous points. Unaligned photos were attributed to factors such as reflections and sediment-induced variations due to water movement.

Subsequent steps included the collimation of GPS-measured points using nine checkerboard targets within acquired images. Several iterations were conducted to achieve optimal results, ultimately leading to a total error of 0.01 m. These preparatory steps paved the way for generating a dense point cloud, autonomously executed by the program with parameters appropriately configured. A dense cloud of average quality was generated, comprising 25,187,361 points and available for export in various formats for potential integration with other software.

Utilizing the dense cloud, a mesh was generated—a partitioned representation of a surface through triangular cells that form a grid, accurately defining the object in space. The mesh types include the "simple" triangular mesh, the "solid" continuous and homogeneous surface, and the "textured" mesh incorporating color information extracted from project images. In this case study, a medium-quality textured mesh was created, consisting of 1,999,999 triangular surfaces.

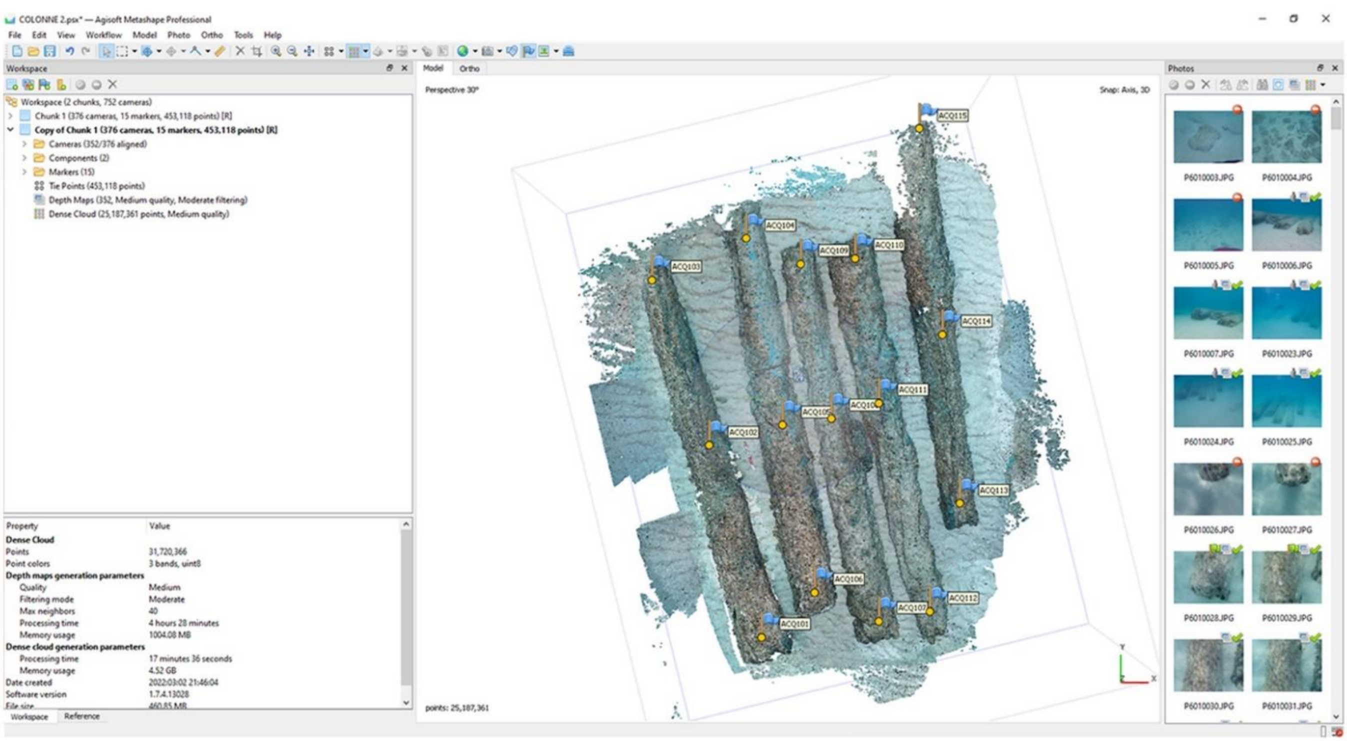
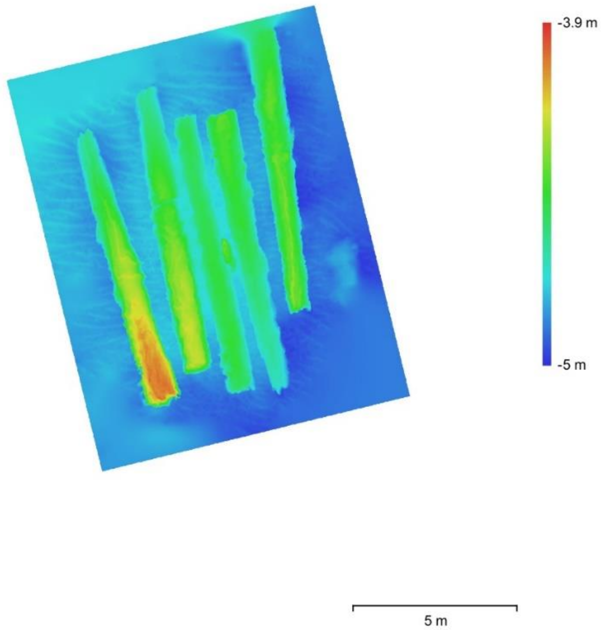



Fig 5-17) Dense Cloud in Medium Quality Produced by Agisoft Metashape Software

Subsequently, a digital elevation model (DEM) was crafted—a static representation illustrating the distribution of land features. The DEM is visually rendered with a color scale, enhancing the understanding of terrain or other surfaces' models.



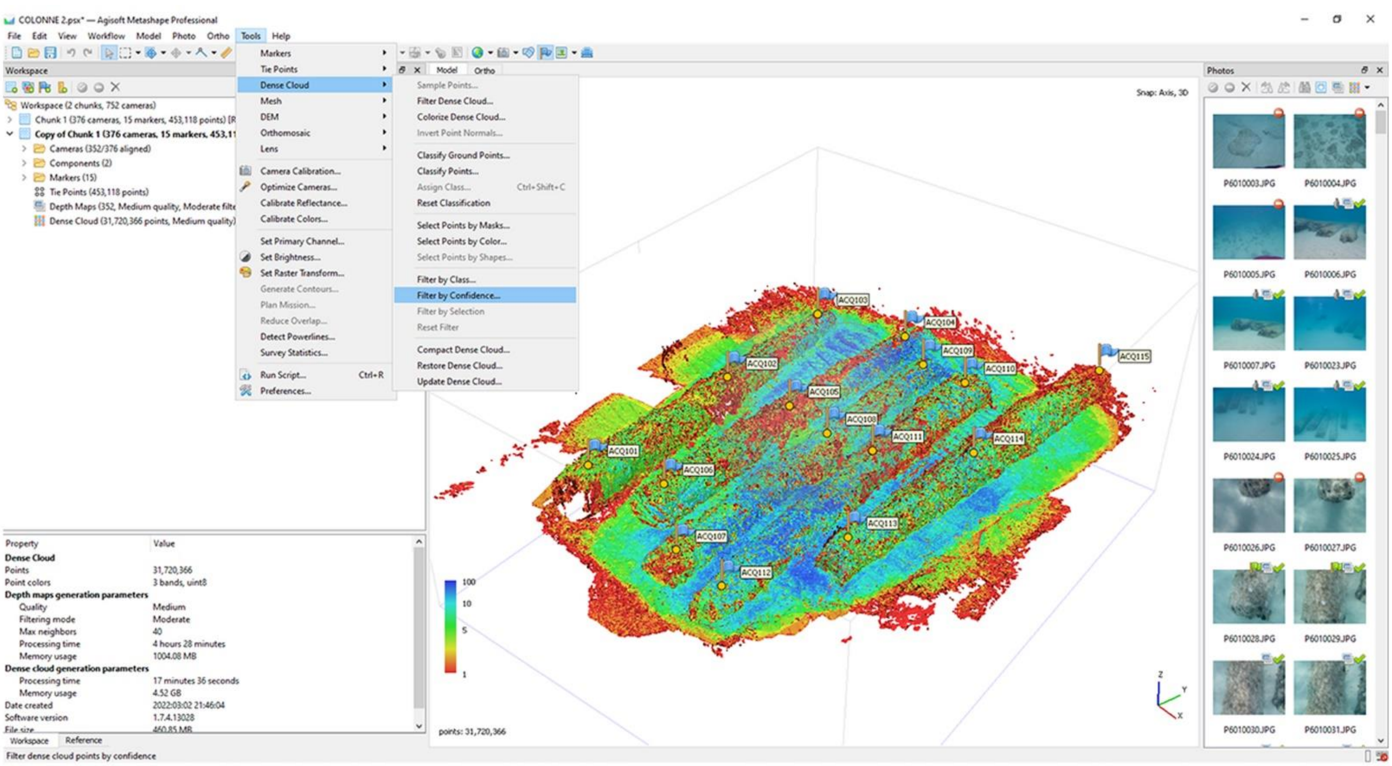




Fig 5-18) Dem Generated on Agisoft Metashape

The final step in the sequence involved the creation of an orthophoto, an image that faithfully represents reality by virtue of its georeferencing and projection onto the horizontal plane. During its generation, prioritising image quality is not a necessity; however, setting the pixel dimensions for its generation is vital.

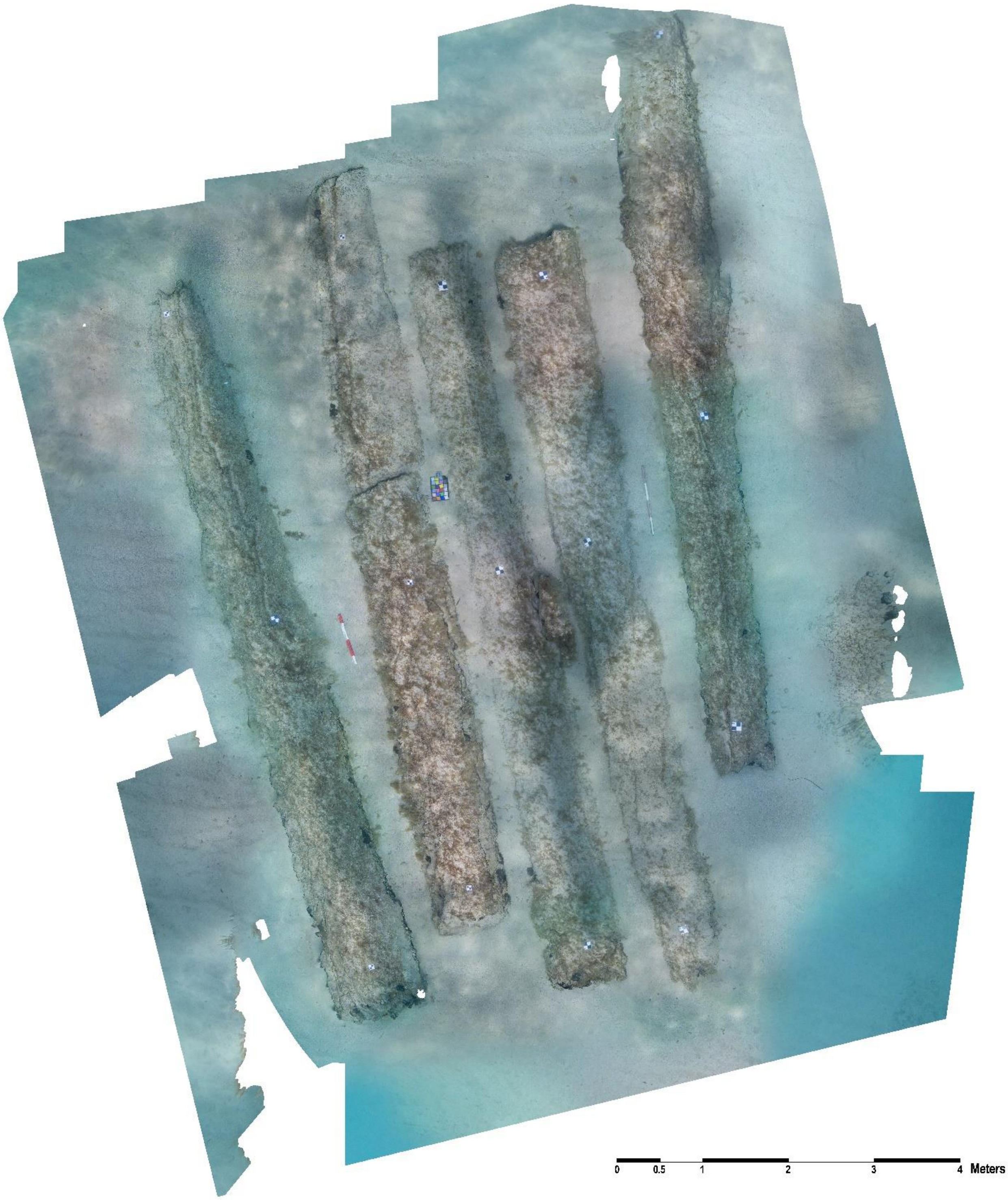



Fig 5-19) Orthophoto Exported from Agisoft Metashape

# 5) The color

An intrinsic facet of data processing of paramount significance involves the phenomenon of diminishing color intensity as one delves deeper into the aquatic realm. This phenomenon stems from the attenuation of light's penetration into water and its wavelength. As the depth increases, specific colors are progressively lost. Notably, red becomes imperceptible even at shallow depths of about 3 meters, followed by yellow (around 10 meters), green (about 17 meters), and finally, blue frequencies, which predominate. Consequently, underwater images are prominently characterized by this prevailing hue.

Over time, diverse software applications employing distinct algorithms have been developed to address the challenge of color distortion. These tools aim to enhance image quality, thereby expediting data processing through alignment software. In the context of our study, we employed the LAB algorithm for color correction. This particular approach, known as the LAB algorithm, hinges on the conversion of input images from RGB space to LAB space. Correcting color imbalances involves changing the components, which stand for color distribution, and then increasing contrast through histogram cropping and stretching. The image is then transformed back to RGB space. This process is notably user-friendly, entailing image insertion into the software and the selection of the preferred correction algorithm. Subsequently, the user awaits the completion of the process. These programs facilitate the application of corrections, significantly augmenting image quality. Nonetheless, it's important to underscore that while these corrections enhance the visual appeal of images, they may not wholly restore "true" colors. This limitation arises due to the software's lack of comprehensive information pertaining to depth and ambient conditions during image capture. Nevertheless, such algorithms present an excellent compromise, achieving considerable improvements in image quality.[11]

Fig 5-20) Image Comparison with Color Correction

[11] G. Bianco and others, 'A NEW COLOR CORRECTION METHOD FOR UNDERWATER IMAGING', *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XL-5-W5 (2015), 25–32 <https://doi.org/10.5194/isprsarchives-XL-5-W5-25-2015>.

## Chapter 6

# Conclusion

In the course of scrutinizing our case study, an array of intricate challenges emerged, beginning with the imperative focus on safety. In addition to the "classic" problems that come up during surveys, underwater expeditions require a higher level of mental alertness due to the need for careful management of cylinder pressure, the physical condition of dive partners, and the possibility of equipment and diving-related problems. For individuals operating at significant depths, a diving license and requisite gear such as wetsuits, cylinders, and regulators are mandatory prerequisites. Furthermore, the shallow depth of the survey site, situated at a mere 6 meters, imposed arduous constraints on divers, compelling them to maintain equilibrium—neither too close to the seabed to avert disturbances nor too distant from the artifact.

This form of investigation, which is both captivating and enlightening, extends beyond customary preliminary undertakings. In tandem with addressing conventional preparatory requisites, meticulous consideration must be given to weather conditions, sea dynamics, and site attributes. In our particular case study, the underwater archaeologists diligently cleared the site of excess sand prior to our arrival. Regrettably, subsequent winds and surges undermined their efforts, engulfing the site with sand and rendering the water murky, thereby impeding the image capture phase.

Another formidable challenge encountered pertains to the absence of a definitive work plan governing the number of swipes and photographs. The operator, navigating at times against currents, must orchestrate shots to ensure proper image overlap, sustained orientation, and uniformity in swipe patterns. To this end, ropes are often employed to delineate the relief area.

Despite the manifold complexities experienced during both the survey and processing phases, the outcome achieved outcome is commendable. Personally, I find the subject matter immensely compelling, not only from a geomatics standpoint but also as an enriching cultural endeavor. Each submerged artifact concealed beneath our seas carries its own historical narrative. Facilitating access to these submerged wonders in Puglia and throughout Italy entails certain considerations. Recognizing that not all individuals possess diving licenses, a captivating proposition is to "resurface" these sites and relics while preserving their submerged state. Viable avenues include crafting three-dimensional models, videos, and images for digital museum displays or devising immersive virtual tours of the underwater realm. Such initiatives would empower users to explore locales and artifacts inaccessible through conventional means.

For those fortunate enough to engage in diving, a splendid prospect entails guided underwater tours akin to those offered in traditional museums; this form of tourism is already burgeoning in select regions. Underwater surveys harbor diverse objectives, ranging from uncovering and cataloging sites and artifacts to their ongoing monitoring. Over time, certain artifacts succumb to deterioration, rendering periodic surveys, like the one undertaken in our case study, invaluable for monitoring and evaluating the need for intervention and preservation. This utility is particularly pertinent for highly vulnerable relics, such as shipwrecks.

In summation, the potential of applying geomatics to diving is far from fully realized. Its gradual evolution, however, could yield substantial cultural and economic dividends for our nation.

In the realm of Photogrammetric Underwater and UAS Surveys of Archaeological Sites, as exemplified by our comprehensive investigation of the Roman Columns of Porto Cesareo, our journey transcends mere scientific inquiry. It represents a profound commitment to safeguarding the invaluable treasures of our submerged cultural heritage—a commitment that intertwines multiple facets of human endeavor and stands as a testament to our dedication to preserving the past for the benefit of our future.

At the heart of our effort lies the resolute recognition of the multifaceted significance of underwater cultural heritage. Our meticulous documentation process, employing state-of-the-art photogrammetry techniques and Unmanned Aerial Systems (UAS), reveals a complex tapestry of positive outcomes that extend far beyond the realm of academia.

***Archaeology Illuminated:*** The pages of history often lie concealed beneath the waves, waiting to be unearthed through diligent exploration. Our endeavor has cast a luminous spotlight on the hidden remnants of the past, unraveling tales of ancient civilizations that were once considered lost. Through our Photogrammetric Underwater and UAS Surveys, we have unearthed historical narratives that enrich our understanding of cultures long gone, nurturing a deeper connection between our present and our collective human heritage.

***Heritage Conservation Elevated:*** The Roman Columns of Porto Cesareo stand not only as physical structures but also as embodiments of our commitment to preserving the legacy of our ancestors. Our survey efforts transcend the realm of academic research, nurturing a paradigm shift in the conservation of underwater cultural heritage. By employing cutting-edge technology, we ensure the protection of these historical artifacts while simultaneously raising awareness about their importance. This dual impact creates a ripple effect that extends beyond the boundaries of our immediate study, advocating for the safeguarding of submerged cultural treasures on a global scale.

***Cultural Revival and Public Engagement:*** Our thesis transcends the confines of academia, reverberating across society by rekindling interest in submerged historical sites. By translating complex survey data into captivating visual representations accessible to all, we ignite curiosity and inspire a sense of shared ownership of our cultural heritage. Through educational outreach, museum exhibitions, and digital presentations, we bring the Roman Columns of Porto Cesareo to life, facilitating a direct connection between people and their history.

***Collaboration for Sustainable Exploration:*** Our commitment to Photogrammetric Underwater and UAS Surveys underscores the value of collaboration across disciplines. Marine biologists, historians, geographers, and

technologists converge to create a holistic approach that not only documents the past but also pioneers innovative methodologies for future exploration. This spirit of interdisciplinary cooperation fuels advancements in marine technologies and fosters an ecosystem of sustainable underwater exploration.
As we stand on the precipice of concluding our master's degree journey, let us reflect on the profound impact of our thesis topic: Photogrammetric Underwater and UAS Surveys of Archaeological Sites. Our exploration of the Roman Columns of Porto Cesareo has illuminated the positive aspects of documenting underwater cultural heritage. This pursuit has ignited a passion for preservation, rekindled cultural ties, elevated the discourse on heritage conservation, and invigorated collaborative efforts for a more enlightened and sustainable future.
Through this thesis, we have not only delved into the depths of history but also charted a course for a better tomorrow—a future where future generations will celebrate, safeguard, and cherish our shared cultural heritage.

Fig 6-1) The Development Phase: Sequence of Immersive and Interactive Scenes

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