TESIS DOCTORAL

Photogrammetry and image processing techniques for beach monitoring

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Abstract: The land-water boundary varies according to the sea level and the shape of a beach profile that is continuously modelled by incident waves. Attempting to model the response of a landscape as geomorphologically volatile as beaches requires multiple precise measurements to recognize responses to the actions of various geomorphic agents. It is therefore essential to have monitoring systems capable of systematically recording the shoreline accurately and effectively. New methods and tools are required to efficiently capture, characterize, and analyze information – and so obtain geomorphologically significant indicators. This is the aim of the doctoral thesis, focusing on the development of tools and procedures for coastal monitoring using satellite images and terrestrial photographs. The work brings satellite image processing and photogrammetric solutions to scientists, engineers, and coastal managers by providing results that demonstrate the usefulness of these viable and low-cost techniques. Existing and freely accessible public information (satellite images, video-derived data, or crowd-sourced photographs) can be converted into high quality data for monitoring morphological changes on beaches and thus help achieve a sustainable management of coastal resources.

Key words: Sub-pixel shoreline mapping, coastal monitoring, beach changes, satellite imagery, video-monitoring.

Técnicas de fotogrametría y tratamiento de imágenes para a monitorización de playas

Resumen: El límite tierra-agua varía en función de la posición del nivel del mar y de la forma del perfil de playa que continuamente queda modelado por las olas incidentes. Intentar modelizar la respuesta de un paisaje tan voluble geomorfológicamente como las playas requiere disponer de múltiples medidas registradas con suficiente precisión para poder reconocer su respuesta frente a la acción de los distintos agentes geomórficos. Para ello resulta esencial disponer de diferentes sistemas de monitorización capaces de registrar de forma sistemática la línea de costa con exactitud y efectividad. Se requieren nuevos métodos y herramientas informáticas que permitan capturar, caracterizar y analizar eficientemente la información con el objeto de obtener indicadores con significación geomorfológica de calidad. En esto radica el objetivo de la presente tesis doctoral, centrándose en el desarrollo de herramientas y procedimientos eficientes para la monitorización costera mediante el uso de imágenes satelitales y fotografías terrestres. El trabajo aporta soluciones de procesamiento de imágenes de satélite y fotogramétricas a científicos, ingenieros y gestores costeros, proporcionando resultados que

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evidencian la gran utilidad de estas técnicas viables y de bajo coste para la monitorización costera. Mediante ellas se puede convertir información pública existente y de libre acceso (imágenes satelitales, datos de video cámaras o fotografías de la ciudadanía) en datos de alta calidad para el monitoreo de los cambios morfológicos de las playas, y lograr así una consiguiente gestión sostenible de los recursos costeros.

Palabras clave: Detección subpíxel de la línea de costa, monitorización costera, cambios costeros, imágenes satelitales, video monitorización.

Coastal areas have been occupied and used by humans since ancient times. These narrow transition areas that connect terrestrial and marine environments are our planet's most productive and valued ecosystems (Crossland et al., 2005). Only the 8% of the earth's surface corresponds to coastal areas, but 40% of the world population live within 100 km of a coastal zone, and 60% of the world's major cities are located there (Nicholls et al., 2007).

Within coastal areas, the close relationships between humans and coastal resources intensifies the urgent questions of limits and equilibrium, sustainability, and development (Baztan et al., 2015). Beaches began to be the subject of global economic exploitation in the last century, both from an urban point of view and from the generation of economic resources, mainly due to the development of tourism. Turism now accounts for approximately 14.9% of the gross domestic product (GDP) in Spain, with more than 82 million visitors in 2017 –according to the annual report of the World Travel & Tourism Council.

It is therefore essential to improve our understanding of the physical processes occurring in coastal zones. Understanding the response of beaches to different spatial and time scales is a priority for the proper management of this essential resource. Multiple efforts have faced the inherent problems of the shoreline by establishing the rates of erosion or accretion during a limited time interval by analyzing conditioning factors and evaluating the environmental and socioeconomic consequences of changes.

Coastal changes are qualified as problematic when they have negative implications on the resources and uses of coastal space and affect socio-economic interests and natural values. Retrospective studies aimed at trend and evolutionary analysis of coasts may be of great importance for competently facing the imminent threat of climate change. An average rise in sea level (relative to 1986-2005) of between 26 and 77 cm is estimated by the end of the 21st century (IPCC, 2018). Moreover, multiple challenges and problems on the coast are associated with human interventions that are affecting littoral dynamics and fluvial systems as these are the main sources of sediment discharge (Sanjaume and Pardo-Pascual, 2005).

Modeling the response of the shoreline to the effects of waves and sea level variation, especially on unstable coasts such as sedimentary beaches, enables an evaluation of coastal recession and migration from the shoreline to the continent in broad time scales. However, the complexity of the phenomena and processes that interact on the land-sea interface (atmospheric, hydrodynamic and sedimentary processes) make it an oscillating event that produces both advances and setbacks in the position of this line. The land-water limit varies depending on the position of the sea level and the shape of the beach profile as continuously modeled by incident waves. Therefore, since the beach is a space that is profoundly dynamic, it is necessary to discern between those changes related to meteorological processes – with seasonal or oscillating rhythms throughout the year or a more random behavior – and those changes that show a tendency of progressive or continuous change lasting over time (Kraus et al., 1991).

Security and coherence in coastal management is complicated by the confluence of different complex processes. For this reason, understanding and quantifying coastal trends is essential for detecting their magnitude and causes – and offering real solutions. To detail the type of change and its causes, evolutionary analysis at different spatial and temporal scales and with an appropriate degree of precision is necessary (Pye & Blott, 2008).

A deepening at different levels of the evolutionary analysis of a landscape as geomorphologically voluble as coastal areas is obviously important. Technical advances play a decisive role by enabling the definition of the changes with precision and effectiveness. For many years, there was no a specific and valid methodology to facilitate the arduous task of defining the shoreline, obviating the technical limitations and avoiding the assumption of futile simplifications.

Advances in the acquisition methods of topographic data offer new tools for the automated and precise extraction of the coastline and the carrying out monitoring work at different times. Improvements in the global positioning systems in kinematic mode and real time (RTK-GPS), LIDAR (light detection and ranging) and terrestrial laser scanner have been decisive. However, these methods present a drawback: they are very expensive when used for analyzing long coastal sectors with high temporal resolution.

Fortunately, the use of satellite imagery overcomes this problem as these platforms cover wide areas of land with a relatively high temporal frequency (Palomar-Vázquez et al., 2018). We can cite the case of a Landsat platform operating since March 1984. Over 30 million images have been downloaded since 2008 and these systems have contributed enormously to developing several fields of research, such as natural resource management, forestry, ecology, or climate change (Hermosilla et al., 2019). Recently, in 2015, the European Space Agency (ESA) launched the Sentinel program, which offers free images covering the all of the Earth at 20 m resolution (Sentinel-2). If both Landsat and Sentinel missions are joined, we can analyze long sectors of the coast with a high combined revisit time (16 days with Landsat and 10 or 5 days with Sentinel-2). This is, without doubt, the world's main territorial image database, and means a real revolution in terms of availability of information on the Earth's surface. However, a weakness is that their coarse spatial resolutions (20-30 m) make it necessary to solve the problem of determining with sufficient precision the position of the shore. The working precisions must be in accordance with the magnitude of the change to be detected.

The whole of this doctoral thesis has shown the capacity of photogrammetric and image processing techniques for coastal monitoring at different time and spatial scales. These are shown throughout the current PhD dissertation which is an edited compilation from the eight papers listed in the following paragraphs with the approval of co-authors.

The literature review shows the potential of well-known fixed coastal video monitoring systems (Argus, Sirena, Cosmos, Horus) intended for site specific evolutionary studies. However, these systems are expensive and complex to maintain and present certain requirements that limit and make them difficult to extend to other places. Their associated software requires understanding the characteristics and parameters of particular cameras, as well as accurate and adequate terrain control points to georeference the photos. A versatile tool such as C-Pro (presented in Chapter 2 of this doctoral thesis and in Sánchez-García et al., 2017) enables automatic georectification of any beach terrestrial photograph regardless of the conditions. The tool adapts its methodology according to the available information to achieve the best possible spatial resection adjustment and thus offer a suitable result − even when photogrammetric conditions are very poor. In addition, its robustness is largely due to the inclusion of two extra equations corresponding to the horizon line that depend on the external and internal camera orientation parameters and reduce the number of terrain points needed. Different assessments carried out by using C-Pro tool (Sánchez-García et al., 2019b, Sánchez-García et al., 2020) showed an RMSE within 1.54 m.

The C-Pro tool is shown to be very effective for analysis and coastal management because of its easy acquisition, speed, low cost, and volume of data, and because any person with a conventional camera can take a photograph. This fact has been reflected throughout the thesis (especially in Chapter 4) where its application has enabled registering the state of the coast at a specific time and validating instantaneous satellite-derived shorelines (SDS) on different beaches. Moreover, it has been used to georeference images from recreational video cameras "surfcams" and so facilitate their use for scientific purposes (Andriolo et al., 2016a, 2016b, 2018). Its implementation in other novel citizen monitoring projects will also be very useful since these are spreading to numerous sites and where the necessary requirements for

traditional methods are probably unavailable (see Chapter 5 of the thesis and in Harley et al., 2019). However, surfcams are expected to offer the worst conditions because their placement was planned simply to provide visual information of the beach and wave conditions for surfers. Therefore, even the use of remote control points obtained from Google Earth has been explored (Andriolo et al., 2019).

Secondly, and encompassing larger spatial scales, it is well known that satellite imagery plays a decisive role. Since the USGS in 2008 and ESA in 2015 made their database freely available, Landsat and Sentinel satellite images constitute the main territorial database worldwide. Bearing this in mind, the current doctoral thesis extensively worked on the evaluation and improvement of the Almonacid-Caballer, 2014 algorithm. The goal was to obtain from these mid-resolution images multiple accurate shoreline data for trend and coastal evolution analysis. Throughout the thesis, the obtained results have been conditioning the development of the methodology, varying and adjusting to the needs of processing and evaluating data. Dealing with a large volume of information forced the development of automated modules – developed by the CGAT-UPV group – to minimize analysis time and facilitate its use.

According to the tests carried out so far, a good location of the input shoreline at pixel level was essential for the algorithm's search window to be made in the right place – former thresholding techniques used to define this initial line were not always successful. Therefore, Chapter 3 of the thesis (Sánchez-García et al., 2019a) dealt with this problem by means of working with a neighborhood able to adapt itself according to the image radiometry and improve the final sub-pixel accuracy. The transition between land and water was found where the maximum radiometric variation in terms of divided differences occurred. The accuracy of the final sub-pixel shoreline is not conditioned by the precision of the input line.

Working in parallel after the completion of the works in Chapter 4 of the thesis being Almonacid-Caballer, et al. (2016), Pardo-Pascual et al. (2018), Sánchez-García et al. (2020) completed the evaluation by demonstrating with which parameters and bands or indexes of the satellite images, the

algorithm (presented as SHOREX) achieved greatest accuracy. It was seen that the algorithm seemed more accurate in the final shoreline detection when working with small neighborhoods. However, this fact required ensuring the quality of the input line around which to perform the sub-pixel search. Accordingly, the use of a threshold input line per image was changed – this step also slowed down the process – and a unique digitalized or available shoreline for the whole set of images was used. While the reliability of the line was still uncertain, the protocol (presented in the last work of Chapter 4, Sánchez-García et al., 2020) consists of working first with large neighborhoods and ensuring that the real shoreline was contained, and then continuing with a second iteration where smaller neighborhoods would define accurately the sub-pixel shoreline. In this case, a centered interpolation is first used and then the least squares method is used to define the land-water surface over an upsampled satellite image. In this work, between the years 2013 and 2017, 91 satellite-derived shorelines (SDS) were assessed by comparing with high-resolution shorelines obtained simultaneously through video-monitoring getting accuracies below 3.57 m RMSE for L8 and 3.01 m for S2.

At this point, where the accuracies reached are at the level of other systems such as video monitoring, the SHOREX methodology is presented as very effective for coastal monitoring. Despite the advantages of having such a magnitude of data, a correct management is necessary. Hence, the idea of obtaining annual average lines to work in coastal evolution analysis (seen in first work of Chapter 4, Almonacid-Caballer, et al., 2016). With this, changes due to factors related to meteorological processes – with seasonal or oscillating rhythms throughout the year – were avoided and separated from those useful for long-term studies with progressive changes over time. Focusing on a shorter time scale, this same idea could resemble the work with timex images in photogrammetry whose aim was to obviate the random and oscillating behavior of the waves and make shoreline definition easier.

This dissertation contains all its potential and practical utility in the monitoring of coastal segments to enable predictions. High-resolution coastal evolution models play an important role but require multiple shorelines for their calibration

and evaluation (Jaramillo et al., 2020). Therefore, this synergy gives rise to powerful coastal evolutionary studies resolving the temporal limitation of the images with the model, and the spatial limitation of the model with the images. Valuable coastal hazard maps and warning systems that are able to highlight critical situations may be derived.

This research work seeks to bring the photogrammetry and remote sensing worlds closer to regional scientists, engineers, government and coastal managers by providing new evidence about the usefulness of low-cost and feasible techniques. These can turn existing and freely available information (satellite imagery, crowdsourced data, or internet-streamed beach images) into high-quality data for the continuous monitoring of beaches and a consequent sustainable decision-making for coastal resources. In addition, using mundane information and involving the local community generates many benefits by making science and engineering expertise more accessible to the public, encouraging greater interactions, and knowledge sharing between local stakeholders and experts, and leading to a greater democratisation of decision-planning on coastal management.

Acknowlegments

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