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Close-range airborne Structure-from-Motion Photogrammetry for high-resolution beach morphometric surveys: Examples from an embayed rotating beach

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A B S T R A C T

The field of photogrammetry has seen significant new developments essentially related to the emergence of new computer-based applications that have fostered the growth of the workflow technique called Structure-from-Motion (SfM). Low-cost, user-friendly SfM photogrammetry offers interesting new perspectives in coastal and other fields of geomorphology requiring high-resolution topographic data. The technique enables the construction of topographic products such as digital surface models (DSMs) and orthophotographs, and combines the advantages of the reproducibility of GPS surveys and the high density and accuracy of airborne LiDAR, but at very advantageous cost compared to the latter. Three SfM-based photogrammetric experiments were conducted on the embayed beach of Montjoly in Cayenne, French Guiana, between October 2013 and 2014, in order to map morphological changes and quantify sediment budgets. The beach is affected by a process of rotation induced by the alongshore migration of mud banks from the mouths of the Amazon River that generate spatial and temporal changes in wave refraction and incident wave angles, thus generating the reversals in longshore drift that characterise this process. Sub-vertical aerial photographs of the beach were acquired from a microlight aircraft that flew alongshore at low elevation (275 m). The flight plan included several parallel flight axes with an overlap of 85% between pictures in the lengthwise direction and 50% between paths. Targets of 40 × 40 cm, georeferenced by RTK-DGPS, were placed on the beach, spaced 100 m apart. These targets served in optimizing the model and in producing georeferenced 3D products. RTK-GPS measurements of random points and cross-shore profiles were used to validate the photogrammetry results and assess their accuracy. We produced dense point clouds with 150 to 200 points/m², from which we generated DSMs and orthophotos with respective resolutions of 10 cm and 5 cm. Compared to the GPS control points, we obtained a mean vertical accuracy less than ±10 cm, with a maximum of 20 cm in marginal sectors with sparse vegetation and in the lower intertidal zone where water-saturated surfaces generated lower-resolution data as a result of a lack of coherence between photographs. The overall results show that SfM photogrammetry is a robust tool for beach morphological and sediment budget surveys. Our SfM workflow enabled the discrimination of beach surface features at a scale of a few tens of centimetres despite the low textural contrasts exhibited by the quartz beach sand and the relatively uniform upper beach topography, as well as the calculation of beach sediment budgets. 66,000 m³ of sand were removed from the northern sector of the beach, of which 22,000 m³ were transferred to the southern sector in the course of rotation. Finally, we briefly highlight: (1) the advantages of SfM photogrammetry compared to other high-resolution survey methods, (2) the advantages and disadvantages of, respectively, a microlight aircraft and an unmanned aerial vehicle (UAV) in undertaking SfM photogrammetry, and (3) areas of potential future improvement of the SfM workflow technique. These concern more extensive cross-shore deployment of ground control points to reduce possible tilt, and oblique cross-shore photography to improve parallax.

1. Introduction

Data products generated by accurate and high-resolution topographic surveying are becoming increasingly important in understanding beach morphological changes and processes at timescales of days, months or years, as well as in the monitoring of the impacts of episodic

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events such as storms. There are various techniques to monitor beach morphology and evolution with derived digital elevation models (DEMs). These include video-imaging ARGUS systems, Airborne Light Detection and Ranging (LiDAR), ground-based Terrestrial Laser Scanning (TLS), traditional topographic monitoring using a Real Time Kinematic Differential Global Positioning System (RTK-DGPS), or a total station, and photogrammetric techniques. Each of these techniques has advantages and limitations in terms of spatial and temporal coverage, accuracy, and operational expertise and software needs and costs (James et al., 2013). For example, TLS is very efficient for an object size of 10s to 100s of metres. Despite the increasing use of this tool on beaches or rocky cliffs and its accuracy, it still requires significant expertise in data collection and processing and is a costly technique. LiDAR allows for rapid collection of data and operates over large areas (>1 km) at high spatial density. Its vertical accuracy, close to 10 cm, is well within that of beach topographic changes that commonly occur following storms, and, consequently, it is adequate to monitor such changes (e.g., Sallenger et al., 2003). However, LiDAR surveys are commonly conducted rather infrequently due to high cost and the prior required careful organization (James et al., 2013; Ouédraogo et al., 2014a), and there are, indeed, only few examples in the literature involving multiple LiDAR surveys over short periods of a year or two (e.g., Montreuil et al., 2014). Video imaging systems such as ARGUS (Plant and Holman, 1997) allow for high frequency surveys (10 min to 1 h interval range) over areas of 100 m to several km (Harley et al., 2011). However, despite their low cost, these techniques require specialist analytical software and technical and scientific expertise, and are, therefore, not readily accessible. In contrast, RTK-DGPS and total station techniques are accurate and accessible but they suffer from the low spatial density of points necessary for DEM construction. This disadvantage of areal coverage may be partially offset by the mounting of RTK-DGPS stations on all-terrain vehicles that can cover large areas (e.g., Harley et al., 2011), but vehicle tracks can alter surface features being studied.

New recent developments in photogrammetry are such that this technique is now emerging as an alternative and complementary tool for coastal scientists and managers (e.g., Gonçalves and Henriques, 2015). The technique, based on stereoscopy between image pairs, is not new, as it has been used for decades to reconstruct landform topography and to produce maps. The manual alignment of stereoscopic image pairs is a time-consuming task based on input from aerial cameras. The accuracy of the DEMs generated by this technique was lower than that of LiDAR (Ouédraogo et al., 2014a). Advances in computer vision and image analysis are, however, generating innovative developments in photogrammetry through the technique of Structure-from-Motion (SfM), which offers an automated method for the production of high-resolution digital surface models (DSMs) with standard cameras (Fonstad et al., 2013; Javernick et al., 2014; Agisoft, 2015).

SfM photogrammetry has been employed in recent years in the morphometric reconstruction of landforms, geological outcrops (Marzolff and Poesen, 2009; Westoby et al., 2012), and braided river channels (Javernick et al., 2014). The technique has been recently applied by Harwin and Lucieer (2012); James et al. (2013); Mancini et al. (2013) and Casella et al. (2014) to beach morphological studies. However, none of these studies has used SfM photogrammetry to carry out beach morphodynamic assessments and sediment budget quantification, both of which require repeated high-resolution surveys. In this work, we address this research gap by using close-range photographic surveys from a microlight vessel. The implementation of this technique is accessible to non-specialist users, as demonstrated by Westoby et al. (2012); Fonstad et al. (2013); Hugenholtz et al. (2013); James et al. (2013); Javernick et al. (2014); Ouédraogo et al. (2014b), and Gonçalves and Henriques (2015). This low-cost method includes the advantages of reproducibility and accuracy of measurement of RTK-DGPS and LiDAR surveys (e.g., Montreuil et al., 2014). Moreover, the field protocol is easy to organise and reproduce: it combines an aerial photographic survey and deployment of targets on the beach georeferenced by RTK-DGPS.

We tested SfM photography on Montjoly beach (Fig. 1), a highly dynamic embayed beach in Cayenne, French Guiana, affected by a unique type of beach rotation influenced by the alongshore migration of mud banks formed north of the mouths of the Amazon River in Brazil. We highlight, from three experiments conducted between October 2013 and October 2014, the utility of this photogrammetric technique in the generation of high-quality beach morphometric data products such DSMs and orthophotos and in the quantification of morphological and mass budget changes associated with beach rotation.

2. Study site

Montjoly beach is a 3.5 km-long body of sand between rocky headlands in Cayenne, French Guiana (Fig. 1). The beach, composed essentially of quartz sand (>90%), has an average width of 100 m, and bounds a lagoon characterised by an inlet that is seasonally closed but which is now kept manually open to avoid flooding of the neighbouring urban zones of Cayenne. Montjoly beach lies along the pathway of large mud banks that migrate alongshore from the mouths of the Amazon River to those of the Orinoco in Venezuela (Anthony et al., 2010, 2014), sourced by the large mud supply of the Amazon. Each mud bank can be up to 5 m thick, 10 to 60 km long and 20 to 30 km wide, and migrates at rates of 1 to 5 km/year (Gardel and Gratiot, 2005). Headland-bound beaches on this 1500 km-long muddy coast of South America are limited to the vicinity of Cayenne and Kourou in French Guiana (Fig. 1), the only sectors where notable outcrops of bedrock composed of migmatites and granulites occur. Montjoly and the rare sandy beaches on this muddy coast are important both economically and ecologically, providing outlets for recreation and routes, and nesting sites for protected marine turtles (*Lepidochelys olivacea*, *Cheloniamydas*, *Eretmochelys imbricata*, *Dermochelys coriacea*). The presence of mud significantly alters the behavioural patterns of Montjoly and these sandy beaches, by modulating the influence of seasonal changes in trade-wind wave energy. Mud directly welds onto the beaches for months to years as a migrating mud bank approaches, leading to unique examples where ocean-facing beaches are completely incorporated into a temporarily prograded muddy intertidal-to-shoreface system. During such phases, the mud-bound foreshore and muddy shoreface are rapidly colonized by mangroves. Subsequent mud erosion and mangrove forest destruction during inter-bank phases (corresponding to the space between two successive alongshore-migrating wave-dissipating mud banks) mark the resumption of normal beach dynamics. This involves the restitution, to the beach sand budget, of sand sequestered in the previous bank phase within the shoreface mud deposits. The main effect of these changes on the longer bay beaches is a form of beach rotation (Anthony et al., 2002; Anthony and Dolique, 2004), unique at the global scale. Such rotation does not result from climate-induced variations in deepwater wave approach directions, as is generally reported for rotating beaches (e.g., Thomas et al., 2010), but from short to medium-term (order of a few years) changes in nearshore bathymetry induced by the migrating mud banks. These bathymetric changes affect wave refraction and dissipation patterns, inducing strong longshore gradients in waves. These wave-energy gradients generate, in turn, longshore movements of sand in these headland-bound beaches, resulting in alternations of erosion and accretion areas over time. Anthony and Dolique (2004) defined these beach morphological changes in terms of a simple, four-stage conceptual model, comprising bank, inter-bank and transitional phases that are characterised by dramatic beachface retreat or advance of up to 50 m a year (Fig. 1), which is much larger than the seasonal cycle of beach change (±10–20 m) characterising the storm-free tropical beach of Montjoly (Anthony et al., 2015).

Montjoly beach is affected by trade winds from the northeast that are mainly active from January to April. Waves impinging on the