TITLE PAGE

Drones as tools for coastal monitoring: multi-temporal analysis of beach topography.

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Abstract

The application of light Remotely Piloted Aircraft Systems (RPAS, or drones) coupled with Structure from Motion and Multi-View Stereo techniques in earth sciences is increasing, especially for which concerns the monitoring of the rapid evolution of geomorphological features. In this paper, the topographic changes of a stretch of coastline in North-Western Italy have been studied. The same stretch of coastline has been surveyed three times in 5 months, obtaining digital elevation models and orthophotos of the beach. The difference in beach topography between each time step has been calculated, and changes in beach topography in light of sea storms and human activities affecting the area have been investigated. The results show that drones and photogrammetry are low-cost, high-resolution and efficient tools that can be employed effectively to map changes of beach topography through time, which in turn are essential for beach management actions.

Keywords Beach erosion, Drones, RPAS, Beach monitoring, Unmanned Aerial Vehicles

1. Introduction

Coastal erosion is one of the main natural processes defining the evolution of a shoreline through time. Along beaches, erosion removes sediment from the coastal system and transports it offshore throughout the action of waves and currents. In general, coastal erosion is considered a problem in need of management when it occurs in areas where the human occupation of the coast is significant. At global scale, common figures state that the global population density within 100 kilometers of the coastline is nearly 3 times higher than the global average density (Small and Nicholls, 2003), and that 10% of the human population is living less than 10 meters above sea level (McGranahan et al., 2007). An often-cited number states that 70% of the word's soft coasts are suffering erosion

problems (Bird, 1987).

The management and decision-making process in coastal areas is often based on studies investigating rates and modes of coastal changes, which can be derived from different kinds of beach monitoring, either direct (i.e. GPS surveys on the shoreline or topographic transects) or indirect (e.g. lidar or aerial photography). Recently, new survey techniques based on Remotely Piloted Aircraft Systems (RPAS, often also called Unmanned Aerial Vehicles, UAVs, or drones) started to be employed in geomorphological and ecological studies (Everaerts 2008; Colomina & Molina 2014; Anderson & Gaston 2013), and are becoming common survey methods. The most common geomorphological application of RPAS consists in mounting a camera on a rotor-wing or fixed-wing remotely controlled or programmed aircraft and taking almost-nadir pictures of the ground that are then analysed with Structure from Motion (SfM) and Multi-View Stereo (MVS) reconstruction algorithms to obtain Digital Elevation Models (DEMs) and orthophotos of the terrain.

At present, studies are starting to go beyond the simple assessment of the accuracy of orthophotos and DEMs that can be obtained with RPAS and SfM with MVS techniques, and to use RPAS to obtain data to address specific environmental or geological problems (Niethammer et al. 2012; Casella et al., 2014; Woodget et al., 2014; Eltner et al., 2014; Peréz-Alberti and Trenhaile, 2014). In this paper the data obtained with RPAS has been used to assess coastal changes of a beach in Northern Italy (NW Mediterranean) over a period of 5 months. Drones are closing the gaps in small scale remote sensing (Berni et al., 2009; Watts et al., 2012), as they allow the acquisition of topographic data at low altitude and their cost allows to repeat survey at short time spans. The coastal zone seems to be an ideal ground for the application of multi-temporal RPAS surveys, as the evolution of these environments happens often fast and requires efficient, low-cost and sufficiently accurate monitoring techniques.

2. Methods

2.1 Study area

Our study area is located in Liguria, an Administrative Region of Italy in the NW Mediterranean (Fig.1c). The region is often hit by severe storms (Parodi et al 2012; Rebora et al 2013; Fiori et al 2014) associated with sea storms, which put in danger population and cause several damages to the coastal zone (Orlandi et al. 2008; Pasi et al. 2011). Due to the importance of coastal erosion problems in the Region, several research initiatives have been directed towards understanding the dynamics of its coastal areas (e.g. Brignone et al., 2012), and monitoring the evolution of the coastal system with different techniques (e.g. Vacchi et al., 2012; Casella et al., 2014). Recently, the Liguria Regional Authority has made available vector files of the shoreline (wet/dry line) extracted from orthophotos made in 1944, 1973, 1983 and 2003. The first flight was done by the UK Royal Air Force during WWII, while the latter were performed with the aim of documenting the shoreline changes that started to affect the Region after the economic boom of the 60's and 70's. In those years, both the population and the tourism industry grew exponentially in the coastal parts of the Region (Fierro et al., 2010).

The focus of our study is a part of the shore of the municipality of Borghetto Santo Spirito, a small coastal town of western Liguria. The evolution of the coastal area of this town is representative of the evolution of many Northern Mediterranean coastal areas. Borghetto was a small village at end of 1800, when the railroad was constructed to connect the main cities of Genoa (Italy, to the East) and Nice (France, to the West). Materials for the construction of the railroad were quarried from a local watercourse, named Varatella river, causing the reduction of the sediment input in the budget of sediments of the beaches. This lead to the erosion of the coastline (Fierro et al., 2010). Since the construction of the railroad, the coastline has been affected by engineering works (e.g. groynes, parallel defences) that were aimed primarily at protecting the railway from sea storms. In 1944, the shoreline was running near the railway (Fig.1a). From the 60s to nowadays, the shoreline

has been object of several interventions of beach nourishment and coastal engineering that allowed the creation of beaches, which started to be exploited for tourism purposes (Fig.1a, Fierro et al., 2010). The most recent engineering work (2006-2008) are three artificial islands located in the western part of the town (Fig.1b), that have been associated to two major beach nourishments in 2003 and 2007 (Fig.1a), with a total amount of 13,900 m^3 of sediment discharged in the area. This part of the town is the most affected by coastal erosion problems, as all sediment inputs are blocked by a rocky promontory (Capo Santo Spirito) to the west and by a major groyne that blocks the input of sediments from the Varatella River to the east.

As it was the subject of repeated beach interventions to mitigate coastal erosion, the westernmost part of the town (Fig.1b) was the object of several beach monitoring campaigns, which consisted mostly in differential GPS (DGPS) surveys of the wet-dry line (Fig.1b) and bathymetric surveys. The results of those surveys indicate that, following the interventions in this area, the shoreline has advanced and now it fluctuates yearly around a new equilibrium. In winter 2013-2014, a portion of this area using a camera mounted on a RPAS platform has been surveyed, with the aim of documenting the evolution of the beach topography of this beach at sub-yearly scale and relating coastal changes to sea storms hitting the shoreline in the periods between the surveys.

2.2 Remotely Piloted Aircraft Systems (RPAS), photogrammetry and GIS tools.

In this work a RPAS (Mikrokopter Okto XL) equipped with a Canon G11 camera has been used to obtain aerial pictures with 3648x2736px resolution. The maximum take off weight of the RPAS was of 1.8 Kg. Flights were programmed using the Mikrokopter OSD tools software to cover the entire area shown in Fig.1b. The altitude of the flight was 70m, the speed 1 m/s and the shoot was one picture every 2 seconds. During our flights, one pilot and one observer have been employed. The pilot had the duty to perform take-off and landing operations and interrupt the GPS-guided flight in case of unexpected behaviour of the RPAS. The observer had the duty to follow the flight on the ground station and communicate to the pilot changes from the predefined path. There are laws for flying RPAS that vary according to countries and operative scenarios. An overview of national regulations is contained in Colomina and Molina, 2014. For a more detailed description of the system used in this paper, see Casella et al., 2014.

In order to generate DEMs and orthorectified images from near-nadir photos acquired during our flights Agisoft Photoscan (http://www.agisoft.ru) has been used. Photoscan is a software that orients and matches automatically large datasets of images, and processes them in four main steps. As a first step, the software aligns the photographs using a SfM algorithm (Ullman, 1979). The SfM algorithms detect image feature points and subsequently monitor the movement of those points throughout the image dataset. This information is used as input to estimate the locations of those feature points and to render them as a sparse three-dimensional point cloud.

Estimation of the camera position is one of the main components in SfM, since SfM algorithms mainly depend on the accurate knowledge of the camera positions (Hartley and Zisserman 2003; Szeliski 2010). Outputs of this first step are: (i) a point cloud of three-dimensional points representing the geometry of the study area; (ii) the camera positions at the moment of image acquisition; (iii) the internal calibration parameters (focal length, principal point location, three radial and two tangential distortion coefficients). Since these first processing steps estimate the calibration parameters, there is no real need to apply calibrated cameras and optics during the image acquisition stage (Verhoeven, 2011). The second step builds a dense point cloud. In coastal zone surveys, most pictures are partially occupied by the sea, which must be excluded from the beach topography. To remove the sea from the calculation of the point cloud, the Photoscan mask function which allows to remove manually selected area has been used. In the third step, the algorithms operate on the pixel values to build the majority of geometric details. All pixels are utilized

in the MVS reconstruction algorithm (Scharstein and Szeliski, 2002; Seitz et al., 2006), which enables proper handling of fine details present in the scenes and represents them as a mesh. In this step, the software applies an algorithm based on an advanced computer vision solution that enables the creation of high-quality three-dimensional content from a series of overlapping aerial images (Verhoeven, 2011). In the fourth step, the mesh is textured with the photographs. From Agisoft Photoscan, the orthophoto and the DEM have been exported into a GIS software. With this, after the georeferencing procedure described below, differences between the co-registered DEMs have been calculated.

In order to georeference the DEM and orthophotos produced with Agisoft Photoscan, 8 Ground Control Points (GCPs) collected using a GPS system (Trimble ProXRT) have been used. 10 minutes of static data at each point has been collected, and postprocessed using the 1-second data of the GNSS base station 'Istituto G. Falcone' (http://www.gnssliguria.it/postprocessing.html), which is located 1.5 Km from our study area. The final accuracy of our GPS data is better than ±10 cm (XYZ). All our elevations were referred to the EGM 2008 global geoid model. As targets for the GCPs, fixed structures on the ground, such as the centre of sewer covers, mosaics on the ground such as edges of structures or the centre of boulders forming the groynes have been used. Permanent structures can be recognized in different set of photos taken at different times, allowing to georeference each set using the same GCPs, reducing the survey time. An alternative method is to place mobile targets for the time of the flight, such as rectangular coloured sheets and repeat the GPS survey every flight.

During the GPS survey additional control points (CPs) along continuous GPS transects on invariant surfaces (e.g. concrete structures or walking areas not subject to change in time) have also been collected. The GPS data has been postprocessed using the 1-second data of the GNSS base station 'Istituto G. Falcone' and points having vertical accuracy higher than 10 cm (e.g. 15 cm) have been discarded. For each dataset, the Root Mean Square Error (RMSE) between the CPs and the values of the DEM at the same location has been calculated. The RMSE was calculated using the equation:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (CP_i - D_i)^2}{n}} \qquad (1)$$

where CP is the elevation of the CP measured with post-processed GPS data, D is the elevation of the DEM at the same point and n the total number of CPs.

In order to compare the DEM with the shoreline surveyed with DGPS, the wet/dry line has been traced on the orthopotos. The wet/dry line is the boundary between wet and dry sand. Thanks to the calm sea conditions during our flights, the low tidal ranges and the high inclination of the beach profile, this coincides roughly with mean sea level at the time of measuring.

3. Results

3.1 RPAS Flights, accuracy of DEMs and sea conditions between the surveys

In this study, three flights have been done, covering the same area (~0.01 km^2) at different times. Each flight resulted in a total of ~130 photos shot at ~90° angle. Excluding blurred or moved pictures and the areas where less than 9 pictures overlapped, 65-70 pictures for each flight have been used as input for the software workflow. The time to collect a single set of pictures was 8 minutes (using one battery for each flight). The survey has been repeated the 1 November 2013, 4 December 2013, 17 March 2014 using the same flight parameters. After comparing the elevation of CPs and DEMs at 254 points, the vertical accuracy of the DEMs has been determined as 0.15-0.16 m (RMSE, Fig.2).

As regards accuracy of the DEM, a further analysis involving the number of pictures overlapping at each survey has been done. Fig.2 shows that there are areas where less than 4 pictures overlap. In these areas (gray in Fig.2) the DEM has been extracted

anyway, but it has been considered not reliable in our multitemporal analysis.

In order to understand the natural drivers of coastal changes in the study area Fig.3 shows an analysis of wave data in the period between our three surveys. First, wave data (significant wave height, mean wave direction and peak period) from the Capo Mele buoy, which is part of the Liguria Region buoy network (http://servizi-meteoliguria.arpal.gov.it/boacapomele.html) has been downloaded. The buoy is located about 20 km south of the study area (43°55'18"N 8°10'50"E). From this dataset, all the sea storms that had a significant wave height of more than 2 meters at the buoy (gray lines in Fig.3) have been extracted and used as input to MIKE 21 Spectral Wave (SW) model developed by DHI (former Danish Hydraulic Institute). MIKE 21 SW model has been implemented for the study area using the mesh grid and the configuration described in Casella et al., 2014. The model has run for each sea storms and wave data have been extracted from the output of each run at about 500 m offshore of the study area (black lines in Fig.3).

In the period between the first two surveys (1 November-4 December) the wave buoy registered two sea storms (Fig.3, upper part), which hit the study area mainly at a E-NNE angle and low intensities (significant wave height less than 0.5 meters the first sea storm, around 1-1.5 meters the second). In the period between the second and the third survey (4 December-17 march 2014) the study area was hit by four sea storms with prevailing SE direction (Fig.3, lower part), all of them reaching peak wave heights of 1.5-2 meters.

3.2 Coastal changes

Fig.4 shows the results of the difference between DEMs obtained for our study area at different times. In the left frame, the difference between the DEM obtained the 1st of November and the 4th of December 2013 shows four patterns of change. In the southernmost tip of our study area, volume changes indicate that sediment has been quarried from the beach and brought landward. Calculating the volume of the accumulated material it has been calculated that ~518.9 m^3 of material have been moved using an automatic excavator. The track marks of the excavator are evident in the orthophoto taken the 4th of December 2013. Another volume change is a net erosion in the central part of the beach (marked with number 1 in Fig.4). Here, around 632 m^3 are missing in the DEM of the 4th of December. Analysis of the orthophotos shows that the missing material is a grove of reeds that was cut between the 1st of November and the 4th of December. Retreat of the wet-dry line, lowering of the beach profile in the northernmost part and aggradation of the beach in the central part provide evidence that, although small, the sea storms hitting the area between our first two survey (Fig.3, upper part) caused significant beach topography changes. As the eroded volume of sediment does not match the volume of the aggradation, there might be a sediment input from the submerged beach and from the beaches located east of our study area (see Fig.1b).

A very different evolution can be inferred from the comparison of the DEMs obtained between the 4th of December 2013 and the 17th of March 2014 (right panel in Fig. 4). The strong southeastern sea storms hitting the shoreline in this period caused the progradation of the shoreline to its summer position (compare the shoreline surveyed the 17th of March 2014 with the June shoreline surveyed with DGPS, shown as dashed line in Fig.4) and the general aggradation of the beach profile. As only a minor area of erosion can be identified in the southernmost tip (where the presence of the rocky promontory of Capo Santo Spirito, Fig.1b, blocks further sediment inputs), it is likely that a large part of the sediments come from the shallow submerged area in front of the beach.

4. Discussions

4.1 RPAS as beach monitoring technique

Techniques for beach monitoring can be divided in two major categories: those based on *in situ* observations and those employing analysis of remotely sensed data. Among the first ones the most used are high-accuracy GPS surveys (Morton et al., 1993; Harley et al., 2010) and total stations or terrestrial laser scanners (Lee et al., 2013). These techniques

are relatively inexpensive and have a good accuracy (2-6 cm vertical, Lee et al., 2013) but they require large efforts to map wide areas. Common techniques to map larger areas in shorter times are remotely sensed data, such as aerial photographs or webcam images (Hapke and Richmond, 2000; Taborda and Silva, 2012), satellite images taken at different times (Blodget et al., 1991) or airborne lidar mapping (Stockdon et al., 2002). Such techniques have as main limitations their cost and the availability of images in periods of interest.

Beach monitoring is subject to a trade-off between time, cost, accuracy and resolution of the survey (both spatial and temporal). As an example, if one wants to understand the short-time evolution (weeks to months) of a coastal system, traditional in situ measurements can be used with sufficient temporal resolution (i.e. they can be used to map the evolution of an area on a monthly basis), but they allow to map limited areas and can provide only limited three dimensional information (e.g. along transects). On the other side, airborne orthophotography and lidar provide good spatial resolution, but their cost often does not allow performing surveys at short time intervals. Similar trade-offs are common in other research disciplines, such as habitat monitoring or wildlife conservation, where capturing short-term changes of an observed phenomenon is often limited by the observation technique employed.

The use of small RPAS for remote sensing, landscape mapping and environmental monitoring allows to partially overcome such problems since they can provide data at high and customly-adjustable frequency (Everaerts, 2008; Delacourt et al., 2009; Niethammer et al., 2010; Niethammer et al., 2012; Hugenholtz et al., 2013, Stumpf et al., 2013; Ouédraogo et al., 2014). Typically, small RPAS are relatively low cost (5-10K €), and their limited dimensions (few tens of centimeters and usually < 5kg) make them easily and rapidly deployable. In our study area, RPAS allowed us to obtain orthorectified photographs and DEMs of the same coastal area at three times over a period of 5 months.

As regards the survey efficiency, the study area (0.01 km^2) has been mapped with a flight of 8 minutes. This translates into a survey efficiency of 7.5 Ha per hour, which is low if compared with airborne surveys (e.g. lidar) but is high compared to laser scanner or DGPS surveys. The final vertical accuracy (±16 cm) of the DEM produced is in line with most studies using similar techniques in similar areas (Mancini et al., 2013), but is low if compared to lidar or most traditional direct survey techniques (typically 2.5-5 cm). It is worth noting that the smoothness and uniformity of sediment surfaces limits the effectiveness of matching algorithms (Mancini et al., 2013). Similar problems might be created by water reflections, which should be masked to avoid unwanted errors in the matching process.

4.2 RPAS multi-temporal surveys: a support to coastal zone management

The results obtained in our study also have some management implications. First, it has been documented the possibility to detect changes due to human activity that involve the movement of sediments on the beach and the removal of vegetation. Moving or nourishing sediments on the beach is considered analogous to beach nourishment (Regional Laws 13/1999, 6/2001, 3/2007 and 5/2011, which receive National and EU framework directives). The Regional Laws state that if more than 10m^3 of sediment per linear meter are moved on the shoreline, the subject in charge of the movement is required to perform an environmental evaluation of the action. This evaluation should include description of the site, source and quantity of sediments involved and considerations on potentially threatened habitats or species. In Italy, the subject in charge of the action is not necessarily a public authority, but is in many cases a private beach manager, who receives the right to use the beach from the State for a number of years for commercial purposes in exchange of a yearly rent.

Regional Authorities may choose to employ RPAS multi-temporal surveys for the control of such actions. The movement of sediments usually take place in late October along the

Liguria coastline (as well as other Italian coastlines), therefore one flight at the end of the summer season (September) and one in November should catch all the sediment movements done along the coast. In fact, once DEM and orthophoto are extracted, volumes of sediments moved or imported to a beach can be calculated using common GIS tools. Another management implication of the multi-temporal survey presented is found in the application of drones to obtain data on the short-term evolution of the beach topography after the placement of an infrastructure (according to regional law 1793/2005), like the ones present in the study area.

Analyzing changes in beach topography in light of the intensity and direction of sea storms hitting the shoreline, it is possible to gather some information on the short-term dynamics related to the coastal defences that have been recently placed in the study area. Looking only at the yearly evolution of the shoreline (Fig.1b) it might be concluded that after the emplacement of those defences the shoreline has advanced, and since then it oscillates around an average position. Our data suggests that when the shoreline retreats after smaller sea storms from the East (left panel of Fig.4), there is a volume gain on the emerged beach and virtually no loss of sediments towards the submerged beach. When a series of strong storms from Southeast hits the shoreline, our data suggest that the beach responds with an aggradation and progradation of the beach topography, and possibly there is a net transport of sediments from the submerged beach to the emerged one (right panel in Fig.4). Also in this case, no sediment appears to be lost from the emerged beach towards the submerged area. It is worth noting that three average-intensity southeastern sea storms are enough to shift the shoreline to its summer position.

5. Conclusions

Beach erosion is a significant natural process, which affects coastal population and properties. The management of sandy coasts relies on beach monitoring to gather data on the intensity and rates of beach evolution, and monitoring is subject to trade-offs between accuracy, costs and resolution of the survey.

The last four years have seen an exponential increase of research activities based on data collected from drones. Flying platforms have become smaller and capable of lifting more weight, and sensors are starting to be tailored specifically for drone applications. The learning curve for drone pilots is becoming less steep, and is counterbalanced by national regulations putting limits to the flying areas, and requiring among other things specific pilot training and risk assessments of the flight operations. In coastal environments, the application of SfM and MVS methods from drone photographies may prove challenging due to the uniform nature of the lansdcape. Also, flights in coastal areas might be difficult due to the risks of gusty winds or rapid changes in meteorological conditions, and corrosion due to marine spray requires a frequent maintenance of the drone.

For these reasons, coastal areas are one of the most challenging environments for drone-based research. On the other side, the rapid rates and the entity of changes along most coastal zones, especially sandy beaches, make them the ideal ground for the application of such tools. In this study it has been demonstrated that methods employing aerial photographs from drones analysed with SfM and MVS algorithms can be effectively used for multi-temporal monitoring of coastal areas, and the data obtained can be used for management purposes. Our results are accurate enough to provide information on how the study area evolved in a period of 5 months, and have been obtained with a survey efficiency and cost that is unmatched by other common survey techniques.

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References

Anderson K, Gaston KJ (2013). Lightweight unmanned aerial vehicles will revolutionize spatial ecology. Frontiers in Ecology and the Environment 11: 138–146. http://dx.doi.org/10.1890/120150

Berni JAJ, Zarco-Tejada PJ, Suárez L, Fereres E (2009). Thermal and narrowband multispectral remote sensing for vegetation monitoring from an unmanned aerial vehicle. IEEE Transactions on Geoscience and Remote Sensing 47: 722-738.

Bird E (1987). The modern prevalence of beach erosion. Marine Pollution Bulletin 18: 151–157.

Blodget HW, Taylor PT, Roark JH (1991). Shoreline changes along the Rosetta-Nile Promontory: monitoring with satellite observations. Marine Geology 99: 67–77.

Brignone M, Schiaffino CF, Isla FI, Ferrari M (2012). A system for beach video-monitoring: Beachkeeper plus. Computers & Geosciences 49: 53–61.

Casella E, Rovere A, Pedroncini A, Mucerino L, Casella M, Cusati LA, Vacchi M, Ferrari M Firpo M (2014). Study of wave runup using numerical models and low-altitude aerial photogrammetry: A tool for coastal management. Estuarine, Coastal and Shelf Science, 149: 160-167. doi:10.1016/j.ecss.2014.08.012

Colomina I, Molina P (2014). Unmanned aerial systems for photogrammetry and remote sensing: A review. ISPRS Journal of Photogrammetry and Remote Sensing 92: 79–97.

Delacourt C, Allemand P, Jaud M, Grandjean P, Deschamps A, Ammann J, Cuq V, Suanez S (2009). DRELIO: an unmanned helicopter for imaging coastal areas. Journal of Coastal Research Special Issue 56: 1489–1493.

Eltner A, Baumgart P, Maas HG, Faust D (2014). Multi□temporal UAV data for automatic measurement of rill and interrill erosion on loess soil. Earth Surface Processes and Landforms. doi: 10.1002/esp.3673

Everaerts J (2008). The use of unmanned aerial vehicles (UAVs) for remote sensing and mapping. The International Archives of the Photogrammetry. Remote Sensing Spatial Information Sciences XXXVII Part B1, Beijing 2008.

Fierro G, Berriolo G, Ferrari M (2010). Le spiagge della Liguria occidentale – analisi evolutiva. Regione Liguria – Ass. Pianificazione territoriale, Urbanistica Ed., 174 pp.

Fiori E, Comellas A, Molini L, Rebora N, Siccardi F, Gochis DJ, Tanelli S, Parodi A (2014). Analysis and hindcast simulations of an extreme rainfall event in the Mediterranean area: The Genoa 2011 case. Atmospheric Research: 138, 13-29.

Hapke C, Richmond B (2000). Monitoring beach morphology changes using small-format aerial photography and digital softcopy photogrammetry. Environmental Geosciences: 7, 32–37.

Harley MD, Turner IL, Short AD, Ranasinghe R (2010). Assessment and integration of conventional, RTK-GPS and image-derived beach survey methods for daily to decadal coastal monitoring. Coastal Engineering: 58, 194–205.

Hartley R, Zisserman A (2003). Multiple View Geometry in Computer Vision. Cambridge University Press: Cambridge.

Hugenholtz CH, Whitehead K, Brown OW, Barchyn TE, Moorman BJ, LeClair A, Riddell K, Hamilton T (2013). Geomorphological mapping with a small unmanned aircraft system (sUAS): feature detection and accuracy assessment of a photogrammetrically-derived digital terrain model. Geomorphology: 194, 16–24.

Lee JM, Park JY, Choi JY (2013). Evaluation of Sub-aerial Topographic Surveying Techniques Using Total Station and RTK-GPS for Applications in Macrotidal Sand

Beach Environment. Journal of Coastal Research, Coastal Education & Research Foundation, Special Issue: 535–540.

McGranahan G, Balk D, Anderson B (2007). The rising tide: Assessing the risks of climate change and human settlements in low elevation coastal zones. Environment and Urbanization: 19, 17–37.

Morton RA, Leach MP, Paine JG, Cardoza MA (1993). Monitoring beach changes using GPS surveying techniques. Journal of Coastal Research: 702–720.

Niethammer U, Rothmund S, James MR, Travelletti J, Joswig M (2010). UAV-based remote sensing of landslides. Int. Arch. Photogram. Rem. Sens. Spatial Inf. Sciences, vol. XXXVIII. ISPRS Comm. V., Newcastle-upon-Tyne, U.K.

Niethammer U, James MR, Rothmund S, Travelletti J, Joswig M (2012). UAV-based remote sensing of the Super Sauze landslide: evaluation and results. Engineering Geology: 128, 2–11.

Ouédraogo MM, Degré A, Debouche C, Lisein J (2014). The evaluation of unmanned aerial system-based photogrammetry and terrestrial laser scanning to generate DEMs of agricultural watersheds. Geomorphology: 214, 339–355.

Orlandi A, Pasi F, Onorato LF, Gallino S (2008). An observational and numerical case study of a flash sea storm over the Gulf of Genoa. Advances in Science and Research: 2, 107–112.

Pasi F, Orlandi A, Onorato LF, Gallino S (2011). A study of the 1 and 2 January 2010 sea-storm in the Ligurian Sea. Advances in Science and Research: 6, 109-115.

Parodi A, Boni G, Ferraris L, Siccardi F, Pagliara P, Trovatore E, Foufoula-Georgiou E, Kranzlmueller D (2012). The “perfect storm”: From across the Atlantic to the hills of Genoa. Eos Trans. AGU 93(24),225.

Pérez-Alberti A, Trenhaile AS (2015). An initial evaluation of drone□based monitoring of boulder beaches in Galicia, north□western Spain. Earth Surface Processes and Landforms: 40(1), 105-111.

Rebora N, Molini L, Casella E, Comellas A, Fiori E, Pignone F, Siccardi F, Silvestro F, Tanelli S, Parodi A (2013). Extreme rainfall in the Mediterranean: what can we learn from observations? Journal of Hydrometeorology: 14, 906–922.

Rovere A, Casella E, Vacchi M, Parravicini V, Firpo M, Ferrari M, Morri C, Bianchi CN (2014). Coastal and marine geomorphology between Albenga and Savona (NW Mediterranean Sea, Italy). Journal of Maps: 1-9.

Scharstein D, Szeliski R (2002). A taxonomy and evaluation of dense two-frame stereo correspondence algorithms. International Journal of Computer Vision: 47, 7–42.

Seitz S, Curless B, Diebel J, Scharstein D, Szeliski R (2006). A comparison and evaluation of multi-view stereo reconstruction algorithms. Proceedings of the CVPR ’06 IEEE Computer Society Conference on Computer Vision and Pattern Recognition – Volume 1. IEEE Computer Society: Washington, DC, pp. 519-526.

Small C, Nicholls RJ (2003). A global analysis of human settlement in coastal zones. Journal of Coastal Research: 19, 584–599.

Szeliski R (2010). Computer Vision: Algorithms and Applications. Springer-Verlag: London.

Stockdon HF, Sallenger AH, List JH, Holman RA (2002). Estimation of shoreline position and change using airborne topographic lidar data. Journal of Coastal Research: 18, 502–513.

Stumpf A, Malet JP, Kerle N, Niethammer U, Rothmund S (2013). Image-based mapping of surface fissures for the investigation of landslide dynamics. Geomorphology: 186, 12–27.

Taborda R, Silva A (2012). COSMOS: A lightweight coastal video monitoring system. Computers & Geosciences: 49, 248–255.

Ullman S (1979). The interpretation of structure from motion. Proceedings of the Royal Society of London B203: 405–426.

Vacchi M, Rovere A, Schiaffino CF (2012). Monitoring the effectiveness of re-establishing beaches artificially: methodological and practical insights into the use of video transects and SCUBA-operated coring devices. International Journal of the Society for Underwater Technology: 30, 201–206.

Verhoeven G (2011). Taking computer vision aloft – archaeological three-dimensional reconstructions from aerial photographs with PhotoScan. Archaeolical Prospection: 18, 67-73.

Watts AC, Ambrosia VG, Hinkley EA (2012). Unmanned aircraft systems in remote sensing and scientific research: Classification and considerations of use. Remote Sensing: 4, 1671-1692.

Woodget AS, Carbonneau PE, Visser F, Maddock IP (2015). Quantifying submerged fluvial topography using hyperspatial resolution UAS imagery and structure from motion photogrammetry. Earth Surface Processes and Landforms: 40(1), 47-64.

FIGURE CAPTIONS

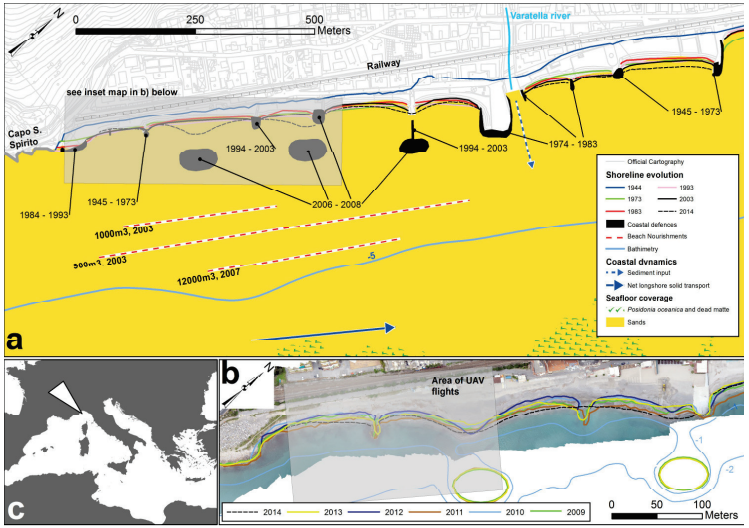


Fig.1 a) the shoreline and the nearshore area of Borghetto Santo Spirito showing the main geological and biological bottom coverages (Rovere et al., 2014). The figure also shows the shoreline traced as wet-dry line on orthophotos (1944-2003, data from Regione Liguria) and the shoreline surveyed with DGPS in June 2014 (data from Borghetto S.S. Municipality). The dashed blue arrow indicates the main sedimentary input from the Varatella River, while the solid blue arrow indicates the main littoral drift in the area (Rovere et al., 2014). The dashed red lines indicate the location of beach nourishment (labels indicate year and quantity of sediment used) and are indicative of the coastal stretch where the sediments have been damped onshore (data from Regione Liguria). Coastal defences and their year of construction are also indicated (data from Regione Liguria). b) Detail of a), area where the RPAS flights have been performed. The shoreline data have been

provided by the Municipality of Borghetto S.S., and represent the wet-dry line at different years surveyed with DGPS. Bathymetric data have been provided by the Borghetto S.S. Municipality. c) Location of the study area in the Mediterranean Sea.

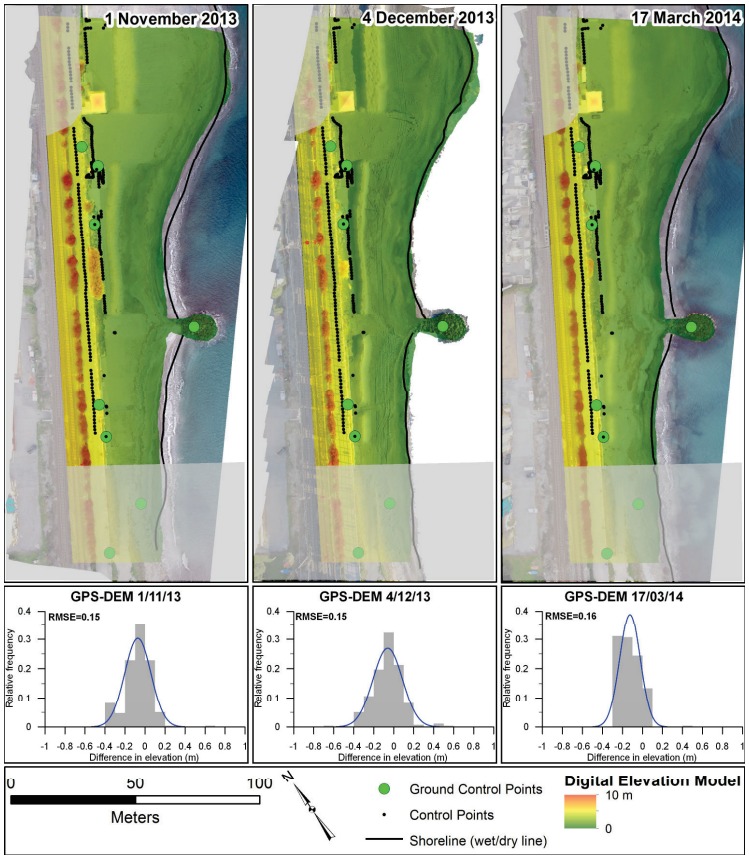
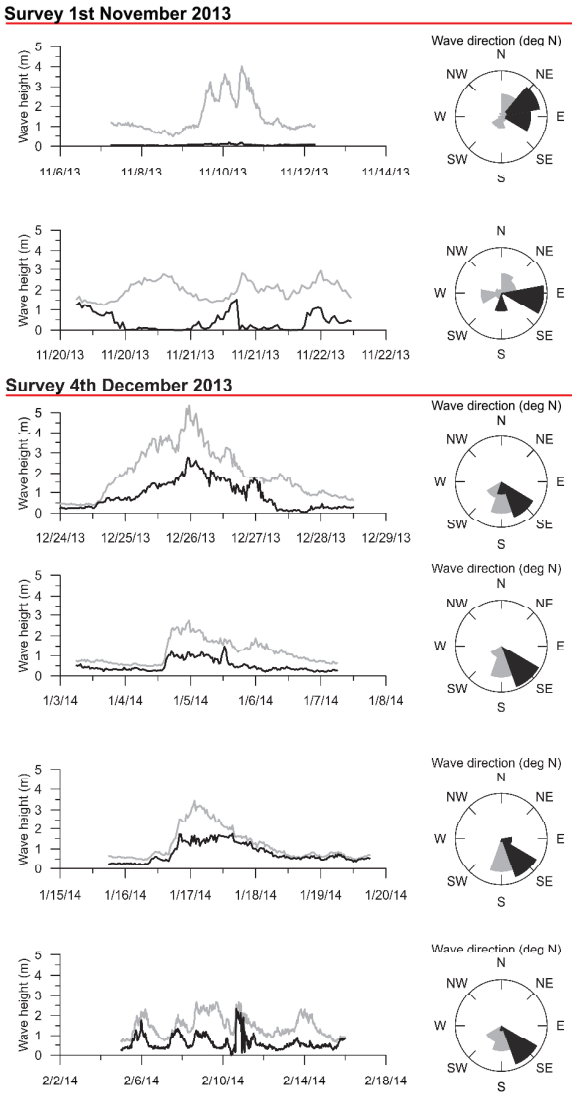
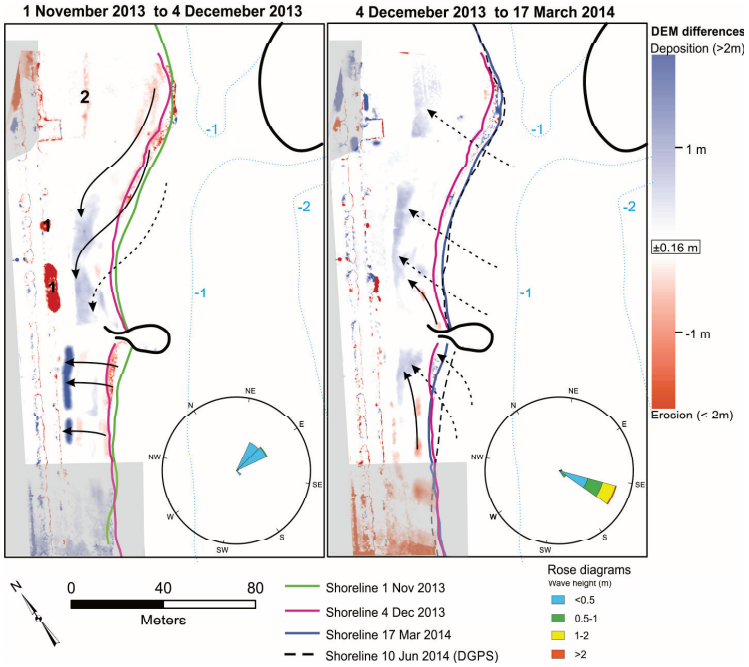


Fig.2 Orthophotos and Digital Elevation Models obtained from RPAS flights and SfM-MVS algorithms in the three surveys. The three boxes below the maps indicate the frequency distribution of the difference in elevation between the GPS Control Points shown in the corresponding figure and elevation extracted from DEM. The gray area indicates zones where less than 4 pictures overlap in at least one of the surveys, making the final DEM less accurate.



514 **Fig.3 Wave height and direction for sea storms in the study area as recorded by the**
515 **Buoy of Capo Mele (gray line and gray areas in the rose diagram) and wave height**
516 **500 meters offshore in front of the study area calculated using MIKE21 spectral**
517 **wave module (black line and black areas in the rose diagram). Dates are shown in**
518 **MM/DD/YY format.**



519

520 **Fig.4 Difference between Digital Elevation Models obtained from our different**
521 **surveys (dates are indicated on top). Solid arrows indicate the movement of**
522 **sediments that likely happened onshore, while dashed arrows indicate movement of**
523 **sediments that likely involved sediment input from the submerged beach. Light gray**
524 **areas indicate zones where there are few pictures overlapping (see Fig.2), therefore**

where the DEM differences have been considered not reliable and are not discussed in the text. The solid black lines indicate the structures for coastal defence, shown also in Fig.1 and Fig.2. Bathymetric data have been surveyed in Summer 2013 by the Borghetto S.S. Municipality and are the same in both frames. 1-Area where a grove of reeds was cut in the time between the two surveys; 2-Area of 5-10 cm of erosion, probably caused by strong NE winds that blew away sediment from the top of an artificial dune (visible in Fig.2).