Underwater photogrammetry in Antarctica: long-term observations in benthic ecosystems and legacy data rescue

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Abstract

The need for sound baseline information about community structure and composition against which changes can be detected and quantified is a well-recognised priority in Antarctica. Here, the collection of such data is challenging, especially at sea, where long-term monitoring is usually logistically feasible only in the proximity of permanent research stations. In recent years, underwater photogrammetry has emerged as a non-destructive and low-cost method for high-resolution topographic reconstruction. We decided to apply this technique to videos, recorded during standard SCUBA surveys of Antarctic benthos in Tethys Bay (Ross Sea, Antarctica) in 2006 and 2015 and originally not meant for photogrammetry. Our aim was to assess the validity and utility of the photogrammetric method to describe benthic communities from the perspective of long-term monitoring. For this purpose, two of the transects surveyed in 2015 were revisited in 2017. Videos were processed with photogrammetric procedures to obtain 3D models of the seafloor and inhabiting organisms. Overall, a total of six 20 m-long transects, corresponding to a total area of ~200 m² of seafloor were analysed. Accuracy of the resulting models, expressed in terms of Length Measurement Error (LME), was 1.9 mm on average. The 2017 transects showed marked differences in some species, such as a 25–49% increase in the number of sea urchins Sterechinus neumayeri (Meissner, 1900) and the complete disappearance of some sponges Mycale (Oxymycale) acerata Kirkpatrick, 1907. Our analyses confirm the efficacy of photogrammetry for monitoring programmes, including their value for the re-analysis of legacy video footage.

Keywords Antarctica · Photogrammetry · SCUBA-recorded videos · Long-term monitoring · Image-based analysis

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Introduction

One of the major constraints in the understanding of temporal variation in ecological communities is the lack of time-series information on which to base assessments of the rates and direction of natural change (Magurran et al. 2010). The need for sound baseline information against which anthropogenically and/or naturally induced changes can be detected and quantified is a well-recognised priority in the field of ecology. In this field, Long Term Ecological Research (LTER, Callahan 1984; Strayer et al. 1986) is specifically designed to produce time-series data enabling the detection of possible changes occurring at any time scale (Magurran et al. 2010).

In polar areas, due to challenging field conditions and the high logistical costs, long-term monitoring programmes are an arduous task for researchers. In Antarctica, there are a few examples of marine LTER studies focusing on (i) coastal oceanography (Palmer station LTER programme, https://pal.lternet.edu/, Smith et al. 1995); (ii) environmental impacts of research bases and human presence (Conlan et al. 2004, 2010; Stark et al. 2006a, b; Tin et al. 2009); (iii) time-series data about pinniped populations (Salwicka and Rakusa-Suszczewski 2002), krill (El-Sayed 1994) and plankton ( Hosie et al. 2003, 2014); (iv) the frequency of ice scouring events on benthic biota (Deregibus et al. 2017). However, benthic components of the Antarctic marine realm are rarely investigated in a comprehensive temporal manner (Gutt and Starmans 1998; Constable et al. 2016) and long-term data on their dynamics is urgently needed (Smith et al. 1995). The availability of long-term data on Antarctic benthic communities would lead to an increased understanding of (i) growth performance in slow-growing and long-living key species, (ii) impacts and disturbance of episodic events (e.g. iceberg-scouring), (iii) inter-annual variability in food delivery, and (iv) shifts in community structure not due to stochastic events.

One of the most relevant and insightful examples of Antarctic long-lasting investigations at permanent benthic sites is the study of recruitment and growth of sponges on artificial structures in McMurdo Sound (Dayton 1989; Dayton et al. 1974, 2013, 2016). In this case, sampling activities were conducted over more than 40 years of study at variable intervals of time between subsequent visits, rather than on a regular, pre-planned basis (Dayton et al. 2013). Such data are useful for ecological monitoring, but the nature of temporarily irregular observations preclude the detailed understanding of inter-annual dynamics and hence of the precise timing of events. In the literature, similar cases abound and while these data may be of help in creating a robust reference baseline, they should be considered as “then and now” comparisons (Lotze and Worm 2009). True monitoring should rely on the availability of “repeated measurements collected at a specific frequency over multiple time units”, since only such observations can confidently disclose underlying periodicity (Thompson et al. 1998). In Antarctica, this aspect is generally fulfilled only in proximity to permanent research bases, where the maintenance of accessible permanent sites for ‘long-term’ observations is less challenging logistically, facilitating repeat visits in subsequent field seasons and ensuring the greatest amount of information, consistency, repeatability and reliability possible at sea (Hill and Wilkinson 2004).

Among the wide variety of methodologies usable in long-term monitoring programmes of benthic communities (e.g. Hill and Wilkinson 2004; Rees 2009), ‘non-destructive’ techniques, i.e. those that do not remove organisms or physically damage the communities studied, are preferable to ‘extractive’ or ‘destructive’ ones (Solan et al. 2003). This is particularly true considering that the overarching objective of ecological studies is conservation (Mallet and Pelletier 2014). Especially in polar areas, where benthic communities are often fragile, slow-growing and with long recovery times (Gutt and Starmans 2002; Teixidó et al. 2004), non-destructive methodologies represent suitable tools to study these environments. Because no organisms are removed, they also preserve their original position on the substrate hence enabling the analysis of spatial patterns. The downside is that a precise taxonomical characterisation of observed taxa is more difficult without collecting specimens (Pech et al. 2004; Bowden 2005; Macedo et al. 2006; Flannery and Przeslawski 2015).

Recent technological advances have contributed considerably to the development of non-destructive methodologies to study benthic dynamics and spatial patterns. These include (i) improved underwater optical recording systems, such as high-resolution digital video and photography with underwater apparatus (e.g. Jaffe et al. 2001; Jaffe 2015, 2016; Mullen et al. 2016; Peirano et al. 2016; Chennu et al. 2017), (ii) the optimisation of image sampling and mapping techniques of the seafloor for 3D photogrammetric reconstructions (e.g. Nicosevici et al. 2009; Pizarro et al. 2009, 2017) and (iii) development of new software for benthic imagery analysis (e.g. Teixidó et al. 2011; Trygonis and Sini 2012; Kohler and Gill 2006).

The use of photographic or video sampling is especially useful as it allows permanent records that facilitate comprehensive image analyses, reduces the time spent underwater and the requirement for divers with experience in species identification (Parravicini et al. 2009). Moreover, these sampling methods are nowadays accessible to a wide user community, thanks to the availability of affordable and off-the-shelf photographic equipment coupled with advances in
automatic image processing algorithms that have recently simplified and sped up photogrammetric procedures for 3D modelling (Remondino and El-Hakim 2005, 2006; Remondino et al. 2012, 2014).

Photogrammetry, i.e. the science or art of obtaining reliable measurements by means of photographs (Thompson 1966), is a flexible and powerful technique used in scientific and engineering applications, where the extracted information must comply with predefined accuracy, reliability and completeness (Förstner and Wrobel 2016). The photogrammetric process consists, in brief, of the three-dimensional reconstruction of the shape and location of an object starting from a set of images of that object (e.g. still frames extracted from videos, as in the case of our transects, or photographs). The result of this process is the production of digital and graphical outputs (i.e. the 3D model with its derived geometric elements) with the purpose of deriving accurate and reliable 3D measurements of the object from images (Luhmann et al. 2013; Granshaw 2016). Recent enhancement of photogrammetric algorithms have improved the process of automation and resulted in easy-to-use tools for 3D modelling of both simple assets and complex scenes (Snavely et al. 2008; Westoby et al. 2012; Micheletti et al. 2015). Thanks to such tools, rapid processing of large image blocks (Remondino et al. 2017) is obtained by exploiting Graphics Processing Unit (GPU) accelerated computing, i.e. the use of a GPU together with a Central Processing Unit (CPU). Despite the easy generation of 3D geometries (point clouds or polygonal models), even by non-experts, fully automated image-based methods need standardised protocols and procedures to ensure that results’ quality meets predefined requirements (Nocerino et al. 2014). In this context, automatic photogrammetry (Ullman 1979; Pollefeys et al. 2008; Verhoeven et al. 2012; Westoby et al. 2012) has thus emerged as a low-cost method for high-resolution topographic reconstruction, also ideally suited for low-budget research and application in remote areas (Westoby et al. 2012). The use of image-based techniques for underwater 3D recording and mapping, however, is not new. The basics of mathematical formulation for underwater photogrammetry were available since the 1960s (Tewinkel 1963; Shmutter and Bonfiglioli 1967; Karara and Faig 1972; Masry 1974; Slama 1980; Fryer and Kniest 1985; Kotowski 1988), with first regular applications being in underwater archaeology (Bass 1970) and in seafloor exploration and monitoring (Pollio 1968).

In marine ecology, a number of studies have employed automatic photogrammetric techniques to analyse the complexity of coral reefs and seafloor (e.g. Friedman et al. 2012; Hu et al. 2012; Leon et al. 2015; Bennecke et al. 2016; Ferrari et al. 2016; Raoult et al. 2016; Storlazzi et al. 2016), demonstrating high levels of robustness and effectiveness of the technique in measuring terrain features, like surface rugosity, and in mapping coral colonies. However, to the best of our knowledge, until now underwater photogrammetry has never been performed in Antarctica. Photogrammetry can, indeed, be also exploited in extreme or logistically challenging underwater environments, such as Antarctica, where field activities necessarily have to be efficient and rapid, to minimise bottom times and, at the same time, to guarantee useful results with the minimal environmental impact.

In this study, we, thus, present the first application of this technique to describe Antarctic shallow-water rocky-bottom benthic communities. 3D reconstructions of benthic habitats were obtained using imagery from available ‘historical’ (i.e. not originally designed for photogrammetry) video transects recorded in 2006 and 2015. Originally, these videos were just intended as a complementary tool (2006) or the main sampling tool (2015) for non-destructive visual surveys of benthic communities and habitats. In 2017, two of the 2015 transects were revisited, acquiring comparable data after a two year temporal gap. Due to the versatility of photogrammetric techniques and to the quality of the images acquired during those studies, it was possible to obtain a permanent record of benthic communities, i.e. the 3D models, and examples of the variety of data valuable for ecological analyses that can be extracted from the models.

This contribution is devoted to presenting the methodologies and protocols for image sampling, processing and analysis, that can be reproduced by other research groups and applied in other coastal Antarctic locations. Here we present just a few quantitative results to demonstrate the reliability and utility of the methods; the full data analysis, with spatial and temporal comparisons, will be the subject of another paper.

Materials and methods

Study site

The study area is located in Tethys Bay (Fig. 1, hereafter TB), a 2 km wide embayment close to the Italian coastal base “Mario Zucchelli”, in Terra Nova Bay (Ross Sea, Antarctica). TB’s northwest side is dominated by a steep granite cliff and the seafloor is characterised by a moderate slope with scattered gigantic granite boulders, amongst softer substrates composed of coarse sands, cobbles and gravels. In this area, the annual sea-ice layer persists until the second half of December and starts breaking out from the beginning of January.

Data presented here were collected in the framework of two different SCUBA sampling surveys, both conducted in south TB (TBS). The first was carried out in 2006 by New Zealand researchers from the National Institute of Water and Atmospheric Research (NIWA) (Fig. 1 green dots and shapes) and the second in 2015 by researchers from the
Italian National Antarctic Program (PNRA) (Fig. 1 red dots and shapes). In both cases, field activities were performed during early summer (end of November—beginning of December) (Table 1). The 2006 New Zealand sampling survey was part of a larger research programme that surveyed other sites in the Victoria Land area. The NIWA survey’s design and purposes have been described in previous papers (Cummings et al. 2006, 2018; Thrush et al. 2010). Briefly, three sites, located ~ 50 m from each other, were established in TBS. At each site a hole was drilled in the sea ice to access the seafloor (exact locations of holes are provided in Table 1) and survey 20-m-long transects (respectively TBS_NIWA_T1, TBS_NIWA_T2, TBS_NIWA_T3) using videos.

The Italian activities took place during the XXXI PNRA expedition in the framework of the project “ICE-LAPSE” (PNRA 2013/AZ1.16). In this case, a single hole was drilled in the ice at the site named “Zecca” (Schiaparelli 2010; Table 1). From this, divers reached the starting points of three different transects (Table 1) located, respectively, at 22 m (transect BTN_PNRA_T1), 19 m (transect BTN_PNRA_T2) and 17 m (transect BTN_PNRA_T3). Transects were ~ 20 m in length. Finally, thanks to the ongoing cooperation between NZ, Korean and PNRA researchers, in 2017 NZ and Korean researchers revisited the BTN_PNRA_T1 and BTN_PNRA_T2 fixed transects established in 2015, producing video-sampling replicates of these same transects after two years.

Field operations and image acquisition

Although sampling activities belonged to two different research projects (i.e. NIWA, PNRA and NZ/KO) occurring in different years, underwater operation and image acquisition followed comparable protocols. Concerning the 2006 NZ sampling methods (Cummings et al. 2006, 2018; Thrush et al. 2010), at each site divers laid a shore-parallel 20-m transect tape, marked at 1 cm intervals along its length, on the seafloor. Transects were videoed (using a

Table 1 Transect locations: coordinates of holes drilled in the fast ice (NIWA) or starting points of transects (PNRA) and the sampling periods related to each set of videos

| Location            | Transect label | Depth | Lat. S (DD) | long. E (DD) | 1° Sampling date        | 2° Sampling date        |
|---------------------|----------------|-------|-------------|--------------|-------------------------|-------------------------|
| South Tethys Bay    | TBS_NIWA_T1    | 21    | 74.68997    | 164.1131     | 18–23 Nov 2006          |                         |
| South Tethys Bay    | TBS_NIWA_T2    | 21.5  | 74.68993    | 164.111      | 18–23 Nov 2006          |                         |
| South Tethys Bay    | TBS_NIWA_T3    | 21    | 74.68992    | 164.1088     | 18–23 Nov 2006          |                         |
| “Zecca”             | BTN_PNRA_T1    | 22    | 74.690115   | 164.103662   | 8 Dec 2015              | 14 Nov 2017             |
| “Zecca”             | BTN_PNRA_T2    | 19.4  | 74.69017    | 164.103914   | 10 Dec 2015             | 14 Nov 2017             |
| “Zecca”             | BTN_PNRA_T3    | 17    | 74.690219   | 164.1038     | 10 Dec 2015             | 14 Nov 2017             |
Sony HVR-HD1000E, in an underwater housing equipped with lights) with the lens perpendicular to the seafloor at fixed height above it (~1 m). Similar methods were used during the 2015 PNRA survey. Along each PNRA transect a metric tape was deployed to identify a ~20-m-long path whose starting, midway and ending points were marked by using heavy fixed bodies (e.g. stainless steel stakes, steel beams or concrete blocks; for their positions see Table 2), which enabled relocation of the exact transect position. Transects were recorded by divers who maintained a regular swimming pace (about 0.15 m/s) and distance from the bottom of about 1 m. The camera used was a SONY HDR-HC7 placed in a flat (i.e. without an additional spherical external lens) underwater housing (Isotta SPJ2) equipped with a couple of lights mounted on flex arms. Video-transects were recorded in two sequences, corresponding to the backwards and forwards paths between the start and end markers, thus following a boustrophodonic pattern. PNRA transects were georeferenced by recording geographic coordinates of the start, mid and end markers of each transect using a couple of GNSS receivers and antennas (Leica GS10 and Leica AS10, respectively) connected to a base station (Mario Zucchelli Station 3; used as station for topographic surveys), in a Real-Time Kinematics (RTK) mode. Under these conditions, the georeferencing procedure provides ~5 cm-level precision (manufacturer value for the GNSS system) over a wide area surrounding the station. Depth was recorded using a SCUBA computer placed next to each transect marker (Table 2). Finally, during a 2017 visit, a team of NZ and Korean divers repeated the video-sampling procedures on BTN_PNRA_T1 and BTN_PNRA_T2 by using a mirrorless digital camera, a Sony A7IIs, equipped with a Sony FE 16-35mm f/4 ZA OSS Vario-Tessar T* Lens (fixed at 16mm), housed in a Nauticam Housing NA-A7II with a dome port, and equipped with a couple of LED video dive light (Keldan 4X Compact). The features of the different cameras are reported in Table 3.

Video pre-processing

Videos were pre-processed according to the following steps (Fig. 2):

- Digitisation of the original 2006 and 2015 video format (HDV1080i standard DV cassette) using Sony camera related frame grabber
- De-interlacing of the 2006 and 2015 videos with opensource VideoLAN software (VLC)
- Still frames extraction at the original video frame rate
- Frame selection

### Table 2

Geographic coordinates of fixed heavy bodies used to mark PNRA (Italy) transects’ paths

| Fixed body name | Item type          | Transect     | Depth | Lat. S (DD) | Long. E (DD) |
|-----------------|--------------------|--------------|-------|-------------|--------------|
| T1.1            | Concrete block     | BTN_PNRA_T1  | 22    | 74.690115   | 164.103662  |
| T1.2            | Steel stake        | BTN_PNRA_T1  | 22.4  | 74.690043   | 164.103987  |
| T1.3            | Steel stake        | BTN_PNRA_T1  | 23.1  | 74.689997   | 164.104079  |
| T2.1            | Concrete block     | BTN_PNRA_T2  | 19.4  | 74.690170   | 164.103914  |
| T2.2            | Steel beam         | BTN_PNRA_T2  | 19.5  | 74.690133   | 164.104254  |
| T2.3            | Steel beam         | BTN_PNRA_T2  | 19.1  | 74.690121   | 164.104436  |
| T3.1            | Steel beam         | BTN_PNRA_T3  | 17    | 74.690219   | 164.103800  |
| T3.2            | Steel beam         | BTN_PNRA_T3  | 17.6  | 74.690171   | 164.104137  |
| T3.3            | Steel beam         | BTN_PNRA_T3  | 17    | 74.690151   | 164.104449  |

PNRA transects were georeferenced by recording geographic coordinates of the start, mid and end markers of each transect using a couple of GNSS receivers and antennas (Leica GS10 and Leica AS10, respectively) connected to a base station (Mario Zucchelli Station 3; used as station for topographic surveys), in a Real-Time Kinematics (RTK) mode

### Table 3

Features of the different cameras used in the video surveys

| Field team   | NIWA            | PNRA            | NZ/Korea  |
|--------------|-----------------|-----------------|-----------|
| Year         | 2006            | 2015            | 2017      |
| Camera model | Sony HVR-HD1000E| Sony Handycam HDR-HC7 | Sony A7s II |
| Image resolution (pixel) | 1920×1080 | 1888×1062 | 1920×1080 |
| Frame rate (fps) | 25            | 25              | 50        |
| Pixel size   | 3.3×3.3 μm      | 2.6×2.6 μm      | 18×18 μm  |
| Focal length | 4.5 mm          | 7.5 mm          | 16 mm     |
For the frame selection, only the best and most significant frames were retained and used as input to the photogrammetric workflow. The selection procedure is based on the approach described in Nocerino et al. (2017). The frames are firstly selected according to their quality, so that those not sufficiently sharp and affected by motion blur are delimited as in silico operations, ending with the final outputs of these elaborations and their possible use for geospatial and statistical analyses (in red boxes, as potential application of the obtained dataset). Boxes’ shapes are derived from flow chart symbols. (Color figure online)
under the https://doi.org/10.1594/PANGAEA.895098.

Photogrammetric procedures

The 3D reconstruction of the seafloor transects was performed by using the photogrammetric procedure provided by the software Agisoft PhotoScan Professional (v1.2.6) (Fig. 2), which has proven to be a valuable tool in different applications (Verhoeven et al. 2012; Westoby et al. 2012; Burns et al. 2016). Thanks to this user-friendly software, it is possible to obtain 3D meshes (and related mesh textures and orthoimages) of complex scenes or objects in an automatic way, starting from multiple images of the scene or object (Verhoeven 2011). The standard workflow for image processing comprised the following steps:

1. **Structure from motion (SfM):** image features are automatically extracted and matched across the images. These features, known as tie points, are used to compute the image positions and orientation as well as the camera calibration parameters. The result of this step is a sparse digital representation of the scene, i.e. a sparse point cloud made up of 3D tie points.

2. **Dense image matching (DIM) or multi-view stereo (MVS):** once the position and orientation of the images are calculated, a pixel in one image can be matched with the homologous pixel in the other images. The approach usually finds correspondences between ‘couple’ of images (stereo correspondence) and then performs regularisation in the object space. A dense point cloud, reproducing the scene with high details, is the output of this step.

3. **Mesh generation:** by interpolating the dense points generated by the DIM step as vertices of the three-dimensional mesh, the model surface is reconstructed.

4. **Mesh texturing:** this step allows the projection of the colour information from the images to the mesh geometry, providing a high-resolution texture.

5. **Orthophotomosaic:** a photographic 2D representation based on an orthographic projection is built by removing perspective distortions from the photographs (i.e. image scale varying with distance to the object) using the generated 3D model.

The main photogrammetric terms used are defined in Table 4; the terminology and definitions are mainly derived from Granshaw (2016).

Model accuracy assessment

Model accuracy is defined as “the closeness of the result of a measurement to the true value” (Granshaw 2016) and can be evaluated in terms of Length Measurement Error (LME), which represents the difference between the photogrammetrically measured length values of scale bars and their reference length values (Luhmann 2010; Luhmann et al. 2013). It depends on a variety of factors, including video quality and resolution, camera network, stability of the camera interior parameters, but also the number and features of objects used as reference for the model’s scale. Due to the presence of the transect metric tape that the divers followed while recording video, it was possible to recognise in the frames’ sequences a number of segments in which the metric tape was well visible and outstretched and hence the scale marks were unambiguously distinguishable. Within these segments, three couples of control points, distant 10 cm to each other, served as known distances to set the model’s scale (i.e. as scale bars). In few cases, we had to adapt this general procedure to the availability of well visible control points on reference known distances. Hence, in few cases for the BTN_PNRA_T1 and BTN_PNRA_T2 models the adopted scale bar was 20 cm (see Table 6 of Results).

Geospatial procedures

The generated orthoimages were imported into the GIS platform where they were finally georeferenced by using a zero-order polynomial transformation with a shift tool in ArcGIS® software by Esri (v10.5). The zero-order polynomial transformation process involves identifying a few number (also just a unique point) of ground control points with known x–y coordinates that link points on the raster dataset with points in the spatially referenced data. Control points are locations that can be accurately identified on the raster dataset and in real-world coordinates. In 2006, control points were represented by the starting points of transects; in this case, no fixed markers were deployed on the sea floor. Conversely, in 2015, heavy markers (i.e. stainless steel stakes, steel beams and concrete blocks) were fixed to the seafloor as permanent markers in order to fix the transect path. Coordinates of these markers are reported in Table 2. Thanks to this procedure, two of these transects (BTN_PNRA_T1 and BTN_PNRA_T2) were revisited after two years, in 2017, and the exact same path was able to be videoed. In order to compare the same area, it was necessary to consider only the surface corresponding to the overlapping portions of the orthophotos generated...
from 3D models (Fig. 3). This elaboration was carried out in QGIS Geographic Information System (Open Source Geospatial Foundation Project. https://qgis.osgeo.org, v2.14.15-Essen) by using the vector layers intersection procedure. Once georeferenced, rasters were analysed in order to obtain distributional and abundances data of the main benthic epifauna organisms, clearly visible and recognisable in the orthoimages. For each taxa on every transect, a new vector layer was created to record the coordinates of each single specimen, thus obtaining a point pattern layer (Fig. 3, yellow and red dots, see figure legend for details). In the case of sessile megabenthic species (such as large sponges), coordinates have also been separately recorded in order to identify single specimens and monitor them through years.

**Volume estimation**

In order to obtain a first indicative estimation of the volume of two specimens of *Mycale (Oxymycale) acerata* Kirkpatrick, 1907, clearly visible in 2015 and totally absent in 2017, we tested one of the possible approaches for estimating the volume of the 3D mesh portion corresponding to the specimen, thus obtaining informative data about volume loss after 2 years. In this approach, the portion of the 2015 model corresponding to each specimen of *M. acerata* was manually contoured and isolated from the rest of the model. Then, after filling holes in the mesh, we estimated the volume of the sponge 3D model using the measure volume tool in Photoscan Pro.

### Table 4 The main photogrammetric terms used as defined in Granshaw (2016), except * (definition derived from Luhmann et al. 2013) and ** (definition from Agisoft Photoscan Pro v.1.2 manual, retrievable from: www.agisoft.com/pdf/photoscan-pro_1_2_en.pdf)

| Term And/Or abbreviation | Definition |
|---------------------------|------------|
| Accuracy                  | The closeness of the result of a measurement, calculation or process to the true, intended or standard value |
| Camera calibration        | Determination of the inner (interior) orientation and lens distortion parameters of a camera |
| Control point             | Point with known, directly measured or surveyed coordinates which enables spatial referencing and adjustment of photogrammetric work |
| Dense point cloud         | Point cloud with a huge number of close X, Y, Z data points |
| Digital surface model (DSM)| Refers to uppermost surface both of topography and features (buildings, vegetation, etc.) as seen on an aerial/satellite image or first-return pulse from a laser scanner |
| Feature extraction        | Object detection and recognition |
| Ground Sample Distance (GSD) | In aerial- or satellite-borne digital imagery, GSD represents the pixel size expressed in ground (object space) units by reference to the image scale |
| Image matching            | Important procedures for identifying corresponding (homologous, conjugate) features in two or more stereo-images |
| Length Measurement Error (LME)* | Difference between a measured (displayed) length \( L_m \) and the calibrated reference length \( L_r \): \( \text{LME} = L_m - L_r \) |
| Mesh                      | Wireframe model, see also TIN |
| Multiview Stereo (MVS)    | Three or more images covering each part of an object, often using convergent imagery and SfM |
| Orthoimage (also orthophoto or orthophotomosaic) | Differentially rectified image (perspective transformation to an orthographic one), correcting for most distortions including photo tilt and ground relief, though residual distortion (e.g. from buildings) may remain |
| Overlap                   | Areas common to two or more images |
| Photogrammetry            | Deriving accurate and reliable 3D measurements from images |
| Point cloud               | Large number of X, Y, Z data points produced by laser scanning or dense image matching. Can be converted to a TIN (mesh) by Delaunay triangulation to form a DSM |
| Real-time kinematic (RTK) | GNSS method that uses reference base station(s) to provide real-time (simultaneous) corrections to rovers (or receivers) |
| RMS reprojection error**  | Root mean square reprojection error averaged over all tie points on all images |
| Structure from motion (SfM) | Solves the camera self-calibration and scene geometry simultaneously and automatically, using image matching and a highly redundant bundle adjustment. Determines 3D coordinates (structure) by the motion of the camera to several (multiview) positions around an object |
| Tie Point                 | Point common to two or more stereoscopic pairs of photographs within the overlap of adjacent strips of photography, used to establish connections between strips in block triangulation |
| TIN                       | Triangulated (triangular) irregular network |
Results

Photogrammetric 3D reconstructions

The 3D model reconstruction process was carried out on the three sets of video-transects (NZ, KO and Italian) that, despite being recorded in different years (2006, 2015 and 2017), showed comparable features (Table 5): (i) video duration ranged from a minimum duration of 2 min and 13 s in 2006 (transect TBS_NIWA_T3) to a maximum duration of 5 min and 12 s in 2017 (transect BTN_PNRA_T1); (ii) swimming velocity approximately 0.15 m/s in the three sets; (iii) distance from the bottom was about 1 m; (iv) length of the transects was comprised between ~ 16 and ~ 23 m (transect BTN_PNRA_T2 and transect TBS_NIWA_T3, respectively). From each video, the number of selected frames for photogrammetry ranged from ~ 4 to ~ 22% of the total number of extracted frames (Table 5).

Taken together, the six models generated from the 2006 and 2015 transects cover a total area of ~ 200 m² (Table 5) of the seafloor of southern Tethys Bay, at depths ranging from 17 to 23 m (see Table 1 for single transect locations). Overall, the models enabled the recognition of benthic epifauna organisms, dominated by the presence of the sea urchin Sterechinus neumayeri (Meissner, 1900), sea stars of the genus Odontaster Verrill, 1880, ophiuroids (e.g. Ophionotus victoriae Bell, 1902) and sponges (e.g. M. acerata). A view of one of the 3D models (TBS_NIWA_T2) is shown as example in Fig. 4. Some highlights referring to a M. acerata specimen (BTN_PNRA_T1_Myc 1) are available at the Italian National Antarctic Museum (MNA) page on Sketchfab© 3D models repository for Cultural Heritage (https://skfb.ly/6B7N7 and https://skfb.ly/6BtvY). In the 3D models, the average Ground Sampling Distance (GSD) was about 0.7 mm, with a RMS reprojection error varying from 0.5 to 1.4 pixels (see Table 4 for variable definition and Table 5 for measurements). Finally, the model’s accuracy, estimated as Length Measurement Error (LME) varied considerably (measurements in Table 6), consistently with videos features and model RMS reprojection error. The mean LME of 1.9 mm is an order of magnitude lower than the size of the macro species documented along the transects and considered for the abundances estimation, all larger than 10 mm. The resultant orthophotos were imported as raster in QGIS and used for further spatial analyses (Fig. 3), that can include a variety of possible application (Fig. 5).

A more technical description of photogrammetric features of the models and further details about related measurement and errors is available in Piazza et al. (2018). A fully quantitative analysis of spatial patterns of different species and simulation of the best sampling designs will be provided in a separate paper (Piazza et al. in prep).

Validation of the technique: analysis of 2006 legacy data and 2015–2017 comparison

Data pertaining the NIWA transects videoed in 2006 (not revisited in the following surveys) are reported in Table 7.
This dataset highlights a marked dominance of *S. neumayeri* specimens (up to 58 ind/m²), followed in terms of abundance by *Odontaster* sp. specimens (about 4 ind/m²). A few specimens of *Adamussium colbecki* (Smith 1902) were present in the area in 2006 (from 2 to 10 ind. for the entire transects’ length).

In the 2015 site “Zecca” transects, species composition and abundances were similar to those noted at the site of the 2006 transects (Table 7). However, a remarkable reduction of *A. colbecki*, once abundant in the past at “Zecca” (Schiaparelli, pers. comm., Online Resource 1), was evident. Preliminary comparisons between the 2015 and 2017 “Zecca” transects revealed a high dynamism in some species, with notable shifts in echinoderm and sponge populations. In particular, we found (i) a variation in the total number of *S. neumayeri* specimens, which increased in 2017 of 25 and 49% in transect BTN_PNRA_T1 and T2, respectively (Table 7); (ii) the complete disappearance of two massive specimens of *M. acerata* (BTN_PNRA_T1_Myc2 and BTN_PNRA_T2_Myc1) after 2 years, corresponding to an estimated total volume loss of 0.035 m³ (Fig. 6; Table 8). Another *M. acerata* specimen (BTN_PNRA_T1_Myc 1) was present in both the temporal replicates of transect BTN_PNRA_T1 but, due to the incompleteness of the 2015 model in the portion corresponding to the sponge body, we were not able to estimate the volume variation. This specimen was adequately videoed only in 2017 (links to on line resources are given in the previous section) and its estimated volume corresponded to 0.023 m³.

### Discussion

Long-term monitoring programmes must focus on time- and cost-efficient methods when working in locations subjected to harsh environmental conditions, such as in polar areas. When sampling is at sea and the research targets benthic organisms living in shallow nearis- rocky-bottom areas, SCUBA activities have traditionally been the elective method, even in Antarctica (e.g. Brueggeman 2003; Dayton et al. 1969,1970; Gruzov and Pushkin 1970). Here coastal seawater temperatures are as low as − 1.92 °C for much of

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**Table 5  Videos and derived 3D models’ features**

| Field team | NIWA | PNRA | NZ/Korea |
|------------|------|------|----------|
| **Year**   |      |      |          |
| 2006       | TBS_NIWA_T1 | BTN_PNRA_T1 | BTN_PNRA_T1 |
| 2015       | TBS_NIWA_T2 | BTN_PNRA_T2 | BTN_PNRA_T2 |
| 2017       | TBS_NIWA_T3 | BTN_PNRA_T3 | BTN_PNRA_T3 |

| Video duration (min) | 02:21 | 03:10 | 02:13 | 03:47 | 04:59 | 05:00 | 5:12 | 05:07 |
|---------------------|-------|-------|-------|-------|-------|-------|------|-------|
| Total no. of frames | 3525  | 4376  | 3124  | 5678  | 7485  | 7366  | 15,600 | 15,350 |
| No. of processed frames | 778  | 892   | 582   | 694a  | 722a  | 513   | 666a  | 619a  |
| 3D model coverage area (m²) | 43  | 49.3   | 44.8   | 21.8b | 22.4b | 22   | 82.6b | 40.3b |
| Mean distance from bottom (mm) | 948 | 964    | 974    | 930   | 949   | 813   | 954   | 1170 |
| Ground Sample Distance (GSD) (mm/pixel) | 0.806 | 0.818 | 0.821 | 0.54 | 0.546 | 0.467 | 0.742 | 0.909 |
| No. of 3D tie points | 219,539 | 151,157 | 246,045 | 102,246 | 629,689 | 90,872 | 97,360 | 236,406 |
| RMS reprojection error (pixel) | 0.837 | 0.687 | 0.939 | 1.4 | 1.12 | 1.43 | 0.546 | 0.665 |

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*The corresponding sets of frames selected for photogrammetry are retrievable at the Pangaea Data Publisher for Earth & Environmental Science repository (respectively at: https://doi.pangaea.de/10.1594/PANGAEA.895054; https://doi.pangaea.de/10.1594/PANGAEA.895097; https://doi.pangaea.de/10.1594/PANGAEA.895338; https://doi.pangaea.de/10.1594/PANGAEA.895377)

*Original areas were standardised for the specimens abundance calculation by taking into account only the overlapping portions of the orthophotos obtained from the 3D model’s orthographic projection, as described in “Geospatial procedures” paragraph of “Materials and methods”
the year, thus, sampling methodologies involving SCUBA diving are obviously constrained by the shorter dive times feasible under such conditions compared to those at mid or low latitudes.

Amongst the possible benthic sampling techniques, diver-operated video-recording methods offer a variety of advantages by reducing: (i) overall time spent by divers underwater, (ii) logistical costs (i.e. no need for supporting ships or several personnel units, which are instead mandatory when ROVs are deployed), and (iii) technological requirements (i.e. essentially only a robust underwater recording system is needed). The advantages of video-based techniques are not only in the practicalities of sampling, but also in the valuable ecologically relevant information that can be obtained by applying post-recording analytical tools. At present, among all the available techniques for analysis of SCUBA-recorded video, photogrammetry is one of the more widely used techniques, as demonstrated by the ever increasing number of published papers (e.g. in coral reef studies, Burns et al. 2015a, b, 2016; Young et al. 2017).

Photogrammetric techniques provide a variety of outputs (see Fig. 2) such as, for example, (i) 2D images (i.e. orthophotos) or 3D models to be analysed with GIS tools; (ii) 3D Point Clouds to be compared in 3D model analysis software (e.g. Cloud Compare, https://www.cloudcompare.org/); (iii) 2D plots, cropped from orthophotos (Fig. 5), usable in software specifically dedicated to the elaboration of benthic images (e.g. photoQuad, Trygonis and Sini 2012;
Moreover, the combination of underwater photogrammetry with GIS-based georeferencing and the multiple geospatial analytical tools available enable the analysis and comparison of fixed seabed areas (or transects), and investigate changes in the benthos. In particular, the opportunity to register the position of single sessile specimens and hence evaluate any modification over time (e.g. in recruitment and aggregation patterns, species composition or abundances, etc.) is unprecedented and fulfils the main aim of long-term monitoring programmes. This analytical procedure (Figs. 2, 3), which would not be possible with other ‘traditional’ sampling methods (especially extractive or destructive ones), greatly expands our analytical capabilities in the understanding of benthic spatial patterns and their changes in such remote locations.

Our study also suggests the potential value and the usefulness of ‘historical’ videos to create 3D models, i.e. even those that were not originally recorded with photogrammetry in mind (Mertes et al. 2014; Bojakowski et al. 2015). In these cases, videos can be ‘rescued’ for photogrammetry and monitoring if they meet some basic requirements, such as (i) an adequate quality and definition of images; (ii) the possibility of extracting useful images with a minimum overlap of 60% between subsequent still frames (Ludvigsen et al. 2006; Drap 2012); (iii) a quasi-zenithal camera position towards the bottom; (iv) the presence of at least two markers of known size to scale the model; (v) the presence of permanent markers to find again a transect (or a fixed plot) and repeat sampling through time. This is especially true in the case of photogrammetry where 3D models can also be physically overlapped to evaluate changes. The resultant imagery can then be used to disclose remarkable ecological information about species composition, organism abundances and spatial patterns, which are often the targets of LTER-type monitoring programmes. The access to this kind of ‘historical’ data, therefore, strengthens our capability of detecting changes, since we can potentially backdate reference baselines and increase the amount of available legacy data.

In our case, since no permanent markers (e.g. stakes or concrete blocks) were deployed in the 2006 NZ transects, it would be now difficult to repeat these surveys by following the original path. Nevertheless, they are indeed important as they provide a window on the 2006 situation in terms of
Table 7  Total abundances (Tot.ab.) and densities (ind/m²) of the main vagile epifaunal taxa counted in the orthophotos of Transect BTN_PNRA_T1 and BTN_PNRA_T2 in 2015 and 2017

| Transect          | Planar area of orthophoto (m²) | Year   | Tot.ab. | Tot.ab. ind/m² | Tot.ab. | Tot.ab. ind/m² | Tot.ab. | Tot.ab. ind/m² | Tot.ab. | Tot.ab. ind/m² |
|-------------------|-------------------------------|--------|---------|----------------|---------|----------------|---------|----------------|---------|----------------|
| BTN_PNRA_T1       | 28.3                          | 2015   | 198     | 8.32           | 183     | 7.69           | 188     | 7.96           | 178     | 7.53           |
| BTN_PNRA_T2       | 23.63                         | 2017   | 13      | 0.46           | 22      | 0.78           | 4       | 0.17           | 1       | 0.04           |
| BTN_PNRA_T2       | 23.63                         | 2017   | 13      | 0.46           | 22      | 0.78           | 4       | 0.17           | 1       | 0.04           |

**Echinodermata**

| Taxa               | Tot.ab. | ind/m² | Tot.ab. | ind/m² | Tot.ab. | ind/m² | Tot.ab. | ind/m² | Tot.ab. | ind/m² | Tot.ab. | ind/m² |
|--------------------|---------|--------|---------|--------|---------|--------|---------|--------|---------|--------|---------|--------|
| Odontaster sp.     | 162     | 3.46   | 194     | 3.87   | 232     | 5.04   | 198     | 8.32   | 183     | 7.69   | 188     | 7.96   |
| Diplostemon brucei | 0       | 0      | 2       | 0.04   | 3       | 0.06   | 3       | 0.11   | 13      | 0.46   | 3       | 0.13   |
| Ophiuroidea        | 5       | 0.11   | 4       | 0.08   | 5       | 0.11   | 5       | 0.18   | 22      | 0.78   | 4       | 0.17   |
| Holothuroidea      | 1       | 0.02   | 0       | 0      | 0       | 0      | 14      | 0.49   | 12      | 0.42   | 8       | 0.34   |
| Sterechinus naumayeri | 2739  | 58.47  | 2228    | 44.5   | 1895    | 41.13  | 1601    | 56.57  | 2794    | 98.73  | 1239    | 52.43  |

**Mollusca**

| Taxa               | Tot.ab. | ind/m² | Tot.ab. | ind/m² | Tot.ab. | ind/m² | Tot.ab. | ind/m² | Tot.ab. | ind/m² | Tot.ab. | ind/m² |
|--------------------|---------|--------|---------|--------|---------|--------|---------|--------|---------|--------|---------|--------|
| Adamussium colbecki| 2       | 0.04   | 3       | 0.06   | 10      | 0.22   | 3       | 0.13   | 4       | 0.17   | 2       | 0.08   |

**Arthropoda**

| Taxa               | Tot.ab. | ind/m² | Tot.ab. | ind/m² | Tot.ab. | ind/m² | Tot.ab. | ind/m² | Tot.ab. | ind/m² | Tot.ab. | ind/m² |
|--------------------|---------|--------|---------|--------|---------|--------|---------|--------|---------|--------|---------|--------|
| Pycnogonida        | 6       | 0.13   | 0       | 0      | 0       | 0      | 1       | 0.03   | 0       | 0      | 0       | 0      |

Notes:
- Original areas were standardised for the abundance estimate by taking into account only the overlapping portions of the orthophotos obtained from the 3D models orthographic projection, as described in the Geospatial procedures paragraph of the "Materials and methods".
volumes at that site (Table 7). In the future, using georeferencing information (i.e. starting points and path directions) and the 3D models we have developed, it will probably be possible for divers to install the required permanent markers, hence allowing more repeatable monitoring also at this site. Conversely, in 2015, because georeferenced and fixed markers were in place along the established transects (i.e. starting, middle and endpoint, Table 2), it was possible to easily record new videos in 2017 and, after having defined the truly overlapping areas (Fig. 3), estimate the differences in benthic invertebrate abundances. In the near future, if more accurate scale markers specifically designed for photogrammetry are used (guaranteeing a LME less than 1 mm), the 3D models obtained will also enable accurate measurements of the sizes of single specimens, and hence allow estimates of the population structure of key benthos such as *S. neumayeri* and *A. colbecki*. Similar morphometric analyses could also be conducted on large sessile organisms, such as *M. acerata* and, by repeating measurements of selected metrics, it will be possible to accurately estimate their growth dynamics, as already shown for coral reef (Bennecke et al. 2016; Ferrari et al. 2017) and deep-sea vent megabenthic communities (Thornton et al. 2016).

Undeniably, there are some difficulties in the use of videos not initially meant for photogrammetry, related to practical aspects of video recording and image processing, such as the presence of moving objects captured in the field of view (e.g. ropes and weights of the SCUBA equipment) and/or the unavailability of specifically designed scale markers. However, ‘undesired’ items can be easily removed by adequately masking areas of interest (Fig. 7), while scale markers can be obtained from a metric tape (Fig. 8), to reach an acceptable level of accuracy (Table 6).

While a fully quantitative comparison of the two years of data is not yet available (Piazza et al. in prep.), the high dynamism of specimen abundances is clear. A first striking outcome was the disappearance of two large specimens of the sponge *M. acerata*. The ability to ‘virtually dissect’ the whole sponge bodies from the transect models, and hence estimate their volumes, allowed an estimate of the total volume lost between 2015 and 2017. From these estimated volumes, moreover, it is possible to derive the wet weight of a taken species’ organism by using a regression formula (e.g. Numanami et al. 1986). Finally, further conversions based on taxon-specific conversion factors already available in the literature (e.g. Dayton et al. 1974; Brey et al. 1988, 2010; Barthel 1995; Thatje and Mutschke 1999) could enable the generation of biomass data in terms of g Corg and kJ, and link the estimates of volume lost (or gained) from the 3D models to energy contents. The second important observation was
Fig. 7  Masking procedure allows effective cropping out of items covering the seafloor, such as moving objects, or the rope seen in figures (a) and (d). During the pre-processing phase (see Fig. 2), it is possible to adjust each frame that accidentally contains items to be removed (a) in its field of view, creating a mask (b) to be applied to all the frames involved (e). In this way, instead of the uncorrected orthoimage (d), a final one can be obtained (e) in which the obstacle disappears and the sea floor is clearly visible.

Fig. 8  Scale marker identification enables the model scale to be set, based on a number of segments (in our case, at least 3) in which the metric tape (followed by divers while recording video) was well outstretched and the scale marks were unambiguously distinguishable. Within these segments, three coupled control points, 10 cm apart, were pinpointed as extremes of the scale bars. In this example, two consecutive and coupled markers are shown: “meter10_90cm” (a) and “meter11_100cm” (b). Each marker is recognisable in at least five frames (c) and used to define the corresponding scale bar’s extreme. The scale bars are finally visible in the 3D model (d) and used to set the entire model scale.
the great reduction of *A. colbecki* at the site “Zecca”, one of the most visited sites for biological sampling in the vicinity of the Italian Base “Mario Zucchelli Station”. Here, specific conservation measures should be adopted and scientific sampling of this Vulnerable Marine Ecosystem (VME) species ([https://www.ccamlr.org/en/system/files/e-sc-xxviii-a10.pdf](https://www.ccamlr.org/en/system/files/e-sc-xxviii-a10.pdf)) avoided, in order to protect the local population, which was previously much more abundant ([Schiaparelli and Linse 2006](https://www.ccamlr.org/en/system/files/e-sc-xxviii-a10.pdf), and reference therein and Online Resource 1). Further surveys of the permanent transects at the site “Zecca” will be crucial in the future to monitor this population over time and quantify fluctuations in its abundances.

Finally, photogrammetry in Antarctica can be particularly productive due to the extreme transparency of the seawater in pre-bloom conditions (i.e. October to December in Terra Nova Bay), when the pack ice is still present and there is no advection of phytoplankton from off-shore areas. In fact, although the ice coverage represents a logistic obstacle to divers, on the other hand it ensures the best available environmental conditions for photogrammetry, by preventing light penetration into seawater and hence phytoplankton proliferation ([Lizotte 2001](https://www.ccamlr.org/en/system/files/e-sc-xxviii-a10.pdf)) as well as protection from swells. Videos obtained at this time of the year are particularly suitable for photogrammetry, as they do not require appreciable backscatter-associated adjustments during image processing. Conversely, the acquisition of videos for photogrammetry during a phytoplankton bloom should be totally avoided due to the extremely poor quality of the footage obtained. The absence of light penetration also prevents the formation of caustics, that are a challenging issue in ice-free shallow water due to the projection of light rays reflected or refracted by water surface ([Forbes et al. 2018](https://www.ccamlr.org/en/system/files/e-sc-xxviii-a10.pdf)), representing one of the main disturbances that should be removed in ice-free shallow waters’ images before to apply photogrammetric reconstruction ([Agrafiotis et al. 2018](https://www.ccamlr.org/en/system/files/e-sc-xxviii-a10.pdf)).

**Concluding comments**

High-performing image-based methodologies, such as photogrammetry, due to their non-destructive nature, have to be highly touted in monitoring activities, especially when performed in vulnerable marine ecosystems such as in the Antarctic. The Scientific Committee for Antarctic Research (SCAR) is actively promoting the creation of structured and comprehensive sets of priority targets for Antarctic ecological research ([Kennicutt et al. 2015, 2016](https://www.ccamlr.org/en/system/files/e-sc-xxviii-a10.pdf)) and the selection of appropriate ecosystem Essential Ocean Variables (eEOVs, [Constable et al. 2016](https://www.ccamlr.org/en/system/files/e-sc-xxviii-a10.pdf)). To this end, the SCAR Expert Group ANTOS (Antarctic Near-shore and Terrestrial Observing Systems, [www.scar.org/science/antos/home](https://www.scar.org/science/antos/home)) is now actively working to establish a network of “legacy sites” for long-term observations, including standard parameters and protocols for sampling.

We suggest that photogrammetry-based methods could represent one of the most powerful tools in this direction and advocate that these techniques could be widely used in long-term monitoring activities focusing on the Antarctic benthos. We also hope that a permanent repository of 3D models of Antarctic benthic communities and habitats could be established in the near future, enabling us to archive legacy information of the highest relevance for the whole scientific community.

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**Compliance with ethical standards**

**Conflict of interest** No conflicts of interest to declare.

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