

Article

Assessment of Remote Sensing Techniques Applicability for Beach Morphology Mapping: A Case Study of Hvar Island, Central Adriatic, Croatia

Marin Mićunović ^{1,*} , Sanja Faivre ¹  and Mateo Gašparović ² ¹ Department of Geography, Faculty of Science, University of Zagreb, Marulićev trg 19/II, 10000 Zagreb, Croatia; sfaivre@geog.pmf.hr² Faculty of Geodesy, University of Zagreb, Kačićeva 26, 10000 Zagreb, Croatia; mateo.gasparovic@geof.unizg.hr* Correspondence: mmicunov@geog.pmf.hr

Abstract: This study investigates the quality and accuracy of remote sensing data in beach surveys based on three different data sources covering a 10-year period (2011–2021). Orthophotos from State Geodetic Administration Geoportal and satellite imagery from Google Earth were compared with orthophotos generated from UAV using ArcGIS Pro and Drone2Map. The beach area and length of 20 beaches on the island of Hvar were measured using each data source from different years. The average deviation for beach area (−2.3 to 5.6%) and length (−1 to 2.7%) was determined (without outliers). This study confirms that linear feature measurement is more accurate than polygon-based measurement. Hence, smaller beach areas were associated with higher errors. Furthermore, it was observed that morphological complexity of the beach may also affect the measurement accuracy. This work showed that different remote sensing sources could be used for relatively accurate beach surveys, as there is no statistically significant difference between the calculated errors. However, special care should always be addressed to the definition of errors.

Keywords: beach; remote sensing; accuracy; coastal geomorphology; Google Earth; UAV; Croatia; Adriatic; Hvar



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1. Introduction

Coastal areas, and beaches in particular, are dynamic geomorphological features that are constantly changing. Natural processes, such as waves, tides, rainfalls, relative sea-level changes, combined with anthropogenic activities, lead to changes in the morphological characteristics of beaches. Some of them change rapidly, within a few hours, others slowly, over several decades [1]. Beaches make up 40% of the world's coastline, 70% of which are subject to erosion [1]. More precision is recently provided for sandy beaches revealing that 24% of them are subject to erosion, and 28% are prograding, while 48% are relatively stable [2]. Growing anthropic pressures combined with climate change and sea-level change, e.g., as in References [3–7], makes beaches today highly vulnerable features.

There are many different methods for coastal research, e.g., for coastal monitoring, vulnerability, or risk assessment [8–11]. However, all research studies need detailed, precise, and high-resolution data. In the past, beach surveys used simple measuring instruments that combined rope, strike, clinometer, and maps. For a time, lower accuracy GNSS was used for mapping and profiling beaches. Today, remote sensing techniques (satellite-and UAV-based) are most commonly used and generally combined with GNSS field measurements. In the last decade, remote sensing data have become readily available and have better spatial and temporal resolution, so the number of papers using a remote sensing methods constantly increase (Figure 1).

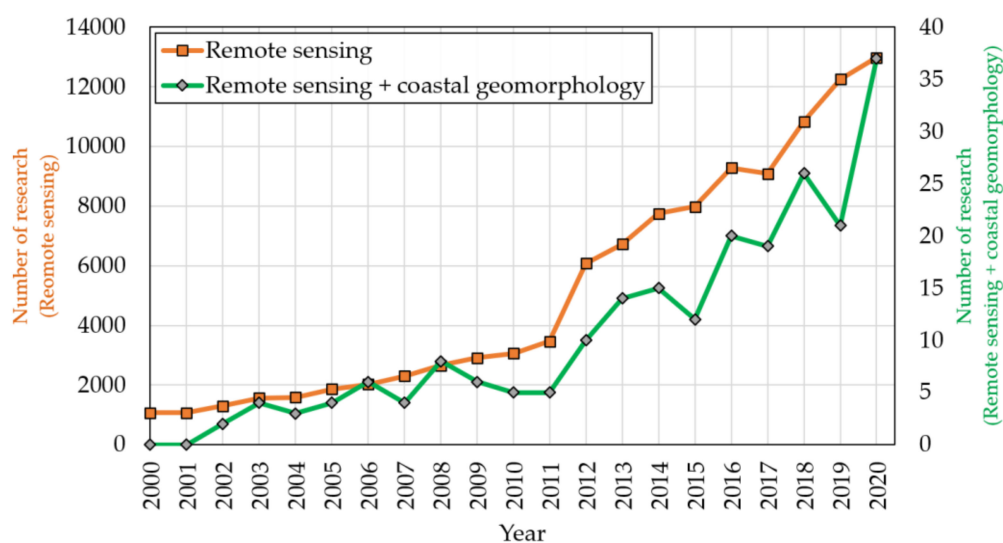


Figure 1. The number of WoSCC research articles focused on the “Remote sensing” and “Remote sensing” + “coastal geomorphology” topics per year in the last 20 years.

This study provides a brief overview of remote sensing techniques in geomorphology, particularly coastal geomorphology, i.e., beach surveys. This study aims to investigate the quality and accuracy of satellite and aerial photo data in beach surveys. This is effectuated through the systematic measurements of the size and length of 20 gravel pocket beaches on Hvar Island from different satellite images and aerial photographs (orthophotos) versus recent UAV-based measurements through the definition of its average errors. Measurements were effectuated on sources covering a 10-year period with the aim to provide an averaged beach size and length database representing the reference point for further decadal analyses of morphological changes of beaches.

2. Remote Sensing Techniques in Geomorphological Investigations

An important task in geomorphology is to document and analyze landform change. Direct observations can be done for a short period of time and limited areas, while different remote sensing techniques are available for longer time scales. Aerial photography and satellite images today provide an important means of monitoring landforms. This is particularly applicable to features which are in constant change. Likewise, unconsolidated sediments form a beach body that could be subject to frequent geomorphic activity, so significant changes in form may occur.

Remote sensing is applicable to many different types of geomorphological studies: fluvial, e.g., as in References [12,13], karst, e.g., as in References [14,15], glacial, e.g., as in Reference [16], and particularly in coastal geomorphology, e.g., as in References [17,18]. Figure 1 shows a number of Web of sciences core collection (WoSCC) research articles in last 20 years for topics of “Remote sensing” and topic of “Remote sensing” + “coastal geomorphology”. The figure shows trends in research on the topics. It can be easily showed that, although the number of articles of “Remote sensing” + “coastal geomorphology” is significantly smaller that “Remote sensing” articles, the trends are quite similar.

2.1. Satellite Images

The development of satellite imagery is accompanied by its increase in resolution and quality. Consequently, data from the early days could only be used at small scales, while today’s imagery reaches a resolution of less than 0.5 m. Moreover, satellite images have a limitation in small scale measurements considering that they are taken from higher altitudes [19].

Satellite imagery has tremendous advantages, for example, in the study of vast or difficult-to-access areas, such as aeolian landforms [20] or glacial processes [21]. Even

though rapid development, increasing global coverage, and many free or relatively cheap data allow easier and more frequent investigations, they could not replace traditional geomorphological fieldwork. Typically, the highest resolution satellite is not precise enough to determine geomorphological changes at small scales, requiring more advanced techniques or fieldwork at local scales [22].

Satellite imagery provides detailed multispectral features and allows advanced geomorphological analyses. The most common research is related to geomorphological mapping, i.e., distribution of geomorphological features and recognition of processes [23,24]. However, other processes, such as anthropogenic impacts that reflect morphological changes, are also often studied. One of such widespread influences relates, e.g., to studies of land cover changes [25–29]. In addition, multispectral features are often used to study hazards, e.g., floods [30], or forest fires, e.g., as in Reference [31]. Furthermore, reforestation, which usually occurs after deagrization, thus, could have an impact on reducing gullying processes influencing beach erosion [32,33].

Today, thanks to the precise and high spatial resolution of satellite images, digital elevation models (DEM) and digital surface models (DSM) can be extracted in high resolution, which is revealed to be important in geomorphological analyses. Some studies resulted in relatively accurate models from e.g., WorldView 2–3 [34,35].

2.2. Unmanned Aerial Vehicle (UAV)

At the beginning of the 21st century, an unmanned aerial vehicle (UAV), also called a Remotely Piloted Aircraft System (RPAS) or drone, became one of the most commonly used methods in geosciences because of its affordability, ease of use, high spatial resolution, and image quality. The UAV is usually used on a local scale. For larger areas, it is better to combine satellite data or available data from other airborne systems, such as aircraft. The acquisition of images by UAVs can be automatic, meaning that the mission is planned in advance by the software, or it can be carried out directly by the pilot. The collected georeferenced images are usually processed using photogrammetric techniques, resulting in orthophotos, DEM, DSM, or point clouds. Low altitude UAV data collection provides very high spatial resolution from 0.01 m to 0.1 m.

UAV provides a fast and efficient survey that is suitable for geomorphological surveys. It can provide a multitemporal comparison for the studies of short-term landform change. Its disadvantage relates to spatial and temporal limitations. Depending on the drone's battery, it lasts about 20–30 min on average; on the other hand, the distance is limited to ~2 km on average due to the signal quality. It provides repeated surveys with high-resolution products that can monitor a wide range of geomorphic processes [36]. Consequently, one of the fastest-growing applications of UAVs is right in geomorphology [37]. Compared to satellite imagery, UAV offers even higher quality and resolution, making it applicable at a smaller scale; however, it requires fieldwork. It has been used for geomorphological mapping [38], karst surveys [39], analyses of river flows [40], and many others. Often, authors combine satellite imagery, UAVs, or other remote sensing techniques to obtain more accurate and higher quality data.

2.3. Investigations of Beach Morphology

Beach surveys and techniques can be direct or indirect [41]. Direct methods and techniques refer to in situ measurements using GNSS or topographic measurements [32,33,42] and indirect referring to remote sensing data from satellites and aerial photographs [43,44]. Prior to remote sensing capabilities, a standard technique in beach surveys related to terrain profiling and evolved through echo sounders [45]. Today, a huge database of satellite imagery of relatively high quality, covering a longer period of time and a large spatial coverage, has influenced a rapidly growing number of beach surveys (Figure 1). The availability and simplicity of UAVs have also contributed to the growing number of beach surveys. Table 1 shows some recent papers that applied remote sensing techniques to beach surveys. Using different data sources, they obtain models with very high resolution

from 2 m to less than 0.01 m. It can be seen that UAV models provide slightly better resolution (<0.1). Satellite images, especially those from the last century, have low resolution up to 80 m, while recent ones have much better, even high, resolution. Moreover, recent investigations [46] obtained the resolution of 0.5 m from automated extraction of coastlines (WorldView satellite). According to the listed data, remote sensing techniques have proven to be time-saving and useful methods for various beach surveys.

Table 1. Review of papers where remote sensing was used in the studies of shoreline change and beach investigations.

Reference	Location	Focus of the Study	Remote Sensing	Accuracy (m)
Adebisi et al., 2021	Malaysia	Shoreline	Satellite imagery	10–30
Alexandrakis and Poulos, 2014	Greece, 18 beaches	Beach slope and width	Aerial photographs and satellite imagery	0.5
Amaro et al., 2014	Brasil, Ponta Negra	Beach dune system and shoreline	Satellite imagery	0.6–80
Casella et al., 2016	Italy, Liguria region	Shoreline and volume	UAV Mikrokopter Okto XL—extra camera	0.095
Casella et al., 2020	Germany, Wadden sea, Sylt island	Shoreline and volume	UAV DJI Phantom 2—different cameras	0.01–0.04
Domazetović et al., 2021	Croatia, Iž-Rava island group	Shoreline	Satellite imagery and UAV DJI Matrice 600 Pro	0.01–0.5
Escudero et al., 2019	Mexico, Isla del Carmen	Shoreline (spit)	Aerial photographs and satellite imagery	0.5–2
Lafon et al., 2004	France, Arcachon bay	Beach dune system and shoreline	Satellite imagery	20
Laporte-Fauret et al., 2019	France, Truc Vert	Beach dune system	UAV DJI Phantom 2 and 4 + GoPro4	0.1
Liu et al., 2012	China, Yellow river delta	Shoreline	Satellite imagery	30–80
Ružić et al., 2019	Croatia, Island of Krk	Shoreline, beach and cliff	Digital ortho-photo (Croatian State Geodetic Administration)	0.5
Ružić et al., 2021	Croatia, Island of Krk	Shoreline, beach, and cliff	UAV DJI Phantom 4 Pro	0.0326
Shaw et al., 2019	Australia, Safety bay (Perth)	Beach area and shoreline	UAV DJI Phantom 4, Matrice 200, Matrice 600, Riegl Mini VUX LiDAR	0.001–0.1
Specht et al., 2020	Poland, Sopot	Shoreline	Satellite imagery	<1
Splinter et al., 2018	Australia, Sydney	Beach dune system and shoreline	LiDAR, UAV, Satellite imagery, and fixed camera	0.01–2
Tatui et al., 2019	Black sea	Shoreline	Satellite imagery	0.6
Topouzelis et al., 2017	Greece, Lesvos	Beach dune system	UAV Iris + Canon camera	0.0234
Warnasuria et al., 2018	Sri Lanka, Jaffna Peninsula	Shoreline	Satellite imagery	0.3–2
Yoo et al., 2016	South Korea, Songjung	Shoreline	UAV DJI	0.004
Zanutta et al., 2020	Italy, Ravenna	Shoreline	UAV DJI Matrice 600 and Spark	0.027–0.043

Since a beach is a very dynamic form, it responds to changes caused by waves, storms, tides, and to anthropogenic influences. The erosion or deposition of beach material is monitored and studied through remote sensing techniques all around the world. Satellite remote sensing allows long-term studies of beach morphology changes, while UAVs are better suited for short-term changes, such as changes inferred from an intense event. In general, the majority of beach surveys using UAVs focus on multitemporal studies [41].

Satellite and multispectral imagery have been used for various studies related to beaches: their development [47–49], morphodynamics [50–52], vulnerability [53], or, e.g., beach erosion, on a larger scale [54–58]. In recent years, the use of UAV has become one of the most commonly used methods for monitoring [17,59] or short-term morphological

alteration [43,60]. UAV is also combined with archival maps and photographs to detect beach evolution [61]. Data collected by UAV are processed with photogrammetric techniques to obtain DEM, DSM, orthophoto, and point cloud. In addition, the data are also used for multispectral analysis, depending on the specification of the UAV camera.

The number of beach surveys along the Croatian Eastern Adriatic Coast has increased in the last decade. Accordingly, a research methodology is being developed from surveys being conducted by direct in situ measurements in the field, using GNSS receivers, handheld cameras, and usually in combination with other methods (e.g., repeat photography) [32,33,42,62], towards the use of photogrammetric SfM methods by means of a handheld camera that provide creation of high-resolution models [63,64]. Recent studies use UAV for data collection, whose images are also processed with photogrammetric techniques and result in very high-resolution models [61,65]. UAV products should significantly improve coastal and beach surveys in Croatia [10].

3. Study Area

Hvar is the longest and fourth-largest Croatian island located in Central Dalmatia along the Eastern Adriatic Coast (Figure 2). It has a particular elongated shape and is oriented in an east-west direction. The island's geology is relatively simple, consisting mostly of limestone and dolomite from the Cretaceous period, Paleogene flysch, and sporadically Quaternary deposits. At the central part of the island, the highest altitude reaches 628 m, and it gradually decreases to the east and west.

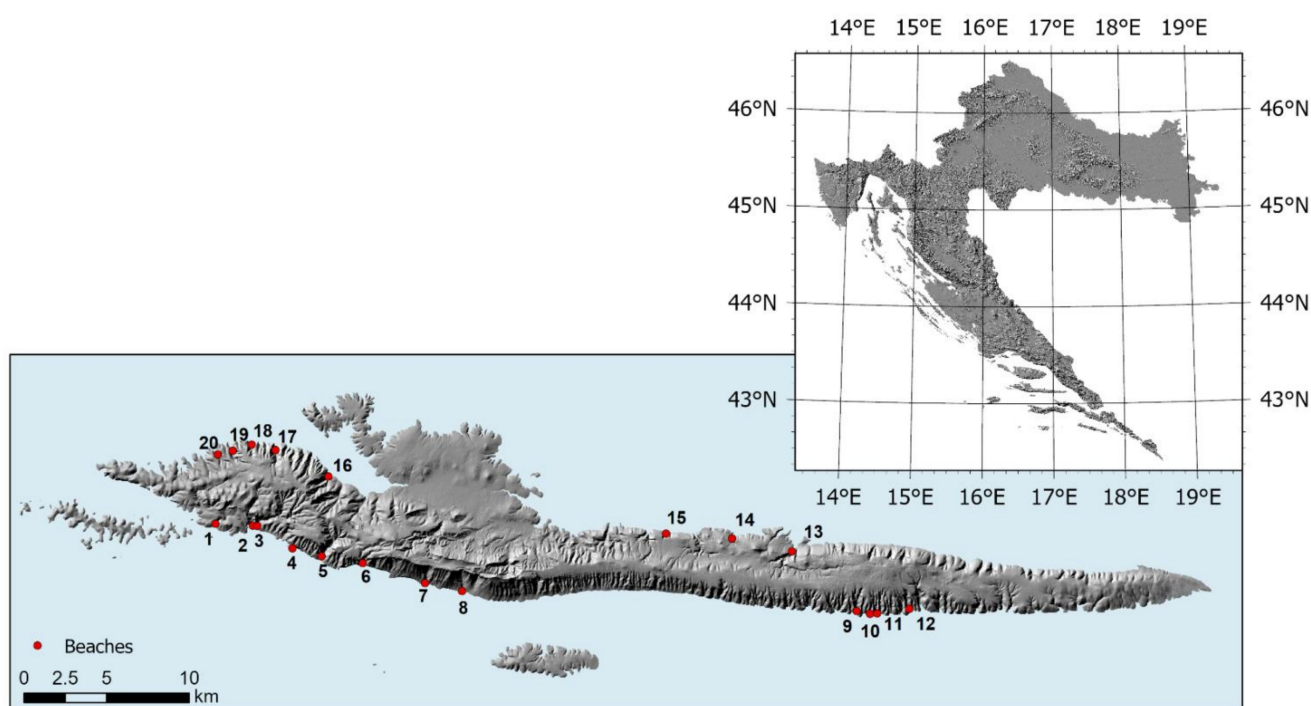


Figure 2. Island of Hvar with beach locations.

The research area includes 20 pocket beaches. Most of them are composed of gravel or pebbles. To obtain representative statistical data, we selected beaches along the entire island coast ranging from $\sim 150 \text{ m}^2$ to $\sim 1800 \text{ m}^2$ (8 on the northern side and 12 on the southern side of the island).

The island has a Mediterranean climate—Csa, with hot and sunny summers and mild, rainy winters. It is the sunniest part of Croatia, often called the sunny island, and also one of the most important touristic destinations in Dalmatia. Thus, the beaches are a very important natural resource for tourism. Today, they are also under increasing

anthropogenic pressure. These activities reinforce natural changes, such as erosion, so that beach replenishment is very often required [33,66].

The southern side of the island is affected by sirocco (south-east quadrant) winds that have the greatest impact on the coast, forming larger waves influencing short-term changes in beach morphology. The northern side is dominated by bora (north-east quadrant) wind. The current warm period led to more frequent extreme events, such as increasing precipitation extremes [67]. Such short-term rainfall events may cause important morphological changes of beaches [32].

Tides in the Adriatic are of semidiurnal type. In the Northern Adriatic, their amplitudes are higher than in the rest of the Mediterranean [4,68], which, thus, could influence beach morphology [17,59]. In the Central Adriatic, they are much lower, with an average amplitude of 25 cm [29,69–71], so they do not have an important effect on beach morphology. The influence of average tides on beach area measurements is tested on Lučiče beach (Figure 2, beach no. 6), a beach without anthropogenic influence. The beach was surveyed with a GNSS receiver and recorded with a UAV on high and low tide on the same day. The collected data were processed and analyzed. First estimation of area difference between low and high tide was around 6%.

4. Methods and Materials

4.1. Data Acquisition

To investigate the accuracy of aerial orthophotos and satellite imagery as a base for further studies of decadal changes of beach morphology, we effectuated repeated measurements of beach area and length of 20 defined beaches from different sources and years.

For data collection, we used UAV: DJI Phantom 4 Pro v.2.0 (Da-Jiang Innovations, Shenzhen, China). The drone has an RGB camera FC6310 with a resolution of 20 megapixels. The mission was not planned but was coordinated by the pilot on-site. The average flight altitude was 20–30 m, and the overlap between images was 70–80%. Flight duration averaged 15 min. During the fieldwork, about 3500 images were collected at 20 different study locations. We also used Trimble GNSS GeoxH 6000 (Trimble Navigation Limited, Sunnyvale, CA, USA) to collect ground control points (GCP), 3–8 at each beach. In the moment of collecting GCP's positions (x,y,z), GNSS receiver was connected to Croatian Positioning System (CROPOS) which obtained higher horizontal and vertical accuracy (<0,1 m). Surveying was done in accordance with Croatian laws, including registration of drones, reservation of the portal AMC—Airspace Management Cell and permits from the State Geodetic Administration. The fieldwork took place from 5 to 11 November 2020 (first part), and from 16 to 22 May 2021 (second part).

The orthophotos were created using the software Drone2Map, which is based on structure-motion algorithms (SfM). SfM is an automatic photogrammetric technique for generating orthophotos, DEM, DSM, and point clouds from overlapping images [72,73]. Even though drones provide GNSS metadata to the images, ground control points (GCP, collected by Trimble GNSS receiver) were used for better accuracy of the model. Drone2Map combines imagery from UAVs and imported GCPs that are manually merged with the imagery. Tie-points were automatically determined on all images using SfM algorithm. Photogrammetric data processing resulted in high-resolution models.

This study used historical satellite imagery from the desktop application Google Earth Pro (GE) (Google LLC, Mountain View, CA, USA). The oldest imagery covering the island of Hvar is from 1985; however, since this was almost 40 years ago, the resolution was very low, so it could not be used.

Furthermore, due to the elongated shape of the island, satellite imagery had not always covered the entire island at the same time (e.g., the western and eastern part of the island was not recoded by imagery in the same year). Consequently, we analyzed all available satellite images at Google Earth Pro, which covered the island in the same

year and had acceptable resolution (Table 2). Thus, we selected 5 generations of satellite imagery: 2013, 2016, 2018, 2019, and 2020.

Table 2. Satellite imagery and airborne orthophoto specification.

No.	Date	Source	Remote Sensing	Resolution
1	21.6.2011	Croatian State Administration	Orthophoto	0.5
2	10.6.2014	Croatian State Administration	Orthophoto	0.5
3	26.8.2017	Croatian State Administration	Orthophoto	0.5
4	17.9.2019	Croatian State Administration	Orthophoto	0.5
5	10.7.2013	CNES/Airbus	Satellite	0.5
6	11.7.2013	CNES/Airbus	Satellite	0.5
7	19.4.2016	CNES/Airbus	Satellite	0.5
8	20.4.2016	CNES/Airbus	Satellite	0.5
9	18.9.2018	Maxar Technologies	Satellite	0.5
10	3.10.2018	Maxar Technologies	Satellite	0.5
11	18.10.2018	Maxar Technologies	Satellite	0.5
12	22.3.2019	Maxar Technologies	Satellite	0.5
13	31.7.2019	Maxar Technologies	Satellite	0.5
14	29.8.2019	Maxar Technologies	Satellite	0.5
15	22.6.2021	Maxar Technologies	Satellite	0.5
16	27.4.2021	Maxar Technologies	Satellite	0.5
17	5–11.11.2020	Fieldwork—UAV	Orthophoto	0.02–0.05
18	16–22.5.2021	Fieldwork—UAV	Orthophoto	0.02–0.05

We also used orthophotos provided by the State Geodetic Administration from Geoportal (further in the text—SGA). Orthophotos have been produced from aerial photography every 2–3 years since 2011. Today, there are 4 different orthophoto generations with 0.5 m resolution (2011, 2014, 2017, and 2019). They are freely available at the Geoportal site (<https://geoportal.dgu.hr/>, accessed on 15 October 2021) and can be connected to the software GIS via Web Map Service (WMS). An example of used sources is shown in Figure 3.



Figure 3. Image quality and resolution according to different sources used: (a) Geoportal orthophoto, (b) Google Earth imagery, (c) UAV orthophoto, on the example of Dubovica beach.

4.2. Measurements and Accuracy Assessment

This study measured beach areas and lengths from three different data sources. Beach is defined as a non-vegetated sediment body (Figures 3 and 4). If vegetation was too high and masked the view, the beach boundary was approximated using the method of generalization. Some of the beaches were modified by anthropogenic activities, so the boundary was determined following constructions (walls or buildings). All beach measurements were done in the same way, manually in the scale 1:500–1:1000. We measured each beach area and lengths min 3 times and then calculated the average values.

From the orthophotos provided by the State Geodetic Administration (SGA), beaches were measured using the Area measurement tool in the Geoportal Web and connecting the Web Mapping Service with the software GIS (<https://geoportal.dgu.hr/services/dof/wms>, accessed on 15 October 2021). No important differences between the two have been observed; consequently, they are not further discussed.

From satellite images, beaches were measured in the application Google Earth Pro using the ruler tool—polygon—which has been shown to be relatively accurate for measurements at scales smaller than 1:30,000 [74].

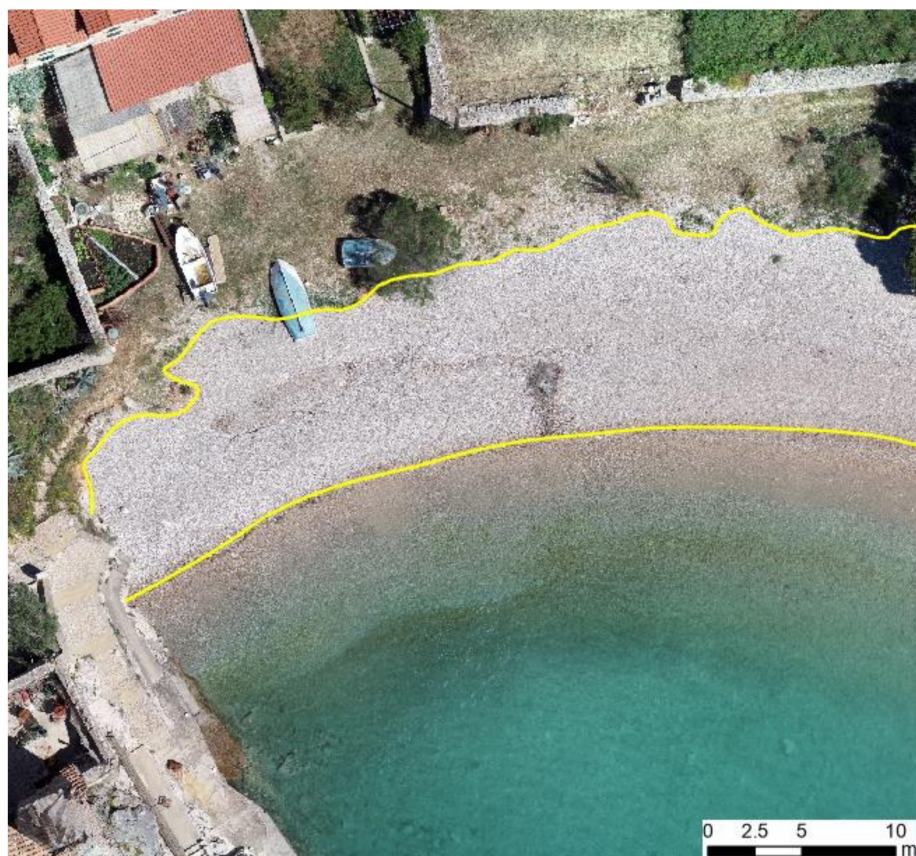


Figure 4. Example of beach boundary determination on Dubovica beach.

In addition, finally, orthophotos generated by a UAV were analyzed in GIS using ArcGIS Pro 2.7.3. software (ESRI Company, Redlands, CA, USA). The beach areas and lengths were done using the area measurement tool (Figure 3). Two sites (beaches Grabovac and Zečja) were not measured due to low image resolution (high vegetation or shade).

The average values of beach areas and lengths were calculated for each beach, based on all available sources for each year, and separately according to the sources (Geoportal and satellite images).

All measured values were examined with Shapiro-Wilk test to check if the beach areas and lengths values are normally distributed. The accuracy of the values was calculated using several statistical methods: ΔA_i —area error, which is used for RMSE calculation; and RMSE (Root Mean Square Error), which presents standard deviation of the residuals and %ERROR—percentage error.

$$\Delta A_i = A_{SGA/GE} - A_{UAV},$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n \Delta A_i^2},$$

$$\%ERROR = 100 - \left[\left(\frac{A_{SGA/GE}}{A_{UAV}} \right) 100 \right],$$

$$A_{SGA/GE} = \text{beach area measured on Geoportal/Google Earth},$$

$$A_{UAV} = \text{beach area measured on UAV}.$$

UAV, combined with GNSS, has been shown in many works to be an efficient tool for high-resolution results [17,41,75]. The spatial resolution of UAV orthophotos is the most accurate and has ten times better resolution than SGA or GE (Table 2), so it was chosen as a reference value. All measured values from GE or SGA were compared to UAV. Finally, we used Kruskal–Wallis non-parametric method to test the statistical significance (Figure 5).

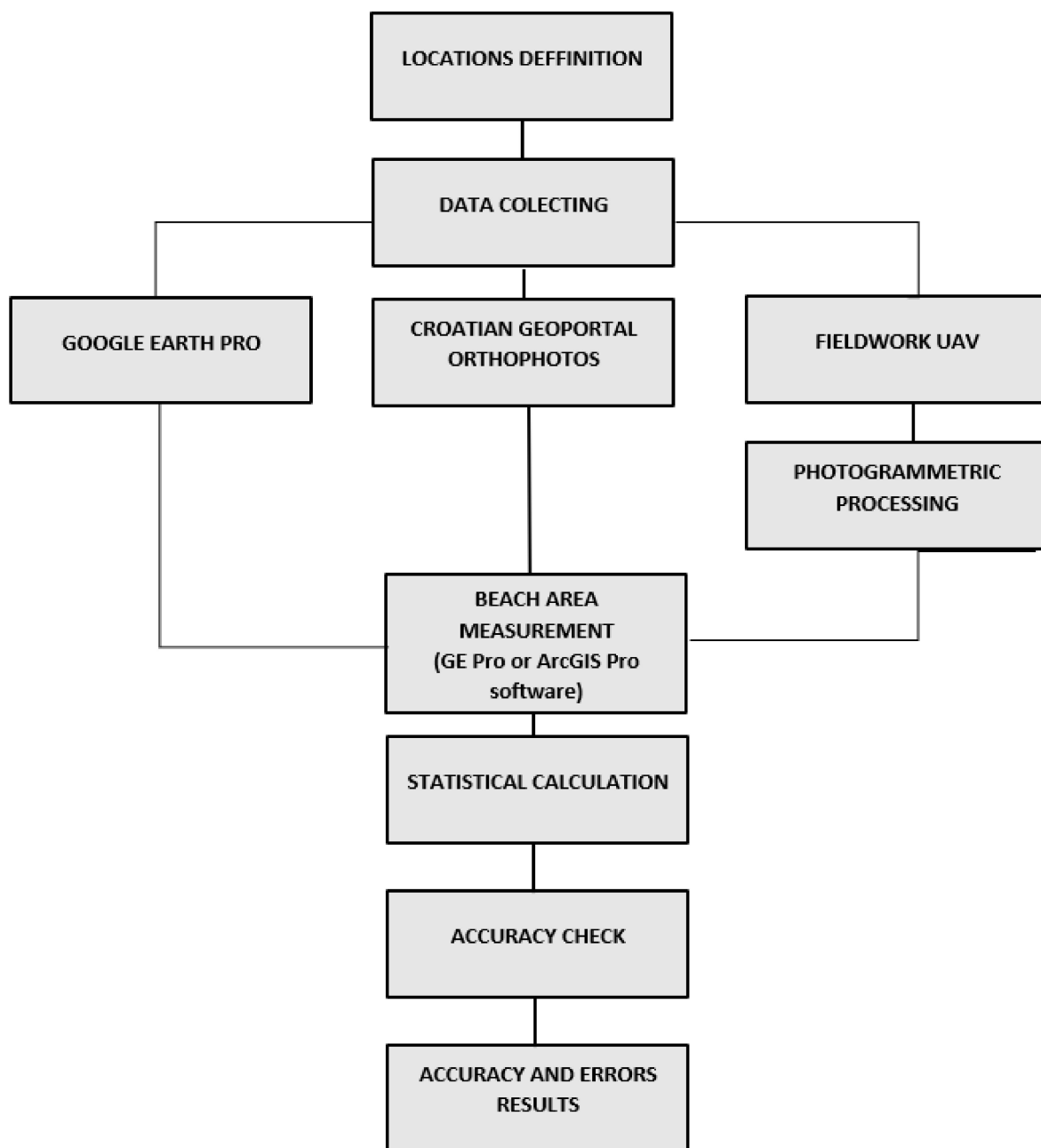


Figure 5. Research workflow.

5. Results

Measurements from three different data sources (Geoportal (SGA), Google Earth (GE), and UAV) from different years yielded 198 beach area and 200 beach length values for twenty locations, which are shown in the Figure 6.



Figure 6. Generated orthophotos from UAV for 20 locations (numbered the same as in Figure 2, Tables 3 and 5).

5.1. Beach Area

The average beach areas, obtained from Geoportal (SGA) and Google Earth (GE), are less than the UAV, with the exception of 2021GE (Table 3). In general, the beach areas measured on the Geoportal orthophoto have slightly smaller values than those measured from Google Earth (22.7 m² and 5.7 m² less than the UAV, respectively). The Geoportal (SGA) and Google Earth (GE) strongly correlate with UAV values, (r^2) ranged from 0.981 to 0.997.

In addition, the average values from Geoportal and Google Earth were compared separately with the UAV values, and a very small difference was found (SGA $r^2 = 0.971$; GE $r^2 = 0.991$).

The average values of the beach area are presented chronologically (Figure 7). It can be seen that the deviation from the reference value also changes chronologically, as shown by the trend line. In the first part of the decade, the deviations are larger, while, in the recent period, they are lower. In addition, comparing different sources (satellite—orthophoto), it was observed that values of satellite images (GE) are slightly closer to the average value than the SGA orthophoto.

The mean area of each beach measured from different sources overlap (Figure 8). Data from Table 3 and Figure 8 show that smaller beaches revealed slightly larger differences.

Table 3. Beach area values.

No	Beach Name	State Geodetic Administration (m ²)					Google Earth (m ²)					UAV (m ²)	Average (m ²)	SGA	Average (m ²)	GE	Average (m ²)	Total
		2011SGA	2014SGA	2017SGA	2019SGA	2013GE	2016GE	2018GE	2019GE	2021GE								
1	Pokonji dol	1494.46	1464.82	1492.82	1412.47	1567.58	1516.24	1564.62	1487.77	1566.4	1587.06		1466.14		1540.52		1515.42	
2	Mola Milna	779.33	796	716.11	803.92	857.35	843.27	797.01	853.66	825.29	802		773.84		835.32		807.39	
3	Vela Milna	1674.04	1699.92	1724.05	1710.87	1779.94	1813.58	1794.62	1786.19	1794.35	1828		1702.22		1793.74		1760.56	
4	Zoraće Velo	894.45	874.79	923.74	979.78	946.96	962.91	986.93	981.25	987.23	936.9		918.19		973.06		947.49	
5	Dubovica	1351.23	1325.45	1345.41	1349.12	1381.44	1385.9	1387.41	1380.05	1375.51	1343		1342.8		1382.06		1362.45	
6	Lučišće	390.94	407.56	439.37	365.1	414.81	418.05	412.93	402.26	364.82	371.3		400.74		402.57		398.71	
7	Jagodna	290.08	291.3	293.61	289.03	295.71	278.39	276.62	329.85	291.77	286.63		291.01		294.47		292.3	
8	Ivan dolac	843.84	849.57	941.43	819.21	817.08	874.68	925.48	902.39	851.49	849.93		863.51		874.22		867.51	
9	Skozanje	581.53	551.22	591.15	646.04	592.04	606.86	623.6	604.29	560.37	581.35		592.49		597.43		593.85	
10	Soca	147.26	173.65	185.73	149.63	159.55	158.71	152.64	164.38	151.28	175.9		164.07		157.31		161.87	
11	Kožja	447.68	474.71	452.4	439.39	471.52	449.85	451.41	473.72	460.61	486.04		453.55		461.42		460.73	
12	Torac	408.12	448.44	482.53	326.96	421.85	390.54	380.69	384.68	343.84	401.12		416.51		384.32		398.88	
13	Pokrivenik	1200.57	1051.75	1147.11	1036.2	1056.54	1074.18	1112.89	1074.14	1025.89	1044.47		1108.91		1068.73		1082.37	
14	Dubac	373.77	401.02	375.69	479.95	476.09	422.1	486.23	486.12	543.49	624.31		407.61		482.81		466.88	
15	Zečja	354.03	336.29	377.59	357.94	354.76	345.9	338.71	346.81	*	366.93		356.46		346.55		353.22	
16	Radočin dol	426.11	331.69	370.99	427.21	453.4	469.22	402.87	423	462.09	460.63		389		442.12		422.72	
17	Lučišće (Brusje)	1119.36	1094.5	1080.7	937.18	1031.15	1037.64	1042.82	1018.25	1038.12	1025.2		1057.94		1033.6		1042.49	
18	Grabovac	391.69	374.16	396.78	*	377.74	360.13	371.78	325.98	343.28	316.75		387.54		355.78		362.03	
19	Stiniva	801.8	810.69	786.78	813.7	777.42	789.94	794.7	857.96	826.16	807.83		803.24		809.24		806.7	
20	Sviračina	311.13	301.64	305.72	298.02	287.71	293.51	288.15	319.01	342.01	358.37		304.13		306.08		310.53	
Average		714.07	702.96	721.49	717.99	726.03	724.58	729.61	730.09	744.95	732.69		709.99		727.07		724.44	

* no data (low image resolution)

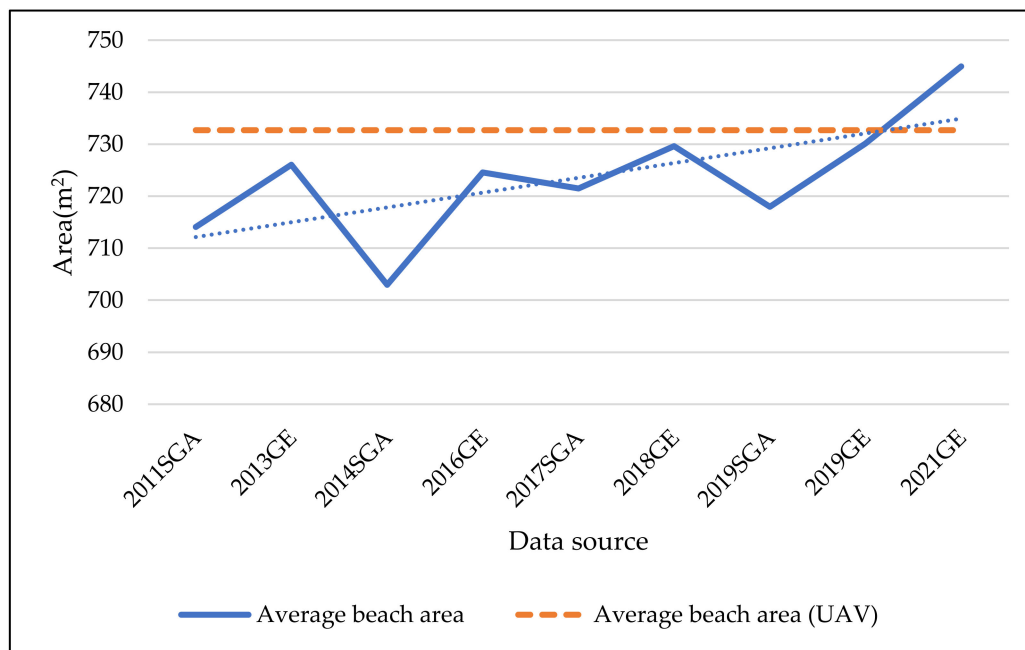


Figure 7. Average beach areas according to years and sources (2011–2021); UAV relate to 2020–2021 field measurements.

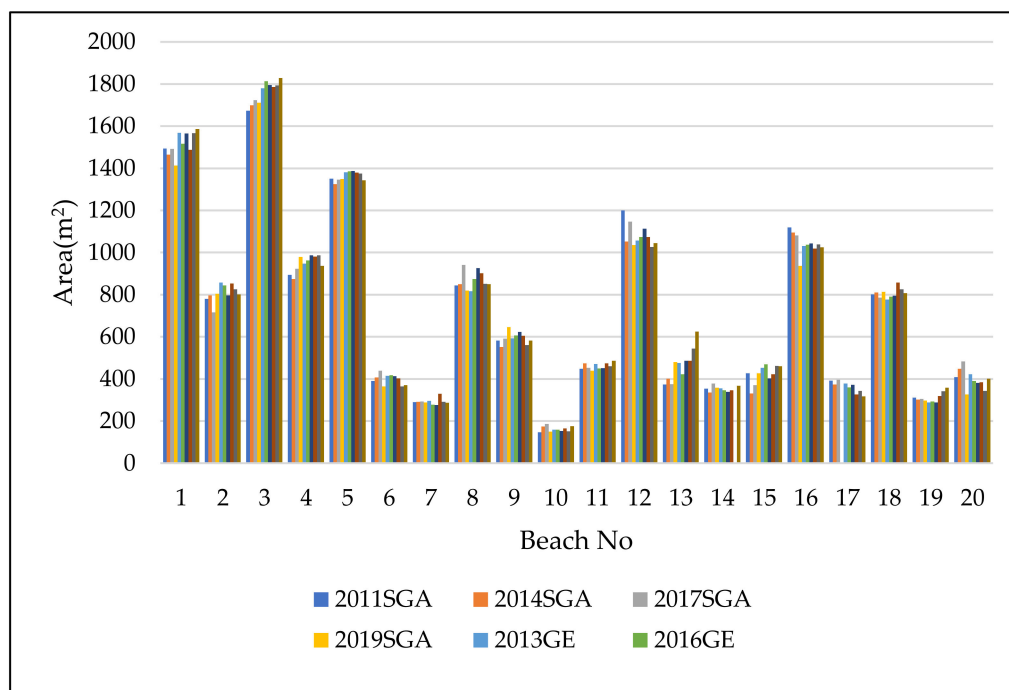


Figure 8. Beach area values (2011–2021).

As the Shapiro-Wilk test showed, the deviation from the normal distribution ($p = 0.03$) nonparametric tests were further chosen.

The accuracy error was tested first using the RMSE (Table 4). The GE2021 satellite imagery revealed the lowest error, while the SGA2011 orthophoto showed the highest. In general, Geoportal has an average error 28.08 m² higher than Google Earth. When the RMSE is ordered chronologically, the trend points downwards, which means a reduction in error over the years (approaching the present) (the newer the source the smaller the error). In addition, as can be seen in Figure 8, there is a difference between the measured areas

quality between small and large beaches. The calculated average RMSE for smaller beaches (with an area of less than 650 m²) is about 20 m² higher than the RMSE for larger beaches (Table 4).

Table 4. Beach area RMSE (Root mean square error).

Source	All Beaches (m)	Small Beaches (m)	Large Beaches (m)
2011SGA	84.46	82.41	86.90
2014SGA	77.13	84.51	67.01
2017SGA	84.10	91.34	74.29
2019SGA	70.02	61.87	78.08
2013GE	46.58	55.50	32.52
2016GE	56.36	68.83	35.61
2018GE	51.92	57.94	43.45
2019GE	50.13	49.04	51.43
2021GE	31.70	35.42	26.96
SGA average	70.57	75.44	64.13
GE average	42.49	50.07	30.79
Total average	52.61	60.48	40.99

The measurement error was also tested with the percentage error. It ranges from -4.1 to 8.1% for all measurements, and, when the outliers are removed, the result changes from -2.3% to 5.6% . The boxplot diagram (Figure 9) shows slightly larger errors for the Geoportal orthophoto measurements with errors from -6.1% to 8.5% . The 2017 measurements SGA have the largest error from -9.3% to 11.9% . The satellite image measurements show much better results. The average error ranges from -3.8% to 7.9% . The 2021 images provide the lowest error, -2.7% to 6.1% , with respect to the reference value.

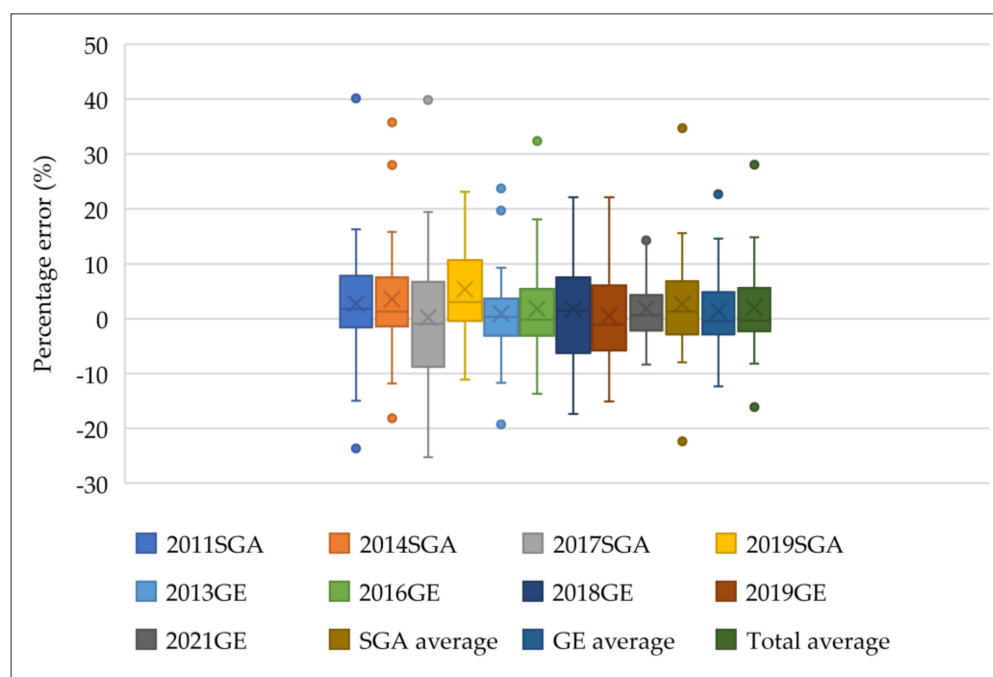


Figure 9. Beach area percentage error.

The calculated percentage errors were tested with the non-parametric Kruskal–Wallis test, which showed that there is no statistically significant difference ($p = 0.572$) between the calculated errors from the listed sources.

5.2. Beach Length

The average values of beach length show relatively similar results between the sources (Table 5). The smallest length value was measured on Jagodna beach, 17.47 m, while the longest relates to Lučišće (Brusje) beach, 127.41 m. Their average length value (UAV) is 65.24 m. SGA and GE average measurements have very similar values; they differ by only 0.24 m.

Table 5. Beach length values.

No.	Beach Name	Croatian Geoportal Orthophoto (m)				Google Earth (m)					UAV (m)	SGA Average (m)	GE Average (m)	Total Average (m)
		2011SGA	2014SGA	2017SGA	2019SGA	2013GE	2016GE	2018GE	2019GE	2021GE				
1	Pokonji dol	92.49	93.03	89.63	89.48	89.87	89.89	91.4	88.51	89.01	94.25	91.16	89.74	90.76
2	Mola Milna	47.28	48.59	47.56	46.23	46.86	48.87	48.43	48.63	48.3	49.25	47.42	48.22	48
3	Vela Milna	84.02	79.02	77.28	78.27	79.08	78.9	78.14	77.23	80.81	78.83	79.65	78.83	79.16
4	Zorače Velo	69.62	68.29	68.26	67.73	67.29	68.26	67.86	67.96	67.73	68.4	68.48	67.82	68.14
5	Dubovica	107.52	106.84	104.65	105.92	105.21	104.6	106.81	106.48	105.09	108.36	106.23	105.64	106.15
6	Lučišće	34.57	34.83	34.34	34.96	35.29	35.17	35.21	36.77	34.04	34.3	34.68	35.3	34.95
7	Jagodna	16.28	17.07	16.71	16.89	17.88	16.87	17.31	17.89	17.21	17.47	16.74	17.43	17.16
8	Ivan dolac	43.76	46.65	43.21	42.89	44.59	45.16	44.78	44.38	44.81	43.56	44.13	44.74	44.38
9	Skozanje	79.81	79.56	75.65	74.95	77.99	78.06	78.82	77.38	77.25	78.36	77.49	77.9	77.78
10	Soca	20.82	21.37	21.98	21.2	22.04	21.72	21.7	21.25	21.57	20.85	21.34	21.66	21.45
11	Kožja	57.85	56.68	56.87	57.37	58.56	59.27	58.35	57.63	57.56	57.11	57.19	58.27	57.73
12	Torac	59.9	59.13	58.91	60.09	60.73	60.32	60.21	60.53	59.95	61.34	59.51	60.35	60.11
13	Pokrivenik	87.02	90.91	90.12	90.49	92.04	91.86	89.01	91.63	91.38	93.36	89.64	91.18	90.78
14	Dubac	38.49	37.89	37.08	39.02	40.03	38.79	37.71	39.08	38.75	39.04	38.12	38.87	38.59
15	Zecja	28.4	28.14	29.1	29.04	30.08	29.35	28.95	29.42	30.1	30.18	28.67	29.58	29.28
16	Radočin dol	78.19	79.81	78.65	78.91	80.35	80.2	79.48	80.17	79.16	80.69	78.89	79.87	79.56
17	Lučišće (Brusje)	125.18	126.65	125.13	126.43	123.38	125.5	125.59	127.13	128.39	127.41	125.85	126	126.08
18	Grabovac	55.43	54.76	53.42	55.03	52.8	53.05	54.01	54.42	54.43	51.52	54.66	53.74	53.89
19	Stiniva	121.47	125.41	123.48	126.43	122.5	123.2	123.93	125.26	124.71	125.68	124.2	123.92	124.21
20	Svirčina	44.41	43.31	42.02	42.31	42.28	42.08	42.88	43.03	44.38	44.85	43.01	42.93	43.16
	Average	64.63	64.9	63.7	64.18	64.44	64.56	64.53	64.74	64.73	65.24	64.35	64.6	64.56

The lowest value is measured on the SGA2017, while the highest value relates to SGA2014. The average value of Geoportal differs by 0.89 m from the UAV, while the value of Google Earth differs by 0.65 m. Each source was compared to UAV, the reference value which revealed very strong correlation ($r^2 \geq 0.997$). All measured values overlap (Figure 10). Only some larger beaches show very small differences.

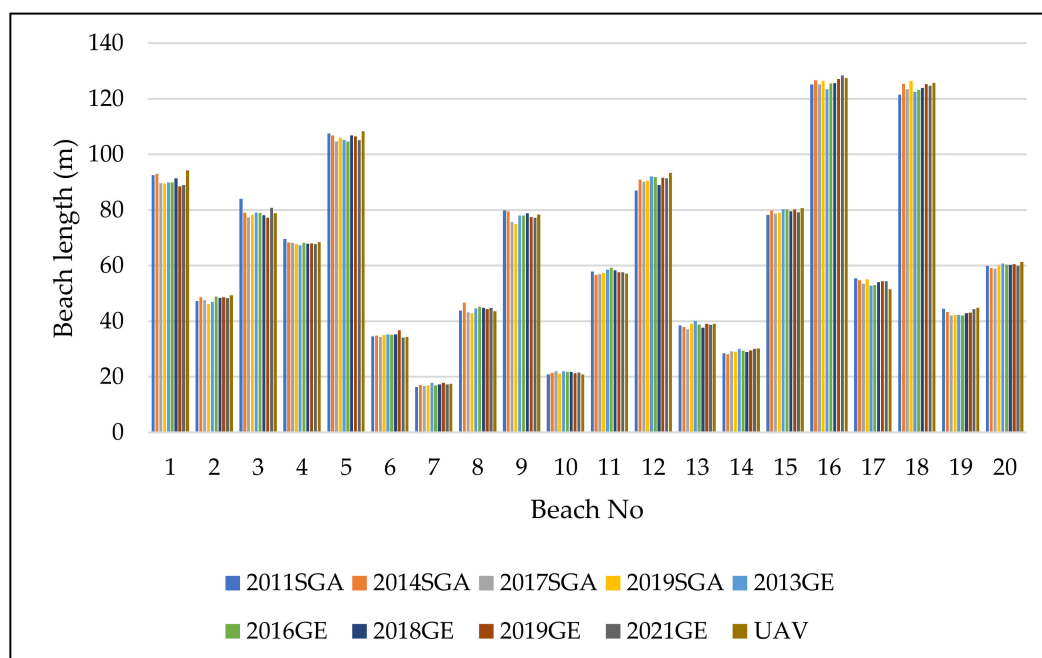


Figure 10. Beach length values (2011–2021).

These differences are tested with the RMSE (Table 6). The lowest RMSE was calculated for the SGA2014, and the highest error for the SGA2011. The average error is slightly lower for the Google Earth values than for the Geoportal values, with a very small difference of

0.1 m. However, difference in RMSE was observed according to beach size (length), 2.03, for large beaches, and 1.24 for small beaches.

Table 6. Beach length RMSE.

Source	All Beaches (m)	Small Beaches (m)	Large Beaches (m)
2011SGA	2.55	1.69	3.32
2014SGA	1.53	1.55	1.51
2017SGA	2.20	1.81	2.60
2019SGA	2.08	1.84	2.33
2013GE	2.00	1.15	2.69
2016GE	1.82	1.30	2.31
2018GE	1.71	1.33	2.08
2019GE	1.79	1.38	2.20
2021GE	1.82	1.17	2.38
SGA average	1.76	1.50	2.03
GE average	1.65	1.12	2.12
Total Average	1.65	1.25	2.03

The percentage error showed that the average deviation of SGA and GE from the UAV value was -2.35 to 2.18 . When the outliers are removed, the deviation is smaller, from -1.01 to 2.68% . The boxplot diagram (Figure 11) shows that the average deviation of beach lengths obtained from Google Earth measurements is smaller than those from Geoportal. However, the difference is very small ($< \pm 1\%$). The Kruskal–Wallis test showed that there is no statistically significant deviation ($p = 0.322$).

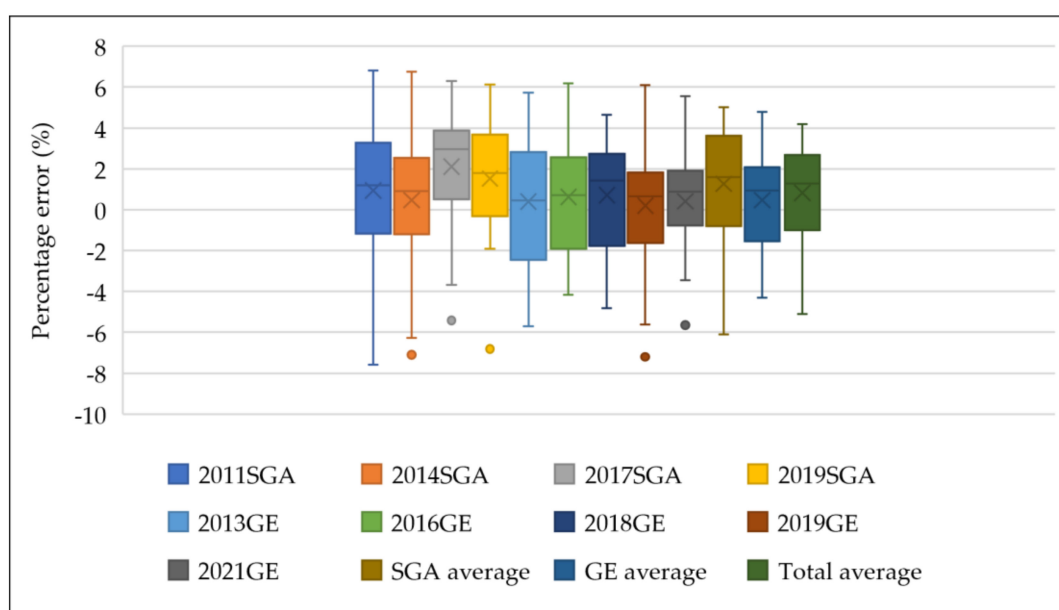


Figure 11. Beach length percentage error.

6. Discussion

This work has demonstrated that there are no significant statistical differences between values obtained from different sources. All measured beach areas and lengths have showed relatively similar values. However, there is a difference in the error range. In this study, the models generated by UAV resulted in measurements of very high resolution (0.02 – 0.05 m), while satellite imagery and available orthophotos proved to be slightly less precise (compared to UAV), with an average deviation of -4 to 8% for beach area, and -2 to 2% for beach length. Excluding the outliers, the deviation reaches -2.3 to 5.6% for beach area, and -1.01 to 2.68% for beach length, while error (RMSE) reaches 7.2% for beach

area, and 2.5% for beach length. Both, percentage error and RMSE, showed similar range of deviation. As the measurements cover in total a 10-year period, natural and anthropogenic processes [40] may also affect the obtained results.

Depending on the size of the beach, differences in measurement errors were observed. Larger beaches revealed lower errors in beach areas but higher variation in beach length measurements, while it is just the opposite in the case of small beaches. This may be related to the beach boundary definition, which is often more challenging in the case of small beaches, as approximations revealed to be more often. Even if digitizing errors are low in the case of small beaches, they represent a high percentage error.

Beach length measurement errors were revealed to be very low. In the case of length measurement, large beaches have somewhat larger errors. This may be related to more complex morphology (more curved shoreline) (Figure 12) compared to small, simple beaches.

Trend analysis of the calculated error over the 10-year period showed that the error value decreases chronologically, which may be related to the quality of satellite imagery and resolution increase through the years.

Most studies that use aerial images in geomorphology focus on linear features (e.g., shoreline change, changes of watercourses), while only a small number of them examine features as a whole. Solazzo et al. [75] studied aeolian forms and tested the accuracy of dune measurements from two different aerial images. They selected 4 different dunes with large surface areas (4000–8000 m²) and calculated a deviation of 4%, which is quite similar to the deviation of beach area measurements. Swanson et al. [76] calculated uncertainty in aerial photography measurement for river width and areas. They used digitized and georeferenced aerial images from 1985 to 2008 and found out that river width error was 2–6% for the recent data, while those from 1985 had a higher error. River area measurement error was 3–12%. The error decreases chronologically, so recent photos are most accurate. In addition, measurements on a smaller polygon, e.g., river islands, resulted in higher error than those on the larger areas. Those results could be related to Hvar Island beaches, where the calculated error is higher on small beach areas and also decreases chronologically.

Apart from geomorphological landform measurement, accuracy could also be tested using, e.g., cadastral data. Lopes and Nogueira [74] compared Google Earth satellite imagery in terms of point, line, and polygon measurements with the accurate cadastral data. They found that the values measured on linear features differ for 0.44%, while polygon measurements differ for 3.54%. The calculated errors are close to errors obtained here in the case of beach area measurement on the island of Hvar. In general, higher errors are to be expected when measuring geomorphological features than other objects due to the problem of boundary definition; consequently, some approximation is required.

Many circumstances can affect the accuracy of measurement. The accuracy of beach length measurement is very important because a low error could lead to significant discrepancies in the final results [56]. Therefore, to decrease the measurement error to a minimum, the number of measurements can be increased. Here, beach area and length measurements were done at least 3 times for each source and year. The complexity of beach morphology could affect the detection of the coastline in orthophotos [43]. For sandy beaches, the definition of coastline is usually easier, due to the simple recognition of the wet-dry boundary [17], which leads to higher measurement accuracy. Complex beaches with different sediment sizes can affect the lower measurement accuracy. In addition, vegetation, shade, or even deposited banks of seagrass species (*Posidonia*) can affect the difficulty of shoreline detection. In this case, two beaches from different sources could not be measured in our study.



Figure 12. Example of beach length measurement on (a) a small beach (Kožja) and (b) a large beach (Dubovica).

7. Conclusions

This study investigated the accuracy of remote sensing techniques in beach surveys. Several available remote sensing sources were found to be sufficiently accurate for beach measurements. A measured beach area and length values from the SGA and GE sources correlate very strongly with the UAV ($r^2 \geq 0.97$). Their calculated error for beach area (7.2%) and length (2.5%) was found to be in a different range. Although most of the beaches are small, according to UAV measurements, with the surface area ranging from 175.9 to 1828.0 m² and a length from 17.47 to 127.41 m, the calculated error is higher in the case of beaches of smaller surface areas and in the case of beaches of larger lengths.

As it is not possible to accurately distinguish the short term morphological changes from most of the data sources available, particularly from older ones, they are part of the obtained errors. The acquired geodatabase on Hvar Island beaches is crucial for further investigations of beach evolution and determination of beach vulnerability, as well as for future beach management, as Hvar Island is one of the most important touristic destination along the eastern Adriatic coast.

The results have shown that different remote sensing sources could be used for an accurate geomorphological survey of beaches, considering the calculated error. Thus, remote sensing data, which is free and readily available, may allow a spatial and temporal study of beach morphology over decades. In addition, it could be globally applied for similar investigations, not only in coastal geomorphology, but also in other scientific disciplines.

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