Precision Assessment of Artec Space Spider 3D Handheld Scanner for Quantifying Tufa Formation Dynamics on Small Limestone Plates (PLs)

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Abstract: In this paper precision assessment of the 3D handheld scanner *Artec Space Spider* was evaluated and critically observed. Namely, a new application of handheld 3D scanners has been found in quantifying tufa formation dynamic (TFD). Such measurements should be characterized by a high level of data quality because tufa usually grows only a few millimeters annually. Therefore, a small limestone plate (PL) used as a substrate on which TFD will be studied was scanned five times by two independent observers. Interval scans of PL were processed using *Artec Studio 15 Professional*. Data processing consisted of five steps. The precision assessment was determined by statistical analysis of derived sections and colored distance map (CDM). Results showed that *Artec Space Spider* generates reliable results considering the characteristics of the scanned object and it certainly can be used for TFD analysis. Also, results suggested that the application of *Artec Space Spider* in the quantification of TFD can be regarded as a better approach in the context of measurement reliability compared to other direct and indirect methods. The subject of future research will be the precision and accuracy assessment of various 3D handheld scanners in scanning tufa formed in different temporal resolutions with various surface complexity.

1 INTRODUCTION

Artec Space Spider is a non-contact active 3D handheld scanner produced by Artec 3D. This 3D scanner emits a pattern of structured light (SL) to the observed object or scene and measures its deformation (Abdel, 2011). It enables robust high-quality capture of 3D geometry and can be actively used throughout several fields (Eiríksson et al., 2016, pp, 1). Data in this type of scanner is acquired in relation to the internal coordinate system. Therefore the position of the scanner must be determined using specific reference features on the scanned surface (Abdel, 2011).

Artec Space Spider is an ultra-high-resolution 3D scanner intended for precisely capturing small objects and complex details with accuracy up to 0.05 mm (Artec 3D, 2020) and high resolution (Table 1). Due to its superior precision, long-term repeatability in data capture, and automatic temperature stabilization it has been regarded as an excellent solution for metrology applications (Motley, 2020). It combines structured light 3D scanning (blue LED) with an image-based approach (Reichert et al., 2016).

Table 1: Specifications of the *Artec Space Spider*.

Specifications	*Artec Space Spider*
3D point accuracy[1]	0.05 mm
3D resolution[2]	0.1 mm
3D accuracy over distance	0.05 + 0.3 mm/m
Working distance	0.2 – 0.3 m
Volume capture zone	2 000 cm³
Angular field of view (H*W)	30 × 21°
Texture	Yes
Texture resolution	1.3 mp
3D reconstruction rate	7.5 fps
Data acquistion speed	1 mln points/s
3D light source	Blue LED
2D light source	White 6 LED

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Datasets collected using the 3D handheld scanners, intended for specific applications, should meet certain specifications and provide the officially stated data quality standards (Georgopoulos et al., 2010, Abdel, 2011). Data quality represents the ability of a given dataset to satisfy the set objective (Campbell, Shin 2011). However, there is no general agreement on which set of dimensions defines the quality of data (Batini et al 2009, pp 6.). This term generally covers two primary attributes of accuracy and precision. It should be noted that not enough focus has been placed on precision analysis and quantitative accuracy of SL systems (Eiríksson et al., 2016, Campanelli et al., 2016).

Precision, or "repeatability" of measurement, can be defined as the internal accuracy of a device that is determined through repeated measurements under equal conditions (Hofer et al., 2005). Accuracy, which has several definitions (Batini et al 2009, pp 7), can be defined as the "nearness" of measurement to an actual or "real" value (Campbell, Shin 2011). Analyzing the data quality of the 3D handheld (SL) scanner is a challenging task, which has only seen few published standards and guidelines (Eiríksson et al., 2016). Sometimes, data quality specifications given by device producers should be taken with caution because these values vary from instrument to instrument and depend on the user's expertise and individual calibration (Abdel, 2011). Furthermore, it is not uncommon that in the official pamphlets of specific devices measured precision (formal error) is presented as accuracy (Santos et al., 2000).

Due to the high-resolution digital capture of scenes or objects at submillimeter levels of accuracy, and reduced time of data acquisition, *Artec Space Spider* and similar scanners have been used in a wide range of scientific fields and other activities from reverse engineering processes and product design (Allegra et al., 2016, Artec 3D, 2020), healthcare industry (Allegra et al., 2016, Koban et al. 2016, Modabber et al., 2016, Seminati et al., 2017, Verhulst et al., 2018, Dessery, Pallari, 2018, Ritschl et al., 2019, Özsoy et al., 2019, Varga et al., 2019, Artec 3D, 2020, Winkler, Gkantidis, 2020), forensics (Sivanandan, Liscio, 2017, Buck et al., 2018, Zhang et al., 2020), video game industry (Artec 3D, 2020), soil erosion process (Wang et al., 2019), heritage and cultural preservation (Allegra et al., 2016, Artec 3D, 2020), etc. Recently, a new potential application of handheld 3D scanners has been found in quantifying tufa formation dynamic (TFD) (Marić et al., 2020) on small limestone plates (PLs). However, this research requires the performance of interval PL scanning within a specific local coordinate system (LCS) in order to quantify and analyze spatio-temporal changes at the specific location of the PL surface (Marić, et al., 2021). Such measurements should be characterized by a high level of data quality because tufa usually grows and erodes, in most cases, only a few millimeters a year (Marić et al., 2020). Therefore, the main objective of this paper was to assess the precision of the *Artec Space Spider 3D* handheld scanner in quantifying TFD on small limestone PLs. The analysis is conducted on an artificial limestone plate (PL) that lacks tufa formation on its surface. This was done because (1) in most studies similar substrates (specific PLs) are used; (2) if you want to study TFD using a 3D scanner, then it is necessary to scan an empty PL because it represents the initial (reference) model; (3) these type of object (without formed tufa), represents the most difficult case for scanning because they have very small dimension and lacks distinctive features and color. Therefore, we wanted to test the worst possible scenario, in which, in one year of studying TFD only a tenth of a millimeter of tufa growth occurs, or tufa growth does not occur at all.

The precision assessment was done using the two approaches; (a) colored distance maps and (b) defined metrics from multiple (n=5) sections of the PLs.

The scope of this research can be interesting to the researchers who use similar 3D handheld scanners to model small objects whose properties make them difficult to scan. However, the results of the paper are primarily intended for the scientists whose primary scientific interest is TFD and are considering using 3D handheld scanners and similar PLs design for monitoring the tufa growth and erosion.

The paper was organized in the following chapters. First, the *Introduction* describes in detail the handheld 3D scanner and its applications. The possible application in the studying of TFD is mentioned. In order to determine its applicability in this type of research, it was decided to determine its precision given that the 3D point accuracy is stated in the official specifications. The *Material and Method* chapter describes in detail the data processing workflow which consisted of several steps. In the *Results and discussion*, the derived results of precision from two used approaches are presented. Then, in the *Conclusion*, the main findings of this research were highlighted, and the consideration for future research is given.

2 MATERIALS AND METHODS

The research methodology consisted of several steps that included: (1) interval (n=5) scanning of the selected PL before its immersion in the tufa-forming watercourse; (2) processing of the acquired scans, which consisted of several sub-steps that were unified for all interval scans; and (3) a precision assessment using two stated approaches (Figure 1).

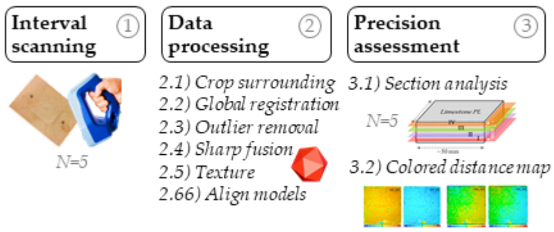

Figure 1: Simplified methodological framework.

2.1 Scanning Procedure

In order to assess the precision of the *Artec Space Spider* interval scanning of a specific limestone PL (area ≈ 25 cm²) was conducted. This type of object is the most challenging for scanning when optical 3D scanners are used. Namely, 3D scanners rely on an object's unique geometry and in this case PL lacks distinctive characteristics such as texture, features, and color. However, this type of PL is often used in TFD studies.

Scanning was done in an environment of constant light exposure. The same PL was five times scanned with *Artec Space Spider* by two independent observers, each on two separate occasions. On the surface of the PL there was no sedimented tufa because the data quality assessment needs to be determined on the smallest scanned surface within the TFD research (initial model). This refers to the first measurement, i.e reference state of the PL before it was mounted in tufa forming watercourses. PL was set on the created local coordinate system (LCS) and then measured interval, five times with *Artec Space Spider*. The LCS was used because the 3D scanner axis (X, Y, Z) is relative to the scene being scanned. Therefore, the LCS eases the adjustment of the 3D model position onto one of the coordinate planes. Each scanning took around 10-15 seconds. Distance adjustment indicator in the *Artec Studio 15 Professional* was used to determine the ideal scan distance. True localization was adjusted by either moving 3D handheld scanners farther away or closer to get the best possible quality of the scan. The scanning was performed at a speed of around 6-7 frames per second (fps).

2.2 Data Processing

Scans of interval measured PL were processed using *Artec Studio 15 Professional*, an industry-acclaimed software package for advanced 3D scanning and data processing. Geometry + Texture scanning mode was used. Segmentation of the scans did not occur during scanning. Data processing consisted of five steps. First, (1) *crop surrounding*, with rectangular selection tool was used, to delete unnecessary scanned area around the PL. Then, using the (2) *global registration* (GR) option frame positions across all scans were optimized preparing them for further processing. It converts all one-frame surfaces to a single coordinate system using the information on the mutual position of each surface pair (URL 1). Prior to the conduction of the GR, user-defined parameters (*key frame ratio* - KFR and *feature search radius* - FSR) were changed. KFR was set on 1 and FSR was set on 3 mm. KFR determines how many surfaces are treated as key frames. A higher value than 0.7 can significantly slow down the algorithm. The value of FSR was slightly lowered in relation to the default value because a small object with similar features was scanned. In each scanning frame registration quality was improved after GR (Table 2). After the GR, the maximum error values decreased to a good classification result (URL1).

Table 2: Maximum error values[1] for interval measurements after the GR.

Scan ID	*Artec Space Spider*	
	Before GR	After GR
01	0.1	0.1
02	0.2	0.1
03	0.1	0.1
04	0.2	0.1
05	0.2	0.1

[1] Error is the parameter that reflects frame registration quality. For scans, it shows the maximum value among all the frames. The larger the value, the less accurate the alignment (URL 1).

After the GR, large outliers and some noise were deleted with (3) *outlier removal* tool. Outliers can introduce additional errors in the model or produce unwanted fragments. This approach for every surface point calculates the mean distances between it and a certain number of neighboring points, as well as the standard deviation of these distances. If the mean distances are greater than an interval defined by the global-distances mean and standard deviation then the point is recognized as an outlier and deleted. A unique model surface was created using a (4) *sharp fusion* tool. This creates a polygonal 3D model by solidifying the processed captured and frames. Mode *sharp fusion* was used because it perfectly reconstructs fine features. Option *simplify mesh* was not used because it decreases the number of polygons. Then (5) texture was projected from the individual frames onto the fused mesh. Finally (6), each derived mesh model (n=5) was aligned according to the created LCS by using the *rigid align* option and four markers placed at the same location within LCS.

2.3 Precision Assessment

2.3.1 Section Analysis

Precision assessment of *Artec Space Spider* was calculated using two approaches following examples in literature (Patel et al., 2015, Reichert et al., 2016, Varga et al., 2019, Seminati et al., 2017, Ozsoy et al., 2019).

In the first approach, from derived models (n=5) specific metrics were calculated from multiple (n=5) sections placed at an interval of 1.5 mm across the PL height (Z-axis). This is one of the measurement tools included in *Artec Studio*. A section is the plane that splits the model or scans into parts. Once the sections are created, the panel displays its geometrical data. The following metrics were used: *MeshVolume* (MV), *MeshArea* (MA), *Area* (M), and *Perimeter* (P) (Figure 2). These metrics *Artec Studio* automatically generates and assigns them the listed acronyms. These names have not changed. MA is called *MeshArea* but it represents the area of the outer edge of a plate. M (*Area*) is actually, the surface area of the plate that includes the top and the outer edges (not the bottom).

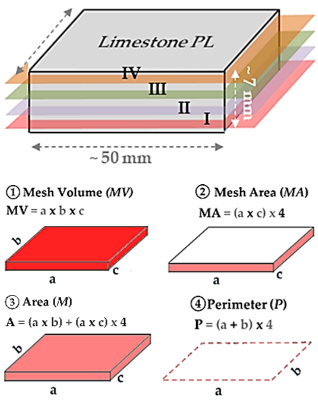

Figure 2: Schematic representation of derived metrics.

First, the average value of defined metrics for each section was calculated which represented the most probable (reference) value. Especially, total MV (sum of MV sections) was calculated for each measurement. Then, the absolute deviation (AD) and percent deviation (PD) of the remaining metrics for each section were derived. Finally, the precision of *Artec Space Spider* is expressed as mean absolute percent deviation (MAPD) for each defined metric. Furthermore, relative standard deviation (RSD) as a measure of precision, which quantifies the average dispersion of a set of observations from an estimate of the set's mean value, was calculated. The RSD tells whether the "regular" SD is small or large when compared to the mean for the data set.

2.3.2 Colored Distance Maps (CDM)

In the second approach, colored or surfaces distance maps of interval models were created. These maps help to determine the variability in the shape and volume of the surfaces (URL 2). This approach is often used in quality control where comparison of the original model with the scanned one is necessary. In total 20 colored distance maps were made where each model served as a reference one. For example, first, *model_1* was regarded as reference (model1-model2), then *model_2* was regarded as reference (model2-model). This process was conducted for a comparison of five interval models. The *Artec Studio* calculated *mean absolute distance* (MADi), *mean absolute deviation* (MADe), *mean signed distance* (MSD), and *root mean square* (RMS) for each comparison. The RMS error is a frequently used statistic metric in evaluating the degree of inaccuracy (Campbell, Shin 2011). It shows the variation between the compared 3D surface. Lower RMS value indicates a similar shape (higher precision), while the higher values indicate higher disparity (lower precision) in 3D models (Ozsoy et al., 2019). However, the calculated RMS error from *Artec Studio* matches the STDEV function in Excel. MADi is the average of absolute deviation values (all deviations become positive). MSD is an average value of all deviations (+ and -). MADe represents the excel AVEDEV function which returns the average of the deviations value from the mean for a given set of data.

3 RESULTS AND DISSCUSSION

3.1 Section Analysis

Table 3 shows the total MV (mm^3) of PL for each measurement and derived AD and PD. The reference (mean) MV of scanned PL was 18012.2 mm^3. MAPD was 0.387 %. The highest AD and PD were recorded in the fourth measurement and amounted to 88.71 mm³ or 0.493%.

Table 3: Total MV for measurements and derived mean AD and PD.

Measurement (s1+s2+s3+s4+s5)	Total MV (mm³)	AD (mm³)	PD (%)
M1	17942.8	69.45	0.3856
M2	17986.2	26.00	0.1443
M3	18097.6	85.38	0.4740
M4	18100.9	88.71	0.4925
M5	17933.6	78.64	0.4366
MEAN	18012.2	69.64	0.3866

This value is acceptable because an empty PL was scanned which represents the worst-case scenario in TFD studies, one in which no tufa formed. However, when precipitation occurs, the PL surface would have a more recognizable shape, texture, and color making it easier to scan and register. Also, the MV would be bigger which would potentially reduce the PD. Precision assessment of various scanners at scanning tufa formed in different intervals (3, 12 months) and with various surface complexity (plant fragments, macroinvertebrates) will be the subject of future research. Table 4 shows MAPD derived the remaining metrics.

Table 4: MAPD for MA, M, and P.

ID	Section	PD for *MA*	PD for *M*	PD for *P*
M1	Plane1	0.105	0.088	0.040
	Plane2	0.119	0.115	0.049
	Plane3	0.134	0.103	0.032
	Plane4	0.149	0.084	0.036
	Plane5	0.176	0.055	0.068
M2	Plane1	0.014	0.097	0.045
	Plane2	0.019	0.129	0.049
	Plane3	0.024	0.133	0.051
	Plane4	0.032	0.141	0.076
	Plane5	0.059	0.090	0.035
M3	Plane1	0.109	0.088	0.043
	Plane2	0.121	0.045	0.022
	Plane3	0.134	0.037	0.018
	Plane4	0.145	0.024	0.012
	Plane5	0.182	0.064	0.031
M4	Plane1	0.217	0.004	0.019
	Plane2	0.233	0.037	0.015
	Plane3	0.254	0.037	0.017
	Plane4	0.280	0.044	0.002
	Plane5	0.321	0.121	0.038
M5	Plane1	0.206	0.276	0.107
	Plane2	0.216	0.235	0.084
	Plane3	0.230	0.235	0.067
	Plane4	0.244	0.244	0.087
	Plane5	0.268	0.329	0.019
MAPD		0.160	0.114	0.043

As expected, *Space Spider* in is more unreliable when generating MV compared to other derived metrics (Table 5).

Table 5: RSD derived for defined metrics.

	Section	MV	MA	M	P
M1_5	Plane1	2.101	0.168	0.159	0.065
	Plane2	2.087	0.181	0.149	0.057
	Plane3	2.078	0.196	0.147	0.049
	Plane4	2.075	0.213	0.149	0.062
	Plane5	3.312	0.246	0.186	0.063
mean RSD		2.331	0.201	0.158	0.059

3.2 CDM Results

Green values on the following Figures (3, 4, and 5) show areas with zero error, red shows error above the reference surface, and blue below. The average RMS error for all compared CDMs was 0.030 mm. Average MADi was 0.0328 mm and average MADe was 0.0248 mm. All derived statistic metrics had a smaller value of declared manufactured accuracy value. No specific imprecision patterns were observed in the respective CDMs.

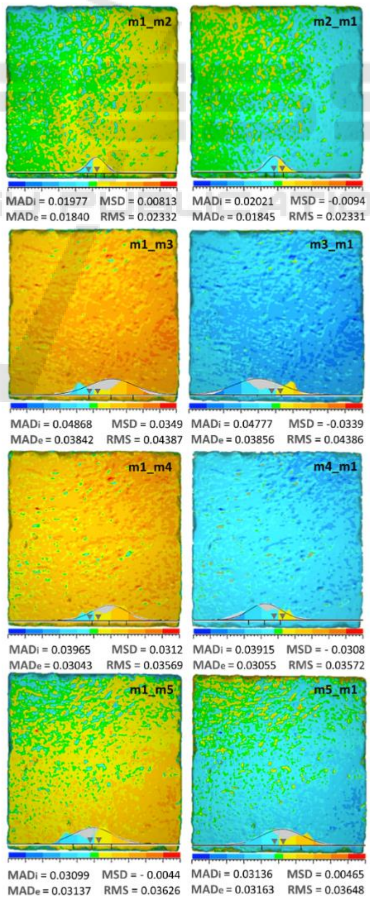

Figure 3: Derived colored distance map (1).

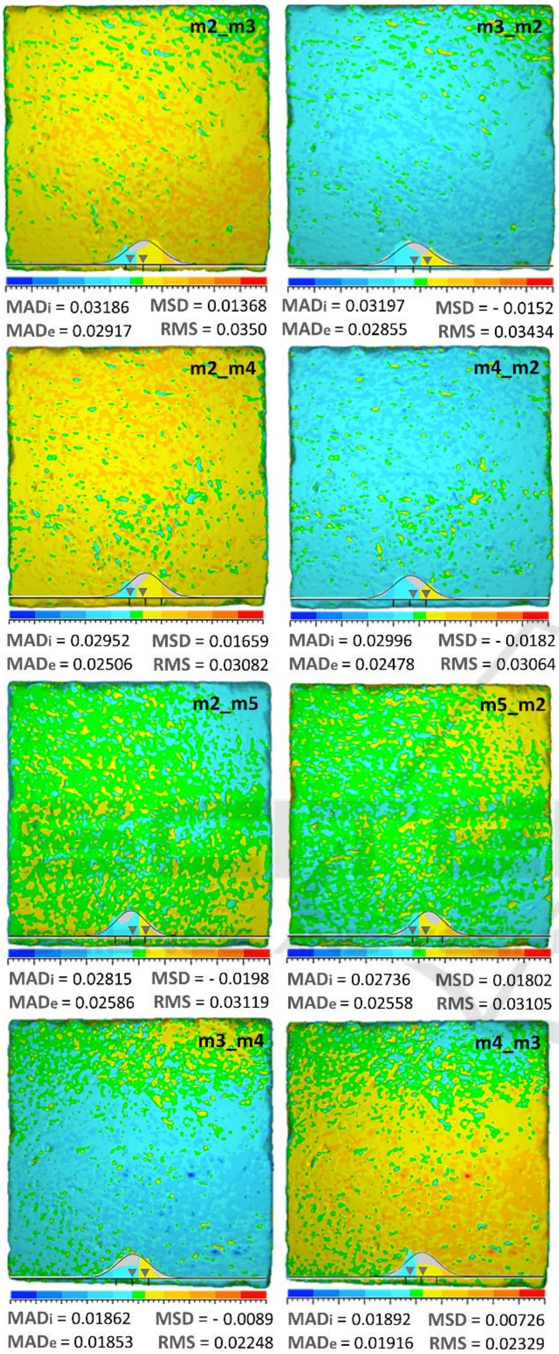

Figure 4: Derived colored distance map (2).

Tufa growth and erosion rates can be expressed as the height/thickness (mm a^{-1}), volume (mm^3 a^{-1}), and mass (g a^{-1}) formed at some period of time (Gradzinski, 2010). In general, when considering the annual tufa growth rate expressed through height, it is around a few mm a^{-1}, depending on a wide range of parameters (Vázquez-Urbez et al., 2010, Marić et al., 2020). So, if the TFD is expressed through a

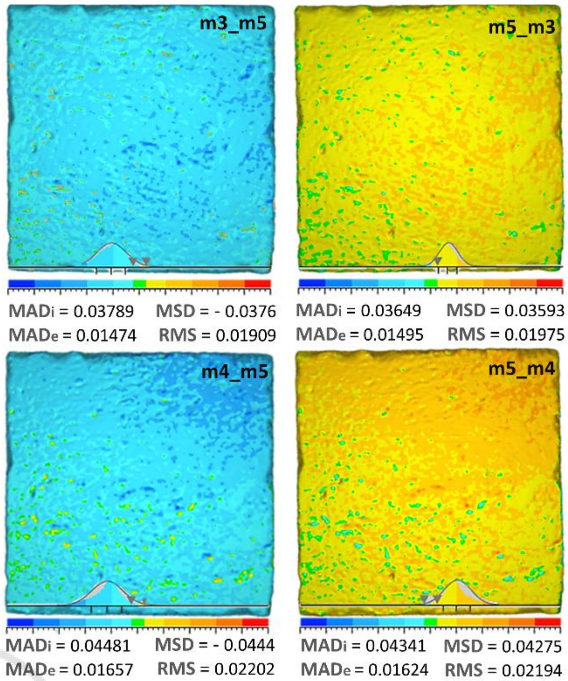

Figure 5: Derived colored distance map (3).

volumetric approach, on a PL surface of 25 cm^2, when 4 mm of tufa is formed, the MV of tufa would be 10 000 mm^3. Since the determined highest AD for MV is 88.71 (mm^3) this would result in an unreliable calculation of the tufa MV by 0.8871%.

If the TFD is analyzed using the height (mm a^{-1}) approach, and since all metrics in CDM had a smaller value (around 0.035 mm) of declared manufactured accuracy, then this would result in an unreliable calculation of the tufa height by 0.875 %. However, it should be noted that the reliability of the measurement can be better after the formation of tufa occurs. It might seem contradictory but there is a lot of complexity when it comes to scanning this type of object (small, empty PL). In the next interval measurements, after the volume of the scanned PL increases, ie the tufa occurs on the PL surface, the scanning process should be easier.

4 CONCLUSION

The aim of this study was to assess the precision of *Artec Space Spider* in scanning the small limestone PLs used for monitoring TFDs.

Although *Space Spider* is a high-quality 3D scanner, its application in TFD measurement may be limited due to the fact that they do not have a fixed LCS which makes interval comparison of 3D models easier and due to the fact that limestone PLs used for monitoring TFD does not necessary have distinctive characteristics (surfaces features). Therefore, the first, initial scanning of a PL which does not have formed tufa on its surfaces, can be very difficult.

The first drawback was solved by adding markers, i.e creating the LCS for model alignment. The results of the precision assessment showed that *Space Spider* generates reliable results considering the characteristics of the scanned object (empty PL) and it certainly can be used in TFD analysis. Data obtained with a *Space Spider* has high reproducibility and reliability.

In future research, the comparison of the tufa growth and erosion results obtained using hand-held 3D scanners and other indirect and direct methods (Marić, et al., 2020), that can express growth and eruption rates through volume (mm^3 a^{-1}) and height (mm a^{-1}), will be done.

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