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Analytical Non-Metric Close-Range Photogrammetry for Monitoring Stream Channel Erosion

Image coordinate measurements with a cartographic digitizer yield results comparable to those obtained with a stereocomparator.

Abstract: *Vertical stereopairs are recorded before and after storms with a non-metric 35-mm camera from a platform (H = 9.5 m) constructed over a gauged stream channel. Image measurements are easily undertaken on positive film enlargements with a cartographic digitizer, and provide the input* x,y *image coordinates required for an analytical solution. Studies to-date have produced mean errors of approximately ±3 mm in the* X *and* Y *terrain coordinates and ±6.5 mm in* Z (1/1500 H). *These accuracies approximate those obtained from measurements on the original negatives undertaken with a stereocomparator. The procedures described provide accurate results at minimum cost, and can be used to monitor stream channel erosion. Computer graphics routines provide an efficient means of constructing* DTMs, *contour maps, and three-dimensional displays of changes in elevation due to storm runoff. Non-metric close-range photogrammetry appears to provide an inexpensive, efficient, and accurate means for monitoring gully and stream channel erosion.*

Introduction

Analytical photogrammetric techniques are being developed to measure stream channel erosion from non-metric stereophotographs. Channel and gully erosion are problems of major concern to the U.S. Department of Agriculture's Agricultural Research Service (ARS) and Soil Conservation Service (SCS). However, traditional methods of measurement such as transit or level surveys and erosion pins are cumbersome to implement and often of insufficient frequency or accuracy to detect small changes resulting from storm events (Hadley, 1977). Close-range photogrammetry, on the other hand, offers a means of obtaining accurate measurements of a stream channel at frequent intervals with minimum disturbance to the study area.

Although the versatility of close-range techniques is well established, the ease of measurement and the accuracy to which coordinates can be determined vary according to the method and instruments used (Lo and Wong, 1973; Karara, 1975; Welch and Dikkers, 1978; Collins and Moon, 1979). Major problems often encountered with these techniques include the requirements for expensive metric cameras and sophisticated instrumentation (e.g., monocomparators, stereocomparators, or special stereoplotters) (Torlegard and Dauphin, 1975; Cooper, 1979; Meussig, 1982). In addition, highly trained personnel may be required to operate the equipment or to conduct the measurements. Consequently, the attractive features of a photogrammetric solution are often offset by hardware or personnel considerations (Atkinson, 1980).

In this paper, a method is described in which a standard 35-mm camera is employed to obtain pre- and post-storm photographs of a stream channel from which the amount of erosion (or deposition) can be quantitatively determined by analytical

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photogrammetric techniques. Image measurements are conducted with a cartographic digitizer similar to that available to most federal, state, or local agencies, and computer graphics permit the display of terrain features and of changes in elevation and volume. These methods potentially can be used by office staff having a minimal amount of photogrammetric training or experience.

Study Area

Lampkin Branch is a stream on the property of the Southern Piedmont Conservation Research Center (USDA-ARS) at Watkinsville, Georgia. This stream drains a 230-hectare gauged watershed of mixed-land uses, including pasture, cropland, woodland, and residential housing. As it was anticipated that changes in the channel due to storm runoff would be most noticeable at the meander bends, the study site was placed at a meander upstream of a V-notch weir used to monitor runoff and sediment load. The maximum vertical relief at that point is 1.5 m (Figure 1).

A photographic platform supported by two 10-m telephone poles cemented approximately 1.75-m deep in the stream banks and steadied by guy wires was constructed over the study site. The platform spans the stream and consists of two 7.3-m long supports upon which a floor of boards was constructed. A level railing was provided for safety and as a support for camera stations 9.45 m above the stream bottom.

Ground Control

Ground control was required to provide a common reference system from which stereomodels recorded on different dates could be rectified by analytical procedures. The ground control points consisted of 18 capped one metre iron stakes driven into the stream bottom and surrounding banks to a depth of approximately 85 cm. The white caps of 55-mm diameter were designed to provide an image target of 0.12 mm at the nominal photo scale of 1:440. A black dot was placed in the center of each cap to serve as a pointing mark during the field survey.

The *X*, *Y*, *Z* terrain coordinates of the 18 control points were established in a local coordinate system using a Kern DKM 2AE theodolite and conventional triangulation and trigonometric surveying procedures (Figure 2). This coordinate system is based on three permanent reference points located at stable places around the site so that in the event the control stakes are removed or displaced new points can be quickly established. Figure 3 indicates the layout of control in the stream channel and the location of reference points and camera stations relative to the model area. The coordinate errors in the local system for all ground control points averaged ± 1.2 mm in *X*, *Y*, and *Z*, or approximately 1 part in 10,000.

Photography

A base of 3.81 m was established on the platform to provide 70 percent overlap in the long direction of the photo format ($B/H = 0.40$). Black-and-white stereophotographs were subsequently recorded before and after several major storms during the Spring and Summer seasons of 1980 (Table 1) with a Honeywell Pentax Spotmatic 35-mm SLR camera equipped with a wide-angle lens ($f = 21$ mm). In order to clear the platform when exposing the photos, the camera was attached to a tripod, ex-

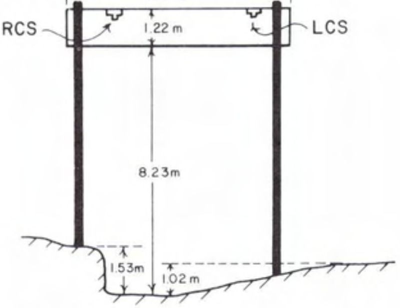


Fig. 1. The photographic platform and dimensions.

Fig. 2. Surveying the control points from reference point A. Note the control stakes in the stream and the photographic platform in the background.

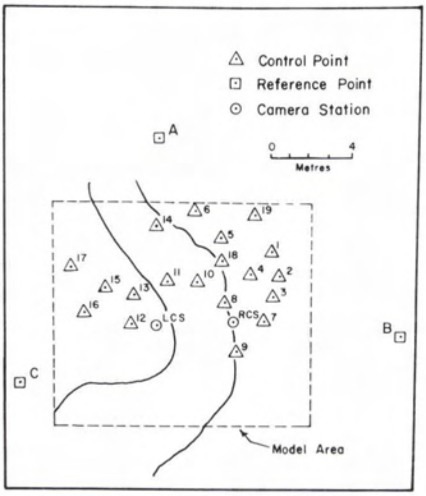


FIG. 3. Locations of control points, reference points, and camera stations relative to the nominal stream channel location. Dashed line indicates the approximate area of the stereomodel (12.3 × 8.2 m).

tended from the railing and oriented for vertical photography by means of a level bubble placed on the camera back. All photographs were recorded on Kodak Plus-X panchromatic film.

Before recording the photographs, the site was prepared by randomly distributing approximately eighty 50-mm diameter point markers on the stream banks, and at breaks in the terrain. These markers provided a dense network of points which could be readily observed and measured on all photographs. The time of day as well as the lighting conditions varied between dates, but an effort was made to obtain the photographs on overcast days to reduce glare and to eliminate shadows caused by trees. Normally, photographs were taken at intervals of one-half *f*-stop over an exposure range of two *f*-stops to permit the selection of negatives of optimum contrast and lighting. The original negatives at a scale of 1:440 were then enlarged by factors ranging from 9.2 (1:48) to 7.2 (1:61) and printed as positive film transparencies on Agfa Gevaert thick base (7 mil) film. In the printing operation, care was taken to level the enlarger, center the negative, and retain the edges of the frame so as to insure the geometric fidelity of the enlarged image.

DATA REDUCTION

All control and signalized points appearing on a stereopair were identified and annotated. Image measurements of annotated points were then conducted on each enlarged transparency with an Altek AC90SM Super-Micro digitizing system (25-μm resolution) to obtain the input x, y coordinates necessary for an analytical photogrammetric solution (Figures 4 and 5). Three rounds of measurements for one hundred points on each photo of a stereopair were accomplished in approximately one and one-half hours. Measurement precision of the x, y coordinates averaged ± 0.03 mm on the enlarged image (1:61 scale), or ± 1.8 mm on the ground. When reduced to the original negative scale, this precision is equivalent to approximately ± 4 μm, which is approaching the precision of a photogrammetric comparator.

A set of analytical photogrammetry programs provided by S. Murai (Murai *et al.*, 1980) was modified for use on the University of Georgia IBM 370/158 computer system and employed to derive object space (X, Y, Z) coordinates. These coordinates are computed by standard procedures in three linked programs: (1) the transformation of image coordinates based on the nominal principal point to coordinates within the photo plane as defined with respect to the exposure center; (2) single photo resection involving the collinearity equations to determine exterior orientation parameters by the method of least squares; and (3) determination of object space coordinates by spatial intersection of rays from the stereopair (American Society of Photogrammetry, 1980).

Four options or cases may be implemented during the resection (Table 2). In Case 1, the elements of exterior orientation are established with

TABLE 1. LIST OF MODELS, DATES, SCALES, AND STORM CHARACTERISTICS

Model Number	Date	Negative Scale	Enlargement Factor	Enlarged* Scale	Total Precip. Between Dates (mm)	Change in Volume (m^3)
2**	5/08/80	1:440	9.2	1:48		—
					196	
3	5/28/80	1:440	8.5	1:52		−3.75
					0	
4	6/13/80	1:440	7.2	1:61		−0.12
					77	
5	6/26/80	1:440	7.2	1:61		+0.10
					11	
6	8/08/80	1:440	7.2	1:61		+0.82
					15	
8	9/23/80	1:440	7.7	1:57		−2.10

* Scale of enlargements as determined by the analytical program.

** Baseline data. All comparisons made are based on this model as representing the original conditions.

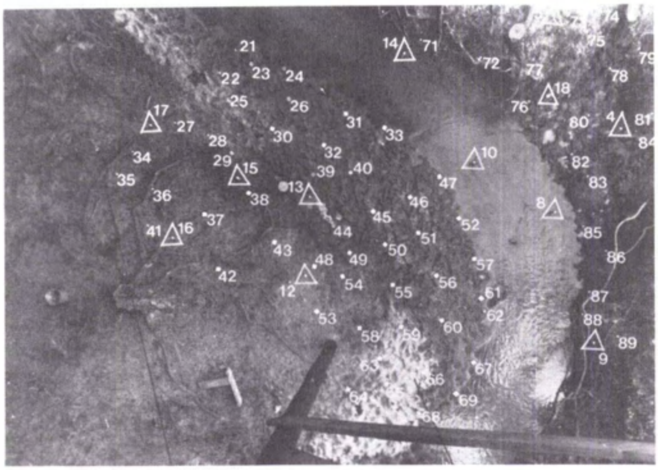


FIG. 4. Photograph with control points (triangles) and signalized points (white markers) annotated (Model 2, 5/08/80). Point 11 is not visible.

the coordinates of the principal point (x_p, y_p) set to zero and a nominal value for the focal length specified. A Case 2 solution involves the determination of both elements of interior and exterior orientation, whereas, in Case 3, a standard model for correcting lens distortion is incorporated. A Case 4 solution includes compensation for both lens and film distortions.

In practice, the accuracy of the resection for each case may be assessed through an examination of the mean residual errors resulting from the iterative solution of the collinearity equations. For example, it is evident from Figure 6a, that the residual error of ± 11 μm for a Case 4 solution is approximately $3\times$ better than the ± 30 μm error resulting from Case 1.

The adjusted image coordinates resulting from each case were then used in the intersection program to produce X, Y, Z terrain coordinates for all signalized points. As shown in Figure 6b, the accuracy of the Z coordinates improved dramatically

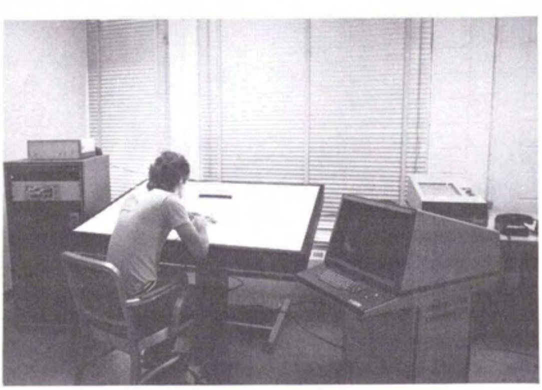


FIG. 5. The Altek digitizing system used for making image measurements on enlarged film transparencies.

with the inclusion of additional terms. Case 4, for example, produced mean residual errors of ± 3 mm in X and Y and ± 6.5 mm in Z. The vertical error of ± 6.5 mm is equivalent to approximately 1/1500 of the object distance, which is quite satisfactory for studies of channel erosion.

THE CARTOGRAPHIC DIGITIZER AS A MONOCOMPARATOR

The project was designed to develop an efficient and inexpensive means for deriving image measurements with a cartographic digitizing table, and for calculating terrain coordinates from the measurements. Although a digitizer is used primarily for the measurement of points, lines, and areas from map data, it also can be used to measure points on enlarged photographs to sufficient precision and accuracy for analytical adjustments. For example, with enlarged film transparencies, the precision at the negative scale is computed by dividing the precision (e.g., ± 0.03 mm) by the enlargement factor. Thus, if a 5 to $10\times$ enlargement factor is employed, the precision will range from about ± 8 to ± 4 μm. This is adequate for erosion studies and landform analyses, and approaches the precision obtained from measurements on the original negatives with a mono- or stereocomparator.

An effort was made to compare the accuracies obtained from digitizer and comparator measurements, and to obtain some insights into the merits or limitations of the digitizer. One model was measured at the University of Tokyo using the original negatives and a Jena Stecometer stereocomparator (1 μm readout), and at the University of Georgia on enlarged scale positive transparencies with the Altek digitizer. The digitizer measurements resulted in residual errors for x and y comparable to those obtained from the

TABLE 2. UNKNOWNS FOUND DURING SPACE RESECTION (MURAI *ET AL.*, 1980)

	Unknowns			
Case	Exterior Orientation	Interior Orientation	Lens Distortion*	Film Distortion**
1	$X_0,Y_0,Z_0,\omega,\phi,\kappa$			
2	$X_0,Y_0,Z_0,\omega,\phi,\kappa$	x'_p,y'_p,f		
3	$X_0,Y_0,Z_0,\omega,\phi,\kappa$	x'_p,y'_p,f	D_1,D_2	
4	$X_0,Y_0,Z_0,\omega,\phi,\kappa$	x'_p,y'_p,f	D_1,D_2	$a_1, \ldots, a_6$

* corrections for radial lens distortion are applied such that

$$\Delta x = x(D_1r^2 + D_2r^4)$$
$$\Delta y = y(D_1r^2 + D_2r^4)$$

where r = radial distance of each image point x,y from the principal point.
** corrections for film distortion are applied according to the equations

$$\Delta x = a_1x + a_2y + a_3xy + a_4y^2$$
$$\Delta y = a_5xy + a_6x^2$$

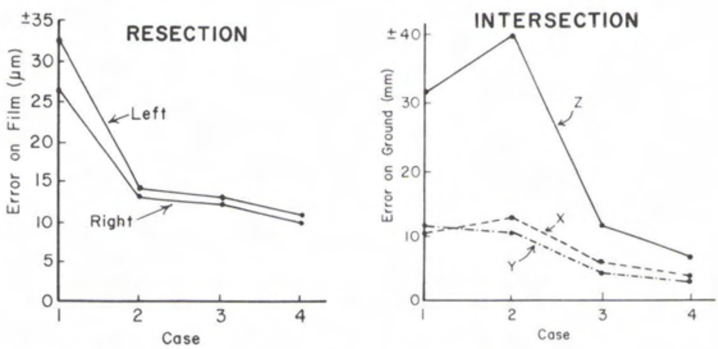


FIG. 6. (a) Image coordinate (x,y) errors at the film negative scale resulting from the single photo resection process as a function of the number of adjustment terms (Cases) for the left and right photos. (b) Terrain coordinate errors from the intersection program related to the adjustment cases. The Z coordinate error is minimized for Case 4 (terms for lens and film distortion included).

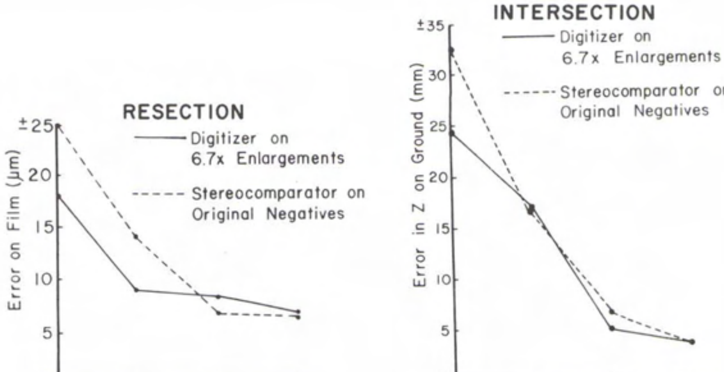
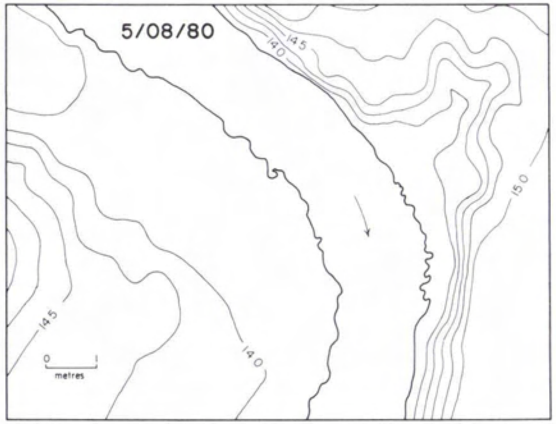


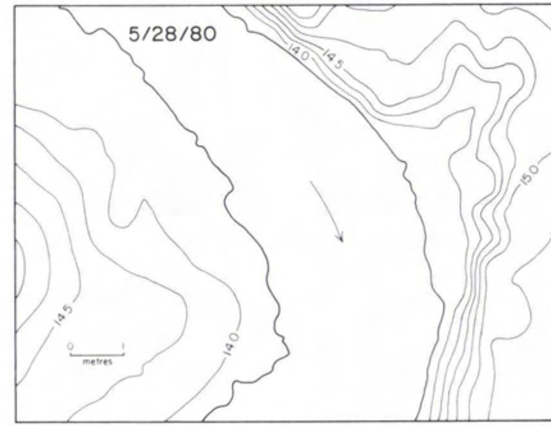
FIG. 7. (a) Comparison of the accuracy of resection between x,y coordinates measured on the Altek digitizer and Jena Stecometer stereocomparator. (b) Comparison of the accuracy of Z coordinates derived from measurements with the Altek digitizer and Jena Stecometer stereocomparator.



(a)

(b)

FIG. 8. (a) Topographic map from Model 2 (5/08/80). Contour interval = 0.25 m. (b) Photo from Model 2.



(a)

(b)

FIG. 9. (a) Topographic map from Model 3 (5/28/80). Contour interval = 0.25 m. (b) Photo from Model 3.

stereocomparator when both sets of errors were reduced to negative scale (Figure 7a). Minimum errors of approximately $\pm 8\ \mu m$ were obtained with the Case 3 and Case 4 adjustments.

Computation of Z terrain coordinates and their residual errors with the intersection program produced comparable results for the stereocomparator and digitizer measurements for all cases (Figure 7b). As discussed in the previous section, Case 3 and Case 4 adjustments produced minimum errors of about ±6 and ±4 mm, respectively. These comparisons between coordinates derived from digitizer and stereocomparator measurements indicate that a cartographic digitizer can be used with enlarged film transparencies to derive terrain coordinates of ample accuracy for erosion and microscale landform studies.

Analysis of Changes in the Stream Channel

The computed X, Y, Z coordinates are randomly spaced throughout each model. Thus, point-by-point comparisons of measurements on models from different dates are difficult. In order to facilitate comparisons, a regular 0.5-m grid of interpolated values (for which corner and mesh point coordinates were common to all models) was generated for each model. These digital terrain models (DTMs) were produced with the CalComp General Purpose Contouring Program (GPCP-II), and contour maps with a 0.25-m contour interval were plotted (Figures 8 and 9). Sequential changes in channel configuration due to storm runoff may be analyzed from these maps.

A FORTRAN program (PROFILE) was developed to analyze the changes in the stream channel using the DTMs produced from sequential models. This program generates profiles along the rows and columns of the grid intersections at two-metre intervals (Figure 10). In addition, the volume of material in each model referenced to a fixed datum is computed. The net volume of sediment eroded or deposited in the stream channel is easily calculated by taking the difference in volume for any two dates (Table 1). Three-dimensional graphic displays of the terrain or of the changes in elevation and volume may be generated from the DTMs

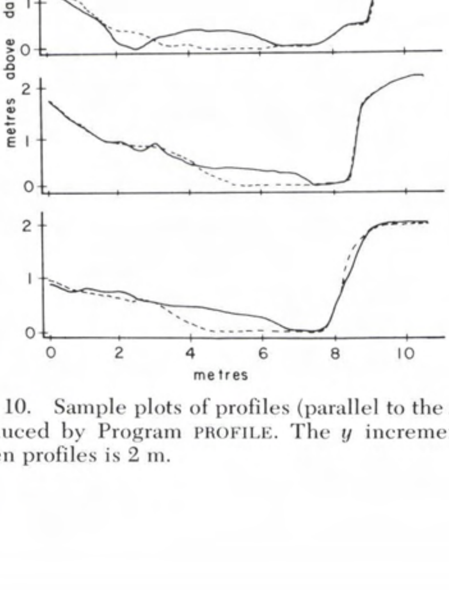


FIG. 10. Sample plots of profiles (parallel to the x axis) produced by Program PROFILE. The y increment between profiles is 2 m.

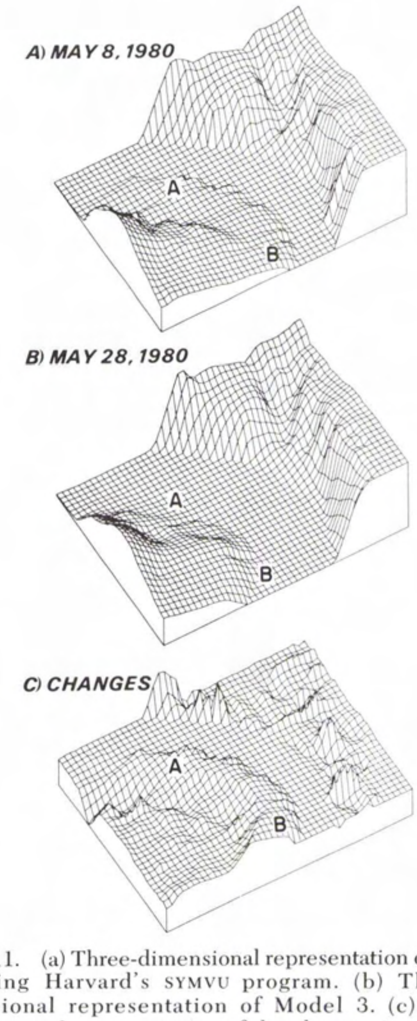


FIG. 11. (a) Three-dimensional representation of Model 2 using Harvard's SYMVU program. (b) Three-dimensional representation of Model 3. (c) Three-dimensional representation of the changes in elevation occurring during the 20-day interval between the photographs comprising Models 2 and 3. Notice that the primary areas of change due to stream action occur at the point bar at A and B.

with the aid of programs such as Harvard Laboratory's SYMVU or with CalComp's 3-D package (Figure 11).

Conclusion

The temporal changes in a stream channel can be monitored using close-range photogrammetric techniques. Procedures are simplified by recording stereophotographs with a non-metric 35-mm camera system and conducting measurements on positive film enlargements with a cartographic digitizer. Lens and film distortions are mathematically corrected for each model, thus eliminating the need for precise camera calibration. In this instance, analytical photogrammetric techniques provided terrain coordinate accuracies of ± 3.0 mm in X, Y and ± 6.5 mm (1/1500 H) in Z. These accuracies are comparable to results obtained from stereocomparator measurements of non-metric photographs or from an analog stereoplotter and non-metric photographs. As digitizer measurements of a single model can be completed within one to two hours, routine surveillance of a dynamic stream system is facilitated.

It is envisioned that these procedures may be adopted by federal, state, or local agencies with little difficulty and expense because of the overall simplicity of the technique. Cameras and cartographic digitizers of the required quality are already accessible to most agencies or may be purchased at reasonable cost. Although the analytical solution requires the use of a computer for data reduction, once the necessary photogrammetric and graphics programs have been established, measurement and analysis may be undertaken by existing office personnel with a minimum amount of training. Thus, it appears that the need for expensive and specialized photogrammetric instruments and for highly trained personnel can be reduced.

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