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Analysis of the influence of different GNSS positioning strategies on RPA trajectory modeling with photogrammetric applications

Análise da influência de diferentes estratégias de posicionamento GNSS na modelagem de trajetória de RPA com aplicações fotogramétricas

Patrick Otto Busch*, Tiago Lima Rodrigues, Leonardo Ercolin Filho*****

*Departamento de Geomática, Universidade Federal do Paraná, patrickotto@ufpr.br
**Departamento de Geomática, Universidade Federal do Paraná, tiagorodrigues@ufpr.br
***Centro de Pesquisas Aplicadas em Geoinformação, Universidade Federal do Paraná, leonardo.ercolin@ufpr.br

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Abstract

The geodetic positioning of RPAs (Remotely Piloted Aircraft) via the Global Satellite Navigation System has gained relevance with the use of RTK (Real Time Kinematic) and PPK (Post-Processed Kinematic) positioning methods, which proposes a reduction in time and cost in photogrammetric support in the field. As long as the observables are recorded, the solution can be post-processed, independent of baseline extension (LB) and base correction signal reception via radio link. In this context, the company Guandalini Positioning has been developing a solution called GPPK (Guandalini PPK), which makes use of an on-board GNSS receiver (L1 or L1/L2 GPS, GLONASS) and a photo -sensor system to identify the exact moment of acquisition of the images. In this work, using GPPK, the influence of different GNSS PPK processing strategies was analyzed in the context of aero-photogrammetric surveys. Through statistical analysis, the trajectories obtained by each strategy could be considered statistically equal. Despite this, using the accuracy analysis of the results obtained based on checkpoints, it is clear that the use of a short LB presents better results than a long LB, possibly due to the occupation time and the restriction of the Emlid receivers (which makes up the GPPK) in working only with the L2C observable. Furthermore, the inclusion of the L2 carrier in short LB did not significantly influence the accuracy, as did the increase in the acquisition frequency of the observables.

Key words:
Aerial photogrammetry, Processing, Adjustment.

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Resumo

O posicionamento geodésico de RPAs (do inglês *Remotely Piloted Aircraft*) via Sistema Global de Navegação por Satélite tem ganhado relevância com a utilização de métodos de posicionamento RTK (do inglês *Real Time Kinematic*) e o PPK (do inglês *Post Processed Kinematic*), uma vez que propõe uma redução de tempo e custo no apoio fotogramétrico em campo. Desde que as observáveis sejam gravadas, a solução pode ser pós processada, independente de extensão de linha de base (LB) e de recepção de sinal de correção da base via link de rádio. Neste contexto, a empresa Guandalini Posicionamento vem desenvolvendo uma solução denominada GPPK (Guandalini PPK), o qual faz uso de um receptor GNSS (L1 ou L1/L2 GPS, GLONASS) embarcado e um sistema foto sensor para a identificação do exato instante de aquisição das imagens. Neste trabalho, utilizando-se o GPPK, analisou-se a influência de diferentes estratégias de processamento GNSS PPK, no contexto de levantamentos aerofotogramétricos. Mediante análises estatísticas as trajetórias obtidas por cada estratégia puderam ser consideradas estatisticamente iguais. Apesar disso, a partir da análise de acurácia dos resultados obtidos com base em pontos de verificação, tem-se que a utilização de LB curta apresenta melhores resultados do que LB longa, possivelmente devido ao tempo de ocupação e a restrição dos receptores Emlid (que compõe o GPPK) em trabalhar apenas com a observável L2C. Além disso, a inclusão da portadora L2 em LB curta não influenciou de forma significativa a exatidão, assim como o aumento da frequência de aquisição das observáveis.
Palavras-chave:
Aerofotogrametria, Processamento, Ajuste.

I. INTRODUCTION

RPAs (Remotely Piloted Aircraft) are often used for recreational purposes, however, professional use has grown significantly. The use of this type of equipment, specifically in the case of aerial photogrammetric surveys, has been widespread in different areas and for different purposes, as by Colomina and Molina (2014), Nex (2022) and Osco et al. (2021), partly due to its ease of use, but also sometimes aiming for better cost-benefit and a gain in time spent acquiring final products. In this context, the use of GNSS (Global Navigation Satellite System) with INS (Inertial Navigation System) provides an increase in processes, as it makes it possible to obtain the position of the camera's perspective center (CP) at the time of taking photos (as long as they have lever-arms values) and the aircraft's orientation (ERCOLIN FILHO, 2017).

However, traditionally, as can be seen in Espinhosa (2006), Vidal (2013), Viana (2017), Silva (2018), Lopes (2019), Garcia (2019), Pedreira et al. (2020), Amorim (2020), Garcia (2020), among others, there is a GNSS or GPS (Global Positioning System) navigation receiver on board the RPA providing absolute positioning instantly. That is, without recording data in an observables file for post-processing, without the ability to receive and process differential corrections and without the possibility of real-time kinematic relative positioning (RTK). This

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provides positioning accuracy of the order of metric magnitude (SEBEER, 2003), since simple-point positioning (PPS) is performed using the pseudo-distance originating from the civil code of L1 GPS or GLONASS carriers.

Given this issue, the search for better levels of precision has given rise to possibilities of using the RTK method, correcting the aircraft's positioning, in real time, using a reference base. As an example, there is the eBee RTK from Sensefly PT (ROZE, 2014), the DJI MATRICE 300 RTK (DJI, 2022), the DJI Phantom 4 RTK (DJI, 2021), among others. However, it is known that the use of RTK has some limitations such as the range of the radio link that transmits corrections from the base station, in cases where the base station cannot be located close to the survey region, as well as environmental conditions that provide obstructions (e.g., trees, buildings, steep drops in level, etc.) (BARBOSA et al., 2010). In the case of NTRIP (Networked Transport of RTCM via Internet Protocol) there is the issue of availability and quality of mobile phone signal (3G or 4G) (GUANDALINI, 2012).

Considering that the base and rover observables are recorded at the time of survey, positioning can be obtained with a post-processed solution. With this, it is possible to apply more complex corrections, the independence of extension in LB (baseline), and the independence of reception of signals from the base station(s) (LEICK, 2004). Thus, there is the possibility of positioning with greater precision and accuracy, and consequently, obtaining more accurate position values for the cameras' CPs when images are taken. As examples of work developed using a geodetic GNSS receiver embedded in RPA, with positioning post-processing to estimate RPA trajectories, we can mention Dinkov and Kitev (2020) and Ercolin Filho et al. (2020).

It is worth mentioning that improvements in photogrammetric surveying occur in both direct and indirect georeferencing, with the latter reducing the number of control points on the ground as an advantage compared to the traditional case, as pointed out in Famiglietti (2021).

In view of the above and taking into account that research previously carried out in this field has not investigated the influence of different GNSS processing strategies in providing RPA trajectories for the processing and generation of photogrammetric products, the present work proposes to investigate such aspects.

In this context, experiments were defined based on the use of the PPK method, using different carriers (L1 and L1/L2), both considering and disregarding the correction of the phase centers of the onboard GNSS antenna. Furthermore, different base stations were used, with long and short LB extensions, and with different observable acquisition frequencies. In this work, to situate the reader, the concept of long LB will be related to

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lengths greater than 15 km, according to the principles of Monico (2007). The variables used in the strategies are justified by the different scenarios that users may have in the field.

II. MATERIALS AND METHODS

Test area and definition of experiments

Experiments were defined based on the use of the PPK method, using different carriers and bases positioned on short and long baselines, at observable acquisition frequency rates of 0.2, 1 and 15 seconds. The 0.2 s interval was defined empirically to analyze the scenario in which the base receiver is able to record data in this interval. In total, 10 experiments were carried out, organized as shown in Table 1. For short baselines, the GPS and GLONASS observables were used, with only L1 used first, and then L1 and L2 together, without linear combination. For long baselines, the ionosphere-free observable (LI) was used.

To acquire the data, the GPPK1 and GPPK2 Kits from the company Guandalini Positioning were used, embedded in DJI's RPA Phantom 4 Advanced. The kits consist of a geodetic GNSS receiver, an adapted multi-GNSS antenna and a photo sensor that, coupled to the RPA LED, correlates the moment the photo was taken and its coordinates.

Table 1 – Trajectory experiments and their characteristics.

Experiment	Method	Settings		
		Interval	LB Extension	Carriers
1	PPK	0.2s	Short	L1
2	PPK	1s	Short	L1
3	PPK	15s	Short	L1
4	PPK	0.2s	Short	L1 and L2
5	PPK	1s	Short	L1 and L2
6	PPK	15s	Short	L1 and L2
7	PPK	0.2s	Long (330km)	L1/L2 (LI)
8	PPK	1s	Long (330km)	L1/L2 (LI)
9	PPK	15s	Long (330km)	L1/L2 (LI)
10	PPK	15s	Long (115km)	L1/L2 (LI)

Source: The author (2022).

To develop the work, a study area located in the Physical Education complex of the UFPR Polytechnic Center campus was selected, as indicated in red in Figure 1. The area contains buildings, exposed soil, vegetation and other natural and artificial elements, and does not have a steep slope in terms of relief.

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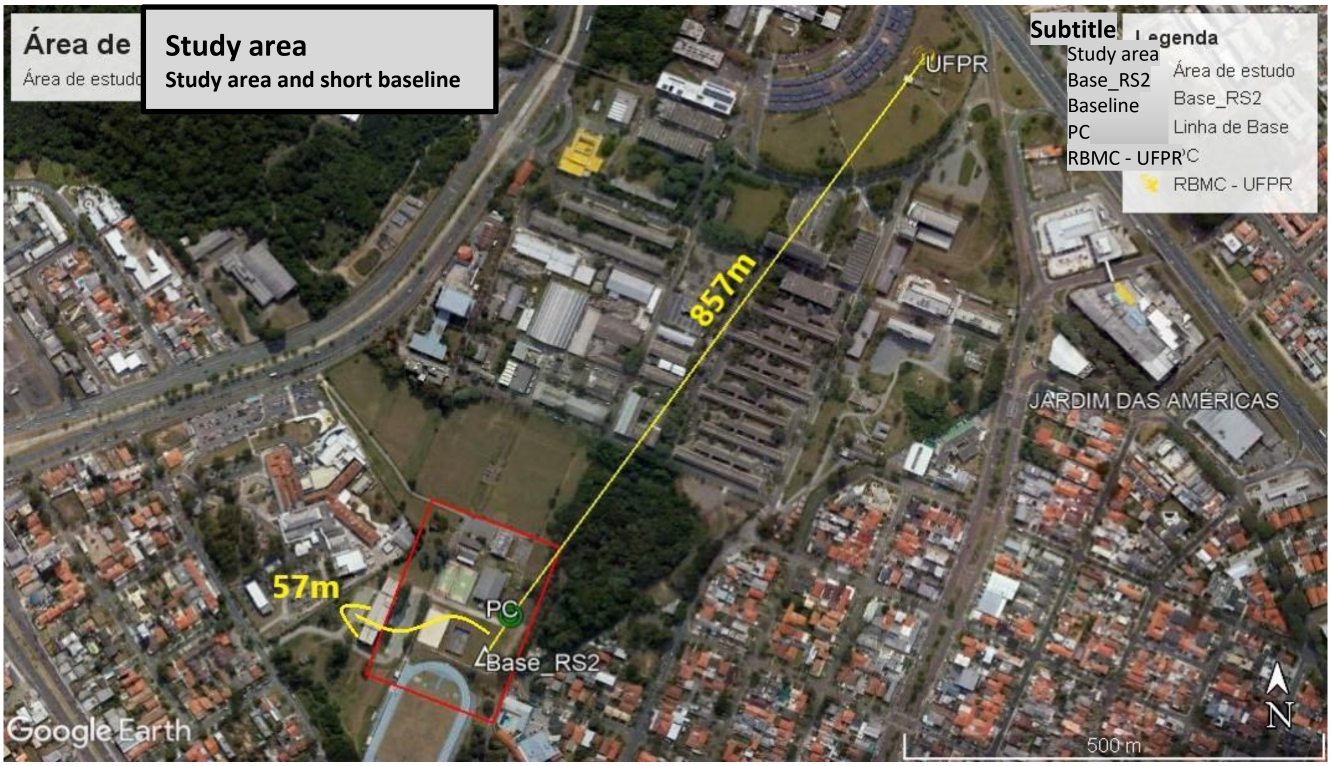

Figure 1 – Study area and short LB (prepared by the authors).

Regarding the experiments with processing intervals of 1 s and 15 s, the RBMC (Brazilian Continuous Monitoring Network) stations UFPR and POLI were used for the short and long LB configurations, respectively. The length of LB, adopting the UFPR station as the base station, is less than 900 m. In comparison, the length of LB adopting the POLI station as the base station is around 329 km (Figure 2). Alternatively, considering the experiments with a processing interval of 0.2 s, Emlid's Reach RS2 receiver was used for both short (~57 m) and long (~329 km) bases. The RBMC SCAQ station was also used to experiment with a LB of approximately 115 km at an interval of 15 s from the observations, as indicated in Figure 2. This was with the aim of having a second analysis of long LBs. It is worth noting that for this station the 1 s frequency is not available to users.

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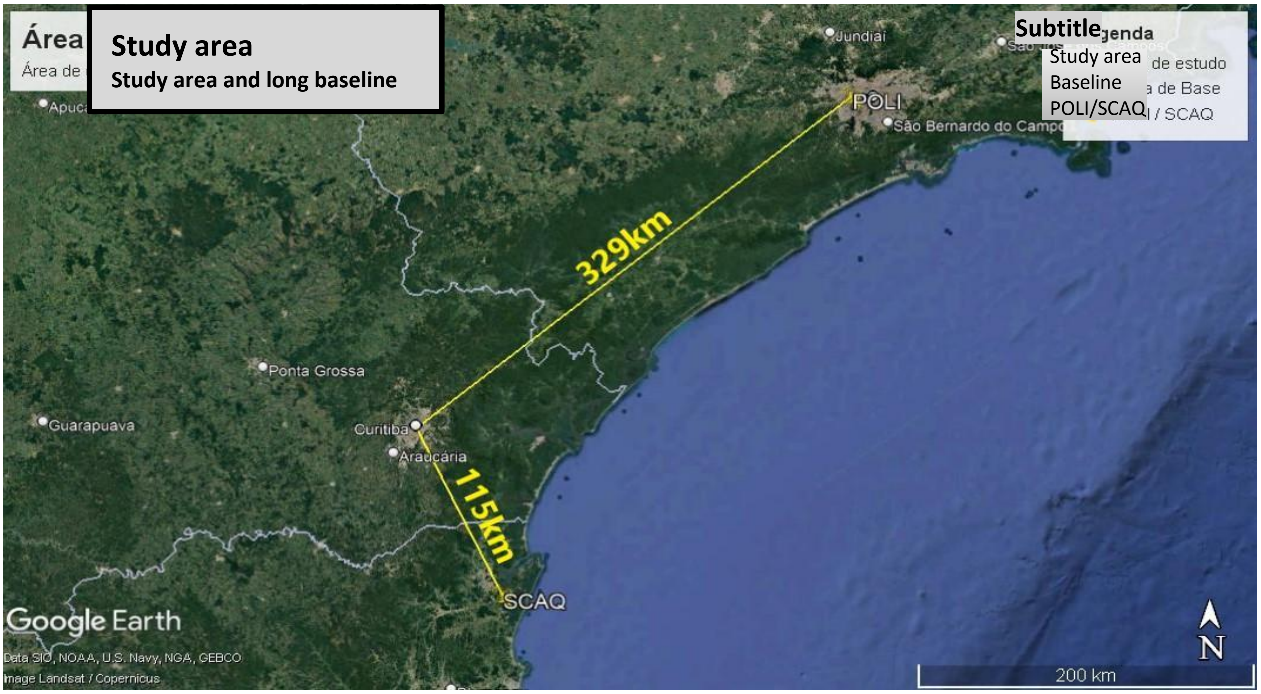

Figure 2 – Study area and long LB (prepared by the authors).

Once the study area was selected, the aerial photogrammetric survey was carried out to obtain the necessary data to carry out the experiments. The flight plan was prepared in the Drone Deploy – Mapping for DJI application (launched on August 19, 2015 by the company Drone Deploy) and used a flight height of 90 m, longitudinal overlap of 80% and lateral overlap of 60%. Subsequently, two flights were carried out, crossed with each other, generating a total of 111 photos with a ground-sample distance (GSD) of approximately 2.7 cm/pixel. The RPA used was DJI's Phantom 4 Advanced, with Guandalini's GPPK2 Kit attached (Figure 3).


Figure 3 – DJI PHANTOM 4 ADVANCED, with the Guandalini PPK2 KIT attached and an example of field tracking with a marked point. (prepared by authors).

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Still within the context of the photogrammetric survey, control and verification points were defined throughout the study area. In total, 13 photo-identifiable targets were marked to serve as control and verification points (Figure 3b). The coordinates of these points were collected by GNSS positioning using the RTK technique via NTRIP with the RBMC UFPR station as a reference base sending corrections to the Emlid Reach RS2 receiver. The surveys took place in accordance with the specifications, recommendations and general standards for geodetic surveys (Resolution PR nº5 -31/03/1993), defined by IBGE – Brazilian Institute of Geography and Statistics, for the preparation of Cartography and Topography services. The checkpoints were used in this project with the objective of evaluating the quality primarily of the orientation and subsequently to evaluate the quality of the generated products, in the context of the Cartographic Accuracy Standard for Digital Cartographic Products (PEC-PCD – DSG, 2015).

To estimate the interior orientation parameters (POI), an in-service calibration of the RPA camera was carried out prior. This occurred in the same study area, and conventional photogrammetric processing was used, that is, without relative injunction of position in the CP, using the available data (control points and images). The support points were also adjusted relatively in order to improve the geometry necessary for the recovery of the POE (External Orientation Parameters) and POI at the time of carrying out the aerial covering.

The estimated POI were focal length f; the coordinates of the PP x_P and y_P; Brown's model coefficients for radial lens distortion K_1, K_2, K_3; and the Conrady model coefficients for off-center lens distortion P_1 and P_2.

Trajectory processing

With all the RINEX files in hand, the processing of all trajectory experiments using the PPK method was carried out in the RTKLIB v. application. 2.4.3 Emlid b33. Table 2 presents the processing configurations. The method used to resolve ambiguities was LAMBDA (TEUNISSEN, 1995), with a Ratio-Test value equal to 3.

It is worth noting that, after estimating the trajectory, for photogrammetric processing, with the photo taking times indicated by the photo sensor system present in the kit, from an interpolation process are automatically calculated, in GPPK software, the coordinates of the phase center of the GNSS receiver antenna for these instants. An event log is generated by RTKLib where the software calculates a position solution and generates a file extension "events.pos", containing the positions of the events based on the E, N and U coordinates of the Local Geodetic System. Returning this file to GPPK and reprocessing the data, the software adds the internal three-dimensional displacement data from the phase center(s) to the camera's CP (lever-arms), resulting in the adjusted coordinates in the same file of each CP for the flight. Table 3 presents the lever-arms values used, which were previously measured using a stainless steel ruler with a millimeter scale and

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already established in the GPPK software by default.

Table 2 – Processing configurations in the PPK method in RTKLIB v. 2.4.3 EMLID B33.

Settings	**short LB**	**long LB**
Observable	L1 and L1+L2	L1/L2 (LI)
Elevation Mask	15°	15°
Kalman filter	*Combined*	*Combined*
Ephemeris	Broadcast	Precise
Tropospheric modeling/mapping function	--	Saastamoinem/Niell
Ionospheric Modeling	--	Observable LI + 2nd and 3rd order correction of the ionosphere with the RINEX HO application
Geodynamic effects	--	Earth Tide Correction, Ocean Tidal Load (.BLQ files), Pole Movement
Correction of the phase center of satellite antennas	Correction applied with IGS14.atx file	Correction applied with IGS14.atx file
Correction of the different trends of the C1C and C1W codes	Fix with P1C1.dcb file for month	Fix with P1C1.dcb file for month
Constellations	GPS, GLONASS	GPS, GLONASS

Source: The author (2022).

Table 3 – Lever-arms values used.

Lever-arms(m)	
LX	0.000
LY	-0.015
LZ	0.175

Source: The author (2022).

Photogrammetric processing

The coordinates of the CPs of each flight image, obtained when estimating the trajectories, and the calibrated POI values were used in the experiments in the study area as parameters imposed in the phototriangulations in a relative way, according to their variances. The variances for the CP coordinates were propagated in the interpolation from the GNSS trajectory solutions resulting from processing in RTKLIB.

For all experiments indicated in Table 1, phototriangulation was carried out with direct and indirect georeferencing, using both one and seven control points, so that it was possible to generate comparative data, and mainly, to refine the POI and POE. The use of one point was considered a minimum quantity and the most

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economical scenario for this purpose, while seven points could be used in order to analyze the effect of refinement with a greater degree of freedom. More information regarding the use of control points in indirect georeferencing can be found in Andrade (1998) and Tommaselli and Reiss (2005). In Figure 4, the working environment in Agisoft Metashape is shown as an example, with the images aligned and the support points marked.

Verification of the accuracy of each phototriangulation was carried out by calculating the root-mean-square error (REQM) of the discrepancies at the checkpoints.

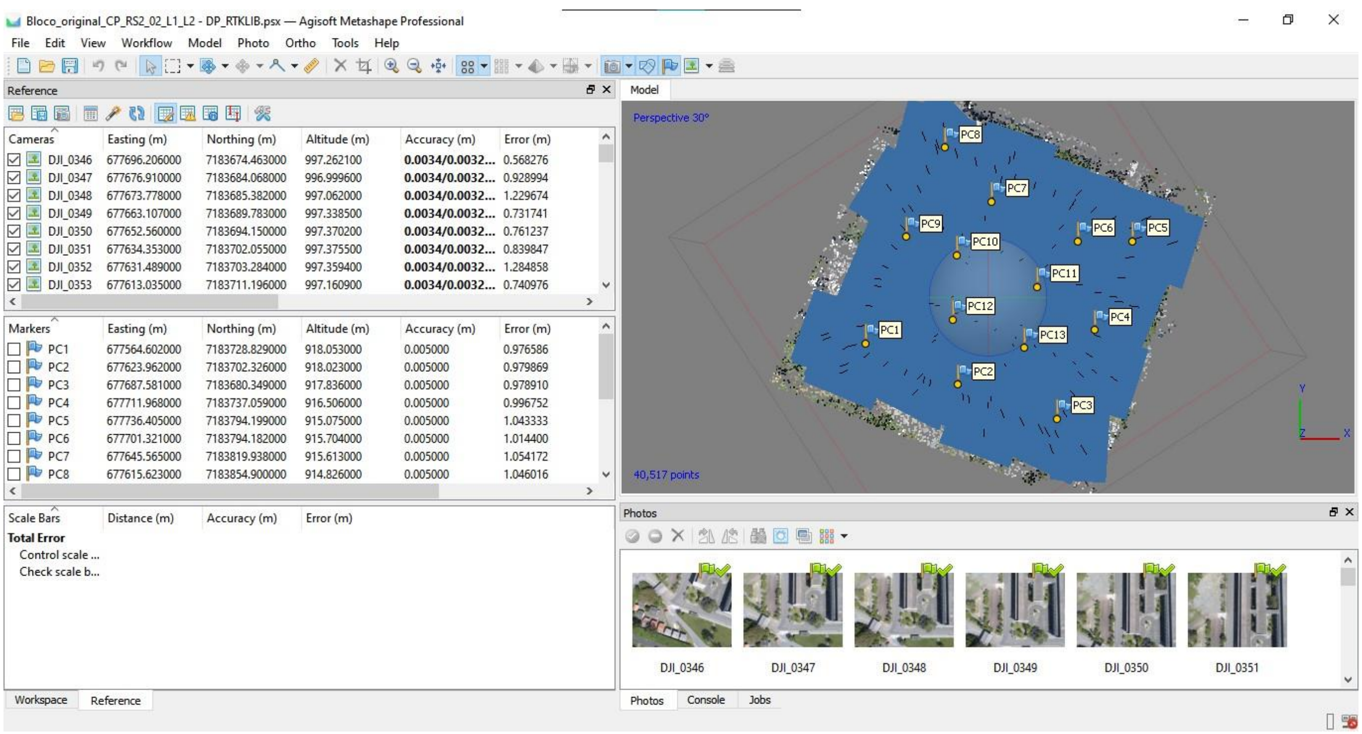

Figure 4 – Example of Agisoft Metashape work environment. (prepared by the authors)

III. RESULTS AND DISCUSSION

Trajectory estimation results from GNSS processing strategies

Figure 5 presents the precision values of the E, N and U coordinates obtained in experiments 1 through 6 with short LB. For experiments 1 and 2, the formal accuracies in the E and N components were in agreement at the submillimeter level, with averages around 0.007 m, generally below 0.012 m. Regarding the U component, in experiment 1 the accuracies were on average 0.012 m and always below 0.015 m, with little variation, in the order of mm; however, in experiment 2 these were slightly better, with an average of 0.010 m. This may be related to the higher percentage of fixed ambiguity solutions during the trajectory; 45.8% versus 99.6%. For

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experiment 3, the accuracies were worse in relation to those obtained in experiments 1 and 2; in components E and N, on average, there were 0.010 m and 0.012 m, respectively, with values varying from 0.008 to 0.021 m. For the U component, the average was 0.018 m, with values varying from 0.013 to 0.031 m.

In the case of experiment 2, the values presented for the altimetric component were expected in view of the higher percentage of fixed ambiguity solutions obtained for this experiment.

Another issue verified in experiment 3 was the amplitude of variation of accuracies in an approximately cyclical format. This, as well as the worse accuracies, was expected, considering the low sampling (15 s) for interpolation, in relation to the sampling in previous experiments.

As in Dinkov and Kitev (2020), it was observed that the accuracy values at checkpoints obtained in studies of the PPK method for direct georeferencing were stable for a short baseline.

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Figure 5 – Coordinate accuracies E, N and U of CP for experiments 1 to 6 with short LB. (prepared by the authors).

For the experiments using the L1 and L2 frequencies, with short LB, there was a slight improvement due to the addition of the L2 observables and the fixation of all ambiguities during the flight period. In experiments 4, 5 and 6, precision values in both planimetric components were below 0.006 m, with averages of 0.005 m or better. For the altimetric component, in experiments 4 and 5, the results were also close to the submillimeter level, with averages around 0.008 m. For experiment 6, the results were worse, on average 0.011 m. In this case, although the approximately cyclical behavior was verified, the amplitudes were smaller, a direct consequence of the improvement with the inclusion of L2 in the processing. Additionally, it is understood that for the scenario of a dual-frequency receiver working in a short LB, the frequency rate used for each experiment

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may not have as much influence on the characteristics of the results obtained, compared to the case of just using a receiver L1.

The values found here for short LB reflect the three-dimensional discrepancies of the checkpoints launched in the study area, and as in Ercolin Filho et al. (2020), the three-dimensional geodesic position provided by the PPK Kit trajectory was considered.

Compared to other techniques, such as PPP (Precise Point Positioning), for example, the results are better, mainly due to the short travel time. Generally, with the traditional PPP method, approximately 30 minutes are required for a position solution to be achieved at a decimeter level of accuracy, in static processing (ALVES et al., 2011; IBGE, 2020). In PPP, when all errors are adequately treated and a long period of observations from dual-frequency receivers is used, a high level of accuracy is obtained (MONICO, 2007; ZUMBERGE et al., 1997).

Grayson (2018), who analyzed the possibility of using kinematic PPP to provide a trajectory using “fixed wing” RPA, achieved accuracies of around 0.02 to 0.03 m for the planimetric coordinates of the trajectory points and 0.10 m for the altimetric component.

In the experiments simulating the use of GPPK2 in long LB, it was possible to observe that there was no similarity in the results obtained between the experiments. While experiments 7 and 10 generated almost 100% of points with a fixed ambiguity solution during the trajectory (flight), experiments 8 and 9 had the majority of trajectory points with a floating solution, 99.4% and 99.7%, respectively. As a result, as can be seen in Figure 6 that the accuracies of the three-dimensional coordinates for experiments 7 and 10 were the best, with averages of 0.014, 0.014 and 0.033 m in E, N and U for experiment 7, and 0.020, 0.021 and 0.052 m in E, N and U for experiment 10. The values in planimetry were between 0.008 and 0.019 m in experiment 7, being less variable than in experiment 10, which had minimum and maximum values equal to 0.009 and 0.032 m. However, in altimetry, in experiment 10 the values were much more discrepant and with greater amplitudes, in relation to experiment 7, especially in the first part of the trajectory, varying between 0.026 and 0.077 m.

Considering what was obtained by Teppati Losè et al. (2020), which used data from CORS stations (Continuous Operating Reference Stations) at distances between 8 km and 68 km from their study area, the values achieved here for long LB deserve greater attention considering that this deals with a distance between two and five times greater.

In all experiments, there was an improvement in accuracy in the altimetric component in relation to direct georeferencing, when 1 control point was included in the phototriangulations. This is possibly due to

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refinements in POI values and CP positions. This improvement was already expected, given the same type of results obtained by Ercolin et al. (2020). It is worth noting that, even though the camera was calibrated in flight, the POIs tend not to be stable, since the camera is not photogrammetric.

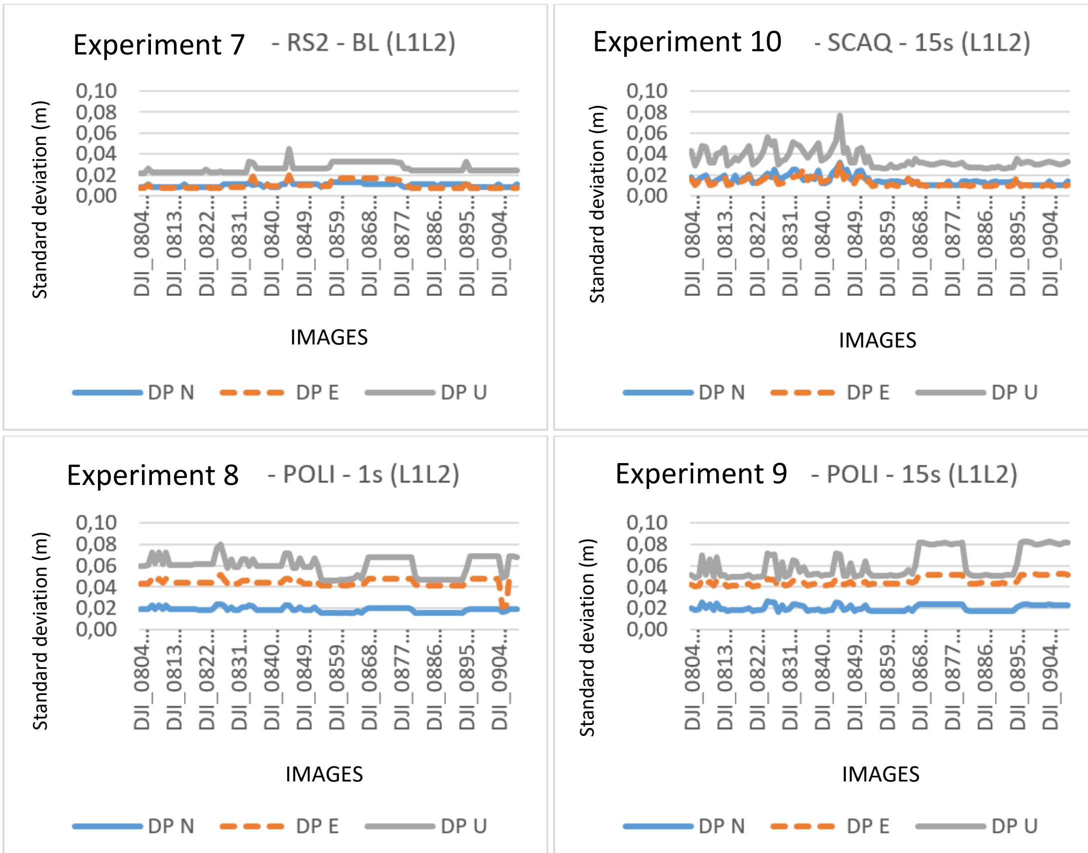

Figure 6 – Accuracies of the CP coordinates E, N and U for experiments 7 to 10 with long LB. (prepared by the authors)

In relation to experiments 8 and 9, the formal precision values were close to the millimeter level, as observed in Figure 6, with the averages in the N component being 0.020 and 0.021 m. In component E, due to the predominantly floating solution, the accuracies were worse than in N, being 0.036 and 0.046 m, respectively for experiments 8 and 9. For the altimetric component, the values were between 0.046 and 0.082 m, with averages of 0.063 and 0.065 m, respectively for experiments 8 and 9.

In general, the effect of lower sampling, of 1 and 15 s, proved to be more harmful in the case of long baselines. This is due to the two aforementioned issues of using only the L2C signal and the occupancy time well below the recommended level. Also for these reasons, the results were worse in relation to those obtained with short LB.

Considering all experiments, from 1 to 10, the coordinate precision values (automatically estimated as

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standard deviation by the software) were generally below 0.09 m for both the planimetric and altimetric components, with the smallest variation found in the experiments with short LB.

Still, in terms of formal precision, in the case of experiments with long LB, the worst precision values in relation to results with short LB are due to two issues. The first is related to occupation time; as recommended by IBGE (2008), to have accuracies in the order of millimeter magnitude on baselines greater than 100 km, the minimum occupation time must be at least 4 hours. Since the entire occupation time, considering the initialization period, lasted around 30 minutes, the results are largely at the decimeter level.

The second issue is that EMLID receivers do not generate L2P observables, they only work with the received L2C observable, according to catalog information (available at https://www.guandalinibr.com/wpcontent/uploads/2020/06/PPK2_CATALOGO_V5_2.pdf) and information contained in the brand's official Forum (https://community.emlid.com/). Since only a few satellites in the GPS constellation transmit this civil signal, the formation of ionosphere-free observables occurs with few observables. Thus, the number of satellites usable in the solution is smaller than in the solution without short LB combination. This, together with the issue of the availability of satellites for the formation of double differences, means that the system of equations in each epoch has a smaller number of equations and degrees of freedom in the adjustments. Consequently, formal accuracies are achieved with lower precision.

In the case of the long LB of 115 km, SQAC station, with 15 s frequency (experiment 10), the results were better since the LB is smaller. However, the results are still worse than those obtained with short LB.

To overcome this problem, two solutions are possible to improve results: either a longer field occupation time is used at startup, which is worse for the user in terms of time savings; or virtual stations can be used to have short LB, as done by Teppati Losè et al. (2020).

Considering the precision results and all statistical tests between the pairs of experiments with short LB, it can be seen that the most suitable trajectory, in the case of using the RBMC station as a base, is the one with 1 s frequency of acquisition of observables, if possible with the GPPK2 kit considering the L1 and L2 observables without linear combination. On the other hand, considering the results for long LB, it appears that the most suitable trajectory, also using the RBMC station as a base, is the one with 1 s frequency of acquisition of observables.

Analysis of accuracies with checkpoints

In Figure 7 below, graphs are presented with planimetric accuracy (REQM) values resulting from E and N, and altimetric accuracies achieved using the checkpoints in each experiment, without using control points

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(direct georeferencing), using one and seven control points. It is observed that, almost in general, the accuracies in the altimetric component were worse, due to two fundamental issues; the first is related to parallax (ERCOLIN FILHO, 2017) and the second is related to the lower precision of trajectories in the U component, as previously presented.

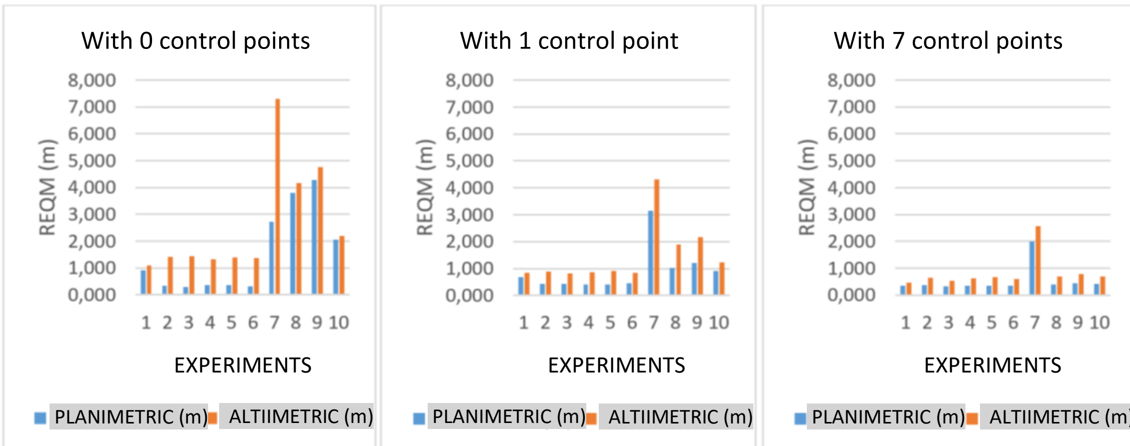

Figure 7 – Planimetric and altimetric accuracies in the experiments, obtained with Checkpoints. (prepared by the authors).

Other results that can be observed are: i) the lower level of accuracy in experiments with long LB, due to worse precision, and possibly worse accuracies, of the trajectory coordinates (Figure 6) and; ii) improvements in accuracy with the increase in the number of control points, indicating that refinements in POI and POE are important, especially in the case of long LB. Improvements with POI refinements were already expected, given the same type of results obtained by Ercolin et al. (2020), mainly in the U component. In this context, it is worth highlighting that, even though the camera was calibrated in flight, the POIs tend not to be stable, since the camera is not photogrammetric, even though the DJI Phantom 4 Advanced camera is made up of a mechanical shutter (global shutter) and has a high level of stability, significantly superior to other systems from the manufacturer. However, as the improvements were greater in the case of long LB, the refinements in POE were more effective, overcoming the problem of short screening time.

Another post-refinement result is that the discrepancies between the accuracies in the experiments decreased, with the exception of experiment 7, in which there is possibly lower accuracy in the trajectory coordinates. It is worth noting that in this experiment an Emlid RS2 receiver was used as a base, instead of the RBMC POLI station, which justifies the discrepancy in relation to the REQM results of experiments 8 and 9. In the case of experiment 10, using the SCAQ station as a base, the smaller extension of LB proposed lower accuracies in relation to experiments 7, 8 and 9, in the case of direct georeferencing and refinement with a

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control point. After the refinements with seven control points, the differences in accuracy were almost null, indicating that with the increase in the number of control points, the issue of LB extension becomes irrelevant.

In the case of experiment 1, with direct georeferencing, the worse planimetric accuracies in relation to experiments 2 to 6 may be related to the relatively low percentage of fixed solutions to ambiguities during the trajectory.

Regarding the frequency of acquisition of observables, with the exception of experiment 1, there was practically no difference in the short LB results, whether in the case of direct georeferencing or with refinements. In the case of experiments with long LB, except experiment 7, the increase in frequency proved to be beneficial in the case of direct georeferencing and less relevant with refinements.

In relation to the use of L1 and L2 frequencies without combination in the case of experiments involving short LB (experiments 4, 5 and 6), in relation to experiments 1 and 2, there was a slight improvement, decreasing with the increase in the number of points of control. This is in line with the slight improvements in terms of trajectory coordinate accuracy.

Comparing the results obtained in experiments 1 through 6 with those obtained by Daakir (2017), by Stöcker (2017) and by Dinkov and Kitev (2020), we have the same order of magnitude in terms of accuracy – the centimeter. In the case of using direct georeferencing, analyzing accuracy values found in the works of Padró (2019), Kalacska (2020) and Žabota and Kobal (2021), a greater proximity to the results obtained in experiments 7 through 10 is observed, since the order of magnitude obtained for the sampling frame varies between the decimeter and the meter.

Finally, after the phototriangulations were carried out, MDS (Digital Surface Model) were generated with a spatial resolution of 5 cm and orthophotos with a spatial resolution of 2.7 cm. From the planimetric positional analysis, in the PEC-PCD light, considering class A, for all experiments, except experiment 7, the indicated scale is 1:5,000. For altimetry, also considering class A, except for experiments 1 and 7, the indicated scale was 1:10,000. In the case of experiments 1 and 7, the indicated scales were 1:5,000 and 1:25,000, respectively.

IV. Conclusions

Given all the experiments carried out here and the results obtained in each of them, it appears that the most advantageous scenario in terms of accuracy and costs for users would be experiment 3. This is because the free RBMC base file of 15 s is available for 24 hours and would not require joining 1 s files, made available for 1 hour, if the survey has a time interval that requires more than one file. In the context of short LB, the

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GPPK1 kit is already sufficient, and the use of the GPPK2 kit with the inclusion of L2 frequencies does not provide significant accuracy gains.

If there is no possibility of a short LB, the initialization time must be consistent with that indicated in IBGE (2017), especially since only the L2C signal is used, due to the limitation of the receiver itself on board the RPA, which reduces the possibility of formation of ionosphere-free observables and, therefore, the number of available satellites. As a less costly alternative solution, the use of virtual stations, as carried out by Teppati Losè et al. (2020), is recommended and will be tested in future work.

Regarding photogrammetric processing and accuracies calculated with checkpoints, it is understood that in relation to direct georeferencing, the effects of including a control point in phototriangulation were positive and even more evident with the use of seven control points. In this case, accuracies improved, especially in the altimetric component. This is because small changes in POI values can greatly affect the orientation accuracy of the photogrammetric block, especially when no GCP (Ground Control Point) is included in the processing.

It is understood that the use of a larger set of control points in the field increases mapping costs, however, they demonstrated considerable relevance for the refinement of POI and especially CP positions in the case of long LB. It is worth noting that, to carry out the PEC-PCD analysis, there will always be a need to obtain points in the field, in this case for verification.

A very important issue, which can be seen in Ercolin Filho et al. (2020), is that better results can be achieved with greater freedom of refinement in the CP positions, provided by relative injunctions with lower weights (less rigid injunctions). That is, by considering larger uncertainties in the coordinates. In this context, in future work we intend to test the use of coordinate accuracies multiplied by scale factors, such as 1.96, (95% in Z statistics) or 2.58 (99% in Z statistics).

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provided materials and resources such as laptops, cell phones and items related to possible maintenance procedures.

V. References

ALVES, C. M. D.; MONICO, J. F. G.; ROMÃO, V. M. C. Analysis of PPP accuracy from the solution of GPS ambiguities in short periods of occupation. Brazilian Cartography Magazine, No. 63/5, p. 585-600, 2011.

ANDRADE, J. B. Photogrammetry. Curitiba: SBEE, 258 p., 1998.

BAPTISTA, P.; BASTOS, L.; CUNHA, T.; BERNARDES, C.; DIAS, J. A. Monitoring Sandy Shore Morphologies by DGPS – A Practical Tool to Generate Digital Elevation Models. Journal of Coastal Research, vol. 24, n.6, p.1516-1528, 2008.

BARBOSA, E. D. M.; MONICO, J. F. G.; ALVES, D. B. M.; OLIVEIRA, L. C. Integrity in RTK and RTK network positioning. BC - Bulletin of Geodetic Sciences, Curitiba, v. 16, no. 4, 589-605 p., 2010.

CHANG, X. W.; YANG, X.; ZHOU, T. MLAMBDA: A modified LAMBDA method for integer least-squares estimation. Journal of Geodesy, vol. 79, no. 9, p. 552-565, 2005.

COLOMINA, I.; MOLINA, P. Unmanned aerial systems for photogrammetry and remote sensing: A review. ISPRS Journal of photogrammetry and remote sensing, vol. 92, p. 79-97, 2014.

ERCOLIN FILHO, L. Calibration of a multi-camera photogrammetric system for use in mapping applications with direct georeferencing. Thesis (Doctorate in Geodetic Sciences). Postgraduate Course in Geodetic Sciences, Earth Sciences Sector, Department of Geomatics, Federal University of Paraná, Curitiba, 2017.

ERCOLIN FILHO. L.; PICUSSA, M. S.; DELAZARI, L. S. Analysis of the accuracy of a post-processed kinematic positioning system on board a van-rpa for mapping applications. Proceedings of the XI Brazilian Colloquium on Geodetic Sciences, Curitiba, Paraná, 2020.

FERREIRA, E.; CHANDLER, J.; WACKROW, R.; SHIONO, K. Automated extraction of free surface topography using SfM-MVS photogrammetry. Flow Measurement and Instrumentation, Loughborough, UK, v. 54, p. 243-249, 2017.

GRAYSON, B.; PENNA, N. T.; MILLS, J. P.; GRANT, D. S. GPS precise point positioning for UAV photogrammetry. The photogrammetric record, UK, v. 33, n. 164, p. 427-447, 2018.

GUANDALINI, M. Methodological analysis of relative positioning through GNSS and its applications in engineering: use of the RTK/GSM technique. Doctoral thesis. University of São Paulo, São Paulo, 2012.

HUANG, J. D.; JACKSON, D. W. T.; COOPER, J. A. G. Morphological Monitoring of a High Energy Beach System Using GPS and Total Station Techniques, Runkerry, Co. Antrim, Northern Ireland. Journal of Coastal Research, No. 36, pp. 390-398, ISSN 0749-0208. (DOI: 10211/08-1108.1). 2002.

IBGE. Recommendations for static relative surveys – GPS. Rio de Janeiro: IBGE, 35p., 2008. Accessed on November 29, 2021, available at https://geoftp.ibge.gov.br/metodos_e_outros_documentos_de_referencia/normas/recom_gps_internet.pdf

JAMES, M. R.; ROBSON, S. Straightforward reconstruction of 3D surfaces and topography with a camera: Accuracy and geoscience application. Journal of Geophysical Research: Earth Surface, NW, Washington, DC, v.

ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V. 59, p. 23 – 42, 4/2024
http://dx.doi.org/10.5380/raega.v59i0.94986

117, no. F3, 2012.

KALACSKA, M.; LUCANUS, O.; ARROYO-MORA, J. P.; LALIBERTE, E.; ELMER, K.; LEBLANC, G.; GROVES, A. Accuracy of 3d landscape reconstruction without ground control points using different uas platforms. Drones, Basel, Switzerland, v. 4, n. 2, p. 13, 2020.

LEICK, A. GPS SATELLITE SURVEYING. 3rd Edition, 464 p, 2004.

MONICO, J. F. G. Positioning by GNSS: description, fundamentals and applications. 2. Ed. São Paulo: Editora UNESP, 476p., 2007.

MORTON, R. A.; LEACH, M. P.; PAINE, J. G.; CARDOZA, M. A. Monitoring beach changes using GPS surveying techniques. Journal of Coastal Research, 9, 702–720. 1993.

NEX, F.; ARMENAKIS, C.; CRAMER, M.; CUCCI, D. A.; GERKE, M.; HONKAVAARA, E.; KUKKO, A.; PERSELLO, C.; SKALOUD, J. UAV in the advent of the twenties: Where we stand and what is next. ISPRS journal of photogrammetry and remote sensing, v. 184, p. 215-242, 2022.

PADRÓ, J. C.; MUÑOZ, F. J.; PLANAS, J.; PONS, X. Comparison of four UAV georeferencing methods for environmental monitoring purposes focusing on the combined use with airborne and satellite remote sensing platforms. International journal of applied earth observation and geoinformation, Amsterdam, v. 75, p. 130-140, 2019.

OSCO, L. P.; JUNIOR, J. M.; RAMOS, A. P. M.; JORGE, L. A. C.; FATHOLAHI, S. N.; SILVA, J. A.; MATSUBARA, E. T.; PISTORI, H.; GONÇALVES, W. N.; LI, J. A review on deep learning in UAV remote sensing. International Journal of Applied Earth Observation and Geoinformation, Amsterdam, v. 102, p. 102456, 2021.

TAKASU, T.; YASUDA, A. Development of the low-cost RTK-GPS receiver with an open source program package RTKLIB. In: International symposium on GPS/GNSS. International Convention Center Jeju Korea, 2009.

TEPPATI LOSÈ, L.; CHIABRANDO, F.; GIULIO TONOLO, F. Boosting the timeliness of UAV large scale mapping. Direct georeferencing approaches: Operational strategies and best practices. ISPRS International Journal of Geo-Information, v. 9, no. 10, p. 578, 2020.

TEUNISSEN, P. J. G. The least-square ambiguity correlation adjustment: a method for fast GPS ambiguity estimation. Journal of Geodesy, vol.70, 1995.

TOMMASELLI, A. M. G.; REISS, M. L. L. A Photogrammetric Method For Single Image Orientation And Measurement. Photogrammetric Engineering & Remote Sensing v. 71, no. 6, pp. 727-732, 2005.

ZUMBERGE, J. F.; HEFLIN, M. B.; JEFFERSON, D. C.; WATKINS, M. M.; WEBB, F. H. Precise point positioning for the efficient and robust analysis of GPS data from large networks. Journal of geophysical research: solid earth, v. 102, no. B3, p. 5005-5017, 1997.

O ESPAÇO GEOGRÁFICO EM ANÁLISE
https://revistas.ufpr.br/raega
ISSN eletrônico 2177-2738
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