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Results of Bundle Adjustment with BINGO-F
Toyonaka I + II

Dr.-Ing. Erwin Kruck

1. Introduction

Two photogrammetric flights have been performed in the area of Toyonaka to test and evaluate the possibilities and advantages of airborne kinematic DGPS applications. The main target is to proof that correct and precise results can be achieved with very few ground control points.

This report won't describe the layout and the data of the test flights. This will be particularly provided by Mr. Hasegawa and Mr. Tachibana.

Within the first two chapters the intention an the principle of the new Combined Phase Ambiguity Solution (CPAS) in BINGO-F will be explained briefly. For further details concerning this method please refer to our publication in Vienna 1996.

Furthermore we will give additional hints for the application of DGPS data with GEONAP-K as well as for the combined bundle block adjustment with BINGO-F. Due to our experience some special requirements have to be achieved for getting optimum results from the processing with a minimised effort.

The next chapter will give an overview of computation results for these blocks and comments the results achieved by the GEONAP-K and BINGO-F combination. The results of the two flights will also be demonstrated graphically.

2. Historic development of airborne kinematic GPS

In the past we needed, for the orientation of a single photogrammetric stereo model, at least three ground control points. The introduction of the methods of photogrammetric block adjustments allowed to reduce the number of necessary ground control points to one point for every third model.

The next step for further control point reductions was the introduction of the satellite based Navstar Global Positioning System (GPS):

The principle of precise coordinate estimation for a station point with this system is based on the observation of satellite signals during a certain time period, e.g. one hour. A more precise and faster method is possible, if two or more station points can receive the satellite signals at the same time: In a combined processing the signal differences can be used to estimate the position of these station points relative to each other with a very high precision (DGPS).

The idea to use the airborne DGPS method to estimate the projection centres of the camera release points for a photo flight would allow a reduction of the number of ground control points. This would be a considerable economical advantage as the costs of field work for estimating the ground control points are very high.

However, a precise estimation of the projection centres of a photo flight is limited by several reasons:

- In case of airborne kinematic DGPS only one station is fix, the other one is moving and does not allow to record more than one set of satellite signals for a certain position.
- The orientated relative position between the GPS antenna and the projection centre varies between the strips caused by the heading, pitch and roll of the aircraft.
- In case of a gyro stabilised camera mount, this relative position varies also between all neighbouring exposures.
- The lock to the satellites may be lost during the flight turns.
- The satellite signals cannot be recorded precisely during the camera release. They will be recorded with a frequency of one or two Hertz. However, during one second the aircraft flies approximately 80 meters. Therefore an interpolation must be effected to estimate the position for the camera release point. This interpolation is a loss of accuracy.
- The exposure time of the images must be estimated with a precision more than 0.001 sec, because this time is already related to a flying distance of about 8 cm.

All these influences aggravate the processing of the GPS data and the correct estimation of the antenna positions for the release points. Therefore it’s not always possible to get a stable and correct solution for the whole photo flight.

In the past, the GPS data solution usually was performed strip by strip. This allowed to easily get a solution for the recorded GPS data. Even if the absolute solution for the strip was incorrect, the relative stability and the precision inside the strip have been very good. However, the datum of the strip (three shifts, three rotations and the scale) may be falsified due to the incorrect absolute solution. For longer strips the inner strip geometry may also be falsified. Please refer to chapter 3.

By introducing the so-called "Shift and Drift Parameters", these datum problems can be solved easily. Unfortunately, each strip has its own datum and needs 6 shift and drift parameters. Therefore the stability of the GPS point field in the air is lost. Each line with the GPS data can be moved, rotated and stretched independently like a rubber band. The original stability of the data is lost. Cross strips will become necessary to re-connect the strips, which have been cut during computation.

Conclusion: The necessity of cross strips wasn’t caused by any missing stability of the GPS data, but by the way of data processing.

3. Combined Phase Ambiguity Solution (CPAS)

3.1 Principle of coordinate estimation with GPS

To estimate the coordinates of a ground station, the signals of several satellites will be received and processed. For a precise coordinate estimation the carrier phases will be used. To estimate the distance to a satellite, a phase measurement on the wave of the carrier will be carried out, and then the full wave lengths must be counted and added (see dashes in fig. 1).

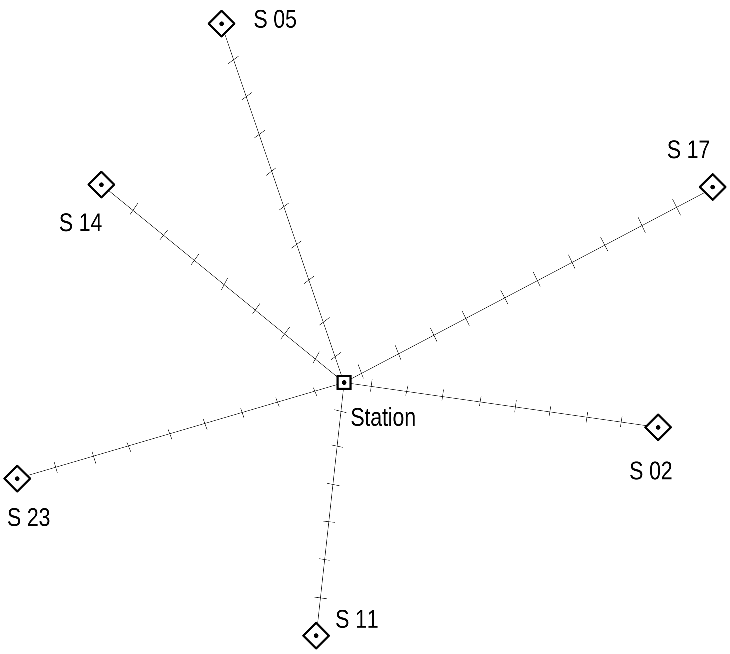

Fig. 1: Configuration for Point Estimation

Unfortunately the number of full wave lengths cannot be counted, but an approximation is given by the running time of the signal. That means, that the solution for the distance is ambiguous.

For better understanding this situation may be compared to a field measurement, where a long distance is measured with a one metre scale; but finally the complete number of full lengths will hardly be remembered. However, the millimetre measurement is precise.

For GPS applications the problem can be solved, as the satellite motion changes the geometric configuration.

This allows to compute the ambiguous counters as soon as the satellites are observed long enough. In case of airborne GPS applications the station (aircraft) moves as well, therefore a longer observation time is necessary for solving the phase ambiguities in a kinematic algorithm.

If the solution for the phase ambiguities is incorrect, position and inner geometry of a flight trace will be falsified. However, even in those cases the relative geometry along a single strip isn't really bad, and the GPS data can be applied with individual shift and drift parameters for each strip. The conclusion is: If an incorrect solution is expected, the processing should preferably be effected strip by strip.

But then additional cross strips have to be used again to link the single strips together. In this case, the original aim of avoiding cross stripes wouldn't be achieved.

3.2 The new approach in BINGO-F (CPAS)

The photos of the cross stripes are more difficult to measure than the regular stripes and cause a lot of expenses. Each additional photo costs about 100 US$, from the planning to the bundle block adjustment. In these small Toyonaka blocks there are already 30 photos in the cross-stripes and therefore additional costs of about 3.000 US$ arise.

To avoid these costs we introduced a new computation method. The basic idea was to take the advantage of the photogrammetric image measurements and of the ground control points for solving the remaining phase ambiguities of the GPS data.

This method seemed to be promising, as the combined processing of GPS observations, ground control points and photogrammetric measurements contain considerably more redundancy than a processing in two steps. The main problem was to combine the data in one single process. It seemed to be impossible to integrate all the photogrammetric data into one GPS-program. The other way round seemed to be impossible, too.

The best solution was to carry out a pre-processing of the GPS-data with GEONAP-K. The coordinates of the antenna position are calculated by GENAP-K, even in the case that the phase ambiguities cannot be solved correctly or even cannot be solved at all. Furthermore, the cycle slips are eliminated as far as possible.

After this processing with GEONAP-K, the interpolation of the antenna position for the camera release points is carried out along the flight way by the program GNINTERP. As input for BINGO-F, GNINTERP prepares a file containing coordinates and release times (events) as well as the geometric configuration of all satellites for each event. Furthermore it provides the information, which of the phase ambiguities have been solved and which weren’t solved (see appendix).

A corresponding unknown will be introduced into the adjustment process for each unsolved phase ambiguity. As result for these unknowns, integer values can be expected. These values indicate the number of wave lengths, which shorten or prolong the distance to the corresponding satellites.

Practically these values won’t be always integer, as many different influences effect on the unknowns. However, in most cases integer values should be reached, at least approximately.

The data provided by GNINTERP have already been transformed into that coordinate type, in which the ground control points are also indicated, e.g. UTM. However, the reference ellipsoid will still be WGS84. Therefore an additional datum transformation (ellipsoid transformation) will be included in the adjustment process in BINGO-F with 7 unknown parameters.

4. Practical results

This CPAS solution has proven its reliability in practical applications in several cases. It has been proven remarkably, that with four corner control points an excellent stability can be reached in a photogrammetric block even without cross stripes. Partly the results with the CPAS-method without cross-stripes are better than the results of conventional methods with cross-stripes (by using the same data material). Even a calculation with only one single ground control point in the centre of the block provides satisfactory results (see appendix). Such a computation is totally impossible with conventional methods using shift and drift parameters.

The expected aim of reaching a reasonable result with only four corner control points without cross-stripes has therefore been fulfilled completely. The requirements for this development have even been surpassed, as the results without cross-stripes are not only equal, but partly better than prior results.

The circumstances, under which better results can be achieved with this method without cross-stripes, aren’t exactly examined yet. Due to our practical experiences, recommendations for practical applications leading to better results can actually be summarised.

Even with the two Toyonaka blocks new experiences have been collected.

5. Requirements for optimum results

5.1 Data recording:

The recording of the satellites signals should be started at least some minutes (5 to 10) before the first photo will be released. If the flight crosses any ground receiver reference station before the area of the photo flight is reached, the data recording should be switched on already at this moment.

The recording of the data must never be switched off during the photo flight.

Each interruption of the recording is equal to a loss of all satellites at that time. The processing reliability depends at a high degree on the continuation of the satellite signal recording during the whole flight. Switching off the recording divides the GPS data into different sections, which can only be processed independently. The advantages of stability of the CPAS method may be lost completely. In the worst case, when all the stripes will be recorded independently, it may happen, that cross stripes will become necessary again, as a single strip is very short and, as pointed out before, a minimum observation time is necessary to get a stable solution for the GPS positions.

In case of the Toyonaka block II, the GPS observations have been divided into 5 partitions (see appendix). The shortest parts of the GPS data are not very efficient for the solution, because the observation time was too short (only three minutes). A solution of all phase ambiguities wasn’t possible. Such configurations should be avoided.

5.2 Sampling rate 1 Hz or 2 Hz:

The highest possible sampling rate should be used in every case. This is especially true, if a flight must be effected under bad weather conditions. If a higher frequency is applied, the interpolation lengths will be reduced.

The best results would be achieved, if the satellite signals could be recorded precisely during the camera release. But this technique is not available yet.

5.3 Number of frequencies:

The recording of the two available frequencies is highly recommended. The necessary atmospheric corrections can be carried out with a better reliability. The dispersion of the computed GPS coordinates will also be reduced.

5.4 Flight performance:

Within both flights the turns had been flown exemplary without losing any satellite lock. This is a considerable advantage for the GPS-data processing. Such a processing can be generally recommended.

5.5 Interpolation

The coordinates have to be interpolated for the camera release points. Usually a time interval of two seconds before and after the release time is used in GEONAP for interpolation. But the second flight shows, that this leads to unsatisfactory results when there is a strong and gusty wind during the flight. Therefore the interpolation has been carried out only between the two nearest recorded points. So, the achieved results has been considerably improved.

5.6 Accuracy of ground control points

The used ground control and check points have an average accuracy of 2 to 3 cm. But several of these points have a lower accuracy. The mean squared residuals (RMS) of the check points in the bundle block adjustment are therefore dependent of the precision of the control and check points as well as of the precision of the photogrammetric procedure.

If four other points would have been used instead of the chosen four corner control points, the RMS-values at the check points diminishes up to 2 cm. For an optimum selection of the four corner control points, a calculation has been carried out. Within this calculation, all data, i.e. photo measurements, all 480 control points and all GPS-data have been processed together in BINGO-F. The points 30030, 310114, 30131 and 310737 have been detected as optimum corner points. They have very small remaining discrepancies. However, for the presentation of the results in this report the given control points 30030, 310114, 30130 and 310742 have been used for all computations. Otherwise the results of the different programs couldn't be compared.

5.7 Estimation of correct weights

The weights of the used measurement data are calculated according to the given standard deviations. But it isn't always easy to find out the precision of the measurement data and the related standard deviations. The different calculations, carried out with other programs, with various weights show clearly, that the selection of weights strongly influences the results.

The adjustment results should preferably be influenced only by objective criteria, and not by the more random subjective estimation of the person carrying out the calculations. Therefore a strict variance component estimation is carried out in BINGO-F, which controls group by group the correctness of the weights according to strict mathematic formula. The standard deviations estimated by this method have been applied for all further computations. Further variations of the weights haven't been carried out and are senseless at all. Tests have shown, that variations of these weights increase the RMS-values of the independent check points.

The rigorous variance component fully confirmed the individual weights of the GPS-data calculated by GEONAP-K in every case. Variations of the weights aren't necessary even in this case.

6. Outlook

We assume that the new CPAS-method will be a new milestone within the development of photogrammetric bundle adjustment. However, the possibilities of applying high-precision kinematic positioning during the photo flight as well as the application of the CPAS-method can furthermore be developed. In future the following items should be developed or at least examined concerning improvement of the results:

- ☞ Rigorous consideration of gyro-stabilised platforms. The possibilities are already given in BINGO-F. However, the practical test with appropriate data for proving the correct processing is still missing. For this purpose, high-precise data are required. The photo flight should be effected at friendly weather conditions. The pilot would then have to swing the aircraft smoothly in all directions. The photos should be taken with a 15 cm camera.
- ☞ Furthermore different interpolation methods should be testes in GNINTERP for optimising the interpolation procedure for different flight conditions.
- ☞ Distance to the reference station: Under economic aspects it seems to be favourable, that the reference station can be far away, without loss of accuracy. Even for this further research is recommended. The necessary photo flights with several reference stations with different distances have already been carried out. The data are completely available, but have to be evaluated.
- ☞ As already mentioned above, the unknown phase positions of the CPAS-method have to be principally integer. For this reason, a research should be carried out, which examines, how far an appropriate influence on these unknowns makes sense, to force them to become integers in the adjustment process.

Toyonaka I - Overview

Case no.	1	2	3	4	5	6
File	FULLDATA	4CCROS	4CNOCR	4CCROSAP	4CNOCRAP	1CNOCRAP
Self Calibration	3+6	-	-	3+6	3+6	3+2
Cross Strips	ON	ON	**OFF**	ON	**OFF**	**OFF**
GPS software	GEONAP	GEONAP	GEONAP	GEONAP	GEONAP	GEONAP
Weights						
Sigma Naught (apriori) [µm]	4.8	4.8	4.8	4.5	4.5	4.5
GCP data: S(apriori) [mm]	22	22	22	22	22	22
GPS data: S(apriori)	Variable	variable	Variable	Variable	Variable	Variable
No. of ground control points	484	4	4	4	4	**1**
RMS X | average residuals	18	31	22	33	19	0
RMS Y | in ground control	16	13	15	21	16	0
RMS Z | points	8	16	10	13	1	0
No. of check points	0	480	480	480	480	483
RMS X | average residuals	-	63	66	43	57	73
RMS Y | in independent	-	63	73	49	48	63
RMS Z | check points	-	93	114	76	74	141
No of GPS positions / photos	230	230	200	230	200	200
RMS X | average residuals	45	44	40	46	40	41
RMS Y | of GPS data	47	54	51	49	43	51
RMS Z |	60	62	62	60	60	61
Total no. of points	18015	1815	1814	1815	1814	1814
SD X | average precision	19	31	32	29	31	38
SD Y | from inverse for	15	27	28	26	27	35
SD Z | all points	34	57	59	53	57	79
Sigma Naught	4.67	4.76	4.32	4.50	4.20	4.30

Toyonaka II - Overview

Case no.	1	2	3	4	5	6
File	FULLDATA	4CCROS	4CNOCR	4CCROSAP	4CNOCRAP	1CNOCRAP
Self Calibration	3+8	-	-	3+8	3+8	3+2
Cross Strips	ON	ON	**OFF**	ON	**OFF**	**OFF**
GPS software	GEONAP	GEONAP	GEONAP	GEONAP	GEONAP	GEONAP
Weights						
Sigma Naught (apriori) [µm]	4.4	4.4	4.4	4.4	4.4	4.4
GCP data: S(apriori) [mm]	30	22	22	22	22	22
GPS data: S(apriori)	variable	variable	variable	variable	variable	variable
No. of ground control points	423	4	4	4	4	**1**
RMS X | average residuals	29	19	12	11	6	0
RMS Y | in ground control	26	27	16	11	7	0
RMS Z | points	7	9	8	2	0	0
No. of check points	0	419	419	419	419	422
RMS X | average residuals	-	89	109	77	97	99
RMS Y | in independent	-	85	114	83	106	70
RMS Z | check points	-	137	159	138	160	217
No of GPS positions / photos	230	230	201	230	201	201
RMS X | average residuals	48	48	48	47	46	46
RMS Y | of GPS data	48	48	42	47	41	42
RMS Z |	46	45	44	44	44	46
Total no. of points	1808	1808	1800	1808	1800	1800
SD X | average precision	20	38	39	37	39	58
SD Y | from inverse for	16	34	35	34	36	51
SD Z | all points	69	113	121	111	119	164
Sigma Naught	4.73	4.93	4.50	4.79	4.36	4.46