Space Photogrammetry: adjustment by the program GLOBO

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Abstract

Even if the present stop of Shuttle missions constitutes a serious obstacle to the developement of space photogrammetry, the contemporary evolution of other positioning techniques (in particular GPS) offers a choice to investigate problems connected with the adjustment of spatial photogrammetric blocks.
In this paper we give ourselves the target of evaluating both the precision and the accuracy considering different choices of control points (i.e. using traditional tecniques or GPS) and operating on real and simulated data.
Particular care has been given to the use of "pseudo-observation" equations regarding the approximate values of unknown parameters.
Moreover we have analyzed the effects on the estimated heights caused by the use of orthometric heights instead of ellipsoidal ones for the control points.
All the adjustments have been made using the program GLOBO and considering the bundles method.

Introduction

One of the most serious problems concerning the use of photographs taken by a space shuttle is to have a reliable set of control points.
The ideal solution would be to establish a network of "ad hoc" points. In particular the most suitable solution to this problem would be the use of the GPS technique, considering the size of the areas involved. Alternatively the coordinates of control points have to be deduced from existing maps since the possibility of recognizing points of networks already existing on the photographs is practically unrealistic.
In this paper we give ourselves the target of evaluating both the precision and the accuracy from considering different choices of control points and operating on real and simulated data.
As for the adjustment of "real" measurements we have to face the problem of translating the a priori cartographic information on the approximate coordinates into "pseudo-observation" equations. Moreover we have taken into account the influence of the use of orthometric heights instead of ellipsoidal ones.
A large set of simulations has been carried out to compare the influence on the parameter estimates of different control point schemes: networks with ground GPS stations only or with both ground GPS stations and GPS on the shuttle.
All the adjustments have been done with the bundle method and using the Institute's program GLOBO. This program has been developed to make the simultaneous adjustment of classical geodetic measurements, photogrammetric measurements and "pseudo-observations" coming from the use of spatial techniques (i.e. coordinates of points derived from a previous adjustment of different kinds of spatial measurements). This

program operates in geodetic coordinates and corrects the classical geodetic equations for the influence of the anomalous gravity field.

1. Adjustment of a pair of photographs taken by Large Format Camera

We started by considering the bundle adjustment of a pair of photographs taken by the Large Format Camera (LFC) during the Shuttle mission - October '84. The photographs, taken from a height of about 235 Km, include an area of about 45000 square kilometers of north-west Italy. The forward overlap is about 70% (see fig. 1.1). The measurements and the relative and absolute orientations have been made on the Zeiss Analytical Plotter C-100; the plate coordinates have been corrected for film deformations exploiting the reseau installed in the LFC. Therefore the standard deviation of measurements has been taken as equal to 3 micrometers. The choice of the 687 measured points has been made taking into consideration well visible points and points which are easily identified on large scale maps. In our case recent technical maps at the scale 1:5000 have been used. The points recognized, mostly road crossing, have been digitized on the map and the N-E coordinates have been trasformed into ϕ, λ, while the orthometric heights have been directly read onto the map. So we have considered a precision in the point determination of 3 m in planimetry and of 4 m in altimetry.

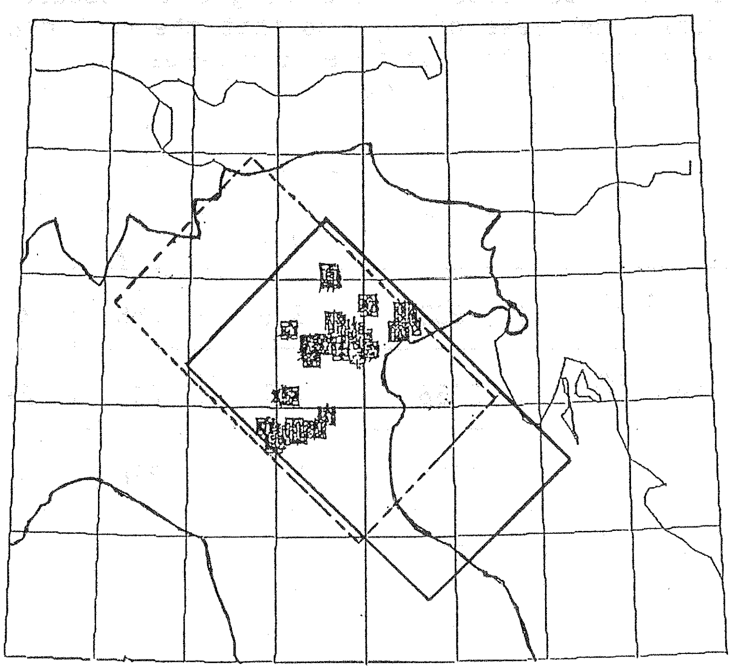

fig. 1.1

We performed two adjustments: the first constraining the strictly necessary number of coordinates to eliminate the rank deficiency; the second considering all the observed points as control points.
Therefore, in the first test we fixed the three coordinates of two points and the height of a third one only. In this way it has been possible to make a first check of both the assumed standard deviation and the quality of measurements. In the second case a "pseudo-observation" equation was written for every observed point coordinate, with a weight proportional to the assumed standard

deviation for its cartographic determination.
In that way we avoid giving a privileged role to same points and forcing the measurements to fit an unreliable geometry.
Looking at the results, reported on the first two rows of table 1.1, we can draw some conclusions:

1) the assumed measurement standard deviation of 3 micrometers seems to be reasonable, since, in the first test, the estimate of σ_o goes back to 3.6 micrometers;
2) in the second test, the considerable increase of σ_o (from 3.6 to 4.7 micrometers) shows that the hypothesis about the a priori standard errors of the approximate coordinates is too optimistic. For this reason, we have performed many other test to evaluate what a priori standard deviation values would be consistent with measurements and with the previously estimated σ_o.

First we introduced the "pseudo-observation" equations for the altimetry only, taking always fixed the points of the minimum constraint test. Varying the weight, we verified that assessing the value of the standard deviation to 4 m provides an estimated $\hat{\sigma}_o$ of 3.7 micrometers, i.e. consistent with measurements.
Thus maintaining this value for altimetry, we constrained planimetry with 8, 6, 5.5, 5 m respectively.
The results are shown in tab. 1.1.
As you can see, the decrease of the weight of pseudo-observation equations produces a decrease of $\hat{\sigma}_o$ so that the root mean square of the standard deviations of the estimates decreases too.
This is a surprising result since to a less precise information corresponds a more precise estimate.

CONSTRAINTS	r = m-n	$\hat{\sigma}_o$ (μm)	R.M.S (σ) (cm) $\sigma_{\hat{\phi}}$	$\sigma_{\hat{\lambda}}$	$\sigma_{\hat{h}}$
no pseudo-observation equations	682	3.6	358	379	1111
$\sigma_{\tilde{\phi}} = \sigma_{\tilde{\lambda}} = 3m;\ \sigma_{\tilde{h}} = 4m$	2736	4.7	241	215	528
$\sigma_{\tilde{h}} = 4m$	1366	3.7	298	306	427
$\sigma_{\tilde{\phi}} = \sigma_{\tilde{\lambda}} = 8m;\ \sigma_{\tilde{h}} = 4m$	2736	3.2	189	183	369
$\sigma_{\tilde{\phi}} = \sigma_{\tilde{\lambda}} = 6m;\ \sigma_{\tilde{h}} = 4m$	2736	3.5	202	193	403
$\sigma_{\tilde{\phi}} = \sigma_{\tilde{\lambda}} = 5m;\ \sigma_{\tilde{h}} = 4m$	2736	3.8	212	200	430
$\sigma_{\tilde{\phi}} = \sigma_{\tilde{\lambda}} = 5.5m;\ \sigma_{\tilde{h}} = 4m$	2736	3.6	207	196	416
$\sigma_{\tilde{\phi}} = \sigma_{\tilde{\lambda}} = 5.5m;\ \sigma_{\tilde{h}} = 4m$ ellipsoidal heights	2736	3.6	206	195	413

$$\text{R.M.S.}(\hat{\sigma}) = \sqrt{\frac{1}{n} \Sigma_i\, \hat{\sigma}_i^2} \quad ; \quad r = \text{redundancy}$$

tab. 1.1

However, the reason for the drop of $\hat{\sigma}_o$ is easily explained if we examine the formula adopted for $\hat{\sigma}_o^2$:

$$\hat{\sigma}_o^2 = \frac{\hat{v}^t P \hat{v}}{m - n}$$

where:

$\hat{v}$ = residuals of equations
P = weight matrix
m = number of equations
n = number of unknown parameters.

In fact the introduction of low weighted pseudo-observations allows the residuals of these equations to became very large without affecting too much the numerator of $\hat{\sigma}_o^2$. Viceversa the denominator increases since the redundancy grows considerably (from 680 to 2736) so that the over all effects is a decrease of $\hat{\sigma}_o^2$.
Now, the following problem arises: to find an unbiased estimate of $\hat{\sigma}_o^2$ when we use "pseudo-observation" equations.
Particularly if we partition the observations as $|y1 \quad y2|^t$ where y1 are the real observations and y2 are "pseudo-observations", taking into account that we set systematically y2 = 0 , the formula for the estimation of $\hat{\sigma}_o^2$ becames:

$$\hat{\sigma}_o^2 = \frac{y1^t \{I - A[A^tA + pI]^{-1} A^t\} y1}{m} \qquad (1.1)$$

where:

A = design matrix of observations
pI = "pseudo-observation" equations normal matrix
(for the sake of semplicity we assume equally weighted pseudo-observation equations)
m = number of real + pseudo-observation equations.

In the limit $p \to 0$, the estimate of $\hat{\sigma}_o^2$ including pseudo-observation equations must tend to the estimate without these equations.
For this reason (1.1) appears a biased estimate of $\hat{\sigma}_o$ since:

$$\hat{\sigma}_o^2(p=0) = \frac{m - n}{m} \hat{\sigma}_o^2 \text{ (without pseudo-observations)} \quad .$$

Since the introduction in the general adjustment of pseudo-observations with correct weights should not change the estimate of σ_o , we have decided to assess the value of the weight in such a way that this condition is satisfied, i.e. so that the $\hat{\sigma}_o$ estimated with pseudo-observations is equal to the one we estimated with minimal constraint only.
In this way the pseudo-observation equations have been used to improve

the accuracy of the estimated parameters with an homogeneous constraint over all the points, avoiding an "easy" gain on $\hat{\sigma}_o$.
Later we investigate if the use of orthometric heights instead of the ellipsoidal ones affected the parameters estimates.
The program GLOBO, as already mentioned, works in geodetic coordinates, ϕ ,λ , and ellipsoidal heights h , so that constraining the orthometric heights of a large number of points, we not only define a different reference system, but we deform as well the internal geometry of the block.
Therefore the l.s. estimate of the parameters would be influenced by the induced deformation.
The first step to verify this hypothesis has been to evaluate the geoid undulation N at the observed points. To this aim we used the estimates of N given by Barzaghi-Benciolini (1986). Starting from a regular grid of undulations we estimated the values of N at the points observed by means of splines interpolation.
Then we compared averages and standard deviations of the corrections $\delta\phi$, $\delta\lambda$, δh starting from two sets of approximate values, the first considering orthometric heights, the second considering the ellipsoidal ones: in principle the two sets should give different results as the approximate values enter also as pseudo-observations.
As you can see in table 1.1 there are no remarkable differences.
These results seems to be reasonable, since in this zone the standard deviation of N is about 1.7 m whereas the measurement photogrammetric precision, referred to ground coordinates, is about 2.4 m, i.e. insufficient to give relevance to this signal. Particularly, it seems that the introduced distortions are absorbed by small changes in the orientation parameters: their estimates in fact varies of a quantity not significant with respect to the standard deviation estimated, but sufficient to balance the effect of N.

2. Simulation study

The analysis of the precision and the accuracy have been done considering the simulated block shown in fig. 2.1.

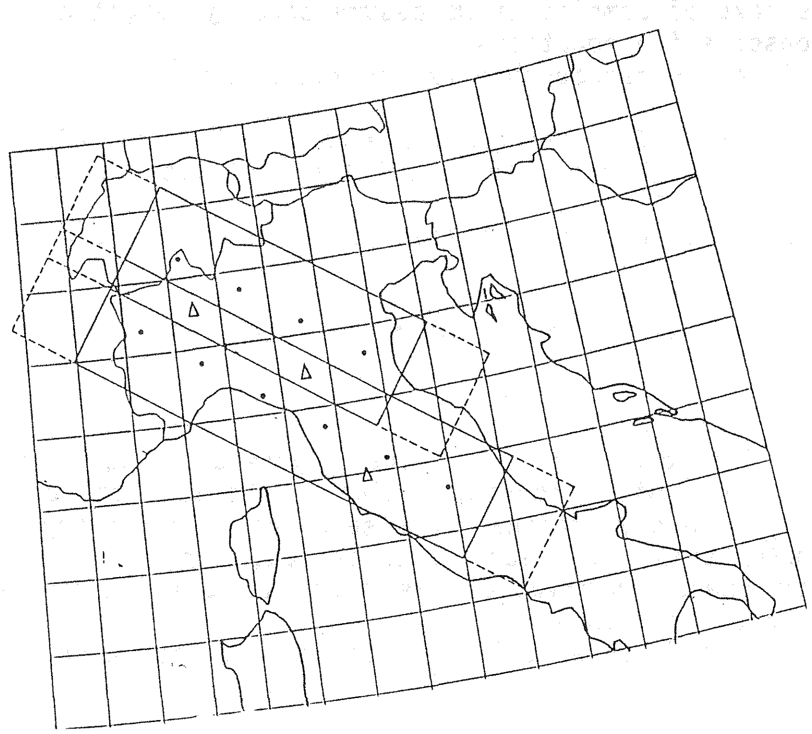

fig. 2.1

It consists of two parallel strips NW-SE oriented (10 photographs); the forward overlap is 70% whereas the side overlap is 25%. We assumed to observe on the plates the points corresponding to a grid of 10'x10' in ϕ and λ ; their orthometric heights have been taken from a data base derived from maps at the scale 1:25000. Furthermore we introduced as observed points the vertices of the National first order network in this area.
The ellipsoidal heights have been subsequently obtained by adding the geoid undulation N as specified above. Altogether we have 688 observed points (about 220 points for every plate), 4378 observation equations and 2124 unknowns.
We were interested in evaluating the size of the estimated parameter errors (i.e. the differences between the simulated and the estimated configuration of the block), so we simulated the observations too. The plate coordinates have then been computed, starting from the approximate values and using ellipsoidal heights for the altimetry.
Our analysis considered the dependence of estimated parameters on:

- the chosen scheme for the ground control;
- the reference surface for the altimetry (geoid or ellipsoidal);
- the size of measurements errors.

The results of the different tests have been summarized giving for every set of estimated parameters x (point coordinates, altitude, projection centre coordinates) both the mean square error of x:

$$m\ s\ e\ (x) = \sqrt{\frac{1}{n}\ \Sigma_i\ (\bar{x}_i - x_i)^2} \qquad (2.1)$$

where:

n = number of estimated parameters
x_i = "true" known value
$\bar{x}_i$ = estimated value

and the root mean square of its standard deviation predicted from l.s. theory:

$$r\ m\ s\ (\hat{\sigma}_{\bar{x}}) = \sqrt{\frac{1}{n}\ \Sigma_i\ \hat{\sigma}_{\bar{x}_i}^{\ 2}} \qquad (2.2)$$

In this sense m s e is a measure of what is called more strictly "precision", while r m s is a measure of the over all "accuracy". When simulating the observations by means of a certain model which is also the same used in the adjustment, the two quantities should be two different estimates of the same object and thus closely comparable.
In this sense most of the time they are used in this paper as a pure check of the program.
The two however differ from one another when the simulated data are generated by adding to the model a non modelled bias, like when we add unmodelled orthometric heights.
Concerning the problem of the choice of the control points, first we constrained planimetrically all the 103 points of the National first order network in the area. Furthermore we assumed the ellipsoidal heights of 28 points to be known. Then, in a more realistic test, we considered a reduced number of control points (6 for the planimetry and 10 for the altimetry). Looking at the results in table 2.1, same

consideration can be drawn:

- the planimetric precision of the estimates is not affected by the number of control points, at the contrary it exists an influence on the heights that are in any way worse estimated;
- to an increase in measurements errors corresponds a delay in the precision of the estimates, as expected;
- the m s e and the r m s ($\bar{\sigma}$) are of the same order of magnitude, so that we can maintain that the estimated values and the theoretical values are not significantly different.

GROUND CONTROL	σ_α (µm)	ϕ (cm)		λ (cm)		h (cm)	
		MSE	RMS($\bar{\sigma}$)	MSE	RMS($\bar{\sigma}$)	MSE	RMS($\bar{\sigma}$)
103 planim.	2	111	114	132	129	315	330
28 altim.	3	166	171	198	193	468	494
6 planim.	2	118	131	133	146	347	362
10 altim.	3	177	196	199	218	519	542

tab. 2.1

Consequently with the conclusions of the first paragraph, we wanted to then compare the parameter estimates errors when orthometric (H) or ellipsoidal (h) control points heights are used.
Two kinds of tests have been performed considering ground control point schemes previously analyzed. The results, obtained taking H or h for both control points and tie points, are shown in table 2.2 (we omit the values of ϕ and λ , since there are no changes).

h (cm)		GROUND CONTROL: 103 planim. - 28 altim.			GROUND CONTROL: 6 planim. - 10 altim.	
		σ plate coordinates in micrometers				
		0	2	3	2	3
E	MSE	5	315	468	347	519
	RMS	5	330	494	362	542
G	MSE	284	399	519	440	576
	RMS	41	332	494	362	542

tab. 2.2

E = with ellipsoidal heights
G = with orthometric heights

In the first test no errors have been introduced on the measurement, to have an idea of the "pure" deformation pattern due to the geoid undulation; as you can see, the m s e is significant. By increasing measurement errors this effect is masked because to the growth of the m s e corresponds a rise in the r m s ($\bar{\sigma}$) , so that globally it becames insignificant. Analogous results are obtained for orientation parameters.
In a second step of our investigation about the ground control two different GPS networks have been simulated. In the first we assume to place a GPS receiver on the Shuttle and three other receivers on ground, along the strips. After a proper adjustment of GPS observations, relative positions (i.e. the differences $\Delta\phi$, $\Delta\lambda$, Δh between a pair of GPS receivers, in particular ground station-projection center of a plate) can be taken as observed. We introduced then in the block adjustment these values as pseudo-observed quantities with various standard deviations, neglecting by necessity correlations and fixing the coordinates of only one ground GPS stations. The results of these tests, introducing measurement errors of 2 and 3 micrometers on plate coordinates and varying the precision of the pseudo-observations from 0.5 up to 5 meters, are shown in tab. 2.3.
We see that, as for previous simulations, none m s e is significant; we note in particular that the decrease in accuracy for point determination, according to less accurate GPS observations, is very little.
In a second GPS ground control network, all the receivers are settled on ground: we kept the stations in the previous configurations for the planimetry (i.e. we assumed to have a GPS received at the same ϕ and λ of a projection centers, for each photograph). In this way we achieved the goal of having the same number of pseudo-observations as in the previous simulation and about the same configuration, but for the heights of the projection centers.
The same kind of pseudo-observation equations has been introduced in the adjustment but, because of the more advantageous GPS scheme, the standard deviations are to be supposed lower.
In fact if one receiver is on a Shuttle while the other is on ground, we cannot assume by differencing that the effect of the ionosphere and the troposphere be cut down.
You can find the results of this second set of simulations in tab. 2.3.
It seems that there is no real dependence of the accuracy of the estimates on the standard deviations of GPS observations (from 0.05 to 0.5 m at least). Assuming for GPS observations the same accuracy, it seems there is no remarkable differences in the r m s (σ) when GPS is settled on ground only and on ground and on the Shuttle.

GROUND CONTROL WITH GPS	σ_α (μm)	φ (cm)		λ (cm)		h (cm)	
		MSE	RMS($\bar{\sigma}$)	MSE	RMS($\bar{\sigma}$)	MSE	RMS($\bar{\sigma}$)
ON THE SHUTTLE σ = 0.5 m	2	116	131	149	140	335	330
	3	174	191	216	206	499	492
ON THE SHUTTLE σ = 1 m	2	119	134	182	143	343	332
	3	174	200	241	214	504	497
ON THE SHUTTLE σ = 2 m	2	135	161	228	208	345	342
	3	185	220	292	229	510	504
ON THE SHUTTLE σ = 5 m	2	192	238	375	225	363	367
	3	240	288	436	282	528	528
ON GROUND ONLY σ = 1 m	2	117	138	143	146	364	375
	3	170	206	202	218	552	560
ON GROUND ONLY σ = 0.5 m	2	115	127	135	139	377	366
	3	170	190	199	207	570	547
ON GROUND ONLY σ = 0.2 m	2	115	123	134	136	386	363
	3	170	184	201	203	580	543
ON GROUND ONLY σ = 0.1 m	2	115	122	135	135	389	362
	3	172	182	202	203	583	542
ON GROUND ONLY σ = 0.05m	2	115	122	136	135	390	362
	3	172	182	202	203	585	542

tab. 2.3

The conclusion could be that, when aiming at determining the coordinates of ground points it is not so important to have an accurate simultaneous determination of the orbit of the carrier; by a comparable amount of GPS measurements on ground will do in any way.

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