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EXPERIENCES AND RESULTS OF THE GPS AERIAL TRIANGULATION TEST URGELL

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ABSTRACT:

In summer 1990 the GPS supported aerial triangulation *Test Urgell* was conducted by the *Institut Cartogràfic de Catalunya* (Barcelona) with the collaboration of the *Institut für Photogrammetrie* (Stuttgart) and the *Rijkwaterstaat* (Delft).

The goal of the experiment was, among others, to analyze the overall error characteristics of kinematic GPS positioning under the conditions of an operational environment and to let the flight and photogrammetric departments of the ICC get in contact with the GPS technology and its application to aerial triangulation.

An important component of the test was a block of 257 images flown at 1:16500 image scale over a test field with simultaneous recording of GPS carrier phase data. In the paper, the experiences and results of this test block are described.

KEY WORDS: aerial triangulation, GPS.

1 INTRODUCTION

In July 1990 a GPS experimental photogrammetric flight, the *Test Urgell* was conducted by the *Institut Cartogràfic de Catalunya* (ICC) in collaboration with two other European institutions: the *Institut für Photogrammetrie* (IfP) and the *Rijkswaterstaat.*

The experiment was preceeded by a kinematic positioning exercise organized by the ICC and the French company SAGEM which took place in November 1989 near Barcelona's International Airport. The *Test Urgell* is part of PoCNav (*Posicionament Cinemàtic i Navegació*), a larger project of the ICC. The long term goal of PoCNav is to develop an operational system which allow general position and attitude determination of airborne sensors for environmental, mapping and numerical point determination purposes, and which facilitate navigation according to a predefined aerial survey plan.

This paper will solely report on the experiences and results of the test. The general approach to and the theory behind the problem can be found in [1, 2, 5, 7, 8, 12] for the GPS supported aerial triangulation and in [3, 4, 10, 11] for the more complex GPS/INS integration for position and attitude determination and for precise navigation.

The goal of the test was manifold. First of all, the overall performance of aerial triangulation with kinematic GPS derived aerial control at a medium image scale —1:16500— had to be assessed (aspect 1). Second, the long term effect in the kinematic GPS positions —drifts— of approximately solved ambiguities and other systematic factors, had to be empirically investigated (aspect 2). Third, the software and procedures developed by the three institutions during the analysis of the data from the dutch test block Flevoland [5, 7, 12] had to be tested against new and better (sic) data. Last, the different groups of the ICC involved in the aerial triangulation process, from the aircraft's crew to the photogrammetric operator, had to have a first contact with this application of the GPS technology.

For the purposes described above two tests were planned: AT for research aspect 1 and DR for research aspect 2. For the tests, four areas —1 AT + 3 DR— were selected as depicted in Figure 1. The three DR test areas (D_1, D_2 and D_3), approximately lay on a straight line.

The aircraft was a *Partenavia P-68 Observer* (twin piston engine, high wing) equipped with a *Wild RC10* camera (153.653 *mm* focal length) and with an *Ashtech LD-XII* dual frequecy GPS receiver.

In test DR the aircraft repeated several times the same operation: flying from one test area to the next one in the way defined by the following sequence

$$D_1\ D_2\ D_3\ D_2\ D_1\ D_2\ D_3\ D_2\ D_1 \ldots$$

Every time that the aircraft flew over D_1, D_2 or D_3, about 20 photographs were taken for the ***a posteriori*** photogrammetric control of the GPS antenna coordinates. This could have been done since in every test area a small control network was available (20 signalised and targeted points at an approximate distance of 460 *m* from each other). All coordinates were referred to the same reference system. Flying height above ground was about 768 *m* which resulted in an approximate image scale of 1:5000.

Unfortunately, for reasons described in Section 3, the data gathered in the test DR could not be processed. The paper will, therefore, concentrate on the AT component of the test.

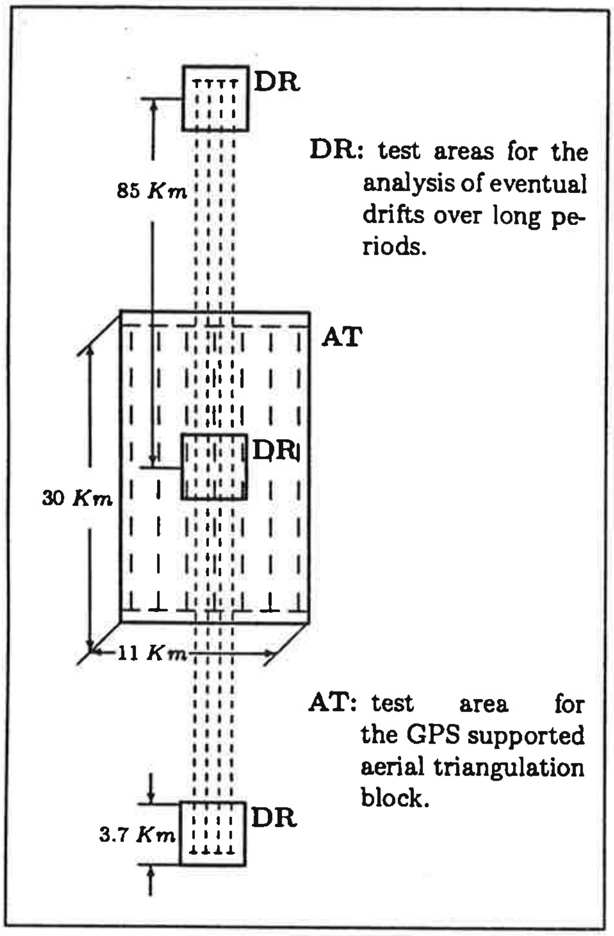

Figure 1: Test areas as of the original plans.

2 THE URGELL AT TEST BLOCK

The AT test block is a standard test block constituted by a high precision terrestrial network whose points can be used either as control or check points, by a photogrammetric network and by the kinematic GPS aerial control observations.

2.1 Terrestrial control network

In the AT area a three dimensional network of 66 points was observed by the ICC and the IfP with *Ashtech* receivers. The network was established in two steps.

First, a basic network of 10 points and 31 difference vectors were observed and adjusted. In a second densification step, 338 difference vectors were observed. The overal precision of the so obtained network is 1.67 *cm*.

The coordinates were further transformed from the WGS84 reference system into a local horizon cartesian reference system.

2.2 Antenna-receiver-camera set-up

Since the ICC's *Partenavia* is a high wing aircraft, in order to avoid satellite oclusions by the propellers, a 1.20 *m* height mast was constructed. The antenna, a single frequency *Adams-Russell AN-712*, was screwed on top of the mast. In the last set-up configuration there was a filter provided by *Ashtech-SAGEM* between the antenna and the receiver.

The receiver was powered by an independent battery so oscillations or other disturbances in the aircraft's power supply could not perturbate the phase observations. Carrier phase data was recorded once per second into a PC *GRiDCASE 1530*. The *LD-XII* receiver had the photogrammetric camera input —an event marker— option which was fed by a photodiode installed in the camera. The photodiode provided time signals for the instant of maximum aperture with a sincronization accuracy better than 1 *ms* when the shutter was released at 1/800 *s*.

The offset between the camera projection center and the antenna phase center was measured and computed after each flight session [9]; i.e., the navigator had the freedom to maneuver the camera before the first photograph was taken, then the camera was held fixed until the vector offset was measured.

In short, with the exception of the mast, this was a similar set-up to that used in the Flevoland test (see [5, 7, 12]).

2.3 Experiment design: photogrammetry

The main block parameters are given in Table 1. A layout of the block is depicted in Figure 2.

The photogrammetric block AT was designed as a standard block of 9 strips (60% x 60% overlap, 25 images per strip) with the addition of 3 cross strips (11 images per strip) as suggested in [2] and with the setting of the nominal overlaps to 65% in order to guarantee a final 60% since the camera was held fixed after the first photograph and since only smooth maneuvers were allowed to the pilot.

All control/check and tie points were originally targeted.

2.4 Experiment design: GPS

A reference receiver was set up on the center of the AT test area, 60 *Km* away from the airport. The original plans were to solve the ambiguities on the ground and compute the trajectory of the aircraft hopping that no loss of lock will occur during the flight.

In order to initiate the kinematic observation the

C	*WILD RC10*	n_s	207	C	camera type	n_s	n. of sig. points
		n_a	1138			n_a	id. pugged tie points
f	$153.653\,mm$	n_t	1202	f	focal lenght	n_t	total n. points
h_g	$2535\,m$			h_g	flying h.ab.ground		
s	1 : 16500	n_{go}	3×257	s	photo scale	n_{go}	n. GPS obs.
v	$265\,Km/h$	n_{DP}	14	v	airplane speed	n_{DP}	id. drift par. sets
p	65 %			p	forward overlap		
q	65 %	Control points		q	side overlap		
			$n_{HV} + n_V$			n_{HV}	num. full control p.
n_i	257	I	$4 + 0$	n_i	id. images	n_V	id. vertical c.p.
n_{AP}	3	II	$4 + 2$	n_{AP}	id. AP sets		
n_s	$9 + 3$	III	$4 + 4$	n_s	id. strips		
n_{is}	$25 - 11$	IV	$4 + 14$	n_{is}	id. photos/strip		
t	$17\,s$	V	$4 + 16$	t	time between exp.		
		σ	$1.63\,cm$			σ	σ control points
n_{po}	2×7894			n_{po}	num. of photo obs.		
σ_s	$2 - 20\,\mu m$	Check-points		σ_s	σ signalized points		
σ_a	$2 - 20\,\mu m$		$n_{HV} + n_H$	σ_a	σ pugged points	n_{HV}	number full ch.p.
m_p	6.57	I	$55 + 0$	m_p	obs./point	n_H	id. horizontal ch.p.
m_i	30.72	II	$53 + 2$	m_i	obs./image		
		III	$51 + 4$				
		IV	$41 + 14$				
		V	$39 + 16$				

Table 1: Main parameters of the block AT.

reference receiver and the airborne receiver remained stationary for about one hour to solve the initial ambiguities.

Once the aircraft took off it smoothly climbed to the desired height describing circles to avoid bank angles greater than 5° that could cause a loss of lock. All this maneuvers were possible because the airport selected (Reus) had a moderate traffic, this could not be done in Barcelona's International Airport.

The turns between strips were also very smooth avoiding inclinations greater than 5°.

The maneuvering within the strips was also restricted. (Recall that the overlap between strips was designed to account for that restriction.) Finally the landing was done avoiding bank angles again greater than the above mentioned 5° and whenever possible another static observation was done.

3 EXPERIENCES

The realization of the *Test Urgell* was affected by a number of unexpected difficulties which ruined most of the project. Actually, only results of a low accuracy and therefore of a questionable value for the photogrammetric community could be obtained. Since, however, anyone who is conducting a similar test may be affected by similar problems it is worth listing them.

Receiver sensitivity to radio sources. It was soon discovered that every time that the pilot (frequencies' range: 117.975 – 136.000 *MHz*) communicated with the traffic controlers all satellites were lost. After many checks and once the manufacturer accepted that the receiver itself was to blame, he provided a filter which solved the problem. The experiment could be further continued, however, after many wasted flying hours and with the GPS window already shifted too early in the morning.

Receiver sensitivity to bank angles. Over the whole experiment the bank angles reached when changing from one strip to the next were carefully kept to a minimum ($< 5^o$). Again, lock to some satellites with an elevation angle greater than 15° was lost. In this case, multipath effects due to the situation of the GPS antenna 1.2 m above the aircraft's fuselage might have had an influence. Similar preliminary tests made with the new generation of *Ashtech P−XII* receivers show a much more robust behavior and therefore indicate that the *LD-XII* receiver was again to blame.

This last problem was present in both AT and DR tests. Thanks to the introduction of drift nuisance parameters in the combined adjustment the data gathered for the AT could be processed as de-

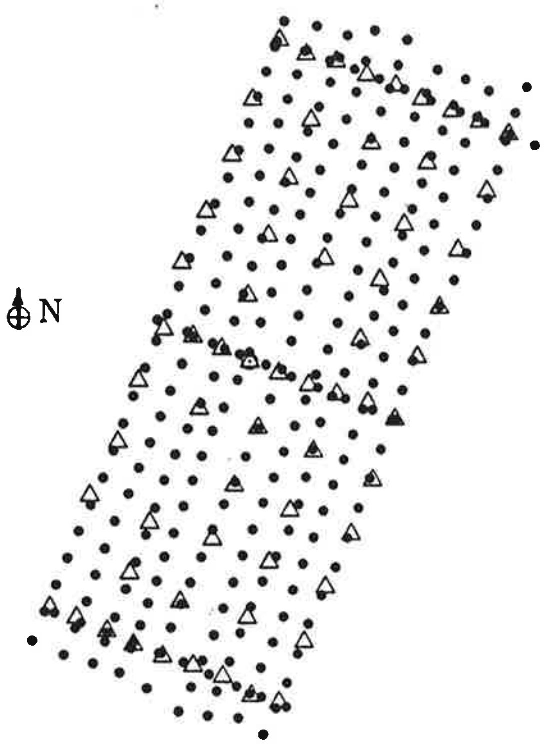

Figure 2: General layout of the block (△: control point, •: projection center).

scribed in the next sections.

Receiver sensitivity to high peak accelerations. During the realization of the DR test strong air turbulences were found in the vicinity of some mountain ranges. In several ocassions this resulted again in a total loss of lock to the GPS satellites. (Contrary to the AT test, continous tracking of four satellites at least was essential for the DR test.)

Image quality. Since the exposure time was 1/800 s, the diafragm was opened to its maximum (4). This unsual aperture for the ICC's *RC-10* resulted in blurred images.

The identification of the targets for the tie points (207!) was just impossible and for the control/check points extremely difficult. In addition to the original identification by means of "punched" orthophotomaps, all control/check points had to be revisited —5 of them could either not be measured or rejected as identification gross errors in a previous conventional bundle block adjustment without GPS aerial control. Thus, the accuracy of the photogrammetric observations was very low. For each particular observation the operator made a guess on its precision which gave *a priori* standard deviations ranging from 2 to 20 μm. This low precision is the decisive factor influencing the results reported in Table 3 and Table 4.

4 DATA PROCESSING

All GPS data has been processed using the *Ashtech* GPPS software. For the rest of the data processing, network adjustments of one type or another (terrestrial control network adjustment, conventional bundle block adjustment, combined GPS and bundle adjustment), the GeoTeX/ACX software [6] has been used.

4.1 Processing of the GPS observations

Since the signal was lost several times (see Section 3) it was not possible to process the data as it was originally planned, so the data were divided into 14 independent data sets. Each data set contained the data recorded for both receivers during the flight of one strip. Due to a loss of lock within the strips 4 and 11, the corresponding data were subdivided into four subsets 4.1, 4.2, 11.1 and 11.2.

Coordinates for each data set thereof were computed independently following the approach described in [7, 8]; that is, amounts closest as possible to the true ambiguities are estimated for a specific epoch at each data set.

"as closest as possible" means either one of the following alternatives:

- solving the initial static baseline between the static receiver and the airborne receiver;
- with the help of the orientation elements of one photograph and the antenna offset vector (In the *Test Urgell* the orientation elements were computed taking as control points nearly the whole terrestrial network. This is not tricky since eventual errors so introduced will be accounted for in the combined adjustment.);
- using pseudorange observations.

"specific epoch" means either

- at the beginning, during the static measurement;
- or given a projection center, at the time of the nearest GPS data epoch.

Since the antenna was a single frequency one the data processed were L1 carrier phase observations.

The trajectory of the aircraft was computed using *Ashtech*'s GPPS. The files containing the GPS data sets, however, could not be directly used as input files. In order to avoid small uncorrected cycle slips, flags referring to satellite health had to be changed. The antenna positions at the exposure instants were linearly interpolated between the positions of the nearest GPS epochs.

4.2 Processing of the photogrammetric observations

Photogrammetric observations were adjusted twice.

First a previous conventional bundle block adjustment without GPS aerial control was processed to compute projection centers for the GPS kinematic processing and to eliminate gross errors from the photogrammetric observations. There were 7627 photogrammetric observations (average of 30.72 observations per image). At this step, 5 terrestrial control points were rejected due to wrong identification on the images.

After the GPS data processing, a combined bundle block adjustment was computed. There was the same number of photogrammetric observations, 3 sets of additional self-calibration parameters (Ebner's 12 orthogonal parameter set), 254 GPS aerial control observations and 14 sets of linear drift parameters; different control and check point configurations were used (see Section 5.2).

5 RESULTS

5.1 Empirical accuracy of GPS positioning

The projection centers of the photographs computed by aerial triangulation were used for testing the projection centers given by the GPS data. The results are summarized in Table 2 where the root mean square values of the differences between both solutions are shown.

Note the differences between Table 2 and Table 3, which show the existence of drifts in the GPS aerial control.

				PDOP	
Strip	X	Y	Z	min	max
1	0.61	1.08	0.79	4.9	5.5
2	0.55	0.99	0.39	3.6	4.0
3	0.58	1.05	0.53	3.2	10.4
4.1	0.61	0.69	0.37	3.9	5.1
4.2	0.29	0.28	0.25	4.0	5.0
5	0.77	0.76	0.88	6.5	38.1
6	0.85	0.48	0.37	4.6	9.8
7	0.69	0.84	0.81	2.5	5.5
8	0.31	0.74	0.39	3.1	4.8
9	0.70	0.65	0.42	5.2	12.8
11.1	1.75	0.92	0.66	5.3	12.3
11.2	0.24	0.41	0.41	4.6	21.6
12	1.68	1.49	1.97	4.8	46.1
13	1.27	0.87	0.38	5.0	5.7

Table 2: r.m.s. of differences at the projection centers between the conventional bundle and GPS determinations (units in meters).

5.2 Ground control configurations

Five different ground control configurations have been considered. Each ground control set consists of 4 horizontal and vertical control points located at the block corners and:

- no other control points (AT-I, Figure 3);
- 2 vertical control points located at the block border, at the ends of the central cross strip (AT-II, Figure 3);
- 4 vertical control points located at the block borders (AT-III, Figure 3);
- 2 vertical control chains located at the block border, at the ends of the strips (AT-IV, Figure 4), as suggested in [2];
- the configuration AT-IV with the addition of 2 vertical control points at the ends of the central cross strip (AT-V, Figure 4).

The above configurations were selected on the basis of this specific block error behavior and are not intended for the establishment of general minimal ground control patterns.

5.3 Results of the combined adjustment

The results for each one of the five control distribution configurations are shown in Table 4 whose amounts are the differences between coordinates obtained in the adjustment of the terrestrial network and coordinates obtained in the combined adjustment.

In Table 4, in addition to the five control configurations, two different sets of check points, F and I, have been used in the empirical evaluations ($\#(F) = 55$, $\#(I) = 25$). F stands for the full set of check points available for each specific control version; I stands for F after removing the check points which lay on the border of the block. The distinction has been made

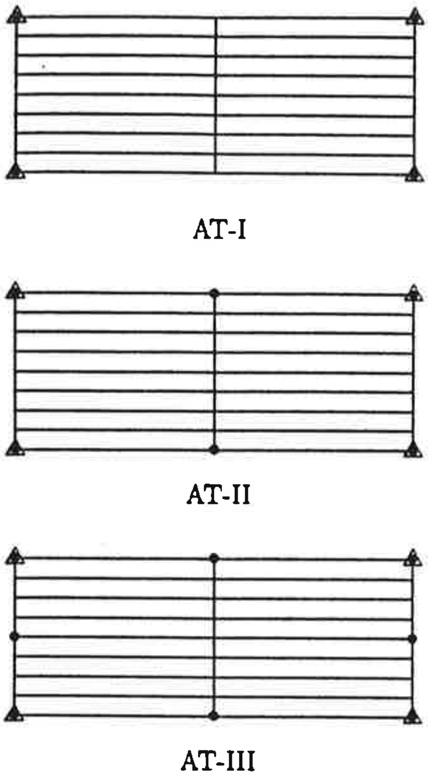

Figure 3: Test block AT control configurations I, II and III (Δ: horizontal control, •: vertical control).

since the largest differences correspond to points in $F - I$.

For the analysis of the results it must be kept in mind that the root mean square value of the photogrammetric residuals, r_p, is $r_p \approx 10\ \mu m$ and that if the mean is taken over the photogrammetric residuals for the check points, then it is $r_p \approx 13\ \mu m$.

Configuration I is affected by large systematic deformations, specially in the height component. These deformations concentrate on the block border. Configuration II is an intermediate one in the sense that there are still large systematic deformations of a similar type.

Configuration III stabilizes, practically, the block geometry. (Further control densification does not substantially contribute to the reduction of systematic effects on the border.) In spite of everything that happened to the *Test Urgell*, the accuracy potential of kinematic GPS aerial control is shown already in this configuration; for the check points in the interior of the block it holds $r_V \approx 0.35\ m$ or, equivalently, $r_V \approx 0.0138\% \cdot h_g$, $r_V \approx 21\ \mu m$.

Configuration IV yields similar qualitative results to those of configuration I; again deformations are still present on the border. The results of configuration V are only slightly better than the ones of config-

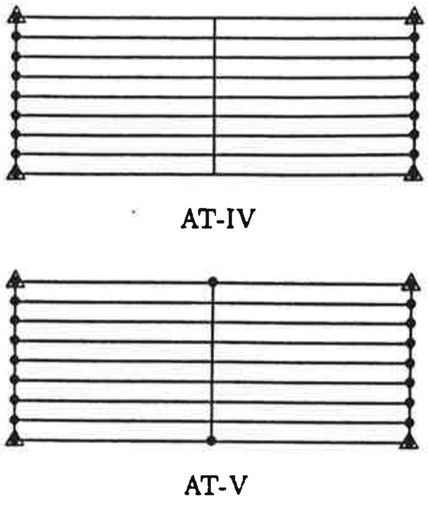

Figure 4: Test block AT control configurations IV and V (Δ: horizontal control, •: vertical control).

AT version	GPS aerial control		
	X	Y	Z
I	0.34	0.35	0.29
II	0.34	0.35	0.29
III	0.34	0.35	0.27
IV	0.33	0.35	0.26
V	0.33	0.35	0.27

Table 3: Residuals of kinematic GPS aerial control observations in the combined adjustment (units in meters).

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AT version		*F*			*I*		
		X	Y	Z	X	Y	Z
I	μ	−.01	.09	−.09	.03	−.04	.22
	r	.35	.47	.99	.43	.45	.72
II	μ	−.00	.09	−.01	.03	−.04	.16
	r	.35	.45	.72	.42	.43	.55
III	μ	−.01	.08	−.14	.02	−.04	.04
	r	.35	.45	.53	.42	.43	.35
IV	μ	−.01	.09	−.25	.02	−.04	.05
	r	.32	.48	.68	.42	.44	.35
V	μ	−.01	.09	−.10	.02	−.04	.07
	r	.33	.47	.45	.42	.42	.30

F: all check points included. μ: mean.
I: check points not on the border. *r*: r.m.s.

Table 4: Results of the combined adjustment (units in meters).

urations III and IV for the *I* set and much better than the ones for the set *F*, similarly as it happens when adding two vertical control points to configuration I.

Because of the poor quality of the data it is a risky adventure to go further in the discussion of the results and to draw general conclusions upon them.

6 CONCLUSIONS AND PROSPECTS

No one of the scientific goals set (Section 1) for the test has been achieved because of the adverse circumstances that played havoc against the experiment. In particular, the analysis of the DR data set had to be cancelled. The analysis of the AT data for the *I* set, however, shows results consistent with the synthetic precision models [2] ($\sigma_H \approx 2.1 \cdot \sigma_0 \cdot s$, $\sigma_V \approx 2.3 \cdot \sigma_0 \cdot s$).

The ICC's *Partenavia P-68 Observer* is now equipped with the new *Zeiss RMK TOP* aerial metric camera, which allows for a straightforward sincronization with the GPS receivers, and with the new *Ashtech P-XII* dual frequency P-code receiver. (In the preliminary tests the *P-XII* exhibits a much better performance than the *LD-XII*.)

The next GPS aerial triangulation block will be flown in June 1992 in the frame of a urban cartography project; image scale will be 1:3500, forward overlap 60% and cross overlap 35%; there will be a ground control/check point every 800 m.

7 ACKNOWLEDGEMENTS

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I.Guillén (pilot) and J.Martí (navigator) of the ICC Flight Department and R.Miguel and M.Miguel (aircraft's maintenance technicians) of *M & S Aviació en General*, were key —and patient— people of the project.

J.Sendra (ENIFOSA) organized the signalization of the test areas in a short time. S.Costa (ENIFOSA), M.Englich and E.Stark (IfP) participated in the observation and adjustment of the terrestrial control network. J.Gili (*Escola Tècnica Superior d'Enginyers de Camins, Canals i Ports*, Barcelona) determined the PC-antenna offset [9].

The artificial point transfer (PUG) was done by C.Ruiz and the photogrammetric measurements by M.Roman, both of the ICC Cartographic Production Department.

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