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GEODETIC CONNEXION BETWEEN FRANCE AND NORTH AFRICA BY SIMULTANEOUS SIGHTING OF THE ECHO I ARTIFICIAL SATELLITE

Report submitted by the French Government

M66-1098

GEODETIC CONNEXION BETWEEN FRANCE AND NORTH AFRICA BY SIMULTANEOUS SIGHTING OF THE ECHO I ARTIFICIAL SATELLITE[1/]

I. GENERAL PRINCIPLES OF SATELLITE TRIANGULATION

The basic principle is very simple: a luminous object is seen against a different star background according to the observer's position on the earth's surface. It can be seen that a photograph of this luminous object and the surrounding stars, will give information which permit the finding of the position of the point on the earth's surface, on the assumption that the positions of other observations points are known.

Let us clarify this idea: the solid earth, assumed to be indeformable and to which is attached a trihedral TXYZ, has a known directional movement through the stars in function of time. This movement being given by astronomy dealing with star position. Fixing the time means immobilizing the position of the trihedral in the stellar field; each star, then constitutes an absolute direction, in relation to the trihedral TXYZ, such direction is given by the star almanac.

In the same way we must "immobilize" the luminous object, which, in practice, makes it necessary to observe simultaneous or nearly simultaneous observations from different points on the earth's surface, which are to be connected.

If the luminous object send only flashes: simultaneity is automatically ensured. If it is continuously luminous; then "artificial flashes" have to be arranged. This can be achieved by using, at the various observation points, rotating shutters which can be synchronized altogether.

"Anna" is a flashing satellite and has been used for geodetic operations. It is more expensive than a continuously luminous satellite; it operates only on command; there has been some failure in its operation.

1/ By the Institut Géographique national.

Echo I and Echo II are continuously luminous satellites and Echo I was chosen for the France - North Africa link.

In practice, each photograph includes:

- A certain number of images of stars, from which it is possible to calculate the orientation of the camera;
- A certain number of images of flashes: in the case of the French observations, the shutter, rotating at 1 rps, gives a series of 60 dots of light or 'flashes' a minute.

In essence, the problem is to interpolate these dots among the known positions of the stars; it should be pointed out immediately that the 60 dots are reduced to one 'central flash' and that one obtains the direction of this 'central flash' in the trihedral TXYZ.

Each photo therefore gives a known direction SF, S being the station and F the fixed point. It will be seen, in the case of the connexion between France and North Africa, how the geodetic problem is tackled on the basis of such fundamental data.

Some values essential for the accuracy:

If an angular precision of 1", or 1/200,000 radian is desired, it is necessary to have

- the accuracy of the rotating shutter reaching $1/10^{-3}$ second
- the siderial time must be known to 1/20 second
- the determination of the position of the stars and the dots on the photographic plate (for a focal length of 30 cm) must have an accuracy of 2 to 3 μ.

II. INSTRUMENTS

In essence the apparatus consists mainly of:

- a 30 cm focal length camera fitted with a rotating shutter and a chopping shutter

- a quartz chronometre regulating the rotating shutter at the speed of 1 rps for photography of the satellite and actuating the chopping shutter for photography of the stars.

The whole apparatus is extremely simple and easily portable.

The time readings are made:

- for the satellite, direct on the graduation of the rotating shutter: the dial of the shutter is illuminated always at the same point at every second pip of the time signal, so that the observer can make a reading correct to 10^{-3} sec.

- for the stars the same principle applies, using a revolving graduated disc incorporated in the quartz chronometre.

III. THE GEODETIC CONNEXION BETWEEN FRANCE AND NORTH AFRICA

The Institut géographique national, in agreement with the Algerian authorities, carried out observations for the geodetic connexion between France and North Africa by simultaneous photographic observation of the Echo I satellite.

Known points:

- Lacanau (near Bordeaux on the Atlantic coast)
- Agde (near Sète on the Mediterranean)
- Oletta (Corsica)

Points to be determined:

- Hammaguir (Western Sahara)
- Ouargia (Eastern Sahara)

In fact, the five points are known within the European adjustment system (the so-called 1950 Europe Adjustment) and the work therefore is designed for comparing the results of conventional geodesy with those of satellite geodesy.

Satellites used

The only observations selected are those made on Echo I as it culminates at approximately 47° 5, which is very suitable for observations over the Mediterranean.

The observations were spread out over the period 4-26 May. It was sometimes possible to record four useful crossings per night.

Echo II was also observed from 20 May onwards, but the results were not retained. Echo II has one useful crossing at the most.

Geodetic configuration

In the final computation, all the observations of absolute directions will provide relations of observations, which will make it possible to fix the unknown points (with a table of errors); however, for the observations themselves, it is necessary to define a general line of work that will from the outset ensure a satisfactory over-all configuration.

The following reasoning may be applied:

First point of view

The central meridian of the zone of observation is approximately 2° E and the central parallel is 38° N. The most important points for the link are the points of the satellite's trajectory along the mean parallel, to the east and west of the central meridian, respectively, the eastern point being vertically over the south of Italy and the western point vertically over Spain. These points are determined by intersection from the three French base points. They themselves, by intersection, determine the points in Africa: considering the figure it will be realized that the latter intersection is satisfactory but that the first is not excellent: the French points constituting rather a short base.

Second point of view

The set of directions defined by the stars determine a certain number of planes: these planes, in association, make it possible to define straight lines joining the points on the ground.

An examination of the figure shows that all the straight lines figure are well defined except that between Ouargia and Hammaguir, because it was difficult to find points in Africa not situated in the shadow cone. Here again it will be realized that the African points are fixed by means of intersection from a French base that was a little too short.

Forecasting of crossing of the satellite

In practice, the point of the satellite's trajectory to be sighted on each crossing is worked out in advance; the co-ordinator of the work chooses this point on the basis of various criteria;

- First, the need for a general geometrical figure of good shape as mentioned above;

- Hours of observation acceptable for photography of the stars: from this point of view, stations at high altitudes are very unfavourably situated in summer;

- Also the satellite must come out of the shadow cone soon enough for the observers not to be caught unawares; in fact, the time of the satellite's arrival cannot be forecast within less than five minutes.

In theory, it would also be possible to take into account the successful observations of the previous nights but in practice that is hardly possible; in fact, the general co-ordinator draws up a plan and follows it almost strictly.

For the forecasts we use the ephemeris of Echo I provided by the Smithsonian Astrophysical Observatory of Massachussetts.

As soon as an ephemeris is received, the crossings of the satellite are numbered and the ephemeris is extrapolated for about a fortnight; the points of crossing are chosen, that is to say the points in the sky towards which all the ballistic cameras are to be directed; an electronic programme then gives a list indicating all the observation data for each station.

In practice deviations of the order of 10 minutes in time and 2-3° longitude are regularly noted between the extrapolated data of the ephemeris and the values of the following ephemeris; such deviations, although undesirable, are within acceptable limits. They result from the fact that as Echo I is very luminous it is extremely sensitive to radiation pressure.

Field work

Only two operators are needed for the photography but in practice it is desirable to have a team of three: throughout the effective period, photographs are taken every two hours nightly; under these conditions it is desirable to allow every operator to rest for one night in three.

The photographic work includes the following phases:

(setting up the camera - two hours before observation)
(starting the chronometre)
loading the camera with a plate
checking the chronometre against the time signals
stars photograph (first exposure)
starting up the disc shutter, adjustment by means of time signals
photography of the satellite at the rate of 1 exposure per second
  except at the 60th second of each minute, this exposure is
  eliminated by a disc manipulated by an operator
stopping the disc: photography of the stars (second exposure)
photography of the fiducial marks
reloading of the camera
setting up the camera for the next observation

The work also comprises:

- development of the plate
- making one annotated paper print showing the satellite's direction of crossing, the numbering of the minutes and the direction of diurnal motion.

The most important factors in field work are:

- steadiness of the camera between the two exposures of the stars; at present this period is 15 minutes and will be reduced to less than 10 minutes.
- time recording on the rotating shutter which must be correct to 10^{-3} seconds

Successful night observations

Approximately 60 positions of the satellite were to be photographed, 60 exposures being made of each. The following table shows the number of successful photographs.

Hammaguir	:	15
Oletta	:	40
Lacanau	:	25
Ouargla	:	40
Agde	:	35

Naturally when any point is observed simultaneously from at least two stations, the results can be processed. In theory the probability of one position in five successful plates is:

$$\frac{15}{60} \times \frac{40}{60} \times \frac{40}{60} \times \frac{35}{60} \times \frac{25}{60} \# \frac{1}{37}$$

In fact there were only 2 entirely successful exposures out of 60.

IV. INVESTIGATION OF PLATES - COMPUTATIONS

The field observations were studied by IGN, with the following stages of computation:

A. Calculation of the theoretical positions of the stars on the plates.

B. Measurement by comparator of the stars and the satellite images.

C. Smoothing of the positions of the satellite images on the plate.

D. Calculation, from the plate co-ordinates of the stars, of the direction cosines in the three-dimensional earth system. Application of the transformation to the plate co-ordinates of the satellite.

E. Study of the dispersion of intersections on Echo from the five stations considered as determined by conventional geodesy.

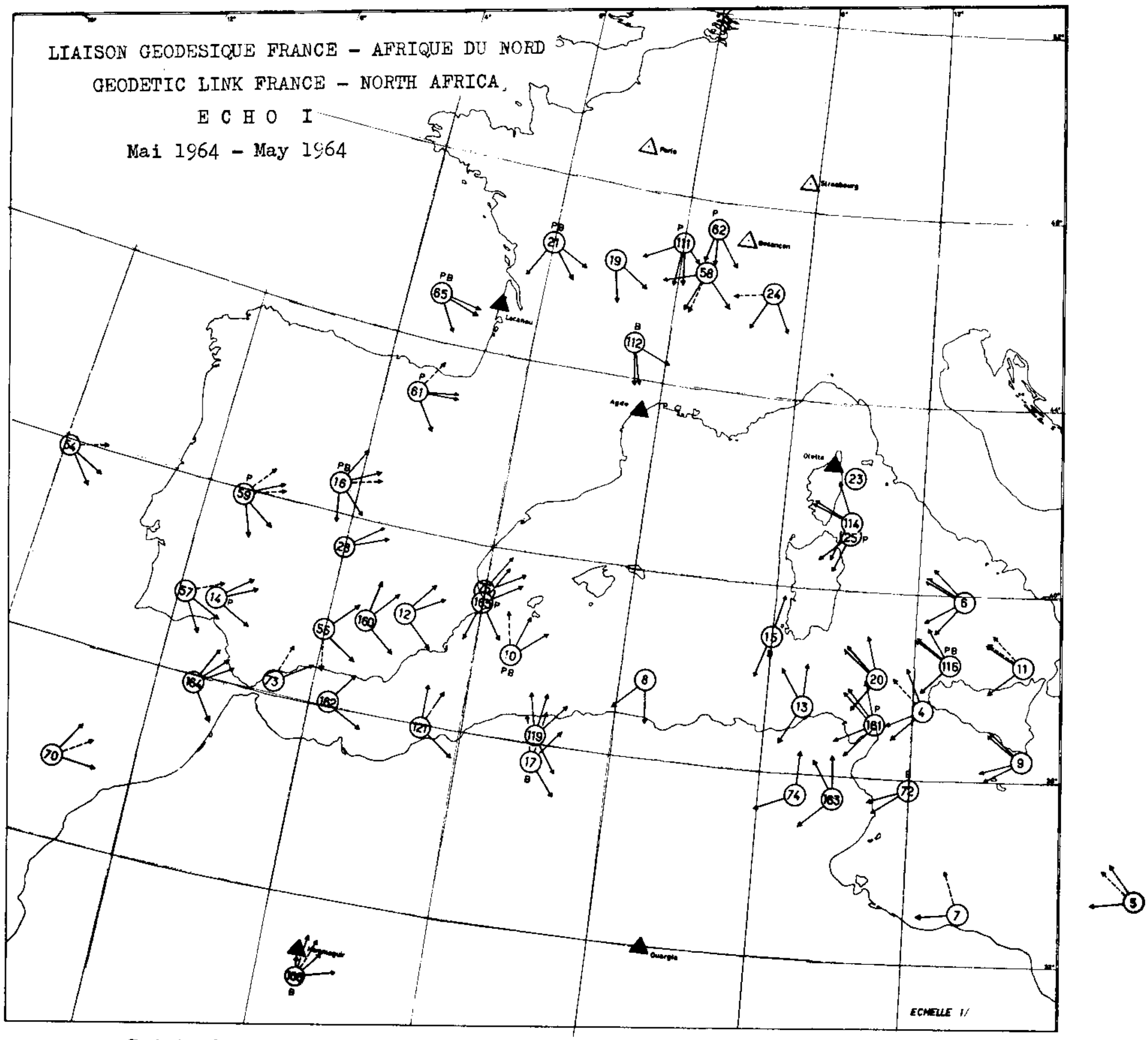
F. Adjustment of the over-all geodetic network from a fixed point considered as origin, and determination of the co-ordinates of the four other stations. Comparison with conventional triangulation.

These six points will be examined below:

A. In view of the small effective aperture of the lenses of the ballistic cameras used (7.0 cm) and the disadvantages arising from unsatisfactory information on stellar positions, IGN has so far preferred to confine itself to perfectly tracked stars and to process those of F.K. 4. During the observations a double exposure is made (one just before and one immediately after the crossing of the satellite).

The observer determines the azimuth and the zenith distance of the camera axis correct to 1 grade or 1/2 grade and determines the time of photography of the stars correct to at least 0.05 seconds.

As the approximate position (zenith distance, azimuth of the axis and exact time of observation) is given for each photographic plate, it is possible by computation to select the stars of F.K.4 that are within a radius of 6 cm from the centre of the plate and to compute the theoretical position (x_c, y_c).



Points du ciel photographiés, avec indication des stations réussies

Points in the sky photographed, with indication of successful stations

⟶ Photo réussie
Successful photograph

---→ Photo peut être utilisable
Photograph perhaps usable

la direction de la flèche permet d'identifier la station
the station may be identified from the direction of the arrow

B : Observatoire de Besançon - Besançon Observatory

P : Observatoire de Paris - Paris Observatory

Refraction is taken into account in this computation.

B. Work with comparator measurement

The Institut géographique national has two Zeiss-Jena comparators for the measurement of plates.

They are installed in an air-conditioned basement in which a constant temperature is maintained to within 2 degrees. The processing of the information on a plate takes about one day. The measurements are made by two operators: the difference in the readings recorded is generally not significant for the stellar images; for the satellite it is at most 5 microns. This difference seems to be due to the unsharpness of the satellite image at the edges in the direction of the trajectory. A study is in hand to detect systematic errors in measurement of the plates. No conclusions have yet been arrived at.

C. Smoothing of the images of the satellite

It might seem attractive to consider all the images of the satellite and to introduce them simultaneously into the over-all adjustment. This procedure has so far had to be avoided owing to the lack of sufficiently powerful computers; an attempt has therefore been made to select from the 60 images of the satellite measured on the plate a small number of such observations that may be considered representative. For this purpose the satellite's co-ordinates are "smoothed".

It may be considered that the satellite's trajectory can be represented in space during one minute by a third degree polynomial. In perspective there appears on the photographic plate a non-negligible fourth-degree term, partly due to the inclination of the trajectory in relation to the plane of the plate and partly to its curvature. It is therefore necessary to find an accurate interpolation formula.

Accordingly, two polynomials are written

$$X = A_1 + B_1 t + C_1 t^2 + D_1 t^3 + E_1 t^4$$

$$Y = A_2 + B_2 t + C_2 t^2 + D_2 t^3 + E_2 t^4$$

from which the coefficients are determined by the least-square method. From the residuals it is possible to estimate the accuracy of the sightings on the satellite. As all general rule, the following mean quadratic errors are found:

$\pm$ 3.3 μ in the direction of the trajectory

$\pm$ 2 μ in the perpendicular direction.

Only the smoothed co-ordinates X and Y for a central value t_o will be used in computing the direction of the satellite and their intersections.

D. <u>Establishment of the formula for conversion of the plate co-ordinates to the terrestial Cartesian system</u>.

The co-ordinates x_o y_o suitably corrected for distortion and x_c y_c of the stars correspond to the same bundle of stellar directions intersected respectively by the theoretical plane corresponding to the approximated azimuthal and zenithal elements.

There is a homographic relation between (x_o y_o) and (x_c y_c)

$$x_c = \frac{a_1 + b_1 x_o + c_1 y_o}{1 + b x_o + c y_o}$$

$$y_c \quad \frac{a_2 + b_2 x_o + c_2 y_o}{1 + b x_o + c y_o}$$

Hence, the relations between observations:

$$a_1 + b_1 x_o + c_1 y_o - b x_o x_c - c y_o x_c - x_c = v$$

$$a_2 + b_2 x_o + c_2 y_o - b x_o y_c - c y_o y_c - y_c = v$$

They contain eight parameters: it was not considered necessary to use more parameters in the formulae for the transformation of the co-ordinates because it is probably better to apply the correct geometric transformation with a small number of parameters than a quadratic

transformation formula with many arbitrary parameters, as the latter method may give a mean quadratic error that is apparently much smaller but may also lead to miscalculation in actual interpolation.

All these relations, adjusted by the least-square method, provide the above coefficients of homographic transformation which, when applied to the smoothed co-ordinates of the images, give the co-ordinates x_F and y_F of the satellite.

By changing the known axes, one can then arrive at the direction cosines in the terrestrial Cartesian system from x_F y_F.

The accuracy of the star photographs can be estimated from the residuals of these equations.

Generally speaking the mean quadratic errors for a plate showing equatorial stars are:

$\pm$ 3 μ in the direction of diurnal motion

$\pm$ 2 μ in the perpendicular direction.

On the whole the mean quadratic error in the smoothed direction of the central flash results from three factors:

- imprecision in pin pointing of the images of the satellite;
- inaccuracy of the formula for transformation of the co-ordinates x_o y_o to x_c y_c;
- error in the time of observation (of the order of 1/1,000 second).

These three errors are of the same order of magnitude (1/200,000).

E. Intersection in space

On the basis of known geodetic co-ordinates, the accuracy of intersections at the satellite's position in space gives an idea of the precision of the method, in so far as it can be admitted that the coherence of conventional geodetic co-ordinates is greater than that given by the satellite connexion - which, by the way, is not correct.

Table 1 summarizes the results obtained.

It should be noted that no phase correction has yet been made for these measurements: in fact, it is difficult to ascertain the exact behaviour of the satellite as a source of light. In particular it would be necessary to find out whether it acts as a perfect reflector or as a diffuser, or whether the light coming from it is both reflected and diffused, and, if so, in what proportion. It is certain that the application of a phase correction would further improve the results.

TABLE 1

	0	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m
Station 1 Oletta	3	12	10	9	8	2	3	1	2	/	50
Station 2 Agde	4	24	54	26	22	14	4	4	/	4	156
Station 3 Lacanau	9	30	28	27	30	11	7	3	3	5	153
Station 4 Ouargla	5	27	38	27	25	21	3	4	4	/	154
Station 5 Hammaguir	4	18	44	40	15	11	3	1	4	1	141
	25	111	174	129	100	59	20	13	13	10	654

This table indicates for each station the statistical distribution of the metric deviation of sightings from the various stations: for example, it shows that at Lacanau Station (No. 3) 30 sightings out of the 50 studied passed at a distance of between 5 and 10 metres from the theoretical position of the satellite sighted. These figures are obviously vitiated by systematic errors resulting from errors in the position of each of the triangulation stations.

To arrive at an idea of the true distribution of deviations in sightings, the following figure resulting from the work described in paragraph F (see Table 2) can be taken as a basis: the mean quadratic error in an observed direction, after free adjustment[1/], is $\pm$ 7.5 x 10^{-6}.

At the time of the observations the mean altitude of the satellite in the zone of work was 1,750 km. If it is admitted that the mean sighting distance was of the order of 2,100 km - the observed distance varies from 1,800 to 2,500 km - this angular error corresponds to a mean quadratic deviation of $\pm$ 16 m, or a probable deviation of the order of 10-11 m. This mean quadratic error is the result of multiple errors of observation, measurements, error in synchronization as mentioned above.

F. All the verifications under E having been made, general adjustment of the network was carried out, adopting point, Agde in this specific case, as the general origin of the network and applying its scale to the side already known by triangulation: Agde-Ouargla.

The results of the comparison and some general indications concerning the comparisons that can be made between the various elements are given in Table 2.

Table 3 is devoted to the study of shutter synchronization. It will be remembered that the shutters are synchronized by time signals received directly by means of a flashing unit on the rotating shutter itself.

1/ That is to say, independently of errors of position of the known stations.

This table shows that it is reasonable to expect synchronization accurate to 1/1,000 second, which is approximately the aim adopted at the outset. This result agrees fairly well with the value for the deviation obtained in examination of the scatter of the sightings: taking into account the fact that, as has been seen, the mean quadratic error of the sightings is of the order of $\pm$ 16 m; and since the error due to measurement of the plates, etc. is known to be of the order of $\pm$ 2-3 microns on the plate, or about 1:150,000 - which roughly corresponds to about 12 metres - it can be seen that this agrees well with the preceding result since the mean quadratic error of $\pm 7.5 \times 10^{-6}$ from the angular point of view can be said to be the resultant of the sighting error on the plate, or approximately $\pm$ 1:150,000 $\approx \pm 6.6 \times 10^{-6}$ plus the synchronization error; or, since the satellite, which is at a distance of 2,100 km, travels at approximately 7.5 m in x 10^{-3} seconds and taking 1/1,000 second as the unit of time,

$$(7.5)^2 = (6.6)^2 + \xi^2 \frac{7.5^2}{2.1}$$

hence $\xi = \pm 10^{-3}$ second.

Conclusions

All these results are encouraging. They show that triangulation by means of luminous satellites of the Echo type, as studied by IGN with light portable equipment, is a fairly delicate operation as far as organization is concerned but, on the whole is simple, rational and accurate.

The accuracy of the France/Algeria operation can be said to be at least 1:100,000 - 1:150,000.

These results were obtained with experimental equipment that was far from being perfect; in particular, the prototypes of the ballistic cameras used were fitted with rather mediocre lenses. Numerous conclusions were drawn from this operation; in particular, it was decided:

- To increase the speed of the photographic emulsions
- To study photographic plates in order to select and sensitize those that were most plane and most suitable optically
- To fit the cameras with very good lenses. The new lenses give every satisfaction in this respect.

As far as observations are concerned it was agreed that each station would in future be provided with two ballistic cameras on parallel axes working simultaneously, so as to provide a mutual checking.

- To obtain the time signals from various transmitters, so as to avoid propagation anomalies, etc.

Thanks to the implementation of these measures it can be stated that stellar triangulation is capable of a very high degree of accuracy: the order of 1:200,000 should easily be obtained. Even higher degrees of accuracy are by no means out of the question; the whole matter is a question of care and of tracing systematic errors. Examination of results gives the clear impression that satellite triangulation is more accurate than conventional triangulation. The scale can only be fixed by very high-precision conventional measurements over very long distances - traverses by geodimetre - or by direct measurement to the satellite using lasers, for example. In any case, the instrument, which is simple in design and easy to operate, seems to be one of the most attractive ever placed at the disposal of the geodesist. It should be used to the utmost of its potential and it can be confidently asserted that it has a great future. World-wide triangulation, various projects of which are at an advanced stage of preparation, is certainly for the near futur.

TABLE 2

	I OLETTA	2 AGDE	3 LACANAU	4 OUARGLA	5 HAMMAGUIR	
OLETTA	+	312,3707.10	323,3657.20	219,6721.93	249,2169.11	Azimuths
	S	02.38	58.19	23.67	68.86	
	+	107,9308.40	115,2334.08	17,0024.70	40,9096.04	Azimuths
	S	03.70	34.29	26.06	95.71	
	+	484,184. 1	888,604. 5	1,232,645. 8	1,669,842.0	Distances
1		182. 6	610. 6	650. 5	839.3	
AGDE		+	331,5492.67	190,8647.20	227,6843.86	Azimuths
		S	96.95	50.20	44.59	
		+	127,9146.67	392,1680.24	23,2734.09	Azimuths
		S	50.16	82.82	34.76	
		+	420,407. 7	1,270,247.4	1,491,208.9	Distances
2			417. 4	--	204.7	
LACANAU			+	173,5505.65	207,2140.75	Azimuths
			S	05.65	37.06	
			+	378,1501.61	5,9437.27	Azimuths
			S	01.89	34.19	
			+	1,555,721.3	1,571,977.8	Distances
3			S	728.0	571,977.9	
OUARGLA	Mean quadratic error of a spatial sighting Emq = $\pm$ 7.5 x 10^{-6}			+	293,2618.82	Azimuths
				S	21.82	
				+	88,3611.65	Azimuths
				S	14.96	
				+	811,352.5	Distances
4				S	345.2	

\+ value arrived at by conventional triangulation
S value arrived at by space triangulation

Azimuths: centesimal system
Distances in metres.

TABLE 2 (Cont'd)

Trirectangular co-ordinates

	Conventional triangulation	Satellite triangulation	
Oletta	4,639,113.45 764,588.58 4,296,137.67	4,639,104.91 764,586.61 4,296,134.08	- 8.54 - 1.97 - 3.59
Agde (origin)	4,640,374.31 283,672.31 4,352,282.36		0 0 0
Lacanau	4,516,066.69 - 94,246.80 4,488,177.22	4,516,055.18 - 94,254.37 4,488,175.61	- 11.51 - 7.57 - 1.61
Ouargla	5,393,662.31 510,808.43 3,355,038.70	5,393,653.18 510,801.91 3,355,030.31	- 9.13 - 6.52 - 8.41
Hammaguir	5,471,590.45 - 290,633.99 3,255,488.81	5,471,575.27 - 290,634.06 3,255,483.04	- 14.82 - 0.07 - 5.77

N.B. The existence of these systematic negative discrepancies seems to prove that the choice of origin was bad as far as altitude was concerned; it will be noticed that a translation of $x + 10$ m, $y = + 3$ m and $z = + 5$ m would apparently have given still more satisfactory results.

The result seems in itself interesting enough from this viewpoint for this small artifice to be dispensed with. It is by the way by no means out of the question that the calculation of the geoid accounts for part of the discrepancy; in the area of the point of origin (Agde) it has not yet been possible to make this calculation because the astronomical survey has not yet been carried out there.

TABLE 3

Date	Time	MQE	Date	Time	MQE	Date	Time	MQE
19/20/6	0^h23 2^h20 4^h22	±1.10 0.92 1.48	28.29.6	21.45 23.48 3.53	0.96 1.05 0.90	13.14.7	0.57	1.25
20/21/6 —	0^h57 2.57 —	1.55 1.05 —	29.30.6	22.21 0.27 2.26	0.46 0.78 1.20	14.15.7	23.32 3.22	1.91 0.77
21/22/6	23^h32 1.32	1.26 2.21 1.32	1.2.7	1.39 3.47 4.48	1.29 1.25 1.18	15.16.7	0.09 2.50	0.87 0.69
22/23/6	0^h07	0.88	2.3.7	2.15 4.19	1.09 0.71	16.17.7	2.17	0.91
23/24/6	22^h45	1.03	3.4.7	22.52 0.51 2.54 3.46	0.48 0.82 0.79 1.66	17.18.7	21.21 1.18	0.91 0.95
24/25/6	1^h22 3.27	1.03 1.09	4.5.7	23.28 3.33	1.05 1.42	21.22.7	23.47 3.15	1.30 1.29
25/26/6	0.02 4.03	0.89 0.32	8.9.7	23.53 3.56 4.43	0.62 0.78 0.72	22.23.7	22.24	0.48
26/27/6	22.34 0.36	1.33 0.32	9.10.7	22.33 0.28	0.93 0.67	23.24.7	23.00	1.05
27/28/6	1.13 3.17	0.58 0.51	12.13.7	22.21 2.37	0.90 0.67			

The resultant mean quadratic error is: $\varepsilon = \pm 0.99 \times 10^{-3}$ second.

Table 3 gives in 1/1,000 sec. the mean quadratic synchronization error of the rotating shutter in relation to the time signals.

The first column shows the date of reception, the second column gives the time and the third the mean quadratic error in the operation of the shutter, which in the IGN procedure, is equivalent to a quartz chronometer.

The procedure adopted to obtain this MQE is as follows: each time reception is made from several continuous transmitters (DIZ, OLB5, MSF, WWV, RWM...). After semi-definitive corrections by the Bureau international de l'heure and adequate propagation correction, recalculated for the station in question, one obtains for each transmitter the chronoscopic condition and operation over the interval of time in question.

Then for each reception all the data observed are adjusted, on the assumption that the operation of the chronoscope is constant during the period of time recording.

The result is a time that is compared with the individual values obtained for each transmitter.

Comparison shows the accidental error corresponding to each reception. From this is deduced the mean quadratic error of reception.

The values reproduced opposite correspond to a station in the continent/Azores link effected in 1966 - in all cases the results are similar.