A PROPOSED AID TO GEODESY :

THE SPATIAL SYSTEM "GEOLE"

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IHB Note. — The object of the present article is not to describe an existent system of positioning by satellites, but rather to present an extensive study of the subject carried out by the French "Centre National d'Etudes Spatiales" (CNES). This study gives not only details of the conditions that such a system must fulfill in order to be of use to both geodesists and hydrographers but also the technical practicalities of putting it into effect.

In view of the worldwide interest that this question arouses the IHB considers that this CNES study deserves to be brought to the notice of hydrographers, even though certain of the theories developed are perhaps addressed more particularly to specialists. Not only does the article deal with questions of direct concern to hydrographers but also international cooperation will be necessary for setting up an accurate worldwide positioning system for points on the earth's surface, and hydrographers will necessarily be associated with such a project.

FOREWORD

For the last 10 years artificial satellites have been available to provide a new means of positioning. There are already many systems available for facilitating the standard work of the geodesist, hydrographer and navigator. (These are : the Doppler, TRANSIT and SECOR distance measuring systems, photographs of satellites against a star background, range and direction finding by laser).

In spite of the obvious interest of these new techniques — some are capable of an accuracy of a few metres at several thousand kilometres — it seems that potential users are hesitating to employ these systems. This hesitation probably arises from the relative complexity of their use. It would seem that to be adopted such a system must be simple to use. This will be quite possible if the ground receivers are automated, and if computations can be carried out at a centre where a large computer is available. Such a system is possible if use is made of the satellite's capability for rapidly transferring the information obtained.

The CNES has developed the EOLE system for positioning wind tracking balloons. This system consists of a satellite and some hundreds of balloon-borne answering beacons. The satellite simultaneously provides for the positioning of the balloons and the transfer of the data used to position the balloon payload (i.e. Doppler and distance data) to an operation centre where the coordinates of the balloons are calculated by computer as soon as the data arrive. The balloon-borne beacons are entirely automated and the satellite is controlled from the ground to interrogate the beacons according to a predetermined schedule. The positioning accuracy is of several kilometres, and this is sufficient for meteorologic ends.

Satellite EOLE will be launched at the end of 1970 by means of an American SCOUT rocket. It was logical to apply the EOLE concept to geodesy, but the accuracy must eventually be amended in a ratio of 1000 and the balloon payload must be replaced by ground beacons. This project, which is named GEOLE — Geodesy and EOLE contracted — is being studied by the CNES.

I. — THE OBJECTIVES OF THE GEOLE SYSTEM

The GEOLE system should make it possible to attain several different objectives :

— the establishment of a global first order geodetic net, comprising 30-40 points, with an accuracy better than 2 metres;

— improvement of the knowledge of the earth's gravitational potential;

— positioning of fixed or slowly moving points (*).

It is this third objective which is of particular interest to us in this study. However, it cannot be attained until the first has been reached since the satellite orbit has to be calculated from the first order net. Implementation and operation of the GEOLE system may be summarized as follows.

Phase 1. During the first months of the satellite's life the first order geodetic net is calculated by using distance measurements and Doppler data. This is a purely geometric matter without any need for celestial mechanics, i.e. for a model of the terrestrial potential (see Section 3).

Phase 2. After phase 1 has been completed it will be possible to use the system for positioning isolated points. Beacons planted at the vertices of the 1st order net now have known positions and they can be used to determine the satellite trajectory in a permanent and continuous manner. In order to determine the coordinates for an isolated point it suffices to plant a beacon and to wait for one or more transits, according to the

(*) Furthermore it should be noted that if the GEOLE satellite were equipped with a radar or laser altimeter it would be possible to use the satellite's positioning system to establish a map of the surface of the oceans, which would be of interest not only to the geodesist but also to the oceanographer (gravimetry, transport of ocean masses, etc.).

accuracy required. Ranges and Doppler data from beacon to satellite locate this beacon at the intersection of spheres and hyperboloids.

II. — BASIC CHARACTERISTICS OF THE GEOLE SYSTEM

The GEOLE system is in fact a combination of a satellite, a set of ground beacons, a ground telemetry station, and a computer. Although the beacons are identical, distinction must be made between the beacons used for the determination of the satellite orbit and the beacons which may be made available to users to enable them to determine coordinates for desired points.

II.1. Basic requirements for the system

The system must basically fulfill the following requirements :

— the best possible accuracy — about 1 metre;

— complete automation for ground beacons;

— transfer of positioning data by employing the satellite;

— centralization of data computation in a place which will be referred to hereafter as the 'operation centre'.

The satellite plays a double role : that of positioning and transfer of information.

The transmission of information between the beacons spaced out around the world and the operation centre is rendered possible by equipping the satellite with a memory. There is therefore a time lag of as much as several hours between the time of measurement and the arrival of data at the operation centre. The satellite memory is also used to store the orders for the beacons to be interrogated.

Figure 1 is a block diagram of the operation of the GEOLE system.

1. The setting up at the operation centre of a satellite work programme for a specific period of time (from 2½ hours up to several days).

This programme takes into account the requests of the users who must supply :

— the date on which the beacon will be planted and ready for interrogation;

— the approximate position of the beacon (to within several hundred km);

— the desired accuracy for positioning and the messages to be transmitted to the beacon.

2. The transmission of this programme to command stations in the network (for instance by teleprinter).

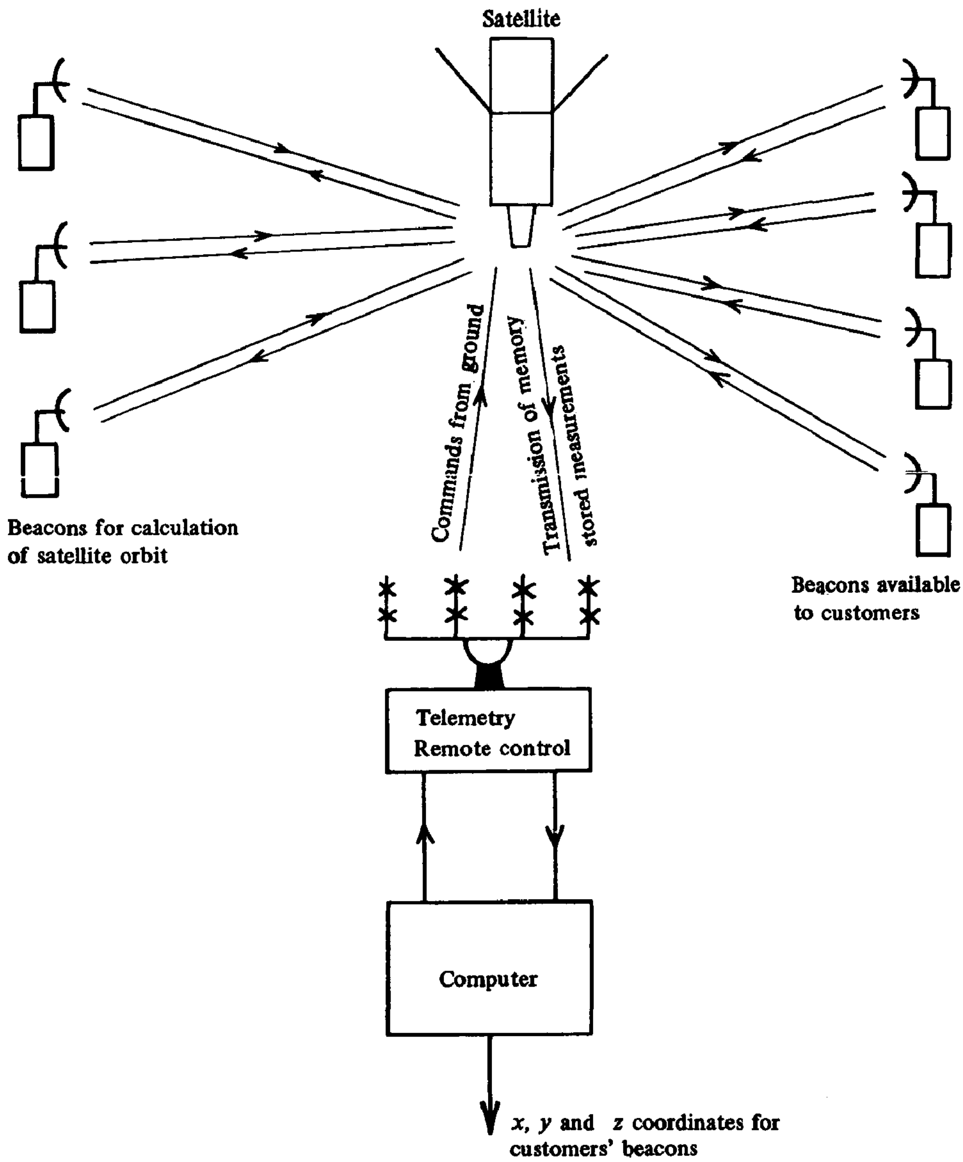


FIG. 1. — Block diagram of circulation of information in the GEOLE system.

3. The automated transmission of orders to the satellite, thus enabling the work programme to be carried out.

4. The storing in memory aboard the satellite of the orders received. These orders consist of the addresses of the beacons to be interrogated, the times of interrogation and the messages to be transmitted to the beacons, i.e. computed positions, end of operation signal, etc.

5. The carrying out of the orders at the times indicated and interrogation of the indicated beacons. At each interrogation — if the beacon is visible, and if its receiver is locked in — the beacon which has decoded its address retransmits this, as well as both the positioning signals and all data sensed at the beacon.

At each interrogation the satellite stores in memory :
- the address of the interrogated beacon;
- the time (by the satellite clock);
- the position data obtained (two distance and two Doppler measurements);
- the data sensed at the beacon (temperature, pressure and humidity for tropospheric corrections); and the messages to be transmitted via the satellite.

6. The passage over a telemetry station and the transmission of the satellite memory content to the ground.

7. The transmission of these data to the operation centre (by teleprinter for instance).

8. Processing in the computer. Computation of the beacon positions and a first processing of the messages received.

9. Transmission of positions and messages to the users.

The mode is a sequential one : there is no simultaneous interrogation of several beacons. During the passage of the satellite above a beacon, this last will be interrogated several times in order to permit interpolation.

The example given below, which is shown in diagram form in figure 2, will illustrate the operation.

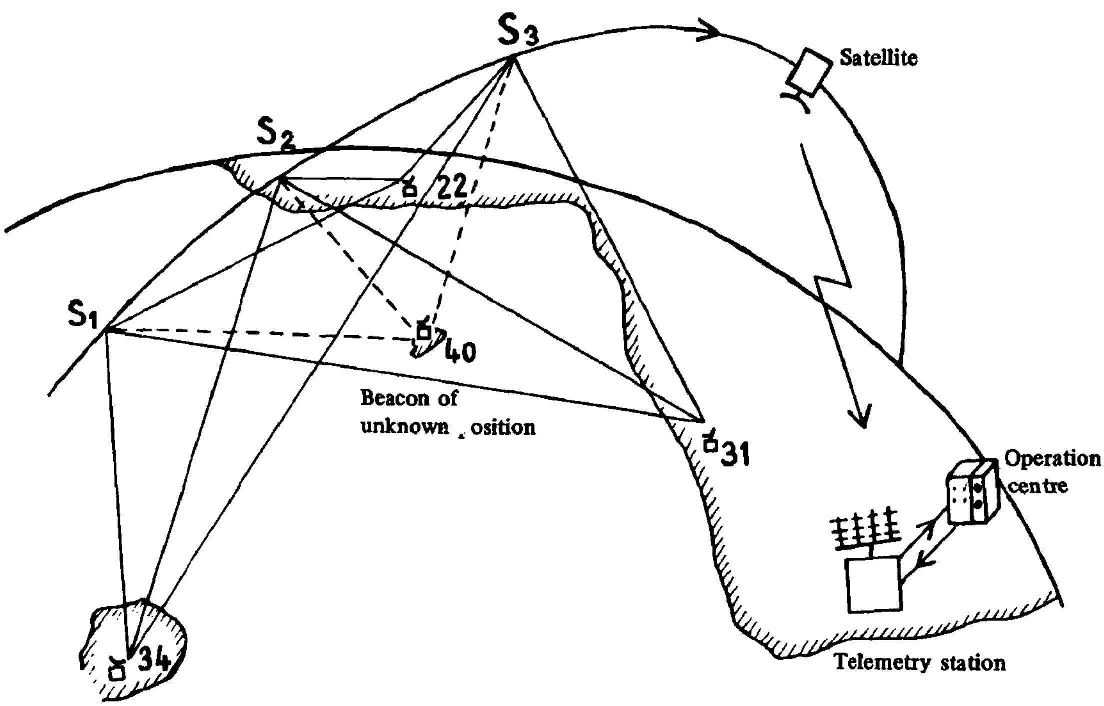


FIG. 2

A user requires the position of a beacon whose number, or address is 40. In the area of this beacon there are three other beacons, Nos. 22, 31 and 34, of known position and address. These beacons will serve for the computation of the satellite orbit.

The work programme elaborated at the computing centre could be as follows :

Time H_0	interrogation of beacon		22
Time H_0 + 5 s	"	"	31
Time H_0 + 10 s	"	"	34
Time H_0 + 15 s	"	"	40

and then interrogation of the beacons of unknown position, followed by the same sequence at $H_0 + 60$ s and $H_0 + 120$ s.

The interpolations allow three groups of pseudo-simultaneous measurements at the four beacons. These measurements with beacons 22, 31 and 34 determine the three positions of the satellite, and the measurements with beacon 40 permit its positioning.

II.2. The choice of frequencies

Accuracy depends on the choice of frequency for the electromagnetic waves used for distance and Doppler effect measurements. To obtain an accuracy of two metres the distance measurements must have an accuracy of two metres and those of radial velocity 0.2 cm/sec.

For a measurement on frequency f the ionospheric errors are to within the second order :

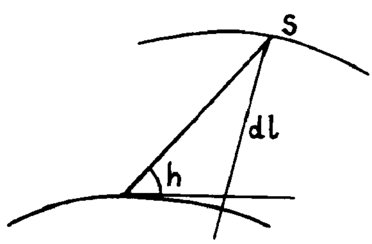
— Distance error Δd (metres) $= \dfrac{40.3}{f^2} \dfrac{N_v}{\sin h}$

f frequency in Hertz

N_v vertical electronic content, between satellite and ground (in electrons/m^2)

$N_v = \int_0^h n dh$ where n = Electronic density

h satellite elevation



— Doppler error ΔV cm/s $= \dfrac{40.3}{f^2} \dfrac{dN_0}{dt}$

N_0 oblique electronic content between beacon and satellite

$N_0 \quad \int_0^1 n\, dl$

The table given below shows a summary of the errors arising for a 20° elevation when the electronic content is very high (60.10^{16} electrons/m^2).

Frequency (MHz)	150	400	1000	2000	5500
Mean Doppler error (cm/s)	270	37	6	1.5	0.2
Mean distance error (m)	2310	325	52	13	1.7
Standard deviation of the Doppler error (cm/s)	100	14	2.2	0.56	0.07
Standard deviation of the distance error (m)	2.8	0.4	0.064	0.016	0.002

Ionospheric errors are aleatory in character on account of scintillations due to a heterogeneous ionosphere. The standard deviations have been computed with an ionospheric correlation time $t_0 = 10$ s and a correlation distance $l_0 = 1$ km, i.e. with extreme values. The electronic content at two points separated by distance l and time t has a correlation of the form

$$e^{-\left(\frac{l}{l_0}+\frac{t}{t_0}\right)}$$

It does not therefore seem possible to measure to within one metre with a single frequency until a frequency of 5.5 GHz has been obtained, and the use of this particular frequency poses difficult technical problems.

In the present state of our knowledge the use of an ionospheric model cannot be envisaged. To overcome this difficulty there are several possibilities :

— measurements on two phase-locked frequencies;

— measurement of the Faraday differential effect. (Measurement of the rotation of the electromagnetic wave plane on two frequencies);

— ionospheric sounding downwards by the satellite (plotting the curve of electronic content versus satellite height).

The first solution appears a priori to be the best.

The pair of frequencies must be so chosen that the residual errors are smaller than the desired accuracy. The table given below shows the residual errors arising from the use of two frequencies for a satellite at a height of 3500 km with a 20° elevation.

MHz pair	150/400	400/2000	1000/2000	1700/2100	2000/5000
Mean residual Doppler error (cm/s)	9	0.025	0.011	0.0025	0.0012
Mean residual distance error (m)	0.4	0.006	0.002	0.001	0.0002
Doppler standard deviation (cm/s)	10.8	0.3	0.13	0.03	0.014
Distance standard deviation (m)	0.6	0.009	0.003	0.0015	0.0003

Any pair of frequencies can be used, except 150 and 400 MHz as these are the TRANSIT system frequencies. The pair adopted will be around 400 and 2000 MHz.

The second solution furnishes indirectly the total content N_0 and its derivative, dN_0/dt. Its implantation is at present being studied.

The third solution does not appear to be really compatible with the GEOLE system in view of the duration of the frequency swing and the storage of data in memory.

II.3. Tropospheric effect

The propagation of waves in the troposphere introduces an average increase of 6.5 m in the actual path at 20° elevation, and a change in Doppler effect for the same elevation of about 4.2 cm/sec. A correction is thus necessary. This may be carried out as the index on the ground is known, but will probably mean that parameters such as pressure, temperature and humidity have to be measured on the ground and transmitted to the operation centre through the satellite.

III. — A BASIC DATUM : THE STANDARD POLYHEDRON

As has been said, the satellite trajectory will be computed from measurements carried out at the vertices of the polyhedron and this entails a change of procedure for geodesists, the consequences of which must be evaluated.

III.1. Choice of a terrestrial datum

The datum chosen for GEOLE does not involve the vertical, and this for the geodesist is certainly a revolutionary idea. This datum is the natural one to choose as it is a trihedron based on four given and fixed points on the earth's surface.

— From this trihedron, which does not need to be tri-rectangular, it will always be possible to define a tri-rectangular trihedron.

— In actual fact, for obtaining coordinates of points a single trihedron would hardly be practicable, and this is why a polyhedron around the world is constructed, a polyhedron passing through the above-mentioned four fixed points. For obvious reasons of homogeneity the whole of the mathematic processing for the polyhedron (including the four fixed points) will be worked out at one and the same time.

III.2. Determination of the polyhedron

In the GEOLE system, whether for determining the vertices or positioning isolated points, the theory of satellite motion is not involved, except for making the best interpolation between measurements. This procedure has one advantage. It does not introduce systematic errors arising, for instance, from a poor knowledge of the terrestrial GM (gravitational constant multiplied by the mass of the earth), or of certain harmonics of the potential with which the satellite would be in resonance.

As we shall prove, it will be possible to determine a polyhedron with distance measurements to a satellite, or more quickly with both distance and Doppler effect measurements. The satellite then plays the role of an auxiliary point.

III.2.1. *Number of unknowns on which the polyhedron depends*

It is easy to demonstrate that a polyhedron having n vertices depends on $3n - 6$ unknowns. A tetrahedron is determined by its six sides, and each vertex is determined by three coordinates in the system of oblique axes which are formed by the three adjacent sides of the tetrahedron :

$$6 + 3(n - 4) = 3n - 6$$

III.2.2. *Determination of a polyhedron by distance measurements*

A distance measurements from a satellite position to a vertex of a polyhedron gives an equation : the satellite's position, however, is unknown (three unknowns).

If distance measurements are simultaneously made from the satellite to the polyhedron's n vertices, we shall have n equations.

If this set of measurements is made for p different satellite positions we obtain np equations and $3p$ unknowns for the satellite position. In all, with the polyhedron unknowns, we shall have $3p + 3n - 6$ unknowns.

The problem of determining the polyhedron will be possible as soon as the number of equations equals the number of unknowns, i.e.

$$3p + 3n - 6 = np$$

whence :

$$3n - 6 = (n - 3)p \quad \text{this leads to } n = 4$$

$$p = 6$$

CONCLUSION. In order to make geodetic determinations by simultaneous distance measurements it is necessary to make simultaneous measurements at four stations from six different satellite positions.

III.2.3. *Determination of a polyhedron from Doppler effect measurements*

It should firstly be noted that it is impossible to obtain the polyhedron dimensions (the scale) from Doppler measurements alone. If we consider the polyhedron as being formed by the stations of the net and the satellite positions where the Doppler measurements are made, to say that we are trying to obtain the network by geometric means amounts to saying that the velocity vectors associated with each satellite position are independent.

Let us suppose that we change the entire polyhedron through a homothetic ratio k, retaining the values of the velocity vectors V. The Doppler effects are thus retained for all stations.

It is then possible to try to obtain a polyhedron to within a certain homothetic ratio k, and for this $3n - 7$ unknowns will have to be determined.

The same reasoning as was followed in Section III.2.2. can be applied, the only difference being the fact that for the satellite a Doppler measurement introduces six unknowns instead of three (data for two satellite positions or for position and velocity). We thus obtain the equation :

$$6p + 3n - 7 = np$$

whence

$$3n - 7 = (n - 6)p$$

which means that

$$n = 7 \quad , \quad p = 14$$

CONCLUSION. With Doppler measurements geometric geodesy cannot be attempted unless simultaneous measurements are made for seven vertices. These seven measurements must be taken from 14 different satellite positions. The polyhedron is then obtained to within a homothetic ratio.

III.2.4. *Determination of a polyhedron from simultaneous Doppler and distance measurements*

The only difference from what is said in Section III.2.3. is that a pair of Doppler-distance measurements from a satellite to a polyhedron vertex will give two equations instead of one.

The equation

$$6p + 3n - 6 = 2np$$
$$3n - 6 = 2p\,(n - 3)$$

Thus $n = 4$; $p = 3$

CONCLUSION. With simultaneous Doppler-distance measurements problems of geodetic geometry can be determined by simultaneous measurements at four stations from three satellite positions. This shows that the combination of radial velocities and distance measurements is most interesting.

III.3. Incorporation of the GEOLE measurements in the local geodetic systems

The datum for the GEOLE coordinates is bound to the basic polyhedron by the choice of the four vertices for this polyhedron. The results of GEOLE calculations will be in the form of coordinates in the available local geodetic net and for instance in the UTM projection.

It is easy to see that in practice it will only be necessary to determine a translation, a homothetic ratio and a rotary matrix in order to pass from the GEOLE system to the corresponding local geodetic system. It will be sufficient to know the coordinates of two points, both in the local and the GEOLE system.

If, furthermore, we have a general distortion of the local geodetic net, this will mean that a further general compensation of the geodetic net will have to be made. We shall need to use the Laplace data theory (*); i.e. we must write all the observations — whether these be for a round of angles with theodolite, celestial fixes, baseline measurements or spatial geodetic measurements — and then proceed to solve the system.

IV. — RESULTS EXPECTED OF GEOLE

The CNES has carried out mathematical studies to determine the errors σ_x, σ_y, σ_z on the polyhedron vertices as well as on any isolated point as a function of the satellite orbit, the measurement errors and the duration of the interrogation time.

IV.1. The polyhedron coordinates error — the optimum orbit

A simulation has been made by placing beacons at the vertices of the World Geometric Satellite Network which the U.S.A. is in process of

(*) See work by H.M. DUFOUR : Toute la Géodésie sans ellipsoïde. Les repères laplaciens. Application plus particulière aux travaux à latitude élevée (Lucerne, 1967, IUGG).

TABLE I

Results obtained from photographs against a star background compared with the results from the GEOLE simulation

Name of station	Photographs of PAGEOS against a star background. Semi-major axis of ellipsoid of error (*)			Simulation GEOLE		
				σ_x	σ_y	σ_z
1. Thule, Greenland	12.13	6.42	5.84	1.55	1.81	1.84
2. Aberdeen, Md, USA	11.54	5.76	5.32	2.14	1.66	2.01
3. Larson AFB, Wash. USA	11.27	5.57	5.26	0.35	0.28	0.26
4. Aleutian Is, Shemya I, USA	20.80	14.22	7.53	1.21	1.07	0.98
5. Tura, Siberia, USSR				0.81	0.70	1.07
6. Kuopio, Finland				0.50	0.49	0.38
7. Pico I, Azores Is.	16.06	11.54	9.42	0.37	0.24	0.24
8. Paramaribo, Dutch Guiana	24.60	18.92	11.28	1.28	0.90	0.70
9. Quito, Ecuador	17.86	14.75	8.82	0.88	0.27	0.52
10. Clipperton Island				0.71	0.60	0.35
11. Hilo, Hawaii, USA	11.63	8.18	5.92	0.94	0.65	0.39
12. Wake Island	16.06	8.54	7.72	1.30	0.83	0.66
13. Kagoshima, Japan	26.04	17.81	11.48	0.97	0.88	0.84
14. Gauhati, India				0.51	0.45	0.43
15. Sabzevar, Iran	20.85	14.01	9.62	0.49	0.40	0.32
16. Sirte, Libya				0.45	0.57	0.41
17. Roberts Field, Liberia				2.24	1.58	1.00
18. Trindade Island				1.96	1.24	1.38
19. Villa Dolores, Argentina	26.25	14.81	13.34	1.27	0.75	1.01
20. Sala-y-Gomez Island				0.97	0.73	0.64
21. Pukapuka Island				0.97	0.66	0.38
22. Uvea I, Wallis Is.				1.38	0.92	0.60
23. Kikori, New Guinea				1.23	1.16	0.57
24. Palembang, Sumatra				0.78	0.89	0.45
25. Male, Maldive Is.				0.56	0.70	0.37
26. Juba, Sudan				0.63	0.53	0.37
27. Bogenfels, Southwest Africa				1.08	0.56	0.61
28. Saunders I, S. Sandwich Is.				1.62	1.04	1.52
29. Peter I, Antarctica				1.70	1.51	2.52
30. Shoal, S. Pacific Ocean				0.96	0.61	0.44
31. Queenstown, New Zealand	14.40	14.39	11.31	0.77	0.59	0.46
32. Denmark, Australia				0.75	0.73	0.41
33. St-Paul Island				0.38	0.38	0.25
34. Fort Dauphin, Madagascar				0.42	0.36	0.30
35. USSR Station, Antarctica				0.48	0.40	0.63
36. France Station, Antarctica				0.57	0.49	0.40

(*) These provisional results were published by Mr. SCHMIDT in the January 1969 number of the review EOS. They relate to results obtained with the PAGEOS satellite.

determining by means of PAGEOS. Ellipsoids of error for the 36 stations have been computed, taking into account the mean square errors on Doppler and distance measurements (σV and σd) between satellite and station as well as on various parameters (height of the orbit, minimum elevation for measurement). Then the station with the largest ellipsoid of error was chosen, and the curves giving the variations of the major axis of this ellipsoid were plotted as a function of the above-mentioned parameters.

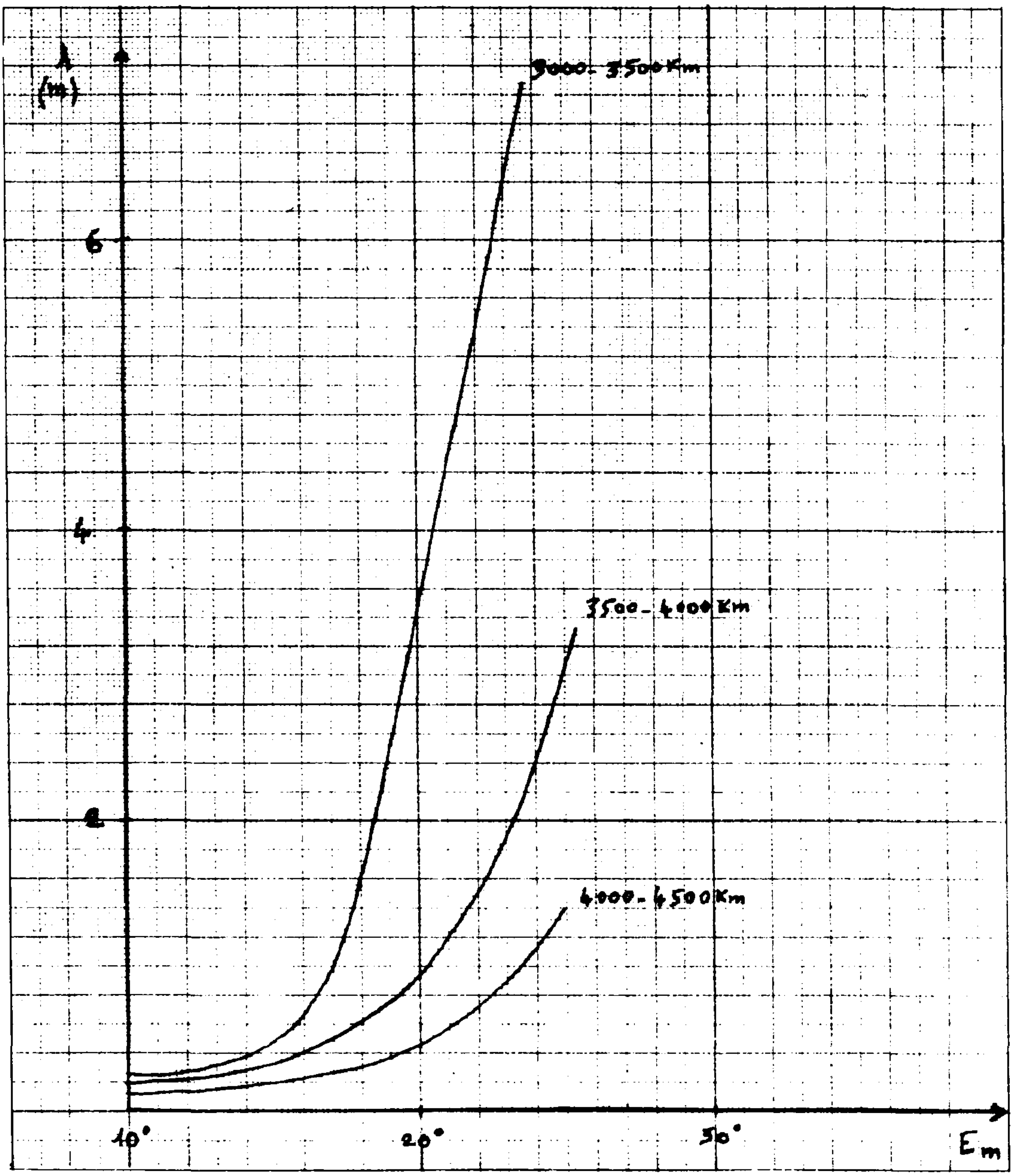


FIG. 3. — Simulation on the polyhedron.
Variation of λ in function of minimum elevation for 3 orbits.
Inclination = 70° $\sigma_{dist.} = 2$ m $\sigma_{doppler} = 0.2$ cm/s

Finally, an optimum orbit should have an apogee of more than 3000 km. The perigee has very little influence. In actual fact for technical reasons (gravity gradient stabilization) it seems that a nearly circular orbit is preferable.

Table I gives the detailed results of a simulation carried out with the following orbit :

perigee	3000 km
apogee	3500 km
inclination	70°

and based on the following assumptions :

distance measurement error (r.m.s.) .... $\sigma d = 2$ m
Doppler measurement error (r.m.s.) .... $\sigma V = 0.2$ cm/s
(on two way travel time)

These results are compared with those obtained in the U.S. from photographing the satellite PAGEOS against a star background.

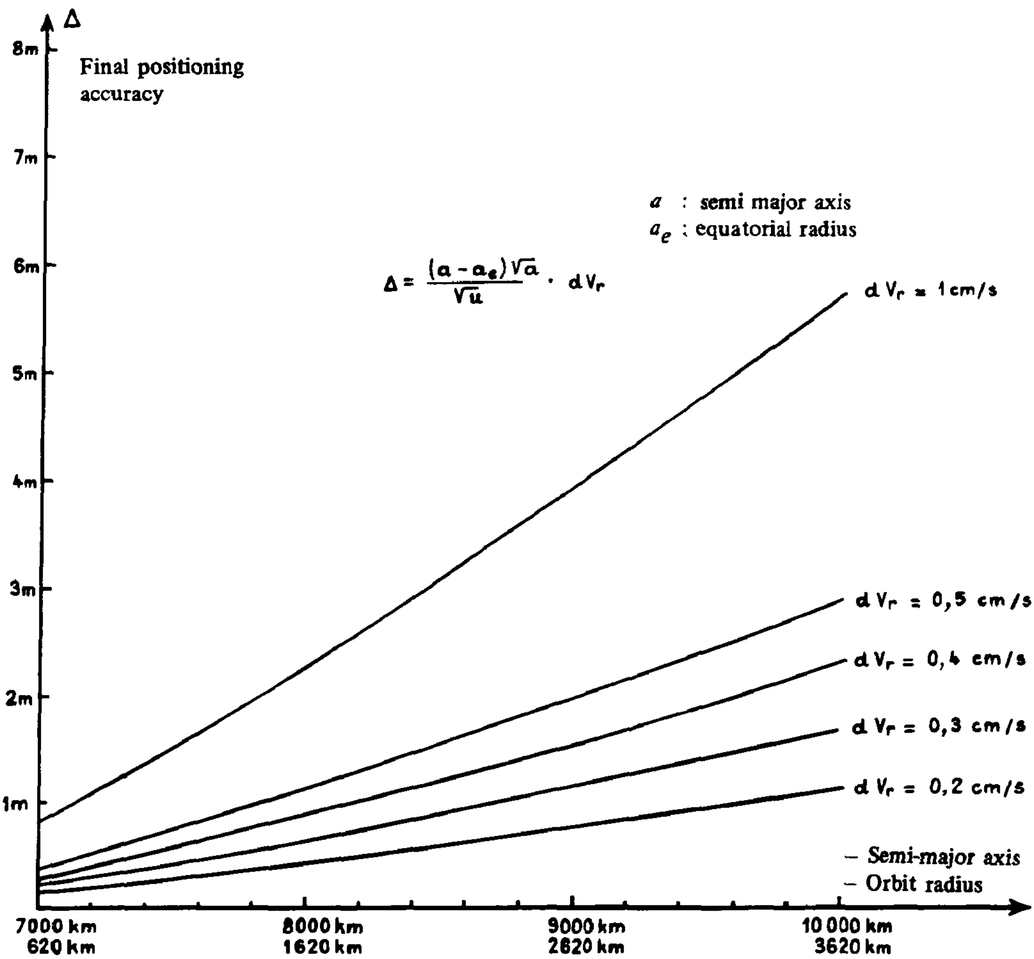


FIG. 4. — Final positioning accuracy Δ in metres in terms of orbital data for various values of the variation in radial velocity.

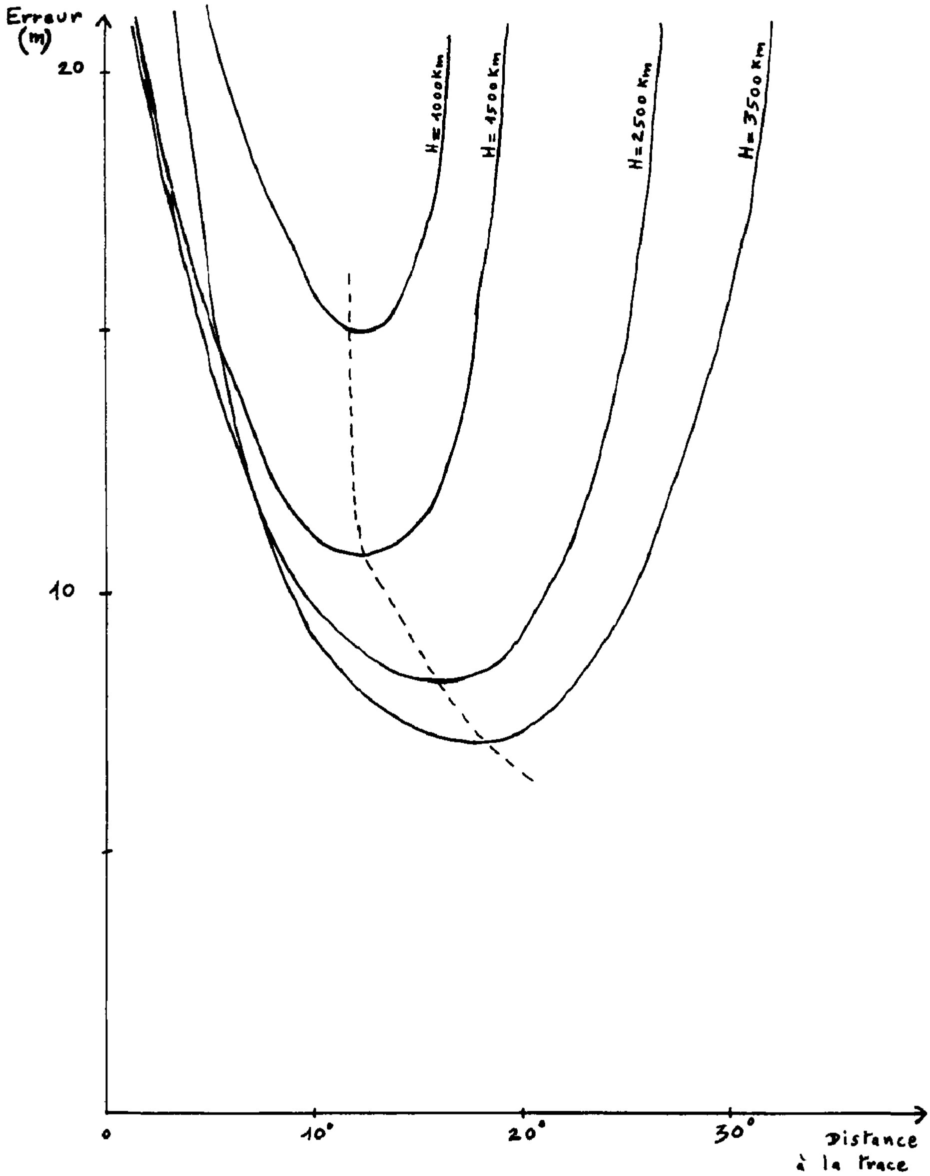


FIG. 5. — Positioning during one satellite pass.
Variation of the error with distance to the subsatellite track for various altitudes.
Minimum elevation $E_m = 20°$.

FIG. 6. — Distance to the subsatellite track.

Figure 3 gives the largest possible polyhedron error (λ) for three different orbits each with the same inclination ($i = 70°$).

IV.2. Positioning an isolated point

An isolated point is positioned from the known positions of the satellite — these positions being either on the same pass or on several successive passes of the satellite above the isolated point.

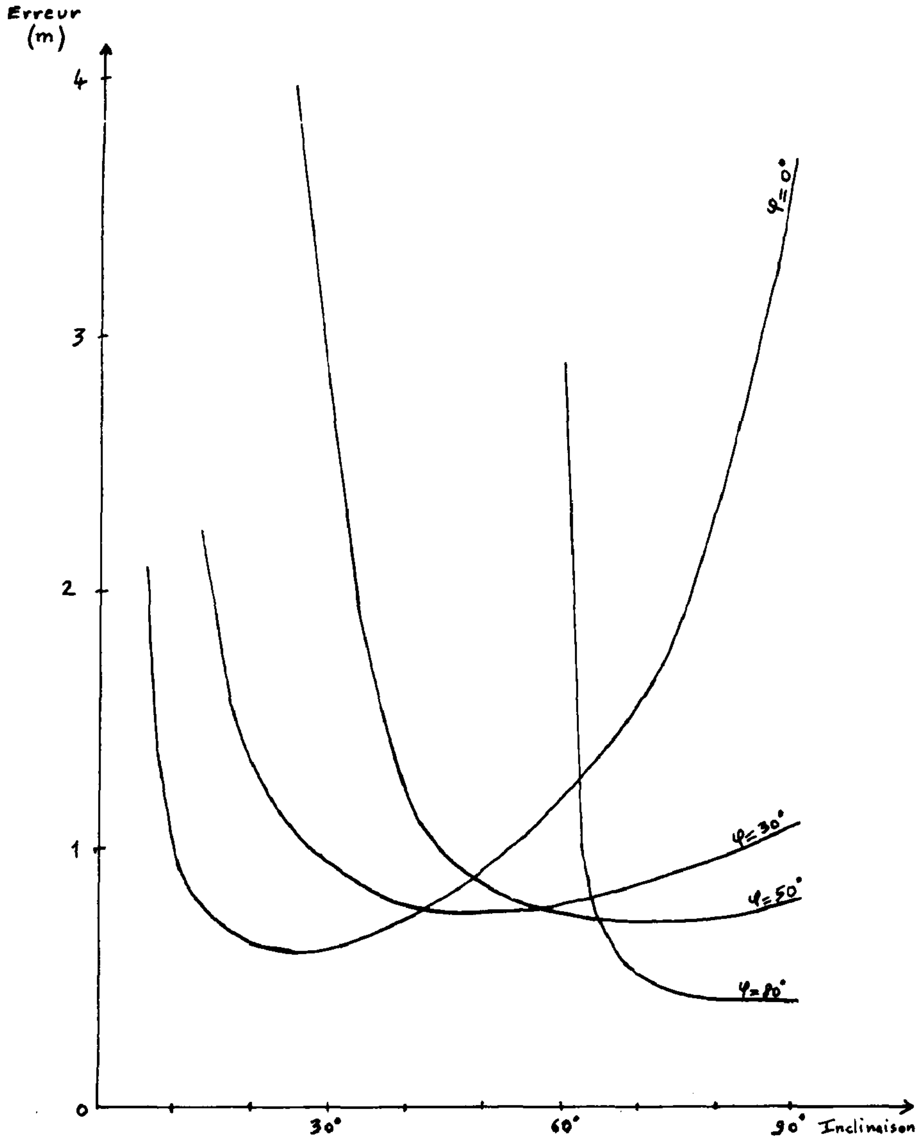


Fig. 7. — Positioning over a day's measurements.
Variation of the error with orbit inclination (altitude H = 3 500 km)
for a beacon in various latitudes.
Minimum elevation $E_m = 20°$.

a) *Final accuracy obtainable with Doppler measurements*

Although it is obvious that a fix error — when supplied by distance measurements — is of the same magnitude as the mean square error on the measurement, the same relationship is more difficult to assess for a Doppler measurement, the more so because it is dependent on the orbit. Figure 4 shows the relation between the Dopper error dV_r and the ultimate positioning accuracy for circular orbits.

b) *Simulation on one or more satellite passages*

The aim of this simulation, which was carried out on a computer, was to approximate the real conditions of use for the GEOLE system. That is to say :

— use of one or more satellite passages above the point;

— introduction of errors in satellite data (position and velocity vector) and in the measurements (σd, σV).

Figure 5 gives the results of a simulation when the positioning was carried out during a satellite pass. In this case the accuracy is dependent on the distance between the point to be positioned and the subsatellite track (figure 6). The system can function even when the station is 3 000 km from the subsatellite track.

Figure 7 shows the results of a simulation when this is carried out after a day of satellite observations. The positioning accuracies are dependent on the latitude of the point to be positioned, the orbit's inclination, and the height chosen for the perigee. From all these studies, it becomes evident that orbits of 3 500 km altitude are of interest, and that there is a gain in accuracy as soon as several satellite passes are used for a positioning.

V. — POSSIBLE APPLICATIONS OF THE GEOLE SYSTEM

As the satellite GEOLE can transfer information from an interrogated beacon to a central station it is consequently possible to :

— collect the measured data from the ground beacons;

— transfer the satellite information to the interrogated beacon.

Use can be made of this last possibility in order that the beacon can be informed by the central station of the end of positioning operations. This will mean that the beacon can then be moved. Moreover, it would also be possible to transfer coordinates computed at the operation centre to the beacon.

We will now examine some of the GEOLE system's possibilities.

V.1. Determination of landmark positions

Let us take the case of a team of hydrographers who have to determine the positions of landmarks on a coast in the absence of a tight geodetic net, and who wish to avoid setting up a triangulation system.

They would procure three beacons numbered, say, 56, 57 and 58. From the start of operations the operation centre would include these numbers among the beacons the satellite is to interrogate, and furthermore the centre would note the required accuracy, say, 10 metres.

If Lighthouse A is the first point to be positioned, the beacon will be placed either on top of the light or else close by, and then put into operation. It will be interrogated each time the satellite passes above it and the measurements obtained will be transferred to the operation centre during the hours that follow. At the operation centre the computation in quasi-real time will be continued. As soon as the positioning error becomes less than 10 metres an end of signal operation will be sent to the beacon. One or even two days may be necessary to obtain the required positioning accuracy on account of the time lag in arrival of information. During this time the hydrographers will not be idle because they will be moving beacons 57 and 58 to other places. As soon as beacon 56 receives its end of operation signal it will in turn be moved, and so on.

We therefore see that there must to an optimum number of beacons available to make allowances for the number of landmarks to be positioned, the accuracy required and the travel time between beacons.

V.2. Marine Geodesy

The aim of marine geodesy is here to establish a geodetic net at either the sea surface or on the bottom in order to be able to start exploiting submarine resources.

Problems of marine geodesy may be solved in two ways :

— establishment of a set of ultrasonic underwater transponders to act as geodetic points;

— use of a sufficiently accurate universal and worldwide means of positioning.

Although the role of the GEOLE system is fairly obvious in the second case (only in certain circumstances), it will be of the greatest importance in the first for the setting up of a geodetic net with transponders as control points. The special purpose ship which is to determine the coordinates of the control points by measuring underwater distances will have a GEOLE beacon aboard and will carry out three successive stations in order to obtain the coordinates of the control point.

TABLE II

Fixed points

	Accuracy (m)			Relative or absolute	Frequency	Time necessary
	φ	G	h			
A.1. Standard geodesy (2nd order net)	1	1	1	R	Once	1 year
A.2. Positioning of radio-positioning system antennae	1-2	1-2	2	R (600 km)	1 week	Fortnight
A.3. Glaciology – Movement of inland ice	2	2	2	R (3000 km)	1 or 2 years	Not significant
B.1. Positioning of landmarks and islands	1 10 20	1 10 20	0.5 0.5 1	R (300 km) R (2000 km) A	Once	1 week – 1 month
B.2. Terrestrial cartography	10	10	10	R	4 days	2 days
C.1. Geophysical observation points	10	10	5	R	1-2 hours	Fortnight
C.2. Topography in desert regions	10	10	10	R	1-2 hours	Fortnight
C.3. Fixing concession boundaries	10	10	3	A	1-2 hours	2-3 weeks
C.4. Calibration of radio positioning system	5-10	5-10	–	R (300 km)	½-3 hours	1 week – 1 month
D. Fixes for use in photogrammetry	10	10	5	R	Once	Fortnight
E. Oil rigs	20	20	–	R	Once	Several days
F. Rock topography (positions of reefs)	20	20	–	R (200 km)	Once	1 month
G. Geological maps	50	50	–	R	12 hours	1.5 day
H. Positioning for Antarctic land parties	100	100	–	R (3000 km)	24 hours	12 hours

TABLE III

Nearly stationary points

	Accuracy (m)			Relative or absolute	Frequency	Time necessary
	ϕ	G	h			
I. Ships on oceanographic station	35	35	—	A	1-2 hours	1/4 hour
J. Moored oceanographic buoys	70	70	—	A	12 hours	24 hours

TABLE IV

Moving surface objects

	Accuracy (m)			Relative or absolute	Frequency	Time necessary
	ϕ	G	h			
K.1. Drifting oceanographic buoys	70	70	—	A	1 hour	2 hours
K.2. Geophysical research vessels	50	50	—	R	1-2 hours	< 1/4 hour
L. Drifting floats	50 200	50 200	— —	R (several miles) A	1/4 hour	24 hours
M.1. Geologic research vessels (for prospection)	100 to 200	100 to 200	—	R	1-2 hours	< 1/4 hour
M.2. Laying of submarine cables	100 to 400	100 to 400	—	R	1-2 hours	< 1/4 hour
N. Naval vessels	Seve-ral 100s		—	R	1-2 hours	< 1/4 hour
O. Merchant Navy vessels (Navigation)	1 n.m.	1 n.m.	—	R	1-3 hours	< 1/4 hour
O.' Merchant Navy vessels (Surface plot)	1 n.m.	1 n.m.	—	R	1-3 hours	Fortnight
P. Hydrographic survey vessels	5 70	5 70	—	R A	1-2 hours	Several hours

CONCLUSION

The GEOLE system will be set up in two stages :

— the first will entail setting up a satellite in combination with about a hundred beacons;

— the second will entail adding several satellites to the system in order to obtain a permanent world coverage. It should be possible to envisage putting a satellite into orbit every 12 or 18 months.

Such a system could only be set up if it were an economic proposition. Those using the system would probably pay on the basis of time used. The cost would depend on the number of contract customers of the system. A rough calculation shows that if the system were to be permanently used with 100 beacons :

— the cost of a distant geodetic point accurate to within 1 metre would be about 800 dollars;

— the cost of a distant geodetic point accurate to within 10 metres would be about 200 dollars.

By the end of the 1970s the GEOLE system could thus become the ideal tool of geodesists, hydrographers, prospectors and topographers.