THE RECENT DETERMINATION OF A WORLDWIDE SERIES OF FUNDAMENTAL LONGITUDES

CONSEQUENCES IN SURVEYING AND THE CONSTRUCTION OF MARINE CHARTS.

by

INGÉNIEUR HYDROGRAPHE DE 1re CLASSE A. GOUGENHEIM (*French Navy*).

I. *METHODS NOW USED IN PRECISE MEASUREMENT OF LONGITUDES.*

1. THE PROBLEM OF LONGITUDES. The measurement of the difference of longitude between two places consists, first, of the determination of local time at each place and, second, of the comparison of the timepieces of the two stations.

It can at once be seen that this double problem makes the determination of longitudes a most delicate operation which can be accurately solved only by perfecting the material placed at the disposal of the observers.

In fact, the time of various instantaneous phenomena must be noted in both cases, then the exact interval of time elapsed between the observations, which is sometimes considerable, must be known — all this with sufficient accuracy, since any error committed is reproduced in its entirety in the difference of longitude.

The manner in which these points have been solved is briefly stated below.

2. THE OBSERVATION INSTRUMENTS. Generally local time is accurately determined by noting the time of transit of known stars across either the meridian, or a small circle of zenith distance 30°. In the first case, a *Transit instrument* is used; the local sidereal time is equal to the right ascension of the observed star. In the second case, the instrument most frequently used is the *prismatic astrolabe* designed by MM. CLAUDE and DRIENCOURT; the method of equal altitudes is then employed.

The noting of the instant of transit has been considerably improved by the use of chronographs which record both the beats electrically transmitted from the standard chronometer of the station and the closing of a contact operated by the observer at the instant of passage of the star. In the transit instrument, the personal equation has even been successfully eliminated, that is, the interval, which is always uncertain, between the instant of passage of the star and the observer's signal. For this purpose an impersonal micrometer is used fitted with a movable wire, actuated by an electric motor by means of a special device, at a speed practically equal to the azimuthal velocity of the star in the field of the telescope. The observer regulates the motor so as to keep the star continuously bisected by the wire. A fixed part of the wire moving mechanism makes successive contacts, which each constitute an imaginary wire, behind which the observed star passes.

3. TIMES-KEEPERS. At the present time clock-makers manufacture timepieces which are able to maintain a very regular rate for long periods. These timepieces are placed in a glass case in which the atmospheric pressure is kept constant. It is necessary, moreover, that they be protected from changes of temperature. Thus they are usually kept in cellars. The standard timepieces of the Paris Observatory are kept at 28 metres below ground level; at this depth, the temperature remains almost constant at 12.5° centigrade.

By means of electrical contrivances the time from these chronometers is distributed throughout the Observatory, either by synchronizing auxiliary timepieces, or by actuating the styluses of recording appliances.

4. COMPARISON OF TIMEPIECES AT GREAT DISTANCES. Until the beginning of the century, the comparison of the timepieces of two stations, of which the difference of longitude was to be determined, was made with considerably less accuracy than the determination of local time.

The most varied methods were used. For short distances, direct optical signals were used; long distances necessitated the transport of timepieces, or the observation of clearly defined celestial phenomena, such as eclipses of the moon or of the satellites of Jupiter, the occultations of stars by the moon, or lunar observations (culmination, lunar distances, lunar altitudes and azimuths).

The electric telegraph enabled a large number of differences of longitude to be measured; but it is only since the 23rd May 1910, on which day, on the initiative of the Bureau des Longitudes and of the French Government the service of broadcasting time by wireless telegraphy was inaugurated, that the standardisation of time became a fact, and all timepieces throughout the world could be compared with each other.

Since that date, the improvement of amplifying appliances has enabled time signals from the most distant stations to be graphically recorded.

II. *DETERMINATION OF A WORLD-WIDE SERIES OF LONGITUDES.*

1. PRELIMINARY STUDIES. The officially-adopted longitudes are considerably affected by the variety of methods and instruments used in their determination, as well as by the variety of the meridians of reference.

Since the appliances just described enable far greater accuracy to be obtained than that with which, for want of better methods, observers had till then to be contented, a methodical revision obviously became necessary.

Accordingly, as early as 1921, the Bureau des Longitudes proposed the establishment of a world-wide network of geographical positions, determined with the utmost precision, by using radio-telegraphy.

The primary stations would form the angles of a polygon, the closing error of which would reveal the accuracy obtained. If the observations were accurate enough, the operations might be carried out again, to make certain that the longitudes did not vary with time, and thus verify the invariability of the continents with regard to each other.

Before attempting a complete operation, however, those concerned wished to make further study of the material and the new methods which would be used, and as to the value of which they did not completely agree.

The comparison made at the Paris Observatory of the different types of astronomical instruments for determining local time (large transit circle of 2 m. focal length, portable transit instruments, prismatic astrolabe) showed that they gave an almost equally accurate result; but the use of the prismatic astrolabe necessitated that the relative personal equations of the observers be taken into account.

American geodesists also appeared quite satisfied with the results obtained with the small impersonal micrometer transit instruments. When atmospheric conditions were favourable, they obtained closing errors not exceeding 0.01^s in the network of stations which they made in the United States.

The accuracy obtained in receiving the time signals was very good, both in recording them graphically, as is done in America, and in comparing them by ear with the beats of the timepiece, as is done by Swiss geodesists.

2. PROGRAMME. As a result of these experiments the International Geodetic and Geophysic Union, which met at Madrid in 1924, decided to go on with the proposed operations. The definite scheme was drawn up by the Commission on Longitudes by Wireless Telegraphy presided over by General FERRIÉ. The International Astronomical Union, which met at Cambridge in 1925, adopted, among others, the following decisions which are quoted below because they contain a certain number of principles which should be strictly adhered to when operations of this nature are carried out.

"The Observatories or astronomical stations taking part in the operation will be divided into two groups, the first comprising the observatories — few in number — which will constitute the primary polygon, and which are obviously of considerable importance (Greenwich, Paris, Washington, etc.), whereas the second group will include observatories or stations which are required only to connect the observatories of the first group, or to form, with other observatories, secondary polygons.

The observatories of the primary polygon will not be definitely settled in advance, but will be selected, after the operation, from among those at which working conditions prove most favourable. The instruments used in the observatories which are to be connected up will be as nearly as possible of the same type. The transit instruments of the first group observatories will be fitted with impersonal micrometers, as mechanical motion is considered to be absolutely necessary.

As many as possible of the radio-receivers will be fitted with devices for recording signals.

In principle, circumzenithal stars from 20 to 25° N. & S. will be observed, (for the transit circles). There is no special table, but the American Ephemeris, with corrections, will be used when possible.

Time-keepers of the first quality will be used, as far as possible, the rates of which can be relied on during several consecutive days.

In principle the radio stations transmitting signals for the operation will be Bordeaux, Honolulu (Pearl Harbour), Saïgon, Annapolis; other stations also, however, may be selected in due course to transmit signals.

The radio signals will be of the 'Scientific Signals' type from, for example, Bordeaux and Saïgon, so as to enable the timepieces to be compared either by ear by the method of coincidences, or by recording. The operations will last two months, and will begin on the 1st October 1926, and will be preceded by some 'trial days.'"

3. OPERATIONS. These were carried out in conformity with the above instructions. Fifty-two astronomical stations, belonging to thirty different nations, decided to take part in them.

Thirty-one emissions of radio-telegraphic signals, on long waves and on short waves, were made each day by nine different stations.

The primary polygon. The French share in the operations, the programme of which had been settled in detail by a sub-Commission nominated by the Bureau des Longitudes, had as its most important object the formation of a belt around the globe, through three approximately equidistant positions situated in neighbouring latitudes, and connecting them to the Paris Observatory, the seat of the International Time Bureau. Moreover, it was necessary to connect numerous astronomical stations of the French colonies to each of these four stations.

The three primary stations adopted were:

Observatories.	*Latitude.*	*Longitude.*
ALGIERS	36°48' N.	0 h. 12 m. 8 s. 5 E. Gr.
ZIKAWEÏ (French)	31°11' N.	8 5 42 9 E. Gr.
SAN DIEGO (American)	32° 7' N.	7 48 48 4 W. Gr.

At San Diego, American observers operated on behalf of the United States, but a French observer, specialized in the use of the prismatic astrolabe, also worked there.

The astronomical instruments used were exactly the same: a small meridian instrument of focal length 0.75 m. with impersonal micrometer and mechanical movement, and a prismatic astrolabe of ordinary type. Moreover, observations were taken regularly with the transit circle of the Algiers Observatory.

The observations at each station were made in connection with the electric beats of the same timepiece at constant temperature and pressure.

Whenever the state of the sky permitted, two series of observations were taken with each instrument during the same night, one before midnight to obtain the difference of longitude from the station to the Eastward which, at the same time, was taking a morning series, the other after midnight in connection with the station to the Westward which was then taking an evening series.

All the positions of the observed stars were taken from the catalogue recently published by Captain W. S. EICHELBERGER of the U. S. Naval Observatory.

All the signals from every radio station which could be recorded were collected at each station ; moreover, vibrations at fifty to the second of an electrically worked tuning fork were inscribed on the recording chronograph and enabled readings to be taken independently of the small irregularities of unrolling of the chronograph recording band.

Further, the prismatic astrolabe observers met before and after the operations in July-August 1926 and in April-May 1927 at the Paris Observatory, where they completed, with their respective instruments and devices for comparing chronometers, a certain number of series by observing the same stars, on masonry piers, very close together, so as to determine the differences of their personal equations.

The weather during the longitude operations was fairly favourable at the three primary stations. The number of series carried out simultaneously was :

17 for Algiers and Zikaweï.
29 for Algiers and San Diego.
13 for San Diego and Zikaweï.

4. RESULTS. (A) *Differences of longitude.* The various astronomical stations, having thus determined their timepiece corrections, were able to publish their local sidereal times of reception of the radio telegraphic signals which they had collected.

The excellence of modern timepieces at constant temperature and pressure enabled their indications to be interpolated and use to be made, for the determination of longitudes, of signals received at times when unfavourable weather did not permit astronomical observations.

The differences of the times of reception of the same signals, corrected for the duration of propagation of the waves, provided values of the differences of longitude.

The following are the figures for the primary stations :

Stations.	*Signals used.*	*Differences of Longitude.*
ALGIERS - SAN DIEGO	BORDEAUX, BELLEVUE, ANNAPOLIS.	8 h. 0 m. 56.900 s. +0 s. 002
SAN DIEGO - ZIKAWEÏ	BORDEAUX, HONOLULU, SAÏGON.	8 h. 5 m. 28.731 s. +0 s. 006
ZIKAWEÏ - ALGIERS	BORDEAUX.	7 h. 53 m. 34.362 s. +0 s. 006
	Total	23 h. 59 m. 59 993 s.

which after compensation for closing error became

ALGIERS - SAN DIEGO..........	8 h. 0 m. 56.900 s. + 0,002.
SAN DIEGO - ZIKAWEÏ	8 h. 5 m. 28.734 s. + 0,003.
ZIKAWEÏ - ALGIERS	7 h. 53 m. 34.366 s. + 0,004.
Total	24 h. 00 m. 00.000 s.

Connected with Paris, Greenwich and Washington.

Stations.	*Signals used.*	*Differences of Longitude.*
ALGIERS - PARIS	ANNAPOLIS, BELLEVUE, BORDEAUX, NAUEN.	0 h. 2 m. 47.614 s. + 0,002.
PARIS - GREENWICH	ANNAPOLIS, EIFFEL, BORDEAUX, NAUEN.	0 h. 9 m. 20.913 s. + 0,002.
PARIS - WASHINGTON. ...	ANNAPOLIS, BELLEVUE, BORDEAUX.	5 h. 17 m. 36.662 s. + 0,002.

A provisional list of differences of Longitude from Greenwich, of a certain number of observatories which took part in the 1926 operations, is given hereafter.

A definite list will be published later giving, in addition, the precise position of the station as well as information concerning the instruments used and the methods of observation and calculation.

Station.	*Longitude Greenwich.*	*Station.*	*Longitude Greenwich.*	*Station.*	*Longitude Greenwich.*
ADELAIDE	9. 14. 19. 849	FLORENCE.......	0. 45. 2. 658	OTTAWA	5. 2. 51. 926
ATHENS	1. 34. 52. 002	HELWAN..........	2. 5. 21. 872	RIO DE JANEIRO	2. 52. 53. 441
BELGRADE	1. 21. 47. 999	HONG-KONG ...	7. 36. 41. 189	SIDNEY	10. 4. 49. 191
BOGOTA...........	4. 56. 19. 54	HONOLULU (Niu).	10. 30. 55. 279	TACUBAYA	6. 36. 46, 74
THE CAPE........	1. 15. 54. 613	MANILLA (Ft MacKinley).	8. 4. 12. 652	TOKIO	9. 18. 10. 110
COLOMBO	5. 19. 28. 758	MANILLA .... (Observatory of Jes. F.).	8. 3. 54. 706	TSING TAO	8. 1. 16. 892
COPENHAGEN ...	0. 50. 00. 662	MADRID..........	0. 14. 44. 973	UCCLE............	0. 17. 25. 941
DEHRA DUN ...	5. 12. 11. 794	MELBOURNE	9. 39. 53. 56	VANCOUVER.....	8. 12. 28. 331
EDINBURGH	0. 12. 44. 096	NOSSI BÉ	3. 13. 5. 932	WELLINGTON ...	11. 39. 4. 013

The above results for the three primary stations and for Paris were obtained by means of transit instruments. The differences of longitude obtained with the prismatic astrolabe, taking into account the differences of personal equation, are deduced by applying the following corrections :

ALGIERS - SAN DIEGO	—0 s.,	02.
SAN DIEGO - ZIKAWEÏ............	+0	01.
ZIKAWEÏ - ALGIERS	+0	01.
ALGIERS - PARIS	—0	06.

It should also be noted that Sir F. DYSON, the British Astronomer Royal, has undertaken to connect the angles of a second primary triangle : Greenwich, Tokio, Vancouver, and that the U. S. Coast and Geodetic Survey is making a polygon of the Pacific including Manilla and Honolulu.

(B) *The accuracy of the measurements.* Accidental errors of astronomical origin are very slight. The mean theoretical error for the whole series at each station does not exceed 0.005 s.

As regards radio-telegraphic signals, it was considered that their accuracy would be greatly superior to that of astronomical determinations. Experience has shown that this is not the case.

In consequence of irregularities of propagation of the waves, and imperfections in the receiving and recording apparatus, it was sometimes found that two signals of one series were received by different stations at intervals of time which might differ by several hundredths of a second.

However, accidental errors from this cause, affecting the differences of longitude, are generally very small and on an average of the order of one thousandth of a second. Systematic errors, without doubt due to delays in recording signals, might cause an error in the longitudes of 0.01 s.

In order to demonstrate the smallness of errors of a changeable character and the absolute constancy of systematic errors, various groupings of difference of longitude have been drawn up.

Astronomical observations and transmission of signals made at practically the same time are grouped together.

Stations.	*Signals.*		*Date T.U.*	*Differences of Longitude.*
ALGIERS-SAN DIEGO........	ANNAPOLIS	3 h. 10	*t*, 1	8 h. 0 m. 56.908 s.
SAN DIEGO-ZIKAWEÏ	HONOLULU SAIGON......	10 h. 30 11 h. 30	*t*, 5	8 h. 5 m. 28.732 s.
ZIKAWEÏ-ALGIERS...........	BORDEAUX	20 h.	*t*, 8	7 h. 53 m. 34.369 s.
			Total	24 h. 0 m. 00.009 s.

Differences of longitude obtained at different dates by different radio signals have also been grouped together :

Stations.	Signals.	Epoch.	Difference of Longitude.
ALGIERS-SAN DIEGO...	ANNAPOLIS 3 h. 10	1st to 10th Oct. 21st Nov. to 1st Dec.	8 h. 0 m. 56.902 s.
SAN DIEGO-ZIKAWEÏ...	HONOLULU 10 h. 30 SAÏGON ..... 11 h. 30	1st to 20th Nov.	8 h. 5 m. 28.729 s
ZIKAWEÏ-ALGIERS......	BORDEAUX 20 h.	11th to 31st Oct.	1 h. 53 m. 34.369 s.
		Total	24 h. 0 m. 00.000 s.

Thus it is seen that systematic errors remain fairly constant.

The agreement of the results obtained, with different observers and apparatus, in the measurement of the difference of longitude between Paris and Washington which, in 1913, was found to be 5 h. 17 m. 36 662 s. (French expedit.)
5 h. 17 m. 36 653 s. (American exped.)
and in 1926 5 h. 17 m. 36 662 s.
constitutes a first-rate check.

Moreover, at the Algiers Station, where two transit instruments of very different type were used and where the observations and the reductions were not carried out in the same way, the timepiece corrections obtained by means of these two instruments differed on an average by 0.004 s. taking into account their difference of longitude.

Finally the excellent agreement which exists between the values obtained with the *prismatic astrolabe* and the *transit instrument* for the three primary stations establishes a tangible proof of the smallness of the systematic errors of the astronomical instruments, which errors are certainly less thean 0.02 s.

In short, "it does not seem to be an exaggeration to assume that the differences of longitude of the principal stations are known to within about 0.03 s. of which 0.02 s. of possible error is of astronomic and 0.01 s. of radiotelegraphic origin." (LAMBERT: *French participation in the revision of longitudes of the world.* Toulouse 1928, p. 122).

c) *Additional results: Velocity of propagation of radio telegraphic waves.* In view of the short distances between stations in relation to the velocity of propagation of waves, the accuracy of the time measurements does not permit this velocity to be calculated with an approximation greater than 10,000 km/sec.

Nevertheless, it should be noted that the velocities calculated on the assumption that the wave would follow the great circle joining the stations, lie between 210,000 and 293,000 km/sec., with an average of 247,000+9,000 km/sec. which values are clearly less than 300,000 km/sec.

The measurements carried out from 1911 to 1914 resulted in values between 221,000 and 296,000 km/sec.

It would be necessary to assume an extension of the distance covered by more than 20 % to obtain the value of 300,000 km/sec.

It is more logical to suppose that the increase in the duration of the passage is caused by recording delays which are greater as the energy received is smaller and, as a consequence, the greater the distance between the emitting and receiving stations. This delay would be of the order of 1/10,000 of a second per 1000 km. for the receiving apparatus used.

Latitude. In the stations where a prismatic astrolabe was used, a value of the latitude was obtained without additional calculation, at the same time as the correction of the timepiece.

At Paris, the mean latitude obtained differed by + 0.02" from the value determined in 1916 by the same observer with the same instrument, in exact agreement with the variation published in the Monthly Notices which give for these two dates a difference of + 0.01". (1)

At Algiers, the examination of 60 values obtained for the latitude shows maxima near full and new moons. The lack of observations due to unfavourable weather at the dates when the values for latitude should be at their minima has not permitted the amplitude of this semi-lunar variation to be determined accurately, but it seems possible to estimate it at 1" approximately. (2)

III. *LONGITUDES IN HYDROGRAPHY.*

1. ADJUSTMENT OF MARINE CHARTS. Except for some particular points of the globe, amongst others the West Coast of Africa, some of the Pacific islands and various lands of the Arctic and Antarctic Oceans, the values now accepted for the longitudes are quite sufficiently accurate for the needs of navigation.

The problem, as regards marine cartography, is rather different. This sets out not only to give mariners documents suited to their needs, but also to provide as exact a representation as possible of the surface of the earth throughout the seas of the world

But if the divergences of geographical positions which are most frequently met with seldom exceed 10 or 15" and produce only graphically inappreciable errors on small scale charts, it is quite a different matter on those of large scale.

If charts of the same area, published at various dates, are compared, it will be seen that there are divergences between them which generally result in a translation of the graduation, since in many cases new determinations of geographical positions have been made in the interval between publications.

Moreover, in the case of charts based on the geodetic triangulations established by various countries, there may be fairly considerable distortions at the junction of these networks, due to the more or less imperfect agreement of the geographical positions of the original points, to the difference of the ellipsoids adopted for the determination of the positions of the various points, and lastly to the independent compensation of each network.

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(1) M^me CHANDON. Report of the French Ac. of Sc. Vol. 186, 1928, p. 1823.

(2) GOUGENHEIM. Report of the French Ac. of Sc. Vol. 187, 1928, p. 231.

In short, in the present-day state of marine cartography, a certain point may have different geographical co-ordinates not only on the charts published by various nations, but also on those of the chart-sets published by a single country.

If it is not possible to alter the graduations and the meridians on the engraved plates as new values for longitudes are adopted, without causing too much damage, the first step towards uniformity in geographical positions might nevertheless be taken by publishing a catalogue of all those which affect hydrography in accordance with the terms of the International Hydrographic Bureau's Circular-Letter N° 20-H dated 12th April, 1927.

This catalogue, which will condense in one volume the values and the discussions which are at present scattered throughout a considerable number of publications, will be of obvious benefit, both for the Hydrographic Surveyor who has to make new determinations, who will have at his disposal, without laborious research, the precise data which he requires for reference, and for the cartographer who will be able to compare rapidly the value of the various documents on which he relies for geographical position and to choose from amongst them the most recent and accurate.

This catalogue should contain the positions fixed during the 1926 operations, which will serve as base for future determinations. The values obtained, though not absolutely definite, constitute in reality, in the present state of technics, a maximum of precision which could be exceeded only after further theoretical and instrumental progress.

It would be an advantage if this catalogue were completed by adding a note on marine charts, indicating the reference meridian, the longitude adopted for this meridian with the date of the determination and, lastly, the quantity by which the longitudes of the chart must be corrected so that they will agree with this meridian.

This note, which it would be easy to keep up to date, would often obviate a search through the catalogue and, in any case, would facilitate it, by at once indicating the point which serves as the base for the geographical positions of the chart.

2. FUTURE DETERMINATIONS OF LONGITUDES. (A) The serious consequences which might be brought about by uncertainty in longitudes, show the necessity of seeking straight off the greatest possible precision when, during a hydrographic survey, a difference of longitude has to be measured.

Hence, for astronomical observations, instead of a transit instrument, the use of which is inconvenient in the field, *a prismatic astrolabe* should be used in preference to a theodolite.

The use of a light *recording chronograph*, on which the beats of a *chronometer with electric contacts* are inscribed, would enable the accuracy of these observations to be considerably improved.

Finally, the error of the chronometer standard time should be determined on by receiving *rhythmic time signals* in preference to other signals. By listening to them with head phones at the same time as to the electric beats of the chronometer, the method of coincidences may be applied, and a very accurate comparison be obtained without difficulty.

At the present time, there are 7 rhythmic signal-stations: Eiffel, Bordeaux, Saïgon, Moscow, Leningrad, Rugby and Nauen. With the exception of the last, all use a similar system.

Moreover, these signals have the advantage of being emitted to within some hundredths of a second and of being controlled by the service to which they belong, which service periodically publishes corrections to be applied to the signals received.

(B) The various points of a country, the geographical position of which it is necessary to know for drawing up charts, are obviously not of equal interest and could be divided into two groups, according to their importance, the first containing only a certain number of principal points, the positions of which should be particularly well determined, and to which those of the second group should be connected.

The International Astronomic Union having decided to go on with the 1926 operations shortly after its next Congress, *i. e.* about in 1933, some very careful time observations will be made at this time at numerous stations throughout the world and additional radio-telegraphic time signals will be probably sent out.

Hence this period seems very favourable for determining the longitudes of points of the first group which might form part of the primary or secondary polygons, the closing error of which will reveal the accuracy obtained, and to the angles of which it will be possible to apply compensation.