Geophysics. — *A gravity expedition of the U. S. Navy.* By F. A. VENING MEINESZ.

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In the course of 1928 the writer received an invitation from the Carnegie Institution of Washington to come to the U. S. A. with the apparatus for maritime gravity survey of the Netherlands Geodetic Commission in connection with an expedition for determining gravity at sea, which the U. S. Navy wished to organize as a consequence of a communication on this subject, received from the International Geodetical and Geophysical Union. The Secretary of the Navy designated the Naval Observatory for making the arrangements for this expedition.

The expedition took place in the autumn and consisted of the U. S. Submarine S-21 on board of which the observations were made and two surface ships, the U. S. Eagles 35 and 58. The captain of the Eagle 35, Lieutenant T. L. NASH had command of the expedition, while Lieutenant JAMES L. FISHER was in command of the U. S. S. S-21 ; the officers of this ship were Lieuts. F. S. HALL, F. DOW HAMBLIN and A. R. SODERGREN. The scientific staff on board the S-21 consisted of Dr. FRED. E. WRIGHT of the Geophysical Laboratory of the Carnegie Institution, Mr. ELMER B. COLLINS, principal Scientist of the Hydrographic Office, and the writer.

The observations have been made with the pendulum apparatus which has been constructed according to the plans of the writer at the laboratory of the Meteorological Institute at De Bilt (Holland) by the chief mechanic L. M. VAN REST ; begun in 1925 it has received its final shape in the spring of 1928 by the rearrangement of the photographic recording apparatus and other smaller improvements.

The apparatus was mounted in the central control room of the submarine. As it was near the meta-centre of the ship, the rolling and pitching of the ship caused hardly any translations of the apparatus, which is of course advantageous. It is hung in gimbals so that it is possible to work even if the rolling or pitching is fairly large ; during the last expedition, a few observations have been made with a roll of 7° to both sides of the vertical and with a slight modification of the gimbals it is hoped that in the future even greater movements may be allowed. In this way it is often possible to make the observations at periscope depth. During the return, however, from Guantanamo across the Atlantic to Washington, the sea was so rough, that two observations, which had been planned above the bottom and the top of the continental slope, could not be made ; the movements at 30 meters depth far exceeded the limit of 7°.

The schedule of the expedition has been arranged according to the different geodetical and geophysical problems in or near the West Indies. We may mention the question if the Gulf of Mexico and the Caribbean Sea are in isostatic equilibrium, if the Mississippi delta shows deviations of isostasy, of the gravity field above the Nares deep North of Porto-Rico and the Bartlett deep South of East Cuba, of the gravity in the Atlantic between Cape Hatteras and the West Indies and especially above the continental slope for that part of the coast of the U. S. The expedition has accomplished the following programme :

Leave	Arrive	Number of Observ.
1 Oct. Washington.	2 Oct. Hampton Roads.	0
4 „ Hampton Roads.	8 „ Key West.	3
10 „ Key West.	14 „ Galveston.	7
19 „ Galveston.	23 „ Key West via Mississippi delta.	7
29 „ Key West.	2 Nov. Guantanamo (Cuba) via Bartlett Deep.	8
5 Nov. Guantanamo.	9 „ St. Thomas via Nares Deep,	9
15 St. Thomas.	19 „ Guantanamo via Caribbean Sea.	6
21 „ Guantanamo.	27 „ Washington.	5

Besides, observations have been made in all the harbours, of which Hampton Roads, Guantanamo, San Juan (during trip from Guantanamo to St. Thomas) and St. Thomas were gravity stations, which have not yet been occupied before. The total number of new stations amounted therefore to 49.

Thanks to the whole-hearted cooperation of the Captain of the U.S.S. S-21, Lieut. FISHER, who ordered all the dives necessary for the observations, the possibilities given by this programme could be realized completely. This implied a great deal of diving that is to say an additional strain for everybody ; often several submergencies were made on one day, once even five in seventeen hours. The helpful assistance of the Captain, the Officers and the crew under all circumstances may be gratefully acknowledged here.

Besides the pendulum observations a great number of soundings has been taken. The submarine was provided with the sonic depth-finder of the U. S. Navy, which has given good results. Not only were soundings possible during submergence but also while going at the surface ; only when the sea was very rough the echo could not be observed. In this way a continuous line of soundings could be taken over the whole route of the expedition with the exception of a few rough days in the Atlantic during

the return voyage. Over the deeps the soundings were taken at short intervals, so that a detailed profile could be obtained ; no instances have been met, as has been the case during the previous voyage with the K XIII over the West Pacific deeps, of irregular and disappearing echo's. To the sides of these deeps, steep slopes have been found — south of East Cuba an inclination of 40° — but, with only few exceptions, the bottom of the deeps appeared to be fairly even.

The results of the gravity observations have been provisionally computed during the voyage itself and at the same time the isostatic reduction of the stations has been made at the bureau of the U. S. Coast and Geodetic Survey, so that the provisional results were already available a few days after the return of the expedition to Washington. The final computations are now being made at the Naval Observatory. As long as they have not been finished, a definite interpretation seems not advisable but a few remarks concerning the provisional results may be given ; it is not probable that the final results will change these conclusions [1]).

The Gulf of Mexico shows a positive anomaly of about 60 millidynes over nearly its whole extension ; only North of Yucatan and South of the Mississippi delta the anomaly is less, but it has still a positive value there of about + 20 m.d. It is not easy to see the significance of this positive anomaly because it seems difficult to accept the existence of stresses in the earth's crust working over so large an area and not showing any evidence of their presence in the adjoining land areas. Have we to look here for a deep-seated cause, connected perhaps to the origin of the Gulf ?

We may recall here to mind that previous observations which have been made in another inland sea, i.e. in the Mediterranean, likewise have given positive anomalies which locally even attained values of about 100 m.d. For the Western part of the Mediterranean, KOSSMAT has proposed the following explanation [2]). The surrounding mountain-chains have sunk after folding, according to the readjustment of isostatic equilibrium and the magma has been pressed away towards the region below the sea, causing there an excess of mass, which has not yet sunk into isostatic equilibrium. The writer has some difficulty in accepting this explanation. Letting alone the question if indeed the pressing away of the magma would cause so much horizontal movements in the subcrustal magma, which seems doubtful to him, he has the objection that, according to this view, the mountain chains ought to show still greater positive anomalies after isostatic reduction than the sea between and that this is not the case in general.

Returning to the Mexican Gulf, we may mention that in the region near the Mississippi delta, where we might expect a positive anomaly because of the large masses of material deposited by the river in the gulf, no evidence

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[1]) All the anomalies mentioned in this paper refer to gravity values, which have been reduced isostatically according to the method of the U. S. Coast and Geodetic Survey.

[2]) FR. KOSSMAT, Die mediterranen Kettengebirge in ihrer Beziehung zum Gleichgewichtszustande der Erdrinde.

of such an effect has been found ; the small anomalies seem rather to be connected to the general trend of anomalies in the whole gulf. We may conclude therefore that there is no evidence of a lag in isostatic adjustment of the delta.

The Caribbean Sea shows also positive anomalies for the part which has been investigated, i.e. the part South of Haiti and Porto-Rico. The mean of the four available gravity anomalies after isostatic reduction is + 40 m.d.

Above the Nares deep, North of Porto-Rico, great departures of isostatic equilibrium have been found, which is not surprising as it may be considered probable that these ocean deeps are not yet in stable condition. Above the deep itself is a great negative anomaly ; before isostatic reduction the deficiency is more than 300 m.d. and after this reduction it is still more than 190 m.d. This result is in good agreement with the few gravity values which have been determined in this region during the previous voyage with Hr. Ms. K XIII. North and South of the deep, the anomaly after isostatic reduction is small ; to the North it is slightly positive, ± +25 millidynes, and to the South, in the harbour of San Juan, slightly negative, —10 m.d. The gravity on the island of Porto-Rico is yet unknown, but in a short time some data will be available ; the U. S. Coast and Geodetic Survey is planning an expedition for supplying a series of land values in connection with the expedition, which obviously will be highly valuable as they will complete the data which have been found. Several stations on Porto-Rico, Haiti, Cuba and on the smaller islands will be occupied.

We mentioned already that South of Porto-Rico anomalies of about +40 m.d. have been found. Resuming the results near the Nares deep, we see that apparently the great negative anomalies above the deep are not accompanied by considerable positive anomalies in the neighbourhood, unless the observations on the island of Porto-Rico will reveal any such anomalies. In this regard the gravity field over this deep shows a different character from the fields which have been found during the voyage of the K XIII over several West-Pacific deeps, the Nero deep near Guam, the Yap deep and the Philippine deep. They all show a strong negative anomaly above the deep, but strong positive anomalies besides the deep ; generally the anomaly to the West side of the deep, i.e. the island side, is greater than the anomaly on the Eastern side, the ocean side. Those positive anomalies diminish only slightly at a greater distance of the deep ; they do not disappear.

The Java deep South of the island of Java, shows again another gravity field. This deep consists of two parallel deeps separated by a submarine ridge ; the Northern one is much less deep than the Southern one. The gravity anomaly field is strongly positive on the Southern edge of the island, shows a negative minimum below the submarine ridge and gets positive again on the Southern edge of the Southern deep ; again the positive anomaly on the island side is greater than on the ocean side.

Reserving a further study of these gravity fields for another occasion,

we will only remark here that they show characteristic differences, so that these deeps apparently cannot be looked at as features in identical circumstances.

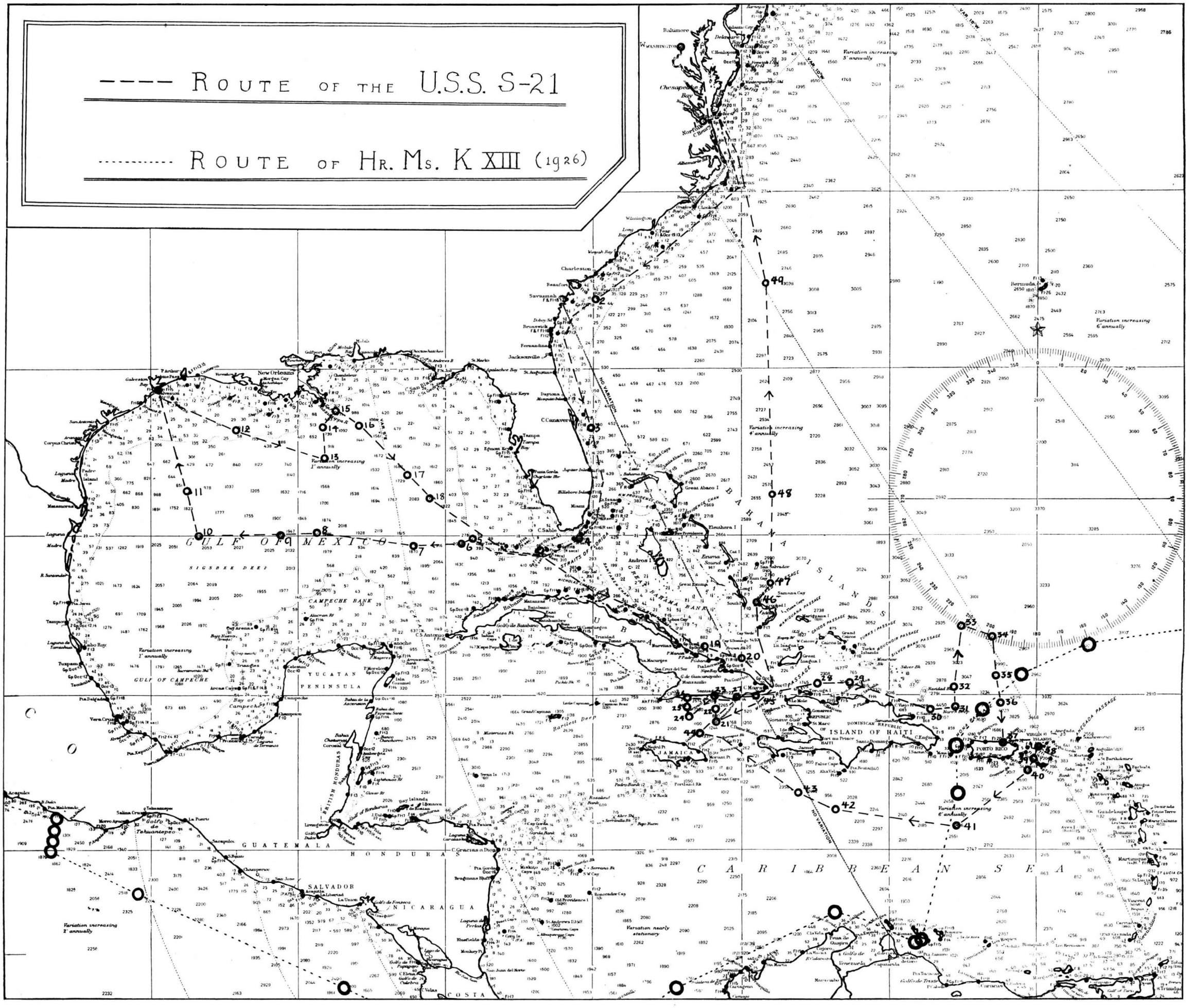
Another result of the last expedition, which is worth mentioning in connection with the Nares deep, is that two stations, North of the island of Haiti, both situated to the West of the deep and in a line with it, show great negative anomalies ($\pm$ —120 m.d.) and even further to the West, in two stations North of East Cuba, the anomalies are still negative : $\pm$ —40 m.d. This seems to indicate that the stresses in the earth's crust, which are related to the formation of the Nares deep, are not confined to the region of the deep itself, but continue much farther Westward. The topography does not reveal this.

The anomalies found above and near the Eastern part of the Bartlett deep, South of East Cuba, are smaller than those of the Nares deep, which have been mentioned. Above the deep itself have been found anomalies of —61 m.d. and +13 m.d., to the North of the deep, near the coast of Cuba +24 m.d. and +56 m.d. and to the South of the deep —14 m.d., +24 m.d. and +24 m.d. Apparently the disturbances of equilibrium are smaller than above the Nares deep.

Lastly the results may be given in this connection for the sea between St. Thomas and St. Croix. The sea-floor shows here a narrow depression with a depth of about 2400 fathoms (4500 m.), while the distance between the ridges of St. Thomas and St. Croix is not more than 40 miles. Gravity in St. Thomas harbour, North of the depression, gave no anomaly and on the ridge South of it, to the West of St. Croix, an anomaly of —11 m.d. ; between those stations a negative anomaly has been found of —61 m.d.

It will be necessary carefully to investigate the isostatic reductions, which have been applied to these values, in order to see if another distribution of the compensating masses may perhaps account for these results. If not, we have here a clear instance of a departure of equilibrium, which is related to a topographic feature and which probably may be interpreted as the effect of a folding or faulting process, which is going on and which presses the bottom of the depression in a position below its equilibrium position.

The gravity found in the Atlantic Ocean on the way back from Guantanamo to Washington between Crooked Island passage and Cape Hatteras gives for the three stations above deep water slightly positive anomalies ; their mean value is +10 millidynes. These stations are all near the bottom of the continental slope. In Crooked Island passage, at the top of the slope, an anomaly of —26 m.d. has been found. The two stations of the U. S. Coast and Geodetic Survey which are near the top of the continental slope for this part of the coast, Beaufort, N. C. and Wilmington, N. C. likewise show negative anomalies, —21 m.d. and —31 m.d. We find here an analogous result, although less pronounced, as has been found in 1926 with the K XIII on the West Coast of Central and North America between Panama and San Francisco ; the value of the anomaly (with


---- ROUTE OF THE U.S.S. S-21
..... ROUTE OF HR. MS. K XIII (1926)
GULF OF MEXICO
CARIBBEAN SEA
BAHAMA ISLANDS
CUBA
YUCATAN PENINSULA
GUATEMALA
HONDURAS
NICARAGUA
COSTA
JAMAICA
ISLAND OF HAITI
PORTO RICO
Washington
Baltimore
Charleston
Savannah
Jacksonville
New Orleans
Havana
Bermuda
Variation increasing 5' annually
Variation increasing 6' annually
Variation increasing 4' annually
Variation increasing 1' annually
Variation increasing 2' annually
Variation nearly stationary
NO VARIATION

regard to sign) is greater above the foot of the slope than above the top. In the last case gravity above the top was about normal while the mean anomaly above the foot of the slope was +65 m.d.

An interpretation of this result would be premature but two remarks can be made. Firstly, it appears difficult to account for it by assuming another location of the compensating masses in the earth's crust than that which has been used for the isostatic reduction ; when examining the question the writer did not succeed in finding any acceptable mass distribution which would explain it. It looks as if we are forced to admit a deviation of equilibrium on these coasts.

Secondly, an explanation of the deviation of equilibrium on the West Coast by a Westward drift of the American continent and consequently the exertion of pressure on the ocean floor, does not seem to be in harmony with the results on the East coast, which are brought back by the last expedition. The reverse ought then to have been found on the East coast, viz. a negative anomaly above the foot of the slope, corresponding to a sucking effect behind the moving continent.

Before and after the expedition base observations have been made with the apparatus as well in the gravity base station, Washington, of the U. S. Coast and Geodetic Survey, as in the Netherlands gravity base station, De Bilt. These observations provide therefore a new check on the comparison of Washington with the international base station Potsdam. The final computations and the application of the final corrections of the time-signals have to be awaited before any conclusions will be possible.

The expedition of the U. S. S. S-21 has been made possible by the cooperation of the U. S. Navy with the Carnegie Institution and the Netherlands Geodetic Commission. Sincere thanks may be expressed to the Secretary of the U. S. Navy, the Hon. CURTIS D. WILBUR, to Admiral HUGHES, Chief of Naval Operations, to Admiral LEIGH, Chief of the Bureau of Navigation and to Captain FREEMAN, Superintendent of the Naval Observatory to whom the writer is feeling much indebted for what he has done in preparing the expedition. The writer wishes to take this opportunity for acknowledging the kind reception which has been given to hem everywhere, in Washington in naval as well as in scientific circles, on board the U. S. S. S-21 and the other ships, and ashore in the different ports which have been touched.

He expresses the hope that the expedition may lead to further research in this direction by the U. S. Navy ; results of great extent and great importance for geodetic and geophysical science might then be expected.