GRAVITY DETERMINATIONS ON THE "CARNEGIE".

by

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The experience of Dr. Vening MEINESZ with the apparatus on board the Dutch submarines, *K XIII*, *K II*, and *K XI*, and in particular on board the United States submarine *S*-21 indicated that it might be possible to obtain gravity measurements on surface vessels. In view of the character and extent of cruise VII of the *Carnegie*, of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, there seemed to be an ideal opportunity for obtaining gravity measurements at sea, in various harbours, and near several islands, which results would have been most desirable for a better determination of the figure of the earth and for futher studies in isostasy.

Accordingly, it was decided to instal a Vening MEINESZ gravity apparatus on the *Carnegie* in San Francisco, in August, 1929, for this was the nearest port to Washington in the remainder of the cruise, and, therefore, required the least amount of transportation of apparatus and of men to instal it and to make the necessary adjustments and tests. Only through the efforts of Dr. Vening MEINESZ and the fine spirit of generous co-operation of Dr. N. E. NORLUND, Director of the Geodetic Service of Denmark, who arranged for an apparatus which had been ordered for that service to be delivered to Washington, was it possible to obtain an instrument in time for standardization in Washington and for installation on the *Carnegie* in San Francisco.

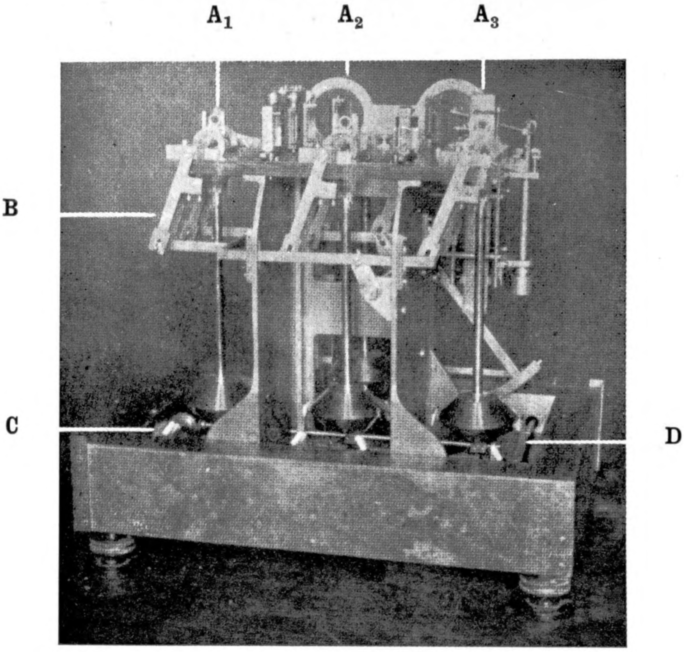
The standardization at the United States Coast and Geodetic Survey gravimetric base station and the preliminary records on the *Carnegie* at San Francisco were made by Dr. F. E. WRIGHT, of the Geophysical Laboratory of the Carnegie Institution of Washington. His experience in working with Dr. Vening MEINESZ on the gravity-measuring cruise of the United States submarine *S*-21 made his assistance invaluable. The instrument was placed in the main cabin of the *Carnegie* about seven feet abaft the chronometer cases and at a position close to the centre of oscillation of the vessel.

The adjustments of the apparatus were completed before the end of August (1929) including the installation of a special radio time-signal amplifier which had been used in Washington for the standardization and which provided for the recording of wireless time signals automatically upon the photographic record of the gravity instrument, in order to make for high precision in the rates of the chronometers used in the gravity determination. Provision was also made to obtain the chronometer corrections aurally by using coincident beats of a mean-time chronometer with rhythmic radio time signals or by using the coincident beats of a fast running chronometer with mean-time radio signals. At sea on board the *Carnegie* the aural method was used entirely, for it was then not necessary to swing the pendulums and to develop the photographic trace, and, moreover, it was found that reliable aural comparisons could be made when radio reception was so poor that the signals could not be recorded automatically. By the aural method the chronometer corrections could be obtained with an estimated probable error of about $\pm$ 0.01 second. Examination of the variability of the daily rates of the chronometers indicated that the precision obtained in the determination of those rates aurally by the coincidence method was all that was justified.

To facilitate subsequent discussion of the behaviour of the apparatus on the *Carnegie* the fundamental principles of the apparaus will be briefly outlined and its construction briefly described. The complete theory and description of the instrument will be found in *Theory and practice of pendulum-observations at sea* by Dr. F. A. Vening MEINESZ, and also in *The gravity-measuring cruise of the U.S. submarine* S-21.

Essentially the Vening MEINESZ apparatus consists of three, nearly isochronous, quarter-metre, half-second pendulums with their knife edges mounted on the same horizontal support so that the pendulums all swing in the same vertical plane. Fig. 1 is a photograph of the pendulum case with the insulating cover removed.

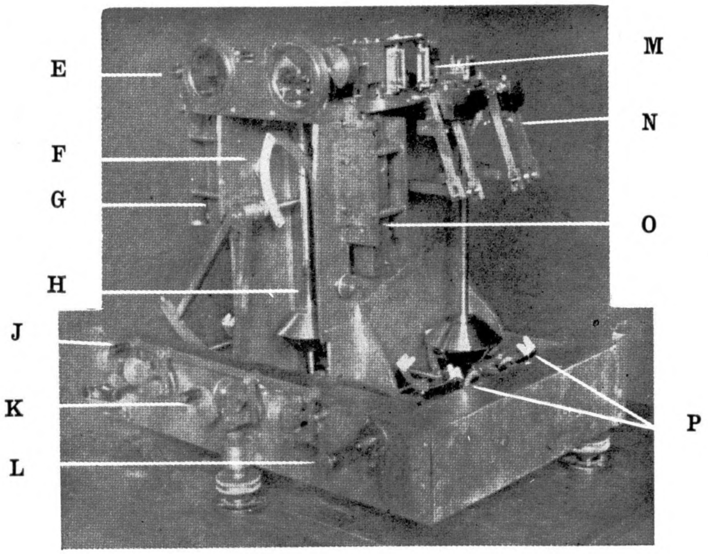
From left to right let the pendulums be identified as Nos. 1, 2, and 3. Just in front of No. 2 there appears a dummy pendulum which serves only to contain a thermometer. Let the angles of elongation, that is, the angles between the vertical and the



Instrument pour la mesure de la Gravité,
Type Vening Meinesz.
(Ouvert)

A Pendules.
B Leviers pour soulever au-dessus des couteaux
C Crochets en ivoire.
D Levier d'amplitude.
E Lentilles.
F Echelle de l'hygromètre.
G Pendule amorti pour le plan d'oscillation.
H Faux pendule.
J Bras d'amplitude couplés.
K Soulevage du pendule.
L Clavette du pendule.
M Prismes.
N Leviers lent et rapide pour le soulèvement des pendules.
O Pendule enregistreur amorti.
P Tenons en ivoire.

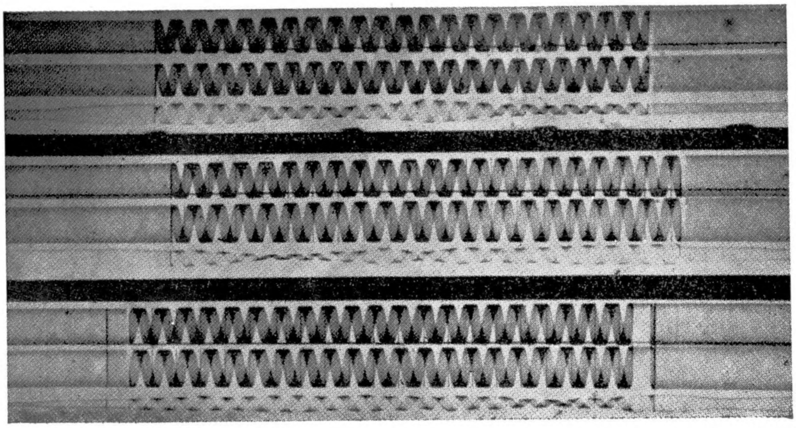
FIG. 1*a*



The Vening Meinesz Gravity Instrument.
(Case removed)

A Pendulums.
B Levers to lift from knife edges.
C Ivory clamps.
D Amplitude lever.
E Lenses.
F Hygrometer scale.
G Damped pendulum for plane of oscillation.
H Dummy pendulum.
J Coupled amplitude arms.
K Pendulum lift.
L Pendulum clamp.
M Prisms.
N Slow and quick action levers for raising pendulums.
O Damped record pendulum.
P Ivory clamps.

FIG. 1*b*



Enregistrements de mesures de gravité obtenus à bord du "Carnegie".

Gravity Records obtained in the "Carnegie".

FIG. 2

axes of the pendulums, be designated as θ_1, θ_2 and θ_3. By means of light-rays reflected from mirrors attached to the tops of the pendulums, the following angles are recorded photographically : $(\theta_1 - \theta_2)$, $(\theta_2 - \theta_3)$, and θ_2. The datum for recording θ_2 is a critically damped pendulum not shown in the photograph. Suppose the whole instrument is subject to horizontal accelerations in the plane of the three pendulums, then the amplitudes of θ_1, θ_2, and θ_3 vary. However, the amplitudes of $(\theta_1 - \theta_2)$ and $(\theta_2 - \theta_3)$ are within limits quite independent of the horizontal accelerations. Thus $(\theta_1 - \theta_2)$ and $(\theta_2 - \theta_3)$ may be considered as the angles of elongation of two fictitious pendulums, each of which is undisturbed by horizontal accelerations. Thus, from the photographic records of $(\theta_1 - \theta_2)$ and $(\theta_2 - \theta_3)$, which are interrupted every half-second by chronometer operated shutters, may be obtained the periods of the two fictitious undisturbed pendulums, in just the same way as the period of an actual, undisturbed pendulum would be determined from a photographic record. This is the fundamental principle of the apparatus. Since the three pendulums cannot be made isochronous over any considerable range of air temperature and pressure, the record of θ_2 is needed for a small correction for this lack of isochronism and also for the correction for amplitude.

The effect of vertical accelerations of the apparatus can be made negligibly small in two ways; first by choosing an initial and a final instant, over the time interval in which the average period of each fictitious pendulum is determined, such that each instant is the middle of a small time interval over which the average vertical accelerations are small — the record itself facilitates this procedure; and second by making the time interval between the two instants sufficiently large. For this purpose observations of half an hour are quite sufficient. Provision is made to record the angle between the vertical and the plane of the pendulum so that a correction for the tilt of the plane of swing may be applied. Finally the whole apparatus is mounted in gimbals.

Reading from bottom to top, figure 2 shows on a reduced scale three records obtained on the *Carnegie* in the harbours of San Francisco, Honolulu, and Pago Pago (American Samoa), respectively. On each record the two upper curves, which have about the same width, are the records of the two fictitious pendulums, that is, the records of $(\theta_1 - \theta_2)$ and $(\theta_2 - \theta_3)$. The lower curve is derived from the middle pendulum alone, that is, θ_2; its variable amplitude indicates how it is affected by the movements of the vessel. The regular amplitudes of the two fictitious pendulums show that these are quite unaffected by these movements. The character of the middle part of the record is changed by slowing up the speed of the photographic paper and by interrupting the recording beam of light for alternate half-seconds in order to facilitate the measurement of certain quantities needed for corrections.

With this outline of the principle of the apparatus and its construction, we may now proceed to a discussion of the behaviour of the apparatus on board the *Carnegie*.

No particular difficulty was experienced in obtaining gravity records on board the *Carnegie* while she was in port at San Francisco, at Honolulu and at Pago Pago (American Samoa), although the amplitude of the middle pendulum in all but one of the records obtained in San Francisco always got quite large considering the small movements of the vessel. This was probably due, not so much to the amplitude of the vessel's movements, as it was to the vibrations caused by the "rubbing" of the vessel against the pier.

Several attempts were made to obtain gravity determinations at sea during the 17-day voyage from San Francisco to Honolulu and again during the 47-day run from Honolulu to Pago Pago. Most of these attempts were unsuccessful because the amplitudes of the pendulums got too large and in a few instances there was actual slipping of the knife edges.

Other unsuccessful attempts to obtain satisfactory records at sea failed either for the same reason or because it was feared that slipping would occur.

Several factors may operate to increase the amplitudes of the pendulums to the point where slipping may occur. One is the unavoidable horizontal acceleration due to the rolling of the vessel. Another, and this Dr. Vening Meinesz from his long experience with the apparatus considers quite important, is the effect of surface waves upon the hull of the ship to produce horizontal accelerations apart from those due to rolling. Finally, there are the elastic vibrations of parts of the apparatus or its support. If the period of such vibrations is near to the period of the pendulums, there will be a resonance-effect which will cause the pendulum amplitudes to get large.

Dr. F. E. WRIGHT, under whose direction the first observations were made on the *Carnegie* in San Francisco harbour, is of the opinion that the lack of rigidity in the platform on which the apparatus was mounted is a factor which must be strongly emphasized to explain just why the pendulum amplitudes got too large for the apparatus to function satisfactorily in most of the attemps to obtain observations at sea.

The *Carnegie* experience suggested, and the experiments of Dr. Vening MEINESZ on board some passenger vessels confirm, that orienting the apparatus so that the plane of oscillation of the pendulums is parallel to the vessel's keel, instead of perpendicular to it, considerably increases the probability of obtaining a successful gravity determination.

Thus, while the contribution in number of gravity stations determined on board the *Carnegie* during the last two months of her cruise is not great, it is felt that in the circumstances even the limited success should prove an encouragement to future scientific expeditions at sea to make further attempts to obtain accurate gravity measurements with the Vening MEINESZ apparatus on surface ships.