LONG-PERIOD VERTICAL OSCILLATION OF THE ICE RECORDED BY CONTINUOUS GRAVIMETER MEASUREMENTS FROM DRIFT STATION T-3

Introduction

When a gravity survey is conducted on land, the gravimeter records essentially static differences in gravitational acceleration from place to place. With the exception of earth tide variations which are usually negligible in most surveys, the observed value of gravity at a given place is constant. The usual corrections made to the observed gravity to reduce all values to a common datum are also fixed for a given place. These corrections, although constant, are important because the gravity value observed is very sensitive to slight changes in altitude and latitude.[1]

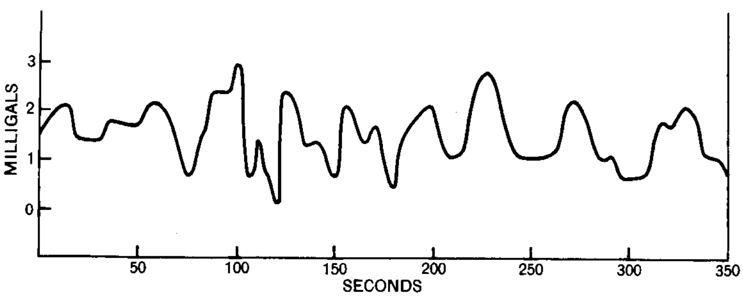

Fig. 1. Typical short-period vertical oscillation observed on T-3 with North American gravimeter No. 113; January 23, 1960.

As a result of the sensitivity of modern gravimeters to slight changes in acceleration (generally a change of 0.1 milligal can easily be detected) some interesting effects are observed when gravity observations are conducted from arctic drifting stations. Here, the gravity observations are no longer constant with time as they are on land. Whereas a land station is essentially fixed in space, a station on floating ice can move easily in all dimensions. The most noticeable effect at drifting stations is the oscillation of the optical crosshair of the meter when the beam is unclamped. This oscillation ranges in period from 20 to 40 seconds with an average amplitude of 1.0 milligal and has been described in the literature[2,3,4] (Fig. 1). It is caused by periodic small vertical displacements of the ice on which the meter stands. To get a representative value of gravity at a given place it is necessary to average a series of values over several cycles of the oscillation. In practice, a reading every 5 seconds for 5 or 6 minutes is made. For Arctic Ocean gravity studies in general, it is the average gravity value that has been used and will be of interest in this discussion. The properties of the oscillations have been considered in a recent paper[5] and shall not be discussed further. It suffices to say that they are observed wherever gravimeter observations are made at stations on floating ice. They have an average peak to peak displacement amplitude of about 0.3 mm. as determined from equation 1 for a simply oscillating system:

$$\ddot{X} = 4\pi^2 X/T^2, \quad (1)$$

where X = the displacement of the ice
$\ddot{X}$ = the maximum acceleration
T = the period of oscillation.

Vertical oscillations of the ice with periods longer than a minute.

Since the gravimeter is so sensitive to changes in acceleration it should be possible to observe vertical oscillations of the ice caused by long-period phenomena such as tides or seiches, as well as the 20- to 40-second oscillations mentioned above. To do this, many more observations over extended periods of time will be required.

The gravimeter is sensitive to static changes of acceleration due to changes of gravity from place to place over the surface of the earth and to changes in instrument altitude over a given place. The change in gravity with altitude is -0.3086 mgal./m. The gravimeter is also sensitive to dynamic changes of acceleration caused by vertical displacement of the meter when the period of the displacements approaches the natural period of the instrument. Thus the gravity meter behaves also like a seismometer. It may, therefore, be used to study a wide spectrum of vertical oscillations of the ice by treating short-period oscillations as dynamic accelerations around a given gravity value and long-period oscillations as static changes in gravity due to changes in altitude. With this in mind, a continuous gravity recording program was begun on T-3 in January 1960 (Fig. 2).

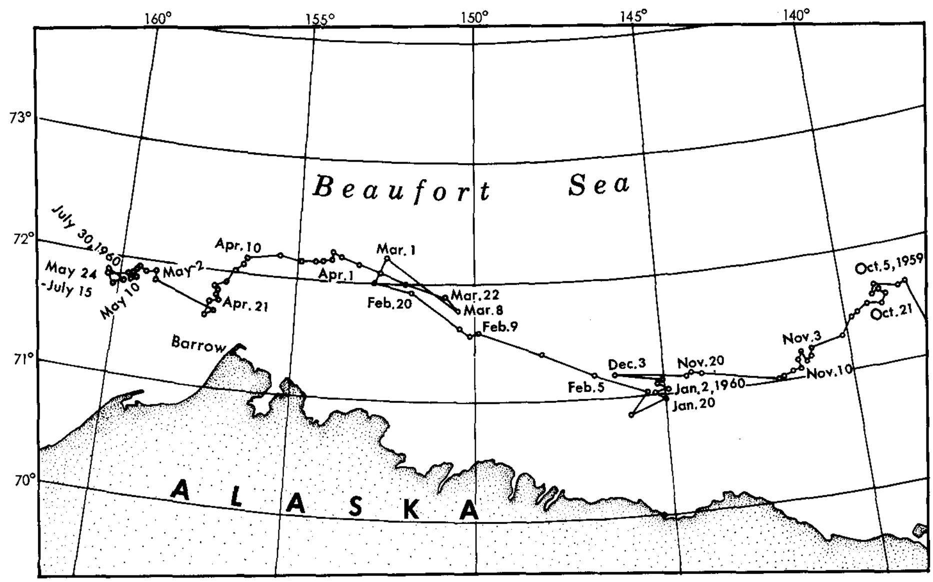

Fig. 2. Section of T-3 (Bravo) drift track, October 1959-July 1960.

Method

For this study it was necessary to read a gravimeter at frequent periodic intervals during each 24 hours continually for many days. To do this, a simple system was developed to make continuous gravity recordings automatically. A Kodak K-100 16-mm. camera with its lens removed was mounted above the viewing tube of the North American No. 113 gravimeter with the eyepiece of the meter removed (Fig. 3). With this arrangement, the collimating lens projected an image of the optical scale and crosshair on the film. This image was in focus at all distances. A clockwork mechanism actuated the camera to take the required readings. Two modes of operation were used in the study; (1) a reading every 5 seconds continually to examine short period oscillation and (2) a series of 17 readings spaced 5 seconds every 15 minutes for longer period studies. A shutter speed of one-half second was used for each reading (Fig. 4).

A sampling every 5 seconds was made so that the 20-to 40-second oscillation described earlier could be averaged out. Although the best value for the gravity field requires an average of 60 to 72 consecutive 5-second readings, 17 consecutive readings represent the best compromise between a reasonable average and the capabilities of the home-made clockwork-cam programming system.

In practice the system worked only when the station was drifting slowly or not at all. Otherwise the overall gravity field changed too rapidly, and constant resetting of the instrument was required. Such calm periods occurred at T-3 during January 24-26, February 11-15, and March 11-18, 1960.

Mode 1: In this mode, an observation was made every 5 seconds continually for 85 minutes. This is simply an extension of the visual method described above, however, it makes it possible to look for periodicities up to several minutes in length.

Two-minute averages of the values obtained every 5 seconds are plotted in Fig. 5. There appears to be a predominant period of about 6 minutes. This would correspond to a peak-to-peak ice displacement of approximately 3 mm. as computed by equation (1). An oscillation of this nature has been observed on ARLIS I with water-level recorders; it has a period of 6 to 12 minutes with amplitudes of 0.1 to 1.5 mm.[6]. A similar oscillation was also mentioned by Hunkins (ref. 4, pp 2484-5).

Mode 2: Every 15 minutes a value for gravity was obtained by averaging seventeen 5-second observations (Fig. 6). The frequent separation of adjacent points is probably due to the 6-minute oscillation described above.

The North American gravimeter No. 113 has a natural period of 17 seconds and has 0.7 critical damping.

Fig. 3. The K-100 camera set-up to record the optical scale of the gravimeter. The meter is mounted on a pedestal extending through the floor of the building.

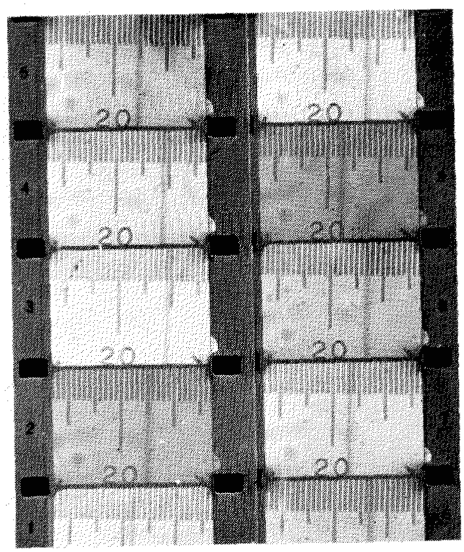

Fig. 4. Section of a record taken with the K-100 camera. Null-point is at 20.

Interpretation

Horizontal movement of the ice, varying from rates of 0 to 30 mi./day, is by far the greatest cause of the more significant variations of gravity. Anomalies due to variation in water depth, changes in bottom lithology and changes in latitude all must be taken into account when interpreting the gravity observations.

If the anomalies due to the horizontal drift of the station could be removed from a finite time series of gravity observations, the remaining variations could be ascribed to vertical oscillations of the ice, either those recorded as dynamic changes of acceleration or those recorded as static changes.

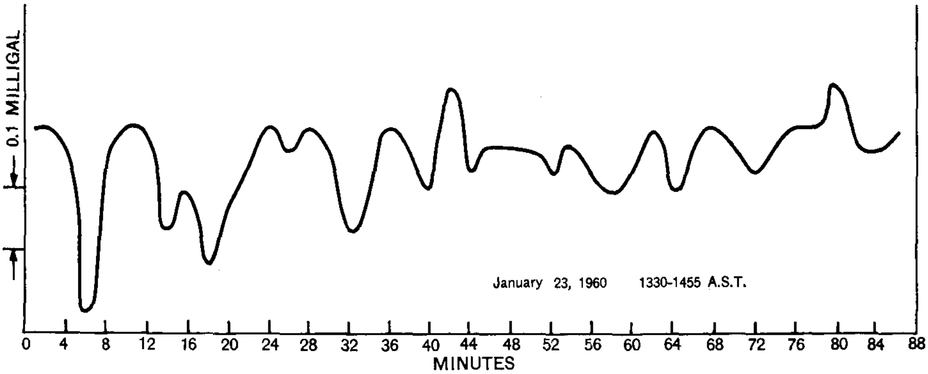

Fig. 5. Two-minute averages of gravity values obtained every 5 seconds plotted versus time; T-3, January 23, 1960.

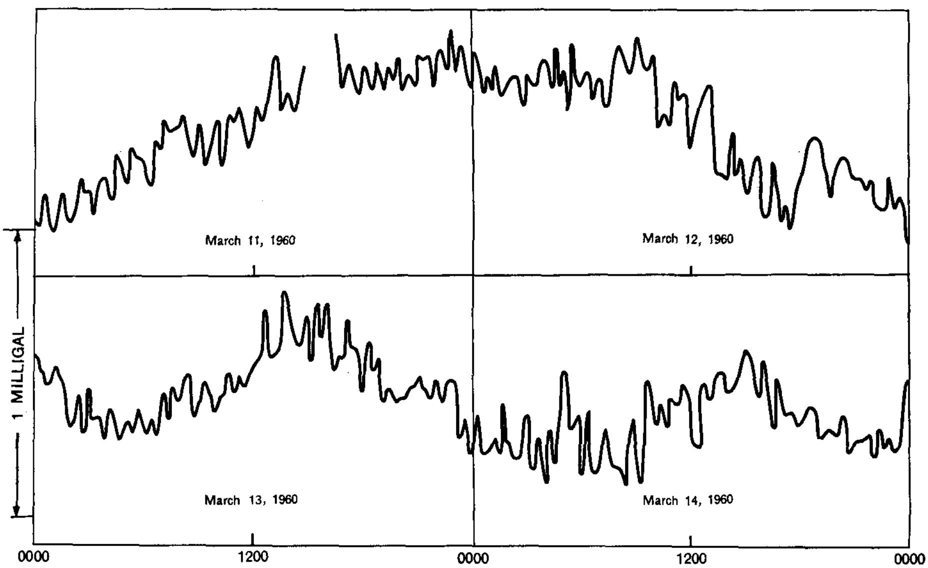

Fig. 6. A typical record of gravity versus time observed from T-3. Sampling rate = 15 minutes (see text). Time is Alaska Standard Time.

Discussion

If the study of vertical oscillations is confined to periods of less than 26 hours in length to exclude anything longer than tidal periods and it can be shown that anomalies owing to all other causes have periods in excess of this, then a filter can be constructed that will essentially remove these anomalies from the desired vertical components.

The undesired gravity effects to be removed are:

1. Change of gravity caused by latitude change; this varies from 0.3 to 0.5 mgal./km. in the Arctic and decreases linearly with latitude in the areas in question. The effect on the gravity record will generally be a linear trend because a drift station on account of its inertia, moves along a straight path over intervals of many days. Such a linear trend will be removed by the filter.

length of the anomaly was made, extending from $\frac{X}{Z} = -2$ to $\frac{X}{Z} = +2$. Knowing the rate of drift of the station and the average water depth, an approximate value for the period of the traversed anomaly can be computed from equation (2)

$$T = L/C \tag{2}$$

where T = period of anomaly in hours
L = wave length of anomaly at observed depth (metres)
C = drift rate in metres/hour.

The results of these computations for the records presented are shown in Table 1. All anomaly periods are significantly larger than the chosen cut-off

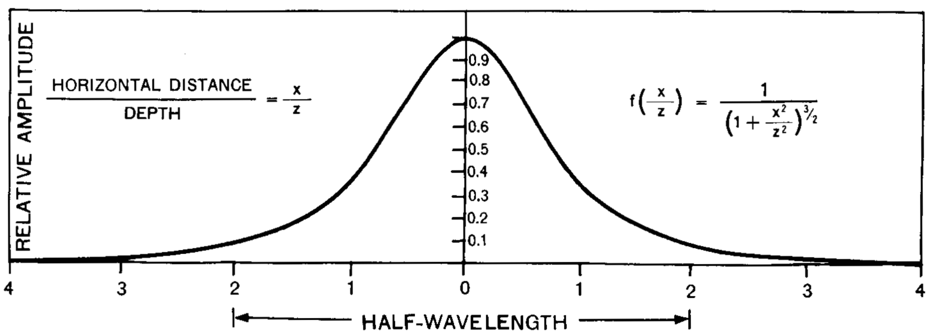

Fig. 7. The wave form of an anomaly produced by a sphere at depth Z surrounded by material of less density. (After Nettleton).

2. Change of water depth or bottom lithology; either change can cause significant variations in the observed gravity. If, however, the observed gravity change at a given station drifting across the anomaly has a period greater than the filter cut-off, this period will be attenuated with respect to shorter periods. The period of the anomaly is a function only of the depth to its centre and the drift rate of the station across the anomaly. Both factors are usually known. The relative gravity field due to a sphere at depth Z can be expressed as a function of the ratio X/Z, where X is the distance measured on the surface from the point directly above the centre of the sphere to any given point (ref. 1, pp 102-8) (Fig. 7). From this plot, a conservative estimate of the half-wave value. Although few anomalies approach the spherical shape chosen for the model, few conceivable models will produce a shorter wave length. It is felt, therefore, that the effect of anomalies due to lithologic or bathymetric changes can be greatly reduced.

It might be thought that two distinct anomalies close together would cause a perturbation of the wave-form shown in Fig. 7. Using adjacent horizontal cylinders as models (they would approximate a submarine valley) a computation (ref. 1, pp 108-9) using a density contrast of 2 would require a cylinder diameter of 100 metres to produce a maximum value of 0.1 mgal; this is the threshold sensitivity of the gravimeter. The bathymetric data for the January and March records do not

Table 1. Average T-3 drift rates, water depths, and estimated wavelengths of possible anomalies during recordings.

Record 1960	*Drift/day* (km.)	*Latitude change/day* (minutes of arc)	*Approximate water depth* (m.)	*Minimum period of possible anomaly* (hrs.)
January	1.8	0.3	525	57
February	5.5	1	2400	84
March	1	0.5	2400	462

suggest bottom variations of this nature. Although only a few depths are known for the February record it is assumed that the bottom topography is similar to that of the March record, since the two areas are in the same geologic province.

over 26 hours in length. This was accomplished by computing an average gravity value for every 2-hour-record segment as given in Fig. 6, and then subtracting the average gravity value for the 26-hour segment in which the 2-hour segment is located, the mid-

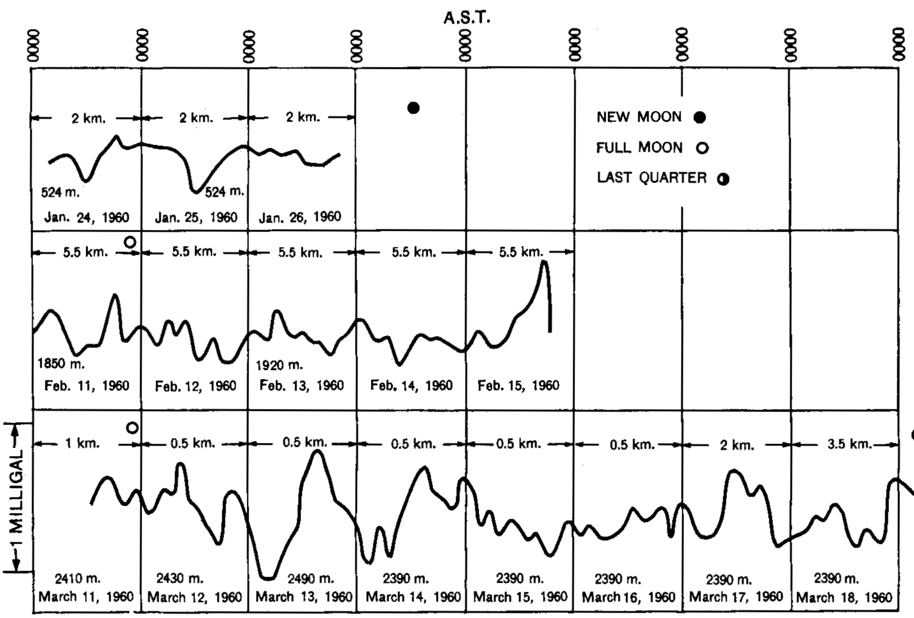

Fig. 8. Plot of relative gravity versus time. Sampling rate = 15 minutes. Periods shorter than 2 hours and longer than 26 hours have been attenuated by a numerical filter. Approximate water depths where known are given below the curve. Distances covered per day are given above the curve.

Removing the anomalies

The undesired anomalies were removed from the gravity data time series with a numerical band pass filter, attenuating periods below 2 hours and

points of both segments being the same. This process is continued throughout the series. The results are plotted in Fig. 8 as a function of time. They can also be considered as gravity profiles with the gradient removed, plotted as a function of horizontal distance. An individual anomaly can then be examined and by means of the "half-width" method the depth to the centre of the anomaly can be determined (ref. 1, pp 122-3). In both the February and March records even the widest peaks would have to be caused by mass anomalies at depths considerably less than those observed. It can be reasonably assumed then that at least the February and March records in Fig. 8 now represent only vertical oscillations of the ice.

The waveforms shown in Fig. 8 are undoubtedly composed of several components, including possibly both a diurnal and semidiurnal variation and a shorter mode around 6 hours in period. A power spectrum analysis of the March record shows clearly this 6-hour period and suggests a 3-hour component (Fig. 9). The energy increase at the long-period end of the plot may be caused by diurnal and semidiurnal components, however, the sharper resolution needed to verify this is not justified with the limited data. At these periods, the dynamic acceleration due to harmonic motion and computed by equation (1) is considerably smaller than the static change in gravity due to the change in altitude from peak to peak. Thus, for an oscillation of 6 hours involving a 1-metre change in altitude of the ice, the dynamic acceleration will be 25 times less than the static change in gravitational acceleration over the same altitude. For a 12 hour period it is 100 times less.

Applying the equation used by Thiel *et al* for measuring tides on the Ross and Filchner ice shelves by gravimetric means, the magnitude of these oscillations can be estimated.[7] They used

$$h \text{ (metres)} = 3.7653 \text{ g} \qquad (3)$$

(with g in milligals)

This is derived from the gravity gradient in free air, -0.3086 mgal./m., and the Bouguer correction, which allows for the changing length of the water column. From equation (3) and Fig. 8 it can be seen that the change in altitude ranges from 0.5 to 1 m. on the average.

Conclusions

It seems clear that vertical displacements of the ice have been detected with the gravimeter. Whether the displacements shown in both the short and long period records are truly periodic can not be determined without more data. With the single station described, nothing can be said about the nature of the motion, whether it is a travelling wave or not, or if there are associated horizontal components. An array of stations on the ice would be desirable for further studies.

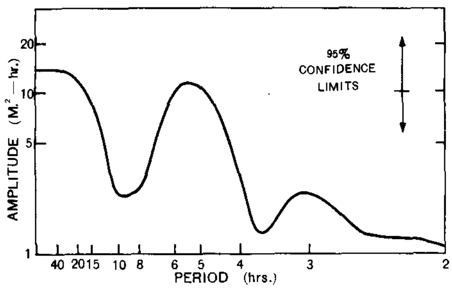

Fig. 9. Power spectrum analysis of the record of March 1960 shown in Fig. 8. Semi-log scale.

Although sufficient data are not available for a complete power spectrum analysis, it does appear that some tidal components, diurnal and semidiurnal, together with a 6-hour component, may be responsible for the observed waveform. The calculated variation in height is of the order of that observed at Point Barrow and Mercy Bay.

The 6-minute oscillation described appears to be real and has been previously observed.

The recording method described, although not as convenient as a specially designed automatic gravity meter, is relatively inexpensive and easy to construct.

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RECENT CHANGES OF SEA-LEVEL ALONG THE NORTHEAST COAST OF BRODEUR PENINSULA, BAFFIN ISLAND, N.W.T., CANADA

Introduction

During the summer of 1962 a survey of Recent changes of sea-level along the northeast coast of Brodeur Peninsula was carried out between 73°38′ and 73°48′N. and 84°15′ and 85°17′W. (Fig. 1). A preliminary examination of aerial photographs indicated an uplift of the land, which is assumed to have been caused by isostatic recovery after the deglaciation of the peninsula.

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Brodeur Peninsula is the most northwesterly land area of Baffin Island. Its northeastern side consists of a plateau of horizontally bedded limestone, which lies between 1,100 and 1,800 ft. above sea-level. The plateau is bounded by steep cliffs that in some instances plunge directly into the sea, but that elsewhere are separated from the shore by a rock bench. The region is dissected by two major rivers, the valleys of which form broad embayments in the plateau, and by numerous small streams. Two types of coastline, relevant to the present study, can be recognized. Where the coastline is cliffed, there is little evidence of the Recent uplift. The major river valleys, on the other hand, probably formed fiord inlets during the earlier stages of the uplift and raised strandlines and river terraces are consequently well developed there.

The aims of the study were to assess the amount of uplift as shown by the postglacial marine limit, to determine whether the uplift has been continuous, or whether it has been interrupted by still-stands, and to establish whether the peninsula has been warped during this period of uplift. It proved impossible during only one season to separate the Recent world-wide eustatic rise of sea-level from the more localized uplift of Brodeur Peninsula. Therefore, the altitude of the highest marine features will provide only a minimum figure for the amount of uplift.

Field methods

Two broad categories of evidence were used in this study. First, raised strandlines were identified and their altitudes accurately measured. Identification was based on the lithology and faunal content of unconsolidated marine deposits resting on the strandlines and