Areal Strain of Solid Earth Tides Observed in Ogdensburg, New Jersey[1]

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Improvements of extensometer measurements and a method of comparing observed tidal strain with theory, almost independent of ocean loading, produce an excellent result of strain of solid earth tides at Ogdensburg, New Jersey. Earth tides are well recorded on an array of three horizontal extensometers oriented at N 29°30′E, N 48°30′E, and S 48°E, which is installed in a deep mine located at Ogdensburg, New Jersey. The extensometers are of the Benioff fused quartz type and are calibrated by a Michelson interferometer, using an Ne-He laser as a monochromatic light source. The present calibration has repeatability with a maximum error of less than 5%. A 29-day series for each extensometer of the array, from 00h 00m 00s February 16 to 23h 00m 00s GMT March 16, 1966, was analyzed. Corrections were made for the effects of instrumental drift, barometric pressure, and thermal variation on the extensometers. The latitudinal-, meridional-, and shear-strain components were resolved from the extensometer array and analyzed by the least-squares method of tidal analysis for the M_2 and O_1 constituents. The observed areal strain of solid earth tides at Ogdensburg, which is nearly independent of the load strain caused by the ocean tidal loading off the Atlantic coast based on the Boussinesq solution, confirms the theoretical tidal strain based on the Gutenberg-Bullen earth model with a New York-Pennsylvania crustal structure, which has the characteristic number values $h = 0.621$ and $l = 0.084$.

Introduction

Results of earth tidal strain measurements referred to in the literature [e.g., *Gutenberg*, 1959; *Melchior*, 1958, 1966; *Tomaschek*, 1957] are based principally on the strain observations obtained by use of superinvar-type extensometers [*Sassa et al.*, 1952; *Ozawa*, 1952, 1957]. The values of h and l, two of the three characteristic numbers for describing the elastic tidal deformation of the solid earth, were determined to be approximately 0.48 and 0.05, respectively. They are considerably smaller than the values theoretically calculated ($h = 0.6$ and $l = 0.08$–0.09) for either the Gutenberg-Bullen model or the Jeffreys-Bullen model, the two earth models generally accepted in seismology [*Takeuchi et al.*, 1962; *Alsop and Kuo*, 1964].

Although the extensometer is excellent for earth tidal strain measurements, instrumental calibration has always been a very critical part of tidal strain studies. It requires an absolute calibration of both amplitude and phase. Because of very small displacements between the fixed and reference piers of an extensometer (for instance, for a 200-foot horizontal extensometer the maximum daily peak-to-peak displacements due to earth tides are found to be about 2 to 3 μ in Ogdensburg, New Jersey), reliable calibration to an accuracy better than 5%, so far as I know, has never been reported. Furthermore, the real earth, with the irregular distribution of waters and land masses, is not at all homogeneous either laterally or radially. Measurements of tidal strain at stations near a coast are generally affected by ocean tides, even at stations far from the coast. This is contrary to the assumptions that the earth is spherically symmetrical with no oceans on its surface and that its physical properties vary only as a function of radius, as the present theory assumes.

During the last few years, an array of three horizontal fused quartz extensometers of the type originated by *Benioff* [1935] has been operated by the Lamont Geological Observatory

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of Columbia University in a deep mine at Ogdensburg, New Jersey. Strain records of earth tides are being obtained continuously. A laser interferometer technique has been developed for calibrating these extensometers accurately. Corrections for the effects of instrumental drift and barometric pressure variation on the extensometers are readily made. Although the three horizontal extensometers are oriented arbitrarily, the latitudinal, meridional, and shear components of strain can now be resolved.

In this paper, the results from analysis of the data for the areal strain of earth tides for the most reliable tidal constituents, M_2 and O_1, for a 29-day series are presented. The areal strain, which is nearly free from the strain caused by ocean tidal loading along the coast of the Atlantic Ocean, provides a means of accurately determining the combination of the characteristic numbers h and l at Ogdensburg, New Jersey, and of testing the adequacy of the present theory of earth tides.

Extensometer Installation

The array of three horizontal extensometers oriented at N 29°30′E, N 48°30′E, and S 48°E is installed in a Y-shaped mine drift on the 1850-foot level (543 meters below the surface and 370 meters below mean sea level) of the Sterling Mine of the New Jersey Zinc Company at Ogdensburg, New Jersey (Figure 1). The station location is 41°05′15″N, 74°35′45″W.

The geological setting of the mine, in general, has been described in detail by *Hague et al.* [1956], and that of the vicinity of the mine drift in which the strain instruments were installed has been described by *Major et al.* [1964]. In brief, the mine drifts of the Ogdensburg station are driven entirely in the Precambrian Franklin formation, which is predominantly foliated coarse-crystalline marble. A major fault, named 'Zero fault,' which passes through the strain installation, is believed to be inactive. The fault strikes approximately N 34°E with an 80°E-to-vertical dip. The N 29°30′E and N 48°30′E extensometers are situated to the west of the fault; the S 48°E extensometer lies entirely east of the fault.

Air circulation and sudden changes in barometric pressure and temperature generally cause undesirable noise on strain records. The mine drifts are therefore equipped with tightly sealed doors to maintain a low noise level. A Bendix barograph monitors the fluctuation of barometric pressure in the recording room adjacent to the instrument drift.

The N 29°30′E and S 48°E extensometers are 60 meters long, and the N 48°30′E extensometer is 51.8 meters long. Variable capacitor transducers drive discriminator circuits whose output is proportional to the relative displacement between the two piers. The voltage output for the tidal strain is displayed unfiltered on a G-10 Varian recorder with essentially flat frequency response characteristics. Detailed information about the instruments may be found in *Benioff*'s [1935, 1955] early publications.

Despite a low rate of instrumental drift, the extensometers require careful calibration and adjustment at intervals of several weeks to achieve reliable results. In the early stage, calibration was done mechanically by displacing a micrometer head, which is in contact with the end of the tube along the longitudinal axis of the extensometer. The output of the displacement transducer was recorded and concurrently the displacement was viewed with a 300× power microscope [*Major et al.*, 1964]. The difficulties in controlling the displacements produced by the micrometer loading necessitated a reduction

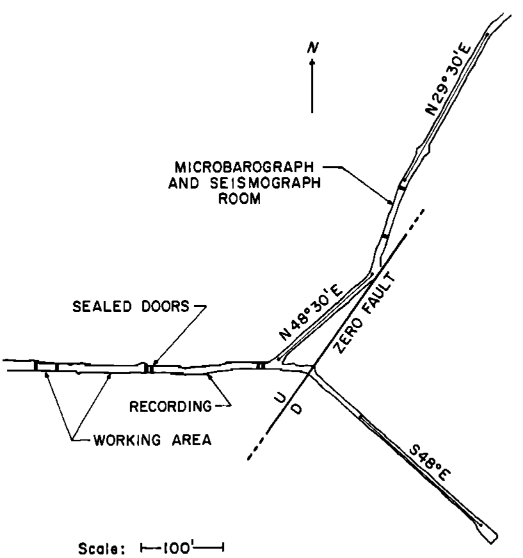

Fig. 1. Configuration of the three-horizontal-extensometer array installed on the 1850-foot level at the Ogdensburg station.

of sensitivity of the displacement transducer by a factor of at least 3 during the calibration. The displacement thus mechanically induced was many times greater than that resulting from the range of earth tidal strain. The present laser interferometry calibration system is greatly improved both in accuracy and in operational convenience over the early calibration method. If desirable, the extensometers can be calibrated daily in the linear operating range of the transducers and recorders without introducing any attenuation or suppression to the system. The transducer end of the extensometer is displaced longitudinally by means of an electromagnetic driving unit, excited by an HP 302 A variable low-frequency oscillator. The induced displacement of the tube is monitored by a Michelson type interferometer, which utilizes an Ne-He laser as its monochromatic light source. This system is capable of determining motion as small as 0.03 μ with good repeatability and errors of less than 5%. The actual setup of the Michelson type interferometer for extensometer calibration (shown schematically in Figure 2) consists of an electro-magnetic driving unit, a standard length leg, and a beam splitter assembly.

Theory

Early derivations of earth tidal strain by *Ozawa* [1952], which have been widely quoted by many authors [*Tomaschek*, 1957; *Melchior*, 1958; *Gutenberg*, 1959], did not include several important terms involving one Love number, h; Shida's number l generally cannot be determined independently of h by strain measurements. *Ozawa* [1957] later published the correct expressions for earth tidal strain. Since this error is scattered throughout the literature, however, it may be of value to summarize here the derivation of earth tidal strain explicitly.

With sufficient approximation, the components for latitudinal, meridional, and shear strains in polar coordinates $E_{\theta\theta}$, $E_{\lambda\lambda}$, and $E_{\theta\lambda}$, due to the tide-generating potential of order 2, W_2, are given by

$$\begin{aligned}
E_{\theta\theta} &= \frac{1}{rg}\left[H(r)W_2 + L(r)\frac{\partial^2 W_2}{\partial\theta^2}\right] \\
E_{\lambda\lambda} &= \frac{1}{rg}\left[H(r)W_2 + L(r)\left(\tan\theta\frac{\partial W_2}{\partial\theta}\right.\right. \\
&\qquad \left.\left. + \frac{1}{\cos^2\theta}\frac{\partial W_2{}^2}{\partial\lambda^2}\right)\right] \qquad (1) \\
E_{\theta\lambda} &= \frac{L(r)}{rg\cos\theta}\left[2\frac{\partial^2 W_2}{\partial\theta\partial\lambda} + \tan\theta\frac{\partial W_2}{\partial\lambda}\right]
\end{aligned}$$

where r is the distance from the center of the earth to the point of observation, and for $r = a$, $H(a) = h$, $L(a) = l$, and g is the gravitational acceleration on the earth's surface.

It is convenient to expand the tide-generating potential W_2 by spherical trigonometry and orbital elements of the moon and the sun in the form [*Doodson*, 1921; *Schureman*, 1941]

For the moon

$$\begin{aligned}
W_{2m} &= \tfrac{3}{2}U_m a g \\
&\quad \cdot\{(\tfrac{1}{2} - \tfrac{3}{2}\sin^2\theta)\sum f_{lm}C_{lm}\cos E_{lm} \\
&\quad + \sin 2\theta \sum f_{1m}C_{1m}\cos E_{1m} \\
&\quad + \cos^2\theta\sum f_{2m}C_{2m}\cos E_{2m}\} \qquad (2)
\end{aligned}$$

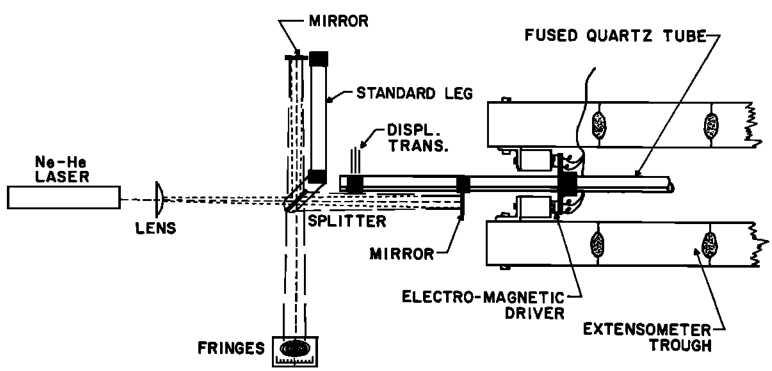

Fig. 2. Schematic diagram showing the actual setup of the Michaelson-type interferometer for extensometer calibration [after *Hade et al.*, 1968].

For the sun

$$W_{2s} = \tfrac{3}{2} U_s ag \cdot \{(\tfrac{1}{2} - \tfrac{3}{2}\sin^2\theta) \sum f_{ls} C_{ls} \cos E_{ls} + \sin 2\theta \sum f_{1s} C_{1s} \cos E_{1s} + \cos^2\theta \sum f_{2s} C_{2s} \cos E_{2s}\} \quad (3)$$

in which

$$U_m = \frac{M}{E}\left(\frac{a}{c_m}\right)^3 \qquad U_s = \frac{S}{E}\left(\frac{a}{c_s}\right)^3$$

where M, S, and E are the masses of the moon, the sun, and the earth, respectively, a is the mean radius of the earth, c_m and c_s are the distances from the center of the earth to the center of the moon and to the center of the sun, f_{im} and f_{is} are the node factors of the tidal constituents, C_{im} and C_{is} are the coefficients of the tidal constituents with $i = l$ for long periods, $i = 1$ for diurnal, and $i = 2$ for semidiurnal components, and E_{im} and E_{is} are arguments of the tidal constituents.

Upon substituting (2) and (1) and disregarding the long-period constituents, we obtain the strain components of the lunar tides on the earth's surface as follows:

$$E_{\theta\theta} = \sum \tfrac{3}{2} U_m \{f_{1m} C_{1m}(h - 4l) \sin 2\theta \cos E_{1m} + f_{2m} C_{2m}[h - 2l(1 - \tan^2\theta)] \cos^2\theta \cos E_{2m}\}$$

$$E_{\lambda\lambda} = \sum \tfrac{3}{2} U_m \{f_{1m} C_{1m}(h - 2l) \sin 2\theta \cos E_{1m} + f_{2m} C_{2m}[h - 2l(1 + \sec^2\theta)] \cos^2\theta \cos E_{2m}\}$$

$$E_{\theta\lambda} = \sum 6 U_m l \cos\theta \{-f_{1m} C_{1m} \sin E_{1m} + f_{2m} C_{2m} \tan\theta \sin E_{2m}\} \quad (4)$$

The strain components of the solar tides can be similarly derived by simple substitution of (3) in (1).

The horizontal strain in any given direction ϵ_i is then

$$\epsilon_i(\alpha, \beta, h, l) = E_{\theta\theta}(h, l)\alpha_i^2 + E_{\lambda\lambda}(h, l)\beta_i^2 + E_{\theta\lambda}(l)\alpha_i\beta_i \quad (5)$$

where α_i and β_i are the directional cosines against the meridian and prime vertical, respectively.

With an array of three horizontal extensometers, the latitudinal, meridional, and shear components of strain may be resolved from (5), simply

$$E_{\theta\theta} = \Delta_\alpha/\Delta \qquad E_{\lambda\lambda} = \Delta_\beta/\Delta \qquad E_{\theta\lambda} = \Delta_{\alpha\beta}/\Delta \quad (6)$$

where

$$\Delta_\alpha = \begin{vmatrix} \epsilon_1 & \beta_1^2 & \alpha_1\beta_1 \\ \epsilon_2 & \beta_2^2 & \alpha_2\beta_2 \\ \epsilon_3 & \beta_3^2 & \alpha_3\beta_3 \end{vmatrix}$$

$$\Delta_\beta = \begin{vmatrix} \alpha_1^2 & \epsilon_1 & \alpha_1\beta_1 \\ \alpha_2^2 & \epsilon_2 & \alpha_2\beta_2 \\ \alpha_3^2 & \epsilon_3 & \alpha_3\beta_3 \end{vmatrix}$$

$$\Delta_{\alpha\beta} = \begin{vmatrix} \alpha_1^2 & \beta_1^2 & \epsilon_1 \\ \alpha_2^2 & \beta_2^2 & \epsilon_2 \\ \alpha_3^2 & \beta_3^2 & \epsilon_3 \end{vmatrix}$$

$$\Delta = \begin{vmatrix} \alpha_1^2 & \beta_1^2 & \alpha_1\beta_1 \\ \alpha_2^2 & \beta_2^2 & \alpha_2\beta_2 \\ \alpha_3^2 & \beta_3^2 & \alpha_3\beta_3 \end{vmatrix}$$

Data and Method of Analysis

The strain records for a full 29-day series, from 00h 00m 00s February 16 to 23h 00m 00s GMT March 16, 1966, for each of the extensometers are shown in Figure 3. The direction of ground compression is downward. The data of the GMT solar-hourly amplitude readings were taken manually from the original strain records on the G-10 Varian recorder and read to a precision of ¼ mm on the chart paper.

During the period of observation, the instrumental drift on the records was approximately linear, with a rate of strain about 6×10^{-8}, 15×10^{-8}, and 2×10^{-8} per month for the N 29°30′E, N 48°30′E, and S 48°E extensometers, respectively. The linear drift was removed from the data by the least-squares method.

The temperature in the mine drift is about 16°C, with a maximum annual fluctuation of less than 1°C. Since the thermal expansion coefficient for fused quartz is about 0.54×10^{-6}

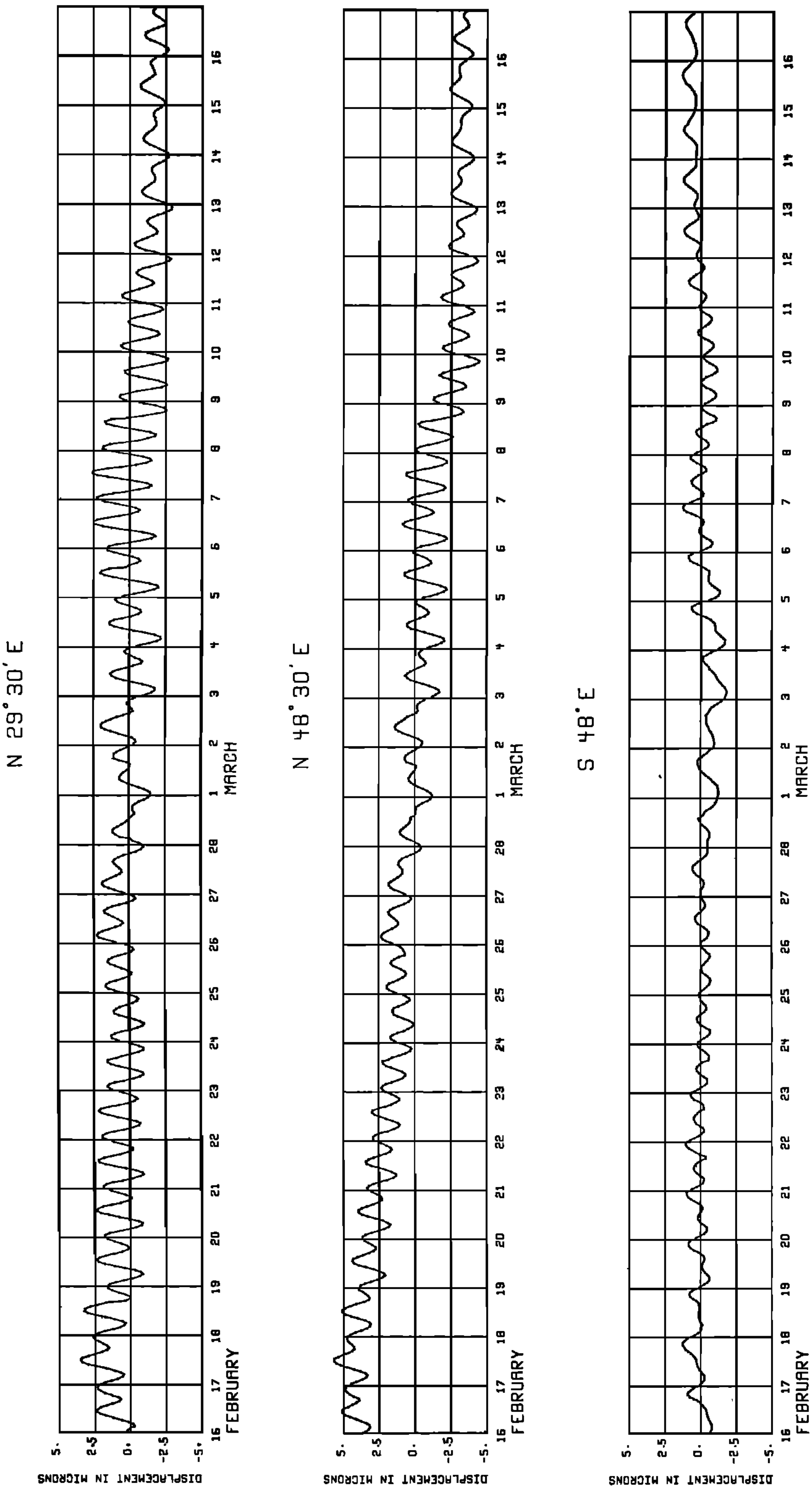

Fig. 3. Original strain data obtained at the Ogdensburg station from 00h 00m 00s February 16 to 23h 00m 00s GMT March 16, 1966. Ground compression is downward.

per °C at 20° to 320°, a thermal variation of 0.01°C would amount to a strain of 0.54×10^{-8}, which is important for the present study.

Several attempts were made, by slowly varying the air pressure in the sealed mine drift, to determine the effect of barometric pressure on the extensometer. Direct correlation of the barometric pressure fluctuation and the strain response of the extensometer was found.

In the present analysis, the combined barometric pressure and thermal effects on the extensometer were corrected by adjusting graphically the amplitude of the barometric pressure measurement in terms of strain measurements until a best fit to the data corrected for instrumental drift was achieved. The final data for resolving the latitudinal, meridional, and shear strain were then obtained by subtracting the strain affected by barometric pressure and thermal variations from the data already corrected for instrumental drift.

The resolved strain components $E_{\theta\theta}$, $E_{\lambda\lambda}$, and $E_{\theta\lambda}$ were analyzed by the least-squares method of tidal analysis for the most reliable constituents M_2 and O_1. A total of eleven tidal constituents, M_2, S_2, N_2, L_2, K_2, O_1, K_1, P_1, Q_1, M_4, and MF, and a constant term were included. These tidal constituents form a system of functions for any finite time interval. The observed strain is in the form

$$f(t) = \sum_{n=1}^{N} [R_n \cos (S_n t - \zeta_n) + P_n] \qquad (7)$$

where P_n is the polynomial representing the unknown drift term, which was deleted in our analysis. In (7) the function $f(t)$ is assumed to be sufficiently smooth in the time series. Equation 7 can have a definite meaning if the summation is extended to finite orders; the rest is considered a scatter obeying the Gaussian law, so that the rule of least squares can be applied [*Horn*, 1959].

Results

The resolved strain components $E_{\theta\theta}$, $E_{\lambda\lambda}$, and $E_{\theta\lambda}$ are shown in Figure 4. The strain component $E_{\theta\theta}$ is about 4 times greater than $E_{\lambda\lambda}$ and is about 2 times greater than $E_{\theta\lambda}$. In principle, it is possible to determine the characteristic numbers h and l uniquely by use of the strain components $E_{\theta\theta}$ and $E_{\lambda\lambda}$ and also l independently by the strain component $E_{\theta\lambda}$, provided that the indirect effects on the tidal strain are negligible. In the present case, the Ogdensburg station is less than 100 km from the Atlantic Ocean. Therefore, it is essential to consider the effect of ocean tidal loading along the coast and even in the open ocean. If ocean tidal loading is assumed to be primarily responsible for the indirect effects on the tidal strain at Ogdensburg and the ocean tidal conditions off the Atlantic coast are known rather accurately, the effect of such a load on the tidal strain can be corrected for.

Attempts were made earlier by *Kuo et al.* [1962] and *Major et al.* [1964] to determine the characteristic numbers h and l by use of two horizontal extensometers N 29°30′E and S 48°E, with correction for the ocean tidal load. Unfortunately, the tides in the open ocean are as yet largely unknown and have to be inferred from coastal stations. Tidal observations off the Atlantic coast for the M_2 constituent are considered to be the best known on the entire coast from Narragansett Bay, Sandy Hook, and Atlantic City to Daytona Beach, Florida. They indicate that the tide is nearly simultaneous along this stretch. The Greenwich epochs for the M_2 constituent of ocean tides vary by only 15° from 355° to 370° [*U. S. Coast and Geodetic Survey*, 1942]. Even in the ocean at Bermuda this epoch is also about 355° to 360°. Nevertheless, cotidal charts of the Atlantic Ocean for the M_2 constituent so far published by various authorities show quite a bit of discrepancy [*Harris*, 1904; *Dietrich*, 1944; *Hansen*, 1952], as shown in Figure 5. There are almost no adequate data available for co-range charts for the Atlantic Ocean. Corrections for ocean tidal loading under these circumstances are difficult.

Ozawa [1957] pointed out, however, that the areal load strain, the sum of the latitudinal and meridional components of the load strain $E_{\theta\theta}'$ and $E_{\lambda\lambda}'$, is approximately zero for the load caused by ocean tides. On the basis of the *Boussinesq* [1885] solution for the distortion of a half-space under a concentrated point load normally oriented, the dominant part of the deformation may be considered elastic; i.e., self gravitation of the earth is assumed to play a small role. *Ozawa* [1957] has shown that the latitudinal and meridional components of strain $E_{\theta\theta}'$ and $E_{\lambda\lambda}'$ caused by the ocean tidal loading

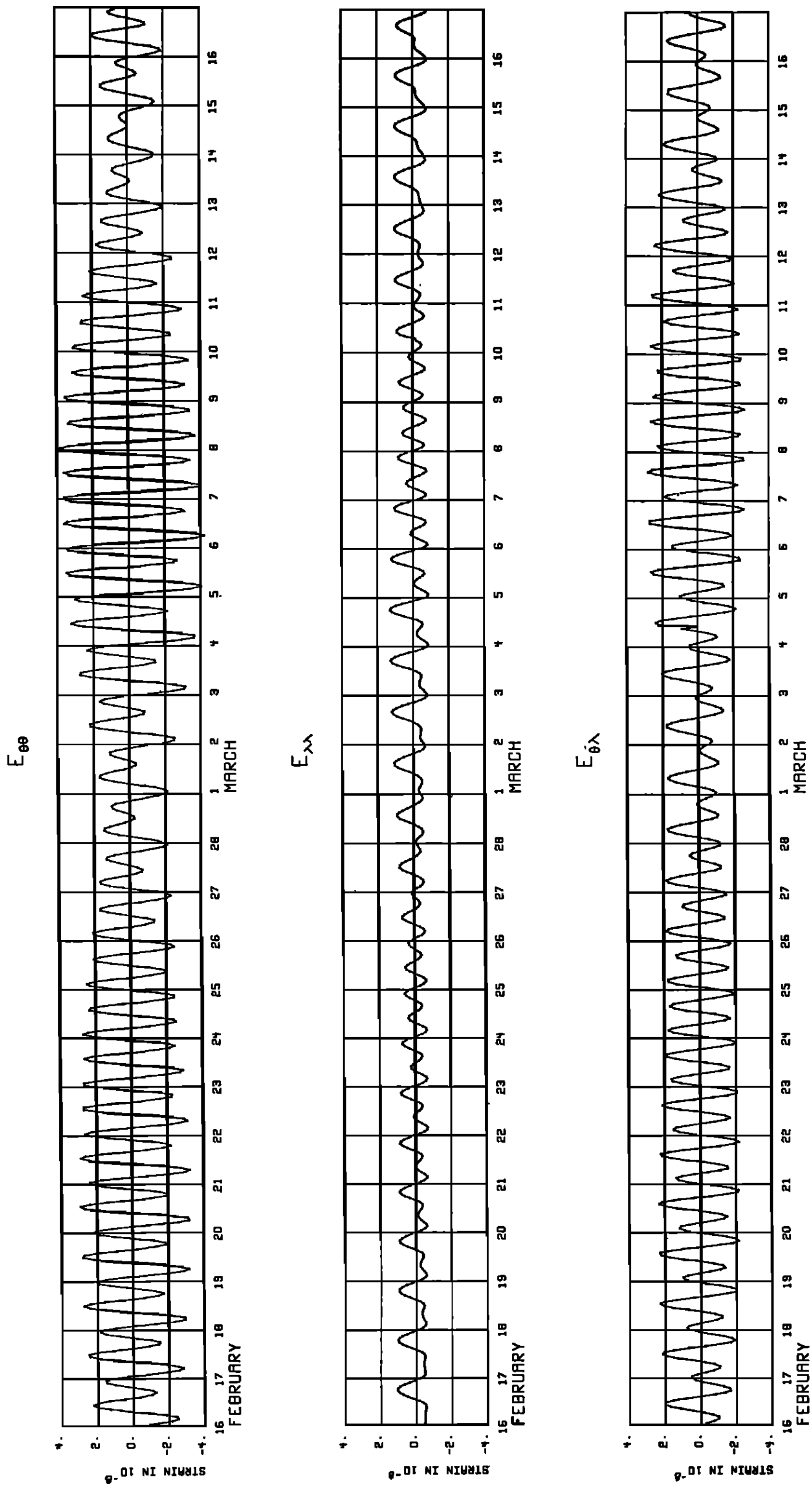

Fig. 4. The resolved latitudinal, meridional, and shear components of strain, $E_{\theta\theta}$, $E_{\lambda\lambda}$, and $E_{\theta\lambda}$, respectively.

may be obtained approximately by numerical integration of the Boussinesq solution over the surface load about the observation point. It can be shown that

$$E_{\theta\theta}' \simeq -E_{\lambda\lambda}' \qquad (8)$$

Equation 8 is significant since it shows that the areal strain of the solid earth tide is virtually independent of the ocean tidal loading. From (4) we have the areal tidal strain $\square$

$$\square = E_{\theta\theta} + E_{\lambda\lambda}$$
$$= \sum 3(h - 3l)U_m\{f_{1m}C_{1m} \sin 2\theta \cos E_{1m} + f_{2m}C_{2m} \cos^2\theta \cos E_{2m}\} \qquad (9)$$

It is obvious that the values of h and l in the areal tidal strain (9) cannot be determined separately unless other constraints are imposed on either h or l.

The areal tidal strain results of the least-squares method of tidal analysis for the resolved strain components $E_{\theta\theta}$ and $E_{\lambda\lambda}$ for the M_2 and O_1 constituents are shown in Table 1. The theoretical values for h and l are calculated to be 0.621 and 0.084, respectively, for the Gutenberg-Bullen earth model with a crustal structure of the New York–Pennsylvania area proposed by *Oliver et al.* [1961]. This crustal structure is considered to be quite well known and may be a close approximation of that for Ogdensburg. The theoretical areal tidal strains for the M_2 and O_1 constituents are also shown in Table 1 for comparison. Agreement between the amplitudes and the combination factor $(h - 3l)$ of the observed and the theoretical areal tidal strain for both M_2 and O_1 is remarkably good. The differences between the theoretical and observed areal tidal strains and combination factors $(h - 3l)$ are about 6% for M_2 and about 10% for O_1. The phase lags for M_2 and O_1 theoretically are zero in comparison with the observed 1.2° for M_2 and 5.7° for O_1, which again are within the limits to be accounted for by the tidal dissipation [*Slichter*, 1963], although the subject of phase lag due to tidal dissipation is still in a state of flux. Minor discrepancies in amplitude and phase between the

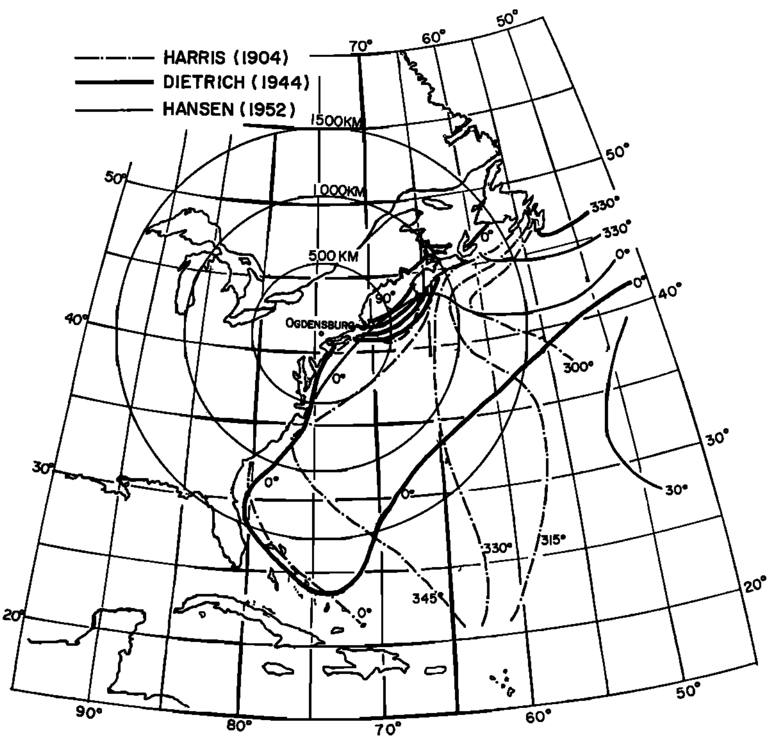

Fig. 5. Cotidal lines for the northwestern Atlantic Ocean according to *Harris* [1904], *Dietrich* [1944], and *Hansen* [1952].

TABLE 1. Observed Areal Tidal Strain at Ogdensburg Compared with Theoretical Tidal Strain Calculated according to the Gutenberg-Bullen earth model with a crustal structure of the New York-Pennsylvania area, $h = 0.621$ and $l = 0.084$

Tidal Constituent	Strain Amplitude $\times 10^{-8}$		Combination Factor $(h - 3l)$		Difference	Observed Phase Lag
	Theor.	Obs.	Theor.	Obs.		
M_2	1.563	1.662	0.369	0.392	6%	1.2°
O_1	1.282	1.150	0.369	0.331	10%	5.7°

theoretical areal tidal strain and that observed may be attributed to an imperfection of the Boussinesq solution of load strain caused by ocean tides and the lateral inhomogeneity of the real earth. Although the thickness of a normal continental crust is about 1/200 of the radius of the earth and the foliated Franklin formation is but a fraction of the crust, the regional and local geologic anisotropy and structural discontinuity may also have some minor effects on the tidal strain.

Conclusions

Under the assumption that the areal load strain due to ocean tides off the Atlantic coast is negligible, the areal strain of the solid earth tide for M_2 and O_1 observed at Ogdensburg does confirm the theoretical areal tidal strain based on the Gutenberg-Bullen earth model with a New York–Pennsylvania crustal structure generally accepted in seismology.

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