

EARTH TIDES:
SURFACE STRAIN MEASUREMENTS IN NE DENVER

by
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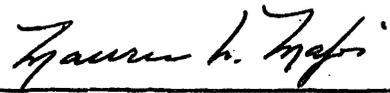
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A Thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science in Geophysical Engineering.

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ABSTRACT

Four quartz-rod strainmeters have been in operation on the Rocky Mountain Arsenal (RMA) NE Denver since 1967. In spite of the fact that these instruments are buried in shallow trenches under approximately 2 meters of surface material, they are recording continuously visible earth tides along with secular and residual strains.

All solar tidal constituents are contaminated by temperature and barometric effects; however, the lunar semi-diurnal (M_2) tidal constituent is little affected by these effects and provides reasonable amplitude (2.54 to 18.30×10^{-9}) and phase ($+15.0^\circ$ to $+19.0^\circ$) values which imply Love's and Shida's numbers ($\underline{h} = 0.53 \pm 0.08$ to 1.45 ± 0.25 and $\underline{l} = 0.076 \pm 0.012$ to 0.320 ± 0.050) comparable to those from other tide measuring devices. These differences are not due to ocean loading effects. Therefore, there must exist a strong indirect effect of unknown origin, perhaps, due to anisotropy. The result of this study implies that the trenched instruments produce useful tidal data and therefore, that the relatively large number of such instruments now deployed for other purposes makes it economically feasible to undertake a detailed study of the effect of regional, geological conditions.

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INTRODUCTION

Several entrenched strainmeters were constructed in NE Denver (Fig. 1) at the time of the controversy about the possible relationships between the RMA Deep Disposal Well and the episodic amount of local earthquake activity in recent years.

Although these instruments were not designed for the earth tide measurements, some of the tidal constituents were easily detectable. Therefore, analyzing these records and comparing the results with the tidal strain data from more conventional strainmeters at the Bergen Park (GOL) station became an interesting subject. GOL is one of the well established and well equipped underground observatories of the Worldwide Network of Standard Seismograph stations and is only 30 miles from the Well.

If once these surface-strainmeter data are proved to be reliable in earth tide studies, it will be quite simple to utilize data from the relatively large number of such stations that have been built already for other purposes.

Denver is about 1400 km from the Pacific coast and is about at the boundary between the Rocky Mountain range in the west and the Great Plains in the east. Because of this

geographic and tectonic condition, the indirect response to the tide generating potential may be of tectonic or geological origin rather than from the oceanic loading effects. Also the determination of the Love's and Shida's numbers and the areal strains in this area may provide some new insight into the elastic or tectonic properties of the area pertinent to the controversy about the RMA well.

INSTRUMENTATION

Table 1 shows the location and individual parameters of all strainmeters used in this study.

As shown in Fig. 1, two pairs of horizontal fused-quartz strainmeters of Benioff design (Benioff, 1959) were installed on the Arsenal within 3 miles of the Well during the spring and summer of 1967 and have been operating ever since. One of each of these pairs of strainmeters (the radial) is directed toward the Well and the other (the transverse) is perpendicular to the first.

At each site a standard of length, consisting of 10-foot sections of fused-quartz tubing shielded by 5-inch-diameter jacket pipe, is buried in a shallow trench with one end fixed to a concrete pier. The sections of quartz are thermally compensated by aluminium compensating cups (Major, 1965). The free end of the quartz extends into a concrete instrument vault which contains a transducer to measure the relative displacement of the free end of the quartz with respect to the instrument vault pier. The transducer is a Benioff capacitive type modified to include integral micrometer calibration and readjustment (Romig, 1967). Strain is computed by dividing the apparent displace-

Table 1
Instrumental Parameters

	GOL	RMA #1	RMA #3
Longitude	105°22'E	104°49'10"E	104°51'09"E
Latitude	50°18'N	39°50'25"N	39°51'50"N
Elevation	7680 ft	5280 ft	5190 ft
Instrument orientation	N/S E/W	N/S E/W	N 19° W W 19° S
Instrument sensitivity	4.92x10 ⁻⁸ F.S. 6.32x10 ⁻⁸ F.S.	2.35x10 ⁻⁷ F.S. 2.35x10 ⁻⁷ F.S.	2.35x10 ⁻⁷ F.S. 2.82x10 ⁻⁷ F.S.
Distance & direction from the RMA Well	29.2 miles W 20° S	1.38 miles south	2.05 miles E 19° N

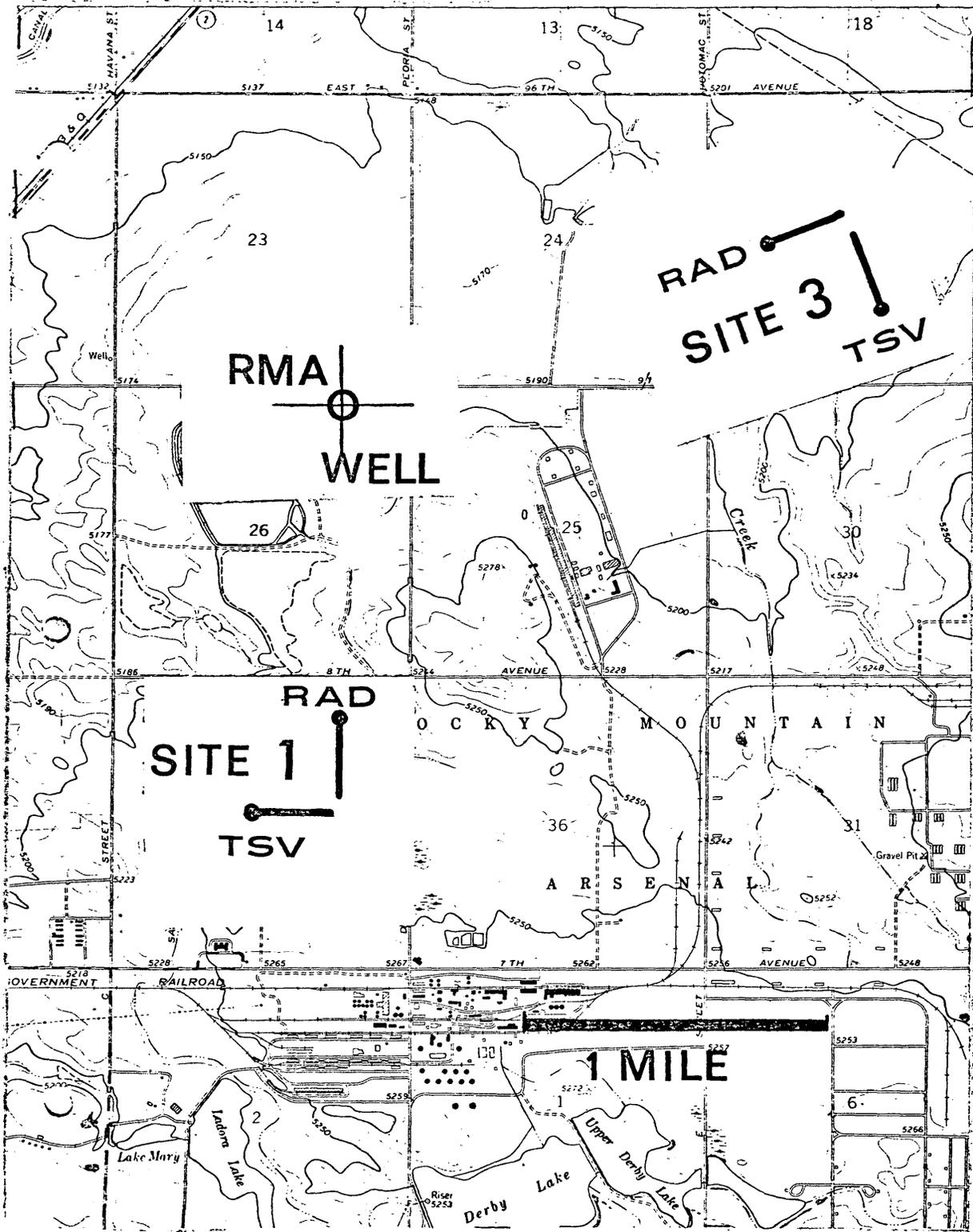


Figure 1. Site map of trenched strainmeters at NE Denver.

ment by the total base length.

Both RMA sites are located in weathered shale, competent rock not being found near the surface in this area.

Instrumentation of the RMA sites included telemetry-controlled drive motors attached to the transducer micrometers. The signals are recorded on 10-inch strip chart recorders located in the Geophysics Department at the Colorado School of Mines. Calibration and readjustment of the strainmeters is accomplished from the School by means of a telephone dial system. The continuity of data from these instruments is good; very little data is lost because of the recorders being off scale, etc.

Micrometers of the same make as those used in these strainmeters have been tested interferometrically (Smookler and Kline, 1971) and found to be accurate within 3 %.

TIDAL THEORY

The response of the earth to the tide generating forces of the astronomical bodies is classically expressed in terms of three coefficients; the Love's numbers \underline{k} , \underline{h} and Shida's number \underline{l} . These numbers specify, respectively, the modification of the primary potential caused by the spatial redistribution of mass resulting from the yielding (\underline{k}), the amplitude of the vertical particle motion (\underline{h}), and the amplitude of the horizontal particle motion (\underline{l}). Taken together in various combinations, they suffice to specify the magnitude of the tidal tilts, the variations of gravity and the tidal strains on the surface of a radially symmetric elastic sphere.

One of the objectives of this study is the determination of \underline{h} and \underline{l} by analysis of the tidal strains observed at RMA stations. Generally, the tidal strains observed are not solely the result of the direct response of the earth to the attraction of the astronomical bodies, but include several superimposed indirect effects; the response of the earth to the variation of meteorologic conditions, to ocean loading effects, and perhaps, to local and regional tectonic effects.

It is possible to write a theoretical expression for

the amplitudes and phase angles of any constituent of the horizontal tidal strain in any azimuth, due to the direct effect alone, in which the only unknown quantities are \underline{h} and \underline{l} .

The observed strain for these constituents, characterized by an observed amplitude and phase, is therefore equal to a known function of \underline{h} and \underline{l} , if the indirect effects are very small. Tidal strain observations in two horizontal azimuths, therefore, provide two simultaneous equations in the two unknowns; \underline{h} and \underline{l} . The functions of \underline{h} and \underline{l} which specify the amplitude and phase of the tidal strains due to the indirect effects have been published by Ozawa (1957).

The tide generating potential, W_2 , a second surface spherical harmonic in terms of the declination of the moon, δ , and the colatitude and longitude, θ and λ , of the point of observation of the earth is;

$$W_2 = \frac{3}{4} g \frac{M}{E} \left(\frac{a^2}{c^3}\right) r^2 \left\{ 3 \left(\sin^2 \delta - \frac{1}{3}\right) \left(\cos^2 \theta - \frac{1}{3}\right) + \sin 2\delta \sin 2\theta \cos(t+\lambda) + \cos^2 \delta \sin^2 \theta \cos 2(t+\lambda) \right\} \quad (1)$$

where g .. gravitational acceleration (980 cm/sec²)

M .. mass of the moon

E .. mass of the earth

$$\left(\frac{M}{E} = \frac{1}{81.30}\right)^*$$

* IAU system (U.S. Naval Observatory, 1968b)

- a.. mean radius of the earth (6.370×10^8 cm)
 C.. distance from earth's center to moon's center
 (3.844×10^{10} cm)
 r.. distance from earth's center to the station
 (6.373×10^8 cm)
 δ .. declination of the moon
 θ .. colatitude of the station (Table 1)
 λ .. east longitude of the station (Table 1)
 t.. hour angle of the moon at Greenwich

The first term in Eq.(1) represents the long period constituent and the second and third terms are the diurnal and semidiurnal constituents, respectively. Since C and δ are functions of time, the exact form of the time variation of W_2 is quite complicated.

The radial, colatitudinal and longitudinal displacement components due to the tide generating potential W_2 are, respectively;

$$u_r = \frac{H(r)}{g} W_2 \quad (2)$$

$$u_\theta = \frac{L(r)}{g} \frac{\partial W_2}{\partial \theta} \quad (3)$$

$$u_\lambda = \frac{L(r)}{g \sin \theta} \frac{\partial W_2}{\partial \theta} \quad (4)$$

where $H(a) = \underline{h}$ = Love's number

$L(a) = \underline{l}$ = Shida's number

The strain components in polar coordinates are;

(Love, 1926, p.56)

$$e_{rr} = \frac{\partial u_r}{\partial r} \quad (5)$$

$$e_{\theta\theta} = \frac{1}{r} \frac{\partial u_\theta}{\partial \theta} + \frac{u_r}{r} \quad (6)$$

$$e_{\lambda\lambda} = \frac{1}{r \sin \theta} \frac{\partial u_\lambda}{\partial \lambda} + \frac{u_\theta}{r} \cot \theta + \frac{u_r}{r} \quad (7)$$

$$e_{\lambda\theta} = \frac{1}{r} \left(\frac{\partial u_\lambda}{\partial \theta} - u_\lambda \cot \theta \right) + \frac{1}{r \sin \theta} \frac{\partial u_\theta}{\partial \lambda} \quad (8)$$

$$e_{\lambda r} = \frac{1}{r \sin \theta} \frac{\partial u_r}{\partial \lambda} + \frac{\partial u_\lambda}{\partial r} - \frac{u_\lambda}{r} \quad (9)$$

$$e_{r\theta} = \frac{\partial u_\theta}{\partial r} - \frac{u_\theta}{r} + \frac{1}{r} \frac{\partial u_r}{\partial \theta} \quad (10)$$

Since the instruments at RMA are in the horizontal plane, the strain components e_{rr} , $e_{\lambda r}$ and $e_{r\theta}$ will contribute nothing to the observations and their considerations may be omitted.

Considering only the semidiurnal term in Eq.(1) and substituting the Eqs.(1) to (4) into Eqs.(6), (7) and (8), the following expressions are obtained for the lunar semi-diurnal constituents:

$$e_{\theta\theta} = \sum \left[h + 2L \left(\frac{1}{\sin^2 \theta} - 2 \right) \right] \cos 2(t+\lambda) \quad (11)$$

$$e_{\lambda\lambda} = \sum \left[h - 2L \left(\frac{1}{\sin^2 \theta} + 1 \right) \right] \cos 2(t+\lambda) \quad (12)$$

$$e_{\lambda\theta} = \sum \left[-4L \left(\frac{\cos \theta}{\sin^2 \theta} \right) \right] \sin 2(t+\lambda) \quad (13)$$

where
$$\sum = \frac{3}{4} \frac{M}{E} \left(\frac{q^2}{c^3} \right) r \cos^2 \delta \sin^2 \theta \quad (14)$$

Eqs.(11), (12) and (13) involve as unknowns only the parameters \underline{h} and \underline{l} . In Eq.(14), the factor $\cos^2\delta$, expressing the effect of the declination of the moon, varies with a period of one lunar month. The amplitude of the variation changes slightly from period to period. For the period studied, $\cos^2\delta$ varies around an average value of 0.888 (U.S.Naval Observatory, 1968a). For comparison with the observed value of M_2 over this interval, one may approximate $\cos^2\delta$ by the constant 0.888. Also, the mean earth-moon distance, 3.844×10^{10} cm, may be substituted for the variable C .

Substitution of the other physical constants appropriate to the two RMA stations, all of which are listed after Eq.(1), reduces the Eqs.(11), (12) and (13) to:

$$e_{\theta\theta} = 2.20 \times 10^{-8} (\underline{h} - 0.610 \underline{l}) \cos 2\tau \quad (15)$$

$$e_{\lambda\lambda} = 2.20 \times 10^{-8} (\underline{h} - 5.390 \underline{l}) \cos 2\tau \quad (16)$$

$$e_{\lambda\theta} = 2.20 \times 10^{-8} (-4.346 \underline{l}) \sin 2\tau \quad (17)$$

where $\tau = (t + \lambda) =$ lunar hour angle

Note that, in Eqs.(15), (16) and (17), $e_{\lambda\theta}$ is 90° out of phase with $e_{\lambda\lambda}$ and $e_{\theta\theta}$, and that the relative amplitude of the various components at a particular station are determined by factors involving, as unknowns, \underline{h} and \underline{l} only. The horizontal strain in any azimuth can be determined from Eqs.(15), (16) and (17) and the familiar expression;

$$e = e_{\theta\theta} \alpha^2 + e_{\lambda\lambda} \beta^2 + e_{\lambda\theta} \alpha\beta \quad (18)$$

where α , β are the direction cosines of the new azimuth with respect to E/W and N/S directions.

Substitution of Eqs.(15), (16) and (17) into Eq.(18) leads to the following expressions for the lunar semidiurnal constituent of the tidal strain, M_2 , in the directions of the instrument orientations.

At the RMA stations, the theoretical tidal strains are:

$$e_{1T} = 2.20 \times 10^{-8} (\underline{h} - 5.390 \underline{L}) \cos 2\tau \quad (19)$$

$$e_{1R} = 2.20 \times 10^{-8} (\underline{h} - 0.610 \underline{L}) \cos 2\tau \quad (20)$$

$$e_{3T} = 2.20 \times 10^{-8} [(\underline{h} - 1.115 \underline{L}) \cos 2\tau + 1.339 \underline{L} \sin 2\tau] \quad (21)$$

$$e_{3R} = 2.20 \times 10^{-8} [(\underline{h} - 4.885 \underline{L}) \cos 2\tau - 1.339 \underline{L} \sin 2\tau] \quad (22)$$

Where e_{ij} is theoretical strain and subscript i meaning RMA #1 or #3 and subscript j meaning radial or transverse components.

As Kuo (1969) demonstrated in a recent paper, areal strain has the special property of eliminating the indirect effects from oceanic tides, assuming the formulae of Boussinesq are valid. Therefore, the areal strain calculations provide one way of checking whether the dominant part of the indirect effects at these stations are from the oceanic loading effects or not.

Since the two sets of strainmeters at RMA #1 and RMA #3 are oriented perpendicular to each other, their areal

strains should have the same equations. From Eqs.(19), (20), (21) and (22), the theoretical areal strains become;

$$A_1 = 4.40 \times 10^{-8} (\underline{h} - 3\underline{L}) \cos 2\tau \quad (23)$$

$$A_3 = 4.40 \times 10^{-8} (\underline{h} - 3\underline{L}) \cos 2\tau \quad (24)$$

where A_1, A_3 are the theoretical areal strains at RMA #1 and RMA #3 respectively.

DATA ANALYSIS

The raw data consist of a total of 4 components of strain data, from RMA #1 and RMA #3 and 2 components of meteorological data from the Stapleton Airport about 5 miles from the RMA Well (Figs. 2, 3 and 4). The strain data contain residual strain components from earthquakes, instrument sensitivity variations and other various indirect effects and other random noises.

The following steps were taken in processing these data. Most computations and plots were done by the CDC-8090 and IC-4000 computers and the Calcomp plotter.

Step 1: The raw strain data were digitized at hourly intervals to one tenth of the small recorder divisions. All steps due to recorder zero shifts, calibration runs and earthquakes were treated as DC-noises and removed to produce continuous data.

Step 2: Using calibration data from the millimicron displacement transducers (Romig, 1967), the four component strain data were reduced to a common sensitivity of 11.8 mm deflection on the recorder paper per 10^{-9} change of strain.

Step 3: Long period linear drifts, over intervals of 2-3 days to 7-10 days were removed by manual picking of

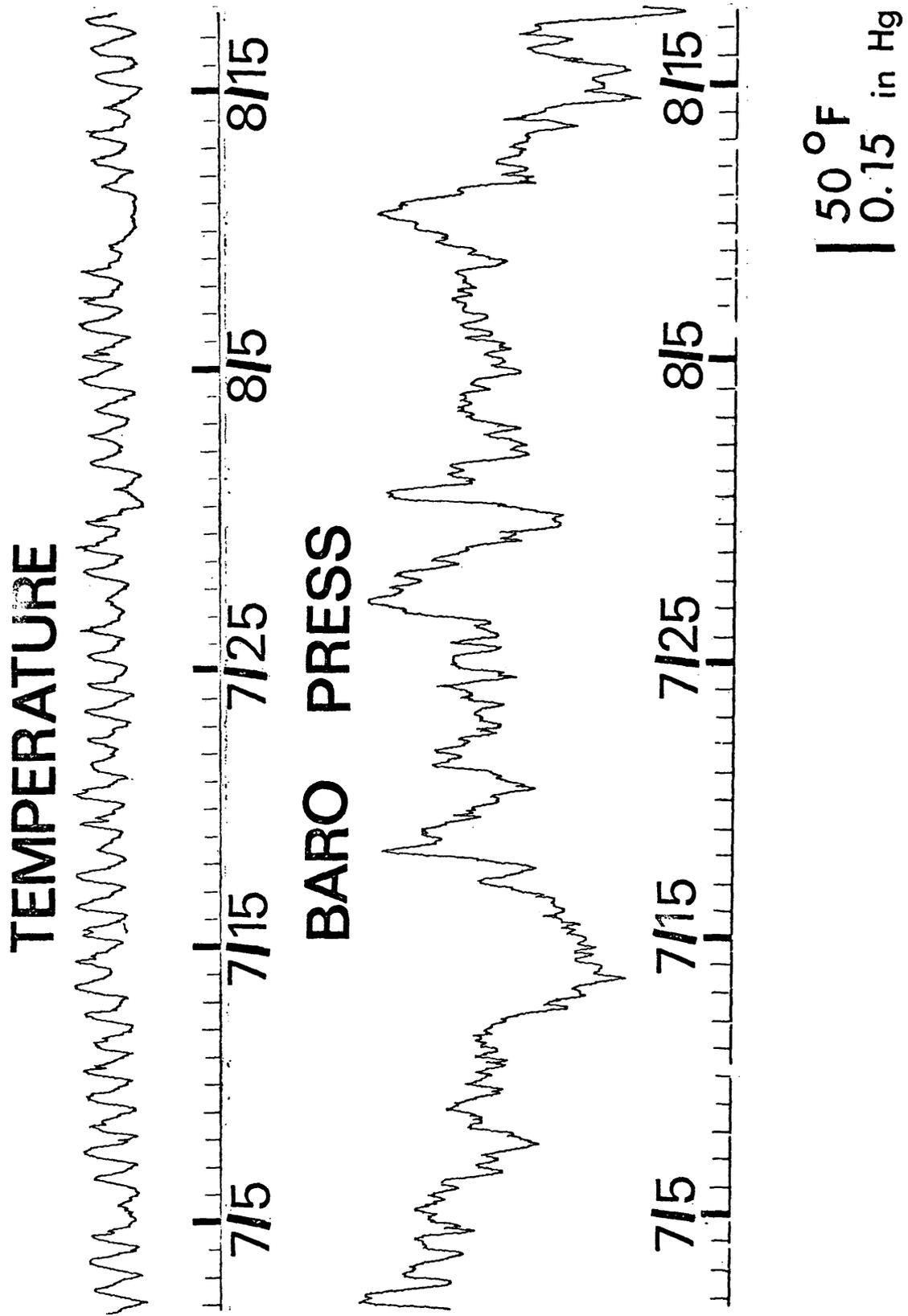


Figure 2. Original meteorologic data

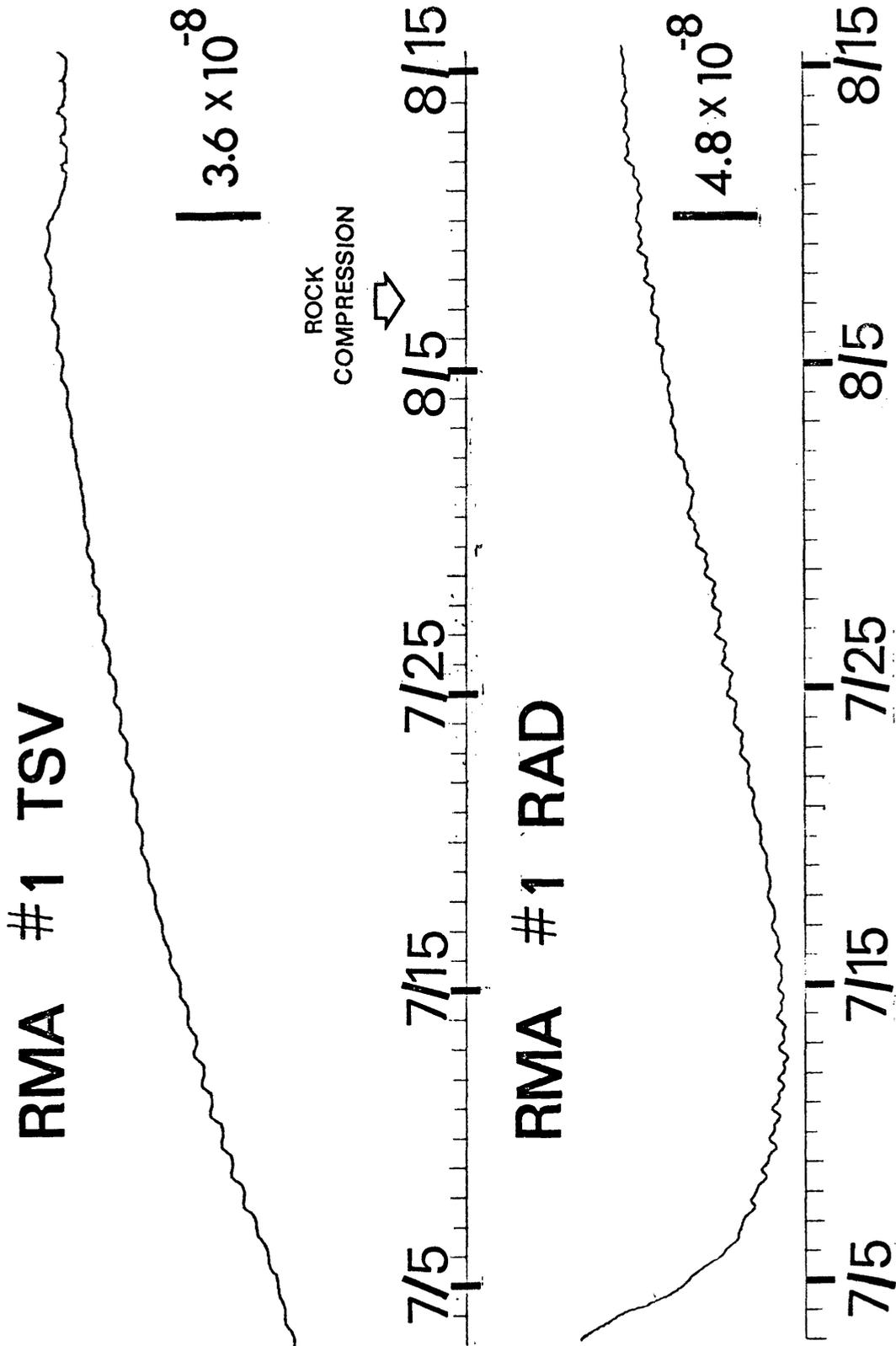


Figure 3. Original strain data at RMA #1.

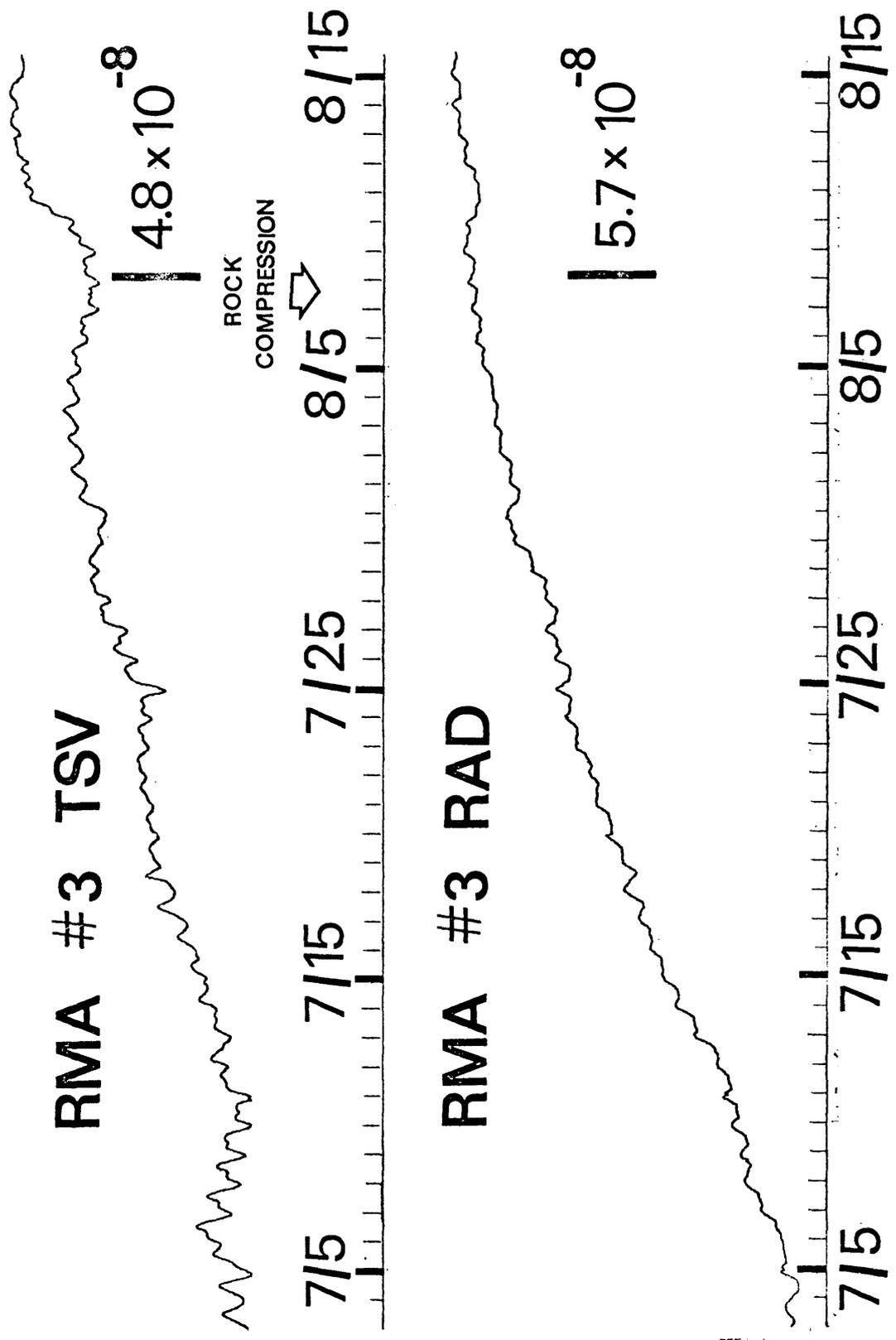


Figure 4.. Original strain data at RMA #3.

linear gradients (Figs. 6,7 and 8). Linear and parabolic drifts of shorter interval were eliminated by the Pertsev's combination of ordinates (Melchoir, 1966).

Step 4: All 6 records were Fourier transformed and plotted on the same scale (Figs. 9, 10 and 11). They show the relative amplitudes in the frequency domain and the interrelationships between strains and meteorological variations.

Step 5: Harmonic analysis of the strain data was done using the method of Pertsev (Pertsev, 1958), one of three tide analysis methods recommended by the International Center of Earth Tides at Brussels. The amplitude so determined are shown below as Eqs. (25) to (28).

Step 6: In the method of Pertsev, the phase angle of each tidal wave is determined by the arctangents of the ratio of the amplitude of the weighted sine transform and that of the weighted cosine transform. Therefore, the result becomes very sensitive to any error in either transform's amplitude value. A better method of phase determination is to cross-correlate the strain data with a synthetic M_2 wave whose amplitude is determined by Pertsev's method and whose initial phase, relative to the lunar hour angle, is varied by 1 minute of angle over a range of angles near the maximum of the cross-correlation product. The phase angles so deter-

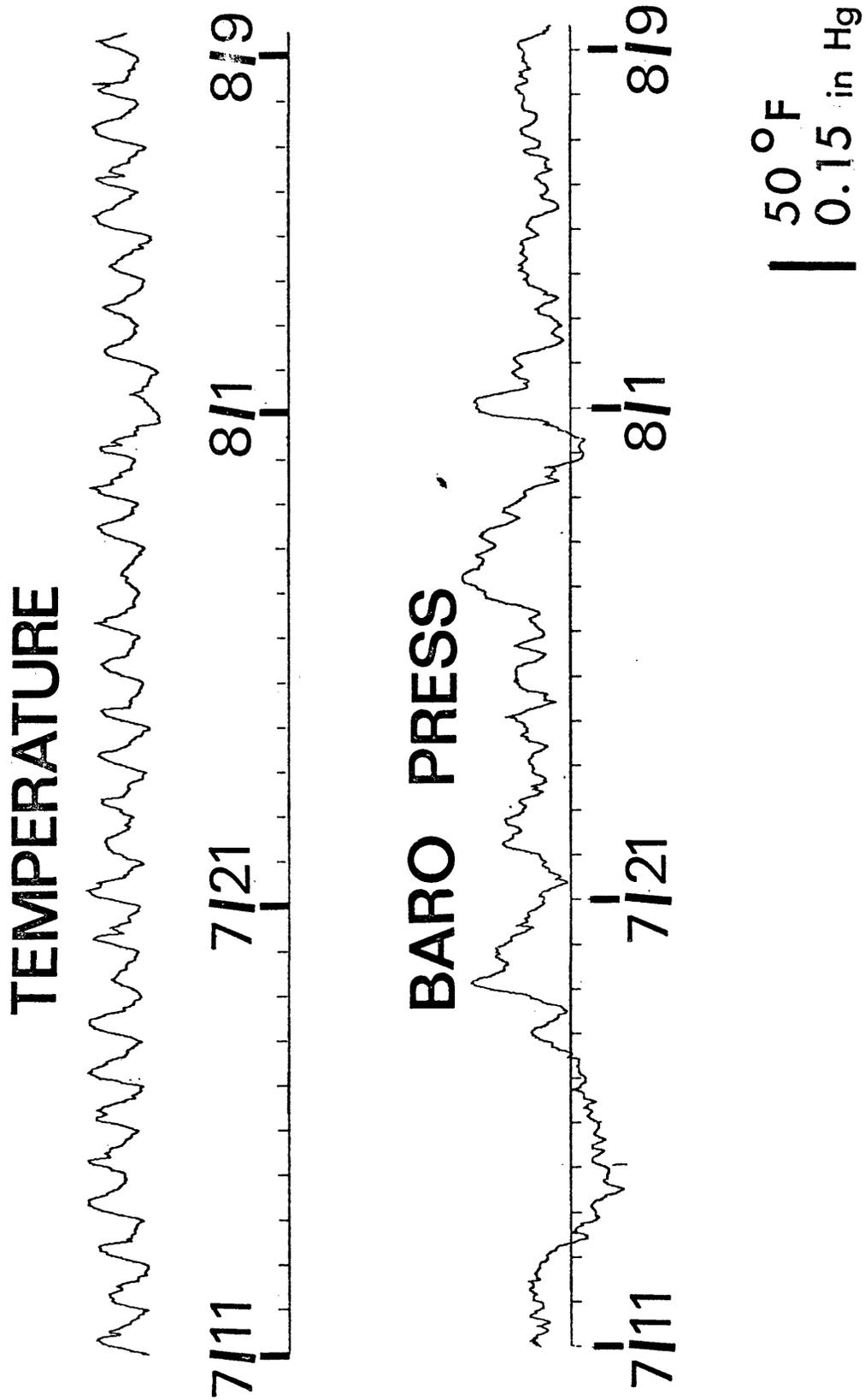


Figure 5. Drift corrected meteorologic data

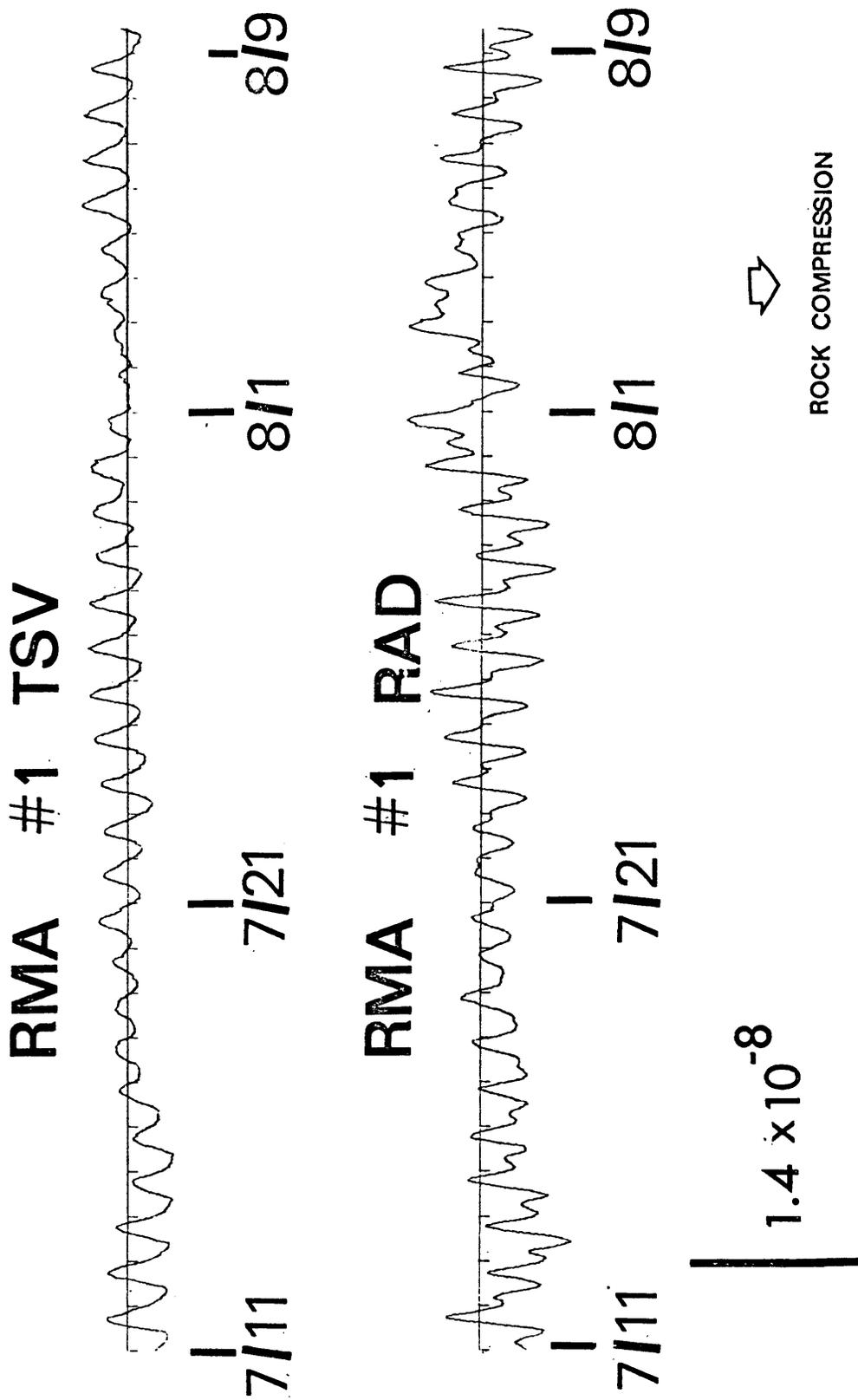


Figure 6. Drift and sensitivity corrected strain data at RMA #1.

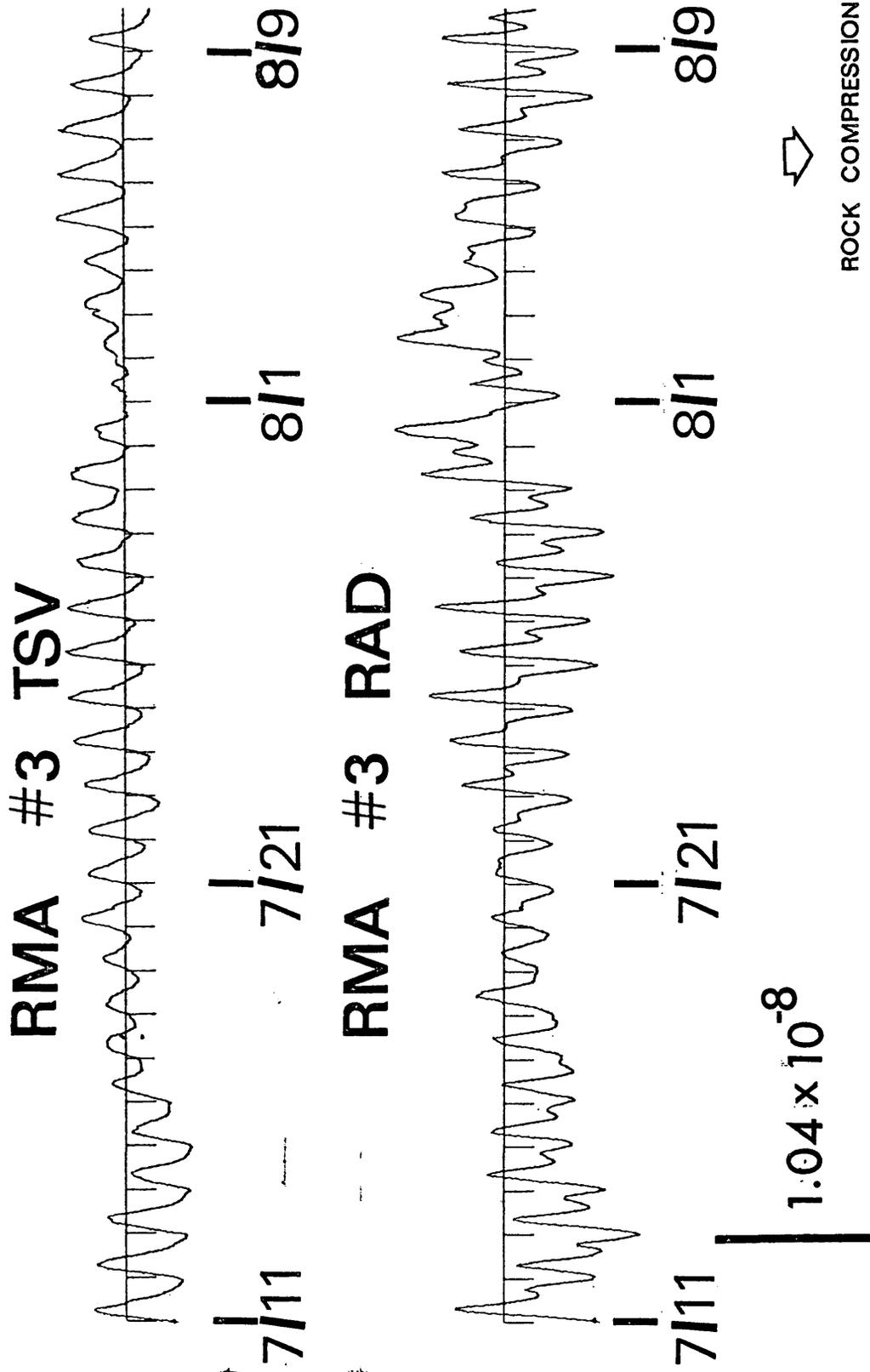


Figure 7. Drift and sensitivity corrected strain data at RMA #3.

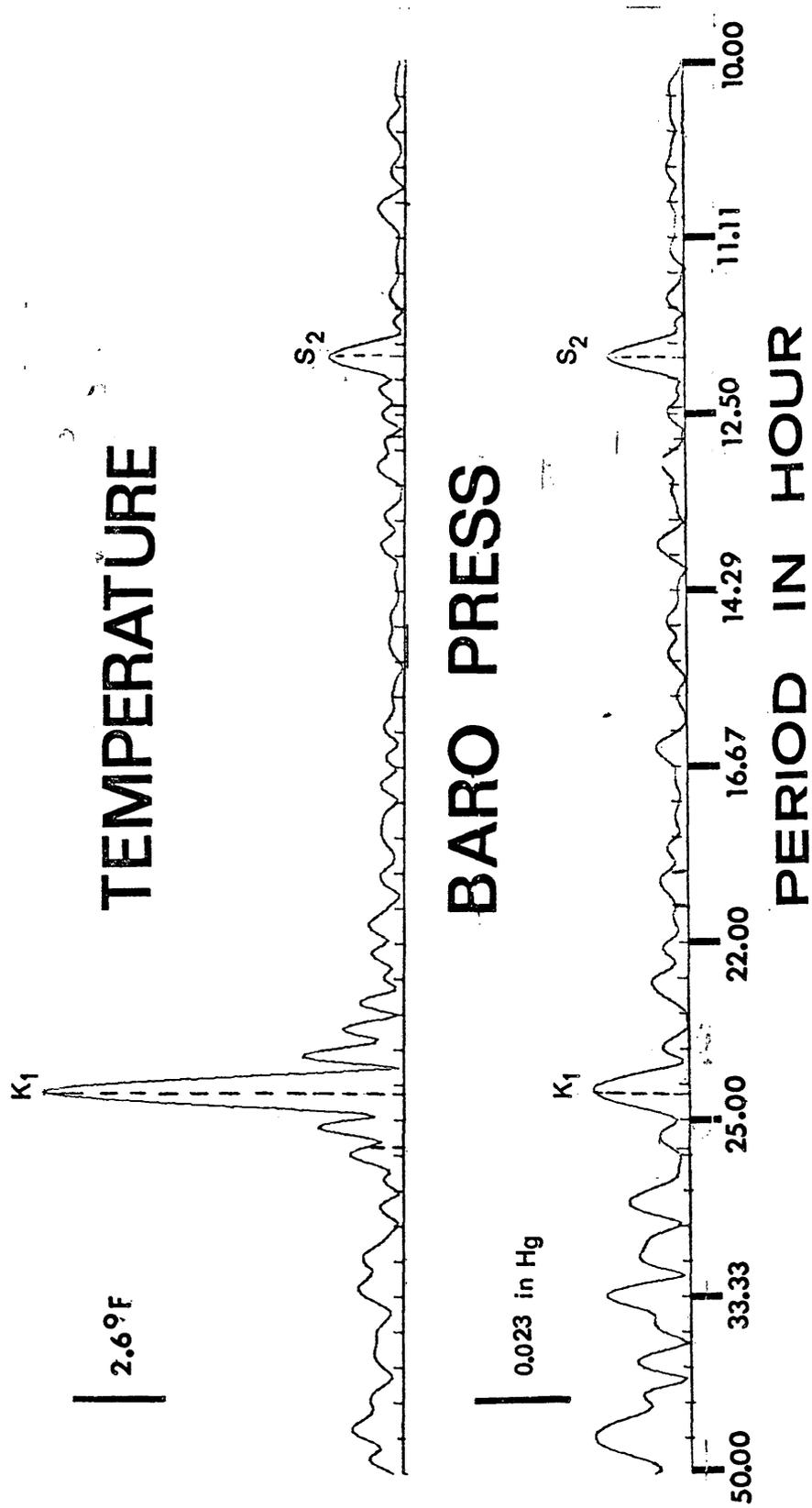


Figure 8. Amplitude spectra of meteorologic data.

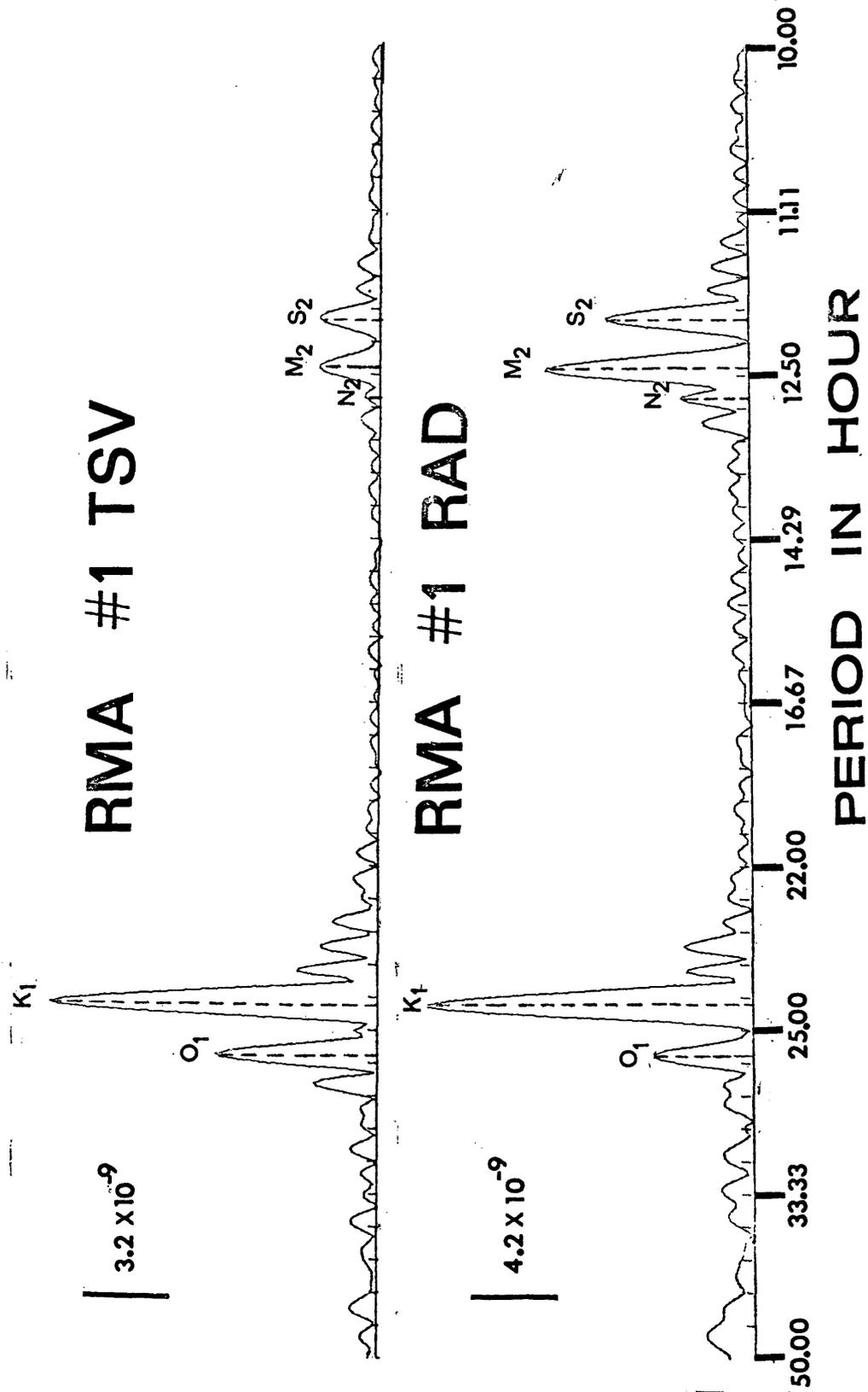


Figure 9. Amplitude spectra of RMA #1 strain.

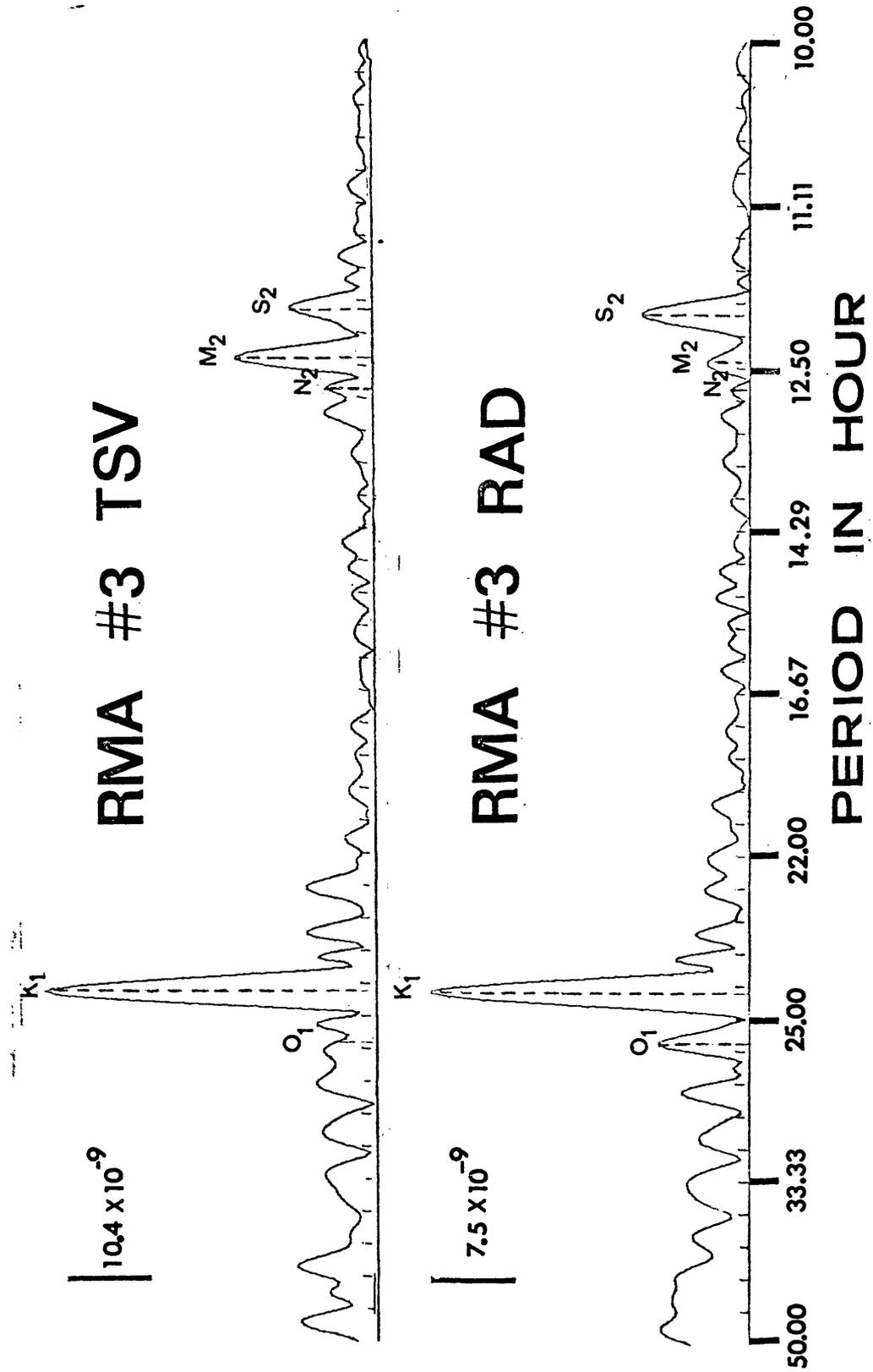


Figure 10. Amplitude spectra of RMA #3 strain.

mined are specified below in Eqs. (25) to (28).

Observed strains during the interval, July 10 to August 11, 1968, were analysed in the way described as the 6 steps. The resulting M_2 amplitudes and the phase angles relative to the lunar hour angle are as follows:

$$e'_{1T} = 2.54 \times 10^{-9} \cos(2\tau + 19^\circ) \quad (25)$$

$$e'_{1R} = 10.55 \times 10^{-9} \cos(2\tau + 17^\circ) \quad (26)$$

$$e'_{3T} = 18.30 \times 10^{-9} \cos(2\tau + 25^\circ) \quad (27)$$

$$e'_{3R} = 5.07 \times 10^{-9} \cos(2\tau - 53^\circ) \quad (28)$$

where e'_{ij} is observed strain. The subscript i refers to RMA #1 or RMA #3 and subscript j refers radial or transverse components.

One may compute Love's and Shida's numbers (\underline{h} and \underline{l}) and the areal strains from these observations. For RMA #1, where the two instruments are oriented in N/S and E/W directions (Table 1), it is simple to calculate the Love's and Shida's numbers. Comparing the amplitudes of theoretical strains in Eqs. (19) and (20) to the amplitude of observed strains in Eqs. (25) and (26);

$$10.55 \times 10^{-9} = 2.20 \times 10^{-8} (\underline{h} - 0.61 \underline{l}) \quad (29)$$

$$2.54 \times 10^{-9} = 2.20 \times 10^{-8} (\underline{h} - 5.39 \underline{l}). \quad (30)$$

Subtracting Eq. (30) from Eq. (29),

$$8.01 \times 10^{-9} = 22.00 \times 10^{-9} (4.78 \underline{l}), \quad (31)$$

where

$$\underline{l} = \frac{8.01 \times 10^{-9}}{22.00 \times 4.78 \times 10^{-9}} = 0.0759 .$$

Substituting \underline{l} as 0.0759 into Eq.(29) or (30),

$$\underline{h} = 0.526 .$$

For RMA #3, where the two instruments are oriented 19 degrees off the N/S and E/W directions, it is not so simple to calculate \underline{h} and \underline{l} . The two theoretical tidal strains of M₂ at this site are:

$$e_{3T} = 2.20 \times 10^{-8} [(h - 1.115 \underline{l}) \cos 2\tau + 1.339 \underline{l} \sin 2\tau] \quad (32)$$

$$e_{3R} = 2.20 \times 10^{-8} [(h - 4.885 \underline{l}) \cos 2\tau - 1.339 \underline{l} \sin 2\tau] \quad (33)$$

These equations are of the form;

$$e = A \cos 2\tau \pm B \sin 2\tau = \sqrt{A^2 + B^2} \cos(2\tau + \varphi) \quad (34)$$

$$\varphi = \tan^{-1} (\mp B/A)$$

Therefore, no unique solution for \underline{h} or \underline{l} can be found by the comparison of the theoretical and observed strains.

On the other hand, the harmonic analysis of the areal strain (Fig.11) shows;

$$A'_1 = 13.09 \times 10^{-9} \cos(2\tau + 17.5^\circ) \quad (35)$$

$$A'_3 = 20.75 \times 10^{-9} \cos(2\tau + 15.5^\circ) \quad (36)$$

where A'_1 and A'_3 are the observed areal strains at RMA #1 and RMA #3 respectively.

Comparing the observed areal strains (Eqs.(35) and (36)) to the theoretical areal strains (Eqs.(23) and (24)), the values of the combination factors ($\underline{h} - 3 \underline{l}$) (Kuo, 1969) are:

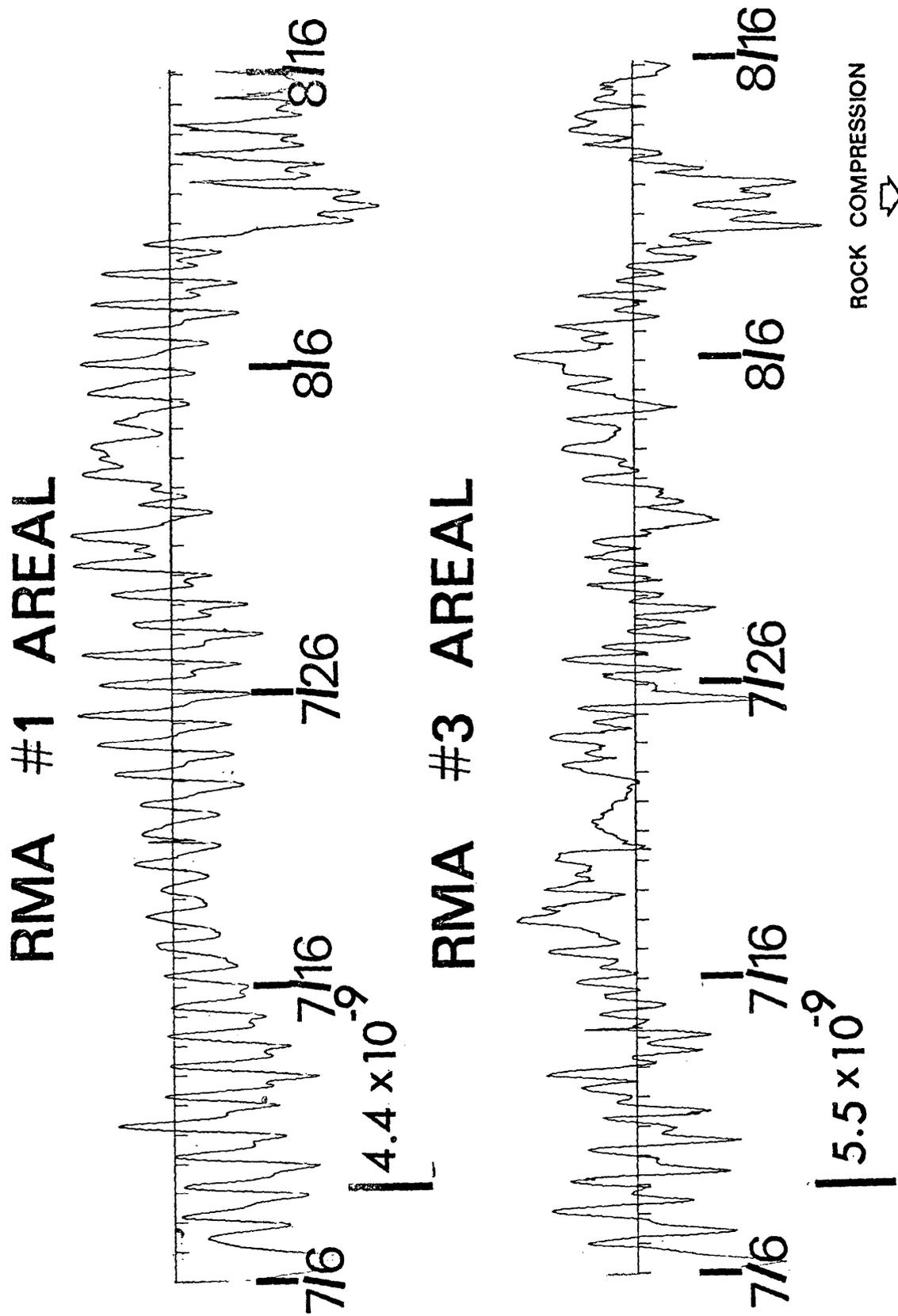


Figure 11. Areal strain for both RMA sites.

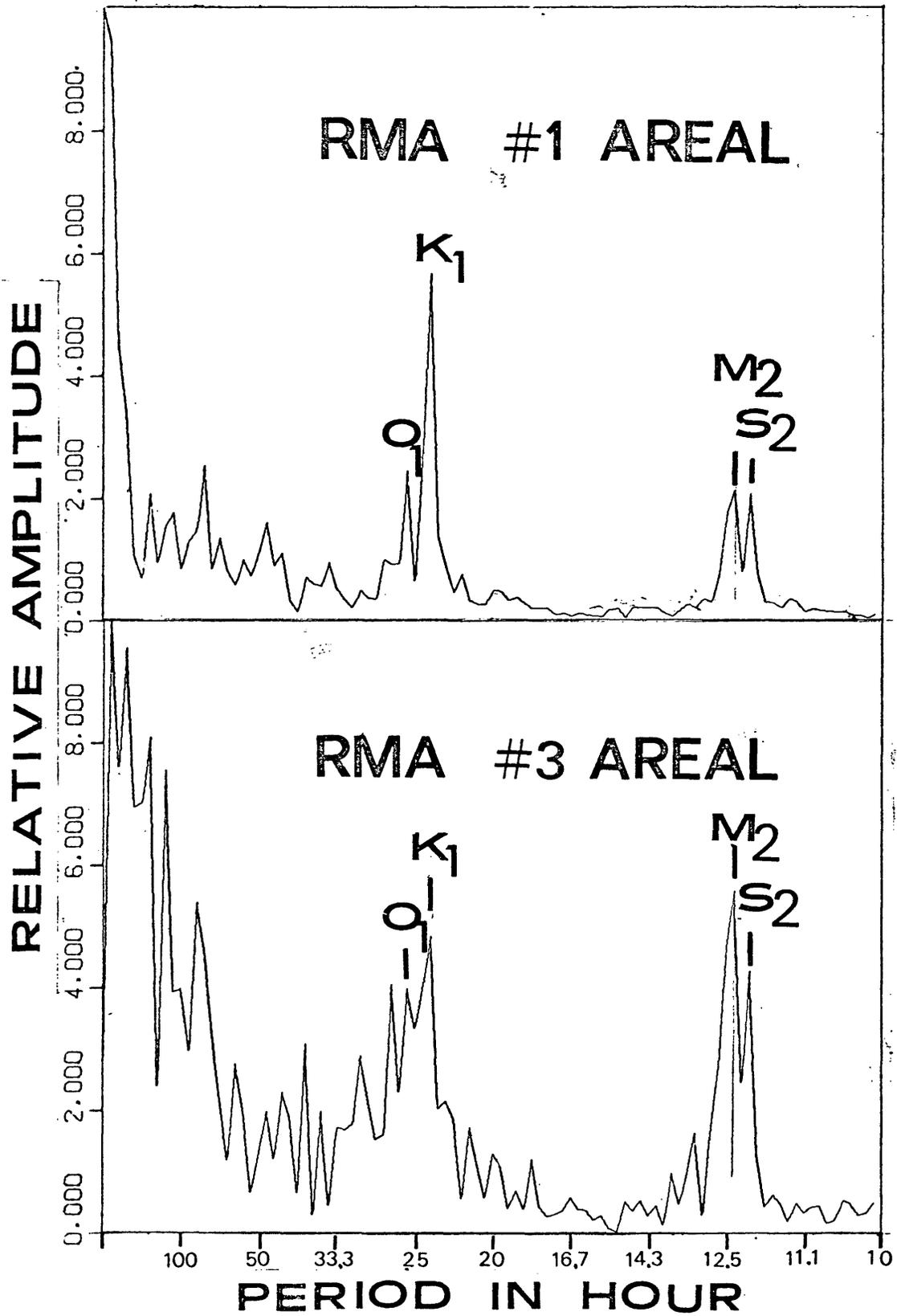


Figure 12. Amplitude spectra of the areal strains.

$$(\underline{h} - 3\underline{L})_1 = 0.278 \quad (37)$$

$$(\underline{h} - 3\underline{L})_3 = 0.472 \quad (38)$$

where subscripts 1 and 3 meaning RMA #1 and RMA #3 respectively.

Let us look again at the observed strains at RMA #1

where

$$e'_{IT} = 2.54 \times 10^{-9} \cos(2\tau + 19^\circ) \quad (25)$$

$$e'_{IR} = 10.55 \times 10^{-9} \cos(2\tau + 17^\circ) \quad (26)$$

$$A'_i = 13.09 \times 10^{-9} \cos(2\tau + 17.5^\circ) \quad (32)$$

From above Eqs.(25), (26) and (36) at RMA #1, areal strain can be considered as just another way to present the observed tidal strains, e'_{IT} and e'_{IR} , since $A'_i = e'_{IT} + e'_{IR}$. From this fact, the relative phase angles of RMA #3 can be estimated to be about $15\frac{1}{2} \pm 3$ degrees phase lead. From Eqs.(32), (33) and (34), the amount of the theoretical phase lead with respect to the lunar hour angle at RMA #3 is:

$$\varphi_{3T} = \tan^{-1} \left[\frac{-1.339 \underline{L}}{\underline{h} - 1.115 \underline{L}} \right] \quad (39)$$

$$\varphi_{3R} = \tan^{-1} \left[\frac{-1.339 \underline{L}}{\underline{h} - 4.885 \underline{L}} \right] \quad (40)$$

where φ_{3T} and φ_{3R} are the relative phase leads of the transverse and radial components respectively.

Rewriting Eqs.(39) and (40) leads to

$$\tan \varphi_{3R} (\underline{h} - 4.885 \underline{L}) = -1.339 \underline{L} \quad (41)$$

$$\tan \varphi_{3T} (\underline{h} - 1.115 \underline{L}) = -1.339 \underline{L} \quad (42)$$

$$(\tan \varphi_{3R} - \tan \varphi_{3T}) \underline{h} = 4.885 \underline{L} \tan \varphi_{3R} - 1.115 \underline{L} \tan \varphi_{3T} \quad (43)$$

And since the observed strains at RMA #3 are;

$$e'_{3T} = 18.30 \times 10^{-9} \cos(2\tau + 25^\circ) \quad (27)$$

$$e'_{3R} = 5.07 \times 10^{-9} \cos(2\tau - 53^\circ) \quad (28)$$

$$A'_3 = 20.75 \times 10^{-9} \cos(2\tau + 15.5^\circ) \quad (36)$$

And the theoretical strains at RMA #3 are;

$$e_{3T} = 2.20 \times 10^{-8} [(\underline{h} - 1.115 \underline{L})^2 + (1.339 \underline{L})^2]^{1/2} \cos(2\tau + \varphi_{3T}) \quad (44)$$

$$e_{3R} = 2.20 \times 10^{-8} [(\underline{h} - 4.885 \underline{L})^2 + (1.339 \underline{L})^2]^{1/2} \cos(2\tau + \varphi_{3R}) \quad (45)$$

where φ_{3T} and φ_{3R} are the same as in Eqs.(39) and (40)

$$A_3 = 4.40 \times 10^{-8} (\underline{h} - 3 \underline{L}) \cos 2\tau \quad (24)$$

The observed strains e'_{3T} and e'_{3R} can be written

$$e'_{3T} = 18.30 \times 10^{-9} \cos(2\tau + \varphi_{3T} + \phi_{3T}) \quad (46)$$

$$e'_{3R} = 5.07 \times 10^{-9} \cos(2\tau + \varphi_{3R} + \phi_{3R}) \quad (47)$$

$$A'_3 = 20.75 \times 10^{-9} \cos(2\tau + \phi_{3A}) \quad (48)$$

where ϕ_{3T} , ϕ_{3R} and ϕ_{3A} are the relative phase lead of the observed with respect to the theoretical for the transverse, radial and areal strains respectively.

Comparing Eqs.(44), (45) and (24) to Eqs.(46), (47) and (48),

it follows that:

$$\varphi_{3T} + \phi_{3T} = +25^\circ$$

$$\varphi_{3R} + \phi_{3R} = -53^\circ.$$

Assuming ϕ_{3T} and ϕ_{3R} to be between 12° and 18° phase lead, that portion of the total phase shift due to instrument orientation alone must be:

$$\varphi_{3T} = 7^\circ \text{ to } 13^\circ$$

$$\varphi_{3R} = -65^\circ \text{ to } -71^\circ$$

With these, the limiting ratios of \underline{h} and \underline{l} can be calculated from Eq.(43) as follows:

$$(\underline{h}/\underline{l})_{12} = 4.3018$$

$$(\underline{h}/\underline{l})_{18} = 4.6416$$

Using the combination factor for RMA #3 (=0.472), \underline{h} and \underline{l} can be calculated:

$$\underline{h} = 1.448 \pm 0.113$$

$$\underline{l} = 0.325 \pm 0.040$$

The observed amplitudes, the relative phase angles and the Love's and Shida's numbers for the lunar semidiurnal constituent (M_2) are shown as Table 2.

Table 2
Observed Amplitudes, Phase angles
and Love's and Shida's numbers

	GOL	RMA #1	RMA #3
AMPLITUDE ($\times 10^{-9} \pm 5\%$)	4.44 (N/S) 2.35 (E/W)	10.55 (RAD) 2.54 (TSV)	18.30 (TSV) 5.07 (RAD)
PHASE LEAD ($\pm 3^\circ$)	23° (N/S) 26° (E/W) 24° (AREA)	17° (RAD) 19° (TSV) 17.5° (AREA)	15° (TSV) 15° (RAD) 15° (AREA)
<u>h-3l</u>	0.16 \pm 0.02	0.30 \pm 0.05	0.47 \pm 0.07
<u>h</u>	(0.22 \pm 0.03)	0.53 \pm 0.08	(1.45 \pm 0.25)
<u>l</u>	(.020 \pm .003)	.076 \pm .012	(.320 \pm .050)

RESULTS AND DISCUSSIONS

The effect of the meteorologic-condition variations on the tidal strain measurements in these shallow-trenched surface strainmeters are shown in Figs. 9, 10 and 11. The amplitude spectra of the temperature and barometric pressure variations show that the most energies are concentrated as two strong peaks at the tidal frequencies of K_1 and S_2 . These two peaks, obviously, contaminated the tidal strains of K_1 and S_2 of all the RMA stations very much. In fact, the tidal strain amplitudes of K_1 are much larger than those of M_2 at all four RMA stations (Figs. 10 and 11) contrary to the theoretical values at this latitude. However, these meteorologic-condition variations have no significant amount of energy at the frequencies of M_2 and O_1 to affect the tidal strain amplitudes. Therefore, it is quite fortunate in the study of strain data from these surface strainmeters that, even under severe temperature and barometric pressure effects, some of the tidal constituents are still uncontaminated and so useful.

Based on the report of Kuo and Ewing (1966) and eliminating the indirect effects from the Atlantic Ocean by using areal strain, Kuo (1969) was able to show that if

the indirect effects of the ocean loading are once removed, the remaining data almost represent the actual earth tides. His observed values for the amplitudes and phase angles of the areal strains and the combination factors ($\underline{h} - 3 \underline{l}$) agree very well with the theoretical values calculated from the earth model of Oliver et al (1961).

However, the fact that the dominant part of the indirect effect is from the oceanic tides in the eastern United States does not also seem to be true in NE Denver, Colorado. Comparison of the areal strains (Table 2) observed at three sites implies that there exists some large indirect effects. The observed differences are not due to the oceanic loading effect because the areal strains do not contain this effect. Besides the large differences in areal strains, the unusual, fairly large phase leads also imply the existence of large non-oceanic indirect effects of unknown origin, operating on all three sites. Although the phase leads in earth tide observations are very rare, Cheh Pan (1970) has also reported large phase leads in his gravitational tide observations at St. Louis.

Considering all these strange results along with the large differences in the amplitude and in the Love's and Shida's numbers, it seems reasonable to hypothesize that the indirect effects in this area might be due to:

- (1) the presence of a fault zone in NE Denver which might serve as an elastic boundary between two tectonic blocks and/or
- (2) the horizontally rapid changing state of stress near the fault zone and/or
- (3) the regional, geological anisotropy due to the anomalous flexure of the Rocky Mountains, etc.

Any further speculation about the exact source mechanism of the indirect effect is inappropriate at present time. However, I plan a more extensive study of this indirect effect by operating about 15 strainmeters near Denver during the summer of 1971 and reducing the dal data from them in the manner described in this study.

CONCLUSIONS

These are shown as encouraging factors from this study of surface strain measurements at NE Denver:

- (1) The trenched surface strainmeters do record the M_2 tidal constituent and produce useful data for earth tide study comparable to those from other tide measuring instruments.
- (2) Therefore, the relatively large number of such trenched surface strainmeters now deployed for other purposes makes it economically feasible to undertake a detailed study of the elastic and tectonic properties of the earth such as the effects of regional anisotropy suggested here as a possible cause of the indirect effects in NE Denver.
- (3) The results of this study imply that, near Denver, Colorado, there must exist some large indirect effects of unknown origin, but definitely not from the oceanic loading.

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