CRUSTAL DEFORMATION AT VERY LONG BASELINE INTERFEROMETRY SITES DUE TO SEASONAL AIR-MASS AND GROUND WATER VARIATIONS

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ABSTRACT

Rearrangements of the geographic distribution of air-mass and groundwater load and deform the earth's crust. The seasonal deformation normal to the earth's surface is calculated at stations involved or interested in VLBI geodesy and at hypothetical sites in Australia and Brazil using global atmospheric pressure data, values for groundwater storage, and load Love numbers deduced from current earth models. The annual range of deformation approaches the centimeter-level measuring potential of the very long baseline interferometry (VLBI) technique at Greenbank, Haystack, and the Brazil site. Baselines between stations of the European network and the northeastern part of the United States and between Brazil and Australia could be affected at this level of accuracy.

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INTRODUCTION

The new space techniques of laser ranging to artificial satellites and the moon and VLBI have the potential of centimeter-level measurement accuracy. With these systems, the accuracy of determining dynamic earth motions can be comparable to the basic measurement accuracies obtainable (National Academy of Sciences, 1978). It is quite obvious that models for these motions will play an important role in the analysis of the data for positioning to centimeter-level accuracies. In this paper, we make a first attempt at one of the many modelling studies which need to be done. We estimate the crustal "breathing" that occurs when seasonal atmospheric pressure systems move across the globe and when there are seasonal variations in groundwater storage. Results are presented for existing VLBI stations in Europe and the United States and hypothetical sites in Australia and Brazil.

Baseline variations between groups of observatories are determined. The mathematical formulation of the problem, the data used, and the principal assumptions made are briefly reviewed.

METHOD

The problem of crustal deformation caused by the redistribution of surface masses is conveniently solved by means of the load Love numbers h'_n and ℓ'_n and the change in potential at the surface arising from the variable load (Munk and MacDonald, 1960). The change in potential may be written as

$$\Delta U = \Sigma \Delta U_n = 4\pi Gr \sum_n \frac{q_n}{2n + 1} \qquad (1)$$

where

$$q_n = \frac{2n + 1}{4\pi} \int_s q(\phi, \lambda; t) \, P_n(\cos\psi) \, dS \qquad (2)$$

is the nth degree surface spherical harmonic representation of the variable surface load q $(\theta, \lambda; t)$ at a particular point on the globe, G is the gravitational constant, r is the earth's radius, $P_n(\cos\psi)$ is the Legendre polynomial, and ψ is the angle between radius vector at the computation point and the radius vector at the disturbing load. The corresponding crustal motions are

$$dr, rd\theta, rd\lambda = \left\{ \sum_n h'_n \frac{\Delta U_n}{g}, \sum_n \ell'_n \frac{1}{g} \frac{\partial(\Delta U_n)}{\partial\theta}, \sum_n \ell'_n \frac{1}{g\sin\theta} \frac{\partial(\Delta U_n)}{\partial\lambda} \right\} \qquad (3)$$

where θ is colatitude, λ is east longitude, and g is local gravity.

We applied equations (1), (2), and (3) to air-mass and groundwater data. The term groundwater refers to moisture stored on the earth's land surface, and includes snow, variable water storage in the

form of plant material, and water between the surface and the shallowest position of the watertable. The complete calculations are rather lengthy. Since the load Love numbers ℓ_n' required for the problem are about two orders of the magnitude smaller than their h_n' counterparts and the radial crustal distortions are already small, we calculated only dr.

DATA

We used the January, April, July, and October averages of sea-level pressure compiled by Schutz and Gates (1971, 1972, 1973, 1974) which are given at gridpoints spaced every 4° of latitude and 5° of longitude over the entire earth. These data need to be adjusted back to station elevation before evaluation of ΔU_n. Laplace's formula was used to make the necessary adjustment. The groundwater calculations are based on van Hylckama's (1956) monthly compilations for 10° × 10° areas. We have taken his January, April, July, and October volumes and divided these by the area of the corresponding compartment to yield surface loads. Data beyond 70°S does not appear and have been ignored. Dahlens's (1976) load Love numbers for earth model 1066 A were preferred for no special reason.

RESULTS

The calculation for the radial deformations due to atmospheric loading and groundwater have been published separately by Stolz and Larden (1979) and Larden (1980),* respectively, and are depicted in contour form on maps for January, April, July, and October. The crustal motion attributable to the atmosphere approaches significance over parts of Asia, in Greenland, and in Antarctica. It is well below 1 cm in other parts of the globe. The deformations due to groundwater variations are also small and reach 1 cm only over the Himalayas and the northern United States. For this study, we have combined the results of Stolz and Larden (1979) and Larden (1980) to produce the amplitude and phase of the annual radial deformation (the annual term of deformation at a particular location is A cos (⊙–phase), where A is the amplitude and ⊙ is the sun's longitude measured from the beginning of the year) at sites which are actively involved or are interested in VLBI experiments. The horizontal gradients of the deformations over Europe and parts of the United States are small. We have averaged the distortions for these regions (table 1). Thus, Owens Valley and Goldstone become SW U.S. (37°N, 246°E), Ft. Davis and Richmond become SE U.S. (30°N, 270°E), Haystack and Greenbank become NE U.S. (45°N, 280°E), and stations in Spain, England, Holland, Germany, Italy, Sweden, Poland, Finland, and Crimea (U.S.S.R.) become Europe (50°N, 10°E). The results are plotted in figure 1. The vertical motions at Greenbank, Haystack, and Brazil have an annual range of roughly 1 cm. Since the VLBI technique measures baselines and it is possible that the motions at two sites compound to produce bigger motions, we studied the baselines listed in table 2. Only the baselines Europe-NE U.S. (a) and Brazil-Australia (c) (an unlikely possibility because the sites are separated by nearly 180° in longitude) vary by approximately 1 cm (figure 2).

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*Larden, D. R., Ph.D. Thesis, University of New South Wales, Sydney, N.S.W., Australia, 1980.

Table 1
Radial Deformation

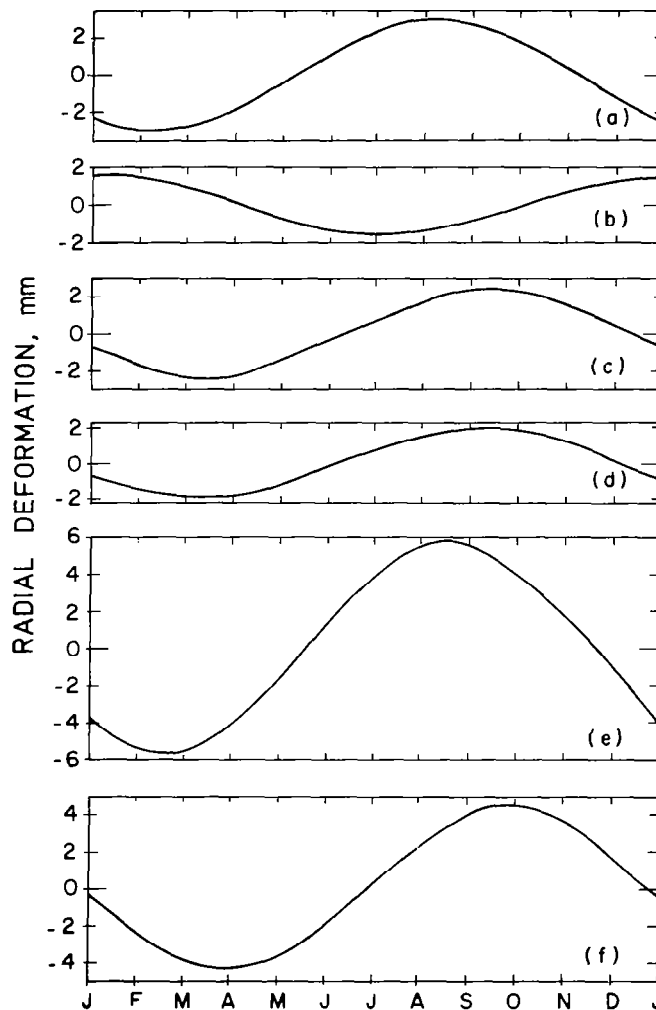|	Amplitude, mm	Phase, deg.
Europe	3.1	233 (a)
Australia	1.7	19 (b)
SW U.S.	2.4	266 (c)
SE U.S.	1.9	260 (d)
NE U.S.	5.8	243 (e)
Brazil	4.5	282 (f)

Figure 1. Radial deformations for sites located in: (a) Europe; (b) Australia; (c) SW U.S.; (d) SE U.S.; (e) NE U.S.; and (f) Brazil.

Table 2
Baseline Variations

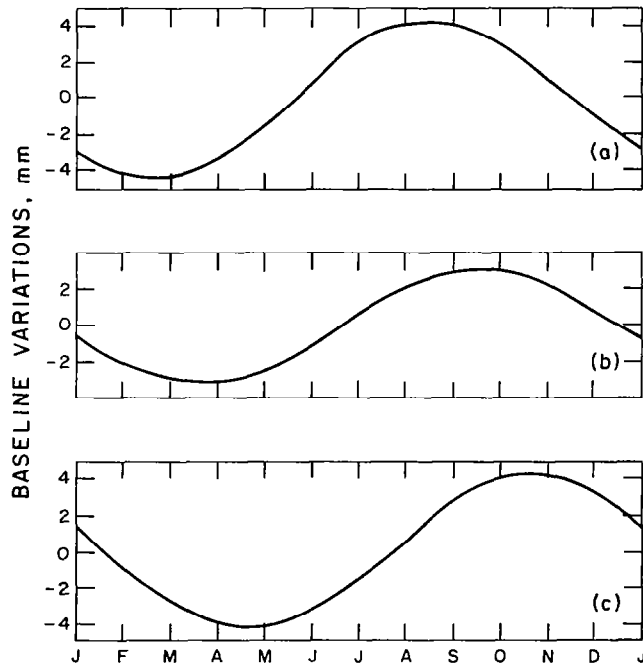|	Amplitude, mm	Phase, deg.
(a) Europe, NE U.S.	4.2	240
NE U.S., SE U.S.	0.9	247
SE U.S., SW U.S.	0.8	264
(b) SE U.S., Brazil	3.0	276
(c) Brazil, Australia	4.2	303

Figure 2. Baseline variations between: (a) Europe and NE U.S.,
(b) SE U.S. and Brazil; and (c) Brazil and Australia.

DISCUSSIONS

When performing the deformation calculations, we need to allow for changes in sea level produced by the response of the oceans to the atmospheric pressure variations and the interchange of water between land and oceans, and atmosphere and oceans. The inverted barometer rule states that for every millibar of atmospheric pressure at a particular place over and above the mean pressure over the entire ocean surface the sea surface is locally depressed by 1 cm. This rule is normally invoked to account for the response of the oceans. This introduces a number of problems. The two main ones are: (1) oceanic mass conservation is implied, which is impossible if we also wish to consider the interchange of water between the constituent parts of the earth; and (2) we end up with a sea surface which is not quite an equipotential. Fortunately, their effect on our results is small (Stolz and Larden, 1979). Data for sea-level variations caused by the exchange of water between land and oceans and atmosphere and oceans are too inaccurate at present to make a reliable estimate of the effect on our results. Larden (1980), op. cit.) has estimated the contribution by assuming that the moisture which is not in the atmosphere or on land during any season is in the oceans. Our results change at most by 1 mm.

Another difficulty, concerning the zero degree load Love numbers, arises from the manner in which we have produced the results presented here. The zero degree load Love numbers vanish if mass is conserved (Rochester and Smylie, 1974), but not if the effect of air mass and groundwater is calculated separately as we have done. Thus, our results contain a zero degree contribution which should not be there. Larden (1980) has considered this problem and finds the results to be in error by roughly 10 percent. This clearly does not affect the conclusion we may draw from the calculations; that is, the general seasonal variations in the continental and intercontinental baselines are small. Accordingly, until considerable improvement is achieved in instrument stabilities and corrections for ionospheric and tropospheric effects, it does not seem necessary to adjust baseline determinations for seasonal variations, and even then, these variations will only be marginally significant.

ACKNOWLEDGMENT

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