Some Geophysical Effects on Geodetic Levelling Networks

by

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ABSTRACT

Seasonal variations in the geometrical shape of the earth's surface due to loading will affect all types of future vertical crustal movement measurements which have high accuracy over long distances. This includes satellite laser ranging, VLBI and absolute gravity measurements. In addition, changes in the gravitational field due to mass displacements will affect satellite and gravity results. This paper examines the geodetic consequences of two geophysical mechanisms that can cause such changes. Firstly, an order of magnitude bound on the secular change in geoid shape produced by plate tectonic activity is estimated and, secondly, the seasonal deformation of the earth's surface due to atmospheric and groundwater loading is calculated. The results are depicted in contour form on regional maps with emphasis given to the areas of North America where the effects are largest. The change in the position of the geocenter is also calculated for each geophysical process and the significance of the results discussed within the context of centimeter geodesy.

SOMMAIRE

Les variations saisonnières de la forme géométrique de la surface de la terre dues aux effets de charge affectent toutes les sortes de mesures de mouvements verticaux de la croûte ayant une haute précision sur de longues distances. Celles-ci incluent les mesures (distances) au laser sur satellites, les longues lignes de base par interférométrie (VLBI) et les mesures absolues de la pesanteur. En plus, les changements du champ gravitationnel dus aux déplacements de masses affecteront les mesures gravimétriques et sur satellites. On étudie dans ce rapport les conséquences en géodésie de deux phénomènes géophysiques qui peuvent causer de tels changements. On évalue d'abord l'ordre de grandeur du changement sélulaire de la forme du géoïde causé par les activités tectoniques et, ensuite, les déformations saisonnières de la surface de la terre dues aux effets de charge atmosphérique et d'eau de surface. Les résultats sont présentés sous forme de courbes de niveau sur des cartes régionales; on donne une attention particulière aux régions de l'Amérique du Nord où les effets sont les plus grands. Le changement de position du centre de masse du à chaque phénomène géophysique est également calculé et la signification des résultats dans le contexte de la géodésie au centimètre près est analysée.
1. **INTRODUCTION**

Vertical movements of the earth’s surface continue to produce many challenging questions of geodynamic interest (see, e.g. Vaníček 1978, Whitcomb 1976, Wahr and Rice 1979). One of the main objectives for studying these phenomena is to gain a better understanding of the subsurface density and strain changes which occur in seismic zones so that reliable models for predicting the occurrence of earthquakes can be formulated.

Besides the classical levelling measurements, there will be several new data types from the next generation of geodetic measuring systems (see, e.g. Anderle 1979, Faller et al. 1979, MacDoran 1979, Smith et al. 1980) that can be used to achieve these goals. However, before these data can be incorporated into the definition of the vertical reference datum and subsequently used to obtain information on the subsurface processes which cause vertical uplift, efforts must be made to assess the significance of the numerous geophysical mechanisms that can influence the measurements at the expected 1 to 3 cm accuracy level for these techniques.

For example, three-dimensional position measurements to the LAGEOS satellite are sensitive to the distortions in the shape of the earth’s surface,
as well as to the movement of the geocenter and changes in the shape of the geoid. It is instructive to point out here that the term geocenter is used in this paper to mean the center of mass of the solid earth and core. Such variations, if large enough, will be important factors in the interpretation of vertical crustal motion data. The level of possible changes in geoid shape also needs to be known in order to compare the conventional levelling results with geometrical results such as those obtained from the Global Positioning System (GPS) of satellites.

Among the geophysical mechanisms that have to be considered are the earth and ocean tides, atmospheric pressure and groundwater variations, sea-level fluctuations, deglaciation and plate tectonic activity. Some of these effects are discussed within the context of this symposium (see, e.g. Anderson 1980, Goad 1980, these proceedings). This paper explores the geodetic consequences of two phenomena, plate tectonic mass transfer and seasonal atmospheric-groundwater loading. Since both involve a form of mass transfer, the extent and nature of geocenter motion must be considered. In addition, the seasonal redistribution of air-mass and groundwater will deform the earth’s surface as the latter responds elastically to the load. Plate tectonic mass transfer, on the other hand, will distort the shape of the geoid causing changes in geoid height.

The discussion which follows attempts to give some insight into the magnitude of these effects in order to help separate the components of spectral similarity. The bulk of the results are presented on regional contour maps with the main emphasis given to the variations over the North American continent. Global maps for the effects of plate tectonic mass transfer on the shape of the geoid and the seasonal deformation of the earth’s surface due to atmospheric loading have been published elsewhere (see Mather and Lardén 1978, Stöza and Lardén 1979).

2. MODELLING PLATE TECTONIC MASS TRANSFER OVER GEODETIC TIME-SCALES

The concept that the earth is made up of a relatively small number of lithospheric plates which are in motion with respect to one another is the central hypothesis of global plate tectonics. The theory implies the transportation of mass as the plates move about the earth’s surface, material rises from the asthenosphere and cools to generate new oceanic lithosphere, and
lithospheric slabs descend to displace asthenospheric material. Chapple and Tullis (1977) discuss the various mechanisms that can cause or impede this process and while mantle convection is a leading contender it is still not clear whether the extent of the convection is confined to the upper mantle or is mantle-wide (O'Connell 1977).

Any attempt to estimate the quantity of mass transferred on a global basis, however, is limited by a lack of observational data which could be used to verify the models. Three major components are needed to approach the problem theoretically. They are (1) a density profile for zones where mass redistribution is likely to occur, (2) some plausible assumptions which hopefully will cover a wide range of mass accumulation, dispersion and displacement processes, and (3) a global plate motion model which defines the velocity, the rotation pole and the boundary of each individual plate.

Figure 1 is a vertical profile showing the density of material in areas where mass accumulation is likely to occur. The densities are based on average values used by Ito (1978) and although more sophisticated modelling could have been employed (see e.g. Törsson et al. 1978) it did not seem warranted for an order of magnitude study.

Several assumptions can be invoked to describe the plate tectonic mass transfer mechanism. Over geodetic time scales (≤10^2 years) it is not unreasonable to treat the problem as a transient one. Thus one might expect a gradual redistribution to occur in the upper few hundred kilometer portion of the earth in zones on the plate boundaries where the continents collide (e.g. Himalayas) and where subduction (e.g. Aleutian trench) and sea-floor spreading (e.g. mid-Atlantic ridge) processes are operating. Along transform faults (e.g. San Andreas fault), the lithosphere is neither created nor destroyed and so any mass redistribution that may occur is probably small.

Table 1 summarizes the characteristics of the three mass transfer models that were constructed by Mather and Larden (1978) and considered for this study. In Model I, the descending oceanic lithospheric slab displaces less dense asthenospheric material at subduction zones to produce a mass excess. Slab thicknesses have been estimated to be between 75 and 100 km but can vary substantially from these values in seismic regions (Walcott 1970). In order to simplify the calculations, a maximum value of 100 km was adopted for the
depth of the lithospheric-asthenospheric boundary (Isaacks et al. 1988). Mass is conserved within each plate by calculating an appropriate negative density contrast for the spreading zones (Jacoby 1970). In this way, the mid-ocean ridge process of upwelling asthenospheric material replacing the more dense lithospheric material as the plates move apart is taken into account.

Model 2 is simply a variant of Model 1 with the subduction concept and the mass conservation principle retained. The major difference lies in the assumption that continental crustal material (\( \rho = 2.7 \text{ g cm}^{-3} \)) accumulates down to a depth of 35 km as the plates collide. In general, lighter continental crust will not submerge with the descending slab because buoyant forces tend to dominate all other forces (Makenzie 1969).

Model 3 is included, not for its geophysical appeal, but to see whether an extreme model for plate tectonic mass transfer can produce significant distortions in geoid shape over the North American continent. In this case, the entire lithospheric and crustal mass (\( \rho = 3.1 \text{ g cm}^{-3} \)) is assumed to accumulate as the plates collide. Both Models 2 and 3 presuppose that over geodetic time the mass transfer rate in subduction zones deviates considerably from the steady state rate applicable over geologic time (>10\(^5\) years). The existence of short-term lagging phenomena in areas where the earth’s rigidity or some other dynamical force prevents any immediate adjustment to maintain isostatic equilibrium cannot be ruled out.

The mass transfer rate is governed primarily by the plate velocities and determinations of these have been made (see, e.g. Solomon and Sleep 1974, Kaula 1975). The calculations presented here are based on the relative velocities of Solomon and Sleep (1974) but, to conform with the hypothesis that the hot-spots are roughly fixed (Burke and Wilson 1972), they have been transformed to a frame in which the African plate is stationary. Digitization of the plate boundaries and zone categorization was accomplished using the plate mosaics featured in Chase (1972), Solomon and Sleep (1974), and Kaula (1975).

3. DATA FOR SEASONAL DEFORMATION CALCULATION

3.1 Atmospheric Pressure and Groundwater

Unlike the plate tectonic mass transfer mechanism, global data sets for the seasonal variations in air-mass and groundwater storage are available.
The term groundwater includes moisture stored on the surface (snow, vegetation, lakes) as well as in the ground. The groundwater calculations are based on van Hylckama's (1968) monthly compilation for 10° by 10° squares. His values for the volume of water in each square were divided by the area of each square to give the surface load.

A full description of the atmospheric pressure data is given in Stoll and Landen (1979) together with the adjustments that need to be made to the data before carrying out the deformation calculations. Oceanic response to atmospheric pressure changes is assumed to be like that of an inverted barometer.

3.2 Load Love Numbers

Several sets of the load Love numbers appear in the literature. In this work, Dahlen's (1976) values are used. The complete calculations, involving both the computation of radial and tangential displacements, are very lengthy and since the tangential displacements are much smaller compared to the radial components the calculations for these were not done. Thus only the load Love numbers $h_n$ are needed.

The significance of the load Love numbers of degree 0 and 1 deserves a special word of mention. A zero degree term is introduced to model the earth's response to a load whose mass is not conserved. This term will vanish if mass is conserved (Rochester and Smylie 1974) but not if the effect of air mass and groundwater is calculated separately as is done here. No attempt has been made to conserve mass in these calculations. It is estimated that the zero degree term contributes about 10% to the total deformation and so its inclusion will not affect the general conclusions that can be drawn from the results presented in Section 4.2. The set of load Love numbers published by Dahlen (1976) includes a zero degree term for completeness.

Terms of degree 1 were omitted from earlier sets of the load Love numbers because their inclusion implied a shift of the geocenter in space. Dahlen (1971) realized this was incorrect for the surface loading problem and noted that the earth responded to a $P_1$ load in two ways. Firstly, there is a displacement of the earth's surface in space and secondly, the earth is deformed. The displacement of the solid parts of the earth in space follows directly from the equations of motion, which show that the position of the
center of mass of the earth plus load is not changed. As the load is redistributed, the solid earth moves to keep the whole system in equilibrium. For all intents and purposes, the magnitude of the shift of the geocenter in space will be the same irrespective of whether the earth is rigid or elastic. Dahlen (1976) assumes this shift has already taken place and computes the load Love numbers accordingly. This approach gives deformation and gravity perturbations relative to the position of the earth's surface after the load is redistributed but before any deformation has taken place.

4. RESULTS

4.1 Geoid Height Changes Due to Plate Tectonic Mass Transfer

The mathematical formulation used to obtain these results is documented in Mather et al. (1979). Changes in geoid height, in millimeters per century (mm cy⁻¹), are shown in Figure 2 for features up to and including degree 12. These results are extracts from the global solutions published previously by Mather and Lardén (1978). It is evident, from the results based on Models 1 and 2, that plate tectonic activity should not be a significant contributor to changes in the shape of the North American geoid; the maximum rate of change in geoid height is less than 5 mm cy⁻¹.

Surprisingly enough, this conclusion almost holds for Model 3 as well. As Figure 2(c) shows, the regions most affected are Alaska, northern Canada, south-western Canada and Mexico. The increase in geoid heights throughout Alaska and northern Canada is a consequence of the mass accumulating at the Aleutian trench just south of Alaska. The maximum change actually occurs on the western coast of Alaska and is approximately equal to 75 mm over one century. This is equivalent to the accumulated random error in height over a 3000 km levelling run which has been surveyed twice, but is much less than the accuracy which has been achieved so far over such long distances. In the mid-northern regions of Canada the rate tends to zero.

To the south a geoid low, extending along the East Pacific rise, predominates. A maximum occurs at the Cocos-Nazca-Pacific triple junction where the geoid height decreases at a rate of 150 mm cy⁻¹. The rates across Mexico are smaller by about a factor of 3. The only other noticeable change is seen in south-western Canada where the geoid height decreases at a rate of about 25 mm cy⁻¹. This is a direct consequence of the dispersion of mass
from the small spreading zone located just off the coast of south-western Canada on the eastern margin of the Pacific plate.

4.2 Radial Surface Deformations Over North America Due to Atmospheric and Groundwater Loading

Seasonal departures in radial position, in millimeters, are shown in Figure 3 for the months of January, April, July and October. These results were obtained using the mathematical formulation given in Stolz and Larden (1979). The truncation limit for the outer zones was set at 90° for the integrations. The effects of air-mass and groundwater were computed separately and then algebraically combined.

The most striking aspect of these maps is the dominant cell situated near the Hudson Bay region where the peak-to-peak annual variation in radial position is almost 1.5 cm. Annual variations of 1 cm peak-to-peak amplitude are also evident between latitudes 45°N and 70°N and longitudes 240°E and 290°E. The departure which occurs in April is a result of the continued buildup of snow and moisture and the higher pressures experienced over the North American continent around winter and springtime. By July, the loading process has reversed; the snow has melted and the pressures have dropped.

A previous study by Urmantsev (1971) on the effects of seasonal atmospheric loading over a 2000 km levelling run in the U.S.S.R. indicated that radial deformations due to air-mass variations alone could be as large as 3.6 cm. Stolz and Larden (1979), however, believe this value is too large by about a factor of 2 and suggest that Urmantsev's choice of sea-level pressures and severe truncation limit is responsible for the discrepancy. In this work, surface pressures are used together with a more realistic truncation limit. Errors arising from the latter are estimated to be no greater than 15% for the North American continent.

4.3 Geocenter Motion

The term geocenter, as mentioned previously, refers in this paper to the center of mass of the solid earth and core. Mass transfer outside the earth's surface causes the geocenter, along with the solid earth, to shift in space whereas mass transfer inside the earth moves the geocenter relative to the earth's surface. The shift of the geocenter in space which accompanies the seasonal redistribution of groundwater and air-mass has been calculated and
shown to be small (Stolz 1976, Stolz and Larden 1979). The combined variation expressed in Cartesian form is

\[ \Delta x = 0.7 \cos \theta + 0.7 \sin \theta \text{ mm} \]
\[ \Delta y = 0.9 \cos \theta + 1.1 \sin \theta \text{ mm} \]
\[ \Delta z = 0.9 \cos \theta + 2.6 \sin \theta \text{ mm} \]

where \( \Delta x, \Delta y, \Delta z \) represent the changes in the components of the geocenter with respect to the center of mass of the earth plus load, and \( \theta \) is the longitude of the sun measured from the beginning of the year. The motion is an elliptical oscillation with the major and minor axes being 5.8 and 1.4 mm, respectively.

The shift of the geocenter due to plate tectonic mass transfer was calculated by carrying out a spherical harmonic analysis of the global changes in geoid height published by Mather and Larden (1978). Expressing these changes as

\[ \delta N(\phi, \lambda) = \gamma^{-1} \sum_{n=0}^{\infty} \sum_{m=0}^{n} P_{nm}(\sin \phi)(a_{nm} \cos m\lambda + b_{nm} \sin m\lambda) \]  \( (1) \)

one can determine the shift of the geocenter with respect to the earth's surface from an expression of the form

\[ \begin{bmatrix} \delta x \\ \delta y \\ \delta z \end{bmatrix} = R^2 (kM)^{-1} \begin{bmatrix} a_{11} \\ b_{11} \\ a_{10} \end{bmatrix} \]  \( (2) \)

where \( \delta x, \delta y, \delta z \) are the components of geocenter motion; \( \phi \) and \( \lambda \) specify the latitude and east longitude of the value for \( \delta N \); \( a_{11}, b_{11} \) and \( a_{10} \) are the conventional first degree terms of the spherical harmonic representation for \( \delta N \); \( R, M \) and \( k \) are the radius and mass of the earth and the gravitational constant, respectively; \( \gamma \) is the value for normal gravity; and \( P_{nm}(\sin \phi) \) is the associated Legendre function.

Values of \( \delta x, \delta y, \delta z \) and their spherical coordinate equivalents are listed in Table 2. The general motion is towards south-east Asia where Models 1, 2 and 3 predict mass accumulation to occur. Seismological evidence confirms that this area of the globe is very active (Leaokie and Molnar 1969).
5. SUMMARY REMARKS

An attempt has been made to estimate the effects of both global plate tectonic activity and seasonal atmospheric-groundwater loading on the geodetic levelling network of North America. Three plate tectonic mass transfer models were considered and the theory of Mather et al. (1979) was applied to determine the order of magnitude of changes in the shape of the geoid and the position of the geocenter with respect to the earth's surface. The results clearly indicate that, unless large-scale mechanisms similar to Model 3 or perhaps the sub-lithospheric flow scheme suggested by Garfunkel (1975) are operating globally, plate tectonic mass transfer will not distort the shape of the geoid or move the geocenter to the extent of detectability within a few years by dynamic satellite methods or by levelling and gravity measurements. Geometric satellite techniques are insensitive to such movements.

Alternatively, the radial surface deformations caused by the combined seasonal variation in atmospheric pressure and groundwater are significant at the 1.5 cm level for the North American continent. All measurement techniques can detect deformation and so steps, along the lines of those outlined in Mather et al. (1979), must be taken to make the appropriate corrections for these effects if the need arises. While seasonal effects can be substantially reduced if the re-observing program is carried out during the same season, this strategy is not always practical. It is important to remember also that the results presented here are based on average seasonal values for air pressure and groundwater and that year-to-year fluctuations in these quantities cannot be dismissed (Lambeck 1980). The shift of the geocenter in space due to atmospheric-groundwater loading is indeed small and well below the detection level of future dynamic satellite and gravimetric measuring techniques.

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-163-
### TABLE 1

**MODELS FOR PLATE TECTONIC MASS TRANSFER**

<table>
<thead>
<tr>
<th>Model Reference</th>
<th>Continent $T^*$ (km)</th>
<th>Continent $\rho^{**}$ (g cm$^{-3}$)</th>
<th>Ocean $T^*$ (km)</th>
<th>Ocean $\rho^{**}$ (g cm$^{-3}$)</th>
<th>Mass Accumulation and Displacement Zones</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>--</td>
<td>---</td>
<td>100</td>
<td>0.1$^+$</td>
<td>7</td>
</tr>
<tr>
<td>2</td>
<td>35</td>
<td>2.7</td>
<td>100</td>
<td>0.1$^+$</td>
<td>1,3,7</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>3.1</td>
<td>80</td>
<td>3.1</td>
<td>1,2,3,4,5,6</td>
</tr>
</tbody>
</table>

* $T^*$ = Slab Thickness  
** $\rho^{**}$ = Density of Slab Material  
$^+$ Only the density difference of 0.1 g cm$^{-3}$ between the lithosphere and the asthenosphere was used for calculating the mass accumulation rate in zone 7.

### TABLE 2

**GEOCENTER MOTION**

<table>
<thead>
<tr>
<th>Model Reference</th>
<th>$\delta x$ (mm cy$^{-1}$)</th>
<th>$\delta y$ (mm cy$^{-1}$)</th>
<th>$\delta z$ (mm cy$^{-1}$)</th>
<th>$\delta r (\phi, \lambda)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-2</td>
<td>2</td>
<td>2</td>
<td>3.5 (35, 135)</td>
</tr>
<tr>
<td>2</td>
<td>-1</td>
<td>4</td>
<td>2</td>
<td>4.6 (26, 104)</td>
</tr>
<tr>
<td>3</td>
<td>-44</td>
<td>64</td>
<td>37</td>
<td>86.0 (25, 125)</td>
</tr>
</tbody>
</table>

-164-
Figure 1. Mass transfer zones and density profile for (a) colliding continental margins and (b) subduction zones.
Figure 2. Changes in geoid height, in mm cy\(^{-1}\), due to plate tectonic mass transfer for (a) Model 1, (b) Model 2, and (c) Model 3.
Figure 3. Departures in radial position due to atmospheric and groundwater loading for (a) January, (b) April, (c) July, and (d) October.