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# ESTIMATION OF CRUSTAL VERTICAL MOVEMENTS DUE TO ATMOSPHERIC LOADING EFFECTS BY GPS OBSERVATIONS

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**ABSTRACT.** The objective of this paper is the estimation of vertical movements of the Earth's crust using data of 45 GPS permanent stations network situated in Europe and North of Asia (Siberia). First, daily positions are calculated with the GAMIT processing GPS data software, developed in the Massachusetts Institute of Technology, for a period of approximately 500 days (November and December 2000, the entire year of 2001 and January and February of 2002). Each daily solution is stabilized in a reference frame with the implication of a similitude transformation in the GLOBK software, also developed in the MIT, with the Kalman filter. The crust deforms vertically due to different phenomena (earthquakes, landslides...). We focused in this project the effects caused by the atmospheric loading, it means the effects of the weight of the air's column which surrounds the GPS stations. This loading is calculated for a $2.5° \times 2.5°$ resolution grid, with meteorological data provided of ECMWF (European Centre for Medium-range Weather Forecasts). The amplitude of these loadings is in the order of few millimetres up to 3 centimetres (Schuh et al., 2003). Finally we compare the vertical GPS permanent stations positions with the vertical movements of the Earth's crust due to atmospheric loading. We observed for some sites in Siberia a predominant effect during winter in the vertical component. For example, for IRKT station (Irkust, Russia) the correlation value for the year of 2001 is 0.61.

**Keywords**: atmospheric loading, Global Positioning System, vertical movements.

**RESUMO.** Este estudo tem por objetivo determinar o movimento vertical da crosta terrestre a partir de observações de uma rede de 45 estações GPS permanentes situadas na Europa e ao norte da Ásia (Sibéria). Em uma primeira etapa, as posições diárias são calculadas com o software de tratamento de dados GPS GAMIT, desenvolvido no MIT (Massachusetts Institute of Technology), para um período de aproximadamente 500 dias (de novembro de 2000 até fevereiro de 2002). Cada solução diária é então estabilizada num referencial através do emprego de uma transformação espacial, etapa realizada através de filtro de Kalman com software GLOBK, desenvolvido também no MIT. O desvio padrão médio obtido para as posições verticais para o ano de 2001 é de sete mm. O solo se deforma verticalmente devido à ação de diversos fenômenos (terremotos, deslizamentos, entre outros). Neste trabalho interessa-se particularmente aos efeitos causados pela atmosfera, ou seja, os efeitos do peso da coluna de ar que rodeia uma região que engloba estações GPS. Essa carga atmosférica é calculada em uma malha de resolução de 2.5° a partir de dados meteorológicos mundiais (ECMWF, European Centre for Medium-range Weather Forecasts). A amplitude dessas cargas é da ordem de alguns milímetros a três centímetros (Schuh et al., 2003). Finalmente comparam-se as posições verticais das estações GPS (séries temporais) com o movimento vertical da crosta terrestre devido aos efeitos das cargas atmosféricas. Foi observado, para certas estações da Sibéria, um efeito predominante no inverno nas componentes verticais. Por exemplo, para a estação IRKT (Irkust, Rússia), o valor de correlação é 0.61 para o ano de 2001.

**Palavras-chave**: carga atmosférica, GPS, movimentos verticais.

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## INTRODUCTION

The Earth is an elastic body, whose crust is in a constant movement, and this displacement is both in vertical and in horizontal directions. Here we focus mainly on the vertical displacement. There are many kinds of phenomena that can be the cause of such vertical displacement: atmospheric pressure, oceanic, water storage, snow coverage and soil humidity loading. The redistribution of ocean, atmospheric and hydrological masses may cause vertical displacements up to 20 mm at mid-latitudes, and larger effects at higher latitudes (Manabe et al., 1991). In this project, we focus only on the displacement due to atmospheric loading.

Atmospheric pressure loading is the vertical displacement of the Earth's crust due to variations in atmospheric pressure. It can be modelled by mathematical functions based on global surface pressure data. These vertical displacements can amount up to centimetre order, principally at continental mid-latitude stations.

The space geodetic techniques, such as GPS (Global Positioning System), evolved into the monitoring of permanent stations, making it possible to determine a position with millimetre precision. These observations, carried out in a continuous way, allow detecting low deformations of the Earth's crust. Knowing the vertical component of the global deformation of the crust, for example the one induced by atmospheric loading, is fundamental for the precise determination of the vertical movements as general.

Several studies trying to detect pressure loading signals in height estimates have been performed during the last ten years: Van Dam & Herring (1994), Mac Millan & Gipson (1994), Haas et al. (1997), Scherneck (2000), Van Dam et al. (2001) and Petrov & Boy (2004).

In this project, we choose to work with a distributed network processing strategy that includes 45 stations (Figure 1) in Europe and Northern Asia, particularly in Siberia. The network includes stations from IGS (International Global Navigation Satellite System Service) and REGAL (REseau Gps permanent dans les ALpes) networks.

## ATMOSPHERIC LOADING

The vertical displacement of a site is produced by the pressure deformation of the surface surrounding the site. The atmosphere constitutes one of the mainly perturbations sources that causes surface's displacement. These deformations can be computed and modelled by mathematical functions.

Pressure loading effects are larger at higher latitudes due to intensive weather systems presented. At mid-latitudes, as at locations near to the sea or ocean, the effects are smaller, due to the inverted barometer response of the ocean (Van Dam et al., 2001).

Figure 2 shows the deviation of the vertical displacement due to atmospheric pressure. The method used convolves the ground pressure data with Farrell's Green's functions (Farrell, 1972) and models the ocean's response as an inverted barometer. Although for island and coastal stations the RMS (root mean square) of GPS heights can be very large, these values are probably not due to atmospheric pressure loading, but due to ocean loading effects. We observe maximum displacements up to 3–4 mm, in central Asia, China, Arabia, India, Australia, Greenland, Antarctica and Alaska (Schuh et al., 2003).

The atmospheric pressure loading is calculated by Jean Paul Boy (Petrov & Boy, 2004) using ECMWF (European Centre of Medium-range Weather Forecasts) pressure data. The surface pressure is convolved using Green's functions to generate the deformation at each node of a $2.5° \times 2.5°$ grid. The Green's function represents surface displacements corresponding to the potential induced by the atmospheric loading which acts in a point whose coordinates (latitude and longitude) are known.

The details of the technique used to model the pressure loading effects by convolving the atmosphere data with the Green's function are well described in Petrov & Boy (2004).

### Estimating crustal vertical movements with GPS

Atmospheric pressure and other kinds of loading (hydrological, snow coverage, soil humidity, etc.) are known to generate noise in GPS vertical time series. This means that GPS technique is powerful for determining vertical displacements of the solid Earth. For all these different kinds of loading signals, the vertical displacements are 3 to 10 times larger than the horizontal ones. Therefore when interpreting geodetic data, it is necessary to evaluate the effects of these loadings.

The observations collected by GPS technique allow the study the Earth's dynamics in a global scale. In many regions of the world, GPS permanent networks were established to monitoring the crust's deformations in a local scale.

The GPS data, including REGAL and IGS networks, were processed using GAMIT/GLOBK that is an analysis software package developed at MIT (Massachusetts Institute of Technology), for the estimation of three-dimensional relative positions of ground stations and satellite orbits.

First, GPS station coordinates for each day of data are processed into loosely constrained solutions with GAMIT. That means that neither the coordinates of the tracking sites nor the GPS satellites orbits are tightly constrained. Although baseline lengths

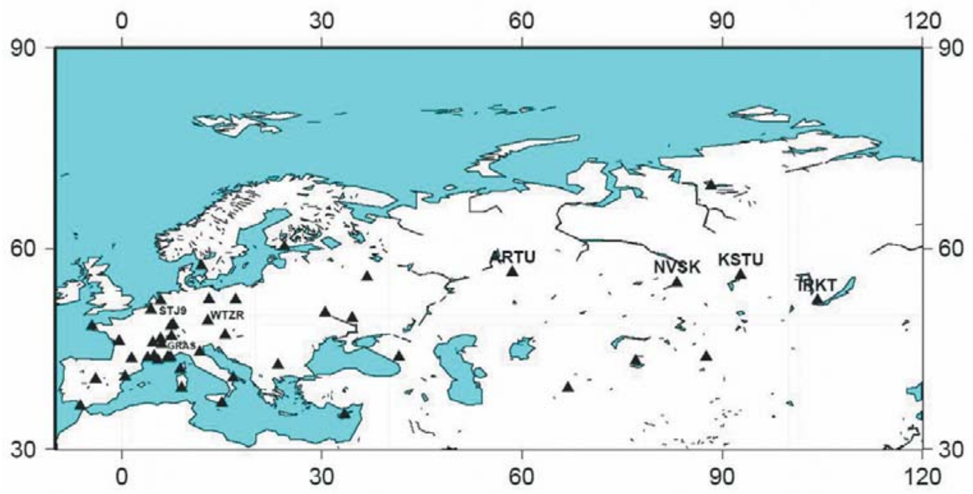

**Figure 1** – 45 GPS stations network (Europe and Asia).

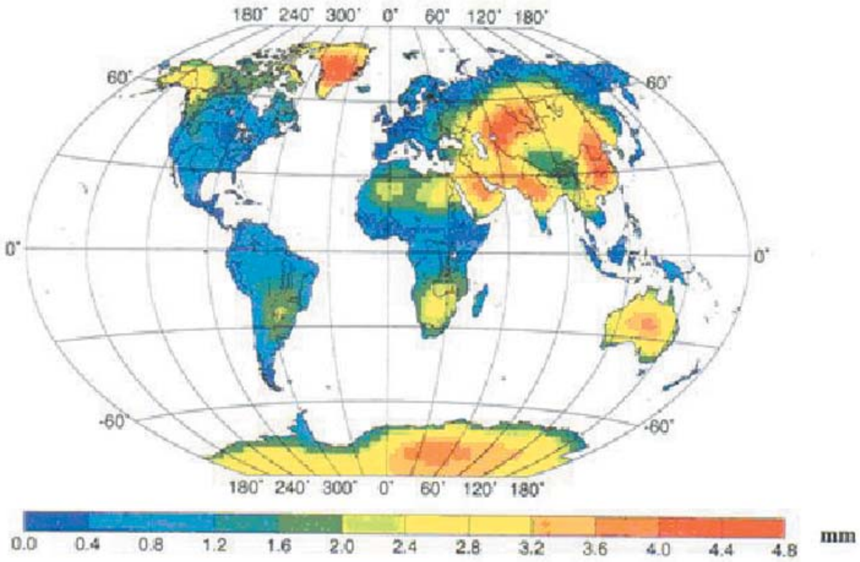

**Figure 2** – Annual amplitude map (mm) of vertical crustal deformation due to atmospheric pressure for 2001 (data from National Centre for Environmental Prediction – USA, Mangiarotti et al., 2001).

are determined very precisely in the loosely constrained solutions, the entire GPS network and GPS constellation can be rotated and translated as a rigid body.

The strategy, already studied as the best choice for the calculus (Bertrand, 2003), includes an elevation cut-off angle of 15 degrees, sessions of 24 and 6 hours and one tropospheric zenith delay parameter every 2 hours.

After all the loosely constrained solution are transformed into a consistent reference frame (ITRF2000, which became the official IGS reference frame from beginning on GPS week 1253 – 01/11/2004) so that we can derive rates of deformation from the time series of the station's coordinates. The reference frame defines the origin, scale and orientation of our geodetic coordinates.

To validate our solutions, they were compared to another two existing solutions for the common stations. Comparing our solutions to REGAL's solutions, for example, we found differences in the order of few millimetres. For the common stations, the mean difference for the north component was –0.06 mm

($\Delta\sigma = 0.02$ mm), for the vertical component 0.06 mm ($\Delta\sigma = 0.09$ mm) and for the east component –0.01 mm ($\Delta\sigma = 0.03$ mm). These differences are low and are due to different strategies of data processing.

## CORRELATION BETWEEN GPS VERTICAL SOLUTIONS AND THE MODELLED ATMOSPHERE

For the studied sites in Siberia (IRKT, KSTU, NVSK, ARTU, NRIL), a strong correlation between coordinate repeatability (EOST solution) and atmospheric loading (Figures 3 and 4) is observed. This correlation could be explained by the local high pressure environment in winter mainly. It is noticed in Figure 4 that the addition of other influences, like snow and soil humidity loading raises the correlation with the coordinate repeatability.

For coastal and island sites, because of a strong contribution of the oceanic loading and the weak variation of the atmospheric pressure, the visual correlation is very poor. In these sites, the variance of the atmospheric loading effect is too small compared to the variance of the ocean loading effect, to have a significant impact on the time series of the GPS vertical position observations.

We can make an analysis more detailed of the results of correlation, classifying the station by latitude and region (Table 1). We conclude that time series for stations in Siberia have high correlation with the atmospheric model, as the stations in high latitudes (above 50°). The correlation values for coastal stations are weak; it can be explained by other loading effects that are present is this regions, as oceanic loading. In continental stations there are various factors that can be disturbing, as snow covering and soil moisture.

**Table 1** – Station classification and mean correlation for each group.

| Site classification | Number of stations | Mean correlation |
|---|---|---|
| Coastal | 15 | 0,26 |
| Continental | 25 | 0,28 |
| Continental (latitude $> 50°$) | 11 | 0,46 |
| Siberia | 5 | 0,55 |

For the year of 2001, we observe that 25% of the stations have a correlation coefficient with the atmospheric loading model over 0.35. The highest values of correlation appear in the northern latitudes, especially in Siberia.

## CONCLUSIONS

The redistribution of ocean, atmospheric and hydrological masses may cause vertical displacements up to 20 mm in mid-latitudes, and larger effects at higher latitudes (Manabe et al., 1991). For this study, we focus on the displacements due to atmospheric loading, which is the vertical displacement of the Earth's crust due to variations in atmospheric pressure. It can be modelled by mathematical functions (Farrel, 1972) based on global surface pressure data. These vertical displacements can amount up to centimetre order, mainly in continental, mid-latitude stations.

Our purpose is to estimate the vertical movements of the Earth's crust with GPS observations and to link it to atmospheric loading. We select GPS data for a period of 16 months, from November 2000 to February 2002. The network processed, a total of 45 stations, include stations in Europe and Northern Asia (particularly Siberia), from REGAL and from IGS.

The atmospheric loading effects were modelled by a point approach in which a 2.5° × 2.5° grid resolution surface, convolved with Green's functions. The meteorological data is provided by the ECMWF (European Centre of Medium-range Weather Forecasts), available for a 6-hour temporal sampling and includes pressure, temperature and humidity data. For the year of 2001 we observe, for whole Earth, a maximum displacement of approximately 4 mm due to atmospheric loading, in continental Northern European sites.

GPS signals propagation is induced by atmosphere and its dynamic processes. We can see that analysing the correlation between GPS coordinate time series and atmospheric loading modelling. The vertical component is the most affected by the changing conditions of the atmosphere. The changing temperature between seasons during the year influencing the humidity of the atmosphere may induce strong annual and seasonal variations in the troposphere's delay and thus a strong anomaly in GPS solutions.

The GPS data was processed with GAMIT/GLOBK software, with a defined strategy of processing. The loose constrained solutions obtained with GAMIT were used as input pseudo-observations to GLOBK and stabilized in a reference frame defined by some IGS stations in the ITRF2000. The final mean RMS obtained for the GLOBK calculated positions for the year 2001 for all the 45 stations was approximately 7 mm.

The GPS permanent networks allow reaching a sufficient temporal resolution to detect transitory geophysics signals. The results demonstrate that global continuous GPS observations are able, in some regions better than in another, to detect seasonal signals, for example for the atmospheric loading. The larger correlation coefficients appear mainly in the high latitude northern hemisphere above 45°.

The quantification of the level of correlation between GPS

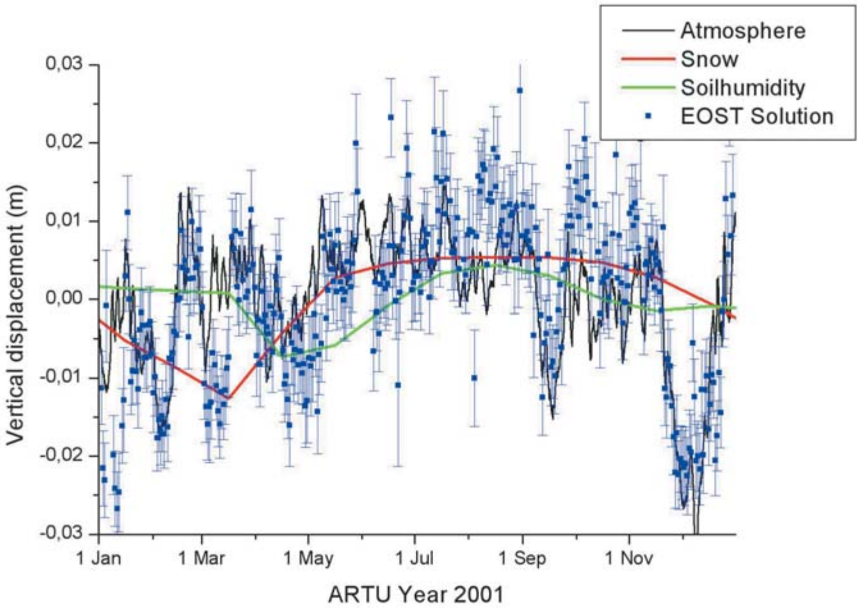

**Figure 3** – ARTU GPS vertical position and vertical loading for atmosphere, snow and soil humidity.

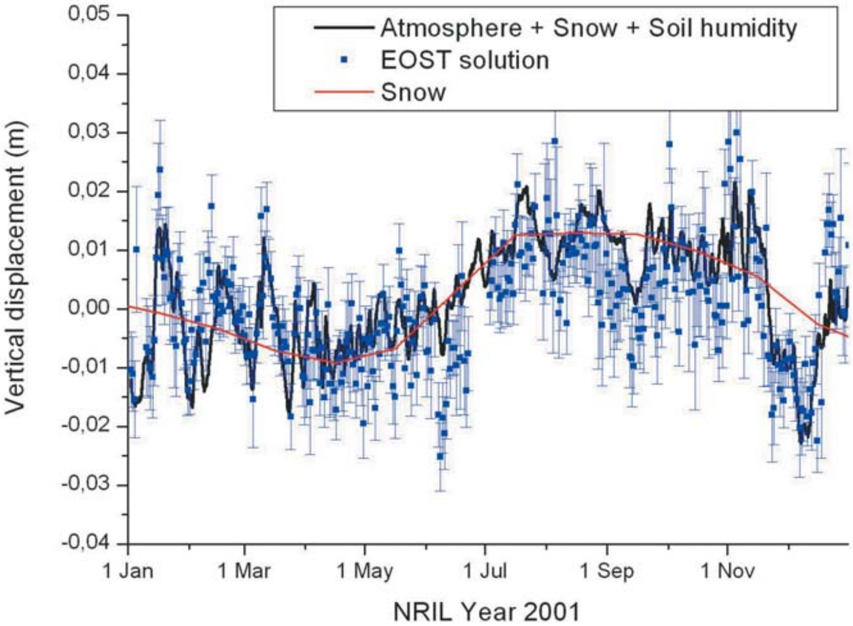

**Figure 4** – NRIL GPS vertical position and addition of vertical loading (atmosphere, snow and soil humidity) and snow.

vertical positions and the atmospheric loading modelling was calculated by the correlation coefficient for the entire network. The minimum value for correlation encountered for the year of 2001 was for an European continental station CHRN (Château Renard, France), 0.06, and the maximum coefficient was for a Siberian station, ARTU (Arti, Russia), 0.65.

It was observed for some continental sites a high correlation between vertical GPS position and atmosphere loading model. The higher correlation values result for stations at high northern latitudes which are exposed to large pressure variations and to a dry atmosphere for some period of the year. The analysis of the processed stations in Siberia (IRKT, NVSK, ARTU and KSTU) shows that in this region, the behaviour of the atmosphere explains the majority of the vertical movements of the GPS stations. In winter, due to the very low temperatures, the air humidity is low.

For the coastal sites, correlation is very weak because of other kinds of influences. The atmospheric loading effects in these regions are too small, particularly compared to the effect of the ocean loading, to have a significant impact on the vertical GPS position.

Some stations situated in the south of our network that have a poor correlation with the modelled atmospheric pressure loading perhaps because of: few available data in the processing period, poor data quality or local pressure variations are smaller when compared to higher latitude sites.

Some sites a very high correlation value between the GPS vertical position time series and the atmospheric loading model, like the site Irkust in Russia. For this site, for the year of 2001, the correlation value for the vertical position was 0.61. For another example, for a site called MARS (Marseille, France), which is a coastal site, the correlation value for the same period, was 0.16. For continental sites, as for example STJ9 (Strasbourg, France), also for the same period, this value reaches 0.23.

Therefore, according to the results of this study, it is important to introduce corrections related to vertical displacements due to atmospheric loading for high precision GPS network processing. Also, a suggestion for further studies is to model ocean loading and have a better insight for coastal stations.

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