ESTIMATION OF ATMOSPHERIC LOADING EFFECTS ON SITE DISPLACEMENTS OF GPS-STATION SOFI

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Abstract. It is performed an analysis focusing on the detection, estimation, separation and elimination of site offsets of permanent GPS-tracking station SOFI excited by atmospheric loading mainly. The seasonal atmospheric responses – total and degree-one spherical harmonic, of an elastic Earth's deformation in cases of different data-meteorological and Earth's mass centers are estimated. Here are analyzed the interactions of different atmospheric components with atmospheric rigid Earth's translation and degree-one deformations and determined the role of periodic and local environmental (pressure and temperature) factors. It is proposed the hybrid models to regress vertical site's variation field and the consistent with the frame treatment of the disturbing local atmospheric signals. The removing of these signals is being suggested to be done by inclusion of model predictions on the observation level in the analysis of GPS-observation or by correction of the time series after the analysis. The estimated degree-one deformations are being proposed for reduction of geometrically defined frames and time series to inertial origin. It is established for the first time for station SOFI the regression dependences between vertical site displacement and local pressure in case of different meteorological and Earth's mass centers, the serious temperature periodic offsets in the North-South direction of station monument and the generating of 43% on vertical GPS-rate by the vertical atmospheric signal.

Key words: displacement, atmospheric loading, time series, degree-one deformation, Earth's mass center

Introduction

The Earth's crust deformation is being caused by processes inside the Earth, by gravitational forces of external celestial bodies, by changes of the centrifugal potential, and by various mass loads.

The Earth's surface is perpetually being displaced in vertical and in horizontal directions due to temporally varying atmospheric, precipitated, oceanic tidal, oceanic nontidal, cryospheric and continental aquatic mass surface loads. The separation of mass signals requires an a priori knowledge the nature of exciting geophysical processes. The global geophysical fluids generate the surface deformations, gravity signals and geocenter variations. These non-geodynamic signals are of substantial magnitude that they govern the scatters in geodetic observations. Loading effects caused by the redistribution of surficial fluids have been observed in high-precision geodetic data (van Dam and Wahr, 1987; van Dam and Herring, 1994; van Dam et al., 1994; Haas et al., 1997; van Dam et al., 2001). If these data have to be interpreted in terms of geodynamic processes (plate tectonics, post-glacial rebound, sea level rise, etc.), then it is becoming necessary to remove loading effects from the geodetic data. These consequences have to be establishing in reference frames relevant for direct comparison with existing geodetic observing techniques and reducing to inertial origin for comparison with other techniques.

High precision GPS-measurements are required for establishment of national basic/fundamental network, the monitoring of crustal deformation, and the determination of sea level changes. Knowing the vertical component of the deformation, for example the induced by atmospheric loading (AL), is fundamental for the precise determination of the vertical movements as general. Some of the GPS-error sources are based on the geophysical effects causing significant site displacements. Before interpretation of GPS-measured changes in station position it should be assessed the role of position changes due to loading phenomena. This is particularly important when the geodetic signal of interest is of the same order of magnitude as the amplitude of the loading signal itself. In this case erroneous conclusions may be drawn with regard to the causes of site variation.

Our purpose is to provide the consistent with respect to reference frame and reliable estimates of AL-effects and to obtain consistent time series of 3-D modeled displacements data set for permanent GPS-tracking station SOFI. Here is being sought

- to elucidate to what extend the site position variations of station SOFI are provoked from AL and periodic geophysical phenomena;
- to investigate a possible correlation of observed site position discrepancies with the regional and local distribution of atmospheric pressure;
- to correlate vertical station variations with available AL-models taking into account different meteorological and Earth’s mass centers, response periods (semiannual and annual) and local environmental factors.

Here we will outline the primary principles involved in modeling the surface displacements induced by AL-mass including the basic theory, the Earth model and the surface pressure load data. We will carry out a study which shows the effect of AL-fields from different meteorological centers on computed displacements of station SOFI with respect to different center of mass of the Earth. The specific analysis and synthesis of interaction of the different components of AL on the GPS-observations will be discussed. The corrections of site variation due to atmospheric signals will be determined using the geophysical and hybrid model approach. Finally, it will be outlined areas for future research to further improve the AL-estimates. We conclude by formulating some recommendations on the procedure for including loading corrections into GPS-data analyses.

Methods for determination of surface atmospheric loading

The accurate modeling of the deformation due to AL requires the knowledge of 1) mass density distribution in space and time; 2) global pressure-distribution in combination with a suitable local model; 3) reference surfaces/levels and datum of atmospheric pressure – meteorological model, geographic function, individual/local station meteorological parameters (the reference level and datum should be a space-dependent and computed from long period average).

Global atmospheric surface pressure data on site and adjacent area (1000–2000 *km*) forms simulation model to explore the nature of seasonal variations. This natural phenomenon is being caused as a site-effect from distant places simultaneously.

The consistent models of the deformation of the solid Earth due to AL are presently available (Rabbel and Zschau, 1985; Sun, 1995; van Dam et al, 2001). There exist three basic models for computing loading corrections to geodetic data: 1) *geophysical models* or simple approximations derived from these models where loading signals must be carried out in the time domain; 2) *empirical models* based on site-dependent data where regression coefficient can only be determined for vertical crustal motions; 3) *hybrid models* from upper two.

At present the *geophysical models* (Merriam, 1992; Sun, 1995; Boy et al., 1998; Neumeyer et al., 1998) are used most frequently for computing the load signals from global atmospheric data. In these models the main elements required in the computation of signal predictions include: 1) an Earth model, which determines the geometry, with specific mechanical properties and, if necessary, the rheology; 2) a mathematical model for the AL including the boundary conditions at the Earth's surface and the extension of the load. Selected parts of continuum mechanics (e.g. elastic theory, or linear viscoelasticity) can be used to solve the boundary value problem to obtain the system's response to a unit load. For the problem of Earth deformation, the system's response is best described by load Love numbers (LLNs) $\{h',l',k'\}$ which can be used to compute the Green's functions of the boundary problem. The geometric effects – deformation, of loading may be computed by convolving models containing the gridded surface mass distribution with a Green's function, describing the unit impulse response of the Earth as a function of load and response location (Farrell, 1972).

The *empirical models* (Rabbel et al., 1985; Neumeyer, 1995) are based on site-dependent data and use the local atmospheric pressure for determining the single and complex admittance based on regression and cross-spectral analysis by fitting local pressure variations to residual values of vertical crustal motions after elimination of Earth's tides, polar motion and other trends from the records of geodetic observations.

We will apply the *geophysical* and *hybrid models* in estimation of surface displacements of station SOFI due to AL with attendant specifying of reference frame. It will be done by a station-centered grid with fixed dimensions in order to correct time series of GPS-coordinates by removing seasonal noise.

Earth's models

The Earth model is being used to determine a loading Green's functions, which are weighed sums of LLNs and yields the Earth's response to a surface mass load. Typically an elastic Earth model with radial structure, such as Preliminary Reference (elastic) Earth Model (Dziewonski and Anderson, 1981) is used here, in which case the Green's function depends on load-response separation only. In our investigation we use thoroughly this model. The differences in the deformations determined for different Earth models – respective for corresponding sets of Green's functions and LLNs, are not significant values.

Used data

Meteorological data

The atmospheric pressure effect consists of the elastic deformation and attraction term. For our case the deformation term is modeled with global 2-D surface atmospheric pressure data. These data and daily temperature changes measured at the ground are inputs for our investigation. For modeling of the attraction term (it is not object for our investigation) 3-D pressure data are required. The response of the ocean to atmospheric forcing needs to be considered. Currently, only two simple models are used for describing the atmosphere-ocean interaction 1) no oceans; 2) inverted barometer (IB) ocean with corresponding land-ocean mask, which correction conserve total oceanic mass.

In our following analysis IB-approach (which reduces contribution of high-frequency atmospheric pressure variations to total load) is included in estimation of atmospheric signals - total, rigid translation and degree-one spherical harmonic response.

Here we use two global surface pressure data sets that are adopted by the International Earth Rotation Service (IERS) Special Bureau of Loading: 1) the data sets from European Centre for Medium-range Weather Forecasts (*ECMWF*) on a 2°,5 × 2°,5 resolution grid; 2) National Centers for Environmental Prediction (*NCEP*). The diurnal pressure and temperature in SOFI- station from National Institute of Meteorology and Hydrology (*NIMH*) of Bulgarian Academy of Sciences are the additional local data.

The applied *geophysical* and *hybrid models* are using local and global atmospheric pressure data measured at the Earth's surface and a standard height-dependent air density distribution. The frequency range of the ground atmospheric pressure changes varies from inverse minutes to years. The total range of the pressure at station SOFI during the processed periods (Jan. 01 1990 - Jan. 01 2006) is 48.8 *hPa*. The reference pressure value for SOFI was calculated by propagating the sea level pressure of 1013.25 *hPa* to the ellipsoidal station height and accounting for geoid undulation.

GPS-data for station SOFI

These data are based on the weekly solutions of site position obtained and obligingly left to us by Central Bureau of European Permanent Network (*EPN*) and covering the period from Jun 25 1997 to September 19 2007. The mean value of the particular component (North, East and vertical) is removed. The Earth plate movement and the region deformation which can produce systematic effects (errors) are eliminated in IERS-coordinates by appropriate methods. We interpret and model the observed site variations $\Delta\vec{s}_{EPN}^{GPS}$ as the sum of various environmental loadings, unmodeled wet troposphere effects, bedrock thermal expansion, errors in phase center variation models and errors in orbital modeling.

The coordinates of SOFI-station show movements within one or two weeks, especially in the East component. The amplitude of the vertical component is about 10-15 *mm*. Because of its high frequency the weekly solutions tend to smooth out the waves less than 10 weeks so that we are able to determine the waves with longer period.

Determination of site displacements due to atmospheric loading

AL-change causes site displacements, variations in the geocenter and translation of the origin of terrestrial reference frames located at the center of mass of the solid Earth (*CE*) or the center of mass of the total Earth system (*CM*). The predominantly seasonal redistribution of surface atmospheric masses affects the measuring GPS-sensor in the following way. The record changes due to displacement of the GPS-monument on the deformed Earth (elastic deformation / indirect effect).

The time series for local displacement vector $\Delta\vec{s}^{\,a}(\Omega)_{CM} \equiv \{\Delta s_h^a, \Delta s_e^a, \Delta s_n^a\}_{CM}$ due to AL (superscript *a*) are determined by *geophysical model* in *CM*-frame from beginning of 1990 to the 30 April 2004 for *NCEP*-operational pressure data sets and the IB ocean model (Fig. 1). Here Ω is geographical position and the triplet $(\vec{h}, \vec{e}, \vec{n})$ consists of unit vectors pointing locally upward, East and North. Similar displacement with respect to *CE*-frame is determined for the both atmospheric models too.

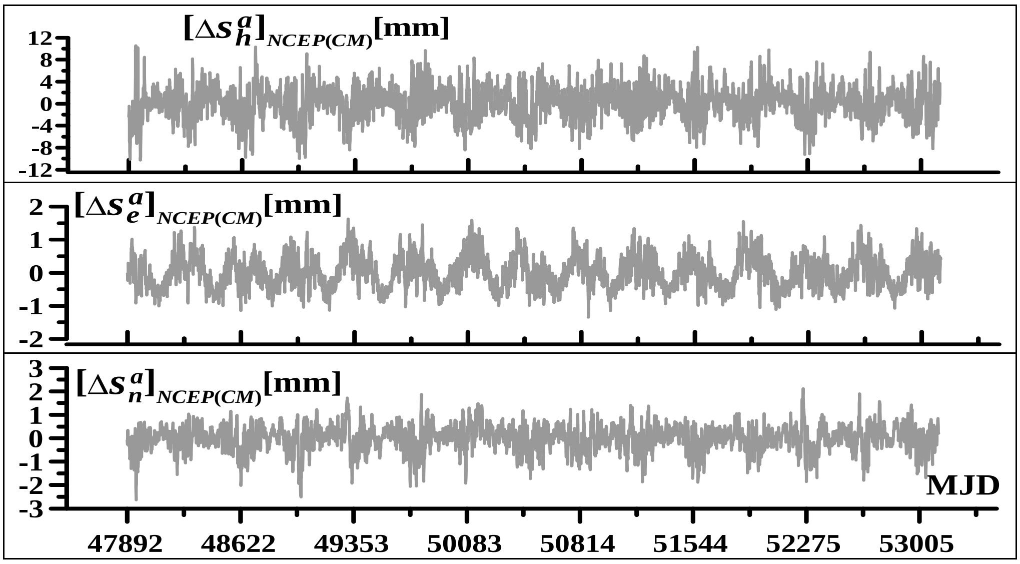

Fig.1. 3D daily surface displacements $\{\Delta s_h^a, \Delta s_e^a, \Delta s_n^a\}_{NCEP(CM)}$ of station SOFI due to atmospheric loading estimated by geophysical method by means of *NCEP*(*CM*)-model.

Dependence upon Earth's mass centers of $\Delta\vec{s}^{a}(\Omega)$

Recent crustal motion is being described as a vector displacement field, which depends on the deformation and the reference frame. In computing the load signals, the special attention must be given to the reference frame. One possibility is to provide the loading products in various frames' origins, for examples, *CM*, *CE*, and center of surface figure (*CF*). To a large extent, the frame selected depends on the degree-one LLNs chosen. Conversion of these LLNs to the appropriate frame can be done prior to the computation of deformations or the frame correction can be done at the end by applying condition equations on the gridded displacements. In any case, a clear specification of the reference frame needs to be attached to the model predictions.

Here will be illustrated the influence on $\Delta\vec{s}^{a}(\Omega)$ of Earth's centers by its manifestation on Δs_h^a which is four times greater than lateral displacements. We estimate the correlation ρ between Δs_h^a referred to *CE*- and *CM*-frame from the data of one and the same meteorological centers (two cases in Fig. 2 with ▲ and ○ symbols), from different atmospheric models (thinner lines) as well as to identical frame origins (thickest lines). It's seen there is not time delay between different values of Δs_h^a.

The correlation is greater in case of identical Earth's and different meteorological centers on account of identical isomorphic parameters α (Blewitt, 2003). These parameters depend on the conceptual definition of the reference frame origin, take part in calculation of degree-one displacement $\Delta\vec{s}^{1,a}(\Omega)$ and are the factors of proportionality in calculation of geocenter translations. These translations influence considerably on the values of Δs_h^a and have one and the same value for the different meteorological centers.

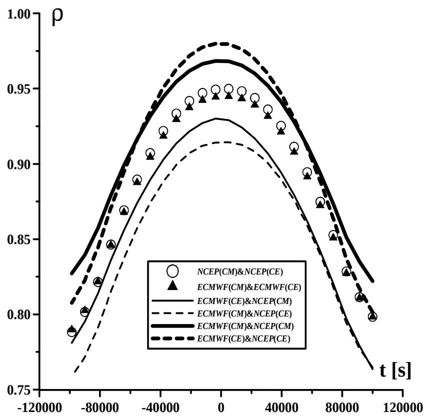

Fig. 2. Correlation ρ between predicted vertical displacements Δs_h^a due to pressure loading related to the different Earth's and meteorological centers.

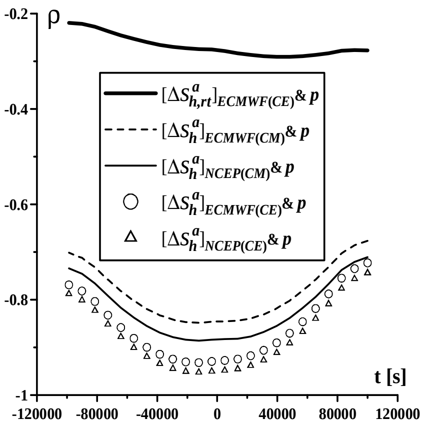

Fig. 3. Correlation ρ between predicted vertical displacements Δs_h^a and $\Delta s_{h,rt}^a$ due to atmospheric loading and local pressure *p* in case of different atmospheric models.

The correlation takes the intermediate place in case of identical atmospheric models and different frame origins. On the other hand the time series related to the different Earth's centers must not process in common nevertheless that the residuals after removing the AL-effect accept the smaller values. In case of different meteorological and Earth's centers the correlation is weaker.

Dependence upon atmospheric rigid translation of $\Delta\vec{s}^{\,a}(\Omega)$

In the terms of LLNs, the loading Earth suffers a rigid body translation in the following representation $h'_1 = l'_1 = -1$ while e.g. Farrell (1972) specifies $h'_1 = -0.290$ and $l'_1 = 0.113$ for the deformation. In different frames the displacement field does not look like a rigid body translation. The last is a special case of degree-one deformation so that the degree-one LLNs are different in different frames in the presence of their established transformed expressions between two systems (Blewitt, 2003).

The degree-one contributions depend on the choice of reference frame, specifically how the origin moves relative to the deforming Earth. The degree-one deformation field for a nonrigid Earth can be described as a combination of deformation field of rigid Earth and the deformational manifestation of a rigid translation (*rt*).

Computation of AL followed closely the method applied for ocean tidal loading. The major difference being that pressure loading occurs on land and that the inverse barometer assumption excludes waters with a depth greater than 300 *m* from being loaded. As a side-effect of the data preparation, the geocenter tide can be computed from atmospheric pressure as well as corresponding to it atmospheric rigid translation $\vec{rt}^{\,a}$ and deformation $\Delta\vec{s}^{\,a}_{rt,CE}(\Omega)$. At the same time deformations in *CM*- and *CE*-frames submit to the analogical expression like homonymous degree-one. This expression gives us a possibility to calculate $\Delta\vec{s}^{\,a}_{rt,CE}(\Omega)$ for different meteorological centers. Hence follow conclusion that anyone (in particular the atmospheric) degree-one deformation field in *CM*-frame can be described as a superposition of degree-one deformation field of rigid Earth plus *CE*-frame's deformation due to geocenter motion of rigid body.

Dependence upon local pressure of $\Delta\vec{s}^{\,a}(\Omega)$ *and* $\Delta\vec{s}^{\,GPS}_{EPN}$

The attempts to determine the vertical pressure loading regression coefficients as a new estimable parameter by GPS-software have not given results for SOFI-station until now. In order to establish the consistency between predicted deformation $\Delta\vec{s}^{\,a}(\Omega)$ and local pressure *p* we first calculated their correlation (Fig. 3.) for different atmospheric models and Earth's centers. The correlations of lateral displacements are insignificant so that the local pressure can not be used to derive the corresponding to them admittances. The *ECMWF*(*CE*)- and *NCEP*(*CE*)-atmospheric models provide the best fit with *p* so that their consistency make them convenient for deriving the Δs^a_h-admittances. In case of one and the same atmospheric models is being realized the stronger correlation in *CE*-frame in comparison with *CM*-frame. It is being observed the time delay from -14000 *s* for all these cases as Δs_h^a outdistance *p*. The deformation $\Delta\vec{s}_{rt}^{\,a}(\Omega)$ depends in a certain inconsiderable extent (ρ = –0.29) on *p* so that $\Delta\vec{s}_{rt}^{\,a}(\Omega)$ is being excited thoroughly from the regional and global AL. Here exists the time delay from +43000 *s* (≈12 hours) between *p* and $\Delta s_{h,rt}^{a}$.

By applying *hybrid model* (*hm*) and using predicted values instead of GPS-observations, we searched for regression coefficients. This approach can only be used for vertical crustal motions. The regression coefficients are determined by fitting *p* from the *NIMH*-data set to the convolution sum of the vertical deformation Δs_h^a predicted by the *geophysical model*. The IB or non-IB model was not used in determining the ocean's response to pressure because this response is neglected for station SOFI. The admittances [*mm*/*hPa*] determined in this manner (see Fig. 4) would still suffer from both the uncertainty in the Green's function and the quality of the local air pressure data.

These coefficients could be used to operationally correct observed vertical position determinations from local air pressure alone. Here we establish that the influence of *p* on predicted Δs_h^a depends on origin of reference frame only in which the deformations are modeled and does not depend on meteorological center. We determined two different admittances by means of that can calculate the predicted displacements

$$\left[\Delta s_h^a(SOFI)\right]_{CE}^{hm} = -0.47(p-947{,}3) \pm 2\,[mm];\ \left[\Delta s_h^a(SOFI)\right]_{CM}^{hm} = -0.55(p-947{,}3) \pm 2\,[mm]. \quad (1)$$

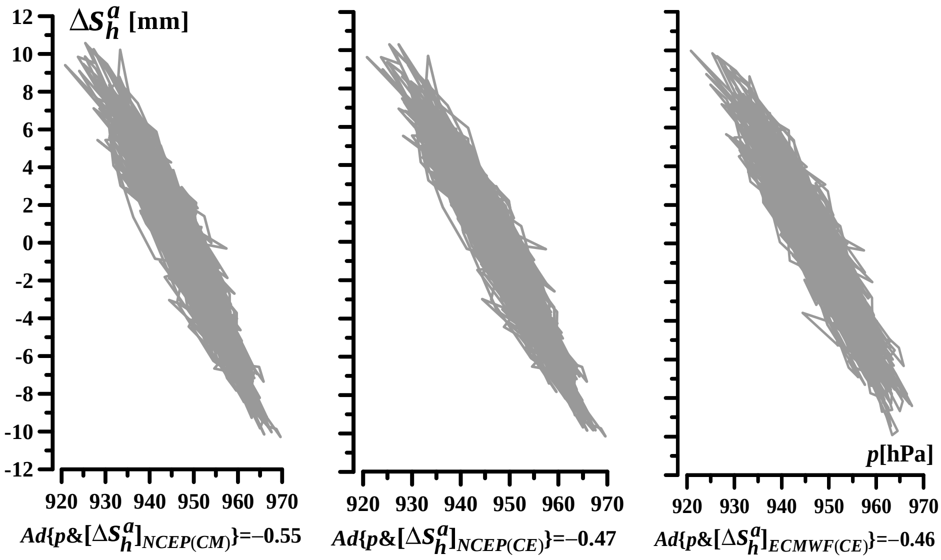

Fig. 4. Admittance (*Ad*) between local pressure *p* [*hPa*] and vertical displacements Δs_h^a [*mm*] due to atmospheric loading in case of different meteorological and Earth's centers.

Here for the first times were being derived these admittances for permanent GPS-tracking station SOFI as well as its reference pressure. It should be noticed that corresponding residuals $Res\left\{\Delta s_h^a - \Delta s_h^{1,a}\right\}$ after removing degree-one spherical harmonic atmospheric response can be predicted by means of formulas (1). Nevertheless the regression coefficients cannot be extrapolated to new site (for which no data exist). They within the precision limits can be used to correct only the GPS-observation (the different observing techniques give different regression coefficients for one and the same location) from Geodetic observatory "Plana", placed 5 *km* south of SOFI. This has to be done after preliminary analysis of both atmospheric pressure data.

The attempt (Kaniuth et al., 2003) to derive vertical pressure loading coefficients from GPS-observation was unsuccessful for this station. We estimate ρ=0.453 between $\Delta\vec{s}_{h,EPN}^{GPS}$ and local pressure and impossibility to derive admittance for them.

Statistics and periodicity of time series of SOFI-station

It is well known that the GPS-estimated height is the most sensible component to variations in the physical/environmental circumstances so that at least 90% of the time series inconsistencies are appearing in this vertical component.

Site-position time series generated from continuous GPS-observations reveal significant seasonal variations, in particular, with an annual period. Before fitting annual and semi-annual periodic signals to the GPS-data (and the predicted deformation as well), we estimated trends and correlations of Δs_h^a, $\Delta s_h^{1,a}$ and $\lfloor \Delta s_h^{GPS} \rfloor_{EPN}$ – displacement established by processing of GPS-observation from *EPN* (Table 1).

Table 1. Statistics of the vertical time series of SOFI-station

Items \ Statistic parameters	Linear trend / Rate		Multilinear least squares fits	
	Value [*mm/yr*]	ρ	ρ	Residual stand. dev. [*mm*]
$\lfloor \Delta s_h^{GPS} \rfloor_{EPN}$	-0.469	0.179		
			0.497	7.08
$\lfloor \Delta s_h^{a} \rfloor_{ECMWF(CE)}$	-0.193	0.182		
			0.910	2.69
$\lfloor \Delta s_h^{1,a} \rfloor_{ECMWF(CE)}$	-0.050	0.298		
			0.497	7.08
$\lfloor \Delta s_h^{GPS} \rfloor_{EPN}$	-0.469	0.179		
			0.586	6.98
$\lfloor \Delta s_h^{a} \rfloor_{NCEP(CE)}$	0.041	0.062		
			0.485	1.87
$\lfloor \Delta s_h^{1,a} \rfloor_{NCEP(CE)}$	0.001	0.007		
			0.587	6.97
$\lfloor \Delta s_h^{GPS} \rfloor_{EPN}$	-0.469	0.179		

The linear trend of $\lfloor \Delta s_h^a \rfloor_{NCEP(CE)}$ and $\lfloor \Delta s_h^a \rfloor_{NCEP(CM)}$ is insignificant. The values of lateral and vertical displacements due to degree-one spherical harmonic atmospheric response do not correspond with respective GPS-rates. It is realized the multilinear least squares fits between every two vertical time series and is estimated correlation of the fits. Here $\lfloor \Delta s_h^{1,a} \rfloor_{ECMWF(CE)}$ demonstrates the time delay (≈12 hours) according to $\lfloor \Delta s_h^a \rfloor_{ECMWF(CE)}$ whilst for the homonymous signals from *NCEP*(*CE*)-model there does not exist time delay.

The correlations between the estimated vertical coordinate variations of SOFI-station and AL-displacements are generally small (ρ≈0.50). The similar phenomenon between corresponding velocity and trend should be analyzed further.

Van Dam et al. (2001) showed that a major annual component is induced by hydrological and atmospheric loading. The annual signals can significantly bias the estimation of site velocities intended for high accuracy purposes such as plate tectonics and establishment of the reference frames. For such applications, annual and semiannual sinusoidal signals should be estimated. Now we will estimate periodicity (*per*) of the vertical components of SOFI time series by means of fitting annual and semiannual waves to them. There are calculated amplitudes and phases of these signals (Fig. 5). The site displacement, caused by surface pressure changes, is seen to have amplitude five less times than of annual $\lfloor \Delta s_h^{GPS} \rfloor^{per}$ and to be out-of-phase with it and residual phasor.

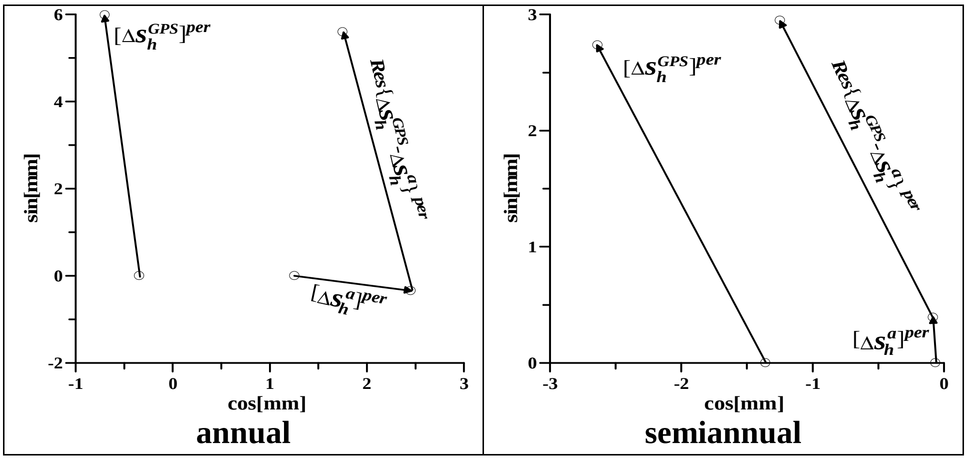

Fig. 5. Phasor diagrams of the annual and semiannual components of the periodic (*per*) effects on the GPS-height ingredient variation during 1997–2005, on the vertical atmospheric displacement and on the residual phasor $Res\{\Delta s_h^{GPS} - \Delta s_h^a\}^{per}$.

The left panel of Figure 5 shows a phasor diagram of the annual component of the GPS-height ingredient variation during 1997–2005, of the periodic effects of AL, as well as the annual component of residual phasor $Res\{\Delta s_h^{GPS} - \Delta s_h^a\}^{per}$. By removing atmospheric effects, the modeled periodic GPS-variation moves farther away from that observed. The discrepancy that remains between $\lfloor \Delta s_h^{GPS} \rfloor^{per}$ and phasor sum is 2.5 *mm* in amplitude and

8.4° in phase difference. For the semiannual components the atmospheric effect has amplitude 7.5 less times than of semiannual $\lfloor \Delta s_h^{GPS} \rfloor^{per}$ and to be approximately in-phase with it. Here the discrepancy in amplitudes is 1.4 *mm* and 3.3° in phase. The discrepancies that remain may also indicate that other processes are important in causing seasonal changes, but their effects are noncyclic mainly after removing sinuous waves.

Analysis of residuals

A better estimate of the spatial variation in surface mass at seasonal frequencies is given by partitioning the total load into individual effects. However, if the trends are removing from modeled surface load displacements this might be a problem for detecting some geodynamical phenomena. That is why our approach is to subtract the contributions of the well determined surface loadings and their degree-one spherical harmonic responses of the modeled sources from observation GPS-data. Since the atmospheric signal playing a dominant seasonal role, we shall analyze, after removing $\Delta\vec{s}^{\,a}(\Omega)$ and $\Delta\vec{s}^{\,1,a}(\Omega)$, the joint contribution of the residual geophysical sources to determine the parameters of some periodic signals. The periodic component of the surface load displacements we will analyze by fitting annual and semi-annual periodic signals to the residuals. The periodicity mostly appears in the height component.

We estimated the vertical atmospheric residual $Res\left\{\Delta s_h^a - \Delta s_h^{1,a}\right\}$ after removing degree-one spherical harmonic atmospheric response, the residual $Res\left\{\Delta s_h^{GPS} - \Delta s_h^a - \Delta s_h^{1,a}\right\}$ of vertical GPS-component after removing effect of AL, $Res\left\{\Delta s_h^{GPS} - \Delta s_h^a - \Delta s_h^{1,a} - sin_1\right\}$ – the previous residual with removing annual sinuous wave and $Res\left\{\Delta s_h^{GPS} - \Delta s_h^a - \Delta s_h^{1,a} - sin_1 - sin_{1/2}\right\}$ – the previous residual with removing semi-annual sinuous wave. The fitting parameters are given in Table 2 and their statistics in Table 3.

Table 2. Fitting of the waves $a(T)sin(2\pi t/T)+b(T)cos(2\pi t/T)$ to the residuals $Res\left\{\Delta s_h^{GPS} - \Delta s_h^a - \Delta s_h^{1,a}\right\}$ and $Res\left\{\Delta s_h^{GPS} - \Delta s_h^a - \Delta s_h^{1,a} - sin_1\right\}$ in case of *ECMWF*(*CE*)-model.

T / Parameters	1 year	6 months
$a(T)$ [mm]	5.9756	2.3497
b(T) [mm]	-0.7523	-0.9430
Amp. [mm]	6.0228	2.5319
Pha. [s]	8512613.9747	4899783.9532
ρ	0.590	0.315

The annual and semi-annual fit to the $\lfloor \Delta s_h^{GPS} \rfloor_{EPN}$ after removing effects of AL according to atmospheric model *NCEP*(*CE*) reduce us to the close values of parameters to these in Table 2 and Table 3.

Table 3. Statistic of the vertical signals for SOFI-station for *ECMWF*(*CE*)-atmospheric model

Items \ Statistic parameters	**Mean** [mm]	**Std. dev.** [mm]	**50%** level [mm]	**68%** level [mm]	**90%** level [mm]	**95%** level [mm]	**99.98%** level [mm]
$\left[\Delta s_h^a\right]_{ECMWF(CE)}$	33.84	2.34	1.60	2.40	3.80	4.70	6.40
$\left[\Delta s_h^{1,a}\right]_{ECMWF(CE)}$	8.02	0.42	0.30	0.40	0.70	0.80	1.60
$Res\left\{\Delta s_h^a - \Delta s_h^{1,a}\right\}$	0	1.96	1.20	1.80	3.30	4.10	6.15
$\left[\Delta s_h^{GPS}\right]_{EPN}$	-0.26	8.16	5.70	7.90	13.60	17.10	22.40
$Res\left\{\Delta s_h^{GPS} - \Delta s_h^a - \Delta s_h^{1,a}\right\}$	0	7.05	5.00	7.30	11.60	13.80	19.75
$Res\left\{\Delta s_h^{GPS} - \Delta s_h^a - \Delta s_h^{1,a} - sin_1\right\}$	0	5.65	3.60	5.40	9.20	11.20	18.15
$Res\left\{\Delta s_h^{GPS} - \Delta s_h^a - \Delta s_h^{1,a} - sin_1 - sin_{1/2}\right\}$	0	5.35	3.40	5.30	8.60	10.50	17.60

All vertical signals have not normal distribution as the most nearly to it is atmospheric degree-one spherical harmonic response $\Delta s_h^{1,a}$. There is not any sort of periodic ingredient in $Res\left\{\Delta s_h^a - \Delta s_h^{1,a}\right\}$ but in $Res\left\{\Delta s_h^{GPS} - \Delta s_h^a - \Delta s_h^{1,a}\right\}$ it is expressed clearly (Fig. 6). The aliased annual and semi-annual signals are visible in the residuals of vertical component of the GPS-time series with the amplitudes up to approximately 7.5 *mm*.

The joint contribution of the residual geophysical sources after removing effects of AL and periodic signals for vertical component $\left[\Delta s_h^{GPS}\right]_{EPN}$ and its probable explaining is shown on Fig. 7.

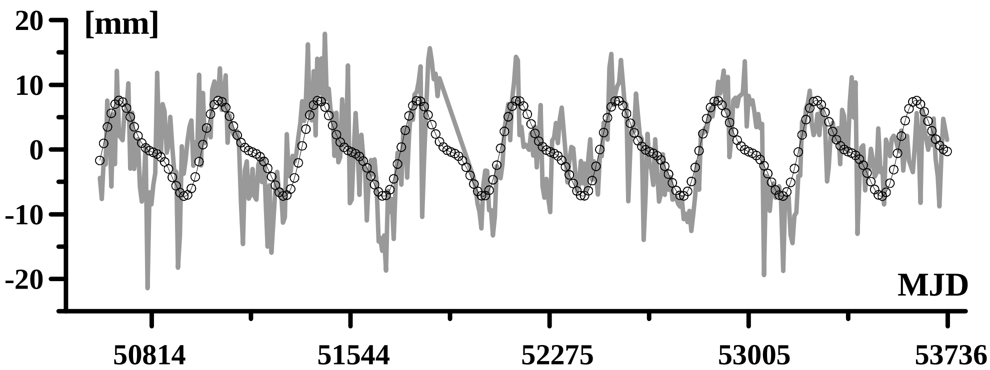

Fig. 6. Annual and semi-annual fit (open dots) to the residuals $Res\left\{\Delta s_h^{GPS} - \Delta s_h^a - \Delta s_h^{1,a}\right\}$ (light line) of vertical GPS-component after removing effect of atmospheric loading of *ECMWF*(*CE*)-model.

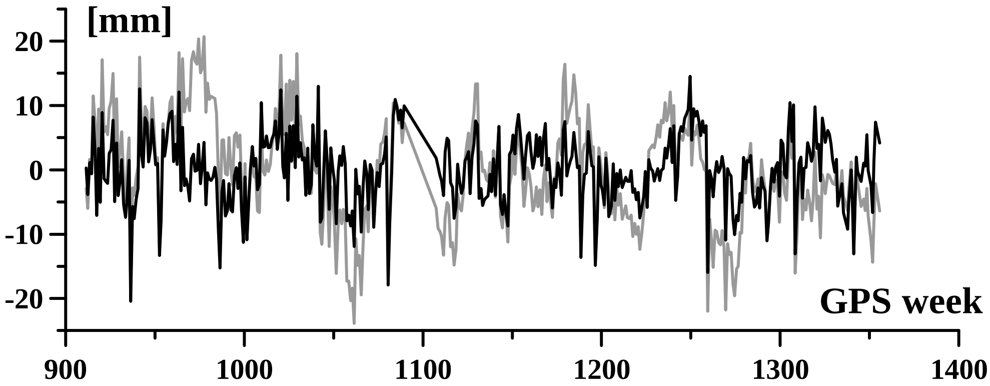

Fig. 7. ITRS time series for vertical component $\left[\Delta s_h^{GPS}\right]_{EPN}$ (light line) and its residuals $Res\left\{\Delta s_h^{GPS} - \Delta s_h^{a} - \Delta s_h^{1,a} - sin_1 - sin_{1/2}\right\}$ (dark line) after removing effects of atmospheric loading of *ECMWF*(*CE*)-model and periodic signals (annual and semi-annual). The residuals most likely due to other sources such as ocean and atmospheric tidal loading, continental water storage loading and contributions from unmodeled wet troposphere effects, bedrock and monument thermal expansion, errors in antenna phase center variation models and errors in orbital modeling.

The greatest part of power carried by vertical GPS-signal is being transferred by two frequencies basically (see Fig. 8) as well as the smaller powers by two other frequencies.

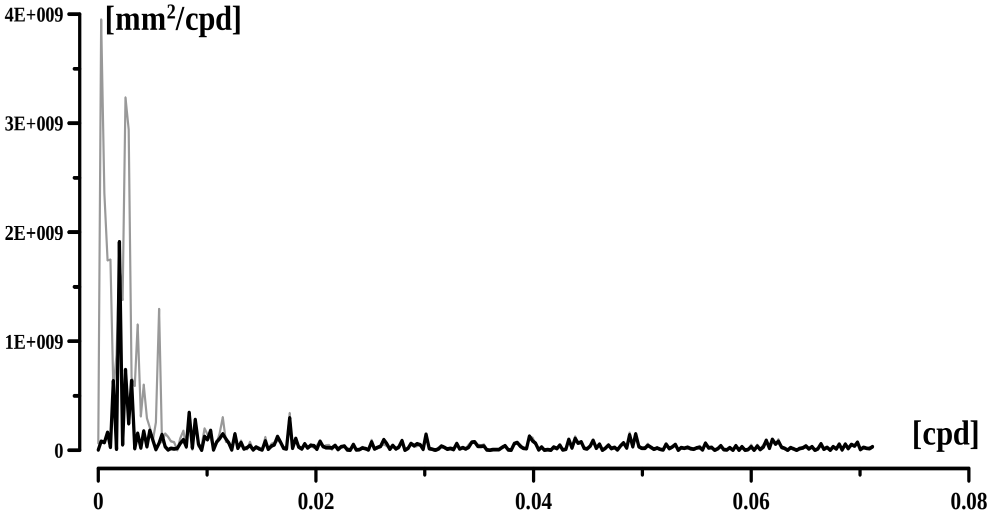

Fig. 8. Power spectral density function for the height component of the GPS-position determination $\left[\Delta s_h^{GPS}\right]_{EPN}$ (light line) and its residuals $Res\left\{\Delta s_h^{GPS} - \Delta s_h^{a} - \Delta s_h^{1,a} - sin_1 - sin_{1/2}\right\}$ (dark line) after removing effects of atmospheric loading of *ECMWF*(*CE*)-model and periodic signals − annual and semi-annual, for SOFI station.

The biggest part of power carried by vertical residuals $Res\left\{\Delta s_h^{GPS} - \Delta s_h^a - \Delta s_h^{1,a} - sin_1 - sin_{1/2}\right\}$ is being transferred by one frequency basically and compounded approximately 50 % on power of $\left\lfloor \Delta s_h^{GPS} \right\rfloor_{EPN}$. The power carried by vertical atmospheric signals is insignificant (13 times less) in comparison with power of $\left\lfloor \Delta s_h^{GPS} \right\rfloor_{EPN}$.

Influence of temperature

The annual term in the horizontal coordinate components most probably indicates monumentation problems. Here we did not establish the appearance of periodic ingredient in the east-west component $\left\lfloor \Delta s_e^{GPS} \right\rfloor_{EPN}$ after removing effects of AL. For the north-south component $\left\lfloor \Delta s_n^{GPS} \right\rfloor_{EPN}$ is being shown the presence of periodic ingredient as for the atmospheric *NCEP*(*CE*)-model its amplitude is 2.6 *mm* (see Fig. 9). The explanation of this periodicity is that it can probably be provoked by environmental nature.

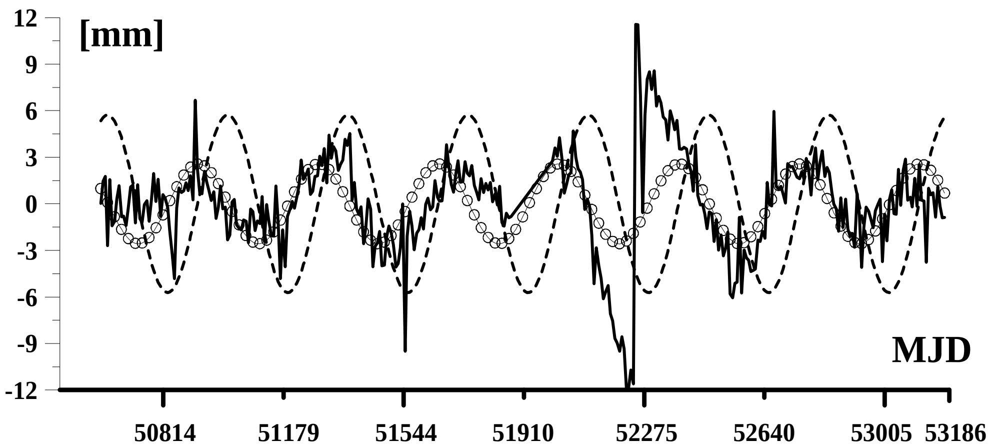

Fig.9. Fitting of annual sinuous wave (open dots) to the North-South residuals $Res\left\{\Delta s_n^{GPS} - \Delta s_n^a\right\}$ (broken line) after removing effects of atmospheric loading of *NCEP*(*CE*)-model from North-South GPS-component and annual sinuous wave of temperature *t*° (dashed curve) in equivalent to *Res* units.

That is why we included in our analysis the local temperature *t*° in SOFI-station. We established insignificant correlation between $\left\lfloor \Delta s_n^{GPS} \right\rfloor_{EPN}$ and *t*°. Both annual periodic signals of *t*° and residual $Res\left\{\Delta s_n^{GPS} - \Delta s_n^a\right\}$ are with phases 21.99° and -67.55° respectively i.e., their moduli are being complemented to 90° approximately. It is shows clearly that exist three-month delay of $Res\left\{\Delta s_n^{GPS} - \Delta s_n^a\right\}$-extremum with respect to opposite temperature-extremum. This can probably explain by serious temperature periodic offsets in the North-South direction of SOFI-station monument.

Suggestions for GPS-observations

Site height time series from continuous GPS-observations provide information of various geophysical processes, which cover wide range of spectrum. With the improvements in GPS-data analysis, we are approaching the stage of using GPS height time series to investigate surface mass loadings causing seasonal crustal deformations and separate them from the tectonic caused vertical motions. The major obstacle is that the systematic errors in GPS-data analysis are mixed with the signals in the height site's variation field. This necessitates removing the modeled from observed time series.

Based on the weekly SINEX solutions for the EPN, from GPS week 911 (mid-1997) to GPS week 1445 (end of third quarter of 2007), we performed an analysis focusing on the detection, estimation, interpretation and elimination of time series inhomogeneities (offsets) excited by AL mainly. The predicted seasonal variations due to pressure redistributions are compared with the GPS-observed variations. Our comparisons indicate that the geophysical AL-model can explain only part – 20%, of the observed signals. After removing effects of periodic signals (annual and semi-annual) this percent is 35%. Their common power represents 50% from this of GPS-signals. The elimination is being suggested to be done by inclusion of the model predictions on the observational level in the analysis of GPS-observations or by correction of the time series after the analysis.

These results have significant implications in regard to the geophysical interpretation of GPS time series and as well as to remove any mis- or unmodeled periodic signals. After removing these seasonal AL-effects then remain the potential contributions from another surface loadings, unmodeled wet troposphere effects, bedrock thermal expansion, errors in phase center variation models and errors in orbital modeling.

To overcome the uneven station displacements and associated uncertainties in frame origin, it is suggested to take into account 1) the estimated degree-one deformations in order to reduce geometrically defined by GPS-technique frame and time series to inertial origin; 2) the experience local models (proposed *hybrid model*) to regress the site's variation field; 3) the other changes of solid Earth environment consistent with dynamics of loadings (other loads); 4) the reasons of established site periodical variation.

Conclusions

We analyzed the deformational effects of AL on weekly SINEX GPS-solutions for position of SOFI-station. These effects are established in case of different meteorological and Earth's mass centers. The interactions of the different atmospheric components (rigid Earth's translation and degree-one deformations) are analyzed. The roles of periodic and local environmental factors (p and $t°$) are estimated. The degree-one AL-responses appearing as local manifestations of geocenter variations are estimated. A statistical analysis of the time series of modeled displacements, their ingredients, coordinate-variations and local environments are performed. After removing of modeled atmospheric signal the residuals show moderate periodic variation. Their amplitudes and phases are averaged and generalized on the whole time span and do not reflect any separate natural process. Therefore we do not recommend them for reduction calculations in data processing. Nevertheless, they could be very useful for comparisons with other loadings. The residuals of GPS-site variation and AL-displacements are being analyzed after removing the seasonal and periodic ingredients. In the end residuals remain parts of environmental sources such as ocean and atmospheric tidal loading, continental water storage loading and contributions from unmodeled tropospherical, bedrock, monumental, orbital and antennal effects.

It is suggested 1) consistent treatment and inclusion in the model of SOFI-site movement of the surface AL-signals; 2) the geometry of station coordinates to be related to motion of the geocenter due to degree-one spherical harmonic response with respect to the inertial terrestrial reference frame; 3) to introduce corrections (as here established) related to vertical displacements due to AL for high precision GPS network processing.

It is established for the first time for SOFI-station 1) the regression dependences between vertical site displacement and local pressure in case of different meteorological and Earth's mass centers; 2) the serious temperature periodic offsets in the North-South direction of monument (this necessitates the derivation of local model for site's behaviour); 3) the generating of 43% on vertical GPS-rate by the vertical AL-displacement.

These results have significant treatment in case of correct geophysical interpretation of time series of GPS-tracking station SOFI. They have particular relevance to studies other seasonal geophysical signals as well. More generally, any errors remaining in the current periodic models are likely propagated into other frequencies. Therefore, care must be taken when making geophysical interpretations from geodetic time series.

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Оценка на атмосферните натоварващи въздействия върху изместванията в местоположението на GPS-станция SOFI

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Резюме. Проведен е анализ за установяване, оценяване, разделяне и елиминиране на изместванията в местоположението на перманентната GPS-следяща станция SOFI, предизвикани най-вече от атмосферното натоварване. Сезонните атмосферни отклики – тоталната и тази от сферична хармоника от първа степен, проявени като деформации на еластична Земя, са оценени за случаите на различни метеорологични и масови центрове на Земята. Анализирано е взаимодействието на атмосферната твърда земна транслация и на деформациите от първа степен (двете са проявление на вариациите на геоцентъра) с атмосферните компоненти. Определена е ролята на периодичните и локалните (атмосферно налягане и температура) фактори. Предложен е хибриден регресионен модел за предсказване на локалното вертикалното изместване. Даден е начин за съгласувано с отчетната координатна система третиране на атмосферните сигнали. Премахването на тези сигнали се предлага да стане чрез включване на моделното предсказване в обработката на GPS-наблюденията или чрез коригиране на времевите редове след обработката. Оценените деформации от първа степен се лансират за редуциране на времевите редове и геометрически изведените отчетни координатни системи към инерциално координатно начало. За първи път са установени за станция SOFI регресионна зависимост между вертикалното й изместване и локалното атмосферно налягане, сериозни периодични температурни измествания на фундамента в северо-южна посока както и намаляване с 43% на линейния тренд на вертикалната GPS-компонента след премахване на атмосферните деформации.