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THE INFLUENCES OF SEISMIC PROCESSES, THE SUN AND THE MOON ON THE SMALL CHANGES OF COORDINATES OF GNSS-STATIONS

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Aim. In order to improve the definition of GNSS-stations coordinate changes, it is important to find out how the processes that occur in the near-Earth space influence the significance of these changes. To describe such processes we can use the seismic activity index, the infrasound rate, and the number of daily flashes in the Sun. In this regard the purpose of this work is to study the influence of the above processes on small changes in the coordinates of GNSS-stations. **Method.** To solve this problem we have selected the coordinates of permanent GNSS-station, seismic activity indicators, infrasound indicators and the number of daily flares in the Sun for the same 295 day epoch. For modeling the influence of processes in the near-Earth space on the definition of coordinate changes the method of constructing a macromodel is developed based on averaged data with the use of a regularization method and with help of the reduction of the approximation basis of many arguments of polynomials. The arguments of the polynomials in the modelling are chosen to reflect the influence of external factors on the coordinates. Parameters and their corresponding multidies of polynomials are found from the identification tasks recorded by the Tikhonov regularization functions. **Results.** We constructed a macromodel that includes parameters of seismic processes, the Sun, the Moon, and the coordinates of the GNSS-station. We have found derivatives and different characteristics of the obtained model. Correlation analysis we used to clarify the assumptions**. Scientific novelty.** For the first time a macromodel was obtained which allows to calculate the influence of the index of seismic activity, infrasound and solar activity on small changes in the coordinates of GNSS-stations. **Practical significance.** After studying this model we obtained results that can be used to increase the accuracy of coordinates obtained using GNSS observations.

Key words: seismic activity, infrasound, solar activity, macromodel, coordinates of GNSS-station.

Introduction

The factors that influence the accuracy of determining the coordinates of GNSS-stations include instrumental factors such as orbital errors, phase center stability, the use of different software [Hardreaves, 1992], factors associated with the satellite propagation environment, and geophysical factors [Hayakawa, 2015] that include the effects of the uneven rotation of the Earth, the effect of the redistribution of atmospheric and oceanic masses, the pressure of snow cover, thermal expansion of rocks, and tectonics of plates [Yankiv-Vitkovska et al., 2007]. However, with the development of modern technologies [Parnowski et al., 2010] the influence of the above-mentioned factors on the determination of the coordinates of a GNSS-station is increasingly offset and there is a need to study other, less obvious factors [Parrot & Soroka, 2007]. These factors include the undiscovered part of the geophysical factors [Kremenetskyi & Cheremnykh, 2009] associated with processes occurring in the near-Earth space, namely seismic processes (seismic activity and infrasound), solar activity and selenogenic processes [Akasofu & Chapman, 1972; Frydman, 2010]. This work is devoted to the study of the influence of such factors on the change of coordinates of GNSS-stations [Yankiv-Vitkovska et al., 2008].

Aim

For finding ways to detect changes in the coordinates of GNSS-stations we set the task to investigate the influence of factors caused by seismic and selenogenic processes and solar activity.

Method

To solve this problem we used a time series in the form of weekly coordinates of the permanent GNSS-station JOZE

$$\bar{x}(t_k),\ \bar{y}(t_k),\ \bar{z}(t_k)\ \ (k=\overline{1,\bar{m}}), \tag{1}$$

where $\bar{m}$ is number of values; t_k are moments of coordinate determination that correspond to daily values for a period of 70-365 days in 2015 [Yankiv-Vitkovska, 2012].

To describe the effect of seismic processes we took the value of seismic activity $g(t)$ and infrasound $v(t)$,

$$\bar{g}(t_k),\ \bar{v}(t_k)\ \ (k=\overline{1,\bar{m}}), \tag{2}$$

defined at the same time points.

The influence of solar activity is described with the daily number of flashes on the Sun:

$$\bar{s}(t_k)\ \ (k=\overline{1,\bar{m}}), \tag{3}$$

Additionally we took into account the influence of the Moon, namely the angular height of the Moon over the horizon $h(t)$ in the area where the station JOZE is located, and the length of the projection on the axis of rotation of the Earth $f(t)$ of a single radius vector, directed from the area of measurement of coordinates to the Moon. However during the construction of the model described below these values were removed from the approximation basis. From this we concluded that within the limits of the achieved accuracy the influence of the moon on small changes in the coordinate determination results is less than the effect of geogenic and heliogenic processes.

On the basis of daily values (1)-(3) by smoothing spline approximation the smoothed hourly values of the same quantities are calculated:

$$x(t_k),\ y(t_k),\ z(t_k),\ s(t_k),\ g(t_k),\ v(t_k)\ \ (k=\overline{1,m}\,), \quad (4)$$

where m is number of hourly values.

The smoothing is applied to facilitate the resolution of the subsequent problem of detection of influence s, g, v on x, y, z.

To model the influence of processes in the near-Earth space on the definition of coordinate changes we developed macromodel [Matviichuk, 2000; Matviichuk & Pauchok, 2006] with such structure:

$$\begin{aligned}
&x_0' = x_1;\ x_1' = x_2;\ x_2' = x_3;\\
&x_3' = P_x(x_0, x_1, x_2, x_3, y_2, y_3, z_2, z_3, s_0, s_1, g_0, g_1, v_0, v_1);\\
&y_0' = y_1;\ y_1' = y_2;\ y_2' = y_3;\\
&y_3' = P_y(x_2, x_3, y_0, y_1, y_2, y_3, z_2, z_3, s_0, s_1, g_0, g_1, v_0, v_1);\\
&z_0' = z_1; z_1' = z_2; z_2' = z_3;\\
&z_3' = P_z(x_2, x_3, y_2, y_3, z_0, z_1, z_2, z_3, s_0, s_1, g_0, g_1, v_0, v_1),
\end{aligned} \quad (5)$$

where P_x, P_y, P_z are polynomials from many arguments. The arguments of these polynomials are chosen to reflect the influence of external factors on the coordinates.

Parameters c_I, c_J, c_K and their corresponding multiindex I, J, K of polynomials P_x, P_y, P_z we found from the identification problems recorded by the Tikhonov regularization functions [Tikhonov et al., 1990]:

$$\begin{aligned}
&\min_{c_I}\left(\sum_{k=1}^{m}\left[x^{(4)}(t_k)-P_x(t_k)\right]^2+a_x\sum_I c_I^2\right);\\
&\min_{c_J}\left(\sum_{k=1}^{m}\left[y^{(4)}(t_k)-P_y(t_k)\right]^2+a_y\sum_J c_J^2\right);\\
&\min_{c_K}\left(\sum_{k=1}^{m}\left[z^{(4)}(t_k)-P_z(t_k)\right]^2+a_z\sum_K c_K^2\right),
\end{aligned} \quad (6)$$

where a_x, a_y, a_z are regularization parameters; symbols $P_x(t)$ $P_y(t)$, $P_z(t)$ are indicated:

$$\begin{aligned}
P_x(t) = P_x(&x_0(t), x_1(t), x_2(t), x_3(t), y_2(t), y_3(t), z_2(t), z_3(t),\\
&s_0(t), s_1(t), g_0(t), g_1(t), v_0(t), v_1(t));\\
P_y(t) = P_y(&x_2(t), x_3(t), y_0(t), y_1(t), y_2(t), y_3(t), z_2(t), z_3(t),\\
&s_0(t), s_1(t), g_0(t), g_1(t), v_0(t), v_1(t));\\
P_z(t) = P_z(&x_2(t), x_3(t), y_2(t), y_3(t), z_0(t), z_1(t), z_2(t), z_3(t),\\
&s_0(t), s_1(t), g_0(t), g_1(t), v_0(t), v_1(t)).
\end{aligned} \quad (7)$$

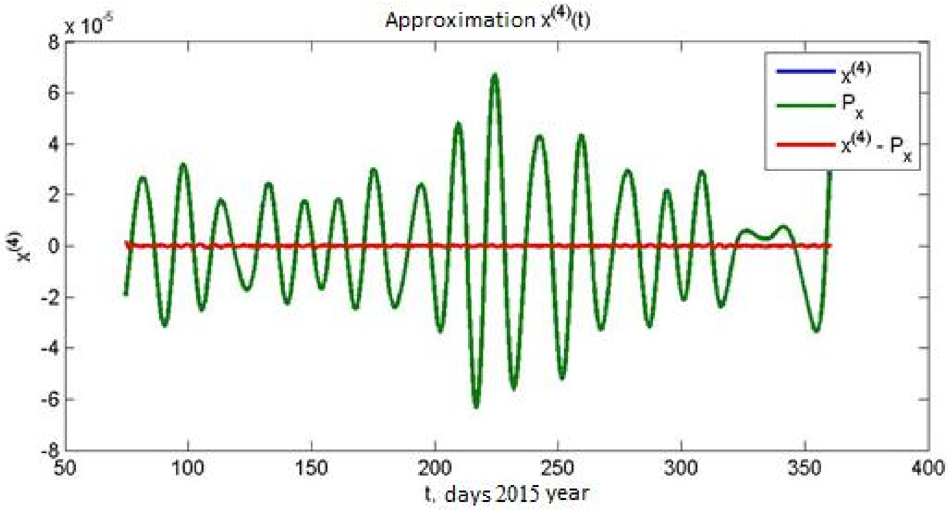
With a full set of coefficients, each of the polynomials of the third degree has 680 terms. To solve the identification problem we used the method of regularization with the help of reduction of the approximation basis of the polynomials of many arguments. [Kurhanevych & Matviichuk, 2000; Pauchok, 2010]. After reduction the number of coefficients in polynomials is reduced to 118-123 elements. Note that precisely as a result of this reduction from the approximation basis of all polynomials is deleted all elements that describe the two parameters of the influence of the Moon $h(t),\ f(t)$.

Results

The results of constructing the above-described model are illustrated in Fig. 1 and Fig. 2.

We calculated that the approximation of the 4th derivatives from the changes of the geodesic coordinates $x^{(4)}(t)$, $y^{(4)}(t)$, $z^{(4)}(t)$ of the polynomials of many arguments (6) has specific features. First, the approximation of the 4th derivative of each coordinate by the corresponding polynomial of many arguments is sufficiently precise. In fig. 1 we showed graphs of approximated derivatives and graphs of approximated dependencies. These graphs do not show any differences between them. The approximation error is of the order of $2 \div 8 \times 10^{-7}$ *м с*$^{-4}$, provided that the approximated quantities are of the order of $2 \div 8 \times 10^{-5}$ *м с*$^{-4}$. That is, the relative error of approaching the 4th derivative of one coordinate by a polynomial from derivatives from the remaining coordinates and external factors s, g, v has order 10^{-2}.

The emergence of such a rather high accuracy of approximation indicates that all quantities (4) are the realization of a certain dynamic process in which direct and inverse (recursive) influences are associated with coordinates x, y, z and derivatives from them, which depend on the s, g, v and derivatives from them. This connection between the named values in a mathematical model is manifested in the fact that one of the derivative coordinates functionally depends on derivatives of all coordinates and three factors of geo-heliogenic origin. Taking into account the existence of a differential isomorphism between the derivatives of x, y, z, s, g, v and the dynamic variables of the process observed in (4), we makes the conclusion that, within the limits of the achieved accuracy, the factors s, g, v dynamically affect on the changes of coordinate x, y, z, and all coordinates are dynamically dependent on each other. This conclusion follows from the presence of small relative error of approximation $D_r = r^{(4)} - P_r$ $(r = x, y, z)$ and the assumption of differential isomorphism [1] between the derivatives from (4) and the variables of the state of an unknown dynamical system, which is observed by the process (4). To confirm the existence of this differential isomorphism we solved the equation (5) with the parameters c_I, c_J, c_K of the polynomials P_x, P_y, P_z found from solving problems (6).



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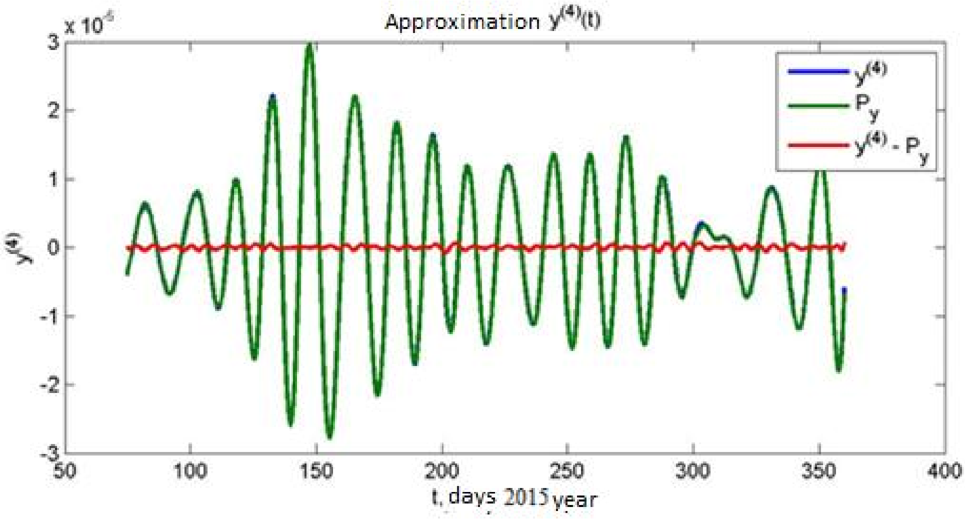

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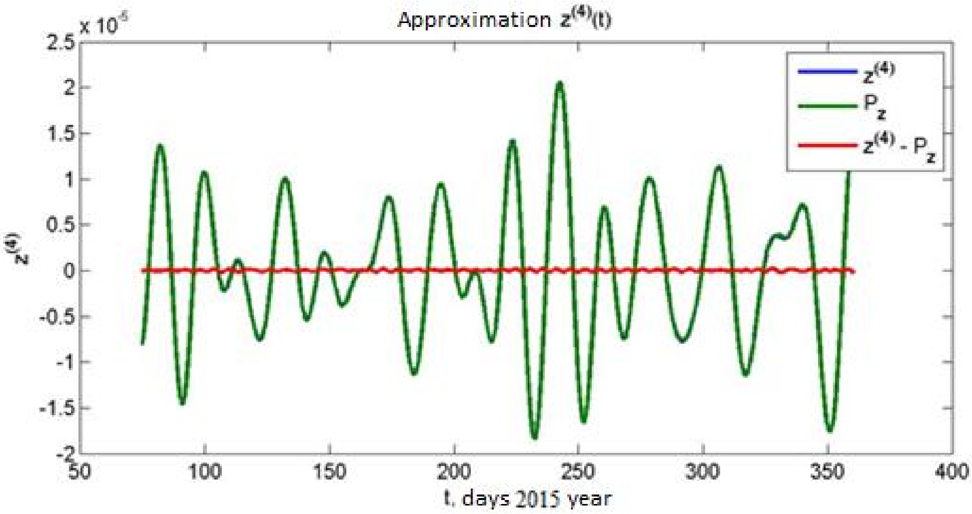

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Fig. 1. Chart (a) $x^{(4)}(t)$ (blue color), its polynomial approximation P_x (green color) and error approximation (red color); chart (b) $y^{(4)}(t)$ (blue color), its polynomial approximation P_y (green color) and error approximation (red color); chart (c) $z^{(4)}(t)$ (blue color), its polynomial approximation P_z (green color) and error approximation (red color)

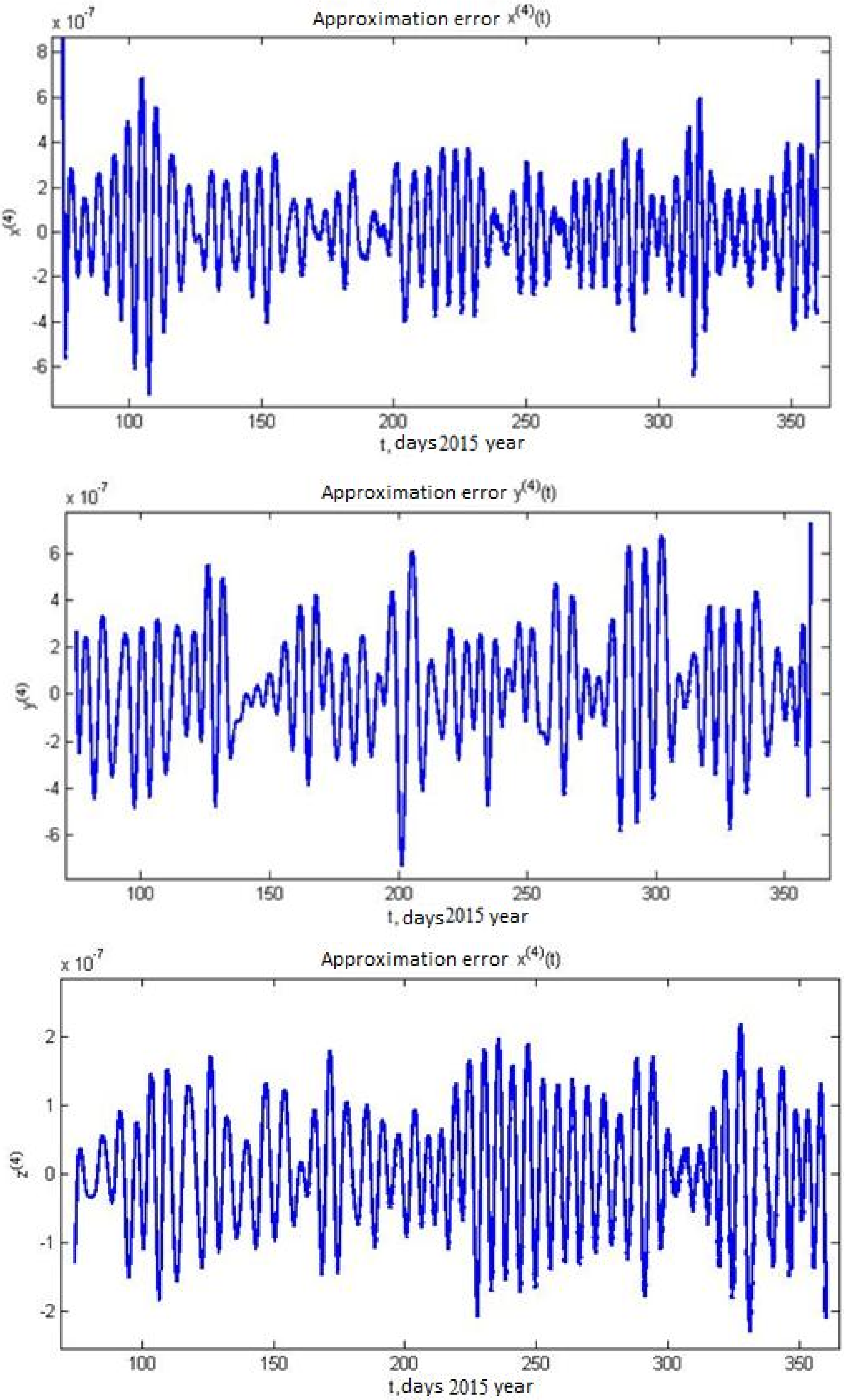
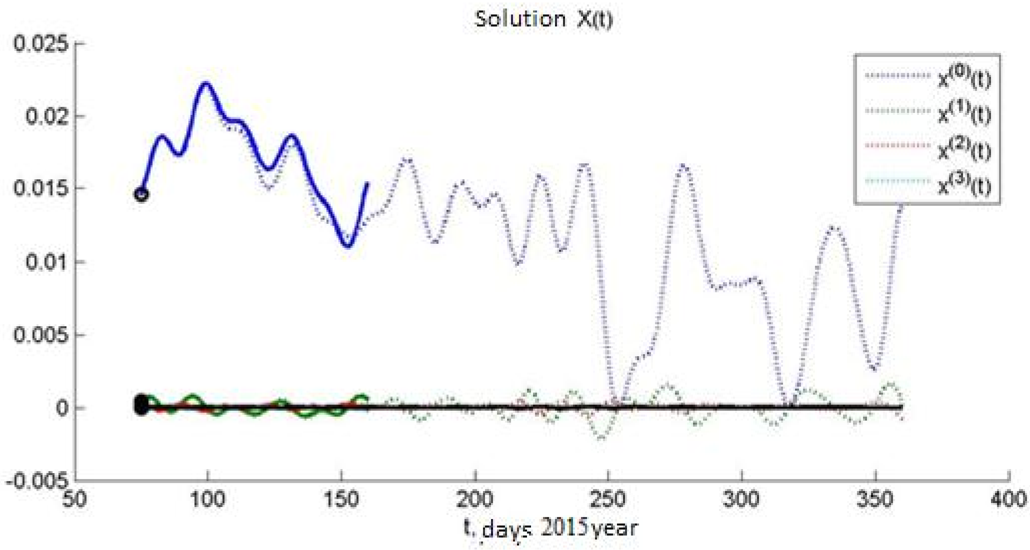


Fig. 2. Approximation error graphs $x^{(4)} - P_x$ (a); approximation error graphs $y^{(4)} - P_y$ (b); approximation error graphs $z^{(4)} - P_z$ (c)



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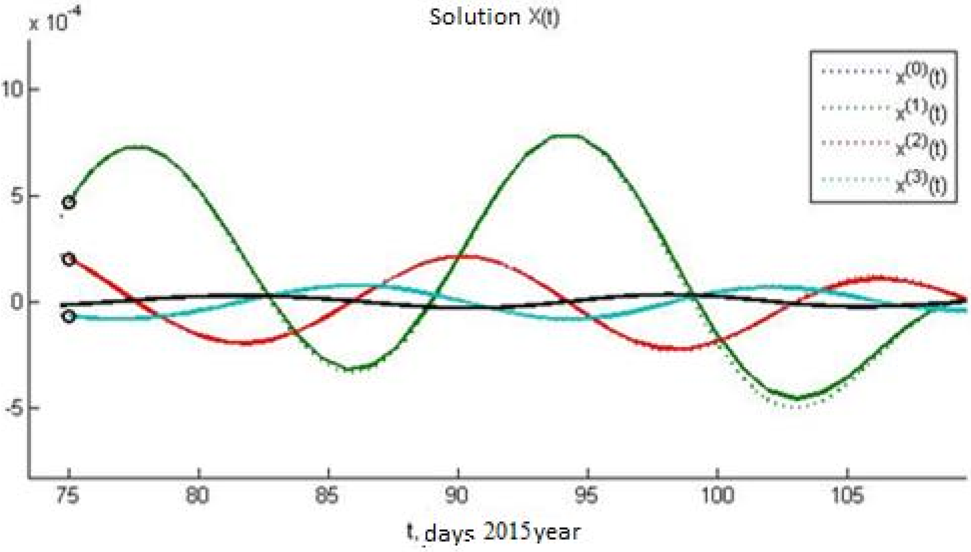

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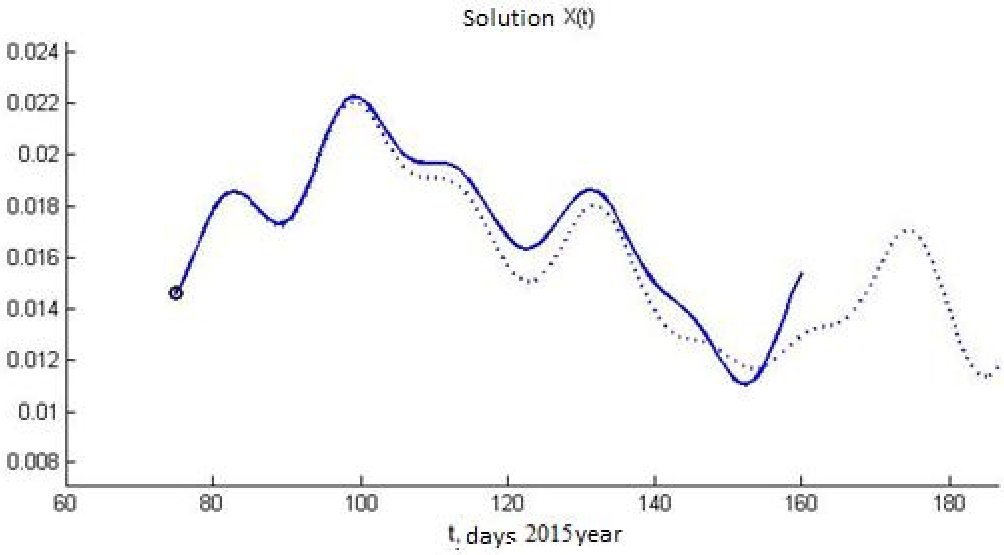

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Fig. 3. Charts of derivatives $x^{(i)}$ $(i=\overline{0,3})$ and the corresponding variables of state x_i $(i=\overline{0,3})$ (a); charts of derivatives $x^{(i)}$ $(i=\overline{1,3})$ and the corresponding variables of state x_i $(i=\overline{1,3})$ on an enlarged scale (b); charts $x^{(0)}$ and the corresponding variable of state x_0 on an enlarged scale (c)

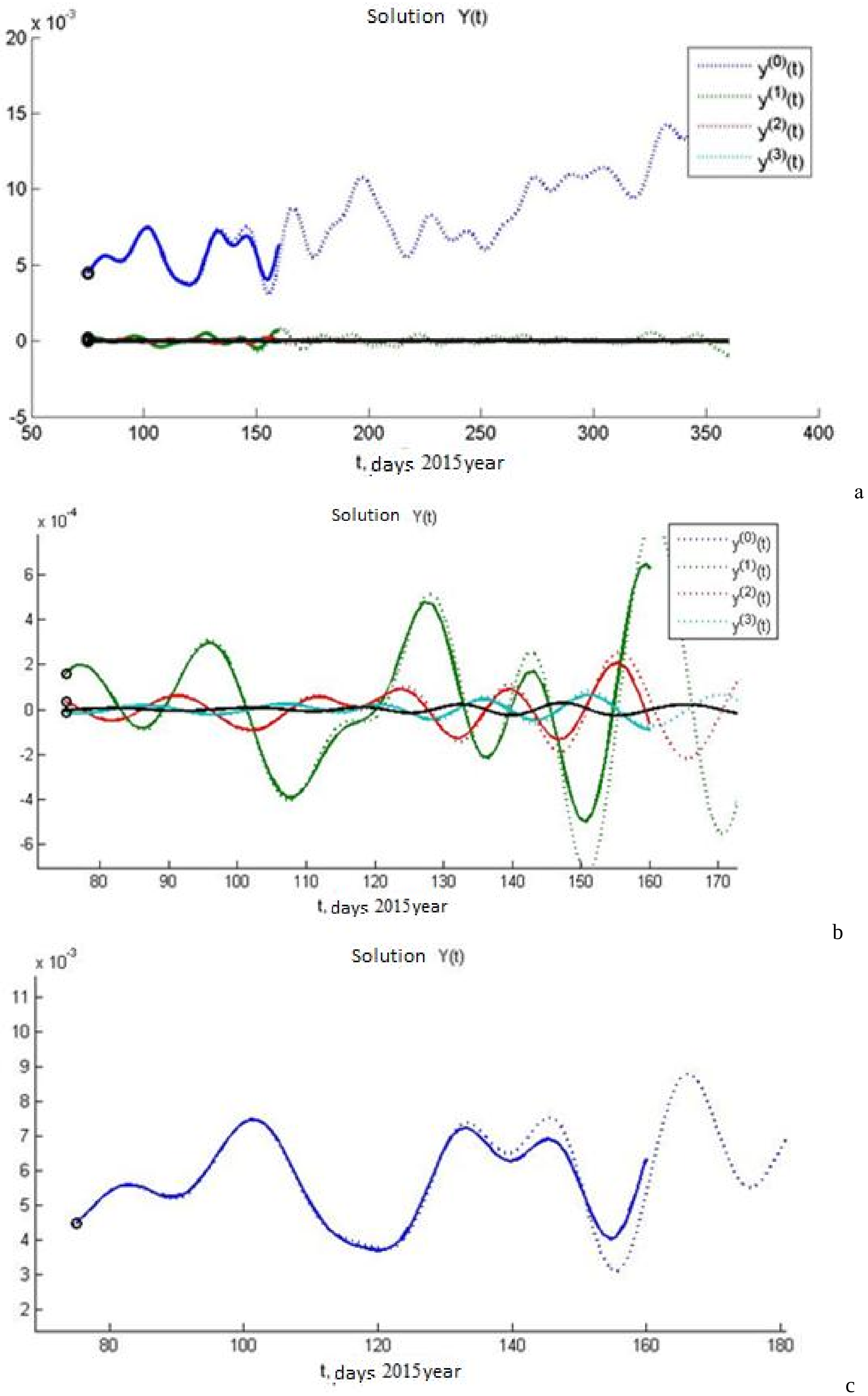
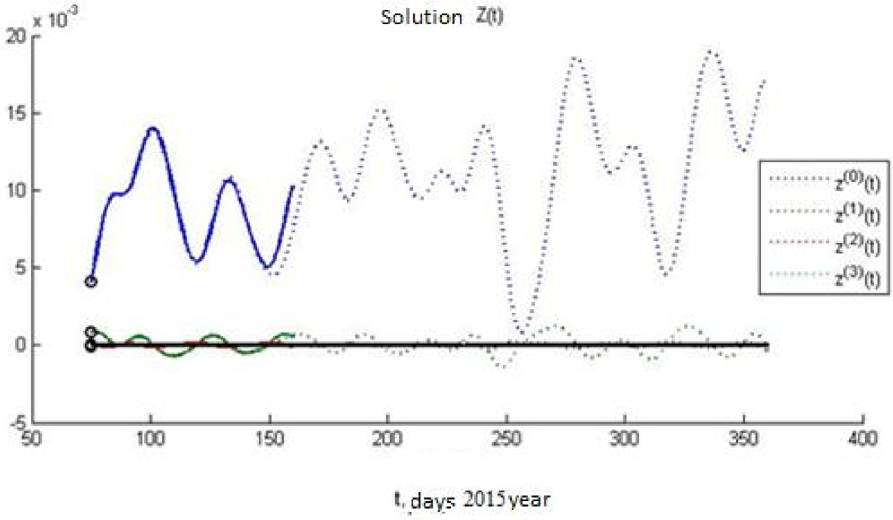


Fig. 4. Charts of derivatives $y^{(i)}$ ($i=\overline{0,3}$) and the corresponding variables of state y_i ($i=\overline{0,3}$) (a); charts of derivatives $y^{(i)}$ ($i=\overline{1,3}$) and the corresponding variables of state y_i ($i=\overline{1,3}$) at an enlarged scale (b); charts of derivatives $y^{(0)}$ and the corresponding variables of state y_0 at an enlarged scale (c)



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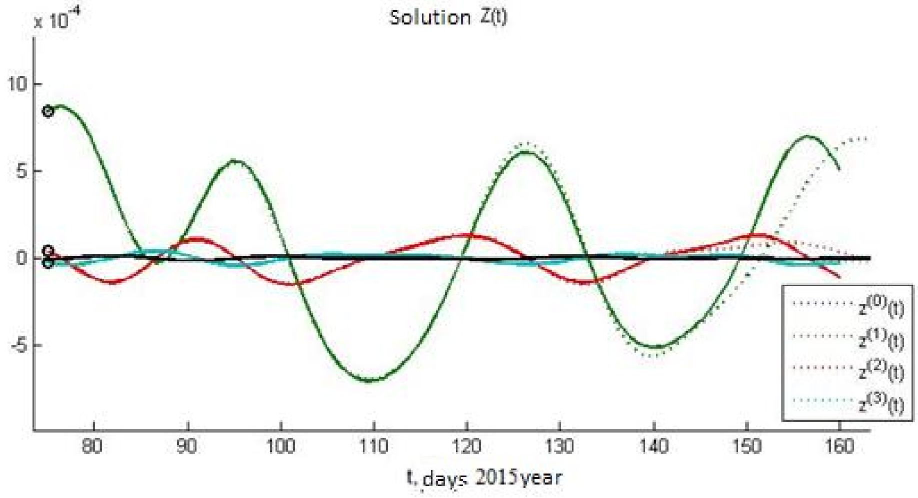

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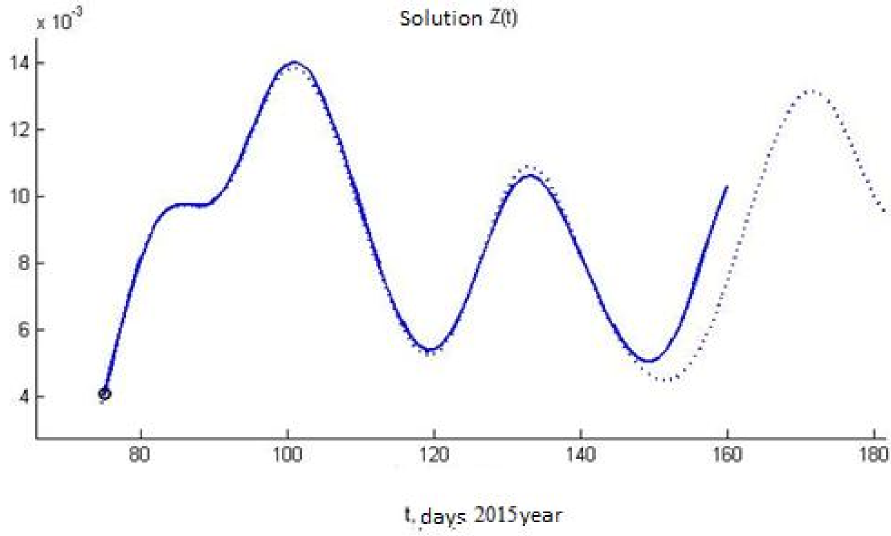

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Fig. 5. Charts of derivatives $z^{(i)}$ $(i=\overline{0,3})$ and the corresponding variables of state z_i $(i=\overline{0,3})$ (a); charts of derivatives $z^{(i)}$ $(i=\overline{1,3})$ and the corresponding variables of state z_i $(i=\overline{1,3})$ at an enlarged scale (b); chart $z^{(0)}$ and the corresponding variable of state z_0 at an enlarged scale (c)

Figures 3-5 shows a graphic of the coordinates derivatives and the corresponding dynamic variables found from solving equations (5).

As we can see from these figures, the macromodel (5), identified by data (4), has high accuracy. Here, this proves the presence of isomorphism between derivatives of (4) and unknown dynamic variables that generate the process represented by values of values (4). This means that the coordinates x, y, z are dynamically interdependent, and they dynamically depend on the solar activity s and geoseismic activity g, v of the external influence.

Let us consider another fact which follows from the solution of the problem (6). In fig. 2 is shown graphs of error approximations $D_r = r^{(4)} - P_r$ ($r = x, y, z$). As we can see from these graphs – the approximation error $D_r(t)$ ($t \in [t_1, t_m]$; $r = x, y, z$) has a qualitative form of a certain dynamic process, and there are no signs of a random variable, characteristic in approximation errors. This suggests that the approximation error $D_r(t)$ ($r = x, y, z$) reflects a certain unregarded component of the external environment impact on the 4th coordinate derivative, and, therefore, in fact, on the coordinates.

Indirect confirmation that the error $D_r(t)$ ($r = x, y, z$) is an unaccounted component (the consequences of a certain external influence) follows from the fact that the expansion of the approximation basis of polynomials P_x, P_y, P_z by increasing the degree and order of derivatives - its arguments - did not improve the accuracy of the approximation (6). After all, as a result of the regularized solution of problems (6) with the help of the reduction procedure – the number of approximation coefficients was reduced, which led to the fact that the approximation error $D_r(t)$ ($r = x, y, z$) became a form of realization of a certain dynamic process.

Proceeding from the assumption that the approximation error $D_r(t)$ ($r = x, y, z$) expresses the unaccounted component of the external influence on the error of determining the coordinate changes, the task is to investigate the laws of its change over time.

To disclose the features of the dynamic component change $D_r(t)$ ($r = x, y, z$), autocorrelation integrals are calculated from $D_r(t)$ ($r = x, y, z$). Graphs of autocorrelation integrals from the "residual" components $D_r(t)$ ($r = x, y, z$) are shown in Fig. 6.

From these graphs we can see that the autocorrelation integral from $D_r(t)$ ($r = x, y, z$) has the form of oscillating function. Repetition of short-term oscillations of this integral occurs within 16.76 days. Half of this value (8.38) is commensurate with the duration of the week, that is, the time interval of averaging, which at one time was used in determining the coordinates for GNSS-stations. This suggests that the selected time interval through which the coordinates are determined is manifested in the detected residual component $D_r(t)$ ($r = x, y, z$).

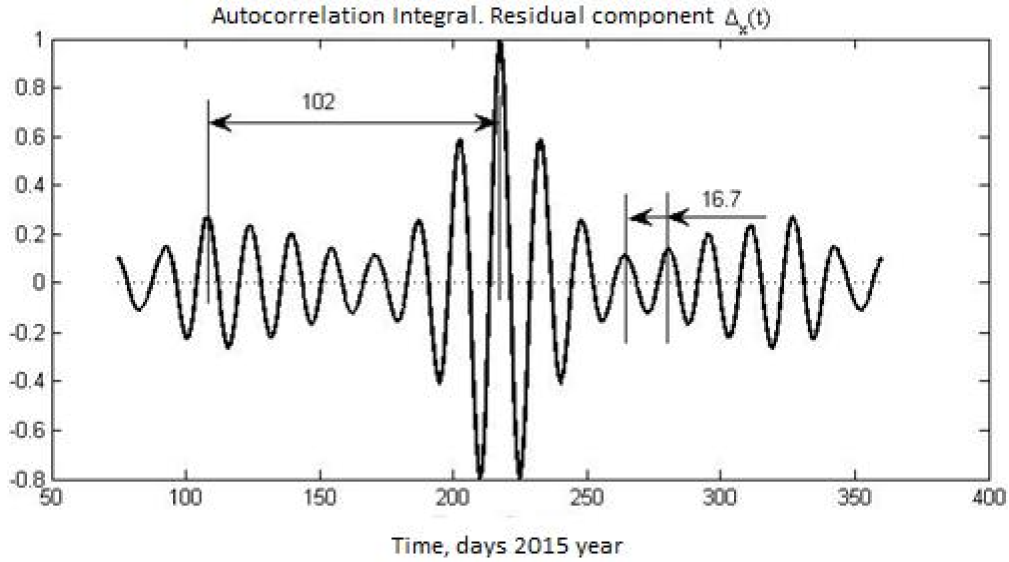
It is interesting that the distance between the two maxima of the enveloping autocorrelation integrals for all coordinates is approximately the same and equal to $101 \div 102$ days.

The oscillatory nature of the auto-correlation integral of the remaining components $D_r(t)$ ($r = x, y, z$) means that, over the intervals of 16.76 days, the average value of the factor (in the model (5)) is then more, then less depends on the values at the past intervals.

In order to clarify the established assumptions, the mutual correlation integrals between functions $D_r(t)$ ($r = x, y, z$) are calculated. Their graphs are shown in Fig. 7.

From these graphs we can see that mutual correlation integrals have two oscillating components. One of them has a period of about 7.70-8.14 days. Another oscillating component has a period of 28.5-29.1 days. This approximates the duration of one week and one month. Periodic repetitions with a lunar duration are clearly visible in Fig. 7c. In Fig. 7a, 7b it is not expressed so clearly. In Fig. 7c ovals are shown in the regions of extremums of the enveloping mutual correlation integral between $D_x(t)$ and $D_z(t)$. In Fig. 7a, 7c these areas are indicated by dotted ovals. It can be seen that the extremums of the envelope of the mutual correlation integrals between all functions $D_r(t)$ ($r = x, y, z$) are placed at almost identical intervals of time, which represent approximately one period of rotation of the Moon around the Earth. This fact indirectly indicates the existence of a peculiar modulating effect of the tidal forces of the Moon on the results of the determination of the coordinates of GNSS-stations. Regarding the coordinates of the JOZE station, this action is most likely to be noticeable in the plane (x, z) and less noticeable in the planes (x, y), (y, z).

Such observations may mean that the tidal forces of the Moon are used to determine the coordinate changes, although, due to the lack of accuracy of the calculations the values $h(t)$, $f(t)$ were removed from the model (5) during the reduction of the approximation basis when solving the identification problems of determining the parameters and multiindices of the polynomials of many arguments.



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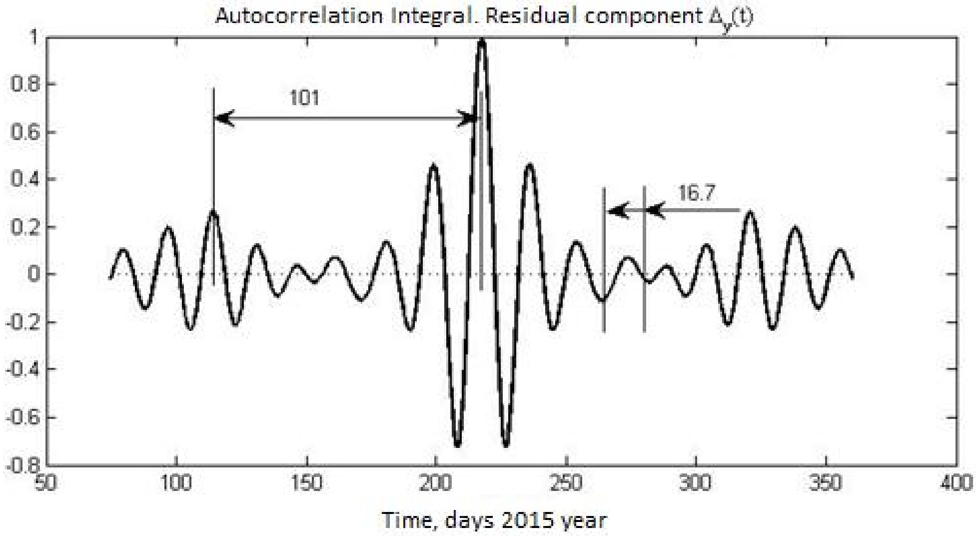

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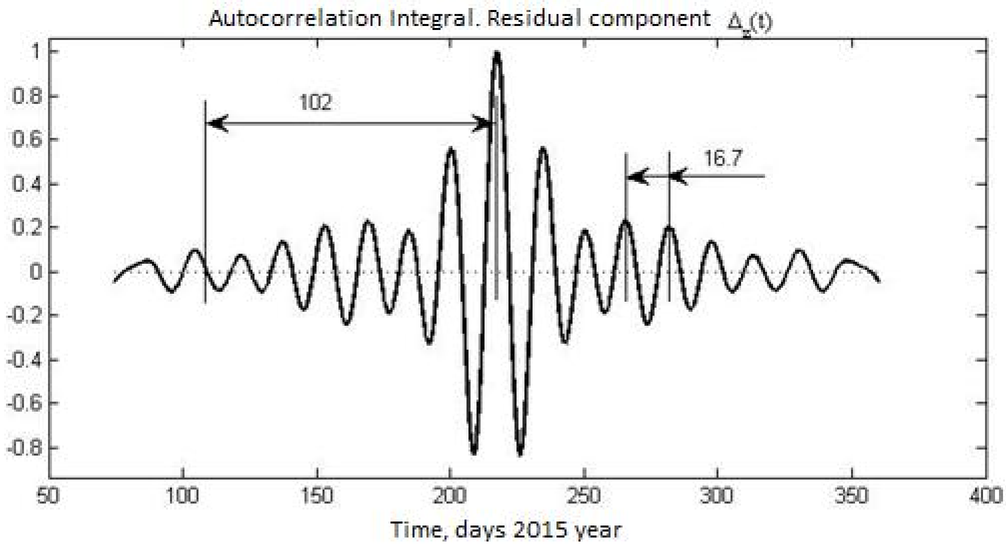

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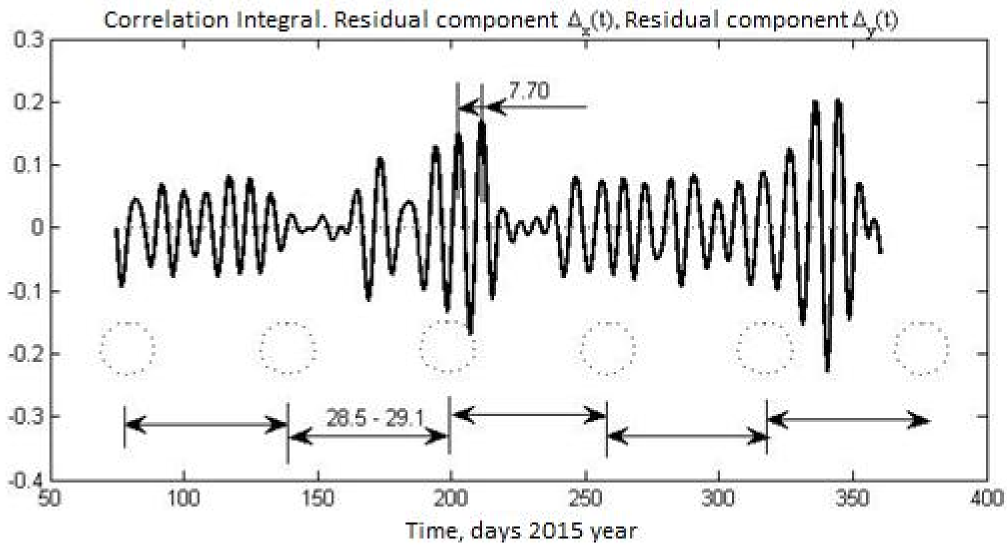
Fig. 6. Graph of the autocorrelation integral from the approximation error $x^{(4)} - P_x$ (a); graph of the autocorrelation integral from the approximation error $y^{(4)} - P_y$ (b); graph of the autocorrelation integral from the approximation error $z^{(4)} - P_z$ (c)



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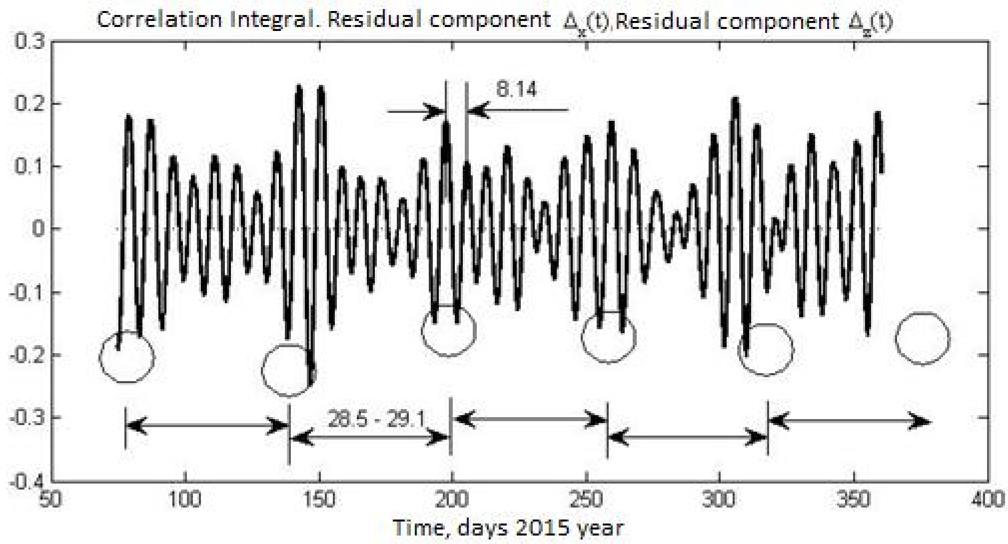

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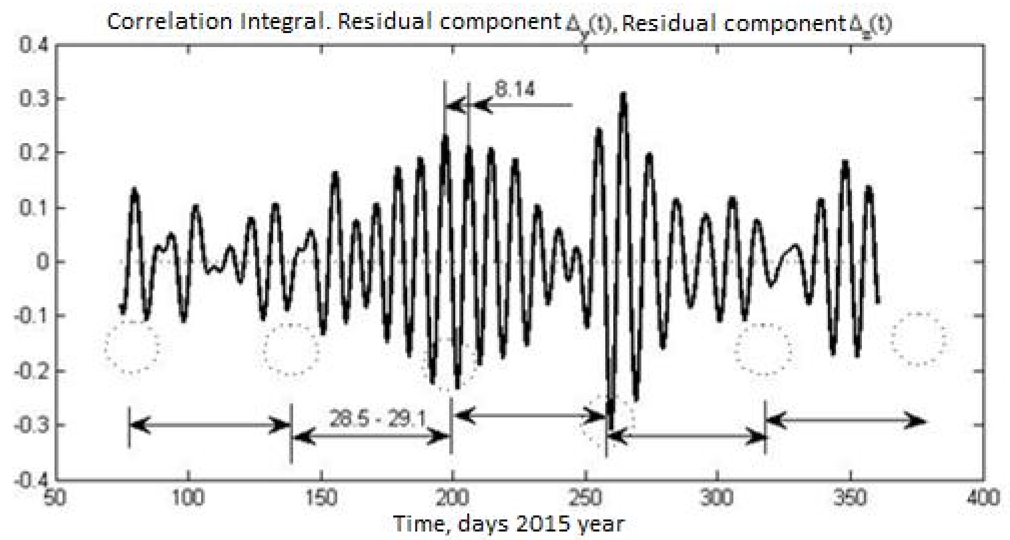

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Fig. 7. Graph of autocorrelation integrals, calculated between approximation errors $x^{(4)} - P_x$ and $y^{(4)} - P_y$ (a); between approximation errors $x^{(4)} - P_x$ and $z^{(4)} - P_z$ (b); between approximation errors $y^{(4)} - P_y$ and $z^{(4)} - P_z$ (c)

Scientific novelty and practical significance

For the first time a macromodel was constructed, which allows to calculate the influence of the index of seismic activity, infrasound and solar activity on small changes of the coordinates of GNSS-stations. After investigation using this model, we obtained a number of results that can be used to increase the accuracy of the coordinates obtained using GNSS observations.

Conclusions

In this paper we can draw the following conclusions:

– we developed a macromodel for studying the influence of processes in the near-Earth space for the determination of coordinate changes of GNSS-stations, during which a regularization method was applied;

– within the limits of the achieved accuracy the factors of solar activity, seismic activity index, and infrasound dynamically influence the change of coordinates x, y, z, and that the latter are dynamically dependent on each other;

– the mutual correlation integrals, calculated between different approximation errors, have two oscillating components.

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ВПЛИВ СЕЙСМІЧНИХ ПРОЦЕСІВ, СОНЦЯ І МІСЯЦЯ НА МАЛІ ЗМІНИ КООРДИНАТ GNSS-СТАНЦІЙ

Мета. Для вдосконалення визначення змін координат GNSS-станцій важливо з’ясувати, як на значення цих змін впливають процеси, які відбуваються в навколоземному просторі. Для опису таких процесів можна використати показник сейсмічної активності, показник інфразвуку та щоденну кількість спалахів на Сонці. У зв'язку з цим метою даної роботи є дослідження впливу вищеперелічених процесів на малі зміни координат GNSS-станцій. **Методика.** Для розв'язання поставленої задачі нами було підібрано координати перманентної GNSS-станції, показники сейсмічної активності, показники інфразвуку та щоденну кількість спалахів на Сонці на одні і ті ж епохи на протязі 295 днів. Для моделювання впливу процесів у навколоземному просторі на визначення змін координат розроблено методику побудови макромоделі за усередненими даними з використанням методу регуляризації за допомогою редукції апроксимаційного базису поліномів багатьох аргументів. Аргументи поліномів при моделюванні вибрано так, щоб відобразити вплив зовнішніх чинників на координати. Параметри і відповідні їм мультиіндекси поліномів знайдено з ідентифікаційних задач, записаних регуляризаційними функціоналами Тіхонова. **Результати.** Побудовано макромодель, яка включає параметри сейсмічних процесів, Сонця, Місяця та координати GNSS-станції. Знайдено похідні та різні характеристики отриманої моделі. Для уточнення встановлених припущень застосовано кореляційний аналіз. **Наукова новизна.** Вперше отримано макромодель, що дозволяє обчислювати вплив показника сейсмічної активності, інфразвуку та сонячної активності на малі зміни координат GNSS-станцій. **Практична значущість.** Після дослідження цієї моделі отримано ряд результатів, які можна застосувати для підвищення точності координат, отриманих за допомогою GNSS спостережень.

Ключові слова: сейсмічна активність, інфразвук, сонячна активність, макромодель, координати GNSS-станції.

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ВЛИЯНИЕ СЕЙСМИЧЕСКИХ ПРОЦЕССОВ, СОЛНЦА И ЛУНЫ НА МАЛЫЕ ИЗМЕНЕНИЯ КООРДИНАТ GNSS-СТАНЦИЙ

Цель. Для совершенствования определения изменений координат важно выяснить, как на значение этих изменений влияют процессы, происходящие в околоземном пространстве. Для описания таких процессов можно использовать показатель сейсмической активности, показатель инфразвука и ежедневное количество вспышек на Солнце. В связи с этим целью данной работы является исследование влияния вышеперечисленных процессов на малые изменения координат GNSS-станций. **Методика.** Для решения поставленной задачи нами было подобрано координаты перманентной GNSS-станции, показатели сейсмической активности, показатели инфразвука и ежедневное количество вспышек на Солнце на одни и те же эпохи на протяжении 295 дней. Разработана методика построения макромодели по усредненным данным с использованием метода регуляризации с помощью редукции аппроксимационного базиса полиномов многих аргументов. **Результаты.** Построено макромодель, которая включает параметры сейсмических процессов, Солнца, Луны и координаты GNSS-станции. Найдено производные и различные характеристики полученной модели. **Научная новизна.** Впервые получено макромодель, что позволяет вычислять влияние показателя сейсмической активности, инфразвука и солнечной активности на малые изменения координат GNSS-станций. **Практическая значимость.** После исследования данной модели получен ряд результатов, которые можно применить для повышения точности координат, полученных с помощью GNSS наблюдений.

Ключевые слова: сейсмическая активность, инфразвук, солнечная активность, макромодель, координаты GNSS-станции.

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