Monitoring and Analyzing Movements of Geodetic Monuments

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Key words: IGS, GPS, Inclination Sensor, Spectral Analysis, Wavelet Analysis

SUMMARY

The movements of a pillar in 1.20 m height, which is an IGS reference station in Istanbul and called ISTA, were monitored continuously using two micro-radian accuracy level dual-axis digital inclination sensors in two periods with 40 days each. Also, for the same periods, the baseline solution between two continuous reference stations, ISTA and KANT, was used for the analysis. The both station are on the same plate that is north side of NAF (North Anatolian Fault). KANT, founded on the ground, is one of the continuous reference stations of MAGNET (Marmara Continuous GPS Network) and organized by Earth & Marine Sciences Research Institute, Marmara Research Center, TUBITAK (The Scientific and Technological Research Council of Turkey).

The inclination sensors data and baseline solutions for two periods were analyzed using Least Squares Spectral Analysis (LSSA) and Wavelet Analysis (WA) techniques. Their results for one period and for two periods were compared and interpreted. The results of comparisons of the analysis of two different periods and also the used analysis techniques were investigated. The movements and behaviors of the ISTA- IGS reference station monument was interpreted with considering the movements of the building, which carries the pillar on its top, weather conditions, atmospheric effects and low-magnitude earthquakes during the measurement periods.

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1. INTRODUCTION

Besides the conventional measurement techniques and satellite based measurement techniques, digital and/or analog precise inclination sensors are also used in geodetic measurements with various aims such as hydrographic measurements, geoid determination with astro-geodetic method, volcanology, industrial applications, deformation monitoring of engineering structures like dams, bridges, viaducts, sky-scrapers.

In this study, the movements of a pillar, which is ISTA-IGS continuous GPS reference station, were monitored. ISTA station was founded as a pillar (1.20 m height) at the top of five-story faculty building. Because of this reason, it is required to monitor and analyze probable effects of the building on the movements of the pillar.

The time series data from inclination sensors and baseline solutions from two continuous GPS reference stations are analyzed with LSSA and WA techniques. The results and interpretations are given in the paper.

2. MONITORING ISTA - IGS REFERENCE STATION

Two digital inclination sensors were used in the measurements. One of the sensors was fixed on the west surface of the pillar via a special steel console platform using steel screws to attach it to the surface. And other sensor was set to the column of the faculty building. The relative positions of both sensors are seen in the Figure 1 and Figure 2a. It is paid attention that the axes directions of both sensors set to be parallel ("-Y" direction to the West and "–X" direction to the North for both sensors). This is important while the data are analyzed and the results are interpreted (Anonym (1998)). In addition to two dimensional inclination values, also the temperature is recorded by the sensors.

The inclination sensors were used because i-) they are suitable for a long term monitoring, ii-) they provide opportunity to compare the movements of both objects-the pillar and the building-at the same time, iii-) they are quite precise measurement equipments (micro-radian) the unit of inclination data is milliradian (1mrad=1000μrad=0.001mm/m=0.0573 degree)

Measurements were carried out in two periods. First period was between 10 March and 05 April 2000 and the second was between 20 February and 22 March 2002. During the first period, weather and atmospheric conditions was so changeable. After the sixth day, the weather was snowy. The temperature differences were near equal to zero. There was no sun in the sky during the three snowy days. These conditions are very useful to test the effects of different atmospheric events on the behaviors of the pillar.

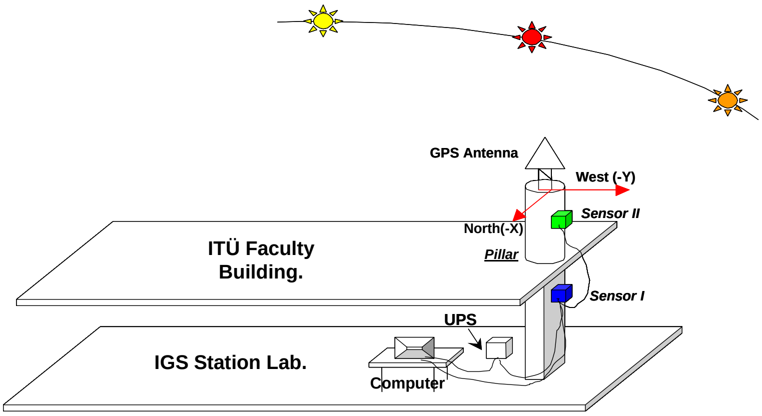


Figure 1: The locations of the sensors and the directions of the axes during the measurements

For the same measurements periods, ISTA-KANT baseline solutions were computed according to 2-hour GPS data. Unlike ISTA, the KANT station had been founded on the ground. The picture of KANT station can be seen in the Figure 2b.

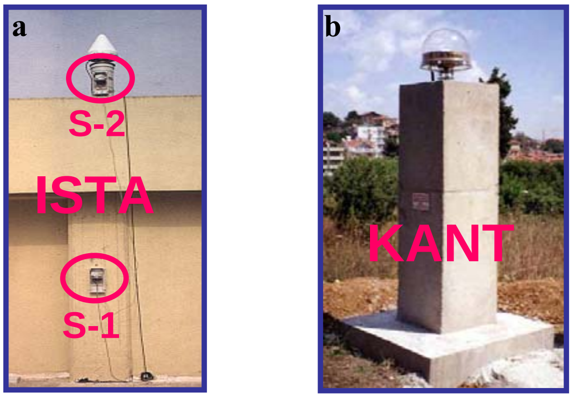


Figure 2 a, b: In a, ISTA reference station and the position of the sensors are seen; in **b**, the KANT reference station is seen

During the both measurements period, it is also considered the earthquakes. The magnitudes, locations and times of the earthquakes are provided from the Kandilli Observatory and Earthquake Research Institute to interpret the sudden changes and peaks of the inclination values and GPS baseline solutions (Table 2.).

3. DATA AND GRAPHS

In Figure 3, the data from both inclination sensors for two measurements periods can be seen. According to the graphs, it can be seen the correlation between the recorded temperature and the inclinations. Figure 4 shows the movements of ISTA pillar with weather conditions. In the sunny day, the inclinations are bigger than to be in the snowy day.

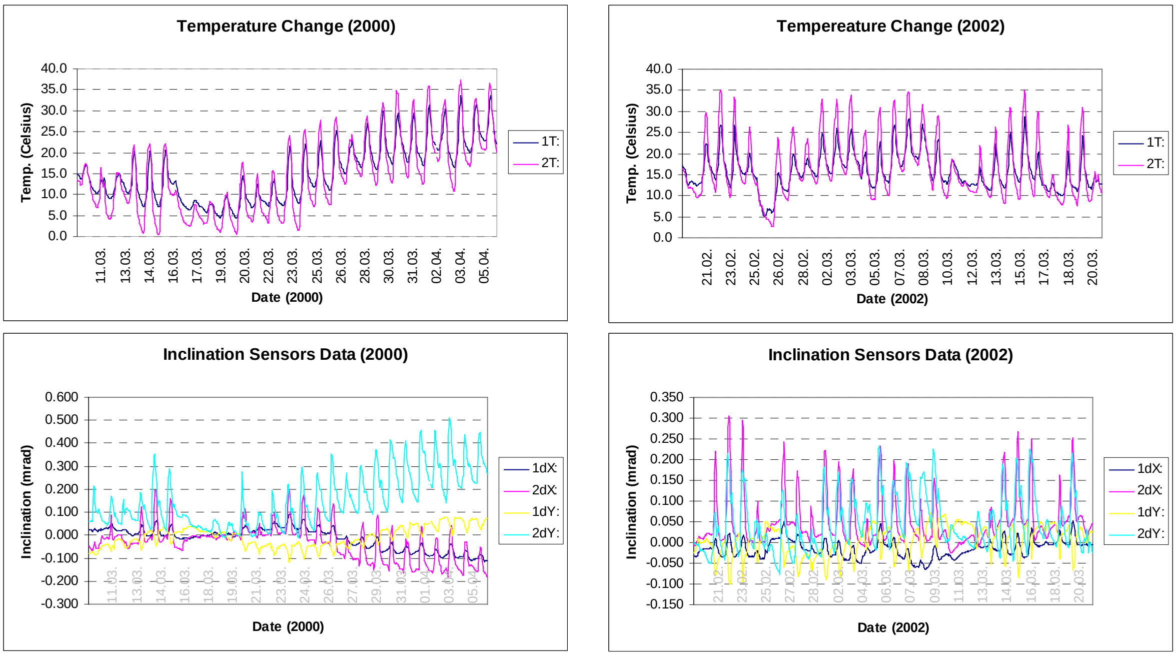


Figure 3: The recorded inclination sensors data (temperature and inclination) for two periods

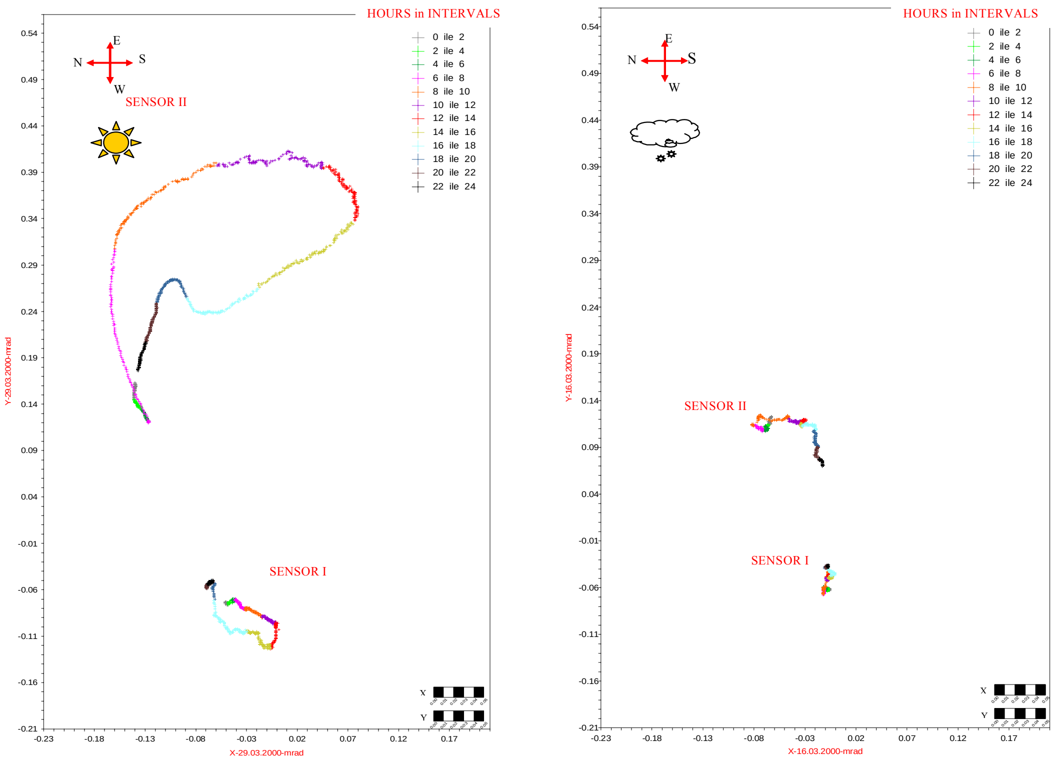


Figure 4: The inclination sensors data for a sunny day and a cloudy (snowy) day

It was seen in the results that while the weather is sunny, the pillar moves depending on the sun. This behavior of the pillar is like a sunflower, because while one side of the pillar grows warm under the effects of direct sun lights, that side expands and pillar inclines to the other side. Then the sun changes the position during the day, at this time other side of the pillar exposes the direct sunlight and expands because this side grows warm, the other side gets cold and becomes stretch (Çelik (1999), (2000), Özöner (2000)).

When the Figures 3 and 4 are investigated, it was seen that the inclination of the building is much smaller than the inclination of the pillar. Another important result from the figures is that the systematic behavior of the daily movements of the pillar. The inclination values in an hour in a day are nearly the same for the sequential days (see Figure 4).

Table 1 shows the maximum and minimum inclinations and amplitudes of two periods in milliradian (mrad). The amplitudes show the maximum changes in the whole period. For one meter height, the amplitudes give the same values in millimeter (mm) unit as movement. Figure 5 shows the horizontal deflection of the pillar during the first period in 2000.

Y: 2000	1dX:	2dX:	1dY:	2dY:
MAX	0.093	0.201	0.080	0.512
MIN	-0.114	-0.182	-0.114	-0.013
AMP	0.207	0.383	0.194	0.525

Y: 2002	1dX:	2dX:	1dY:	2dY:
MAX	0.052	0.305	0.072	0.233
MIN	-0.065	-0.026	-0.100	-0.077
AMP	0.117	0.331	0.172	0.310

Table 1: Maximum and minimum inclinations, and amplitudes for both periods [*mrad*]

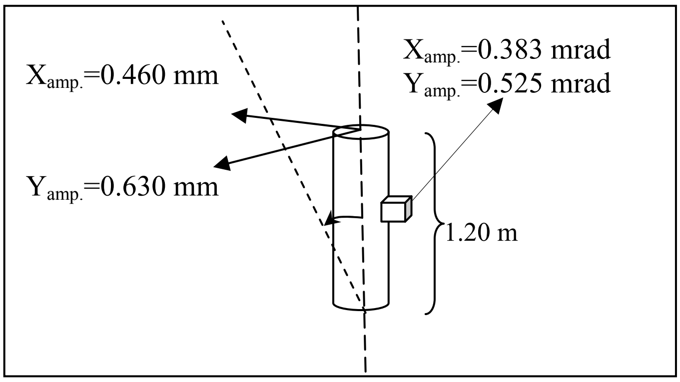


Figure 5: The horizontal deflections of the pillar in the first period in 2000.

DATE	TIME	LAT (deg)	LONG (deg)	DEPTH (km)	MAG (richter)
22.03.2000	14:49	40.76	31.00	7	3.6
27.03.2000	11:02	40.83	30.78	9	3.6
02.04.2000	18:57	40.80	30.24	7	4.1
28.02.2002	08:38	40.82	28.12	12	4.8

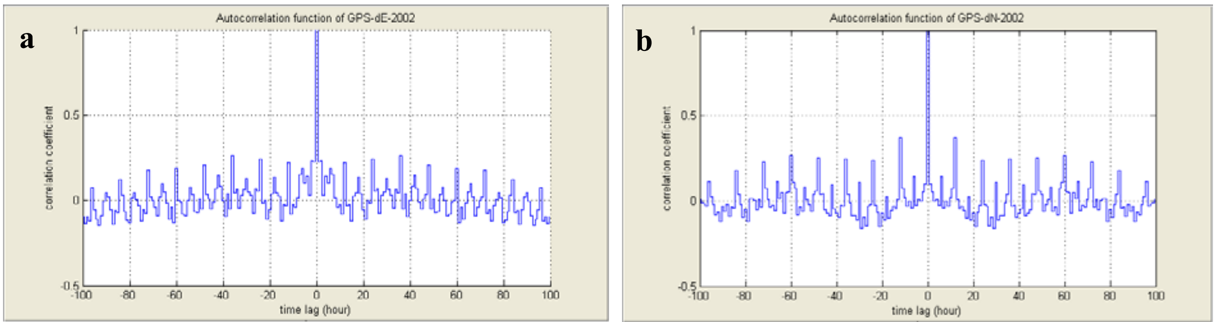
Table 2: The low-magnitude earthquakes recorded in the territory of Istanbul during the monitoring periods

4. DATA ANALYSIS

The inclination data and GPS solutions are analysed using spectral analysis techniques to clarify the amount and periodicity of the deformations of the structure. During the analysis, the correlations between the deformations and the physical effects of the nature on the structure are also tried to be clarified. Naturally the measurements include different signals and random errors. In the analyzing of a time series, generally the possible trend, which may fit linear, quadratic, exponential and so on expressions, is identified and removed in the first step (Pytharoli et al. (2004), Pagiatakis (1999)).

4.1 Autocorrelation and Cross-correlation Functions

Spectral analysis technique is applied to de-trended data. After documenting the periodicity of the data, periods and amplitudes of each periodic signal in the series are estimated. Autocorrelation functions are helpful while determining the periodicities of the series (Box et al. (1994)). This function is to determine the change of linear correlation coefficient of the time series. In similar way as that the autocorrelation function is used to identify the correlations in a single time series, whereas the cross correlation function is used for estimating the correlations between two different time series.



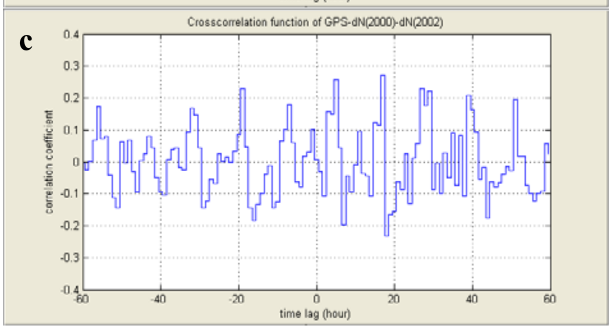


Figure 6: the autocorrelation functions of **a-** dE-2002 (easting) and **b-** dN-2002 (northing) components of GPS, **c-** the cross-correlation function between time series of dN-2000 and dN-2002.

When the correlograms are in Figure 6a and 6b considered it is seen that the autocorrelation coefficients has peaks in every 12hour and 24hour –time lags for Easting and Northing time series in 2002. Therefore the highest period can be assumed as 24hour periodicity for each of the series. The cross-correlation function between the time series of Northing components of both periods is shown in Figure 6c.

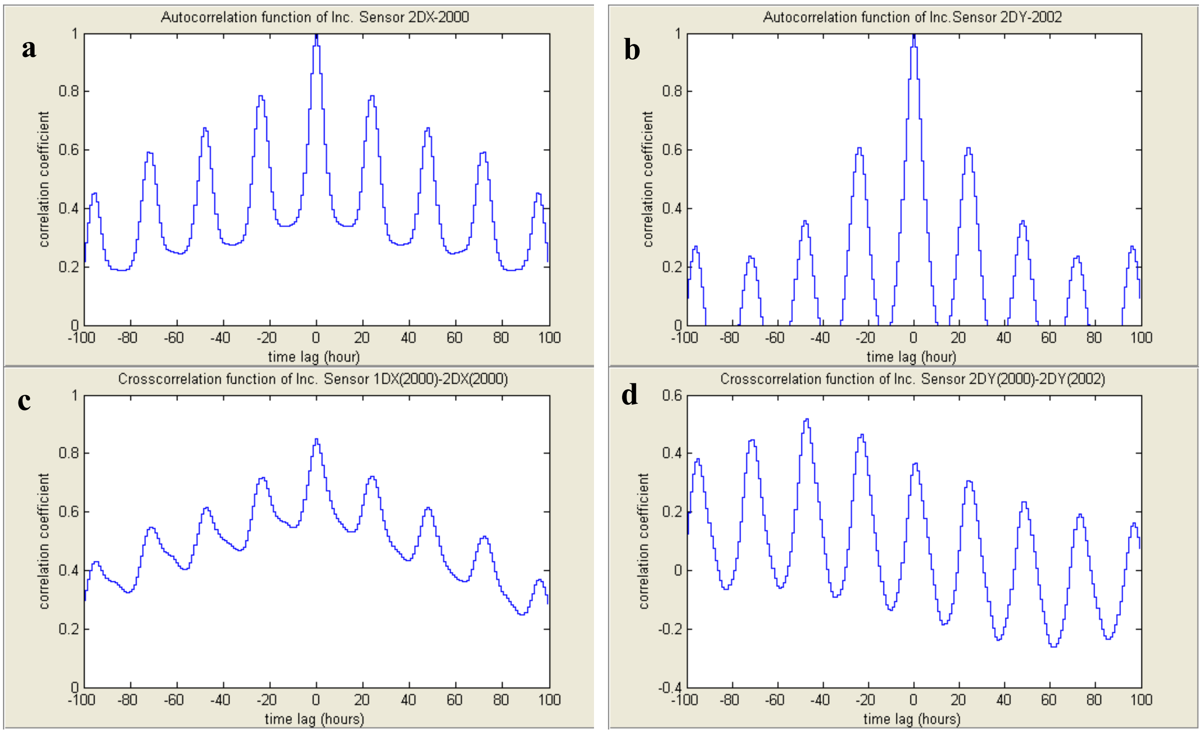


Figure 7: the autocorrelation functions of inclination observations of sensor II – north–south direction (x axis) in 2000 **a**, east–west direction (y axis) in 2002 **b**, – the cross correlation functions of the time series (inclination observations) of sensor–I and sensor–II: the data on the north–south (x axis) directions of both sensors in 2000 **c**; the cross correlation functions of the time series (inclination observations) of sensor–II: the data on the east-west (y axis) directions of both period in 2000 and 2002 **d.**

When the correlograms in Figure 7a and 7b are considered, it is seen that the autocorrelation coefficients has peaks in every 24hour –time lag. Therefore the 24hour period of the inclination movements of the pillar is clarified. Also there are correlations between two sensors and two measurements periods, according to cross-correlation functions.

4.2 The Least Squares Spectral Analysis

In the mathematical background of this spectral analysis technique, the observed time series f is considered as a function of the time t_i, i=1,2,…n. Here, the time series may have equal sampling interval or not. The main objective of LSSA is to determine and clarify the periodic signals in f, especially when f includes both random and systematic noise. With spectral analysis, f is decomposed into two components as a signal $\hat{g}$ and noise $\hat{r}$. %VAR is percentage that shows how much of $\hat{g}$ is contained in f.

LSSA technique is successful for evaluation of signals as a tool to find out the hidden periodicities in a time series having equal or non–equal intervals and this can be said as its distinction from other spectral analysis techniques.

The inclination data were analysed with LSSA method using Least Squares Spectral Analysis Software Version 5.02 here (Anonym (2002)).

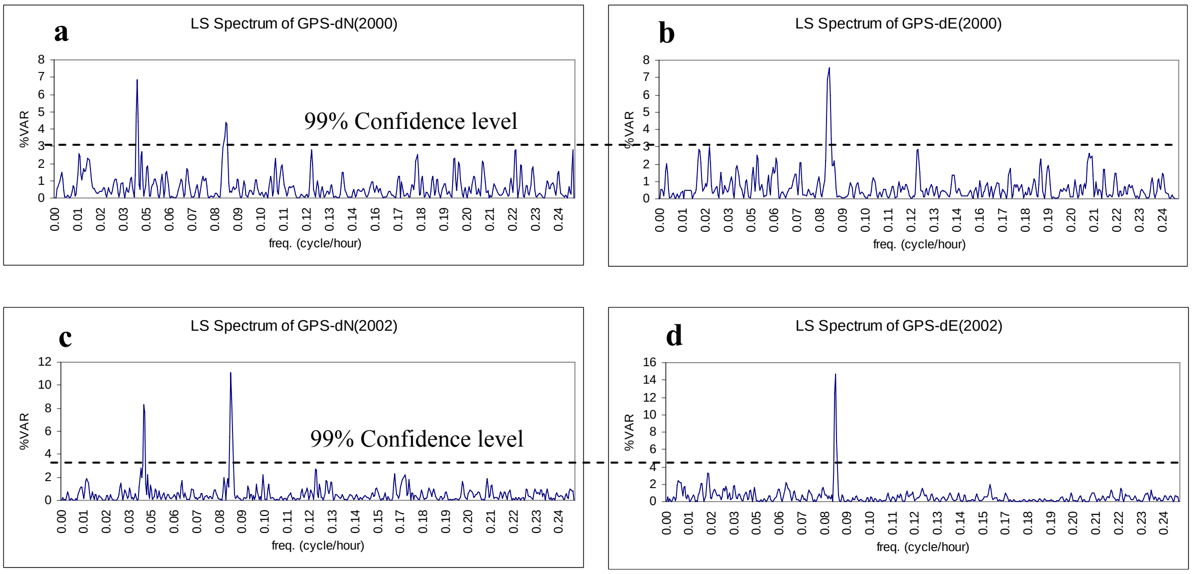


Figure 8: the Least Squares Spectrum of the time series of the Easting and Northing GPS components for both campaigns 2000 and 2002.

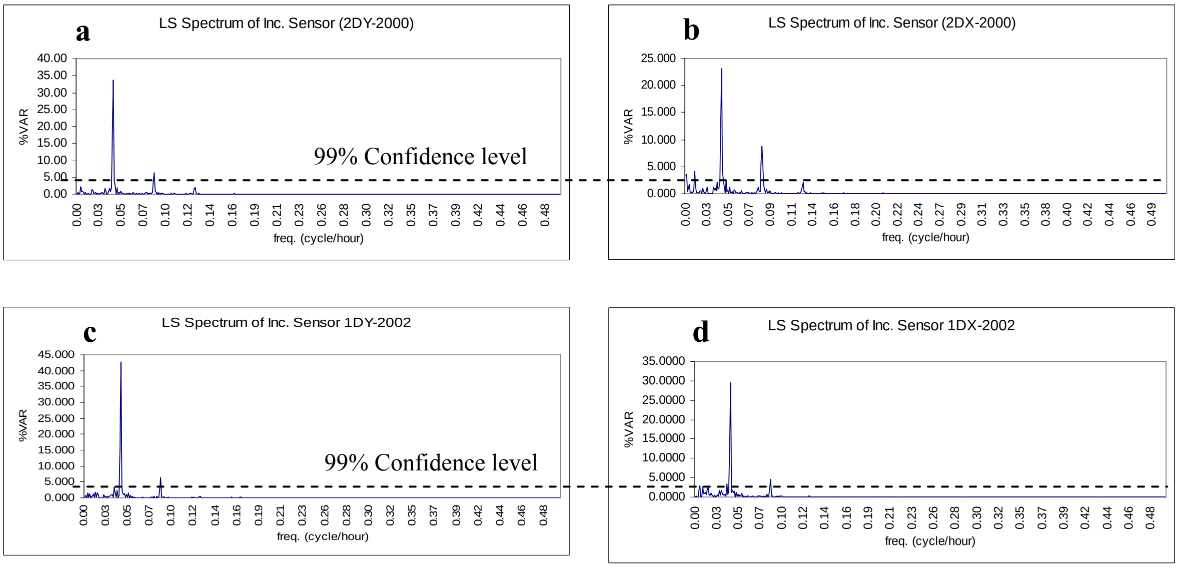


Figure 9: the Least Squares Spectrum of the data of sensor II for 2000, and of the data of Sensor I for 2002.

According to Figures 8 and 9, the Least Squares Spectral Analysis of all GPS baseline solutions and Inclination Sensors data of both measurement periods confirm each other and shows 24hour and 12hour periodicities, except GPS Easting component. The time series of Easting component (dE) of GPS for both campaigns show only 12hour periodicity.

According to LSSA results of GPS baselines, the amplitudes of 12hour and 24hour periodicities of the Easting and Northing components are approximately equal to 0.5 mm.

In addition, the LSSA results of Inclination sensors data show that the amplitude of periodic movements of the Sensor-I is smaller than of the Sensor-II. Also the amplitudes of the 24hour period is two-times bigger than the amplitudes of the 12hour period (see Table 3). In the result, the horizontal deflections of the ISTA station, derived from the inclination data and from the GPS baseline solution are equal.

DESCRIPTION	VALUE	AMPLITUDE	SIGMA	SIGNIF
INC-2DY-2000	(hour)	(mrad)	(mrad)	99.00%
Datum shift	0.00000000D+00	0.18338759D-01	0.49367926D-02	YES
linear trend		0.39439488D-03	0.13252492D-04	YES
Periodic constituent	0.23851822D+02	0.62308967D-01	0.38266342D-02	YES
Periodic constituent	0.11953289D+02	0.31207737D-01	0.34240895D-02	YES

DESCRIPTION	VALUE	AMPLITUDE	SIGMA	SIGNIF
INC-1DY-2002	(hour)	(mrad)	(mrad)	99.00%
Datum shift	0.00000000D+00	-.21981433D-01	0.15679467D-02	YES
linear trend		0.75250431D-04	0.39159487D-05	YES
Periodic constituent	0.23851822D+02	0.26276774D-01	0.10986924D-02	YES
Periodic constituent	0.11953289D+02	0.10095206D-01	0.10988519D-02	YES

Table 3: The LSSA results for inclination data of the Sensor II (2DY) in 2000 and the Sensor I (1DY) in 2002

4.3 The Wavelet Analysis

Wavelet analysis (WA) is a particular time-scale or space-scale representation of the signals which has found a wide range of applications in signal processing and applied mathematics in the last few years. The Fourier transformation is able to reveal the frequencies present in a signal. But it is not possible to say when they are present. This is the starting point for the wavelet transformation.

Wavelet analysis is capable of revealing some aspects of the data, like trends, breakdown points, discontinuities in higher derivatives, self-similarity and etc, that other signal analysis techniques miss. Furthermore, because it affords a different view of data than those presented by traditional techniques, wavelet analysis can often compress or de-noise a signal without appreciable degradation.

If a signal is similar to itself at different scales and spaces (times), then the wavelet coefficients also will be similar at the scales and times. In the coefficients plot, which shows scale on the vertical axis, this self-similarity generates a characteristic pattern. In this study the coif3 wavelet was used in CWT process to get the similarities in the signal.

$$C(a,b) = \int_R s(t) \frac{1}{\sqrt{a}} \Psi\left(\frac{t-b}{a}\right) dt \qquad (1)$$

The wavelet transform is defined with equation 1. Here, *C(a,b)* are the different wavelet coefficients, a is the scale, b is the translation (time, space) s(t) is the signal, t stands for time and Ψ is the wavelet function. That means the wavelet function is scaled and shifted along the axis and therefore the signal, too. This time-scale joint decomposition structure makes wavelet analysis interesting for time series analysis (Percival et al. (2000)).

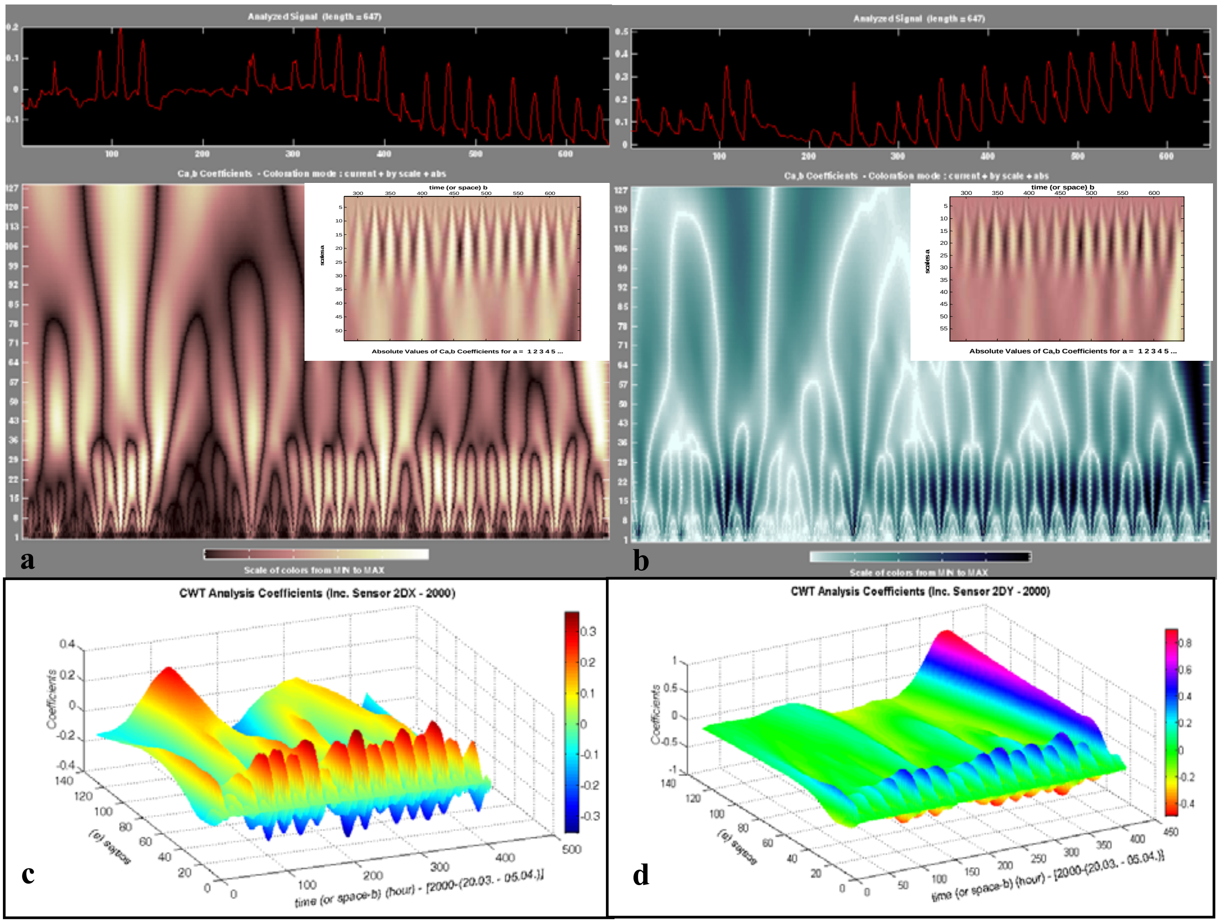


Figure 10: Continuous Wavelet Transform 2D figures of Sensor II X-axis (2DX-2000) Data, **a** - Sensor II Y-axis (2DY-2000) Data, **b-** Continuous Wavelet Transform 3D figures of Sensor II X-axis (2DX-2000) Data, **c** -Sensor II Y-axis (2DY-2000) Data, **d**

According to 2D and 3D wavelet coefficients plots in Figure 10, Similarly LSSA technique 24hour periodicity for two axis of Inclination Sensor II in 2000 can be seen.

In Figure 11a and 11b, the wavelet coefficients plots of the GPS (Easting and Northing components) time series can be seen. According to this two dimensional plots it is difficult to see any periodicity. But, according to wavelet power spectral density estimation of wavelet coefficients in Figure 11c, the 24hour and 12hour periodicities can be recognized.

The wavelet coefficients are used to estimate power spectrum by summation of the squared coefficients in each scale. Also with the summation of the squared coefficients in each space (time), wavelet variance can be estimated.

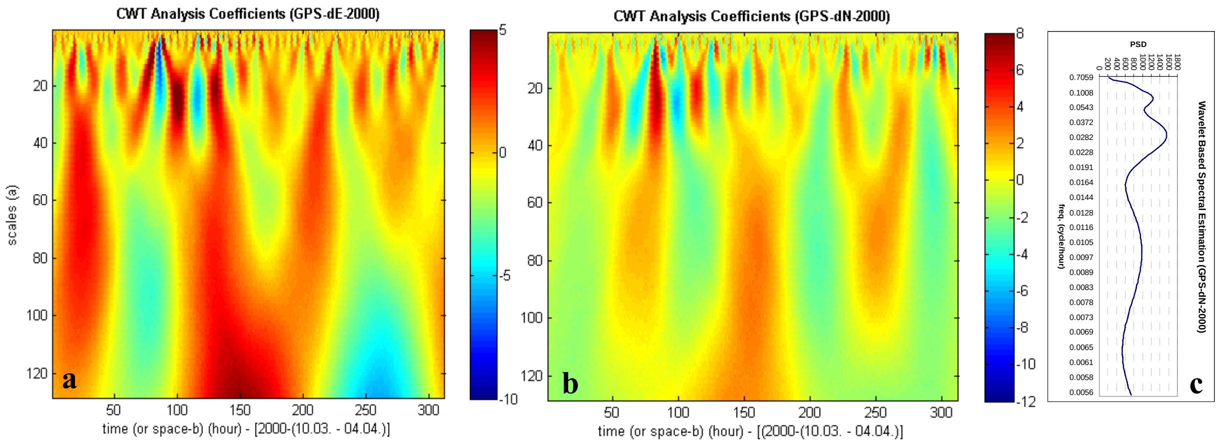


Figure 11: Continuous Wavelet Transform 2D figures of GPS Easting (dE-2000), **a** - GPS Northing (dN-2000), **b** components, - and the Wavelet Power Spectrum of dN-2000, **c**

5. RESULTS AND CONCLUSION

In this investigation, the movements of the monument of ISTA-IGS station have been monitored using digital double axis inclination sensors in micro-radian precision and GPS baseline solutions. Each data set (of inclination sensors and of GPS baseline solutions) from the two periods was analyzed with LSSA and Wavelet analysis techniques. The results of the evaluations of the data were compared and the following results were reached.

In the LSSA and WA of the inclination data and the GPS solutions, the movements of ISTA-IGS continuous reference station have two hidden periodic components in the north–south and in the east-west directions with 12hour and 24hour periods. Autocorrelation and crosscorrelation functions also confirmed the same periods. 12hour and 24hour periodic movements with the amplitudes (given above) depend on warming/cooling effects of the whole body of the structure during the day and are natural. In addition, the movement of the pillar is bigger than of the building and no significant force that the building applied to the pillar was found. The maximum horizontal displacements of ISTA (0.5 mm in X-axis and 0.6 mm in Y-axis) come from Inclination and GPS data. This amount of displacements cannot affect the service of ISTA-IGS station.

As another considerable out come of the study; the inclination data analysis provides an important benefit to interpretation of GPS analysis results. In order to that GPS derived coordinate differences were perceived as the result of elastic movements of the structure instead of constant static deformations on the contrary of the expectations in the beginning.

LSSA and WA techniques show remarkable performance for evaluation of inclination and GPS data as a tool to find out the hidden periodicities and similarities in a time series.

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BIOGRAPHICAL NOTES

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The author graduated from the Geodesy and Photogrammetry Engineering Department of Istanbul Technical University (ITU) in June 1996. In January of 1998, he started to study as Research Assistant in Geodesy Division of ITU. He graduated from Geodesy and Photogrammetry Engineering Master Program of Institute of Science and Technology at ITU in June 1999. He studied “Monitoring and Analyzing Deformations of Karasu Viaduct Using GPS Measurements” as his MSc thesis. He attended to Doctorate Program of Geodesy in Institute of Science and Technology of ITU in the year of 1999. Still, he is studying his PhD thesis with the subject of “Deformation Analysis Using GPS and Precise Levelling Measurements” and employed as a research assistant at ITU. His scientific interests include Deformation Analysis, GPS Measurements and Data Processing, Hardware of Computers.

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