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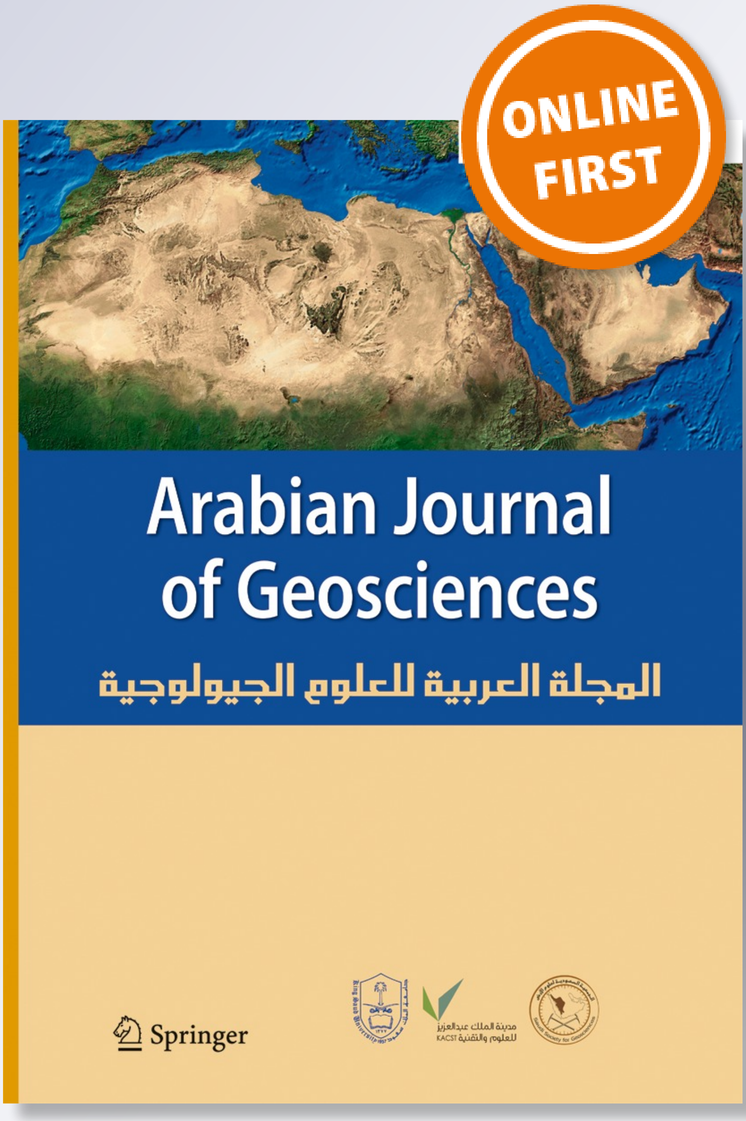

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ORIGINAL PAPER

Constraints on a geodetic time transfer network in Iran

M. Khoshmanesh · M. Mashhadi Hossainali

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Abstract Iran is a developing country, and nowadays, a demand to establish a time transfer system can be sensed more than anytime. On the other hand, global positioning system (GPS) is one of the most efficient and accurate systems in precise time estimation and dissemination domain. This study aims to investigate the different accuracy limiting effects of a time transfer system in a geodetic point of view. For this purpose, a simulation study is performed in which pseudo-range and carrier phase observations are simulated for some GPS stations in Iran. The baselines for time transfer have been chosen in a way that the maximum effect of each bias source can be analyzed. Therefore, the results of this study can be used in order to design the absolute and relative locations of the GPS stations equipped with external atomic frequencies in Iran considering a specific application. As a result, the most prominent bias source is the site-specific troposphere parameters which produce a variation of more than 1 ns in the time transfer results. Other bias sources including bias in the coordinate components and orbital information have a considerable impact only for time keeping purposes. Additionally, the influence of noise of the carrier phase and pseudo-range observations is analyzed. Variations of clock estimations between consecutive epochs up to 70 ps and day boundary discontinuities up to 0.6 ns, respectively, are the results of measurement errors. On the other hand, a time transfer between H-masers located at US Naval Observatory and National Resources Canada has been conducted to pursue a standard and efficient algorithm to deal with the problem of day boundary jumps. The method of overlapping batches with 12 h coverage of each of the involved days is applied to overcome this problem. The results of this method show a considerable decrease in the magnitude of the day boundary jumps.

Keywords Time transfer · GPS · Site-specific troposphere parameters · Day boundary jumps

Introduction

Precise time transfer is one of the most prominent necessities in the modern world. Positioning and navigation services, communications, power grids, banking and finance, emergency services, and environmental resources management are just some examples of the vast variety of applications dealing with precise time transfer. On the other hand, Iran is a developing country, and nowadays, a demand to establish a time transfer system can be sensed more than anytime. It is justifiable to say that a comprehensive study on different aspects of the problem and devising a standard method can be regarded as the most important part of such a project. Therefore, this study aims to investigate the different accuracy limiting effects of a time transfer system in the country from a geodetic point of view.

The utilized method for investigating different bias sources is based on the approach proposed by Dach et al. (2003). They simulated data to study the error propagation for the time transfer solution using global positioning system (GPS) carrier phase observations. Additionally, they showed that the effect of different bias sources may be a function of the direction of the time transfer baseline. Although these two factors are common between this study and the aforementioned research, different extents of the two case studies have led to different results. On the other hand, the approach used in our study aims to determine the absolute and relative positions of the GPS stations to be equipped with external atomic frequencies. This clarifies the demand of an investigation study in Iran through present research.

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Establishment of an accurate and realizable time scale has been always a field of interest and research (McCarthy and Seidelmann 2009). Presence of accurate and precise atomic clocks in the GPS satellites and some of the tie stations of the International GPS Service for Geodynamics (IGS) introduces a great potential in realizing an accurate time scale. A useful description on the IGS time scale as well as the potential of geodetic methods in time estimation and dissemination can be found in Ray and Senior (2003). They report on the IGS/BIPM pilot project whose aim is accurate time and frequency comparisons using GPS phase and code measurements. Results of present paper can be a worthy contribution to this pilot project.

The next section of this paper aims to present the concepts of time transfer using GPS carrier phase and pseudo-range observations. The impact of each of the bias sources dealing with the time transfer results is investigated using a simulation study in the third section. Day boundary jumps will be introduced as a serious problem in time transfer in the forth section of this research. The method devised by Dach et al. (2003) is used for producing a continuous time transfer result.

Time transfer through GPS, the concepts

Time transfer refers to techniques and models used to compare remote clocks. A number of techniques with different accuracies are available today depending on the users' needs. On the other hand, though GPS has been established for navigation and positioning purposes, nowadays this system plays a key role in the accurate time estimation and dissemination domain. GPS has its own time scale called GPS System Time (GST) which is different from UTC, approximately by an integer number. This approximation is in the order of less than microsecond and is generally of order of tens of nanosecond (McCarthy and Seidelmann 2009). The integer offset of GST and UTC is due to the fact that leap seconds (see, e.g., Nelson et al. 2001) are not accounted for in GST. The clocks of the GPS system, located in monitoring sites and in the GPS satellites, are used to realize this time scale.

The observation equation for GPS carrier phase measurements of a station r and satellite s may be written as:

$$\Delta\phi_r^s\lambda = \rho + c(\delta^s - \delta_r) + N_r^s\lambda + \rho_t - \rho_i + \varepsilon \qquad (1)$$

in which ρ is the geometrical distance between the positions of satellite s at transmission and receiver r at reception time. The atmospheric biases ρ_t and ρ_i are the corresponding delays of the carrier signal due to troposphere and ionosphere, respectively. In this equation, δ^s and δ_r are the satellite and receiver clock biases with respect to GST, ε is the observation error and N_r^s is the initial phase ambiguity. In the time transfer problem, the geometric distance ρ is assumed to be known. The known positions of receiver and satellite are used to determine this parameter. Moreover, tropospheric refraction can be modeled and ionospheric refraction may be eliminated using ionosphere-free combination of the GPS phase measurements. Thus, the difference between satellite and receiver clock biases and the initial phase ambiguity constitute the unknown parameters of this equation.

Clock solutions can be obtained either in the network mode or through precise point positioning. In the first case, all the stations and clock parameters are solved in a relative sense. This is due to the appearance of the difference of satellite and receiver clock biases in the system of observation equations. Therefore, in this mode, the clock parameters are estimated for all but one clock. Alternatively, an ensemble of clocks may be chosen as a reference. In either of these two approaches, there are two ways to realize the reference clock. In the first case, the reference clock(s) may be fixed to a priori amount, and no clock corrections are estimated for it. On the other hand, clock corrections can be estimated for all clocks including the reference clock(s). In this case, the sum of clock estimates for all selected reference clocks is set to zero in a so-called zero mean condition solution. Of course, fixing a reference clock to a priori amount makes sense in the case of synchronization of one or more stations with respect to this clock. In this case, the difference between the clock bias of each of the receivers and the corresponding amount for reference receiver is estimated in each epoch. However, presence of observation gap in the reference receiver leads to singularity in the corresponding epochs.

Carrier phase measurements are more accurate than pseudo-ranges. Therefore, they are preferred for estimating the clock parameters. Application of carrier phases is not a straightforward process. This is because the initial phase ambiguities are not a priori known. Additionally, in a time transfer solution using only the carrier phase observations, hardware delays (see, e.g., Powers et al. 1998 and Powers 1999) are absorbed by initial phase ambiguities. This prevents initial phase ambiguities to be integer numbers (Dach et al. 2007). On the other hand, in a pure pseudo-range time transfer solution, the hardware delays remain in the clock parameters. Therefore, to estimate the clock parameters, pseudo-ranges and carrier phase observations have to be used together in a combined data analysis process. This not only makes the de-correlation of the initial phase ambiguities and the clock parameters plausible but also provides the possibility of benefiting the high accuracy of carrier phases for the accurate estimation of the clock parameters. The different accuracy level of the two measurement types is taken into account by weighting the data in the parameter estimation process (Dach et al. 2007).

Since the station coordinates and tropospheric delays are introduced as known parameters to the system of observation equation, their accuracy should be carefully taken into account. These parameters can be also estimated together with the clock parameters in the main system of normal equations.

However, the problem of computing resources will be raised when the amount of epoch parameters is increased (Dach et al. 2007). On the other hand, Dach et al. (2007) show that the results of clock estimates are different in order of tens of picoseconds, when either of these two approaches is used.

Error propagation for time transfer through GPS

A simulation is performed here in order to study the propagation or impact of various sources of error in time transfer using GPS, onto the clock parameters. This is done separately for every source of bias. For this purpose and to understand the challenging features of the time transfer problem in Iran due to each source of bias, the most sensitive baselines to every bias are chosen, and the data are simulated for the involved stations. On the other hand, to obtain a multiple day continuous time series result, data are simulated for three successive days. The main aim of this study is to determine or at least provide some constraints on the absolute and relative locations of the GPS stations to be equipped with external atomic frequencies in Iran. However, maximizing the accuracy of the time transfer results between these stations is the most important criteria in this problem. Most suitable positions for locating the GPS stations to be equipped with external atomic frequencies are naturally the stations of the Iranian Permanent GPS Network (IPGN). Therefore, this simulation study is limited to these stations. The spatial distribution of the IPGN stations which provide a uniform coverage within the country and the network of fiducial points has been used for constraining the IPGN stations as the terrestrial datum in this research is depicted in Fig. 1.

The advantage of a simulation study is that the same inputs and conditions may be used in the process of clock estimation as well. It means that when the condition of simulation is applied in the parameter estimation, the same results should be achieved. On the other hand, varying either of these conditions and input parameters will change the results. Variations in the obtained results reflect the influence of the changed parameter or condition on the sought solution.

Since the positions of satellites and receivers are introduced as known to the time transfer process, the impact of every source bias affecting these parameters has to be analyzed: Ocean tidal loading (OTL), orbital error, and bias in the coordinates of the fiducial points applied for constraining the datum as well as tropospheric refraction are considered as the bias sources affecting the receiver coordinates. Moreover, orbital error can directly influence the clock parameters in time transfer at zero-difference level. Of course, noise in the carrier phase and pseudo-ranges can be regarded as measurement errors. Therefore, the impact of these errors onto the clock estimates should also be analyzed.

Stations' coordinates

Stations' or receivers' coordinates are obtained through least-squares adjustment of doubly differenced carrier phase and code measurements. They are then introduced as known in the clock estimation process. Since the station coordinates are held fixed in this procedure, every bias in the estimated coordinates directly influences the time transfer results. Here, the main aim is to investigate the propagation mechanism of these errors onto the clock parameters. For this purpose, the effect of

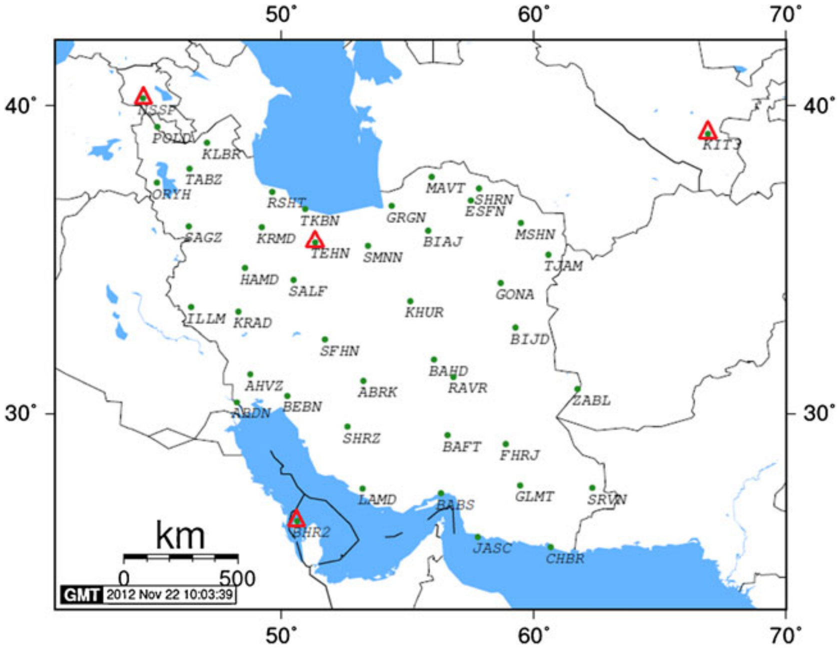

Fig. 1 Locations of the IPGN stations and the IGS fiducial points within and around Iran

1 cm bias in the vertical and horizontal components of stations' coordinates is investigated separately in two different modes: At first mode, the bias is only introduced to the coordinate components of one of the involved stations. The effect of introducing the same amount of biases to the coordinate components of both of the involved stations is analyzed in the second mode. For this purpose, three IPGN stations are chosen in a way that they produce two baselines in west–east (TEHN to MSHN) and north–south (TEHN to SHRZ) directions. The obtained results reveal that the impact of vertical and horizontal biases when applied to one of the involved stations is independent of the direction of the time transfer baselines mentioned above. To come up with an idea on the impact of the length of the time transfer baseline when the receiver coordinates are contaminated by 1 cm bias, the baseline TABZ-MSHN is also analyzed. The length of this baseline is almost twice as large as the length of previous ones. The results reveal that the impact of bias in the coordinate components of one of the involved stations does not depend on the length of the time transfer baseline as well. Figure 2 shows the obtained results.

The maximum variation due to bias in height may reach to more than 20 ps peak to peak in a daily solution. The maximum variations due to *X*- and *Y*-components are 140 and 120 ps, respectively. Another noticeable point which can be seen in these figures is the upward or downward trend of this effect in each processing batch. Therefore, continued upward or downward trend in case of longer processing batches is anticipated. This idea is confirmed using the results of a 3-day solution which is illustrated against the corresponding results for a daily solution in these figures. Considering the length of a processing batch and the resulted variations in the clock estimates, a threshold can be set up for the reliability of the stations' coordinates. Furthermore, comparing the results of a daily solution with the corresponding amounts for a multiple day can assist in detecting the bias in the coordinate components. In fact, the systematic jump in the obtained results (which can be seen for the first and the last day in 3-day solution) reflects the existence of a bias in the coordinate components.

In the second mode, the impact of bias in the coordinate components of both of the involved stations is analyzed. Based on the results reported by Dach et al. (2003), the impact of a bias in the horizontal components is much smaller as compared to the effect of a similar bias in the vertical one. Therefore, we have ignored analyzing the impact of horizontal biases in this research. On the other hand, Dach et al. (2003) showed that increasing the longitude difference between the two involved stations amplifies the impact of a bias in the vertical components of the stations' coordinates. Based on this idea, the longest baseline between the IPGN stations is the most sensitive one to this source of bias. This baseline is directed west–east and is located between stations MSHN, at the northeast of the country, and SAGZ, located at the northwest. However,

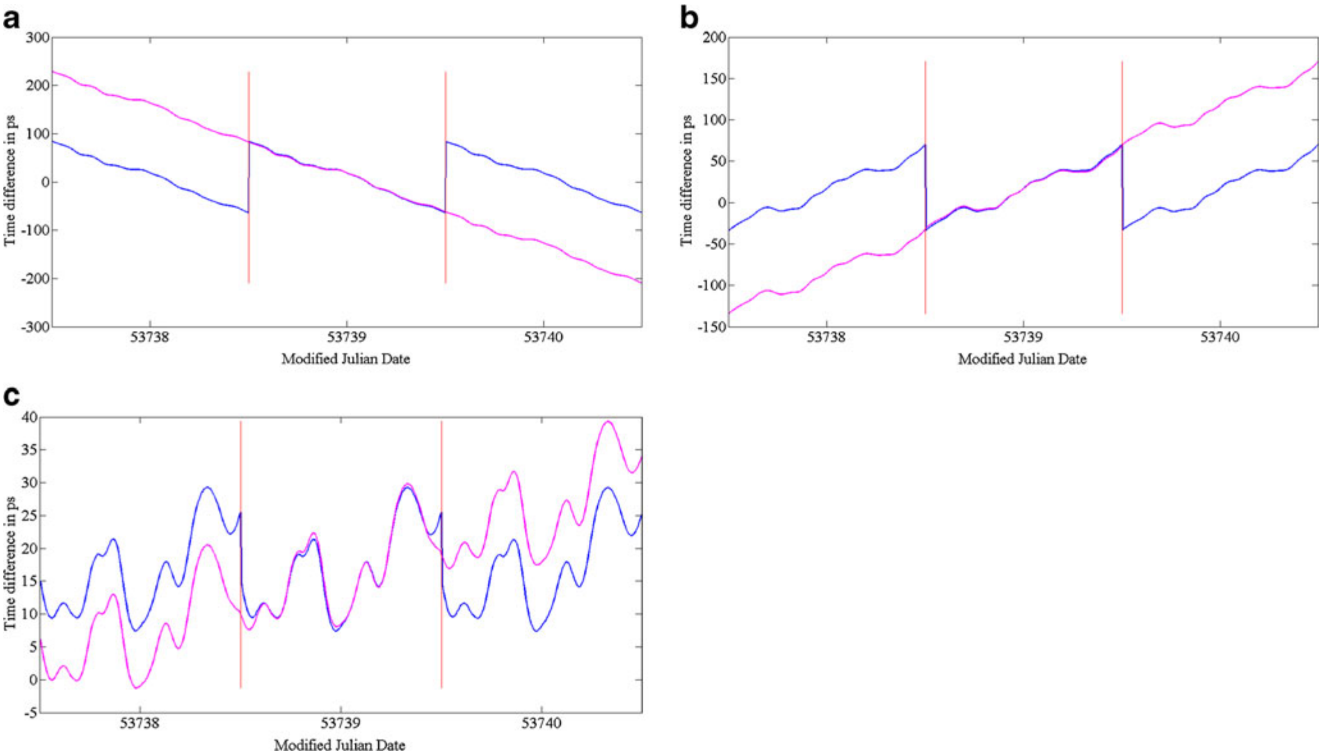

Fig. 2 Effect of 1 cm bias in the height of reference station (TEHN) on the time transfer solution. Simulated data for carrier phase and pseudoranges are not contaminated by noise. *Lines in blue* are the results from daily solutions, and *lines in magenta* are the results from 3-day solution: **a** *X*-component, **b** *Y*-component, and **c** *Z*-component

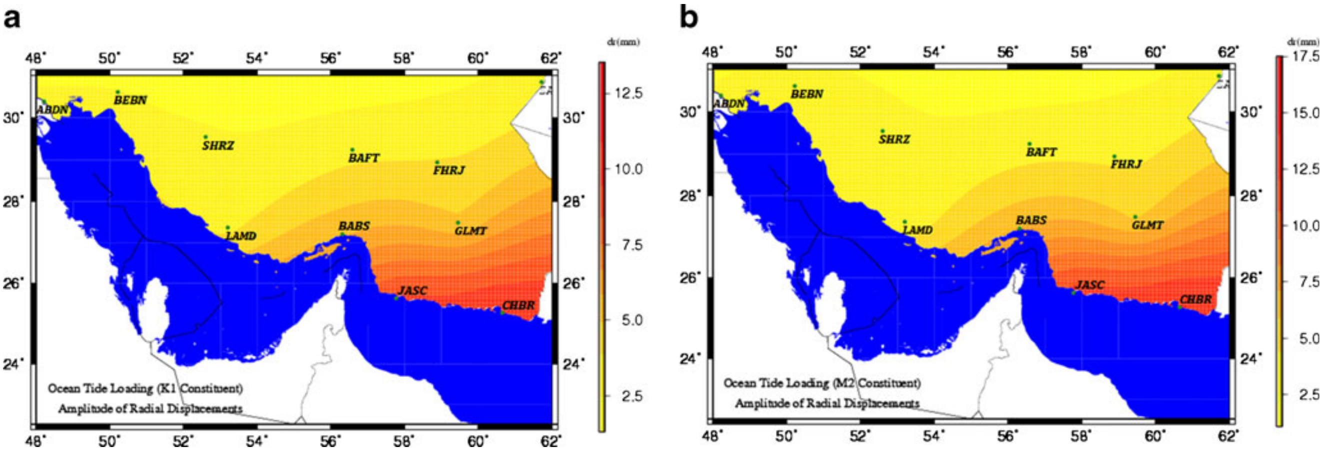

Fig. 3 Magnitude of displacements at southern part of Iran in radial direction due to **a** diurnal constituent (K1) and **b** semidiurnal constituent (M2)

based on the obtained results, a vertical bias of 1 cm leads to sub-picosecond variations in the time transfer results.

Ocean tidal loading

Ocean tidal loading is a periodic crustal displacement caused by the change in the distribution of mass due to ocean tides. The surface displacements may reach up to several centimeters in the vertical component for coastal areas; for inland sites, the impact is much smaller (Vey et al. 2002). Therefore, neglecting OTL leads to introducing biases in the coordinates of the receiver, especially when the station is located close to sea. Based on the results obtained in "Stations' coordinates" section, the impact of this source of bias is maximized in a time transfer baseline whose one station is located close to sea and the other one is in an inland position. In this case, the coordinate components of the coastal station are affected, while the other station is immune against this source of bias.

South of Iran is bounded with Oman Sea and Persian Gulf. As a matter of fact, most of the strategic industries of Iran are located in this area. Thereof, locating one or more GPS stations equipped to be with external atomic frequency in southern area of Iran seems to be a necessity for the country. This clarifies the importance of investigating the OTL's impact on the time transfer results. Southern stations of IPGN start with ABDN in southwest and ends to CHBR located in the southeast of the country. Figure 3 shows the vertical displacement of southern part of Iran due to two major constituents of tide, i.e., the dominating diurnal (K1) and semidiurnal (M2) constituents of the Moon. Ocean loading coefficients required for computing the corresponding horizontal and vertical displacements are obtained from OTL charts which are based on global models and are presented through the web service at http://froste.oso.chalmers.se/loading/.

According to these figures, the magnitude of displacements is severer in the eastern coastal stations compared to the western ones. Thereof, to come up with an idea about the minimum and maximum effect of OTL on time transfer results for the coastal stations of Iran, ABDN and CHBR as coastal and MSHN as inland station are chosen for this study. The impact of OTL on the time transfer between two coastal stations and the station located inland (MSHN) is depicted in Fig. 4.

The impact of OTL is completely different on the two baselines above: A peak to peak variation of about 20 ps is obtained for station ABDN, while the peak-to-peak impact of OTL on the time transfer results for CHBR has a magnitude of

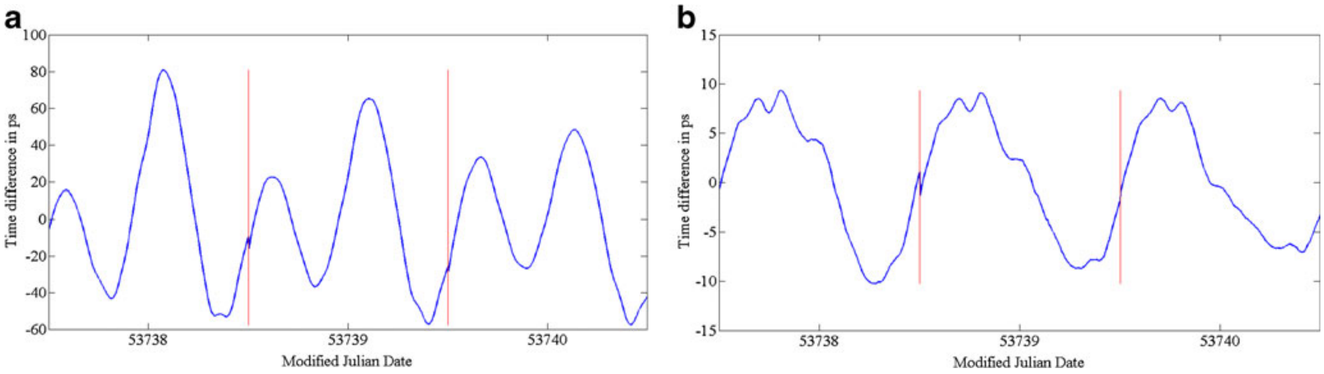

Fig. 4 Effect of ocean tidal loading on time transfer between coastal and inland stations, simulated data for carrier phase, and pseudo-range without noise: **a** CHBR to MSHN and **b** ABDN to MSHN

Table 1 Applied biases in the coordinates' components of fiducial stations (in centimeters)

	NSSP	TEHN	KIT3	BAHR
X	−1	1	1	−1
Y	1	−1	−1	1
Z	−1	−1	1	1

about 130 ps. Also, the periodic variations of the tides, especially semidiurnal effect, can be vividly seen in the obtained time transfer results at this station (CHBR). As the result for timing purposes, IPGN stations located in the southwestern part are preferred to the stations located in the southeastern part of the country.

Impact of datum

GPS networks are commonly fixed or constrained to one or more fiducial points. Kaniuth (1997) demonstrated the impact of biases in a realization of the reference frame onto the relative point positions of a regional GPS network. The types of biases addressed therein include bias in the coordinates of fiducial points and orbital errors. Here, the main aim is to achieve some insight into the sensitivity of IPGN to the biases of the fiducial coordinates. The impact of orbital errors is separately analyzed in the following section. Figure 1 illustrates the set of fiducial points have been used for constraining the IPGN stations as the terrestrial datum.

The biases quoted in Table 1 have been applied to the ITRF2008 coordinates of the fiducial stations above. Coordinates of the network stations are computed using the biased and unbiased fiducial coordinates. Differences of the corresponding components of the stations' coordinates are given in Fig. 5.

According to this figure, the maximum distortion in every coordinate component is less than 1.5 mm except for the Y-component of station TABZ. At this station, the absolute distortion of the Y-component reaches to 1.6 mm. Following "Stations' coordinates" section, this amount of bias in the coordinates of the stations leads to completely negligible variations in the time transfer results.

Tropospheric effect

Troposphere biases are orders of magnitude above the noise level of the phase measurements. Therefore, their influence must be reduced to make full use of the accuracy of these measurements (Dach et al. 2007). The impact of troposphere can be partially removed by either modeling the corresponding delay without using the GNSS observables, e.g., using ground meteorological data or water vapor radiometers, or through their solution in a general GNSS parameter estimation process.

Tropospheric delay (parameter ρ_t in Eq. 1) can be written as (Dach et al. 2007):

$$\rho^s_{t,r}(t,A,z) = \underbrace{\rho_{apr,r}\left(z^s_r\right)}_{\text{a } priori\ model} + \underbrace{\rho^h_{t,r} f\left(z^s_r\right)}_{ZPD} \tag{2}$$

$$+ \underbrace{\rho^n_{t,r}\frac{\partial f}{\partial z}\cos A^s_r + \rho^e_{t,r}\frac{\partial f}{\partial z}\sin A^s_r}_{horizontal\ \ gradients}$$

where t is the observation time, $z_r^{\ s}$ and $A_r^{\ s}$ are the zenith and azimuth of satellite s as observed from station r, $\rho_{\mathrm{apr},r}(z_r^{\ s})$ is the slant delay according to an a priori model, $\rho^h_{t,r}$ and $f(z_r^{\ s})$ are troposphere delay at the zenith of station r or zenith path delay (ZPD) and a mapping function, and $\rho^n_{t,r}$ and $\rho^e_{t,r}$ are the horizontal north and east troposphere gradients. It is noticeable that the tropospheric delays are computed using a priori models while site-specific ZPDs and the gradient parameters are estimated within the processing step. In fact, these parameters are introduced as unknown in the system of normal equations.

Refraction index for the GNSS signals in troposphere is a function of temperature, pressure, and humidity (Musa and Tsuda 2012). Thereof, a time transfer baseline is most sensitive to tropospheric delay if meteorological conditions are different most at its end points positions. To propose such a baseline, having a climate model of Iran is mandatory. Figure 6 shows the climate classification of Iran based on two different meteorological parameters, i.e., temperature and humidity (Alijani et al. 2008).

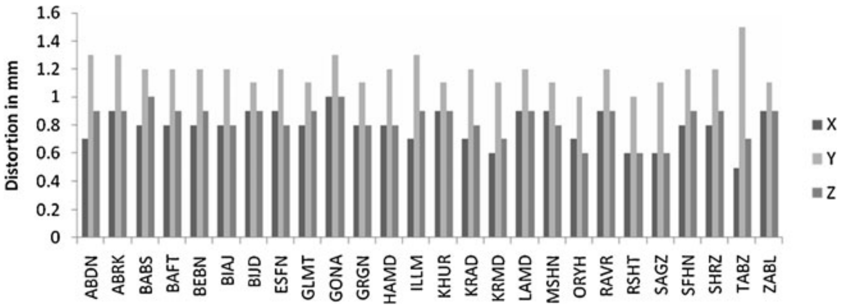

Fig. 5 Coordinate differences (in millimeters) between adjustments with and without applying fiducial point errors

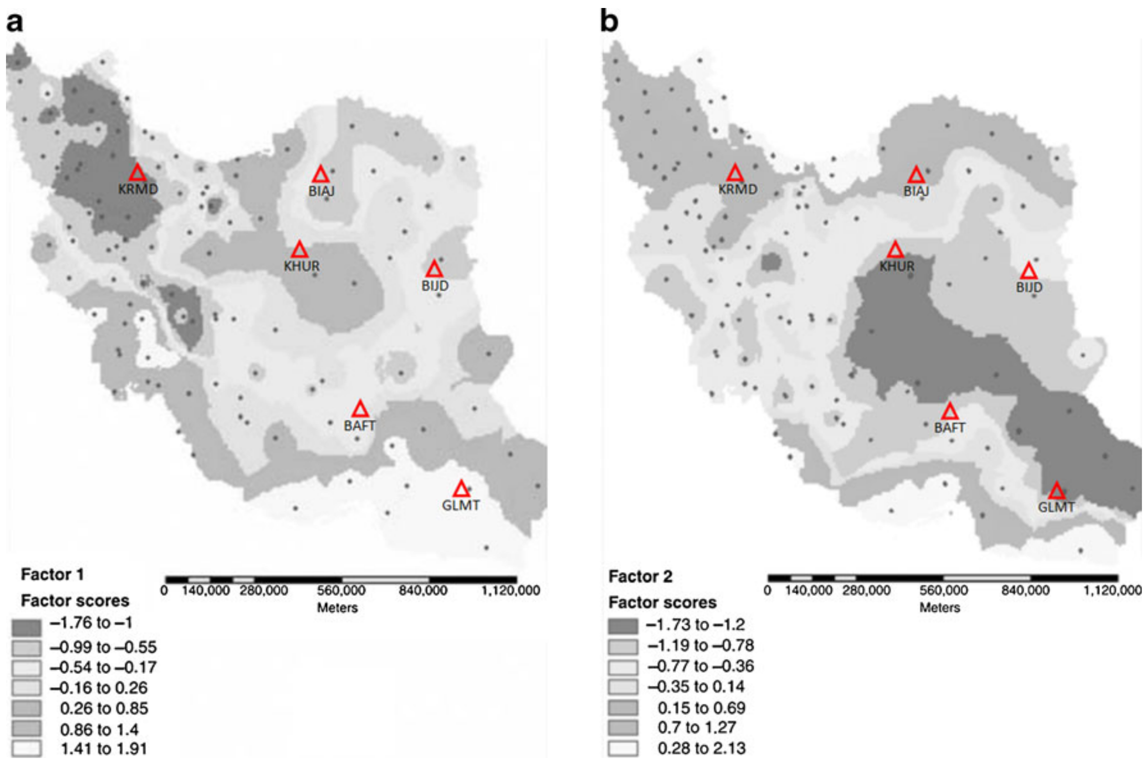

Fig. 6 Meteorological classifications of Iran based on climatological factors: **a** temperature and **b** humidity

Figure 6 suggests KRMD and GLMT as stations with the maximum inconsistency in temperature and humidity. However, to illustrate the minimum impact of site-dependent tropospheric parameters, two pairs of stations with a similar meteorological condition are chosen as well. These are BAFT and KHUR as well as BIAJ and BIJD. The results of the corresponding analyses for DOY 274 of year 2006 are given in Fig. 7.

According to these results, site-specific troposphere parameters play a key role in the accurate synchronization of the external frequencies to be added to the GPS stations in this research. These parameters produce more than 1 ns variations in the clock solutions if meteorological conditions are not the same. This amount of variation is quite considerable in almost all applications in the time transfer domain. However, the impact of these parameters drops off to less than 0.2 ns when the meteorological conditions are similar in both stations involved in the synchronization process. This amount of variations can be neglected in almost all industrial applications of the timing process. Nevertheless, site-dependent tropospheric parameters have to be taken under attention for time scale realization or time keeping, independent of meteorological condition at the timing stations. As a conclusion, locating at least one GPS station equipped with an external atomic frequency as a reference in each meteorological class seems to be a reasonable way to defeat the impact of tropospheric biases for industrial applications of time. However, climate changes has been one of the most prominent scientific concerns of the last few decades as a result of a great many factors like global warming. Kousari and Asadi Zarch (2011) studied the trends of different meteorological parameters using 13 synoptic weather stations in Iran during the last 55 years.

To further clarify the strategy, it should be mentioned that the estimated ZPDs using real measurements are applied to generate the simulated observations, while a priori models are used for eliminating the impact of tropospheric delays in the processing step. These a priori models are a function of temperature, humidity, and pressure. These three parameters can be introduced using meteorological measurements. Alternatively, they can be derived from standard atmosphere models. In the later case which is used in the processing step of this research, height-dependent values for these parameters are assumed. Using ground meteorological data or WVR may lead to a significant drop in the impact of this source of bias. However, this research suffers from the lack of availability of this sort of data. Thereof, the proposed method to defeat the impact of tropospheric refraction on clock estimates is valid merely under assumptions considered in this paper. Since implementing this method leads to eliminating the processes in the double difference—which is necessary for estimating the ZPD values—it can be considered as a cost-effective method in the view of processing burden.

Orbital error

IGS routinely provides precise satellite time and orbital information with initial latencies ranging from 3 h for the least precise orbits to 13 days for the most precise ones. The ultra-

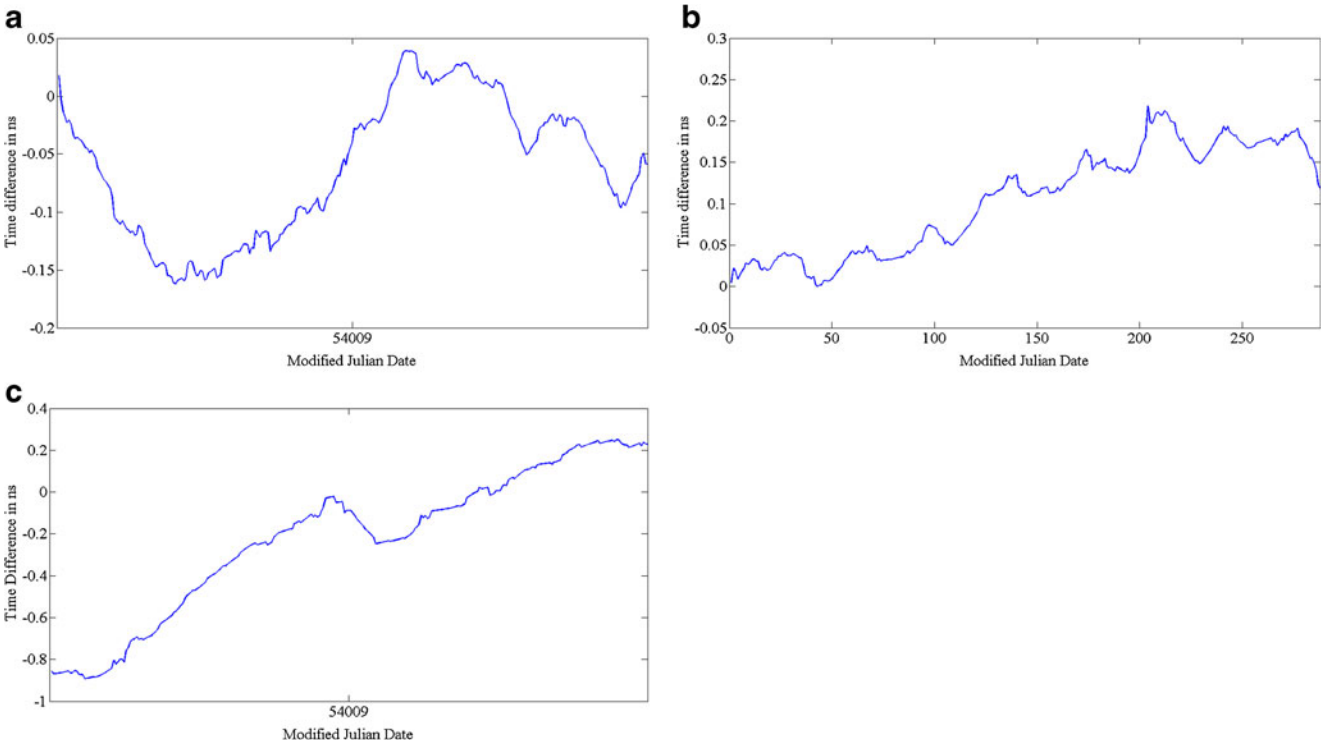

Fig. 7 Impact of site-specific troposphere parameters on the time transfer solutions **a** KHUR-BAFT, **b** BIAJ-BIJD, and **c** KRMD-GLMT; simulated data for carrier phase; and pseudo-ranges are without noise

rapid GPS orbits are released four times a day with an initial latency of 3 h. These products are intended for near real-time applications. Rapid GPS orbits cover the 24 h of the previous day with an initial latency of 17 h. Final GPS orbits are the definitive IGS orbital products and are released with a latency of about 13 days. All of these products are generated from a weighted linear combination of solutions contributed by up to eight independent analysis centers (Griffiths and Ray 2008).

Generally, the accuracy of the IGS final orbits is between 3 to 5 cm (Griffiths and Ray 2008). Error in the orbital information affects the stations' coordinates computed from doubly differenced carrier phase and code measurements. On the other hand, this information has a different role in estimating the clock parameters in zero-difference level. Kaniuth (1997) has studied the impact of a similar bias in the horizontal and vertical geocentric coordinates of satellites as well as the impact of radial, along track, and cross track biases on the station coordinates. This study shows that a bias in the *Z*-component of the geocentric coordinates of satellites can lead to the maximal impact on the estimated coordinates. Therefore, the impact of 5 cm bias in the *Z*-component of the geocentric coordinates of satellites has been investigated herein. According to the obtained results, similar to the impact of biases in the fiducial stations, the maximum distortion in every coordinate component is less than 1 mm. Again, this leads to completely negligible variations in the time transfer results (see "Stations' coordinates" section).

Following Dach et al. (2003), the impact of 5 cm radial orbital error (as the error with the largest impact on the clock estimates) on time transfer between two stations more than 6,000 km apart is about 10 ps for a daily solution. This amount of variation may be considerable for time scale realization, but is completely negligible for other technological applications of time. On the other hand, the longest baseline in Iran is less than 5,000 km. This implies the fact that the impact of orbital error does not impose any constraint in selecting the locations of the GPS stations to be used as the timing network in Iran.

Another challenging problem in orbital information is the difference between orbital products of IGS. Undoubtedly, the different latencies of these products are important in timing applications. Using Bauersima's (1983) handy rule of thumb, the impact of orbital errors is directly related to the length of a baseline. Thereof, the baseline TABZ-CHBR has been selected as the longest baseline within the country for this purpose. Figure 8 compares the effect of rapid and ultra-rapid orbits on the obtained time transfer results. IGS final orbits are used as the required benchmark for simulating the required data.

Based on the given results, the impacts of rapid and ultra-rapid orbits on the time transfer solution are almost the same. Either of rapid and ultra-rapid orbits produces a variation of about 15 ps peak to peak. Therefore, the effect of orbits on the clock solutions is negligible for all the industrial applications of time transfer. Nevertheless, near real-time application of

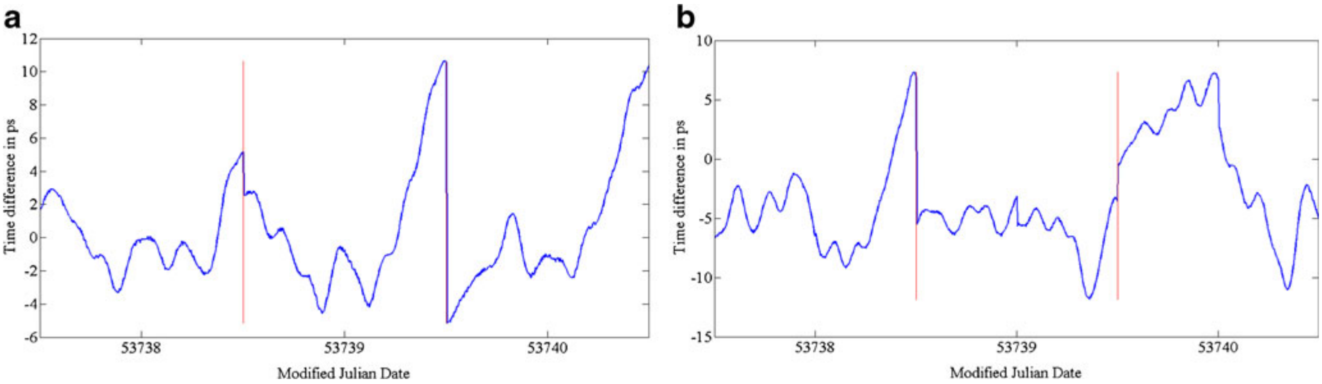

Fig. 8 Effect of rapid and ultra-rapid orbits on the time transfer solution for the baseline TABZ to CHBR, simulated data for carrier phase, and pseudo-ranges are without noise: **a** rapid orbit and **b** ultra-rapid orbit

GPS for time transfer would be only plausible using ultra-rapid orbits.

Noise of observations

Random noise affects GPS pseudo-ranges and carrier phases as it does all geodetic measurements. Sources of the noise are particularly from a human-made device, radio frequency, or electromagnetic interference. A GPS receiver's antenna, like that of any radio receiver, picks up a certain amount of noise in the form of naturally produced electromagnetic radiation. This radiation comes from the sky, the ground, and objects in the antenna's vicinity. The sky noise has two main causes: electromagnetic radiation emitted by the sun and the Earth's atmosphere. On the other hand, the ground and the objects in the vicinity of the antenna radiate energy (Langley 1997). Using best practices for the control of the environment of the GNSS reception hardware is undoubtedly the most effective method for eliminating most sources of errors on pseudo-ranges, e.g., multipath, near-field reflections, or temperature dependencies.

Stochastic model represents the characteristics of observational noise and is given in the form of variance–covariance matrix of the GPS measurements. Different methods have been used to infer a realistic representation of the stochastic properties of the GPS data. Amiri-Simkooei et al. (2007) utilized the concept of least-square variance component estimation for this purpose. On the other hand, Amiri-Simkooei and Tiberius (2007) employed a set of harmonic functions to obtain the stochastic properties of GPS measurements. Analyzing the stochastic properties of the GPS data has been confined to simplified linear combinations of the GPS carrier phase and code measurements. Therefore, a comprehensive analysis of the impact of GPS measurement errors on the time transfer results is left for an independent research. Here, a simplified variance covariance matrix is used to analyze the contribution of measurement errors onto the time transfer results.

In order to investigate the impact of the noise of pseudo-range observations onto the clock parameters, a noise with a priori sigma of 0.5 m is introduced to simulated measurements. Simulated noise is of course a function of the elevation cutoff angle of measurements. In this case, the aforementioned a priori sigma refers to an observation in zenith direction. The a priori sigma of observations at a zenith angle *z* will then be computed using a factor of 1/cos*z* (Dach et al. 2007). The impact of this noise on time transfer between TEHN to SHRZ baseline is depicted in Fig. 9a. As it can be seen in this figure, the noise of

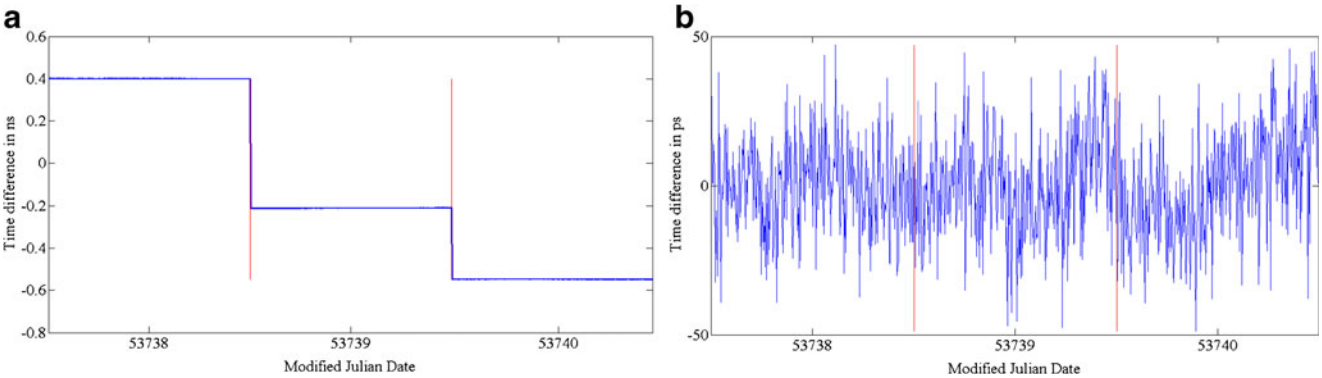

Fig. 9 Effect of noise of observation on the time transfer results for TEHN-SHRZ baseline: **a** pseudo-range observations and **b** carrier phase observations

pseudo-range observation leads to emerging the day boundary jumps. The amount of day boundary jumps due to this amount of noise on code observation reaches to a maximum of 0.6 ns in our case study. It is again emphasized that this simulation study is based on introducing a diagonal variance–covariance matrix. Introducing a more complicated variance–covariance matrix may lead to more accurate and useful results.

The effect of noise of the carrier phase observations has been investigated as well. For this purpose, a noise with a priori sigma of 2 mm has been introduced into the carrier phase observations, while the pseudo-range observations have no noise. The impact of this noise on time transfer is again shown on TEHN-SHRZ baseline (Fig. 9b).

Based on this result, noise in carrier phase measurements leads to emerge high-frequency variations in the clock estimates. In this study, the amplitude of variations is more than 70 ps, while the mean of epoch-to-epoch variations is about 20 ps. Therefore, for the purpose of time keeping, measurement noise should be carefully controlled. Type of receiver plays a key role in this respect (Tiberius et al. 1999).

Day boundary jumps

Small jumps (up to 1 ns) may occur at the day boundaries when the noise behavior varies from one day to another. This indicates that it is not possible to benefit from the entire accuracy potential of the carrier phase observations between consecutive batches in a series of time transfer solution. The discontinuities are due to the fact that the data analysis is usually done on daily basis. Consequently, a jump in the obtained clocks is seen each day at midnight, when a new computing batch is started. In fact, the mean noise characteristic of the pseudo-range observations during one computation batch is responsible for the estimated constant part of the time transfer (Dach et al. 2003). The amplitude of these jumps is highly stations-dependent (Senior and Ray 2001). In the IGS clock solutions, the RMS of the day boundary jumps for the different stations equipped with H-masers shows a large dispersion between stations, ranging from 150 ps to 1 ns (Ray and Senior 2003).

In order to overcome this problem, different methods have been devised: processing over multiple days which is used by NRCan (see, e.g., Orgiazzi et al. 2005), overlapping solutions (see, e.g., Dach et al. 2003, Bruyninx and Defraigne 1999), completely disregarding pseudo-ranges or carrier phase-only processing (see, e.g., Defraigne et al. 2007) and using an independent time transfer method (e.g., TWSTT) to obtain absolute clock datum, resolving single-differenced floating ambiguity estimates to integers (see, e.g., Delporte et al. 2007), or connecting the carrier phase ambiguities between adjacent solutions (see, e.g., Dach et al. 2005). Every method has its own advantages and disadvantages. For instance, stacking the ambiguity parameters (λN_r^s) of the carrier phase observations at the boundaries of the computing batches may cause the problem of the accumulation of the influence of different error sources on the time transfer results over a long time span (Dach et al. 2003).

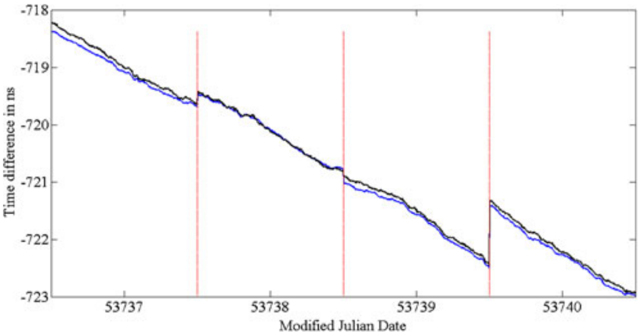

Fig. 10 Clock differences between USNO and NRC1; *black diagram* obtained from IGS clock products, and the *blue diagram* is estimated through present paper

Devising a standard and efficient algorithm to deal with the problem of day boundary discontinuities stipulates presence of real geodetic receivers equipped with external atomic frequencies. On the other hand, this study has a feasibility purpose, and such equipments are not still available in Iran. Therefore, a time transfer between H-masers located at US Naval Observatory (USNO) and National Resources Canada (NRC1) has been conducted here. The outputs of this time transfer for the four successive days are exposed in the Fig. 10. However, the results of time transfer between these two stations are compared with the corresponding amount obtained using IGS clock products. Since the receivers in the IGS tie stations are utilized to realize the IGS time scale (IGST) (Ray and Senior 2003), the clock bias of these stations is estimated with respect to IGST.

In this figure, the results of this paper and the IGS clock products are illustrated using blue and black diagrams, respectively. A jump more than 1 ns is seen between days 53,739 and 53,740. In order to overcome day boundary jumps, the method of analyzing every observation twice in different computing batches which is proposed by Dach et al. (2002) has been

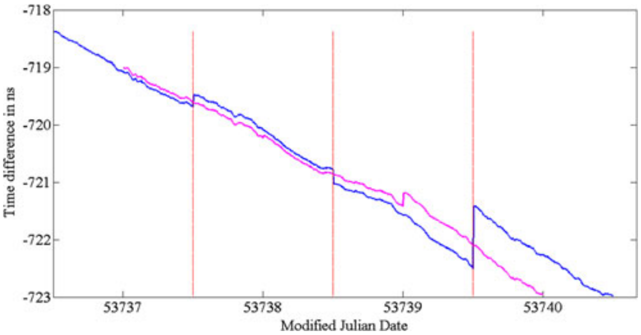

Fig. 11 Clock differences between USNO and NRC; *blue lines* are the results of daily batches; *magenta lines* show the results of overlapping batches

used. In this method, an overlapping session is used to remove the day boundary jumps. For example, a session that starts from 12:00 UTC and ends at 12:00 UTC of the next day is used to fix the problem. The result of this process is shown in the Fig. 11. As it can be seen in this figure, using overlapping batches reduces the jump mentioned above to less than 0.2 ns. Moreover, this method almost eliminated the day boundary jumps between first three successive days.

Conclusion

Nowadays, time transfer through GPS carrier phase and pseudo-ranges is known as a prominent technique. Every time transfer system has its own sources of bias and GPS is not an exempt of this fact. Therefore, analyzing the propagation mechanism of every bias is the first step in establishing a time transfer network. Results of such analysis are some constraints on the absolute and relative locations of the GPS stations to be equipped with external atomic clocks. Here, a simulation approach has been adopted for this purpose. To be more specific, the most sensitive baselines to every sort of bias in the stations' coordinate are chosen first, and then, carrier phase and pseudo-ranges are simulated for the corresponding points. Later, the impact of every bias is analyzed separately using simulated measurements: The effect of 1 cm bias in the vertical and horizontal components of one of the stations' coordinates is independent of the length and direction of the time transfer baselines when the bias is imposed on the observations of one of the involved stations. According to the obtained results for an accuracy of 140 ps and a processing batch of 24 h, coordinate reliabilities of 1 cm are quite sufficient. Introducing the same amount of bias to both of the involved stations led to sub-picoseconds variations in the clock estimates for the longest baseline in Iran. As a conclusion, presence of biases in the coordinates of stations may be completely ineffective on the clock estimates when the vector of biases has the same length and direction for all the involved stations. On the other hand, the impact of bias in the coordinates of fiducial stations used for defining the datum shows a completely negligible variation for all time keeping and time dissemination applications.

Among different sources of bias affecting the coordinates of the stations, site-dependent ZPDs play the most important role. The impact of this source of bias is a function of the difference in the meteorological conditions at the point positions. At worst, site-specific tropospheric parameters can lead to more than 1 ns variations in the clock estimates. Of course, this amount of variation is a result of comparing the estimated ZPDs using real data and a priori models with the meteorological parameters obtained using height-dependent relations. This amount of variation is completely considerable for almost all the timing applications. As a conclusion, locating at least one GPS station to be equipped with an external atomic frequency as a reference in each meteorological class in the country seems to be a reasonable way to defeat the impact of this bias for industrial timing applications. In this way, estimating the site specific ZPD parameters would be unnecessary which leads to a significant decrease in computation time and energy resources. In this regard, precise meteorological classification of Iran is necessary.

The impact of OTL is investigated for the coastal stations located at the south of Iran. The results lead to preference of southwestern coastal stations of the country for locating the GPS stations equipped with external atomic frequency. The magnitude of variations due to this source of bias varies between 20 ps to about 130 ps moving from western to eastern coastal stations.

The impact of bias in the orbital information, either in the doubly differenced observations for estimating the stations' coordinates or the zero difference for clock parameters estimation, does not impose any constraint on location of the GPS stations. Moreover, negligible difference between different classes of orbital information resulted in practicality of either of these IGS's product for industrial applications of time transfer.

Pseudo-range measurement errors, regardless of their source, are responsible for the day boundary jumps. This is seen in the time transfer solution computed using simulated pseudo-ranges whose noise is 0.5 m. A time transfer between H-masers located at the USNO and the NRC1 has been conducted to pursue a standard and efficient algorithm for this problem. Here, the method of overlapping batches with 12 h coverage in each of the involved days is applied. The results of this method show a significant decrease in the amplitude of day boundary jumps as it falls down to less than 0.2 ns. On the other hand, the noise of carrier phase observations produces huge variations on the clock parameters which reach to maximum of 70 ps between consecutive epochs.

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