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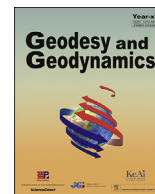
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Houston16: A stable geodetic reference frame for subsidence and faulting study in the Houston metropolitan area, Texas, U.S.

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ABSTRACT

Houston, Texas, is one of the earliest regions to employ continuous GPS technology for land subsidence monitoring. Currently, there are over 200 permanent GPS stations located in the greater Houston area. The need for a consistent and stable reference frame to precisely interpret local ground deformation has become critically important since the 1990s, because of the significant spreading of subsidence. We have established a stable Houston reference frame, designated Houston16, using publicly available GPS observations (>5 years) from 15 Continuously Operating Reference Stations (CORS) located outside of the greater Houston area. Applications of the reference frame in subsidence and faulting studies are demonstrated in this article. Houston16 is aligned in origin and scale with the International GNSS Reference Frame of 2008 (IGS08). A 7-parameter method was employed to transform the GPS-derived positional time series from IGS08 to Houston16. The primary product of this study is the seven parameters for transforming Earth-Centered-Earth-Fixed XYZ coordinates from IGS08 to Houston16. The frame stability of Houston16 is approximately 1 mm/year. Houston16 will be updated every few years to mitigate degradation of the frame's stability with time and to synchronize with future updates of the IGS reference frame.

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1. Introduction

The Houston metropolitan area represents one of the largest subsidence areas in the U.S. [1]. The area has been experiencing land subsidence for nearly a century. Accumulated subsidence of over three meters during the past 100 years has been observed within a large area of southeast Houston [2]. Land subsidence in this region is caused primarily by the depressurization of clay

lenses in the aquifers due to groundwater withdrawal. The Texas Legislature created the Harris–Galveston Subsidence District (HGSD) in 1975 and the Fort Bend Subsidence District (FBSD) in 1989 to regulate groundwater withdrawal within Harris, Galveston, and Fort Bend counties [3,4]. Prior to the 1990s, subsidence within the Houston area was monitored by conducting leveling surveys and through the use of extensometers. Global Positioning System (GPS) has gradually replaced conventional leveling surveys and has become the primary tool for subsidence monitoring in the Houston area since the 1990s. Accurate long-term monitoring of ground deformation is critical to establishing effective regulations on groundwater withdrawal for the purpose of preventing future subsidence and better securing the local infrastructure, such as bridges, roads, underground pipes and buildings.

In the early 1990s, HGSD established a surveying network of approximately 20 permanent GPS stations for the purpose of subsidence monitoring. These GPS sites are also called Port-A-Measure (PAM) stations [5]. A PAM station was designed for a campaign-

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style long-term monitoring solution. A 2.5-m antenna pole was permanently installed at each site. In order to avoid the impact of surface ground deformation associated with the shrink-swell behavior of clay-rich soils in the Houston area, the antenna poles were anchored 6 m below the ground surface. HGSD and FBSD personnel routinely mount GPS antennas on permanent antenna poles to monitor land subsidence. On average, GPS data was collected continuously for one week every month prior to 2005 and one week per two months after 2005. The PAM network has been continuously expanded and the number of total stations has reached over 90 as of 2017. In addition to the PAM GPS network, there are over 40 Continuously Operating Reference Stations (CORS) in the Houston area [6]. These CORS are operated by a joint effort of the National Geodetic Survey (NGS) at the National Oceanic and Atmospheric Administration (NOAA), the Texas Department of Transportation (TxDOT), the city of Houston, and other local agencies. The University of Houston has recently established a real-time GPS network (HoustonNet) with 65 permanent real-time stations. The primary purpose of HoustonNet is to provide a platform for studying multiple urban natural hazards, including subsidence, faulting, salt dome uplift, flooding, and to improve hurricane intensity forecasting in the Gulf Coast region. As of 2017, there are approximately 200 permanent GPS stations within the greater Houston area (Fig. 1). Raw GPS data (Receiver Independent Exchange Format) from these stations are available to the public through the HGSD and data archiving facilities at UNAVCO (<https://www.unavco.org/data/data.html>) and NGS (https://www.ngs.noaa.gov/CORS_Map/).

GPS positions are initially provided as a set of coordinates with respect to a global reference frame. In general, a global geodetic reference frame is realized with an approach of minimizing the overall movements of a large number of selected reference frame stations distributed worldwide, such as the International GNSS Service reference frame of 2008 (IGS08) [7]. As a result, the positional coordinates for most of the GPS stations change over time with respect to a global reference frame. The site movements with respect to a global reference frame are often dominated by the long-term drift and rotations of the tectonic plate. Localized and temporal ground deformation, such as subsidence and fault creeping, could be obscured or biased by plate motions. Thus, a stable regional reference frame is needed for precisely delineating localized ground displacements or structural deformation over time and space. A stable geodetic reference frame, also called a plate-fixed reference frame, indicates that regional “common” movements have been removed or minimized. The regional common movements may include a combination of secular plate motions, glacial isostatic adjustment (GIA), surface mass loading, and other minor secular effects [8]. Several continental-scale reference frames fixed on the North American plate have been developed by the geodetic research community, such as the North American Datum of 1983 (NAD83) [9,10], the Stable North American Reference Frame (SNARF) [11], and the North American Reference Frame of 2012 (NA12) [12]. However, it is difficult to precisely identify ground displacement rates at the level of a few millimeters per year with respect to a continental-scale reference frame. In order to

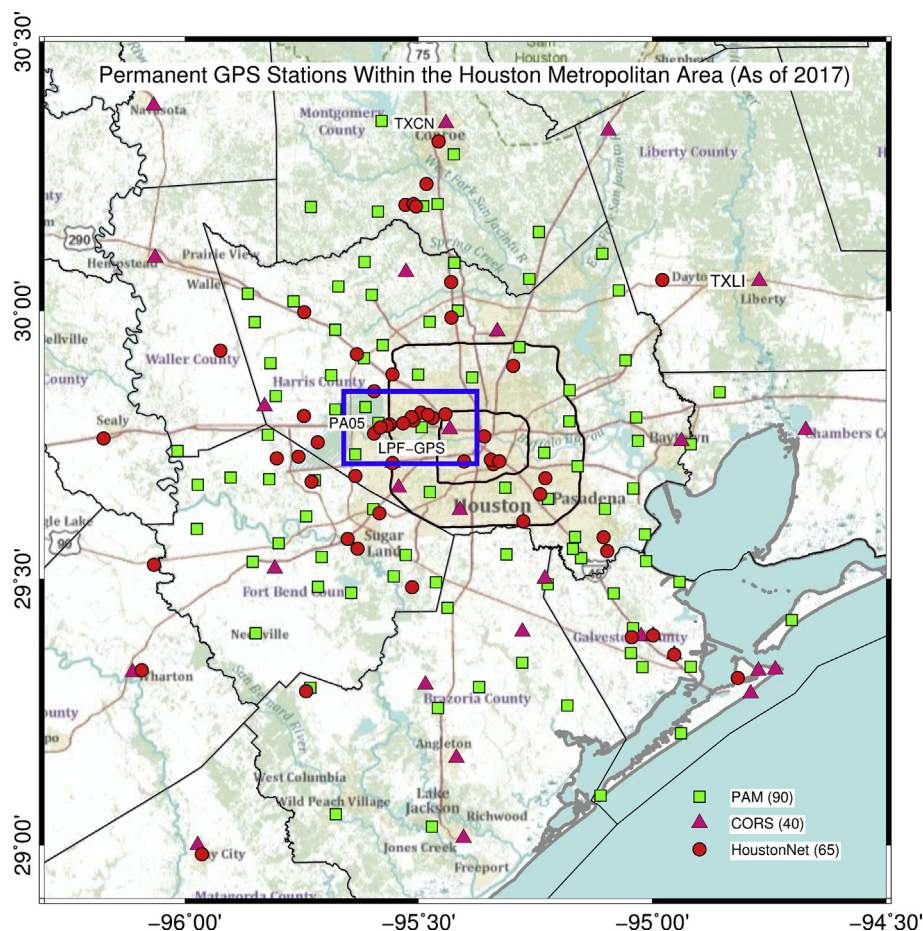


Fig. 1. Permanent GPS stations within the Houston metropolitan area as of 2017. The blue box indicates the location of the Long Point Fault (LPF) GPS array installed by the University of Houston in 2013.

precisely monitor ongoing land subsidence within the greater Houston area, a regional-scale reference frame is developed through this study.

The need for a consistent and stable reference frame has become critically important in the Houston metropolitan area because of the onset of broadly spreading subsidence that has been observed since the 1990s. In order to integrate long-term GPS data collected by different agencies, which may use different equipment to record GPS data in different areas, into a uniform reference frame, a stable Houston reference frame was established in 2013 using available GPS data through the end of 2012 [13]. The initial realization of the regional reference is referred to as Houston12 in this article. It was realized by a 14-parameter simultaneous Helmert transformation from the global reference frame IGS08 by utilizing 10 reference stations. Two of the reference stations are inside the Houston metropolitan area and eight are outside the metropolitan area. Several of Houston12 reference stations had less than 5-years of observations and frequent data gaps. Houston12 was updated in 2014 by adding approximately two years of observations [14]. More high-quality reference stations are currently available than at the time Houston12 was realized. Some of the previous reference stations used in realizing Houston12 have been terminated or the data quality has decreased substantially. Those stations need to be removed from the group of reference stations. This study aims to update Houston12 by removing those reference stations that exhibit poor data quality or are no longer in operation and by adding additional reference stations to improve overall geographic distribution. The updated reference frame is designated as Houston16.

2. GPS data processing

GPS observations need to be processed to achieve high-accuracy positions, high-precision displacements, and finally to obtain reliable and precise site velocity estimations. The accuracy of GPS measurements (positions or displacements) do not solely rely on GPS equipment (antenna and receiver), but largely depends on how the data is collected in the field and how the data is processed in the lab [15–18]. In general, there are two GPS data post-processing approaches used to achieve high-accuracy positioning measurements, relative positioning and absolute positioning. The relative positioning approach uses simultaneous observations from two or more GPS units. One GPS unit is considered a fixed station, which is also called a reference station. The alternative approach, absolute positioning, determines the position of a single GPS station without using any simultaneous observations from other ground GPS stations. Precise point positioning (PPP) is a typical absolute positioning method [19]. This study applied the single-receiver phase ambiguity-fixed PPP method [20] that was employed by the GIPSY-OASIS (V6.4) software package, simplified as GIPSY, for calculating daily positions.

The PPP solutions are defined in an Earth-Centered-Earth-Fixed (ECEF) Cartesian coordinate system that represents a position as a set of X , Y , and Z coordinates. To study ground deformation at the Earth's surface, the geocentric XYZ coordinates were converted to a geodetic orthogonal curvilinear coordinate system (longitude, latitude, and ellipsoid height) referencing the GRS80 ellipsoid. The geodetic coordinates with respect to Houston16 were then projected to a two-dimensional (2D) local horizontal plane. This enabled us to precisely track superficial ground deformation in the north-south (NS) and east-west (EW) directions at each site. The ellipsoid height change over time is used to depict the vertical displacement (subsidence) in this study. The vertical displacements derived from the ellipsoid heights would have practically the same

measurements as those derived from leveling surveys that use orthometric heights [21].

An outlier detection and removal algorithm was applied to the three-component positional time series, which was derived from the daily PPP solutions. Approximately seven to ten percent of the total daily-positions were removed as outliers in this study. The detailed method for outlier rejection was addressed in references [22] and [16].

3. Realization of Houston16

The primary physical and mathematical properties of a reference frame are the origin, scale, orientation, and the changes of these parameters over time. In the surveying and geodesy community, a regional reference frame is often developed through a simultaneous transformation from a well-established and broadly used global reference frame, such as IGS08. A group of common points (reference stations) is used to link these two reference frames.

3.1. Selection of reference stations

The first step to define a regional reference frame is to select a set of long-term (e.g., >5 years) GPS stations that are fixed on the North American plate. The purpose of selecting reference stations is to precisely delineate long-term secular motions of the tectonic plate. Stations at plate boundaries or those close to active faults may retain different site velocities compared to stations within the plate interior. Accordingly, reference stations need to be carefully selected depending on the specific research purposes.

The selection of reference stations is primarily based on the linearity of the positional time series and a combined consideration of data continuity and geographical distribution. The linearity reflects how well the motions can be described by a constant velocity over a period of time. According to our investigations on the daily GPS positional time series within the Houston area, a continuous history of a minimum of five years is recommended to precisely estimate the site velocities associated with secular plate motions [23]. Since Houston16 is designed primarily for monitoring ground deformation (e.g., subsidence, faulting) within the Houston area, the reference stations are preferred to be stable and located outside of the Houston area. The vertical stability of a site can be preliminarily assessed by directly observing the vertical positional time series from the PPP solutions. According to our previous investigations [24], there is not considerable difference between the vertical displacement time series with respect to IGS08 and those with respect to a regional reference frame in the Gulf Coast region. Thus, vertical ground deformation rates with respect to the regional reference frame and IGS08 should be similar. This has been utilized as a clue to assess the vertical stability of a potential reference station. However, it is a challenge to assess the horizontal stability of a site at a level of a couple of millimeters per year prior to having a rigorous stable regional reference frame. A trial-and-error process was employed to exclude those stations that could be affected by localized horizontal ground deformation. The details will be explained in the following section.

3.2. Coordinate transformation

In geodesy, the Helmert transformation is often used to produce a distortion-free transformation of the ECEF-XYZ coordinates between two reference frames. This method transforms a position from one reference frame into another by conducting rotation, scaling, and translation. The Helmert

transformation for a position from the reference frames A to B can be expressed as:

$$\begin{bmatrix} X_B \\ Y_B \\ Z_B \end{bmatrix} = \begin{bmatrix} T_x \\ T_y \\ T_z \end{bmatrix} + (1 + s) \times \begin{bmatrix} 1 & -R_z & R_y \\ R_z & 1 & -R_x \\ -R_y & R_x & 1 \end{bmatrix} \times \begin{bmatrix} X_A \\ Y_A \\ Z_A \end{bmatrix} \quad (1)$$

where X_A , Y_A , and Z_A are the XYZ coordinates with respect to the original reference frame A; X_B , Y_B , and Z_B are the transformed XYZ coordinates with respect to the new reference frame B; T_x , T_y , and T_z are three translational shifts between the two reference frames along the x , y , z coordinate axes, respectively; R_x , R_y , and R_z are three rotations around the x , y , and z coordinate axes, respectively; and s is a scale factor. The seven parameters are determined with a minimum of three “common points” with known coordinates with respect to both systems. In practice, more common points (reference stations) are used to solve the inverse problem by employing the least squares method. The scale factor is often set as zero in frame transformations between a global reference frame and a regional reference frame.

Two methods have been developed to transform a positional time series from a global reference frame to a regional reference frame: a daily 7-parameter method and a 14-parameter method. The daily 7-parameters include three rotations, three translations, and a scale factor as illustrated in Eq. (1). The 14-parameters include three rotations, three translations, a scale factor, and one-time derivatives of these seven parameters over time. The daily 7-parameter method transformed the XYZ coordinates using the Helmert 7-parameters that were calculated for each day separately. For example, the coordinate transformation from IGS08 to NA12 is realized by those daily 7-parameters that are calculated by the Geodesy Lab at the University of Nevada on a daily basis [12]. In contrast to the daily 7-parameter method, the 14-parameter method utilizes the 14 parameters for the coordinate transformation of the entire positional time series. The 14-parameter method has been frequently applied by NGS for realizing the North American Datum of 1983 (NAD 83 (2011)) and other regional reference frames [10]. The 14-parameter method has been further simplified to a 7-parameter method through our recent studies [25,26]. The coordinate transformation of the GPS-derived positional time series from a global reference frame to a regional reference frame can be accomplished through the seven parameters: the epoch aligning two reference frames (t_0), and the time derivatives of three translations and three rotations (T'_x , T'_y , T'_z , R'_x , R'_y , and R'_z). The positional coordinates of a site within Houston16 can be calculated through the following equations [26]:

$$\begin{aligned} X(t)_{\text{Houston16}} &= X(t)_{\text{IGS08}} + T'_x \cdot (t - t_0) + R'_z \cdot (t - t_0) \cdot Y(t)_{\text{IGS08}} - R'_y \cdot (t - t_0) \cdot Z(t)_{\text{IGS08}} \\ Y(t)_{\text{Houston16}} &= Y(t)_{\text{IGS08}} + T'_y \cdot (t - t_0) - R'_z \cdot (t - t_0) \cdot X(t)_{\text{IGS08}} + R'_x \cdot (t - t_0) \cdot Z(t)_{\text{IGS08}} \\ Z(t)_{\text{Houston16}} &= Z(t)_{\text{IGS08}} + T'_z \cdot (t - t_0) + R'_y \cdot (t - t_0) \cdot X(t)_{\text{IGS08}} - R'_x \cdot (t - t_0) \cdot Y(t)_{\text{IGS08}} \end{aligned} \quad (2)$$

here, t_0 denotes a specific epoch that was used to align the two reference frames. It is set as 2012.0 in this study. T'_x , T'_y , and T'_z are the linear trends (rates of change) of the time series of three translations ($T_x(t)$, $T_y(t)$, $T_z(t)$) between Houston16 and IGS08; R'_x , R'_y , and R'_z are the linear trends of the time series of three rotations ($R_x(t)$, $R_y(t)$, $R_z(t)$) around the x , y , and z axis, respectively. The detailed method for calculating T'_x , T'_y , T'_z , R'_x , R'_y , and

R'_z was addressed in Ref. [26]. $X(t)_{\text{IGS08}}$, $Y(t)_{\text{IGS08}}$, and $Z(t)_{\text{IGS08}}$ are positional coordinates with respect to IGS08, which can be obtained through the PPP processing.

Initially, thirty CORS were selected as potential reference stations among over 50 CORS within the large area shown in Fig. 2. The seven parameters (t_0 , T'_x , T'_y , T'_z , R'_x , R'_y , and R'_z) for transforming the positional time series from IGS08 to the interim reference frame were calculated. The XYZ coordinates of each reference station with respect to IGS08 were transformed to the interim reference frame according to Eq. (2). A trial-and-error approach was used to refine the selection. Any reference stations that had a horizontal velocity greater than 1.5 mm/year with respect to the new reference frame were removed from the group of selected reference stations and the aforementioned seven parameters were recalculated. Finally, fifteen CORS were selected as reference stations (or frame stations) for realizing Houston16. The locations of these reference stations are plotted in Fig. 2. The site coordinates and velocities with respect to the newly established reference frame are listed in Table 1. The maximum horizontal velocity of these reference stations with respect to Houston16 is 0.9 ± 0.04 mm/year and the maximum vertical velocity is -1.3 ± 0.15 mm/year. The seven parameters (t_0 , T'_x , T'_y , T'_z , R'_x , R'_y , and R'_z) for transforming ECEF-XYZ coordinates from IGS08 to Houston16 are listed in Table 2. Fig. 3 depicts the data continuity and linearity of these 15 reference stations. All reference stations have a continuous history of longer than five years. The majority of reference stations have a continuous history longer than seven years. The precision (repeatability) of the daily positions (PPP solutions) is 2–4 mm in the horizontal directions and 6–8 mm in the vertical direction.

Fig. 4 depicts the comparisons of a three-component displacement time series of TXLI with respect to IGS08, NAD83, and Houston16. TXLI is located in Liberty County, a rural area outside Houston (Fig. 1). Groundwater use in Liberty County is estimated to be much less than the adjacent Montgomery and Harris counties due to its primarily rural water use. According to groundwater monitoring data collected in this area, the groundwater levels of the two major top aquifers (Chicot and Evangeline) remained above the preconsolidation head (approximately 35 m below the land surface) during the past two decades [27]. There are not any reported infrastructure damages associated with ground deformation in this area. Thus, TXLI can be regarded as a stable site to assess the accuracy (stability) of the regional reference frame. The linear velocity (v) and its corresponding two times “standard error” (2σ) for each time series are marked on each subplot. The standard error (σ) indicates the standard deviation of the uncertainties of the estimated linear velocity. Statistically, “ $v \pm 2\sigma$ ” indicates that there is a 95% possibility that the

true velocity would be within the interval between $v - 2\sigma$ and $v + 2\sigma$, assuming the error fits normally distributed white noise. The horizontal velocities with respect to NAD83 and Houston16 are 1.5 ± 0.02 mm/year and 0.5 ± 0.02 mm/year, respectively. The vertical velocities with respect to NAD83 and Houston16 are -1.7 ± 0.06 mm/year and 0.8 ± 0.06 mm/year, respectively. The velocities with respect to both reference frames (plate-fixed)

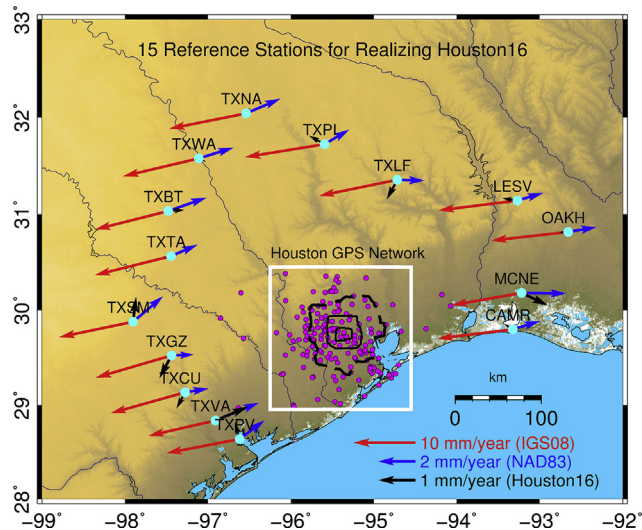


Fig. 2. Map showing the locations of 15 reference GPS stations used to establish the Stable Houston Reference Frame of 2016 (Houston16). The vectors represent the horizontal velocity vectors with respect to IGS08 (red), NAD83 (blue), and Houston16 (black). The white box represents the greater Houston area shown in Fig. 1.

suggest that this site did not experience significant movement during the past decade. However, the sub-millimeter velocities with respect to Houston16 provide a higher level of confidence to verify the long-term stability of this site. Hence, Houston16 achieves a higher accuracy than NAD83 in regard to assessing the stability of a local site.

4. Stability of Houston16

According to the statistics listed in Table 1, the average horizontal velocity of these 15 reference stations with respect to Houston16 is 0.4 mm/year and the average vertical velocity is 0.8 mm/year. The uncertainty (2σ) is below 0.05 mm/year for the horizontal velocities and below 0.2 mm/year for the vertical velocities. The average velocity of the reference stations indicates the stability of the reference frame, which is the ability to extrapolate station coordinates reliably into the past and into the future. Accordingly, the stability is also referred to as predictability or accuracy, which defines the essence of a successful reference frame

for the most stringent users [28]. The useful lifetime of a regional reference frame depends on its stability. According to the above analysis, the stability of Houston16 is at the level of 0.4 mm/year in the horizontal and 0.8 mm/year in the vertical directions. Stability at this level may lead to a positional drift of approximately 4 mm in the horizontal direction and 8 mm in the vertical direction over a 10-year period. The magnitude of the positional drift over 10 years is comparable to the precision of current PPP daily solutions [17,23]. The stability of the regional reference frame will be continuously improved in future updates when a longer time span of observations and more reference stations are available.

Fig. 5 illustrates the comparisons of the three-component displacement time series (2000–2016) at PAM site PA05 derived from two different GPS post-processing methods. The red dots represent the displacements obtained by employing the relative method, carrier-phase double-difference (DD) processing. The displacements are referred to a single GPS antenna (ADKS) that is approximately 50 m away from PA05 [29]. The dark dots represent the displacements obtained by the PPP method. The displacements are referred to Houston16. The antenna at ADKS was installed on the top of the inner pole of an extensometer. The antenna pole was anchored approximately 549 m below the ground surface [30]. Thus the compaction of the shallow aquifer will not cause the vertical movement of the GPS antenna. Long-term GPS observations at ADKS demonstrate that the antenna has been stable during the past two decades [31]. According to our experience with the double difference post-processing method, a baseline as short as 50 m would lead to a sub-millimeter accuracy for daily positions in all three directions [32,33]. Hence, the double difference solutions for PA05 can be regarded as the “true” values to assess the accuracy of the PPP solutions with respect to Houston16. The displacement time series depicted in Fig. 5 suggest that the DD and PPP solutions overlap each other very well during the 17-year period (2000–2016). Overall, the two datasets result in an identical ground deformation interpolation, although the DD solutions retain a higher repeatability than the PPP solutions. The differences between the accumulated total displacements over the 17-year period obtained from the DD solutions and the PPP solutions are below one and a half centimeters in all three directions. The comparison also suggests that Houston16 achieves an accuracy (stability) of below 1 mm per year.

Fig. 6a illustrates a comparison of the three-component displacement time series of TXLI with respect to the earlier version of the regional reference frame (Houston12) and the

Table 1
Locations of Fifteen Reference Stations and their Site Velocities with Respect to Houston16.

CORS	Location (Degree)		Site Velocity (mm/year)			Uncertainty of the Velocity (2σ) ^a (mm/year)		
	Longitude	Latitude	V_{EW}	V_{NS}	V_{UD}	$2\sigma_{V_{EW}}$	$2\sigma_{V_{NS}}$	$2\sigma_{V_{UD}}$
CAMR	−93.33	29.80	−0.21	0.14	−0.36	0.06	0.06	0.17
LESV	−93.27	31.14	−0.40	0.06	0.59	0.04	0.04	0.14
MCNE	−93.22	30.18	0.71	−0.34	0.86	0.04	0.04	0.12
OAKH	−92.66	30.82	−0.24	−0.02	−0.94	0.04	0.04	0.14
TXBT	−97.48	31.03	0.43	0.03	−0.65	0.05	0.04	0.13
TXCU	−97.28	29.13	−0.23	−0.44	−0.49	0.04	0.04	0.12
TXGZ	−97.44	29.52	−0.33	−0.61	−1.26	0.04	0.04	0.17
TXLF	−94.72	31.36	−0.28	−0.52	0.23	0.05	0.05	0.12
TXNA	−96.54	32.04	0.10	0.15	0.74	0.04	0.04	0.13
TXPI	−95.59	31.72	−0.42	0.23	−0.56	0.06	0.06	0.18
TXPV	−96.62	28.64	−0.12	0.44	0.55	0.04	0.04	0.14
TXSM	−97.90	29.88	0.08	0.67	1.55	0.04	0.04	0.12
TXTA	−97.45	30.56	−0.18	−0.07	0.34	0.04	0.04	0.12
TXVA	−96.91	28.83	0.87	0.37	−0.17	0.04	0.04	0.12
TXWA	−97.11	31.58	0.19	−0.09	−0.54	0.04	0.04	0.12
Root Mean Square			0.38	0.35	0.75	0.04	0.04	0.14

^a σ represents the standard error, which indicates standard deviation of the uncertainties of the estimated linear velocity. Statistically, $v \pm 2\sigma$ indicates that there is a 95% possibility that the true velocity would be within the interval between $v - 2\sigma$ and $v + 2\sigma$, assuming the error fits normally distributed white noise.

Table 2

Seven Parameters for Transforming ECEF-XYZ Coordinates from IGS08 to Houston16.

Parameters ^a	Unit	IGS08 to Houston16
T_x	m/year	1.1427832E-002
T_y	m/year	-2.4771197E-003
T_z	m/year	5.8795944E-004
R'_x	radian/year	2.0734184E-010
R'_y	radian/year	-2.0205941E-009
R'_z	radian/year	1.0549129E-009
t_0	year	2012.0

^a These parameters are employed in Eq. (2). Counterclockwise rotations of axes (x, y, z) are positive.

updated version (Houston16). There is not any considerable difference between the displacement time series with respect to Houston12 and Houston16 in the EW and vertical directions. However, there is a slight difference in the NS direction. The displacement time series with respect to Houston12 retains a steady movement towards the south with a minor velocity of -0.6 ± 0.02 mm/year. In contrast, the displacement time series with respect to Houston16 does not show any visible displacement over the 12-year period; the linear velocity is as slow as -0.05 ± 0.02 mm/year. As discussed earlier, TXLI is expected to be a locally stable site. Thus, Houston16 is a more accurate reference frame than Houston12 in tracking horizontal ground deformation over time. The comparison also indicates the need to continuously update the regional reference frame.

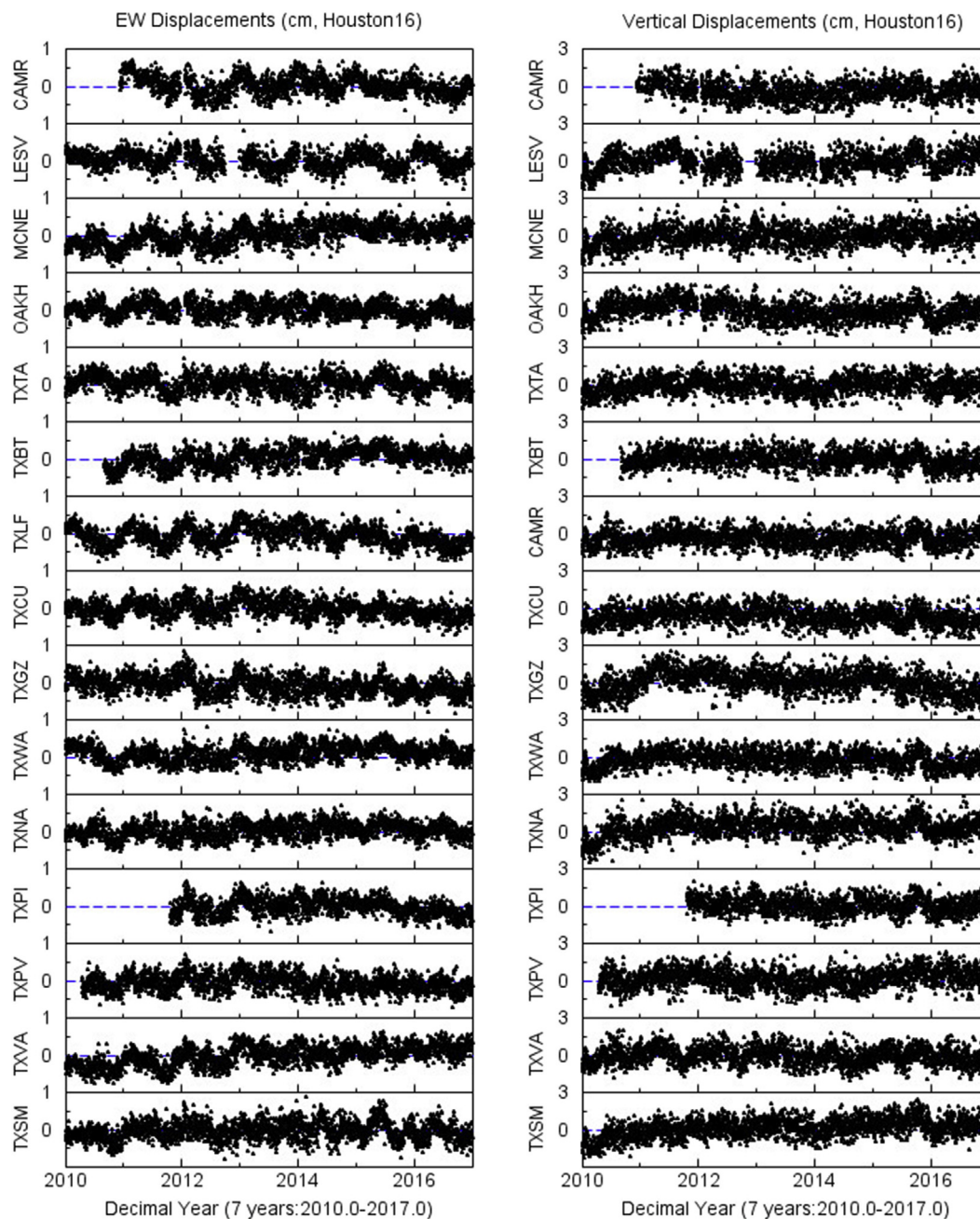


Fig. 3. Displacement time series of 15 reference stations (Fig. 2) in the east-west (EW) and vertical directions with respect to Houston16.

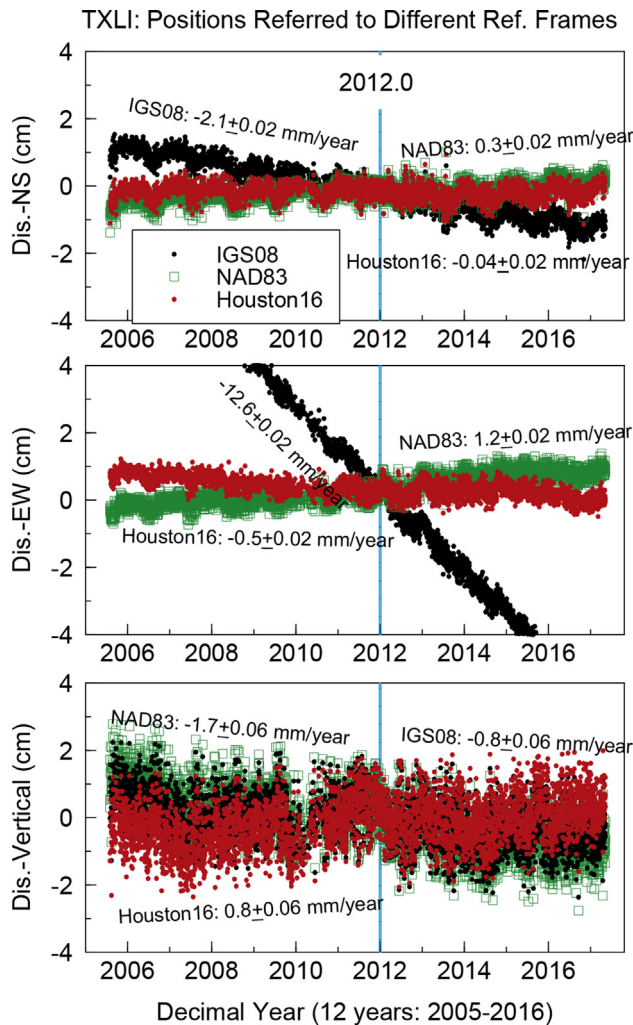


Fig. 4. An example of GPS-derived three-component displacement time series with respect to IGS08 and NAD83, and Houston16. The location of TXLI is plotted in Fig. 1. The linear velocity (v) and its corresponding two times “standard error” (2σ) for each component are marked on each subplot. The standard error (σ) indicates standard deviation of the uncertainties of the estimated linear velocity. Statistically, “ $v \pm 2\sigma$ ” indicates that there is a 95% possibility that the true velocity would be within the interval between $v - 2\sigma$ and $v + 2\sigma$, assuming the error fits normally distributed white noise.

Fig. 6b compares the three-component displacement time series of TXLI with respect to Houston16 and NA12. NA12 is a plate-fixed reference frame for geodetic studies of crustal deformation in North America [12]. NA12 is designed to have no-net rotation with respect to the stable interior of the North American tectonic plate. NA12 is a continental-scale reference frame that is aligned in origin and scale with IGS08. One of the major differences between NA12 and Houston16 is that NA12 is realized by a daily 7-parameter transformation, while Houston16 is realized by a total 7-parameter transformation. In other words, in practice, obtaining a displacement time series with respect to Houston16 is simpler than obtaining a displacement time series with respect to NA12. Fig. 6b indicates that the displacement time series with respect to NA12 and Houston16 agree very well in the horizontal directions. There are slight differences in the vertical direction. The displacement time series with respect to NA12 retains a linear velocity of -0.9 ± 0.06 mm/year; the displacement time series with respect to Houston16 retains a linear velocity of 0.8 ± 0.06 mm/year. The two sets of time series lead to a similar interpolation, which indicates

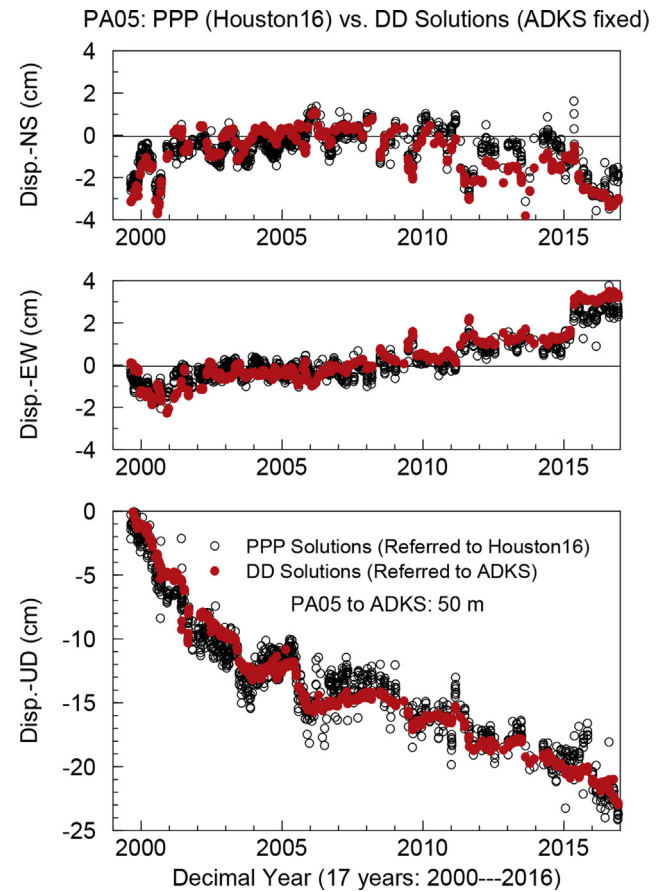


Fig. 5. Three-component displacement time series (2000–2016) at PA05. Dark circles represent the PPP solutions with respect to Houston16. Red dots represent the double-difference (DD) solutions referred to a stable GPS antenna (ADKS). The baseline length between ADKS and PA05 is 50 m. The location of PA05 is marked in Fig. 1.

there is not any considerable subsidence at TXLI. However, the minor annual difference (1.7 mm/year) can be accumulated and lead to considerably different total displacement measurements over a long period of time. Fig. 7 compares the three-component displacement time series of TXCN with respect to Houston16 and NA12. TXCN is located in Conroe, a city about 60 km north of Houston. There is rapid ongoing subsidence in The Woodlands and Conroe area (Fig. 8). The location of TXCN is plotted in Fig. 1. NA12 demonstrates a total displacement of approximately 16 cm over 12 years, but Houston16 exhibits a total displacement of approximately 14 cm during the same time period. A 2-cm displacement over a decade may be a concern for certain applications, such as when assessing the long-term stability of dams, sea walls, and nuclear power plants. For precise ground deformation monitoring within the Houston metropolitan area, Houston16 is the preferred option. The comparisons in Fig. 7 also indicate that the PPP solutions with respect to NA12 achieved a slightly higher precision (repeatability) than the PPP solutions with respect to Houston16. The displacements with respect to Houston16 achieved 2.5 mm, 3.0 mm, and 8.0 mm RMS-accuracy in the NS, EW, and vertical directions, respectively. The displacements with respect to NA12 achieved approximately 1 mm better RMS-accuracy in all directions. This is because the daily 7-parameter transformation employed in obtaining the displacements with respect to NA12 works as a spatial filter. Some common ground deformation, such as seasonal motions, was filtered out by the coordinate transformation.

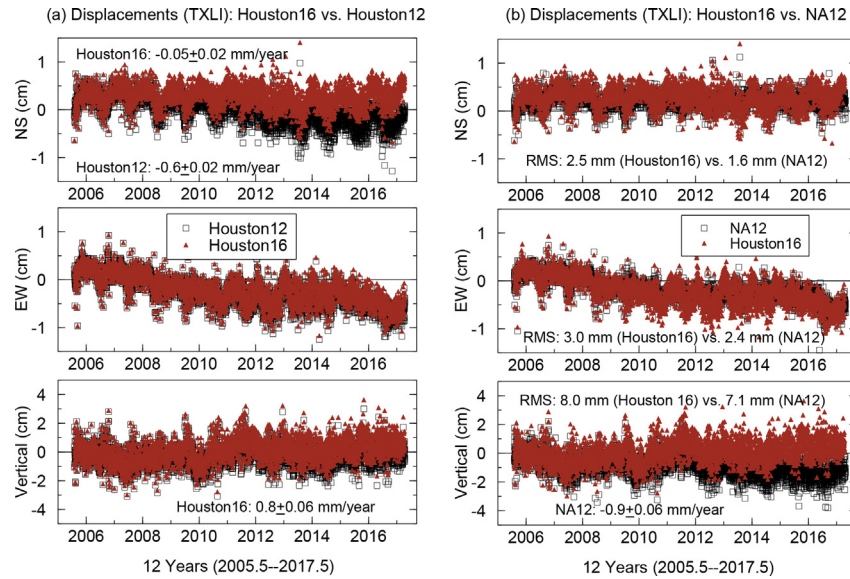


Fig. 6. (a) Comparisons of the three-component displacement time series (TXLI) with respect to Houston16 and its predecessor, Houston12. (b) Comparisons of the three-component displacement time series (TXLI) with respect to Houston16 and NA12. NA12 is a North American plate-fixed reference frame developed by Blewitt et al. (2013) [12].

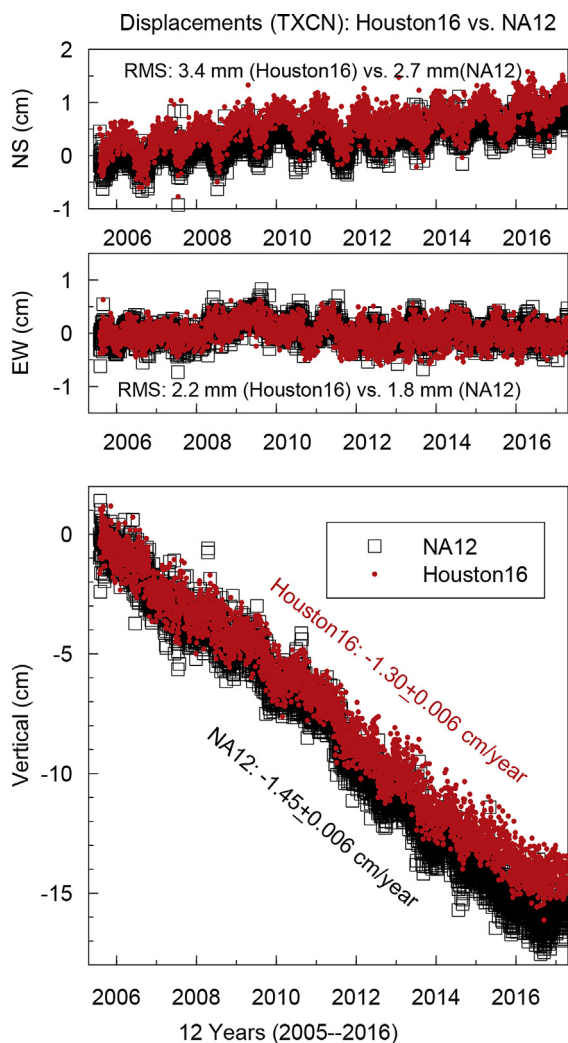


Fig. 7. Comparisons of the three-component displacement time series with respect to Houston16 and NA12 at a subsiding GPS site TXCN.

5. Applications of Houston16

Houston16, as a fundamental component of the regional geodetic infrastructure, provides a consistent reference for delineating the spatial and temporal variations of ground deformation over time and space. Applications of Houston16 for monitoring land subsidence and fault movement are demonstrated in this section.

5.1. Subsidence monitoring

A GPS data processing center was established in 2016 by a joint effort of HGSD and the University of Houston. The center routinely processes GPS data from approximately 200 permanent GPS stations on a daily basis for the purpose of subsidence monitoring. Fig. 8 depicts the land subsidence contours in the Houston metropolitan area during the past 10 years (2006–2016). Observations (>3 years) from 140 permanent GPS stations were used to derive the subsidence contour map. The colored areas represent the groundwater regulation zones enforced by the local groundwater management agencies [3,4]. The contour maps clearly depict the spatial pattern of the ongoing subsidence. Subsidence in downtown Houston and in the southeastern region (HGSD Area I, II) has nearly ceased (<4 mm/year). However, rapid subsidence (>1 cm/year) is occurring in The Woodlands, Spring (HGSD Area III), and Katy (FBSD Area A) areas; moderate subsidence (<1 cm/year) is occurring in many parts of Montgomery County, northwest Harris County, and Fort Bend County.

Fig. 9 depicts the horizontal and vertical velocity vectors of the ground deformation during the two time periods: 1995–2005 and 2006–2016. The velocities are referred to Houston16. The vertical velocity vectors clearly indicate that the overall subsidence rate has decreased since 2006. The rapid subsidence during the period from 1995 to 2005 was up to 3–4 cm/year in the Jersey Village area, which was the center of the subsidence bowl. The subsidence rate was reduced to below 2 cm/year within the Jersey Village area during the period from 2006 to 2016. The reduction of the overall subsidence rates is attributed to the reduction of groundwater withdrawal due to HGSD regulations [27,30].

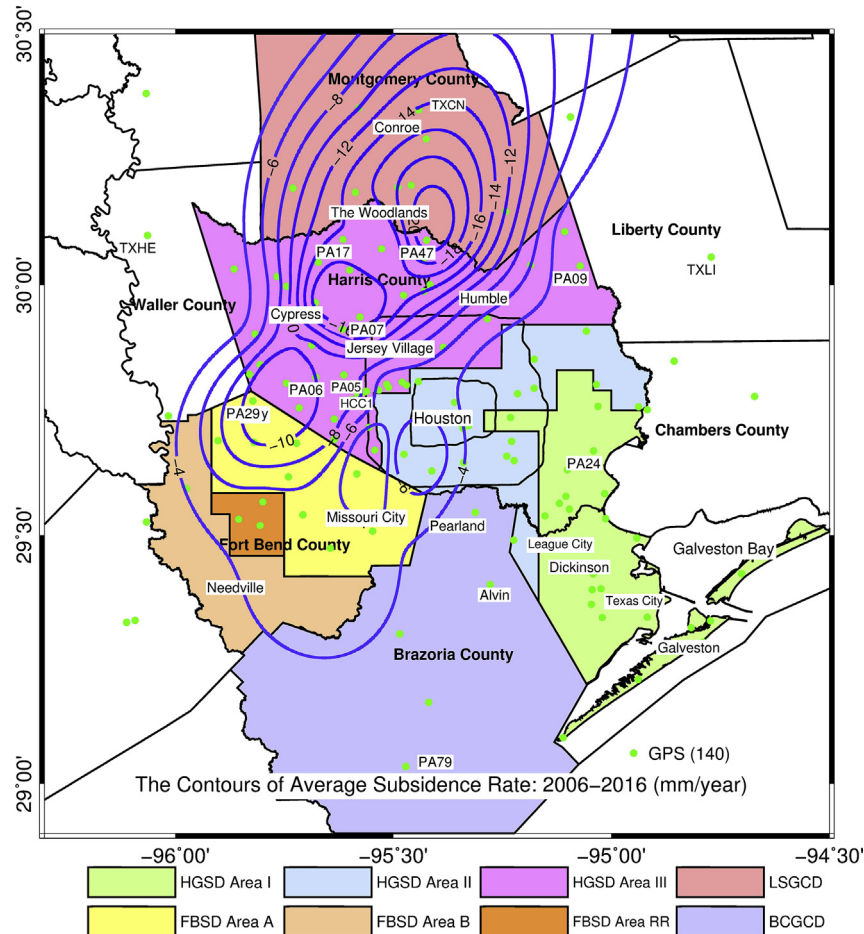


Fig. 8. Contour maps showing the average subsidence rate (mm/year) during the period from 2006 to 2016. The contour map was derived from the subsidence rates at 140 permanent GPS sites (>3 years). The colored areas indicate the current groundwater regulatory zones administered by the Harris–Galveston Subsidence District (HGSD), the Fort Bend Subsidence District (FBSD), the Lone Star Groundwater Conservation District (LSGCD) and the Brazoria County Groundwater Conservation District (BCGCD).

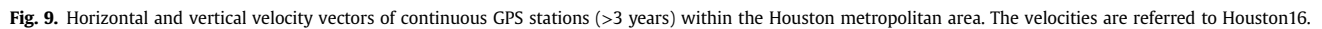
5.2. Long-Point Fault monitoring

More than 150 historically active faults have been identified in the Houston, Texas, metropolitan area [34–36]. Fault movement has caused substantial, costly damage to private and public infrastructure, which includes buildings, roadways, and utilities. The Long-Point Fault is one of those active faults, and it is of particular interest to city planners and civil engineers. It extends over 16 km across west Houston (Fig. 1). Data from a seismic profile shows that the fault extends to a depth at least 5000 meters below the land surface [37]. The Long-Point Fault is a typical concave-upward growth fault.

The University of Houston has installed a GPS array with 11 permanent GPS stations along the two sides of the Long-Point Fault in order to monitor its movement. Fig. 10 depicts the GPS-derived horizontal and vertical velocity vectors along the Long-Point Fault. The surface scarp of the Long-Point Fault can be distinctly seen in the Digital Elevation Model (DEM) derived from airborne Light Detection And Ranging (LiDAR) data. The airborne LiDAR data was collected in 2001 by the Tropical Storm Allison Recovery Project, which is managed by the Harris County Flood Control District (HCFCD, <http://www.hcfcd.org>). A connection between the scarp at the land surface and the Long-Point Fault (subsurface fault) has been verified by previous investigations [e.g., 34, 35 and 37]. The velocity vectors indicate consistent movement towards the northwest direction (approximately 5 mm/year) and subsidence

(approximately 8 mm/year) for all stations along both sides of the fault trace. There is not any considerable variation of ground displacements between stations on opposite sides of the fault. TXHS is a CORS operated by the Texas Department of Transportation. It is located approximately 10 km south of the Long-Point Fault. The observations at this site show almost identical vertical and horizontal velocity vectors as those stations near to the fault. Fig. 11 illustrates a detailed comparison of the displacement time series of two groups of GPS stations: (a) UTEX vs. TXHS, and (b) SPBH vs. CSTE. UTEX is located on the north side of the fault at a distance of less than 1 km to the fault scarp. TXHS is located on the south side of the fault at a distance of 10 km from the fault scarp (Fig. 10). The displacement time series indicate that the two sites experienced almost identical horizontal and vertical ground movements during the past five years. SPBH and CSTE are located at opposite sides of the fault. The 4-year displacement time series indicate no considerable differences between the displacements at these two sites. In summary, the GPS observations did not show any considerable spatial variation of the ground deformation along the Long-Point Fault during the past four years. In other words, the consistent horizontal movement (5 mm/year) towards the northwest direction is not likely caused by the activity of the Long-Point Fault.

The horizontal movement may be associated with the long-term rapid subsidence in the Jersey Village area as depicted in Figs. 8 and 9. According to Fig. 8, a subsidence bowl has been occurring in the Jersey Village area for over two decades. The current subsidence



Thousands of permanent continuous GPS stations have been installed worldwide during the past two decades for different research and application purposes. These publicly available long-term GPS observations enable us to establish rigorous regional reference frames for studying localized ground displacements (faulting, subsidence, and landslides) and structural deformation. This study demonstrated an approach of using publicly available GPS data to establish a regional reference frame and conduct high

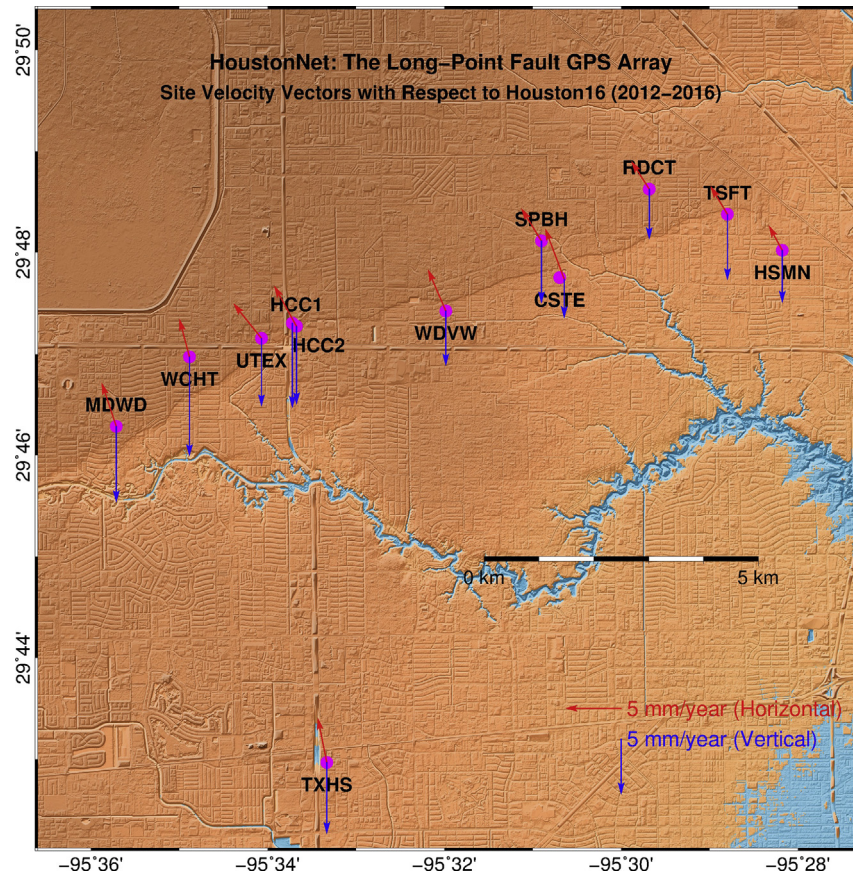


Fig. 10. A map showing the horizontal (pink) and vertical (blue) velocity vectors at GPS sites along the Long-Point Fault. The velocities were derived from three to four years of continuous observations. The surface scarp of the Long-Point Fault can be distinctly seen in the LiDAR DEM. The airborne LiDAR data was collected in 2001 by the Tropical Storm Allison Recovery Project managed by the Harris County Flood Control District (HCFCD, <http://www.hcfcd.org>).

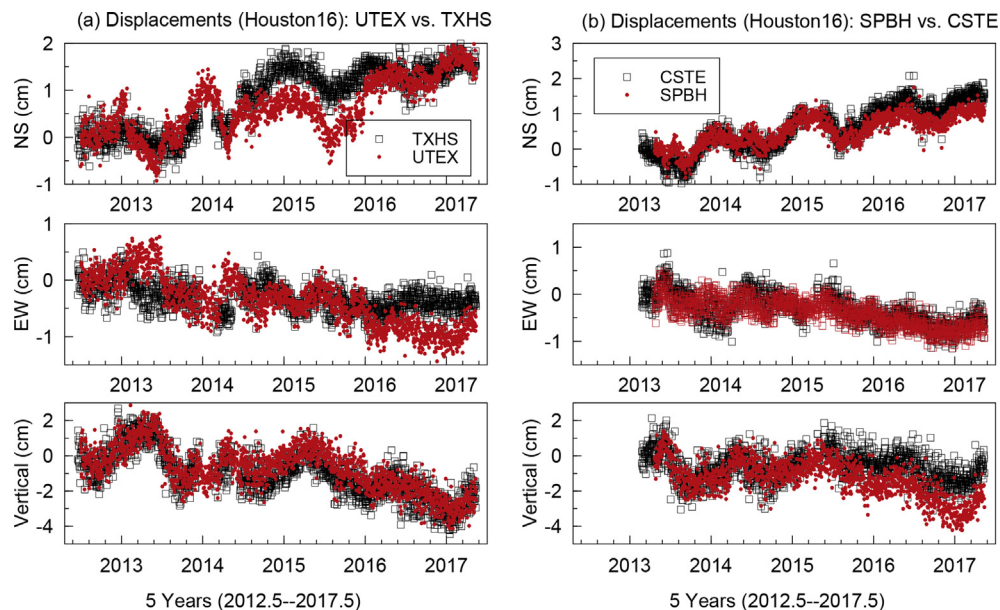


Fig. 11. Comparisons of the three-component displacement time series at four GPS sites along the Long-Point Fault. (a) UTEX is within 1 km of the fault scarp; TXHS is approximately 10-km away from the fault scarp. (b) SPBH and CSTE are located at opposite sides of the fault and both are within 1 km of the fault scarp.

accuracy land subsidence and faulting monitoring in an urban environment. It is hoped that this study will promote the applications of GPS and other global navigation satellite systems (GNSS) in urban geological hazards studies.

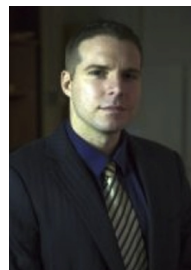
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