Research Article

Using Multisensor SAR Datasets to Monitor Land Subsidence in Los Angeles from 2003 to 2017

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Received 12 July 2018; Revised 6 November 2018; Accepted 27 November 2018; Published 27 February 2019

Guest Editor: Sang-Hoon Hong

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Los Angeles has undergone tremendous deformations over the past few decades, mainly due to human factors such as natural disasters and earthquakes, urban construction, overexploitation of groundwater, and oil extraction. The purpose of this study is to map the temporal and spatial variations of land subsidence in Los Angeles and to use the improved SBAS (small baseline subset) technique and multisensor SAR datasets to analyze the causes of deformations in this area from October 2003 to October 2017. At the same time, the deformation results of SBAS inversion are compared with the GPS measurements and the multisensor SAR dataset deformation, and the results are highly consistent. During the period from 2003 to 2017, there were several subsidence regions and one uplift region in Los Angeles. The cumulative subsidence was -266.8 mm at the maximum, and the average annual subsidence velocity was -19 mm/yr, which was mainly caused by groundwater overexploitation. The maximum amount of accumulated lift is +104.8 mm, and the average annual lifting velocity can reach +7.5 mm/yr. Our results have very strong practical application value and can provide a significant basis for local government services in disaster prevention and mitigation decision-making.

1. Introduction

The Los Angeles area, located in Southern California, is one of the most developed and densely populated areas in the United States. At the same time, it is located in the world's largest seismic zone, the Pacific Rim seismic zone. What is more, there are many faults distributed. On January 17, 1994, a 6.7 M earthquake struck the Los Angeles area and caused more than 1500 aftershocks [1]. 62 people died, more than 9000 people were injured, 25,000 were homeless, transportation facilities were seriously damaged, and cumulative economic losses amounted to more than 30 billion U.S. dollars. So far, many earthquakes have occurred in the area.

Los Angeles is a Mediterranean climate zone that is generally dry throughout the year and has an annual precipitation of only 378 mm, but there is slightly more rainfall in winter. Since only a small amount of rainfall can penetrate the groundwater and many people continue to extract groundwater, it eventually leads to an imbalance in groundwater circulation. At the same time, the fault can prevent the movement of groundwater to a certain extent and the

land subsidence, and uplift of the local area are caused. In the first half of the 20th century, scientists from the US Geological Survey recorded large-scale land subsidence for the first time and found that most of the subsidence was caused by overexploitation of groundwater. Later, the government tried to restore groundwater aquifers by transferring abundant water from the north to the dry south, thereby reducing the amount of subsidence. Regrettably, the subsidence is still continuing, even surpassing the historical high of 30 cm/year.

Whether the earthquake or groundwater exploitation causes surface changes, it will cause huge losses to infrastructure, bridges, roads, underground pipelines, and other infrastructure. At present, the problem of land subsidence has been spread throughout China. Serious land subsidence occurred in cities such as Beijing, Shanghai, and Taiyuan, causing huge economic losses. The continued overexploitation of groundwater is the main reason for the rapid subsidence of the ground in Beijing. At present, there are two main subsidence centers in the north and south, and the surface continues to settle at a rate of 30-60 mm/yr [2].

FIGURE 1: SBAS processing flow.

Therefore, it is of great significance to carry out long-span, high-precision, short-period, and large-coverage monitoring to provide the latest subsidence information to urban monitoring in urban construction.

Compared with conventional measurement technology, InSAR, as a kind of space observation technology, has been widely used in earthquake monitoring and urban subsidence monitoring, because of its all-weather, high-precision, wide monitoring area and low cost [3]. In order to solve the problem that conventional InSAR technology is limited by spatio-temporal and atmospheric delays, researchers have proposed time series InSAR technology, such as Permanent Scatterer (PS) [4, 5] and SBAS [6]. SBAS solves all the interference pairs that satisfy the baseline requirements and uses the singular value decomposition (SVD) method to get the minimum solution. It can monitor long-term surface deformation and overcome the effects of temporal and spatial irregularities and atmospheric delays, thus improving the monitoring accuracy to the millimeter level. Its ability to detect slow deformations accumulated over a long period of time shows great potential.

Many papers have been published on the monitoring of InSAR technology in Los Angeles [7–11]. However, the above papers only focus on deformation monitoring in the short term, without long-term monitoring and analysis. More than one hundred SAR images, including Envisat ASAR, ALOS-1 Palsar, TerraSAR-X, and Sentinel-1 datasets, are involved to analyze the characteristics of ground deformation from 2003 to 2017 by using the SBAS technique. Our results have a very strong practical application value which can quickly monitor the deformation anomaly area and provide significant data to serve the decision-making of disaster prevention and mitigation for the local government.

2. Methodology

SBAS is a newly developed MT-InSAR method, which was first proposed by researchers such as Lanari et al. [12, 13]. This paper uses the improved SBAS method for processing. The adaptive filtering method is used to improve the quality of the interferogram. The high quality interferogram is selected to remove the image with poor interference quality, and the Delaunay Minimum Cost Stream (Delaunay MCF) is used to improve the robustness of the algorithm. SBAS combines the image pairs of a small baseline to generate a series of interferograms with different master image time series. It can increase the time sampling rate by using all the data included in different small baseline subsets to solve the problem that the temporal sampling is too sparse. Then, using the singular value decomposition (SVD) method of the matrix, multiple small baseline subsets are combined to solve the least-quadratic least-squares solution [14]. The frequency characteristics of the delay phase due to atmospheric delay are different in the time domain and the spatial domain. The atmospheric phase is spatially correlated and appears as a low frequency signal in the spatial domain. In the time domain, the atmospheric disturbances during image acquisition are random, and the atmospheric phase is irrelevant in the time domain, which is represented by high frequency signals. Therefore, the effects of atmospheric delay are effectively improved by high-pass filtering in the time domain and low-pass filtering in the spatial domain. Finally, the deformation sequence covering the entire observation time and the land subsidence rate were obtained. The basic principle of SBAS:

- (1) first, obtain $N + 1$ SAR images of the same area, in order of acquisition time $t_0, \dots, t_N$. At the same time,

FIGURE 2: The coverage of the radar image data used in this research overlaid on the Los Angeles map.

it is assumed that each image can interfere with at least another image. Select one of the images as the master image and interfere with the rest of the SAR images to form a small baseline subset. Then, the $N + 1$ SAR image can generate M multiview interferograms with $N + 1$ subsets. M is the sum of the number of interference pairs in each small baseline subset, and the formation of interferograms between SAR images is determined by the time baseline and the spatial baseline

- (2) taking the images t_A and t_B as examples, the j -th differential interferogram is generated from the SAR images acquired from the slave image t_A and the master image t_B ($t_A > t_B$), the interference phase of the pixel with the azimuth coordinate x and the range coordinator can be rewritten as

$$\begin{aligned} \delta\phi_j(x, r) &= \phi_B(x, r) - \phi_A(x, r) \\ &\approx \frac{4\pi}{\lambda} [d(t_B, x, r) - d(t_A, x, r)] + \Delta\Phi_{\text{topo}}(x, r) \\ &\quad + \Delta\Phi_{\text{APS}}^j(t_B, t_A, x, r) + \Delta\Phi_{\text{noise}}^j(x, r). \end{aligned} \quad (1)$$

In the formula, $j \in (\dots, M)$, λ is the center wavelength of the signal; $d(t_B, x, r)$ and $d(t_A, x, r)$ are t_B and t_A moments relative to the accumulated visual variables of the radar line of sight $d(t_0, x, r) = 0$; $\Delta\Phi_{\text{topo}}^j(x, r)$ denotes the residual topographic phase in the differential interferogram; assuming that the DEM introduced in the differential interference process is of high precision, most of the terrain phases can be removed and the residual topographic information in the differential interferogram is small and can be ignored in the subsidence process; $\Delta\Phi_{\text{APS}}^j(t_B, t_A, x, r)$ is the atmospheric delay phase; and $\Delta\Phi_{\text{noise}}^j(x, r)$ denotes decoherence noise

(such as system thermal noise). If we do not consider the atmospheric delay phase, residual topography phase, and noise phase, (1) can be simplified as

$$\begin{aligned} \delta\phi_j(x, r) &= \phi_B(x, r) - \phi_A(x, r) \\ &\approx \frac{4\pi}{\lambda} [d(t_B, x, r) - d(t_A, x, r)]. \end{aligned} \quad (2)$$

- (3) in order to obtain a physically meaningful settling sequence, the phase in equation (2) is expressed as the product of the average phase velocity and time between the two acquisition times:

$$v_j = \frac{\Phi_j - \Phi_{j-1}}{t_j - t_{j-1}}. \quad (3)$$

The phase value of the j -th interferogram can be rewritten as

$$\sum_{k=t_{A,j}+1}^{t_{B,j}} (t_k - t_{k-1}) v_k = \delta\phi_j. \quad (4)$$

Immediately the integration of speed at each time interval between master image and slave image intervals. Written in matrix form:

$$Bv = \delta\phi, \quad (5)$$

Equation (5) is a matrix of $M * N$. Since the multi-primary image strategy is adopted for the differential interferogram of the small baseline subset, the matrix B is prone to rank loss. By using the SVD method, the generalized inverse matrix of matrix B can be obtained. And then the minimum norm solution of the data vector can be obtained. Finally, the integral of the velocity in each time period can obtain the

TABLE 1

(a) Basic parameters of Envisat ASAR dataset

No.	Date	Polarization	Baseline (m)
1	2003-10-29	VV	-213
2	2004-06-30	VV	621
3	2004-09-08	VV	-148
4	2004-11-17	VV	366
5	2004-12-22	VV	619
6	2005-01-26	VV	-428
7	2005-03-02	VV	490
8	2005-05-11	VV	-683
9	2005-06-15	VV	73
10	2005-07-20	VV	-486
11	2005-09-28	VV	-628
12	2005-12-07	VV	676
13	2006-01-11	VV	-212
14	2006-02-15	VV	397
15	2006-03-22	VV	770
16	2006-04-26	VV	-713
17	2006-05-31	VV	673
18	2006-10-18	VV	-281
19	2006-11-22	VV	531
20	2006-12-27	VV	295
21	2007-07-25	VV	-11
22	2007-08-29	VV	300
23	2007-10-03	VV	-166
24	2007-11-07	VV	0
25	2007-12-12	VV	-332
26	2008-01-16	VV	99
27	2008-02-20	VV	-219
28	2008-03-26	VV	180
29	2008-04-30	VV	-92
30	2008-06-04	VV	-73
31	2008-07-09	VV	-149
32	2008-08-13	VV	79
33	2008-09-17	VV	-231
34	2009-02-04	VV	-273

(b) Basic parameters of ALOS-1 Palsar dataset

No.	Date	Polarization	Baseline (m)
1	2006-06-30	HH	-3053
2	2006-08-15	HH	-177
3	2006-09-30	HH	-316
4	2006-11-15	HH	454
5	2006-12-31	HH	-1372
6	2007-02-15	HH	324
7	2007-05-18	HH	518
8	2007-07-03	HH	883
9	2007-08-18	HH	1101

TABLE 1: Continued.

No.	Date	Polarization	Baseline (m)
10	2007-10-03	HH	1257
11	2007-11-18	HH	1640
12	2008-01-03	HH	1575
13	2008-02-18	HH	2506
14	2008-04-04	HH	2836
15	2008-05-20	HH	2731
16	2008-07-05	HH	0
17	2008-08-20	HH	-2469
18	2008-10-05	HH	-1589
19	2008-11-20	HH	-1261
20	2009-01-05	HH	-992
21	2009-02-20	HH	-671
22	2009-04-07	HH	-115
23	2009-07-08	HH	-904
24	2009-08-23	HH	349
25	2009-10-08	HH	626
26	2010-01-08	HH	1011
27	2010-02-23	HH	1525
28	2010-04-10	HH	1751
29	2010-05-26	HH	1646
30	2010-07-11	HH	1703
31	2010-10-11	HH	2443
32	2010-11-26	HH	2529
33	2011-01-11	HH	2850
34	2011-02-26	HH	3446

(c) Basic parameters of TerraSAR-X dataset

No.	Date	Polarization	Baseline (m)
1	2011-03-05	HH	208
2	2011-06-12	HH	356
3	2011-09-19	HH	508
4	2011-10-11	HH	151
5	2011-12-16	HH	77
6	2012-02-20	HH	321
7	2012-04-15	HH	746
8	2012-07-01	HH	435
9	2012-09-27	HH	383
10	2013-01-15	HH	-66
11	2013-06-07	HH	323
12	2013-07-21	HH	149
13	2013-08-12	HH	-72
14	2013-10-28	HH	-130
15	2013-12-11	HH	10
16	2014-01-13	HH	49
17	2014-03-09	HH	92
18	2014-04-22	HH	0
19	2014-06-27	HH	443
20	2014-07-19	HH	404

TABLE 1: Continued.

No.	Date	Polarization	Baseline (m)
21	2014-08-10	HH	275
22	2014-10-26	HH	60
23	2015-01-22	HH	283
24	2015-04-09	HH	-132
25	2015-06-03	HH	-82
26	2015-08-19	HH	95
27	2015-10-02	HH	-78
28	2015-12-07	HH	55

(d) Basic parameters of Sentinel-1 dataset

No.	Date	Polarization	Baseline (m)
1	2015-01-26	VV	28
2	2015-05-14	VV	-123
3	2015-06-07	VV	32
4	2015-07-01	VV	112
5	2015-08-18	VV	-46
6	2015-09-11	VV	-16
7	2015-10-05	VV	-53
8	2015-11-22	VV	-14
9	2015-12-16	VV	-35
10	2016-01-09	VV	59
11	2016-02-02	VV	-25
12	2016-03-09	VV	0
13	2016-04-02	VV	-16
14	2016-05-08	VV	16
15	2016-06-01	VV	3
16	2016-07-19	VV	-20
17	2016-08-12	VV	-66
18	2016-09-05	VV	-54
19	2016-10-11	VV	12
20	2016-11-04	VV	35
21	2016-12-10	VV	7
22	2017-01-03	VV	15
23	2017-02-08	VV	56
24	2017-03-04	VV	-124
25	2017-05-03	VV	10
26	2017-06-08	VV	48
27	2017-07-14	VV	-65
28	2017-08-07	VV	33
29	2017-09-12	VV	-19
30	2017-10-18	VV	-12

deformation variables of each time period. The SBAS timing processing data flow is shown in Figure 1.

3. Study Area and Datasets

The research area is located in Los Angeles, Southern California. It is one of the core areas of the United States. It

contains dense high-rise buildings, high population density, and convenient transportation. The scope of this study is shown in Figure 2.

In order to study the surface changes in Los Angeles over the past 14 years, SAR images of four different satellites were used. The Envisat ASAR images were acquired from 2003 to 2009, and the specific parameter information is shown in Table 1(a). The ALOS-1 Palsar images were acquired from 2006 to 2011, and the specific parameter information is shown in Table 1(b). The TerraSAR-X images were acquired from 2011 to 2015, and the specific parameter information is shown in Table 1(c). The Sentinel-1 images were acquired from 2015 to 2017, and the specific parameter information is shown in Table 1(d).

GPS data was obtained from Nevada Geodetic Laboratory (<http://geodesy.unr.edu/index.php>).

This paper select DEM data with 30m resolution for external reference for simulating and eliminating the topographic phase. In the process, multiview processing is carried out to reduce the amount of data storage, improve the speed of operation, and suppress phase noise. The improved adaptive Goldstein filtering method is used to filter the generated interferogram so as to improve the quality of the interferogram [14]. The interferogram is phase unwrapped using the Delaunay Minimum Cost Flow.

4. Result and Analysis

For multisensor SAR datasets already processed, the annual average displacement velocity map of the Los Angeles area (see Figures 3(a)-3(d)) and time series displacement map were obtained (see Figures 4(a)-4(d)). Eight regions are found and named as regions I to VIII by order. Statistical analysis of the annual average velocity map for different periods. During 2003 to 2009, the average annual velocity of Los Angeles is +0.35 mm/yr, the average annual velocity of the monitored pixel points is between -78.5 mm/yr and +65.7 mm/yr, and the standard deviation among all pixel values is ± 4.6 mm/year. During 2009 to 2011, the average annual velocity of Los Angeles is +1.5 mm/yr, the average annual velocity of the monitored pixel points is between -128.5 mm/yr and +161.2 mm/yr, and the standard deviation among all pixel values is ± 7.3 mm/yr. During 2011 to 2015, the average annual velocity of Los Angeles is +0.7 mm/yr, the average annual velocity of the monitored pixel points is between -17.6 mm/yr and +21.3 mm/yr, and the standard deviation among all pixel values is ± 3.3 mm/yr. During 2015 to 2017, the average annual velocity of Los Angeles is -0.1 mm/yr, the average annual velocity of the monitored pixel points is between -58.7 mm/yr and +23.4 mm/yr, and the standard deviation among all pixel values is ± 3 mm/yr. It can be seen from the above data that most of the Los Angeles areas were in a stable state (slight uplift and subsidence) from 2003 to 2017, and at the same time, they proved that the processing results have good monitoring accuracy (see Figures 5(a)-5(d)).

The purpose of this experiment is to find high-risk areas with large deformation. Based on general engineering experience and experimental results, the area from -5 mm/year

FIGURE 3: Annual average displacement velocity map from October 2003 to October 2017 by multisensor SAR datasets.

to +5 mm/year was defined as a relatively stable area, such as region I-IV (see Figures 5(a)-5(d)). Regions over ± 5 mm/year are classified as potentially disaster-inducing areas, and further research is conducted such as region V-VIII (see Figures 5(e)-5(h)).

By using Google Maps contrast, it was found that stable regions I-IV are located in West Covina, Pasadena. In the stable regions I-IV, the maximum deformation is less than 25 mm, and the annual average rate is less than 5 mm/yr from 2003 to 2017. This shows that the area has a stable texture structure and a balanced groundwater system.

Regions V-VII are Pomona, Ontario, and Upland. From Figures 5(e)-5(g), it shows that regions V-VII have existed serious subsidence from 2003 to 2017, accumulated -266.8 mm, -105.1 mm, and -82.6 mm, and the annual average velocities are -19 mm/yr, -7.5 mm/yr, and -5.9 mm/yr, respectively. What is more, the subsidence center of region V moves to the northeast. By consulting the data, we can see that the area is an urban area with a high population density and a large demand for water. People continue to use groundwater for their lives, resulting in an imbalance in the groundwater circulation system. As early as the 1970s, when the local government discovered the adverse consequences of overexploitation of groundwater, there was a "North-South Water Transfer" project to transfer water from Southern California to reduce groundwater use. Unfortunately, from the point of view of subsidence, the project is still insufficient because the surface still continues to settle and the rate of subsidence is not small. Based on the current results of the settling rate, the subsidence will reach the meter level within a few decades. Land subsidence is not conducive to urban construction, and it is easy to cause the foundation of the building to be unstable, resulting in the collapse of the

building. When the subsidence is severe, the urban facilities will be destroyed, resulting in the shutdown, rupture, deformation, and even collapse of the engineering facilities. The ground subsidence of the road will be uneven or cracked, and the bridge will sink and deform, which will cause potential safety hazards.

Region VIII is located in Santa Fe Springs, where cumulative deformation is +104.8 mm, and the annual average velocities are +5.9 mm/yr. It is speculated that the uplift of the earth's surface is related to the tectonic movement, oil extraction, and recharge. This area is close to the Whittier fault, and the vertical movement of the fault will cause the surface to rise. In the oil extraction process, water injection and recharge are usually performed to increase the extraction efficiency. The reinfusion of water injection will cause the surface to rise slowly.

5. Result Verification

In order to assess the accuracy of the SBAS results, we compared SBAS processing results for GPS data and Sentinel-1 data between 2015 and 2017, as shown in Figures 6(a) and 6(b). At station CIT1, the median error between GPS and SBAS data is 0.89 mm, and the Pearson correlation coefficient is 0.892. At station PRKD, the median error between GPS and SBAS data is 0.77 mm, and the Pearson correlation coefficient is 0.740. It can be shown that there is a strong consistency between the SBAS results and the GPS monitoring data, and the reliability of the experimental results is high.

In the SBAS results from the Envisat ASAR and ALOS-1 Palsar data processing, Figures 7(a) and 7(b) show time series deformation results at Pomona West Side and Rowland

(a)

FIGURE 4: Continued.

(b)

FIGURE 4: Continued.

(c)

FIGURE 4: Continued.

(d)

FIGURE 4: Result of SBAS in the study area. (a) describes the time series displacement in Los Angeles from 2003 to 2009. (b) describes the time series displacement in Los Angeles from 2006 to 2011. (c) describes the time series displacement in Los Angeles from 2011 to 2015. (d) describes the time series displacement in Los Angeles from 2015 to 2017.

Heights from December 2006 to June 2009. The medium errors were 2.70 mm and 1.92 mm, and the Pearson correlation coefficients were 0.810 and 0.758, respectively. This shows that there is a strong consistency between the monitoring results of the two data sources.

In the SBAS results from the TerraSAR-X and Sentinel-1 data processing, Figures 8(a) and 8(b) show time series deformation results at Pomona and Ontario in 2015. The medium errors were 1.22 mm and 0.51 mm and the Pearson correlation coefficients were 0.878 and 0.981, respectively. This also

(a)

(b)

(c)

FIGURE 5: Continued.

FIGURE 5: Continued.

FIGURE 5: The time series displacement of region I-VIII. In Figures 5(e)-5(h), because the data coverage is not completely coincident, a part of data is missing. For the continuity of time-series analysis, the data of the dotted line in the figure is a prediction using a nonlinear curve fitting.

FIGURE 6: (a) CIT1 and SBAS deformation results. (b) PKRD and SBAS deformation results.

FIGURE 7: (a) Pomona West Side time series deformation result. (b) Rowland time series deformation result.

FIGURE 8: Pomona time series deformation result. (b) Ontario time series deformation result.

shows that there is a strong consistency between the monitoring results of the two data sources.

In summary, it can be seen that the results obtained by the multisensor data processing of this experiment are reliable.

6. Conclusion

This paper uses the SBAS technology and multisensor SAR data (Envisat ASAR, ALOS-1 Palsar, TerraSAR-X, and Sentinel-1) to perform long-term land subsidence monitoring over the Los Angeles area from 2003 to 2017. Through the sequence analysis of the deformation evolution process of the surface, uneven deformation was found. When the

deformation reaches a certain level, it may cause the collapse of the building and underground pipes and wires and cause breakage and damage to other basic equipment. At the same time, by monitoring the surface variables, timely feedback to the local departments to provide relevant departments with decision-making basis. Among them, there are serious subsidences in areas V-VII, which are prone to disasters because of the overexploitation of groundwater and the need for timely prevention and control measures. Regional uplift occurred in region VII, which was presumed to be caused by water injection and tectonic movement. However, further research and analysis are needed. At the same time, the cross-validation of the deformation results obtained by multisensor data was performed, and the GPS data and Sentinel-1 deformation

results were further compared to verify the reliability of the deformation results. In summary, the results reflect the advantages of SBAS technology and indicate that multi-sensor SAR data has a certain application value in urban city subsidence monitoring.

Data Availability

The DEM data used to support the findings of this study may be released upon application to the account (<https://www.eorc.jaxa.jp/ALOS/en/aw3d30/data/index.htm>), which can be contacted by email. The Sentinel-1 data used to support the findings of this study may be released upon application to the account (<https://scihub.copernicus.eu/dhus/#/home>), which can be contacted by email.

Conflicts of Interest

The authors declare no conflict of interest.

Acknowledgments

This work was supported the National Natural Science Foundation of China (Grant Nos. 41674006 and 41704019) and by the Science and Technology Plan Project in Fujian Province (grant No. 2017Y3004). We wish to thank the Japanese Aerospace Agency (JAXA) for arranging the ALOS PALSAR data and “ALOS World 3D-30m” data. We also thank China Geological Survey for providing the GPS observation data.

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