Monitoring land subsidence in the southern part of the lower Liaohe plain, China with a multi-track PS-InSAR technique

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Abstract: The lower Liaohe plain is one of the most important industrial zones in Liaoning Province, China, and activities here include oil and gas exploration, aquaculture and salt production. Heavy land use may have contributed to the different magnitudes of land deformation in this region, and this has been detrimental to the environment and economic construction projects in this zone. In this paper, we employ the permanent scatterers interferometry (PSI) technique with L-band ALOS/PALSAR imagery data to monitor the annual land subsidence and produce accumulative time-series maps for the years of 2007 to 2011. The unwrapped grid size was tested in order to recover the maximum deformation. InSAR results from two adjacent tracks were merged by considering the offset over the overlapped area. A PS standard deviation of 0.91 cm/yr was achieved in the vertical direction, according to calculation from two independent PS results. Three kinds of land subsidence were analyzed quantitatively over the oil fields, coastal zones, and salt production areas. Some severe land subsidence regions were verified by field investigations.

Key words: Land subsidence, Monitoring, Permanent scatterers, Synthetic aperture radar interferometry (InSAR), ALOS/PALSAR, Multi-track

1 Introduction

The lower Liaohe plain is 23,470 km² in size and is located in the middle of Liaoning Province, China. This

24 region is one of the most important industrial zones in northeast China for activities such as oil and gas exploration,
25 aquaculture, and salt production. While the abundant resources have contributed greatly to the local economy,
26 uncontrolled resources exploitation has caused severe environmental problems such as land subsidence and
27 increases in aridity. Field survey results showed that maximum land subsidence occurred in the Dongguo Marsh
28 Field (Fig. 1) of Panshan country and the extent of subsidence was more than 2.5 m; consequently, a pumping
29 station had to be abandoned and serious impacts on marsh plants and aquaculture facilities have also occurred.
30 Government reports estimate the associated industrial facility loss amount at 136.68 million RMB yuan, the marsh
31 production loss amount at 22.4 million RMB yuan, and the aquaculture loss amount at 21.14 million RMB yuan
32 (Shenyang Institute of Geology and Mineral Resources, 2009). Moreover, the wetland nature reserve is becoming
33 more degraded year by year, and this has seriously affected the habitat and reproduction of precious wildlife.

34 However, up until now, there has been no large-scale high-precision monitoring work conducted in this area;
35 only some local leveling measurements have been taken. Unfortunately, the present leveling data set is not very
36 reliable because of too few historical measurements and incomplete records. In order to investigate the scope,
37 magnitude, distribution, and temporal change of land subsidence in lower Liaohe plain and the possible causes,
38 synthetic aperture radar interferometry (InSAR) would be ideal technology to employ. This technology represents
39 one of the most advanced topography analysis methods, and it has been used successfully in monitoring studies of
40 land subsidence in a number of cities (Zhao et al., 2009; 2011; 2013; Zhu et al., 2013; Zhang et al., 2014; Zhao et
41 al., 2013, 2014; Carnec & Fabriol, 1999; Fielding et al., 1998). To overcome the limitations of using InSAR in
42 areas of heavy vegetation, the permanent scatterers (PS) InSAR technique (Ferretti et al., 2001) was employed here.
43 Specifically, this research obtained deformation data for the lower Liaohe plain by using the archived Advanced
44 Observing Satellite Phased Array type L-band SAR (ALOS/PALSAR) data. StaMPS (Hooper et al., 2013)
45 parameters such as the unwrap_grid_size were analyzed in order to obtain large gradient deformation information,

46 and the PS results from two adjacent tracks were merged into a large coverage deformation map. Then, the land
47 subsidence results were analyzed to determine their different causes. Section 2 presents an overview of the study
48 area. Section 3 presents the methodology involved. Section 4 and section 5 present the results and land subsidence
49 analysis work, respectively, and concluding remarks are given in section 6.

50 **2 Study area**

51 Fig. 1 shows the location of the southern part of the lower Liaohe plain administrative district, which includes
52 Liaoyang, Anshan, Yingkou, Panjin, and Jinzhou municipalities. The total area of this region is about 12,620 km²,
53 and it is approximately 118 km along W-E direction and 107 km along N-S direction. The mountainous regions of
54 Liaodong and Liaoxi are located to the east and west of this plain, respectively. The plain elevation ranges from 10
55 m to 50 m. Weiyuanbao-Panshan, Liaozhong-Dawa, Erjiegou, and Fushun-Yingkou faults cut through this plain in
56 northeast-east directions. The Liaohe, Raoyang, Dalinghe, and Xiaolinghe rivers pass through this region and run
57 into Po Hai to the south. The rich water resources and humid environment have allowed for the development of
58 many wild marshes (Fig. 2a) and alkaline grasses, and this area is the site of a beautiful wetland nature protection
59 zone (Fig. 2b). When autumn comes, the color of the wild marshes turns from green to red forming a beautiful
60 spectacle called the " Red Beach " . These wild marshes cover an area of about 1280 km².

Fig. 1. Location map of the southern part of the lower Liaohe plain, which is superimposed on a shaded relief map of Liaohe. The study area is mainly located in the plain area. Irregular polygons represent the distribution of oil fields in the research region, the red and green lines represent the faults and rivers, respectively, and black rectangles demarcate the coverage of the two adjacent ALOS/PALSAR ascending tracks numbered 436 and 437.

Mineral resources including oil, coal, iron, etc. are abundant in this region. The " Liaohe oil field " in Panjin is the fourth largest oil field in China. Fig. 2 shows the distribution of oil exploitation bases in this plain. Field surveying work uncovered severe damage to the pump station in Panshan caused by the abrupt land subsidence, and it had to be abandoned in 2009 (Fig. 2c). In addition, land subsidence has been detected at aquaculture sites (Fig. 2d) and in areas of salt production (Fig. 2e).

Fig. 2. The lower left panel Google Earth image shows the distribution of oil production bases in the lower Liaohe plain. The study region is demarcated by the black rectangle. (a) Marshes; (b) " Red Beach " which is a wetland nature reserve. The picture of (b) is a natural-color image, and it is a natural phenomenon for the marsh to turn from green to red in autumn; (c) abandoned pumping station in the Dongguo Marsh Field, Panjin; (d) and (e) are Landsat ETM+ images that represent the aquaculture field and the salt production zone, respectively.

The seasonal changes of water cover and heavy vegetation inevitably result in serious incoherence problems for SAR interferometry applications. An earlier study found that the stronger penetrability and longer wavelength of the L-band is helpful for retrieving subsidence values over vegetated terrain and is superior in the case of large deformation gradients compared with the C-band (Strozzi et al., 2003). Hence, L-band ALOS/PALSAR data were chosen for use in this experiment. Then, the PS-InSAR technique was used to derive the annual surface deformation rate and accumulative time-series results. Multi-track SAR data were employed to cover the deformation region at as large of a scale as possible.

3 Methodology

InSAR technology is capable of producing large deformation maps of about 10,000 km². However, it is

88 difficult to assess wide ranging land subsidence because of the limitations posed by a single satellite's acquisitions.
89 While multi-track results for extended land subsidence monitoring can be very useful, there are also many problems
90 that need to be solved (Ketelaar et al., 2007; Ge et al., 2010; Xiong et al., 2014); these issues mainly involve the use
91 of common coordinates and resolution of the different subsidence and geometry position offsets for PS points in
92 overlapped regions. In this section, we present a methodology for solving the above problems.

93 It is easy to convert radar coordinates to map coordinates by using an external digital elevation model (DEM).
94 Different look angles and regimes yield different measurements of subsidence in overlapped regions. Since data
95 cannot be directly merged in different directions, we projected the subsidence to the same direction, e.g., the
96 vertical direction for subsidence. The reason for the geometry position offset is mainly due to the fact that most PS
97 points cannot be identified in every track. In order to solve this, we interpolated both PS points from overlapped
98 regions into the same grid, and then, we obtained the offset deformation. The last part involves choosing the
99 reference datum. Because there was no a priori information for adjacent track data, we did not know which track
100 results would be more stable. As much as possible in order to guarantee the reliability of the results, we calibrated
101 all the offset values of adjacent tracks with a weight, instead of choosing one as a reference datum.

102 The main procedure for multi-track PS-InSAR data processing involves three steps as shown in Fig. 3. These
103 steps include (1) PS-InSAR processing for single track SAR data, (2) calibration of InSAR results with independent
104 data in overlapped areas, and (3) post analysis of large coverage InSAR results. Some improvements to the InSAR
105 processing procedure and special considerations are discussed in detail in the following sub-sections.

Fig. 3. A block diagram of the multi-track processing procedure. The dots encompass the same data processing steps for track 1 and track 2. For the two parts described in part II, the vertical deformation from the LOS deformation and calibration of the two adjacent tracks results in a common datum with weighted offset deformation.

3.1 StaMPS-InSAR processing for single track SAR data

PS-InSAR successfully overcomes the problems of temporal and spatial decorrelation and heterogeneous atmospheric delay, which are common in the conventional differential InSAR processing method. PS-InSAR techniques have been successfully applied in monitoring studies of surface deformation even in less coherent regions (Vilardo et al., 2009; Lauknes et al., 2010; Keiding et al., 2010; Hooper et al., 2007). In this paper, we used StaMPS-InSAR software for SAR data processing to derive the deformation results. The key steps are summarized below. Readers can refer to earlier papers (Hooper et al., 2004; 2007; Hooper, 2006) and StaMPS software manual (Hooper et al., 2013) if they are interested in additional details.

Suppose N interferograms are generated from $N + 1$ SAR images acquired at different epochs on the same track and in the same study area with respect to one master image. The master image that we choose should be

121 based on considerations of both the temporal and spatial baseline and the influence of the Doppler central
 122 frequency (Hooper et al., 2007; Zebker & Villasenor, 1992). Usually, the master image minimizes the sum
 123 decorrelation of all the interferograms. An external DEM (here we used a Shuttle Radar Topography Mission
 124 (SRTM) 30-m DEM) is used to remove the effects of topography. From the co-registered SAR single look complex
 125 (SLC) images, we can detect PS points with phase stability and amplitude dispersion thresholds. Phase unwrapping
 126 is followed by geometric phase correction.

127 Once the PS pixels are selected based on the phase stability, the following steps are only focused on these PS
 128 pixels. For a generic i -interferogram, the wrapped differential interferometric phase of a PS pixel x can be
 129 described as follows:

$$130 \quad \psi_{\text{int},x,i} = W\{\phi_{\text{def},x,i} + \phi_{\text{atm},x,i} + \Delta\phi_{\text{orb},x,i} + \Delta\phi_{\theta,x,i} + \phi_{n,x,i}\} \quad (1)$$

131 where $W\{\}$ represents the wrapping operator and $\phi_{\text{def},x,i}$ is the phase change due to surface movement in the
 132 line-of-sight (LOS) direction, which is the useful part for deformation analysis. The other parts in equation (1) are
 133 nuisance terms, that is, $\Delta\phi_{\theta,x,i}$ is the residual phase due to the look angle error, $\phi_{\text{atm},x,i}$ is the phase due to the
 134 difference in atmospheric delay between passes, $\Delta\phi_{\text{orb},x,i}$ is the residual phase due to satellite orbit inaccuracies,
 135 and $\phi_{n,x,i}$ is a noise term due to variability in scattering, thermal noise, co-registration errors and uncertainty in
 136 the position of the phase center at the azimuth. Three dimensional phase unwrapping is applied to obtain more
 137 reliable unwrapping results. These nuisance terms can be well isolated by using a low-pass filter in the spatial
 138 domain and a high-pass filter in the time domain. Moreover, a low-pass filter in the time domain within a given
 139 Gaussian width can also recover the nonlinear deformation phase. Then, the annual deformation rate and
 140 time-series results can be constructed easily.

141 3.2 Maximum land subsidence monitoring analysis

142 The phase of PS pixels obtained from StaMPS method includes spatially uncorrelated terms (i.e., Gaussian

143 noise). So, it is better to filter these phases in the spatial domain before unwrapping. As a Goldstein filter is
 144 undertaken in continuous phase space (Goldstein & Werner, 1998), the irregular PS pixels need to be interpolated
 145 into the same-spaced grid (Hooper et al., 2007). Grid size is one of the most important parameters during the filter
 146 processing step. A rational value should be chosen in a way that balances the computational burden with the
 147 potential for real surface deformation recovery.

148 The maximum detectable deformation gradient d_x is defined as one fringe per pixel, or the dimensionless
 149 ratio of the pixel size to the half wavelength, which is expressed as follows (Massonnet et al., 1998).

$$150 \quad d_x = \frac{\lambda}{2 \cdot \eta} \quad (2)$$

151 where λ is the wavelength and η is the grid size in the slant range direction. Accordingly, we obtain the
 152 optimal grid size by changing the grid size until the true gradient is less than the calculated one or when the
 153 difference between the i-th and (i+1)-th phase gradients are statistically the same.

154 3.3 Mosaic of multi-track PS-InSAR results

155 If multi-track SAR data are involved, different satellite flight directions and/or different look angles for a given
 156 overlapped research region can provide extra information on land subsidence. The approach is threefold. First, the
 157 LOS deformation from different tracks should be projected to the vertical. Second, histograms of the annual
 158 deformation differences are calculated to obtain mean values (v_i) and standard derivations (δ_i^2). Last, the
 159 deformation offset between two neighboring tracks can be determined based on the weighted mean values.

160 From N sets of v_i and δ_i^2 obtained from N+1 track SAR data, a whole land subsidence map can be easily
 161 achieved by using the corrected mean values $\bar{v}_i$ as defined by the weighted mean values expressed as follows:

$$162 \quad \bar{v}_i = \frac{p_i v_i}{\sum_{i=1}^n p_i} \quad (3)$$

163 wherein p_i is a weight value ($p_i = \frac{1}{\delta_i^2}$). As there is a redundant observation only in the overlapped region of
 164 two neighboring tracks, each $\bar{v}_i$ will be assigned to the un-overlapped region of two neighboring tracks by equal
 165 weights.

166 Following the previous procedure, InSAR data from more than two tracks can also be merged to a whole map.
 167 Then, large coverage deformation results can be analyzed in the spatial and temporal domains, as shown in the third
 168 block of Fig. 3.

169 4 Results

170 4.1 Data sets

171 A total of 40 frames of archived raw (ALOS/ PALSAR) data were used. The data sets are shown in Table 1. Data
 172 for two adjacent ascending tracks (T436A and T437A in Fig. 1 and Table 1) acquired from the years of 2007 to
 173 2011 were available for use. The master image was chosen by taking into account the differences in the Doppler
 174 central frequency and spatial baseline as well as the time intervals of the interferometric pairs. The external DEM
 175 was determined by the SRTM at a resolution of approximately 30 m. As for ALOS/PALSAR data, the fine-beam
 176 double polarization (FBD) images were oversampled to the same pixel spacing as the fine-beam single polarization
 177 (FBS) images to maintain the fine SAR resolution. Fig. 4 shows the spatial-temporal baseline configurations of
 178 ALOS data for tracks 436 and 437. The coverage of two track data is superimposed in Fig. 1, where one overlapped
 179 region covers the cities of Panjin and Yingkou.

180 **Table 1.** Data used in the PS-InSAR processing procedure.

Track	Frame	Date period	Date of master image	Number of SAR data
436	810	01 Mar 2007-25 Oct 2010	17 Oct 2007	17
437	810	31 Jan 2007-11 Feb 2011	24 Dec 2009	23

Fig. 4. The spatiotemporal baseline configuration of ALOS interferometric pairs. (a) and (b) stand for (a) track 436 and (b) track 437, respectively. The red line represents the discarded interferogram (24 Dec 2009-27 Dec 2010).

4.2 PS-InSAR results and deformation modeling for track 437

Here, we use ALOS data from track 437 as an example to show the details of the PS processing procedure, and then, the InSAR results from two neighboring tracks are merged in next section. The 23 L-band ALOS data were acquired from 31 January 2007 to 11 February 2011 along track 437. The master image was taken on 24 Dec 2009 (Table 1). Then 22 interferograms were generated. The StaMPS data processing parameters were set as shown in Table 2.

Table 2. Parameter set for StaMPS processing.

Parameter	Value
max_topo_err (m)	8

filter_grid_size (m)	40
clap_win	32
clap_alpha	1
clap_beta	0.3
density_rand	20
unwrap_gold_alpha	0.6
unwrap_gold_n_win	32
unwrap_grid_size (m)	200,(100), 40, 30, 20

193 Note: For the large gradient deformation in the unwrapping, five different grid values (200, 100, 40, 30, and 20)
194 were chosen for detailed discussions, and 100 m was chosen for the whole patches analysis with the InSAR
195 processing procedure during the last step.

196

197 Fig. 5 shows all 22 unwrapped differential interferograms, where the slave image acquisition date,
198 perpendicular baseline, and time duration with respect to the master image are all superimposed on each frame of
199 the maps. One unwrapped map with a slave date of 27 December 2010 was discarded because of the abnormal
200 phase pattern.

Fig. 5. The 22 unwrapped interferograms for track 437 with respect to the master image acquired on 24 December 2009. The interferogram (24 Dec 2009-27 Dec 2010) marked with the red line exhibits an obvious phase jump, and it was discarded in the following processing steps.

206 The unwrap grid size was tested with different values, e.g., 200 m, 100 m, 40 m, 30 m, and 20 m, within the
 207 patch with large gradient deformation. Fig. 6 shows the cross-section along the profile of the maximum
 208 deformation region; the profile location is shown in the inset of Fig. 7. It can be clearly seen that for the case of an
 209 unwrap grid size of 200 m, the maximum deformation was only 130 mm/yr in LOS direction, and the location of
 210 the maximum deformation region was different from the results obtained with any other unwrap grid sizes. Both
 211 the maximum deformation values and locations for the other unwrap grid sizes were statistically the same. The
 212 slight differences resulted from the use of Goldstein filter with different grid sizes. Eventually, the grid size of 100
 213 m was chosen for the whole patch InSAR processing work. Fig. 7 shows the annual vertical displacement map
 214 generated with the 21 good unwrapped interferograms.

215
 216 **Fig. 6.** Cross-section of the deformation obtained with different unwrapped grid sizes along the profile located in
 217 the inset of Fig. 7. Red line represents the deformation obtained with a grid size of 200 m, and it was
 218 significantly less than that of the other sizes.

Fig. 7. The annual vertical deformation rate map for track 437 (31 Jan 2007-11 Feb 2011). The inset at the top-left corner shows the location of the profile, and the black dotted line represents the profile taken by the maximum deformation zone.

4.3 Fusion of multi-track PS results

Similarly, SAR data along track 436 (01 Mar 2007-25 Oct 2010) were processed to achieve a deformation map in LOS direction. Thanks to the large overlapped region between the two adjacent tracks (Fig. 1), the vertical deformation field could be confirmed, and the PS-InSAR accuracy was estimated with two independent data sets. In addition, the offset was calculated based on the corrected mean values of the two different sets of results over the same region.

Note that InSAR can only measure the deformation in the LOS direction, but the incidence angles vary across the whole image for each track. So the LOS deformation can be transformed into the required direction according to the real requirement. The incidence angles of track 436 and track 437 at the overlapped area were around 37.5° and 40.2° , respectively. Thus, for the same PS pixels, the ratios between LOS deformation and vertical deformation were different. Precisely, each of the PS points were projected into the vertical deformation according to their own

234 incidence angle, as shown in Fig. 7, for the data from track 437.

235 PS points from both tracks in the overlapped region were interpolated into the same grid size, and the
236 differences were calculated in the LOS and vertical directions (Fig. 8). In statistics, the mean value can be used to
237 measure the whole situation of a set of data, and this was chosen as the offset of the overlapped region in this paper.
238 Just because offset existed, the mean difference of the normal distribution function was not equal to 0. After
239 interpolating the overlapped region with the same grid, we analyzed the differential data and removed the extreme
240 data. Fig. 1 illustrates the overlapped region, which covered Po Hai, and in this region the interpolation value
241 reliability was low. Thus, it was necessary to remove this part of the interpolation value set before moving on to the
242 differential data.

243 **Fig. 8.** Histograms of the difference in annual deformation rates for the overlapped region. (a) and (b) represent the
244 histograms in the LOS and vertical directions, respectively (difference deformation rate was obtained when T436
245 was subtracted by T437).

246
247
248 Table 3 lists the two standard deviation values of 0.95 cm/yr and 0.91 cm/yr in the LOS and vertical directions,
249 respectively, and these results indicate that the research region has mainly experienced vertical deformation (i.e.,
250 land subsidence). In fact, we can optimistically declare that the main deformation type in this region is vertical.
251 Because there is only two tracks of SAR data, we corrected the two adjacent tracks' results by just using $\bar{v}_i$. That

is to say, for the two un-overlapped regions, -0.075 cm/yr was added to the deformation rate of T436 and subtracted by T437. And the mean subsidence value of the overlapped region was used as the final subsidence results (Fig. 9).

Table 3. The results of the statistical analysis for the grid interpolation method in the overlapped region.

Direction	Mean value (cm/yr)	Median value (cm/yr)	Minimum (cm/yr)	Maximum (cm/yr)	Standard deviation (cm/yr)
LOS	-0.34	-0.25	-3.87	3.65	0.95
Vertical	-0.15	-0.09	-4.31	3.8	0.91

Fig. 9. Annual vertical deformation rate map (31 Jan 2007-11 Feb 2011) from tracks 437 and 436, where the letters A to G indicate the oil exploitation bases, H shows the salt production zone, and I1 to I7 show the main deformation areas along the coastal zones.

5 Land subsidence analyses

5.1 Large scale land subsidence

From Fig. 9, we can see that most of the southern regions of the lower Liaohe plain are relatively stable.

263 However, there exist about eight regions (labeled with letters from A to H) located in urban areas where subsidence
264 was apparent. Geological data show that the faults in these areas were not active during this monitoring period and
265 had no spatial correlations with the local land subsidence. Coastal zones surrounding Po Hai showed some slight
266 deformation (labeled with numbers I1 to I7 along the dashed line). The land subsidence in urban areas mainly
267 occurred in the vicinity of oil exploration and salt production areas, while subsidence in the coastal zones was
268 detected near the sites of aquaculture production; the coastal zone subsidence may have been caused by sea level
269 changes or groundwater extraction. The average deformation at areas A, B, and C was more than 100 mm/yr, and
270 the maximum subsidence area was located in region C where a deformation rate of up to 236 mm/yr was detected.

271 **5.2 Oil field subsidence and deformation modeling**

272 **5.2 .1 Oil field subsidence**

273 We zoomed into the three severe land subsidence regions (A, B, and C) to closely investigate the potential
274 causes of the land subsidence. The enlarged deformation map is shown in Fig. 10. In this figure, Google Earth
275 images over the Jinzhou oil production field, Huanxiling oil production field, and Shuguang oil production field are
276 shown in insets for the A, B, and C subsidence regions, respectively. In particular, the inset Google Earth images
277 (Fig. 10) indicate the location and intensity of oil pumping in those areas, and the intensity of oil pumping is also
278 proportional to oil production. There was an obvious high spatial correlation between the locations land subsidence
279 and the locations of underground oil exploration. Additionally, larger subsidence values were detected in areas with
280 more oil wells installed, and the area with the greatest oil production was associated with the largest cumulative
281 land subsidence values, as shown in Table 4. Fig. 11 shows the accumulative time-series land subsidence, where
282 slight nonlinear deformation was detected. The accumulative subsidence of the C region reached up to 799 mm in 4
283 years, which was severe enough to produce surface cracks; a pump station was abandoned here (Fig. 2c).

Fig. 10. Land subsidence rate map for the three severe regions labeled as A, B, and C. Insets are Google Earth images showing the locations of oil production at these three sites.

Table 4. Oil production amounts and maximum deformation rates for the three subsidence regions.

Subsidence region	Place name	Annual oil production (10 ⁴ Tons)	Maximum deformation rate (mm/yr)	Cumulative subsidence (mm) (31 Jan 2007-11 Feb 2011)
A	Jinzhou	160	-130	-504
B	Huanxiling	200	-118	-481
C	Shuguang	230	-236	-799

Fig. 11. Accumulative time-series land subsidence over three points (A, B, and C plotted in Fig. 10) from 31 January 2007 to 11 February 2011.

293 **5.2 .2 Deformation modeling**

294 To explain the deformation caused by oil exploration, a uniformly opening sill embedded in an elastic half
 295 space was used to model the vertical deformation (Okada, 1985), and it has been widely used in modeling
 296 water-injection-induced deformation around oil field regions (Ji et al., 2016). It was defined by the following eight
 297 parameters: length, width, depth, strike, dip, opening, and location (two parameters). We introduced linear terms to
 298 account for any possible phase ramp due to uncertain-ties in the satellite positions (Massonnet et al., 1998). The
 299 downhill simplex method and Monte Carlo simulations (Press et al., 1992) were used to estimate the optimal
 300 parameters and their uncertainties, and the root mean square error (RMSE) between the observed and modeled
 301 deformation was used as the prediction-fit criterion. All parameters were freely estimated many times, and the
 302 model parameters were well constrained based on their uncertainties, as shown in Table 5. Fig. 12 presents the
 303 observed (a), modeled (b), and residual (c) deformation for the sill model. Deformation modeling suggests that a
 304 contracted sill was responsible for the observed deformation, which was probably related to oil exploration; the
 305 data fit was acceptable despite the existence of some local residuals. The depth of Shuguang oil production is about
 306 1.6 km (Shenyang Institute of Geology and Mineral Resources, 2009), and this was not too much different than the
 307 value of 1.2 km obtained by the modeling results in this study. Thus, these findings are supportive of the good
 308 reliability of the results.

309 **Table 5.** Parameters for the best-fitting model sill. Uncertainties correspond to a 95% confidence level.

Parameter	Value
Length (km)	4.663 ± 0.007
Width (km)	1.446 ± 0.021
Depth (km)	1.212 ± 0.010
Strike (°)	72.950 ± 0.083
Dip (°)	0
Opening (mm)	438.638 ± 7.705
X coordinate (km)	6.041 ± 0.002
Y coordinate (km)	3.828 ± 0.010

310

311

312 **Fig. 12.** Observed, modeled and residual rate maps. (a) Average deformation obtained from the PS-InSAR data; (b)
313 modeled deformation from the sill; (c) the residuals between the observations (Fig. 12a) and the model (Fig. 12b).

314 **5.3 Salt production field**

315 Let us now focus on another land subsidence region, labeled as H in Fig. 9, which is one of the largest salt
316 production fields (see the Landsat ETM+ image of Fig. 2e). Yingkou salt became famous during the Qing dynasty,
317 over a historical period of about 270 years. Large quantities of water are needed for salt production, and the
318 associated pumping can lead to land subsidence. Fig. 13a shows the annual land subsidence rate map, while Fig.
319 13b shows the accumulative time-series land subsidence. The largest subsidence detected was 60 mm/yr.
320 Time-series deformation results revealed nonlinear deformation from 2007 to 2011, and the maximum accumulated
321 subsidence reached up to 115 mm.

322

323 **Fig. 13.** (a) Annual land subsidence rate map for the H region. (b) Accumulative time-series deformation. Cross

labeled as H shown in (a) indicates the position of the deformation time series displayed by (b).

5.4 Coastal zone subsidence

This study also detected evidence of deformation along the coastal zones, which was possibly due to changes in sea levels or the extraction of groundwater; the annual subsidence rate here was about 50 mm/yr (Fig. 14a). Fig. 2d shows the Landsat ETM+ remote sensing image, from which we can see many aquaculture production sites. During aquaculture production, large quantities of water are used. Nonlinear time-series surface deformation was successfully monitored and the accumulative deformations were between 60 mm and 220 mm over a period of 4 years (Fig. 14b). In addition, yearly periodical surface deformation was also detected, and the results were correlated well with the long-term water level change and seasonal changes.

Fig. 14. (a) Annual land subsidence map for coastal zones, and (b) accumulative time-series land deformation for seven selected points. The orange area in (a) represents Jinzhou Oil Production (Fig. 10).

336 **6 Concluding remarks**

337 L-band ALOS/PALSAR data from two adjacent tracks during the period from 31 January 2007 to 11 February
338 2011 have been successfully used with PS-InSAR technique to map the annual subsidence rate and accumulative
339 time-series deformation over the lower Liaohe plain, China. We enhanced the large coverage PS data processing
340 procedure in terms of three key aspects. First, the unwrap grid size, 100 m, used in this test was optimized to
341 recover the maximum deformation with less computational burden. Second, the accuracy of PS results was assessed
342 based on the results from the overlapped region of two independent SAR tracks, and the standard deviation of the
343 vertical direction is 0.91 cm/yr. Third, the depth of Shuguang oil production was estimated at about 1.2 km by a
344 model sill in this paper. The InSAR results from the two adjacent tracks were well merged by weighted averaging
345 of the offset of the overlapped area.

346 In total, three major land subsidence areas were detected based on the PS-InSAR results, and these areas were
347 located in the oil fields, salt production sites, and coastal zones. The land subsidence rates ranged from 50 mm/yr to
348 236 mm/yr, and non-linear land subsidence in each subsidence area was clearly detected. In regard to the land
349 subsidence over oil fields at Panjin and Jinzhou, where the productive Shuguang oil production wells are located,
350 the accumulated subsidence over 4 years was about 800 mm. The second area of land subsidence in the region
351 located southeast of Yingkou was mainly caused by salt production, which requires abundant amounts of water. The
352 deformation area was about 400 km², and the deformation rate was about 60 mm/yr. The last area of land
353 subsidence was located in coastal zones where aquaculture facilities are concentrated, and the deformation rate was
354 about 50 mm/yr. Moreover, seasonal time-series deformation fluctuations were well detected.

355 This research provides a good example of a PS-InSAR application for large coverage deformation monitoring.
356 With this technique, different spatiotemporal land subsidence characteristics can be analyzed quantitatively. In
357 future studies to confirm the mechanisms of land subsidence and temporal fluctuations of the deformation results,

358 more geological data such as data on sea level change and salt production data should be collected.

359 **Acknowledgements:**

360 ALOS/PALSAR data are copyrighted by JAXA/METI. The SRTM DEM can be freely downloaded from
361 http://e4ftl01.cr.usgs.gov/MODV6_Dal_D/SRTM/SRTMGL1.003/2000.02.11/. This research was supported by the
362 Natural Science Foundation of China (Grant Nos. 41372375, 41274005, 41304016, and 41274004) and the
363 National Basic Research Program (973 Program) (Grant No. 2014CB744703). Thanks to the excellent software
364 package StaMPS, which can be freely downloaded from the website
365 <http://homepages.see.leeds.ac.uk/~earahoo/stamps/index.html>. Special thanks go to Sun Qifa and Du Jizhong of the
366 Shenyang Center at the Shenyang Institute of Geology and Mineral Resources for providing field investigation data
367 and for useful discussions about InSAR.

368

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436

437 Figure Captions:

438 **Fig. 1.** Location map of the southern part of the lower Liaohe plain, which is superimposed on a shaded relief map
 439 of Liaohe. The study area is mainly located in the plain area. Irregular polygons represent the distribution of oil
 440 fields in the research region, the red and green lines represent the faults and rivers, respectively, and black
 441 rectangles demarcate the coverage of the two adjacent ALOS/PALSAR ascending tracks numbered 436 and 437.

442

443 **Fig. 2.** The lower left panel Google Earth image shows the distribution of oil production bases in the lower Liaohe
 444 plain. The study region is demarcated by the black rectangle. (a) Marshes; (b) " Red Beach " which is a wetland
 445 nature reserve. The picture of (b) is a natural-color image, and it is a natural phenomenon for the marsh to turn from

446 green to red in autumn; (c) abandoned pumping station in the Dongguo Marsh Field, Panjin; (d) and (e) are Landsat
447 ETM+ images that represent the aquaculture field and the salt production zone, respectively.

448

449 **Fig. 3.** A block diagram of the multi-track processing procedure. The dots encompass the same data processing
450 steps for track 1 and track 2. For the two parts described in part II, the vertical deformation from the LOS
451 deformation and calibration of the two adjacent tracks results in a common datum with weighted offset
452 deformation.

453

454 **Fig. 4.** The spatiotemporal baseline configuration of ALOS interferometric pairs. (a) and (b) stand for (a) track 436
455 and (b) track 437, respectively. The red line represents the discarded interferogram (24 Dec 2009-27 Dec 2010).

456

457 **Fig. 5.** The 22 unwrapped interferograms for track 437 with respect to the master image acquired on 24 December
458 2009. The interferogram (24 Dec 2009-27 Dec 2010) marked with the red line exhibits an obvious phase jump, and
459 it was discarded in the following processing steps.

460

461 **Fig. 6.** Cross-section of the deformation obtained with different unwrapped grid sizes along the profile located in
462 the inset of Fig. 7. Red line represents the deformation obtained with a grid size of 200 m, and it was significantly
463 less than that of the other sizes.

464

465 **Fig. 7.** The annual vertical deformation rate map for track 437 (31 Jan 2007-11 Feb 2011). The inset at the top-left
466 corner shows the location of the profile, and the black dotted line represents the profile taken by the maximum
467 deformation zone.

468

469 **Fig. 8.** Histograms of the difference in annual deformation rates for the overlapped region. (a) and (b) represent the
470 histograms in the LOS and vertical directions, respectively (difference deformation rate was obtained when T436
471 was subtracted by T437).

472

473 **Fig. 9.** Annual vertical deformation rate map (31 Jan 2007-11 Feb 2011) from tracks 437 and 436, where the letters
474 A to G indicate the oil exploitation bases, H shows the salt production zone, and I1 to I7 show the main
475 deformation areas along the coastal zones.

476

477 **Fig. 10.** Land subsidence rate map for the three severe regions labeled as A, B, and C. Insets are Google Earth
478 images showing the locations of oil production at these three sites.

479

480 **Fig. 11.** Accumulative time-series land subsidence over three points (A, B, and C plotted in Fig. 10) from 31
481 January 2007 to 11 February 2011.

482

483 **Fig. 12.** Observed, modeled and residual rate maps. (a) Average deformation obtained from the PS-InSAR data; (b)
484 modeled deformation from the sill; (c) the residuals between the observations (Fig. 12a) and the model (Fig. 12b).

485

486 **Fig. 13.** (a) Annual land subsidence rate map for the H region. (b) Accumulative time-series deformation. Cross
487 labeled as H shown in (a) indicates the position of the deformation time series displayed by (b).

488

489 **Fig. 14.** (a) Annual land subsidence map for coastal zones, and (b) accumulative time-series land deformation for

490 seven selected points. The orange area in (a) represents Jinzhou Oil Production (Fig. 10).

Figure 1

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