**Ground subsidence in Tucson, Arizona, monitored by time-series analysis
using multi-sensor InSAR datasets from 1993 to 2011**

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37 **Abstract**

38 The groundwater in Tucson, Arizona, is a major source for water supply to human
39 residential areas and agricultural use, and the groundwater extraction causes ground
40 deformation responding to aquifer-system compaction. Using multi-temporal C-band
41 and L-band SAR images from ERS/Envisat and ALOS PALSAR satellites, we mapped
42 the ground displacement in Tucson. The InSAR-derived ground displacement based on
43 small baseline subset technique (SBAS) is compared to compaction from
44 extensometers, land subsidence from GPS survey, and groundwater elevation at wells.
45 Tucson is characterized by slow and relatively small subsidence over areas with upper
46 stratigraphic till early 2000s when the groundwater had been extremely depleted and by
47 uplifts in areas where the water level has been recently recovered into the slight increase
48 of water table because of recharge into the aquifer. Our multi-sensor SBAS InSAR-
49 derived vertical displacements enabled to monitor the temporal variability in the spatial
50 extent and magnitude of the ground deformation, suggesting that recent ground
51 subsidence is slowing down and the ground motion in places is stable. Our results can
52 provide scientific basis for sound management of ground water pumping and recharge
53 over the study area.

54

55 *Keywords:* InSAR, SBAS, groundwater extraction, Tucson, Aquifer-system compaction,
56 ground subsidence

57

58 **1. Introduction**

59 The groundwater is a major source for supplying drinking water to residents in
60 arid lands, irrigating plants for agriculture, and flowing into lakes or rivers. The rain
61 water, snowmelt, and inflow from upper watershed leads into the recharge of
62 groundwater, and the discharge is made by natural flow and human demands for
63 industrial, municipal, and agricultural purposes. Natural condition is balancing between
64 recharge and discharge, but the balance has been threatened by extreme consumption of
65 groundwater for developing arid areas of Phoenix and Nevada in the United States,
66 Libya, and India. The groundwater depletion caused the disappearance of a crucial
67 water resource as well as the aquifer-system compaction and ground subsidence. More
68 than 80 percent of the identified subsidence in the United States is caused by human
69 activities on subsurface water (Galloway et al., 2000). To conserve the groundwater and
70 circumvent more rapid consumption from the subsurface, the elaborate resource
71 management and intensive governmental efforts are required.

72 In Tucson, Arizona, the groundwater has been a critical resource for urban and

73 rural communities, and the rapid urbanization and growing population has been heavily
74 dependent on groundwater because of the lack of surface water. The excessive
75 consumption of groundwater led to the decrease of water table as much as 14 m
76 between 1989 and 2005, and the declined water level before 1989 was much bigger than
77 this number (Carruth et al., 2007). The groundwater pumping in excess of natural
78 recharge was the major cause of aquifer-system compaction and associated land
79 subsidence in Tucson area (Pool and Anderson, 2007). Since the Arizona's 1980
80 Groundwater Management Act, the temporal variations of groundwater table, soil
81 compaction, and land subsidence have been monitored by gauges in wells, borehole
82 extensometers, and annual GPS survey at multiple stations (Carruth et al., 2007; Pool
83 and Anderson, 2007). These methods provide a good precision of measurement on
84 subsurface condition, but each has limitation in detecting land-surface motion over large
85 areas associated with groundwater depletion. For example, the water level at wells is not
86 highly correlated with surface deformation in many cases, and the extensometers cannot
87 measure the compaction occurring below the anchor depth of the devices. The annual
88 GPS survey in sparse stations, which is labor-intensive, does not measure the surface
89 displacement with high accuracy like continuous GPS. In contrast, the spatially detailed
90 images of ground displacements generated from SAR interferometry (InSAR) can help

91 to monitor the ground subsidence in Tucson.

92 The InSAR is an invaluable tool for measuring displacements over a large area
93 with high accuracy of sub-centimeter and high spatial resolution of 30 m after spatial
94 averaging and geocoding. The InSAR processing for detecting displacements after
95 removing topographic and orbital error phases and reducing as much atmospheric
96 artifact as possible is particularly called the differential InSAR (DInSAR). The DInSAR
97 has been used for detecting horizontal and vertical displacements caused by catastrophic
98 natural disasters of earthquakes and volcanoes, anthropologic deformation caused by
99 mining and oil/gas extraction, and deformation induced by melting of permafrost
100 (Hanssen, 2001; Tong et al., 2010; Lu et al., 2007; Samsonov et al., 2011).

101 In particular, the DInSAR was used for measuring the surface displacements
102 related to aquifer system compaction and uplift accompanying groundwater discharge
103 and recharge (Lu and Danskin, 2001; Galloway and Hoffman, 2007). Several
104 researchers (Galloway et al., 1998; Hoffmann et al., 2003) mapped aquifer-system
105 compaction and subsidence in the Antelope Valley, California, by integrating DInSAR,
106 GPS, and extensometers, and successfully estimated the groundwater flow, storage
107 change, and compaction over large areas. The water decline and clay thickness map in
108 Las Vegas Valley was analyzed with subsidence map based on DInSAR, GPS, and

109 leveling (Amelung et al., 1999; Bell et al., 2002) and inelastic and elastic deformation
110 caused by seasonal variation was detected by DInSAR time-series analysis. Schmidt
111 and Burgmann (Schmidt and Burgmann, 2003) used the DInSAR for measuring surface
112 subsidence by groundwater extraction in Santa Clara Valley, California and found the
113 Silver Creek Fault to disrupt the groundwater flow and cause steep displacement
114 gradients. The recent advance in the DInSAR technology can improve the accuracy of
115 surface deformation measurements. The small baseline subset (SBAS) algorithm
116 exploiting multi differential interferograms of small baselines could be used to enhance
117 the understanding of the underlying deformation process in the groundwater-withdrawn
118 region with dense temporal interval (Berardino et al., 2002). The advantage of SBAS
119 technique is that it could minimize the atmospheric phase in InSAR pairs, capture the
120 pattern of deformation in time and space, and estimate non-linear time series of
121 deformation during a long time span by analyzing DInSAR pairs with short
122 perpendicular baselines (Berardino et al. 2002; Lanari et al., 2004; Samsonov et al.,
123 2011).

124 In this paper, the SBAS InSAR technology was applied for detecting ground
125 subsidence in Tucson, caused by groundwater depletion. Using sufficient SAR data
126 archive from early 1990s to 2011, the spatial extent and magnitude of surface

127 deformation in Tucson has been estimated. Our study utilized ERS-1/2, ENVISAT, and
128 ALOS PALSAR, and the results of multi-sensor SBAS InSAR processing are analyzed
129 in spatio-temporal scale with supplementary data from gauges, extensometers, and GPS
130 survey.

131

132 **2. Methodology**

133 Standard DInSAR processing with small perpendicular baselines is required
134 before performing SBAS InSAR processing. The N interferograms are generated from
135 M SAR images, which are coregistered on a common master image, by multiplying
136 master complex image with a conjugate of slave complex SAR data. To avoid spatial
137 decorrelation, a small orbital separation should be selected for further time-series
138 analysis. Moreover, the threshold of temporal baselines based on radar frequency and
139 coherence should be considered to prevent temporal decorrelation. The interferometric
140 phase of each interferogram is composed of a phase component caused by deformation,
141 topography, orbital error, atmosphere, and random noise term, respectively. The phase
142 components but deformation are reduced by using digital elevation model (DEM), least-
143 square fitted 2nd order polynomial, and noise-suppressing filters. Because topography
144 provided by DEM sources has relative error terms and atmospheric phase is not easy to

145 be removed from a single InSAR pair, the deformation phase cannot be reliably
 146 obtained. If there is no phase unwrapping error, the observed interferometric phase ϕ_{ifgs}^k
 147 of k^{th} differential interferogram consists of deformation ϕ_{def}^k , topographic ϕ_{topo}^k ,
 148 atmospheric ϕ_{atm}^k , and noise ϕ_{noise}^k ,

$$149 \quad \phi_{ifgs}^k = \phi_{def}^k + \phi_{topo}^k + \phi_{atm}^k + \phi_{noise}^k \quad (1)$$

150 In equation (1), both topographic phase and atmospheric phase terms are related
 151 to errors and residuals in DInSAR processing. The residual topographic phase term is
 152 estimated as (Berardino et al., 2002, Samsonov, 2010),

$$153 \quad \phi_{topo}^k = \frac{B_{\perp} \cdot \Delta z}{R \cdot \sin \theta} \quad (2)$$

154 where R is the line-of-sight distance between satellites and targets, θ is incidence
 155 angles, $B_{\perp}$ is perpendicular baselines, and Δz is topographic error term. The
 156 atmospheric phase can be classified into turbulent mixing and vertical stratification
 157 contributions (Hanssen, 2001). The turbulent contributions are considered as a random
 158 phase both in space and time while the vertical stratification contribution is correlated
 159 with elevation (Delacourt et al., 1998; Beauducel et al., 2000; Chaabane et al., 2007;
 160 López-Quiroz et al., 2009). Removing the effect of vertical stratification is a relatively
 161 easy step by using a linear correlation between interferometric phase from each
 162 interferogram and elevation from DEM, but the turbulent contribution, assumed as

163 random, can be reduced by computing a least square solution from many interferograms
164 acquired under favorable conditions less influenced by spatial and temporal
165 decorrelation (Samsonov et al., 2013). The key feature of SBAS InSAR is that it can
166 reduce the random atmospheric phase from many InSAR pairs as well as estimating
167 topographic error terms related to the perpendicular baseline. Additionally, ionospheric
168 effects can induce the azimuthal image and Doppler Centroid distortion on low
169 frequency (L-band) radar system (Franz et al., 2006), but the artifacts due to ionosphere
170 were negligible in our used L-band SAR images.

171 To integrate the InSAR pairs from multi-sensor, additional process is needed to
172 correct the effect of the different wavelengths. As proposed by a previous study (Pepe et
173 al., 2005), ERS and ENVISAT SAR sensors have different center frequency (5.30 GHz
174 for ERS-1/2 and 5.33 GHz for ENVISAT ASAR) and it is difficult to generate
175 interferogram from ERS/ENVISAR pairs. Instead, the ENVISAT InSAR pairs can be
176 integrated into SBAS algorithm, by multiplying the correction term ($\lambda_{ENVISAT} / \lambda_{ERS}$,
177 $\lambda_{ERS}=5.656$ cm and $\lambda_{ENVISAT}=5.624$ cm) with unwrapped interferometric phases. If the
178 track of ENVISAT and ERS is identical, the incidence angle of ERS and ENVISAT is
179 similar in most cases (Table 1).

180 The fundamental equation for SBAS can be expressed as the following form,

$$Bv = \Phi_{ifgs} \quad (3)$$

where B matrix has dimensions of N by $M-1$ (N and M are the numbers of interferograms and SAR images, respectively), Φ_{ifgs} ($N \times 1$) is a vector of observed interferometric phase ϕ_{ifgs}^k , and v vector consists of $M-1$ mean velocities between time-adjacent acquisitions to be calculated. The v vector is unknown as,

$$v^T = \left(v_1 = \frac{\phi_1^{inc}}{t_2 - t_1} \quad \cdots \quad v_k = \frac{\phi_k^{inc}}{t_{k+1} - t_k} \quad \cdots \quad v_{M-1} = \frac{\phi_{M-1}^{inc}}{t_M - t_{M-1}} \right) \quad (4)$$

where ϕ_k^{inc} is an incremental phase from t_k (acquisition date of k^{th} SAR data) to t_{k+1} (acquisition date of $k+1^{\text{th}}$ SAR data). In B matrix, if a k^{th} interferogram spans the time represented by the column n , then the b_n^k term is equal to the time interval between the consequent images, otherwise zero (Berardino et al., 2002; Samsonov, 2010). In order to correct the topographic error, a perpendicular baseline of each interferogram should be attached to the right side of the B matrix. Additionally, in low coherence areas, which do not have consistent scattering between acquisition dates, the interferometric phase is set to zero, and the phase value should be excluded for SBAS analysis.

For example, if we assume that four SAR images are acquired at time of $t_1, \dots, t_4$ five interferograms are generated from intervals $t_2 - t_1, t_3 - t_1, t_3 - t_2, t_4 - t_2, t_4 - t_3$, and the interferometric phase at a pixel of a particular pair (here, InSAR pair between $t_2 \sim t_3$) is zero due to low coherence, which could be improperly estimated as

199 non-deformation, the SBAS equation can be formulated as ($\Phi_{ifgs}TBv = \tilde{B}v(5)$),

$$200 \begin{pmatrix} \phi_{ifgs}^{1-2} \\ \phi_{ifgs}^{1-3} \\ \phi_{ifgs}^{2-3} \\ \phi_{ifgs}^{2-4} \\ \phi_{ifgs}^{3-4} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} t_2 - t_1 & 0 & 0 & B_{\perp}^{1-2} \\ t_2 - t_1 & t_3 - t_2 & 0 & B_{\perp}^{1-3} \\ 0 & t_3 - t_2 & 0 & B_{\perp}^{2-3} \\ 0 & t_3 - t_2 & t_4 - t_3 & B_{\perp}^{2-4} \\ 0 & 0 & t_4 - t_3 & B_{\perp}^{3-4} \end{pmatrix} \begin{pmatrix} v_1 \\ v_2 \\ v_3 \\ \frac{\square z}{R \cdot \sin \theta} \end{pmatrix} \quad (6)$$

201 If pixels of all interferograms have high coherence and their phase unwrapping

202 is properly performed, T matrix will be same as $I(N \times N)$ identity matrix. When

203 interferometric phase of k^{th} interferogram is set to zero due to low coherence, $k \times k$

204 diagonal term of T matrix will be zero. Due to the introduction of T transformation

205 matrix, changing the size of design matrix B is not needed for pixels of all

206 interferograms. Another problem of $\tilde{B}(N \times M)$ matrix is a rank deficiency, because

207 critical links of InSAR networks are often missing (i.e. unlinked InSAR pairs in Fig. 3)

208 due to low coherence of many pairs. In addition, the images might be divided to

209 separate networks due to the baseline configuration. The combination of all available

210 interferograms is based on a minimum norm criterion of the velocity deformation

211 (Berardino et al., 2002). The SVD (Singular Value Decomposition) inversion of $\tilde{B}$

212 matrix enables to solve equation (5) and obtain the unknown v vector, but the

213 incremental phase delay of v vector is set to zero by SVD, which biases the subsidence

214 temporal behavior and subsidence rate (López-Quiroz et al., 2009). The solution for the

215 problem is using Tikhonov regularization (Tikhonov and Arsenin, 1977) or low-pass
 216 filtering in the time domain (Samsonov and d'Oreye, 2012). Another solution is
 217 considering the quadratic behavior of the incremental phase delay and adding constrains
 218 to design matrix $\tilde{B}$. The solution supposes that deformation increases or decreases with
 219 second order polynomials in time. Additionally, applying Gaussian filter in time to
 220 estimated incremental phase smoothes deformation with avoiding the effect of rank-
 221 deficiency and residual atmospheric error. We added the following constrain to the
 222 inversion as proposed by previous study (López-Quiroz et al., 2009),

$$223 \quad \sum_{k=1}^m \phi_k^{inc} = a(t_m - t_1) + b(t_m - t_1)^2 + c \quad (7)$$

224 where a, b, c are constants describing the quadratic behavior of incremental phase terms
 225 of v vector at time of m . After this constraint is added to equation (5), the matrix system
 226 becomes $\Phi_{ifgs}^c = B^c v^c$

$$227 \quad \begin{pmatrix} \phi_{ifgs}^1 \\ \vdots \\ \phi_{ifgs}^N \\ 0 \\ \vdots \\ 0 \end{pmatrix} = \begin{pmatrix} \begin{pmatrix} 0 & 0 & 0 \\ \vdots & \vdots & \vdots \\ 0 & 0 & 0 \end{pmatrix} \\ \gamma \cdot \begin{pmatrix} t_2 - t_1 & 0 & 0 & \cdots & 0 & 0 & -(t_2 - t_1) & -(t_2 - t_1)^2 & -1 \\ t_2 - t_1 & t_3 - t_2 & \ddots & 0 & \vdots & 0 & -(t_2 - t_1) & -(t_2 - t_1)^2 & -1 \\ t_2 - t_1 & t_3 - t_2 & t_4 - t_3 & \vdots & 0 & \vdots & & & \vdots \\ \vdots & \vdots & \ddots & 0 & \vdots & 0 & \vdots & \vdots & -1 \\ & & & t_{M-1} - t_{M-2} & 0 & \vdots & & & \vdots \\ t_2 - t_1 & t_3 - t_2 & \cdots & t_M - t_{M-1} & 0 & -(t_M - t_1) & -(t_M - t_1)^2 & -1 \end{pmatrix} \end{pmatrix} \begin{pmatrix} v_1 \\ \vdots \\ v_{M-1} \\ \frac{\square z}{R \cdot \sin \theta} \\ a \\ b \\ c \end{pmatrix} \quad (8)$$

228 where the weight γ is a scaling factor for the additional matrix of B^c
 229 $((N + M - 1) \times (M + 3))$, and the factor should be small enough so as not to affect the

230 inversion of the major design matrix $\tilde{B}$. The inversion of $B_c^T B_c$ calculates the
231 incremental phase delay included in v vector and its integration results in the cumulative
232 deformation phase at particular time.

233

234 **3. Study area and data processing**

235 *3.1 Characteristics of study region*

236 Our study region is Tucson city in Arizona of southwest USA (Fig. 1). The
237 city's elevation ranges from 600 to 1300 m, and most residential areas in downtown are
238 located between 800 m and 900 m at a relatively flat area contrary to mountains in the
239 west (Tucson mountains) and north (Santa Catalina mountains). The Santa Cruz River,
240 which flew along the west side of the Tucson, was a perennial river, but now a dry river
241 bed for most of the year except flooding by seasonal rains. Since the Santa Cruz River
242 became dry and the surface water had been gradually vanished, the city has been
243 dependent on the pumping of groundwater for residential use and agricultural irrigation.
244 Consequently, the water level measured in wells has been dramatically dropped as much
245 as 30 m since 1900s. The land subsidence and earth fissure occurred in Tucson and
246 southern Arizona and damaged the roads and civilian properties, but the phenomenon is
247 depending on the geological condition. The aquifer-compaction and land subsidence are

248 associated with many parameters including soil composition, clay thickness, and soil
249 consolidation. The groundwater withdrawal in dry lands does not necessarily mean
250 ground subsidence, because regions with over-consolidated and incompressible soil, or
251 relatively thin aggregate clay thickness are less sensitive to the variation of water table
252 in aquifer. Furthermore, in areas with thick aquitards, the subsidence is often delayed
253 after water table is decreased (Galloway and Hoffmann, 2007). The geological
254 composition in Tucson can be grouped into three stratigraphic units (lower, middle, and
255 upper) and stream-channel alluvium (Fig. 2). The lower stratigraphic unit consists of
256 conglomerate, sandstone, mudstone, and gypsiferous mudstone. The middle
257 stratigraphic unit consists of clayey silt, mudstone, and gravel conglomerate. The upper
258 stratigraphic unit consists of gravel, clayey silt, and thin surficial alluvial deposits
259 (Carruth et al., 2007). Among those stratigraphic units, the upper stratigraphic unit is
260 more subject to land subsidence by groundwater extraction and, therefore, the Tucson
261 regions with upper stratigraphic unit have been more exposed to land subsidence. To
262 recover the groundwater storage and stop water level declines during the last several
263 decades, the Central Arizona Project pumped significant artificial recharge into the
264 aquifer. As a result, the recent groundwater withdrawal has been decreased, and the
265 water level in many wells indicates the increase of water table (Pool, 2005; Carruth et

266 al., 2007).

267

268 3.2 SBAS data processing

269 For this study, 17 ERS-1/2, 24 ENVISAT ASAR, and 8 ALOS PALSAR images
270 (listed in Table. 1), covering the Tucson metropolitan area (Fig. 1), were utilized. ERS-
271 1/2 images including two ERS-1/2 tandem pairs of January, 11, 1996 ~ January, 12,
272 1996 and April, 25, 1996 ~ April, 26, 1996 were acquired from 1993 to 2002.
273 ENVISAT ASAR images are obtained between 2004 and 2010. Both ERS and
274 ENVISAT ASAR images are from the same descending track of 456 (Table 1),
275 meaning a similar radar geometry, but ERS/ENVISAT InSAR pair cannot be generated
276 due to the difference in center frequency. There is no temporal overlap of ERS and
277 ENVISAT SAR data, causing a data gap between 2002 and 2004. The ALOS PALSAR
278 images were acquired from ascending track, and the ALOS images covers a relatively
279 short time period from late 2009 to 2011 in contrast to C-band sensors.

280 For SBAS processing, ERS and ENVISAT InSAR pairs with perpendicular
281 baselines smaller than 500 m are generated. Furthermore, InSAR pairs with a good
282 coherence should be selected for reliable DInSAR processing including phase
283 unwrapping (Fig. 3(a) and (b)). 28 ALOS InSAR pairs (Fig. 3(b)) are also created from

all 8 SAR images, because L-band InSAR pairs in Tucson are less influenced by temporal and spatial decorrelation related to a large perpendicular baseline and a long time interval (Sandwell et al., 2008).

1-arcsec national elevation dataset (NED) was used to remove topographic contributions in DInSAR processing of ERS, ENVISAT and ALOS pairs. The precise orbit information of ERS and ENVISAT is provided by Delft institute for earth-oriented space research (DEOS). However, several InSAR pairs of ERS, ENVISAT, and ALOS are deteriorated by orbital error fringes, which are then removed by 2nd order polynomial estimation in range and azimuth direction. From the figures (Fig. 4) of ERS, ENVISAT, and ALOS differential interferograms, one can recognize that there are only few phase variations in ALOS InSAR images (Fig. 4(e) and (f)), as the L-band sensor (wavelength of ~24 cm) is less sensitive to slow-developing deformation by groundwater extraction in Tucson (i.e. 2.2 (C-band) and 0.53 (L-band) radian change according to 1 cm line-of-sight change) (Luo et al., 2014). Also, it is recognizable that C-band interferograms of Fig. 4(a), (b), (c), and (d) show obvious signatures of ground subsidence in downtown of Tucson, but other generated interferograms, not included in Fig. 4, are deteriorated by atmospheric artifacts, particularly turbulent contributions that do not correlate in time. In contrast, the effects of vertical stratification were negligible

302 due to the flat terrain of our study area and their correction was not applied. For
 303 example, Fig. 4(c) spans a short period, but many areas in the interferogram contain
 304 atmospheric artifacts. Phase unwrapping after smoothing interferograms was applied by
 305 minimum cost flow (MCF) algorithm.

306 One problem in integrating ERS and ENVISAT to SBAS algorithm in our
 307 dataset is a data gap between the two groups of InSAR pairs (Fig. 3(a)), and the gap
 308 causes a rank deficiency in SBAS processing owing to missing a critical link. To solve
 309 the problem, the linear deformation rate is estimated from each ERS and ENVISAT
 310 SBAS processing, and simulated temporary interferogram between the gap is generated
 311 from averaging two linear deformation rates:

$$312 \quad \frac{1}{2} \left(\left(\frac{\sum \phi_k^{inc}}{\sum t_k} \right)_{ERS} + \left(\frac{\sum \phi_k^{inc}}{\sum t_k} \right)_{ENVISAT} \right) \cdot (gap\ days / yr) \quad (9)$$

313 The temporary interferogram is plotted as a dashed black line in Fig. 3(a). After SBAS
 314 processing from ERS/ENVISAT and ALOS, all outputs are filtered by Gaussian filter in
 315 time domain to suppress still-remaining atmospheric phase. Only 8 and 4 selected
 316 deformation maps are shown in Fig. 5 and Fig. 6, respectively. The selected SBAS
 317 InSAR-derived deformation maps are shown in Fig. 5, 6, and 7. forty time-series of
 318 vertical displacements corresponding to each ERS and ENVISAT acquisition date are
 319 generated (Fig. 5), and the number of C-band time-series is equal to M (number of SLC

320 data)-1. Seven time-series of vertical displacement corresponding to ALOS acquisition
321 date is then created (Fig. 6). A linear deformation rate (Fig. 7) is also estimated from C-
322 band and L-band SBAS processing. Note that the C-band deformation rate is calculated
323 from 1993 to 2010, and the L-band deformation rate is from late 2009 to 2011. Because
324 ALOS PALSAR data span relatively short period and their sensitivity to small
325 deformation was low compared to C-band dataset, we did not integrate the 2 results but
326 tried to assess them separately. Additionally, due to the same reason, we focused on
327 analyzing C-band results more than L-band time-series products.

328

329 **4. Results and discussion**

330 The water level in the subsurface has been monitored at wells densely located in
331 Tucson (operated by USGS Water Resources of Arizona). Because many wells were
332 installed before 1980s, a long-term monitoring related to groundwater extraction has
333 been possible (i.e. Fig. 8; 10-year interval groundwater level). The groundwater level
334 from 1980s to 1990s (Fig. 8(a)) was dramatically dropped as much as 25 m, and the
335 region of groundwater withdrawal was concentrated on a major residential area in
336 Tucson. The amount of groundwater extraction was gradually reduced during 1990s
337 (Fig. 8(b)), and the water level during 2000s (Fig. 8(c)) was recovered into a slight

338 increase as a result of an artificial recharge into the aquifer-system. For 30 years
339 between 1980s and 2010s (Fig. 8(d)), most of water decline occurred during the first 10
340 years: the maximum water decline exceeded 25 m, and most parts except the southern
341 area had water level decrease of approximately 12 m.

342 The annual GPS survey campaign was conducted in multiple sites (red crosses
343 in Fig. 9(a)), and the extensometers (blue crosses) measured the compaction of aquifer-
344 system. The GPS-survey technique primarily estimated the vertical deformation from
345 measured ellipsoid heights, and the increased compaction measured by extensometers
346 implies downward land surface motion between land surface and the depth at which the
347 bottom of the extensometer is anchored (Carruth et al., 2007). The extensometer data
348 was acquired from USGS monitoring sites, and the annual GPS survey data is from
349 previous USGS report (Pool et al., 2007; Carruth et al., 2007). The green arrows (Fig.
350 9(b)) describe the compaction at the extensometer monitoring sites, and the length of
351 arrows describes the amount of compaction from October, 2005 to September, 2012.

352 Although there is a small number of extensometers, the region affected by large
353 groundwater extraction indicates large compaction possibly leading to ground
354 subsidence. The vertical deformation measured from annual GPS survey varies among
355 station locations, and the maximum subsidence between 1998 and 2005 reached 9.14

356 cm (Fig. 9(b)).

357 From the results of ERS/ENVISAT SBAS processing (Fig. 5), a noticeable land
358 subsidence occurred in the center of Tucson city, around Davis Monthan Air Force
359 Base, and near the Tucson international airport. The deformation maps show the
360 cumulative land surface motion with respect to the acquisition date of the first SAR
361 image (June, 22, 1993). The vertical deformation in the center of Tucson city is about 14
362 ~ 20 cm during 17-year period from 1993 to 2010, and the maximum subsidence of 24
363 cm occurred in the northern area of Tucson international airport. ALOS SBAS InSAR
364 processing (Fig. 6) has allowed us to obtain time-series of vertical deformation from the
365 first ALOS acquisition date (October, 17, 2009). The pattern of accumulated subsidence
366 from ALOS InSAR pairs is different from that of ERS/ENVISAR processing due to the
367 difference in the time-span and sensitivity to small subsidence. The linear deformation
368 rates are calculated from the SBAS results derived from the 2 datasets separately,
369 ERS/ENVISAT (Fig. 7(a)) indicate the maximum subsidence rate of 1.6 cm/year during
370 17 years, and ALOS SBAS processed results (Fig. 7(b)) delineate slowed maximum
371 subsidence rate of 0.6 cm/year between 2009 and 2011 (Note that The PALSAR
372 products in Fig. 6 and Fig. 7 are noisier than the ERS/ENVISAT results due to narrower
373 color range).

374 When the compaction from extensometers and time-series of subsidence from
375 SBAS processing are compared (Fig. 10), the ERS/ENVISAT and ALOS results of land
376 subsidence from 2006 to 2011 have general agreement at stations of WR53 and X419,
377 though both show difference between estimated deformation and compaction at
378 XAVIER and 23CBA. When we focus on the ERS/ENVISAT SBAS InSAR-derived
379 deformation (Fig. 10) in time-series, the subsidence in WR53 is about 0.8 cm with the
380 compaction of 0.5 cm, and the vertical surface motion and compaction has a similar
381 amount. Based on only the extensometer measurements, it is hard to determine the
382 accuracy of SBAS InSAR processing (RMSE (Root Mean Square Error) 0.37 ± 0.11
383 cm). When considering the characteristics of the extensometers that cannot measure the
384 subsurface change below the bottom of the device, the comparison is within a category
385 of general agreement. The vertical displacements from ERS/ENVISAT and ALOS
386 SBAS InSAR processing and ellipsoid height change since 1998 (Pool et al., 2007) are
387 compared (Fig. 11). The accuracy of vertical measurement using GPS technology (error
388 bars in Fig. 11) is assumed to be 2.032 cm (Carruth et al., 2007). In most monitoring
389 stations, the results from GPS survey and SBAS InSAR show a similar pattern over
390 time, and the SBAS-derived deformations are within the uncertainties of GPS
391 measurements. Also, though ALOS pairs span only a short time period, the results from

392 both ERS/ENVISAT and ALOS SBAS InSAR processing are in a good agreement. In
393 sites of B7A, WR56A, WR142, X419, and C45, both of GPS and SBAS InSAR-derived
394 deformation describes the ground subsidence due to the groundwater extraction.

395 However, in some places of MAGNETIC, WR53, and WR52, the ground was in uplift
396 and it could be attributed to rebounding of ground surface after groundwater recovery.

397 The temporal groundwater elevation measured at wells was also compared with
398 ERS/ENVISAT SBAS-processed vertical displacement (Fig. 12). The pattern of
399 groundwater elevation change was observed in most wells of Tucson. The groundwater
400 level was declining until 2003, and an artificial recharge and reduced consumption of
401 groundwater brought out the recent increase of water table. At station WR56A, the
402 ground subsidence was about 15 cm during observation period. The surface is still
403 subsiding after 2003 despite less rapidity. The continuous subsidence implies that the
404 subsidence could be affected by delayed compaction and inelastic behavior, while the
405 deformation is not recovered but permanent. In WR52, the land surface with increased
406 groundwater level is in uplift. It indicates that the displacement in the location is elastic,
407 while the increase of groundwater caused a recovery of subsurface.

408 The contour deformation map (Fig 13(a)) delineates several major subsidized
409 regions affected by groundwater extraction. A, B, and D regions are near the center of

410 Tucson city, C is close to Davis Monthan Air Force Base, and E region is around the
411 northern part in Tucson International Airport. A and B regions have the subsidence of
412 about 14 cm, and C and D areas are affected by 4 cm subsidence. E regions have the
413 maximum subsidence exceeding 20 cm during 17-year span. When comparing the
414 contours of water level changes and linear deformation map (Fig. 7), and the subsidence
415 map (Fig. 14(a)), A and B regions are close to the areas of maximum water level
416 changes (up to 24 m) since 1980s. C and D areas are overlapped with a region of
417 relatively small water level change (up to 10 m). Because the change of groundwater
418 and surface motion is correlated, the result explains that the groundwater level change
419 caused the ground deformation in A, B, C, and D. On the other hand, other areas with
420 large water level change do not have a significant subsidence. The reasonable
421 assumption is that clay thickness is not sufficient for sensitive response to the change of
422 aquifer-system in the subsurface, or a soil layer is over-consolidated and incompressible
423 and the surface is very stabilized. E region with maximum subsidence is another
424 exception, because the groundwater level change is not highly correlated with
425 subsidence. The E region in Fig. 8(d) and 9(b) is in the mix of increase and decrease of
426 groundwater level, and the change of aquifer-system may not be a major cause of large
427 subsidence. Possibly, the human construction of roads, buildings, and airport can cause

428 a large vertical deformation in E region, but, currently, it is not clear which factors
429 mostly affected the vertical deformation in E area.

430 One of great advantages of SBAS InSAR processing is that it could estimate
431 vertical deformation between two particular acquisition dates. The difference of
432 cumulative deformations of two particular dates can delineate temporal evolution of
433 subsidized areas in Tucson. Images in Fig. 13(b) ~ (g) are generated from the difference
434 of deformation maps (Fig. 5) with about three-year interval, estimated from
435 ERS/ENVISAT SBAS InSAR processing. Red-colored regions in Fig. 13(b) ~ (g) mean
436 ground subsidence, and dark red color is approximated as maximum subsidence.
437 Between 1996 and 1999, B and E region shows maximum subsidence exceeding 1.6
438 cm. During the span of 1999 and 2002, the maximum subsidence (dark red) of B and E
439 embraces the largest area in Tucson. Between 2004 and 2007 (Fig. 13(f)), the
440 subsidence rate of A and B is slowed down, but the C region has enlarged subsidence
441 area since 1999. The recent observation (Fig. 13(g)) indicates a slowing subsidence in
442 most regions of Tucson. The subsidence in A region is almost disappeared, and B region
443 shows only a small subsidence less than 1 cm. The C region near Davis Monthan Air
444 Force Base shows still growing subsidized region from 1999 to 2010. The subsidence
445 area in E region between 2007 and 2010 is much smaller than the areas during other

446 periods. Due to the similar time span, the Fig. 13(g) is well fitted to the result from
447 ALOS SBAS InSAR processing in Fig. 7(b), characterizing a major subsidence in B, C,
448 and E region. The profile along the lines of a-a', b-b', c-c', and d-d' in Fig. 13(c)
449 characterizes the features of slowing-down subsidence in Tucson (Fig. 14). The B and E
450 region shows the most prominent subsidence (~ 5 cm) of 3-year interval from 1993 to
451 2010. In most regions, the subsidence between 1996 and 1999 is most significant and
452 the displacement from 2007 to 2010 is less than that from other 3-year periods.
453 However, the subsidence of C region was recently developed between 2007 and 2010 in
454 contrary to other regions. The images in Fig. 14 attest that the subsidence in most areas
455 is gradually slowing down due to the recharge of groundwater.

456

457 **5. Conclusion**

458 Our multi-sensor SBAS InSAR processing delineated a long-term development
459 of the vertical deformation from 1993 to 2011, though ALOS InSAR pairs covered a
460 relatively short time period between late 2009 and 2011. Most analyses focused on
461 products from ERS/ENVISAT SBAS processing due to a longer time-span and high
462 sensitivity to small and slow-developing subsidence. Although there is no a “real”
463 ground-truth reference in our interest area, the compaction from extensometer the

464 ellipsoid height changes measured by the annual GPS survey show a similar pattern
465 with land subsidence estimated from SBAS processing in spite of differences in certain
466 stations. The 3-year interval maps of vertical deformation reveal the characteristics of
467 subsidence, which had occurred in Tucson. The subsidence during mid- and late-1990s
468 was significant around the large groundwater-withdrawal areas, but our results imply
469 that the recent subsidence in most areas of Tucson is slowing down and is about to
470 cease, based on the estimation between 2007 and 2010. The halting subsidence is
471 attributed to an intense effort to conserve groundwater, because Tucson is recharging
472 groundwater supplies by running part of its share of Central Arizona Project (CAP)
473 water into various open portions of local rivers to seep into their aquifer (Pool et al.,
474 2007). However, the human activities and still-progressing groundwater extraction can
475 be critical for the turn-around of current ceasing subsidence and future development of
476 deformation.

477 Our study has demonstrated that the SBAS InSAR processing is valuable for
478 estimating slow subsidence caused by spatio-temporal responses of aquifer system.
479 However, in this study, we assumed that groundwater withdrawal is the most dominant
480 factor in the subsidence of Tucson. Moreover, the human activities (i.e. constructing
481 buildings and airports) except groundwater use and other natural factors were not

482 elaborately considered, but the future study should focus on unraveling more
483 parameters, which are related with ground motions. Additionally, the future dense
484 temporal and high-resolution SAR observations from Sentinel-1, TerraSAR-X, and
485 ALOS-2 PALSAR-2 will help to obtain more precise measurements and find more
486 robust relationship among ground deformation in Tucson, groundwater extraction, and
487 other parameters.

488

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497

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 585

586 **Figure Captions**

587 Figure 1. Tucson metropolitan area located in Pima county, Arizona.

588 Figure 2. Generalized geological map in Tucson metropolitan area. The geological
589 composition consists of upper, middle, and lower stratigraphic units. The area with
590 upper stratigraphic unit is subject to ground deformation.

591 Figure 3. Diagram of perpendicular and temporal baseline of InSAR pairs ((a) ERS and
592 ENVISAT InSAR pairs; red circles and lines are 29 ERS pairs, and blue circles and
593 lines are 134 ENVISAT pairs. And, dashed black line represents simulated temporary
594 InSAR pair to fill up data gap. (b) ALOS PALSAR InSAR pairs).

595 Figure 4. ERS-1/2 differential interferogram ((a) 1993.06.22~1996.01.11, (b)
596 1993.06.22~1997.03.07), ENVISAT differential interferogram ((c)
597 2004.01.30~2004.07.23, (d) 2004.01.30.2006.06.23), ALOS PALSAR differential
598 interferogram ((e) 2009.10.17~2011.03.07, (f) 2009.12.02~2011.03.07).

599 Figure 5. Time-series of (accumulated) vertical deformations from ERS/ENVISAT
600 SBAS InSAR processing of (a) 1993.11.09, (b) 1996.11.22, (c) 1999.10.08, (d)
601 2000.08.18, (e) 2004.12.10, (f) 2007.10.26, and (g) 2008.09.05, and (h) 2010.09.10.

602 Figure 6. Time-series of (accumulated) vertical deformations from ALOS SBAS InSAR
603 processing of (a) 2009.12.02, (b) 2010.01.17, (c) 2010.06.04, and (d) 2011.03.07.

604 Figure 7. Linear vertical deformation rate (cm/yr) estimated from (a) ERS/ENVISAT

605 and (b) ALOS SBAS processing. The red-colored region represents ground subsidence
606 due to groundwater extraction. The contour means the iso-lines of groundwater level
607 changes measured in wells.

608 Figure 8. 10-year interval groundwater level changes measured at wells of (a)
609 1980s~1990s, (b) 1990s~2000s, and (c) 2000s~2010s, and 30-year water level changes
610 of (d) 1980s~2010s. The red and blue colored dots mean the increase and decrease of
611 water level at wells.

612 Figure 9. (a) Land subsidence monitoring and extensometer stations installed in Tucson,
613 and (b) Ellipsoid height changes measured in monitoring stations from 1998 to 2005;
614 red and blue arrows represent subsidence and uplift at the sites, and the length of arrows
615 expresses the amount of the ellipsoid height change. Green arrows represent the change
616 of compactions, which were measured in the extensometers from October, 2005 to
617 September, 2012.

618 Figure 10. Monthly compaction (blue dots) from October, 2005 to September 2012, and
619 subsidence (red circles) estimated from ERS/ENVISAT and ALOS SBAS processing at
620 monitoring stations of (a) WR53, (b) X419, (c) XAVIER, and (d) 23CBA.

621 Figure 11. Vertical displacements from ERS/ENVISAT (black squares) and ALOS (red
622 dots) SBAS processing, and GPS ellipsoid height change (blue diamonds) from 1999 to

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624 MAGNETIC, (g) WR53, and (h) WR52.
625 Figure 12. Time-series vertical deformation (red circles and lines) from ERS/ENVISAT
626 SBAS processing and groundwater elevation (blue dots and lines) measured in WR56A
627 and WR52.

628 Figure 13. (a) Contour in a plain view of ERS/ENVISAT SBAS InSAR-derived vertical
629 deformation during 17-year span (A, B, C, D, and E regions are mostly affected by
630 ground subsidence), and 3-year interval ERS/ENVISAT SBAS InSAR-derived vertical
631 deformation of (b) 1993.11.09 ~ 1996.11.22, (c) 1996.11.22 ~ 1999. 11.12, (d)
632 1999.11.12 ~ 2002.04.05, (e) 2002.04.05 ~ 2004.12.10, (f) 2004.12.10 ~ 2007.10.26,
633 and (g) 2007.10.26 ~ 2010.09.10.

634 Figure 14. 3-year interval vertical displacements along the profiles of (a) a-a', (b) b-b',
635 (c) c-c', and (d) d-d' in Fig.13(c).

636

637 **Table Captions**

638 Table 1. SAR images used for ERS, ENVISAT, and ALOS SBAS processing

Figure(s)

Figure 1. Tucson metropolitan area located in Pima county, Arizona.

Figure 2. Generalized geological map in Tucson metropolitan area. The geological composition consists of upper, middle, and lower stratigraphic units. The area with upper stratigraphic unit is subject to ground deformation.

Figure 3. Diagram of perpendicular and temporal baseline of InSAR pairs ((a) ERS and ENVISAT InSAR pairs; red circles and lines are 29 ERS pairs, and blue circles and lines are 134 ENVISAT pairs. And, dashed black line represents simulated temporary InSAR pair to fill up data gap. (b) ALOS PALSAR InSAR pairs).

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Figure 12. Time-series vertical deformation (red circles and lines) from ERS/ENVISAT SBAS processing and groundwater elevation (blue dots and lines) measured in WR56A and WR52.

Figure 13. (a) Contour in a plain view of ERS/ENVISAT SBAS InSAR-derived vertical deformation during 17-year span (A, B, C, D, and E regions are mostly affected by ground subsidence), and 3-year interval ERS/ENVISAT SBAS InSAR-derived vertical deformation of (b) 1993.11.09 ~ 1996.11.22, (c) 1996.11.22 ~ 1999. 11.12, (d) 1999.11.12 ~ 2002.04.05, (e) 2002.04.05 ~ 2004.12.10, (f) 2004.12.10 ~ 2007.10.26, and (g) 2007.10.26 ~ 2010.09.10.

Figure 14. 3-year interval vertical displacements along the profiles of (a) a-a', (b) b-b', (c) c-c', and (d) d-d' in Fig.13(c).

Table 1. SAR images used for ERS, ENVISAT, and ALOS SBAS processing

Mission	Date	Path	Direction	Incidence Angle (°)	Mission	Date	Path	Direction	Incidence Angle (°)
ERS	19930622	456	Descending	23.2711	ENVISAT	20060623	456	Descending	22.7884
ERS	19931109	456	Descending	23.2711	ENVISAT	20061110	456	Descending	22.7884
ERS	19960111	456	Descending	23.2711	ENVISAT	20070223	456	Descending	22.7884
ERS	19960112	456	Descending	23.2711	ENVISAT	20070608	456	Descending	22.7884
ERS	19960425	456	Descending	23.2711	ENVISAT	20070817	456	Descending	22.7884
ERS	19960426	456	Descending	23.2711	ENVISAT	20071026	456	Descending	22.7884
ERS	19961122	456	Descending	23.2711	ENVISAT	20080208	456	Descending	22.7884
ERS	19970131	456	Descending	23.2711	ENVISAT	20080523	456	Descending	22.7884
ERS	19970307	456	Descending	23.2711	ENVISAT	20080905	456	Descending	22.7884
ERS	19970829	456	Descending	23.2711	ENVISAT	20090403	456	Descending	22.7884
ERS	19991008	456	Descending	23.2711	ENVISAT	20090717	456	Descending	22.7884
ERS	19991112	456	Descending	23.2711	ENVISAT	20090925	456	Descending	22.7884
ERS	20000121	456	Descending	23.2711	ENVISAT	20100212	456	Descending	22.7884
ERS	20000714	456	Descending	23.2711	ENVISAT	20100423	456	Descending	22.7884
ERS	20000818	456	Descending	23.2711	ENVISAT	20100528	456	Descending	22.7884
ERS	20000922	456	Descending	23.2711	ENVISAT	20100910	456	Descending	22.7884
ERS	20020405	456	Descending	23.2711	ALOS	20091017	203	Ascending	38.7249
ENVISAT	20040130	456	Descending	22.7884	ALOS	20091202	203	Ascending	38.7249
ENVISAT	20040409	456	Descending	22.7884	ALOS	20100117	203	Ascending	38.7249
ENVISAT	20040514	456	Descending	22.7884	ALOS	20100419	203	Ascending	38.7249
ENVISAT	20040723	456	Descending	22.7884	ALOS	20100604	203	Ascending	38.7249
ENVISAT	20041105	456	Descending	22.7884	ALOS	20101205	203	Ascending	38.7249
ENVISAT	20041210	456	Descending	22.7884	ALOS	20110120	203	Ascending	38.7249
ENVISAT	20060310	456	Descending	22.7884	ALOS	20110307	203	Ascending	38.7249
ENVISAT	20060414	456	Descending	22.7884					