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Comment on "Recent subsidence of the Venice Lagoon from continuous GPS and interferometric synthetic aperture radar" by Y. Bock, S. Wdowinski, A. Ferretti, F. Novali, and A. Fumagalli

P. Teatini
Institute of Marine Sciences, National Research Council, Arsenale Tesa 104, Castello 2737/F, IT-30122 Venice, Italy

Department of Civil, Environmental and Architectural Engineering, University of Padua, Via Trieste 63, IT-35121 Padua, Italy (pietro.teatini@unipd.it)

L. Tosi
Institute of Marine Sciences, National Research Council, Arsenale Tesa 104, Castello 2737/F, IT-30122 Venice, Italy (luigi.tosi@ismar.cnr.it)

T. Strozzi
Gamma Remote Sensing A.G., Worbstrasse 225, CH-3073 Gümligen, Switzerland (strozzi@gamma-rs.ch)

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1. Introduction

[1] Relative sea level rise, i.e., the combination of land subsidence and the eustatic rise of the sea level, is a major problem for the safety of Venice since the 1970s [e.g., *Gambolati et al.*, 1974; *Carbognin et al.*, 1977].

[2] The most recent paper on the subject has been published by *Bock et al.* [2012]. In this Comment we (1) dispute the originality of the combined GPS and InSAR method presented by *Bock et al.* [2012] who missed some previous publication on the subject; (2) contest their statement of possible "bias" in our previous analyses which used similar methodologies; (3) question the "precision of 0.1–0.2 mm/yr with respect to a global reference frame" declared by the authors; and, (4) discuss on the meaning of "stability" versus "subsidence" for a

coastal city like Venice settled above ~1500-m thick Quaternary unit with 20–30 m of Holocene poorly consolidated lagoon deposits.

2. Combining InSAR and GPS: A Consolidated Approach

[3] Combination of GPS and SAR-based measurements is a well-known approach, which has been used since the past decade [e.g., *Bawden et al.*, 2001]. Indeed, similar to leveling, SAR-based data are differential measurements, i.e., the displacements of radar reflectors (called PS - Persistent Scatterers - in the following) are relative to a reference point target. Therefore, the movement of the reference has to be known, e.g., form previous leveling or GPS, to calibrate the SAR results and obtain "absolute" displacements.

[4] Usually, for medium and small-scale investigations (on the order of 10 × 10 km^2) one reference point suffices for the calibration [e.g., *Colesanti et al.*, 2003; *Brooks et al.*, 2007; *Teatini et al.*, 2011a, 2011b]. For larger SAR analyses more than one reference is required. In the paper by *Teatini et al.* [2012], which was published online in January 2010 and is dealing with the same issue as *Bock et al.* [2012], the authors explain:

> for large scale SAR investigations such as the one carried out in this study - i.e., the Venice coastland -, more reference measurements evenly distributed in the area of interest are required to constrain the interferometric results. This is due to the inaccuracy in estimation of the orbital baseline due to the not perfect knowledge of the satellite position results in a phase tilt. The "right solution" in terms of PT average velocity is possibly rotated on a slightly inclined plane, with the relative displacement rate for PT some tens of kilometers apart that is characterized by an uncertainty of 1–3 mm/year. To overcome, or at least mitigate, this so-called "flattening" problem, the calibrated IPTA solutions are post-processed using known displacements provided by leveling and GPS in three zones scattered in the study area (p. 74).

[5] This approach is even more deeply described by *Tosi et al.* [2010, p. 122] where it is also clearly reported that the GPS station of Treviso (TREV) has been used for reference and those at Cavallino (CAVA), Chioggia (SFEL), and Padova (VOLT) "to remove or at least mitigate the flattening error."

[6] Therefore, it is at least curious that in the review by *Bock et al.* [2012] exactly these two publications, i.e., *Tosi et al.* [2010] and *Teatini et al.* [2012], are not referenced. The difference between our previous works and that by *Bock et al.* [2012] reduces to the data sets used for the SAR-based investigations, which are composed by 61 SAR scenes acquired by the Canadian RADARSAT-1 satellite between April 2003 and October 2007 for the former and 44 ESA ENVISAT images between February 2003 and December 2007 for the latter, together with the 2-yearlonger GPS series in *Bock et al.* [2012] due to their more recent publication. A certain dissimilarity is also introduced in the approach used to calibrate the SAR displacements with the GPS measurements. In fact, *Bock et al.* [2012] rigorously derive the movement of each GPS along the LOS direction. Conversely, we decided to neglect the GPS west-east residuals with respect to the plate motion r_{WE} because of (1) the small values relatively to the vertical displacements; (2) the incident angle of ENVISAT acquisitions (~23°) smaller than those of RADARSAT-1 (~35°) yielding a less sensitivity to the horizontal components of the displacement; (3) the almost "random" variability of r_{WE} likely due to site-specific conditions (as also shown in Table 3 by *Bock et al.* [2012]); and (4) the large variability of the PS movements in the GPS neighborhood, as clearly shown in Table 4 of *Bock et al.* [2012] where the standard deviation of the velocity of the nearby PS is usually larger than r_{WE}.

[7] Therefore, the data provided by *Bock et al.* [2012] themselves confirm that the GPS representativeness with respect to the SAR solution must be carefully considered when PS are not identified directly on the same structure of the GPS antenna. The significant geologic variability of the shallower deposits in the whole Venice coastland, the various depth of reference of the displacements due to the different type/depth of structure foundations, and possible instabilities of different portions of the same building, usually quite old in the study area, are generally responsible for significant changes of the measured displacements also for adjacent PS [*Tosi et al.*, 2009].

3. Surface Displacement in the Venice Lagoon

[8] Even more relevant is the comparison between the results of *Bock et al.* [2012] and our recent studies [*Tosi et al.*, 2010; *Teatini et al.*, 2012]. Figure 1 shows the annual average rate of LOS surface displacement as provided by *Tosi et al.* [2010] re-colored using the chromatic scale adopted by *Bock et al.* [2012]. To tightly align the references of the two solutions, the one published by *Tosi et al.* [2010] is shifted by −0.3 mm/yr, i.e., the vertical displacement rate of TREV provided by

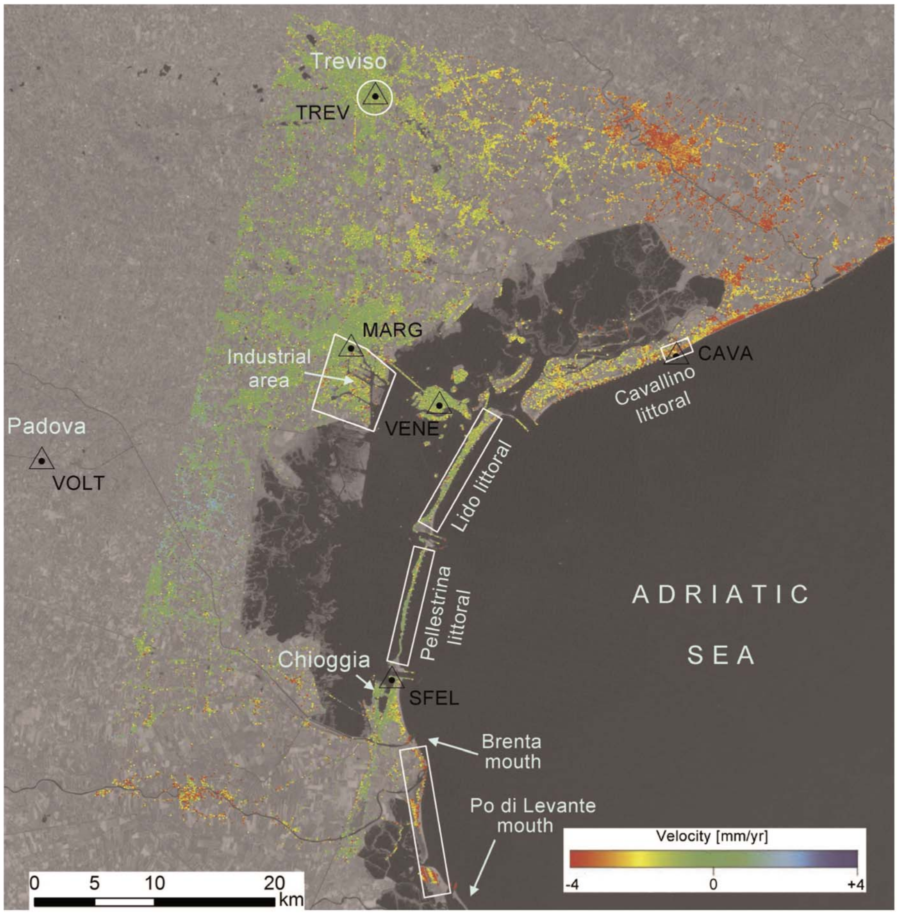

Figure 1. Annual average rate of ENVISAT LOS surface displacement between 2003 and 2007 redrawn after *Tosi et al.* [2010] using the color scale after *Bock et al.* [2012] and shifted by −0.3 mm/yr in order to be aligned with the reference system suggested by *Bock et al.* [2012] in Table 3. The value is obtained from the up velocity for the TREV GPS site, which was considered the fixed reference in *Tosi et al.* [2010], projected along the ENVISAT LOS. The available GPS stations are denoted by black triangles. The white boxes represent the areas used to evaluate the average displacement rates in representative portions of the coastland. Negative values mean land subsidence.

Bock et al. [2012] projected along the ENVISAT LOS. In fact, in agreement with the leveling measurements on the Italian National Geodetic Network used in previous studies about the Venice subsidence [e.g., *Carbognin et al.*, 2004], the Treviso station was considered fixed by *Tosi et al.* [2010]. Figure 1 shows that the city of Treviso and the Pellestrina littoral are almost stable (−0.5 ± 0.8 mm/yr and −0.4 ± 1.0, respectively), the Lido littoral, Cavallino littoral around the GPS station, and the coastland between the Brenta and the Po di Levante river mouths subside at 1.2 ± 1.0 mm/yr, 3.3 ± 1.2 mm/yr, and 3.2 ± 1.4 mm/yr, respectively. Even though with a much larger number of detected PS, the displacements rates provided by *Bock et al.* [2012] re-confirm these values that, on the other hand, are substantially coherent with the numbers previously detected in *Strozzi et al.* [2003], *Teatini et al.* [2005], and *Tosi et al.* [2007]. An interpretation of this variability is provided in *Tosi et al.* [2009].

[9] The more critical point is related to the subsidence of the historic center. A large rumor has been created worldwide by *Bock et al.* [2012, paragraph 20] in relation to the statement that "in the first decade of the 21st Century…the city of Venice and its surroundings are still subsiding."

[10] Indeed, Figure 2 shows that Venice moved over the 2003–2007 period. Figure 2a represents an enlargement of the map provided in Figure 1, i.e., the average displacement rates along the LOS as published by *Tosi et al.* [2010] using the color scale of *Bock et al.* [2012]. Figure 2b reproduces the same map as published in 2010 by *Teatini et al.*

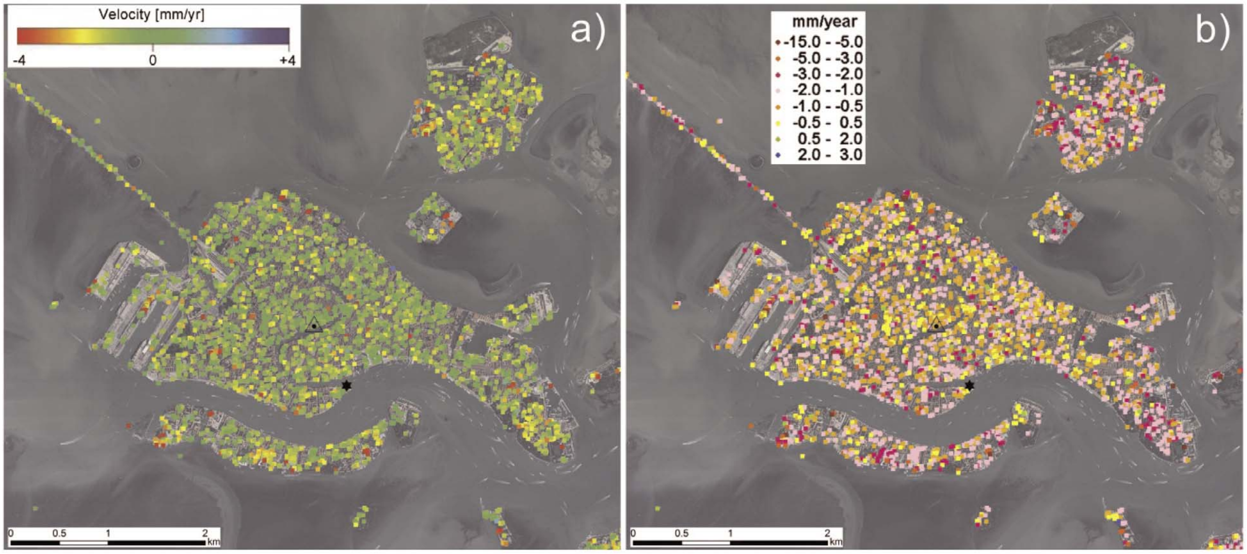

Figure 2. Annual average rate of ENVISAT LOS surface displacement in Venice between 2003 and 2007 redrawn after *Teatini et al.* [2012] using (a) the color scale after *Bock et al.* [2012] and (b) the original color scale highlighting the variability of the movements. The black triangle and star indicate the location of the VENE GPS and Venice tide gauge stations, respectively.

[2012] using a color scale that more clearly highlights the variability of the displacement rates.

[11] Our combined analysis indicates that Venice moved at −1.1 ± 0.9 mm/yr. The frequency distribution of the displacements is shown in Figure 3. Partially in agreement with the findings of *Bock et al.* [2012], these numbers are gently larger (~0.5 mm/yr) than the average displacement rates measured by *Tosi et al.* [2002] and *Teatini et al.* [2005, 2007] using ERS scenes and leveling surveys over the 1993–2000 time interval. However, the comparison between our map, which is mainly colored by light green PS dots (Figure 2), and Figure 6a in *Bock et al.* [2012], which is "dominated by yellow PS dots," (paragraph 27) reveals a certain difference, with sinking rates in the former smaller on the average than the 1–2 mm/yr subsidence range provided by the latter. On the other hand, both the ERS- and RADARSAT-based measurements fall within the standard deviation range characterizing the ENVISAT-based displacements shown by *Tosi et al.* [2010] and *Teatini et al.* [2012].

[12] The following issues have to be remarked:

[13] 1. Although, as observed by *Bock et al.* [2012], VENE can be used only partially to validate the PS measurements (our calibrated LOS velocity value in the GPS surrounding is −0.9 ± 0.2 mm/yr in good agreement with −0.8 mm/yr as measured by the permanent station over the entire period), our results in Venice and the central lagoon are supported by the records of a GPS station in the Marghera industrial area (MARG in Figure 1) and the Venice tide gauge. MARG is less than 10 km far from Venice and the average vertical movement projected along the LOS between March 2004 and March 2011, in the same reference system of the other stations, amounts to −0.9 ± 0.1 mm/yr. The −1.1 ± 0.9 mm/yr PS LOS velocity in its proximity agrees satisfactorily with the GPS. By averaging the measurements in the whole industrial area, we obtain a similar value (−0.9 ± 1.1 mm/yr), which is smaller than the subsidence of 1–2 mm/yr provided by *Bock et al.* [2012] for Marghera. The tide gauge of Venice is characterized by one of the longest sea level records in the world. Here, it is used as an independent technique to quantify the subsidence of Venice by comparing the recorded sea level trend with that measured at the tide gauge of Trieste a coastal city located 200 km north of Venice and known to be stable [*Carbognin et al.*, 2004]. Figure 4 shows the behavior versus time of the difference between the two tide gauge records, i.e., the sinking of Venice. The figure clearly reveals that, after the period 1931–1970 during which anthropogenic subsidence occurred and a few years till to the mid-1970s characterized by a small rebound due to the natural pressure recovery in the multiaquifer system, Venice has statistically continued to subside at a constant rate of 0.8 ±

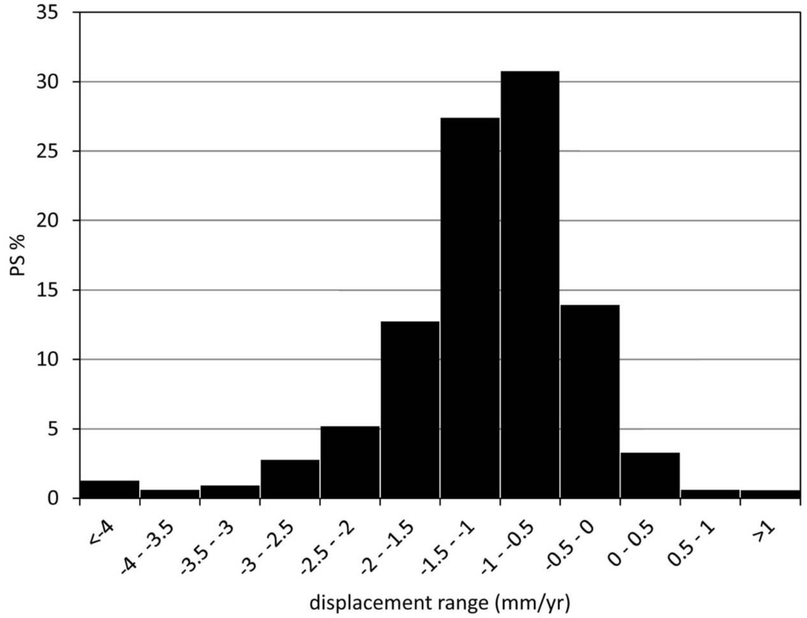

Figure 3. Frequency distribution of the PS displacements detected at the historical center of Venice.

0.4 mm/yr. The trend compares well with the average −0.6 ± 0.4 mm/yr displacement measured in the surroundings of gauge the by the interferometric processing of the ENVISAT images.

[14] 2. Our and *Bock et al.* [2012] SAR-based solutions are both calibrated by tilting, the different results obtained at Venice cannot be related to a bias (tilt) in our previous analyses, as supposed by *Bock et al.* [2012]. Note that Table 4 in *Bock et al.* [2012] highlights how the tilt contribution at Venice amounts to 0.1 mm/yr only ($V_{PS} = -1.23$ mm/yr versus $V_{PS\text{-nocorr}} = -1.33$ mm/yr) in their analyses, i.e., it is absolutely negligible.

[15] 3. The slight increase of the subsidence rates provided in Figure 2 relative to previous ERS-based maps locally calibrated by leveling [*Tosi et al.*,

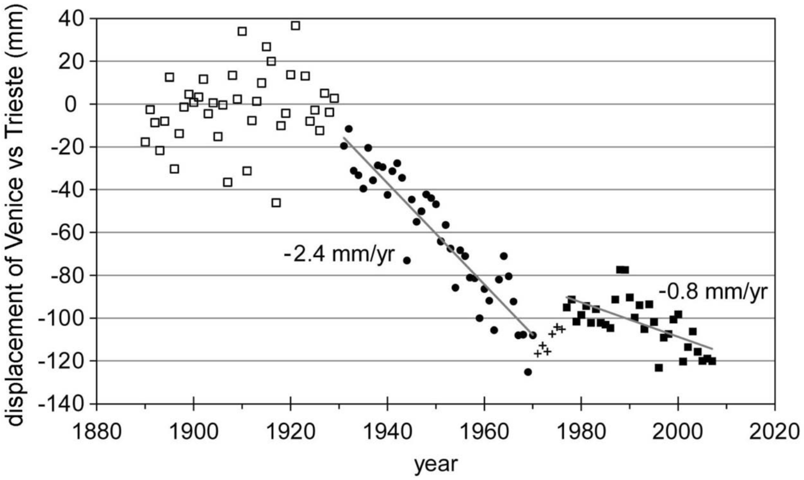

Figure 4. Vertical displacement of Venice relative to Trieste as derived from tide gauge records. The trend observed during the exploitation of the aquifer system (1931–1970) is almost three times that recorded over the last 30 years. The values for the last 4 years are not used because the sea level data in Venice are presently under re-processing for the instability of the tide gauge caused by the restoration works in the surroundings (personal communication of P. Canestrelli, director of Istituzione Centro Previsioni e Segnalazioni Maree, Venezia). Black crosses highlight a surface rebound at Venice after the end of groundwater pumping.

2002, *Teatini et al.*, 2005, 2007] is likely due to a cause different from those supposed by *Bock et al.* [2012, paragraph 17], i.e., "an actual change in subsidence rate over the last decade, or to a possible bias (tilt) in the IPTA analysis." Venice was developed over ancient sandy islands during the first millennium, and the following expansions were done by reclaiming and filling in parts of the lagoon and channels [*Gatto and Carbognin*, 1981]. Palaces, houses, and churches were founded on a strongly heterogeneous, relatively young and compressible deposits [*Zezza*, 2010] using few meter deep wooden piles down to the Late Pleistocene units [*Donnici et al.*, 2011). This heterogeneity is responsible for the significant variability of the subsidence measured in the past by leveling [*Tosi et al.*, 2002, *Carbognin et al.*, 2004] and even more by the recent SAR-based methods (Figure 2b). Walking through Venice everyone clearly appreciates the consequences of this variability looking at the different tilt of adjacent buildings. For this reason the benchmarks of the leveling network developed in the early 1960s to measure the city subsidence were carefully established at the base of apparently stable buildings, on bridges, and pedestrian walkways. Conversely, due to the peculiar features of the urban settlement, i.e., the dense network of very narrow pedestrian "calle" and "fondamenta," the majority of the radar reflectors are located on the palace and church roofs. These ancient buildings move independently more than the city floor due to their own weight and flexible structure made by stones and wood. For example, the same VENE antenna was located on a wooden terrace on the roof of the Papadopoli palace, which is one of the most important and heavy buildings along the Gran Canal.

4. Quality Assessment

[16] In the light of the variability of the displacement rates detected at Venice, it is unrealistic the assertion by *Bock et al.* [2012, abstract] that "our combined GPS and InSAR analysis demonstrates … a precision of 0.1–0.2 mm/yr." A number of factors support this guess. First, the trend of VENE, which varies significantly over nested time intervals, and a velocity dispersion of the PS selected around the GPS stations much larger than this precision range (see the last column of Table 4 in *Bock et al.* [2012]). For the reasons listed above, even if a single GPS station can reach such a precision, its representativeness is significantly lower when no radar target is located in its proximity and on the same structure. Then, the nominal precision of the SAR-based method. An inter-comparison and validation of InSAR methods carried out within the GMES Terrafirma project have shown standard deviations and errors in the range of 0.4–0.5 mm/yr and 1.0–1.5 mm/yr, respectively [*Crosetto et al.*, 2008]. To our knowledge, an InSAR precision of only 1 to 2 tenths of mm/yr over several yearlong time intervals has never been validated in regional-scale applications, also because such an accuracy cannot be easily attained by other monitoring techniques applicable for surveying large areas.

[17] Finally, the accuracy claimed by *Bock et al.* [2012] concerning their outcome contrasts with the color scale used in their Figures 4a and 6a where already a difference of 1 mm/yr is almost impossible to be distinguished.

5. Is Venice "Subsiding" or "Substantially "Stable"

[18] The last and probably most important issue needing clarification concerns with the interpretation of the rates of the Venice movement. In the last years we wrote: "… it can be concluded that, in general, Venice is stable. The vertical displacement rates are between +1.0 and −2.0 mm/year …" [*Tosi et al.*, 2002, paragraph 7], "… The SIMS result shows a general land stability in the central part of the Venice region, including the major cities of Venice …" [*Teatini et al.*, 2005, p. 411], "… the city has been stable over the past decade, with the displacement rates generally smaller than 1 mm/year …" [*Teatini et al.*, 2007, paragraph 32], "… Substantially stable areas, the most important of which are the cities of Venice and Ravenna and their surroundings …" [*Bitelli et al.*, 2010, p. 279], "… shows the displacement rates over the period 2003–2007 at Venice. The measurements confirm the present stability of the historical center but also highlight that small areas of the city and several single buildings subside at a rate up to 3 mm/year …" [*Strozzi et al.*, 2010, pp. 251; *Teatini et al.*, 2012, p. 76].

[19] The question is: what means "general/substantial stability" for the historical center of Venice? Surely, it does not correspond to null displacements as geological subsidence has always driven the evolution of this region [*Brambati et al.*, 2003]. Indeed, we have always associated this concept to the detection of a significant number of leveling benchmarks (in the past) or PS (more recently) distributed in the whole city characterized by sinking rates comparable with the long-term regional geological subsidence estimated, for example, in 0.5–1.0 mm/yr

by *Carminati et al.* [2003]. This is the reason why we suggest interpreting the recent displacements as a substantial stability for the historical city, with the concern for its survival mainly related to the expected sea level rise.

6. Conclusions

[20] In this Comment we have critically discussed a few statements and outcomes recently published by *Bock et al.* [2012]. Their conclusive statement that "the city of Venice continues to subside, at a rate of 1–2 mm/yr …" has to be taken with much caution and does not warrant the great emphasis with which the press has underscored it.

[21] Surely, the monitoring of the city movements will continue to assume a relevant importance. In this context, we agree with *Bock et al.* [2012] on the importance of using permanent GPS stations to calibrate InSAR solutions. Regretfully, we point out that the GPS network specifically installed in the early 2000 by the Venice Water Authority for monitoring the lagoon subsidence has been deactivated in 2011. Based on the experience described above our conclusive suggestion is the equipment of each GPS station with an artificial active or passive InSAR reflector because of the high variability of the surface displacements in coastlands.

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References

Bawden, G. W., W. Thatcher, R. S. Stein, K. W. Hudnut, and G. Peltzer (2001), Tectonic contraction across Los Angeles after removal of groundwater pumping effects, *Nature*, *412*, 812–815, doi:10.1038/35090558.

Bitelli, G., F. Bonsignore, L. Carbognin, A. Ferretti, T. Strozzi, P. Teatini, L. Tosi, and L. Vittuari (2010), Radar interferometry-based mapping of the present land subsidence along the low-lying northern Adriatic coast of Italy, in *Land Subsidence, Associated Hazards and the Role of Natural Resources Development*, *IAHS Publ.*, vol. 339, edited by D. Carreón-Freyre et al., pp. 279–286, Wallingford, U. K.

Bock, Y., S. Wdowinski, A. Ferretti, F. Novali, and A. Fumagalli (2012), Recent subsidence of the Venice Lagoon from continuous GPS and interferometric synthetic aperture radar, *Geochem. Geophys. Geosyst.*, *13*, Q03023, doi:10.1029/2011GC003976.

Brambati, A., L. Carbognin, T. Quaia, P. Teatini, and L. Tosi (2003), The Lagoon of Venice: Geological setting, evolution and land subsidence, *Episodes*, *26*(3), 264–268.

Brooks, B. A., M. A. Merrifield, J. Foster, C. L. Werner, F. Gomez, M. Bevis, and S. Gill (2007), Space geodetic determination of spatial variability in relative sea level change, Los Angeles basin, *Geophys. Res. Lett.*, *34*, L01611, doi:10.1029/2006GL028171.

Carbognin, L., P. Gatto, G. Mozzi, G. Gambolati, and G. Ricceri (1977), New trend in the subsidence of Venice, in *Land Subsidence*, *IAHS Publ.*, vol. 121, edited by J. C. Rodda, pp. 65–81, Wallingford, U. K.

Carbognin, L., P. Teatini, and L. Tosi (2004), Relative land subsidence in the lagoon of Venice, Italy, at the beginning of the new millennium, *J. Mar. Syst.*, *51*(1–4), 345–353, doi:10.1016/j.jmarsys.2004.05.021.

Carminati, E., C. Doglioni, and D. Scrocca (2003), Apennines subduction-related subsidence of Venice (Italy), *Geophys. Res. Lett.*, *30*(13), 1717, doi:10.1029/2003GL017001.

Colesanti, C., A. Ferretti, C. Prati, and F. Rocca (2003), Monitoring landslides and tectonic motions with the Permanent Scatterers Technique, *Eng. Geol. Amsterdam*, *68*, 3–14, doi:10.1016/S0013-7952(02)00195-3.

Crosetto, M., O. Monserrat, C. Bremmer, R. Hanssen, R. Capes, and S. Marsh (2008), Ground motion monitoring using SAR interferometry: Quality assessment, *Eur. Geol.*, *26*, 12–15.

Donnici, S., R. Serandrei-Barbero, C. Bini, M. Bonardi, and A. Lezziero (2011), The caranto paleosol and its role in the early urbanization of Venice, *Geoarchaeology*, *26*(4), 514–543, doi:10.1002/gea.20361.

Gambolati, G., P. Gatto, and R. A. Freeze (1974), Mathematical simulation of the subsidence of Venice: 2. Results, *Water Resour. Res.*, *10*(3), 563–577.

Gatto, P., and L. Carbognin (1981), The lagoon of Venice: Natural environmental trend and man-induced modification, *Hydrol. Sci. Bull.*, *26*(4), 379–391, doi:10.1080/02626668109490902.

Strozzi, T., L. Tosi, U. Wegmüller, C. Werner, P. Teatini, and L. Carbognin (2003), Land subsidence monitoring service in the Lagoon of Venice [CD-ROM], in *IGARSS 2003*, vol. I, pp. 212–214, Inst. of Electr. and Electron. Eng., New York.

Strozzi, T., L. Tosi, P. Teatini, U. Wegmüller, M. Santoro, and L. Carbognin (2010), Advanced monitoring techniques for mapping land displacement on the Venice coastland with satellite SAR data, in *Land Subsidence, Associated Hazards and the Role of Natural Resources Development*, *IAHS Publ.*, vol. 339, edited by D. Carreón-Freyre et al., pp. 249–254, Wallingford, U. K.

Teatini, P., L. Tosi, T. Strozzi, L. Carbognin, U. Wegmüller, and F. Rizzetto (2005), Mapping regional land displacements in the Venice coastland by an integrated monitoring system, *Remote Sens. Environ.*, *98*, 403–413, doi:10.1016/j.rse.2005.08.002.

Teatini, P., T. Strozzi, L. Tosi, U. Wegmüller, C. Werner, and L. Carbognin (2007), Assessing short- and long-time displacements in the Venice coastland by synthetic aperture radar interferometric point target analysis, *J. Geophys. Res.*, *112*, F01012, doi:10.1029/2006JF000656.

Teatini, P., L. Tosi, and T. Strozzi (2011a), Quantitative evidence that compaction of Holocene sediments drives the present land subsidence of the Po Delta, Italy, *J. Geophys. Res.*, *116*, B08407, doi:10.1029/2010JB008122.

Teatini, P., et al. (2011b), Geomechanical response to seasonal gas storage in depleted reservoirs: A case study in the Po River basin, Italy, *J. Geophys. Res.*, *116*, F02002, doi:10.1029/2010JF001793.

Teatini, P., L. Tosi, T. Strozzi, L. Carbognin, G. Cecconi, R. Rosselli, and S. Libardo (2012), Resolving land subsidence within the Venice Lagoon by persistent scatterer SAR interferometry, *Phys. Chem. Earth*, *40–41*, 72–79.

Tosi, L., L. Carbognin, P. Teatini, T. Strozzi, and U. Wegmüller (2002), Evidence of the present relative land stability of Venice, Italy, from land, sea, and space observations, *Geophys. Res. Lett.*, *29*(12), 1562, doi:10.1029/2001GL013211.

Tosi, L., P. Teatini, L. Carbognin, and J. Frankenfield (2007), A new project to monitor land subsidence in the Northern Venice coastland (Italy), *Environ. Geol.*, *52*, 889–898, doi:10.1007/s00254-006-0530-8.

Tosi, L., P. Teatini, L. Carbognin, and G. Brancolini (2009), Using high resolution data to reveal depth-dependent mechanisms that drive land subsidence: The Venice coast, Italy, *Tectonophysics*, *474*, 271–284, doi:10.1016/j.tecto.2009.02.026.

Tosi, L., P. Teatini, T. Strozzi, L. Carbognin, G. Brancolini, and F. Rizzetto (2010), Ground surface dynamics in the northern Adriatic coastland over the last two decades, *Rend. Lincei*, *21*, suppl. 1, 115–129, doi:10.1007/s12210-010-0084-2.

Zezza, F. (2010), The sedimentary structure of Upper Pleistocene–Holocene deposits in Venice and its effects on the stability of the historic centre, *Rend. Lincei*, *21*, suppl. 1, 211–227, doi:10.1007/s12210-010-0089-x.