



## Reply to comment by P. Teatini et al. on “Recent subsidence of the Venice Lagoon from continuous GPS and interferometric synthetic aperture radar”

### Y. Bock

Cecil H. and Ida M. Green Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, University of California San Diego, 9500 Gilman Drive, La Jolla, California 92093–0225, USA (ybock@ucsd.edu)

### S. Wdowinski

Division of Marine Geology and Geophysics, Rosenstiel School of Marine and Atmospheric Science, University of Miami, 4600 Rickenbacker Causeway, Miami, Florida 33149–1098, USA (swdowinski@rsmas.miami.edu)

### A. Ferretti, F. Novali, and A. Fumagalli

Tele-Rilevamento Europa, Via Vittoria Colonna, 7, IT-20149 Milan, Italy (alessandro.ferretti@treuropa.com; fabrizio.novali@treuropa.com; alfio.fumagalli@treuropa.com)

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[1] Unlike most published scientific comments, the comment submitted by P. Teatini, L. Tosi and T. Strozzi on *Bock et al.* [2012] does not dispute the scientific merits of our study, but rather reinforces its approach and main results regarding Venice subsidence. Their main points appear to be that our study (1) did not cite the two last papers that they published [*Tosi et al.*, 2010; *Teatini et al.*, 2012a], (2) received considerable attention worldwide for a rather small level of subsidence, (3) used a methodology that is not “original,” (4) misrepresented some of their

earlier work, and (5) published uncertainties that were too optimistic.

[2] Regarding item 1, we were not aware of either the *Tosi et al.* [2010] or *Teatini et al.* [2012a] papers while we were conducting our research. Indeed the *Teatini et al.* [2012a] paper, which is more relevant to the discussion, seems to have been in press online since 2010, but it was only published in late January 2012 in vol. 40–41 of *Physics and Chemistry of the Earth* in a special issue on the

Venice region, about two months prior to publication of our paper and after our paper was submitted in November 2011.

[3] Therefore, this is just a case of two research studies being conducted independently with different but complementary data sets collected over about the same time period (our GPS data set is about 2 years longer), using a somewhat similar approach, coming to the same basic results and being published at about the same time. Our study received a lot of attention after an AGU press release, while their studies, in less well known journals, did not. Frankly, we were surprised at the extensive media coverage. Perhaps the main difference in exposure (item 2) lies in that we reported on significant subsidence, while they sought to downplay their results by concluding that subsidence has “stabilized” in the city. We estimated that subsidence in Venice is at the level of 1–2 mm/yr over the last decade, with an uncertainty of 0.1–0.2 mm/yr [Bock *et al.*, 2012], while Tosi *et al.* [2010] and Teatini *et al.* [2012a] reported on a subsidence rate of  $1.1 \pm 0.9$  mm/yr. However, we concluded that the subsidence is significant, has a long-term tectonic component, and needs to be taken into account along with sea level rise to preserve the historic city, while they sought to play down its significance. This “controversy” was highlighted in an AGU press release by Kate Ramsayer ([http://www.agu.org/news/press/pr\\_archives/2012/2012-16.shtml](http://www.agu.org/news/press/pr_archives/2012/2012-16.shtml)), in which Teatini was quoted as saying “One millimeter is nothing with respect to the problem that Venice experienced 20, 30 years ago,” said Teatini, “It’s a small amount.” That’s exactly the gist of their comment. We discuss this further below in our response to item 5.

[4] Regarding their comment on our methodology (item 3), we never claimed that our approach integrating GPS and InSAR observations is “original.” Our paper came about as a way to combine the long continuous GPS time series analyzed by SOPAC (<http://sopac.ucsd.edu/>), and 61 Radarsat images processed with the PSInSAR approach by TeleRilevamento Europa to provide a detailed picture of subsidence in the Venice region, with respect to a global reference frame provided by the GPS data. Integration of continuous GPS and InSAR has been discussed for many years as they point out. We were involved in some of the early studies on using GPS to calibrate troposphere errors in InSAR images [Bock and Williams, 1997; Williams *et al.*, 1998], originated the PSInSAR technique [Ferretti *et al.*, 2001], and applied InSAR, PSInSAR and continuous GPS technologies to numerous studies

of subsidence worldwide as referenced in Bock *et al.* [2012].

[5] Teatini *et al.* [2012b] also object to our speculation with respect to their earlier work (item 4). In Bock *et al.* [2012, paragraph 17] we wrote: “Our results differ from the results of Teatini *et al.* [2005, 2007] who indicated a more stable situation in the city. This could be due to an actual change in subsidence rate over the last decade, or to a possible bias (tilt) in their IPTA analysis, similar to the one that we have corrected for in our analysis. It is more likely that the subsidence rate has been steady over the last two decades, and that total subsidence in Venice over this period has been 20 to 40 mm.” We should have made this point clearer. We were not suggesting that the speculated tilt in their earlier works (using data from earlier periods) was similar in magnitude to the one we encountered in our data, rather that it was probably larger in magnitude and that they had not taken this possibility into account. This was remedied in the Teatini *et al.* [2012a] study with data that overlaps the period of our study. In this point we partially agree with the comment and, hence, apologize for our lack of clarity.

[6] We stand by the uncertainties that we quoted in Bock *et al.* [2012] (item 5). We have examined thousands of continuous GPS time series worldwide with respect to a global reference frame (<http://sopac.ucsd.edu/>), many with time spans of 10–20 years. The one-sigma uncertainties (0.1–0.2 mm/yr) that we quoted in Bock *et al.* [2012] are based on well-known maximum likelihood analysis [e.g., Williams *et al.*, 2004] that considers the colored noise in the time series, rather than just the formal uncertainties. Another factor contributing to a low uncertainty is that the decade-long time series for the Venice region are consistent throughout (with no breaks or changes of equipment) and exhibit no coseismic deformation. One problem that we did encounter and discussed in detail in the paper is the local instability at station SFEL. Finally, considering that the scatter in the InSAR time series is at least as good as the scatter in the GPS time series [Bock *et al.*, 2012, Figure 5], our conclusion of the overall one-sigma uncertainty in subsidence rate is fully justified, and indicates that are results of 1–2 mm/yr subsidence within Venice is significant. In fact, a closer examination of our results in the city indicates that subsidence is closer to 2 mm/yr (this is clearly seen in the color scale of Figure 6 in Bock *et al.* [2012]). This is a significant amount compared to the expected sea level rise. As noted in Bock *et al.* [2012, paragraph 2], “The

Venice tide gauge record at Punta della Salute indicates that the relative sea level rose 0.23 m in the 20th century, in which about half (0.11 m) reflects actual sea level rise in the upper Adriatic; the remainder is attributed to land subsidence induced by natural processes and anthropogenic groundwater extraction in the 1960s [Gatto and Carbognin, 1981].” Thus, the rate subsidence in the first decade of the 21st century is consistent with the overall subsidence observed in the 20th century.

[7] In their conclusions as stated in *Teatini et al.* [2012b] suggested the following: “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.” This conclusion has nothing to do with the scientific quality of *Bock et al.* [2012]. Obviously there is great interest in preserving Venice and the efforts that have been expended by the Italian government to do so. In any case, the authors have acknowledged that they generally agree with our approach, if not with the significance that we assigned to them. They continue: “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.”

[8] The last section of *Teatini et al.*'s [2012b] conclusions is concerned with the current state of the Venice continuous GPS network that was deactivated in 2011. We join their concern, as our studies shown the importance of operating the GPS network in order to achieve high precision monitoring of the subsidence of both the city of Venice and its lagoon. Similar to *Teatini et al.* [2012b] we would like to use this opportunity to alert the Venice Water Authority that deactivation of the GPS network will reduce the ability to continue the high precision monitoring of Venice subsidence. We, hence, recommend reactivation and expansion of the continuous GPS network.

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