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# *Interactive comment on* "Hydrological Signals in Tilt and Gravity Residuals at Conrad Observatory (Austria)" *by* Bruno Meurers et al.

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The authors thank Anonymous Referee #1 for the review with very useful comments and suggestions that certainly will improve the paper. We reply in the following and indicate how we plan to react in a revised version provided the editor decides accordingly. We add a reply to each single comment/suggestion of the reviewer.

1. "This paper provides a too detailed description of the processing of gravity and especially, tilt data. HESS is dedicated to hydro(geo)logy, hence, all the details of the SG processing are pure routine, the authors should just provide the basics and refer to previous works, while I'm not sure that the whole discussion on the atmospheric pressure admittance of the tiltmeters is relevant. The authors could publish technical



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challenges into a more technical journal."

Reply: We agree with the reviewer that this part can be drastically shortened. However, we still consider the discussion of atmospheric pressure admittances to be necessary. We show in the paper, that short-term tilt residual anomalies associated instantaneously with heavy rain events exhibit on average a similar admittance as atmospheric pressure does at higher frequencies (about 0.3 mHz). From this observation we conclude that the short-term anomalies caused by rain are due to surface loading by accumulated rain water. At this point, we have to address the problem of admittance function changes at frequencies beyond 1 mHz caused by maintenance. We agree that presenting the details disrupts the flow of the text and we shift all the details into an appendix A.

2. "The discussion of the observed hydrogeological effects deserves more details. An important point is a decrease in gravity during precipitations that is immediately followed by an increase in gravity. If I see correctly, on 2016-07-11, Fig 4 shows the decrease, which is rather small comparing to the increase following just after, as shown by Figure 3 (same e.g. just before 2017-09-22 Fig 3). My interpretation is that during rainfall, gravity decreases because water is stored just above the gravimeter, and after while water percolates under the instrument (see similar effects in Watlet et al., WRR 2020). Of course, the response to rainfall probably depends on the degree of saturation of the saturated/unsaturated zones. Even if the authors do not dispose of groundwater measurements, they could build a simplistic model, to estimate the degree of saturation. A nice, original piece of information is provided by the tiltmeters: do they react more to the water stored immediately above the station, or more when water is supposedly underneath the gallery? Do you see a similar effect with snow, or not? As far as I can see, the snow does not affect tilts, hence we can rule Newtonian or load effects that would deform the rock around the gallery. Can you better quantify the effects of rain on gravity and tilts? Of course, there are admittances, but it is a general rule? Are there events obeying more the rule than others do? Are the responses of

tilts and gravimeter perfectly proportional? So, elaborate, please."

Reply: The event on 2016-07-11 is discussed in detail by Figs. 5 and 9 (please note, figure captions are always below the figure they refer to) discriminating between what we call "short-term" and "long-term" residual anomalies. Fig. 5 shows the instantaneous reaction of both gravity (decrease as water is above the sensor) and N-S tilt (increase due to deformation by surface load) to sudden rain accumulation. Actually, this behavior is seen in almost all (71 of 74) heavy rain events and in also case of fast snow accumulation (example provided in Fig. 8), i.e. snow does affect tilts similar as in case of rain. The associated signals are visible in Fig. 9 too, even if small compared to the long-term signal. The long-term anomalies start much later after sufficient water intrusion downwards into the subsurface has taken place (saturation). This process starts also in case of rapid snow melt as the example presented in Fig. 9 (right panel) shows. Short-term residual anomalies are quantified by Fig. 7. We will make this clearer. Quantifying the long-term anomalies is not easy because the tilt/gravity response to long-term water accumulation depends on the overall subsurface saturation for which we have no constraints based on observations. Nevertheless we will enhance the discussion and add some model calculations based on a simplistic models, which match the observations quite well. We also will address the relations between the gravity and tilt residuals quantitatively, both for the short-term and long-term residual anomalies.

L10 An SG monitors changes in gravity

Reply: Yes, provided the instrument axis is kept aligned to the plumb line. This is usually maintained by thermal levelers. If this system fails, the SG monitors the projection of the gravity vector onto the direction of the sensor axis. We agree: our formulation is not correct.

L11: add a blank: 5.5 m

L14: You should already mention the cavity effect, this is (unfortunately) an important effect

Reply to L11 and L14: We agree and will change the text accordingly.

L20: unclear: what is exactly the difference between Newtonian and loading effects on tilts?

Reply: Please see our reply with respect to the general comment on section 5.

L25: in»at all spatial: : :

L27: loading: provide references

L30: add volcanoes

L34: You should mention the pioneering papers of Baker & Lennon and King & Bilham, both in Nature, 1973 (same remark on L179)

Reply to comments between L25 and L34: We agree and will consider the recommendations.

L41: complex infiltration process: mention that Conrad is a karstic area, where everything is expected to be even more complicated than in other hydrogeological contexts.

Reply: We agree and will add a corresponding statement already here.

Section 2: provide a topographic map around the Conrad Observatory, showing the tunnel.

Reply: We will add a topography map with the observatory outlines.

L48: I'd say: "Trafelberg at an elevation of 1050 m."

L53: there is no indication of the karstification, like e.g., sinkholes easy to detect?

Reply: There is a possibly a sinkhole filled with sediments 100-200 m apart from the observatory. Based on its geometry derived from geoelectric and seismic measurements the maximum estimate of the gravity effect of water accumulation is too small for explain the observation. We add this information.

L59: refer also to Van Camp, Meurers et al., J Geod 2016.

Reply: We will add this reference.

L63: What is “long one end”? Elaborate.

L71: in»at one end: : :

L72: 0.7x250: where does this ‘0.7’ come from? “5.5 m/2 base”: what does the “2” mean?

L73-74: “and an example can be given”: strange sentence. Anyway, in my opinion, this belongs to useless technical details. In this paper, you should just mention than thermal effects are negligible (and this is especially true during rainfall, lasting only a few days in the worst case, while thermal effects would play a role only at longer periods or during maintenance).

L78-80: I do not understand the message. What is the relationship between the 50-100 m length and the resonances?

Reply to comments related to L63-80: We agree that these technical details are not necessary and we will skip them.

L103: “Thies”: use the same wording as for Anton Paar: “A disdrometer (Thies): : :.”

Reply: We agree.

L109: nearby: provide an actual distance.

Reply: the distance is about 150 m. We will add this information.

Section 3: too detailed, esp. for gravity.

L157: pole»polar

Reply: We will shorten this chapter.

Section 4: the discussion on pressure is too detailed and somehow confusing.

Reply: We have re-organized this chapter shifting detailed information disrupting the flow of reading in Appendix A. We hope to have made the relevance of the air pressure admittance investigation for our study much clearer.

L170: 5% of the tidal signal: do you mean that the observations are within 5% of the model? In that case, does the cavity effect play a role? Clarify, please.

Reply: No. We refer to the RMS error of a single observation as derived from the LSQ adjustment of the tidal parameter (provided by ETERNA), taking M2 as reference.

L170: "much less data": provide the actual duration of both SG and tilt series.

Reply: SG time series covers 3512 days, LTS only 1064 days including gaps. Numbers of observations entering the adjustment are about 83500 (SG) and 21700 (LTS).

L176: "However": what's exactly the link between the one-century old paper of Michelson, and the ocean loading at CO?

Reply: We cancel this statement.

L181: calibrations errors: the tiltmeters are not at the same place, and have different baselines. Hence, they (probably?) undergo quite different cavity effects, and therefore, this may explain the differences, is it? Can you discuss this?

Reply: Base length is different, but both sensors monitor the tilt along the tunnel axis (E-W). Therefore we do not expect strong cavity effects for the E-W tilts. You are right, we cannot exclude that cavity effects play a role. We will formulate more carefully.

L194: sensor box: of LTS? Reply: Yes. We will make this clear.

L194-203: this paragraph is not very clear and again, what is the relevant information for this study?

Reply: Please refer to our reply to 1). Both atmospheric pressure and water accumu-





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lation due to rain or snow cause surface loading and deformation. We know that the air pressure admittance of the LTS has changed after maintenance work, but remained stable below 0.3 mHz. Hence, the admittances are comparable and not influenced by instrumental issues below 0.3 mHz.

L213: temperature increase: I suppose that "temperature change" is more appropriate.

Reply: We agree and change the wording.

L214: the faster::: faster": I do not understand. What is the message?

Reply: We know from the paper by Klügel (2003) that rapid air pressure changes can cause quasi-adiabatic temperature changes, which then cause tilt changes. We do not have temperature data in the tunnel accurate enough to reveal such small temperature changes. However, we have some hints that rapid air pressure variations are indeed associated with temperature changes even if we are not able to quantify. An air pressure pattern quickly passing the station will be seen as high frequency signature in the pressure time series; the faster the passing velocity the higher the frequency will appear.

L219: why do we observe differences between the SG and tilt barometers? Different transfer functions? Also, why not directly comparing the barometers rather than working on the admittances?

Reply: Yes, transfer functions differ. The LTS transfer function (tilt sensors as well as air pressure sensor) is not available so far. Determination would require interruption of the time series which is not convenient. In addition, now we know that the frequency transfer function is likely influenced by maintenance/transport which would require repeated in-situ determinations of the transfer function. Based on the atmospheric admittance investigations of the SG performed so far, we can assume the SG pressure sensor to be stable. That is why we take the SG pressure sensor as reference.

L221: no idea about the steady change?

Reply: Unfortunately not.

Section 5: could please better explain the Newtonian effect on tilts? Is it just due to a mass attracting more a side of the tiltmeter than the other side? It would be nice, perhaps in the introduction, to explain the different causes of tilts: Newtonian, loading (causing the crust to tilt), and infiltration in fissure and changes in pore pressure, and so on.

Reply: This is a very helpful suggestion. Newtonian tilt is the pure gravitational effect caused by any mass redistribution which changes the plumb line direction at the sensor location in case of a non-deformable planet. Loading (internal or external) effect on tilt is the tilt caused by deformation which changes the orientation of the surface the tilt sensor is mounted on. We will re-arrange the introduction considering the reviewer's suggestion.

L261: the weak air pressure admittance:::I do not understand your point. And, why is this admittance weaker than NS?

Reply: The tidal analysis shows that the air pressure admittance of the sensors sensitive to the E-W direction (along tunnel axis) is much smaller than for N-S. That means, surface load (either due to air pressure or rain/snow) does rarely produce clear signatures in the E-W tilts. We suppose this is due to the fact that the cavity effect is much smaller for E-W tilt than for N-S tilt. We will add explaining statements.

L265: looking at Figure 8 I see blue dots: it means rain, esp. before 12h or after 23h: could you explain, please?

Reply: Yes, this is correct. The information on the aggregate state of the precipitation particles is derived from the disdrometer data which is very sensitive to even tiny precipitation. As seen from the rain data (magenta color) no observable precipitation accumulation is observed, i.e. the liquid rain does not contribute essentially to water accumulation in the presented case study. We will make this clear in the text or figure caption.

L268-269: use UTC, avoid am and pm

L281: see also Watlet et al, WRR 2020.

L283-284: rather than charge and discharge I'd use "degree of saturation"

Reply: We will consider suggestions given in comments to L268-L284.

L285: do you mean the gravel layer above the concrete ceiling of the gallery? Unclear.

Reply: No, we refer to the gravel sheet below the concrete base plate of the observatory building in front of the tunnel. Before construction of the building, a large amount of rock has been excavated. The remaining cragged and rough rock surface has been leveled by a gravel sheet before constructing the base plate. We will clarify this.

L288: Eventually: do you mean "perhaps"? Reply: Yes.

L293-294: "in advance": looking at the figure it's not so clear Could you quantify (e.g. by computing moving correlation)?

Reply: Thanks for the hint. Indeed there is weak evidence supporting the related statements, therefore we will cancel them.

L308-310: I do not see your point: what's the relevancy of this information?#

Reply: We will make calculation and conclusion clearer.

L314: gravity effects: but, your calculation of the rainfall admittance shows that you (nearly) perfectly model the Newtonian effects on gravity; unclear sentence.

Reply: Here, we refer to the long-term residual anomalies. Model calculations considering the magnitude of the associated E-W, N-W tilt and gravity residuals show that no point source is able to explain the observed signals. We make this clear.

L323: scale»scales





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L329-335: you may quote Tenze et al., Bollettino di Geofisica Teorica ed Applicata, 2012

L330: which array?

L348-349: I do not understand: what is the link between the physics, hydrology and the cavity effect?

Figure 1: specify units on the vertical axis.

Figure 6: specify: modelled gravitational effect.

Reply to above comments: Yes, we will do and make the text clearer.

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