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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 #2 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.

This study reports on the effects of precipitation and snowmelt events on the recordings of a gravimeter and of tiltmeters that are located in an underground observatory. In both instrument types, signals related to these events can be recognized with different amplitudes and evolution in time. With this comparative analysis, the study makes a potentially valuable contribution to HESS in illustrating how geodetic monitoring meth-

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ods might be of use for unraveling hydrological processes and water storage dynamics. However, in this perspective and to make the manuscript more accessible to the hydrological community, I suggest a revision of the manuscripts in particular with respect to the following: In its present form, the manuscript does not make sufficiently clear how environmental processes such as variations in hydrological state variables (water storage) or water fluxes may translate into the observation of the monitoring devices used here, i.e., gravimeters and tiltmeters. Given that the hydrological community is hardly familiar with gravimeters, and even less with tiltmeters, large part of the interpretation of the monitoring data presented in this study remains unclear or inconclusive to the reader as the basic idea behind these instruments is not sufficiently laid out. Thus, I suggest to include in a revised version of the manuscript an introductory part that illustrates the measurement principle of gravimeter and tiltmeters and the influencing factors, and sets up general hypothesis how hydrological dynamics might be seen by these instruments, probably also highlighting in which way the instruments react differently to the same process. On these grounds, in the results and discussion chapters of the manuscript, explaining and discussing the observations at the Conrad Observatory can then be more clearly presented in particular with respect to the following issues: - "Gravity and tilt residuals are associated to the same hydrological process but have different physical causes." (Abstract,). What exactly are the physical causes that makes the difference between the instruments if the fundamental hydrological process is the same?

Reply: Thanks for this valuable suggestion. We will completely re-organize the structure of the paper and add a detailed text explaining the different sensitivity to physical processes like gravitation and deformation and what the sensors are able to detect. We also explain disturbing effects particularly for the tiltmeters (cavity effect) and why this effect is stronger for the N-S tilt component. References to published results based on using gravimeters and tiltmeters in hydro-geological studies will be provided in the introduction already. We will omit technical details or shift them to an appendix for interested readers.

- The “cavity effect” is mentioned in several instances throughout the manuscript as an influencing factor (abstract, line 177, line 229, line 262) but it is not further explained. What is it about and how can it influence the observations? How can thus the statement “Because the tunnel axis is oriented in E-W direction, the N-S component corresponds to the tilt perpendicular to the tunnel axis and therefore is extremely sensitive to cavity effects.” (line 177) be explained?

- Additional explanations to the two points before may also shed more light on “: : :because tilt is affected by the topography and by geometry and size of the cavity where the tilt meters are installed” (line 33). This sentence is not intelligible by its own for someone who is not familiar with tiltmeters.

Reply to both comments: Re-organizing our paper will give opportunity to address the problem already in the introduction and to make it clear (please refer to our reply above).

- Line 227: “However, at long periods the air pressure signal in the tilt meter time series is due to geophysical/geodynamical reasons which are probably dominated by deformation due to air pressure loading.” Also the gravimeter should be sensitive to loading effects that are associated with vertical displacements, right? Can this be jointly analyzed? More basically, even the term ‘loading’ might need to be explained for a hydrological reader.

Reply: Generally a gravimeter is sensitive to deformation effects as well: if deformation is associated with vertical displacement of the Earth’s surface, then the gravimeter moves within the gravity field of the Earth and experiences different gravity. Generally upward and downward movement decreases and increases gravity, respectively. Secondly, deformation always means mass redistribution and consequently a gravity change. However, at local spatial scale, vertical displacement generated by air pressure variation is very small and the associated gravity effect is negligible. At regional or global scale such effects have to be considered. Another effect of the displacement

is inertial acceleration if the displacement is time dependant (seismometer principle). However, this is important only for high frequencies (> 0.1 mHz). We will explain this briefly in a next version of our paper.

- “Newtonian acceleration” Newtonian effect” (line 230, line 241) on the gravimeter needs to be explained with respect to water storage (mass) variations. Also, what is the difference to the ‘Newtonian tilt effect’ (line 243) seen by tiltmeters?

Reply: “Newtonian” is another wording meaning “gravitational”. Any mass movement in the atmosphere and hydrosphere (air mass, water etc.) changes the gravitational potential and consequently the gravity field. Gravimeters are sensitive to the vertical component (or the norm) of the gravity vector while tiltmeters are sensitive to the horizontal component. We will explain this briefly in the introduction.

- Line 257: “: : : the observed total N-S tilt offsets as function of cumulative rain or the surface pressure load exerted by cumulative rain at the end of the respective rain event.” Does a spatially uniform rain event cause a tilt signal? Probably not because also the surface pressure load is uniform? Thus, a tilt signal indicates spatially nonuniform rainfall?

Reply: The gravitational effect of rain/snow water is too small to emerge out of the noise of the tiltmeters. However, like atmospheric pressure variations, also water at the surface exerts pressure onto the surface which results to deformation. Tiltmeters are sensitive to even little deformation and therefore experience a clear signal. This signal might be different if the load is uniform or non-uniform, but this cannot be addressed without further investigation and is out of the scope of our paper.

- Line 262: “The short-term N-S tilt response is therefore interpretable as pure deformation effect (strain induced tilt) due to surface load, which is probably enhanced by the cavity effect.” What does strain-induced tilt mean? How does this relate to the “cavity effect”?

Reply: The cavity effect belongs to strain-induced tilt. You are right, our formulation is confusing, and we will correct this.

- Line 274: “Therefore, deformation due to surface loading rather than due to pore pressure changes explains the observed short-term tilt signal.” This statement is not clear a another effect is introduced that has not been explained before: how and why due pore pressure changes cause tilt signals? How do pore pressure changes relate to water storage changes that occur during a rainfall event?

Reply: Water percolation into the subsurface or injection of water in boreholes is able to change the pore pressure which causes deformation. We will address this in the introduction.

- Line 298: “: : : a clear systematic tendency of the source azimuth (340_ to 350_) is indicated.“ What does this mean? Needs some general introduction or explanation.

Reply: Comparing the E-W and N-S tilt data, the amplitude ratio of the long-term residual anomalies turns out to be about -0.15 on average; E-W tilt is always positive, N-S tilt is always negative. If the observed tilt is caused by gravitational attraction by a volume of stored water, then the source must be located on a line with azimuth of about 170 (the azimuth of 340 to 350° mentioned in the submitted MS was a misprint). We will clarify this.

- Line 347: “It is not the physical source, but the hydrological process, which links the residual anomalies of gravity and tilt.” This statement is not clear. Is a hydrological process different from a physical source? What does this imply?

Reply: The hydrological process is water accumulation (short-term residual anomalies) or infiltration (long-term anomalies). The physical reason for the reaction of gravimeters is different from that of tiltmeters. Gravity residuals predominantly reflect the gravitational effect of water mass accumulation close to the surface (short-term) or water transport downwards (long-term). In contrast, the tiltmeters reflect the tilt due to de-

formation by the water load on topography (short-term) or due to deformation by water percolated into the subsurface (long-term). We think all this gets clearer after having changed the introduction and the discussion accordingly.

Other comments: - Data section 2: I assume that there are no soil moisture or groundwater level data available at the observatory site or close to it? Is there a nearby river gauging station (or a smaller creek gauge) of which the discharge data could be used for comparing to the overall hydrological response of the study area?

Reply: You are right. Unfortunately we do not have any hydrological instrumentation. There is river at the foot of Trafelberg mountain, however it would be unclear what amount of water in the creek stems from the Trafelberg massif or from other catchment areas.

- The manuscript ends rather abruptly. I suggest adding a concluding paragraph on what has been learned from this combined setup of gravimeters and tiltmeters towards their potential for unraveling water storage dynamics and hydrological processes, what are the limitations, what are additional observations that may be needed to disentangle ambiguities in these observations, or similar aspects.

Reply: We will add a short paragraph on these aspects at the end.

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