

## **Detailed Response on all comments on revised manuscript HESS-2021-78**

Dear Bettina Schaepli, Dear Anonymous Referees,

We would like to thank you for your positive comments on our revised manuscript and the time invested to further improve this.

Please find our responses in green.

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**Editor Decision: Publish subject to minor revisions (review by editor)** (09 Aug 2021) by [Bettina Schaepli](#)

Comments to the Author:

The paper has been re-reviewed by the reviewers of the original paper. Both welcome the change of the manuscript type and the modifications of the manuscript. They both provide some additional comments to further improve the paper, which should be addressed before publication.

**Authors:** We highly appreciate the constructive review process and the idea of submitting our manuscript as technical note. In the following, we will reply to the comments of the two referees point-by-point and modify the manuscript accordingly.

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### **Comment on revised hess-2021-78**

#### **Anonymous Referee #1**

Referee comment on the revised version of "Introduction of a Superconducting Gravimeter as Novel Hydrological Sensor for the Alpine Research Catchment Zugspitze" by Christian Voigt et al., Hydrol. Earth Syst. Sci. Discuss., <https://doi.org/10.5194/hess-2021-78-RC1>, 2021

I thank the authors for improving the paper and measuring a new absolute gravity value. This manuscript is now worth publishing as a "technical note", after minor (but important) revisions.

I strongly encourage authors to rework the style. Many sentences are too long, there is too much use of the passive voice (e.g., "Due to a special geological karst situation, the entire catchment is solely drained by the Partnach spring"==> "The Partnach spring drains the whole karst catchment"). This is especially true in the abstract. Be sure to remove unnecessary words such as subjective adverbs or adjectives (e.g., "large"), or the use of the verb "can", which lengthens sentences and weakens your reasoning (e.g., " and can therefore be regarded as a natural lysimeter"==>" and therefore acts as a natural lysimeter").

**Authors:** Several sentences/paragraphes were rephrased accordingly. See below in our detailed responses and throughout our re-revised manuscript.

#### **Comments from Referee Report: hess-2021-78-referee-report.pdf**

LL. 16-18: Long sentence: rewrite and avoid passive tense.

LL. 18-20: Same remark. Moreover, a site cannot be "dominated by something".

**Authors:** These two sentences were modified: "GFZ has set up the Zugspitze Geodynamic Observatory Germany with a worldwide unique installation of a superconducting

gravimeter at the summit of Mount Zugspitze on top of the Partnach spring catchment. This high-alpine catchment is well-instrumented, acts as natural lysimeter and has significant importance for water supply to its forelands with a large mean annual precipitation of 2080 mm and a long seasonal snow cover period of 9 months, while it shows a high sensitivity to climate change."

L. 21, L. 22: crossed out text

Authors: Agreed, done.

L. 29: what does that mean?

Authors: Obviously misleading expression. We modified the sentence to "The snowpack is identified as primary contributor to seasonal water storage variations and thus to the gravity residuals with a signal range of up to 750 nm/s<sup>2</sup> corresponding to 1957 mm snow water equivalent measured with a snow scale at an altitude of 2420 m at the end of May 2019."

LL. 30-31, L. 33: crossed out text

Authors: Agreed, done.

L. 33: delivers

Authors: Agreed, done.

LL. 34-35: crossed out text (see also initial submission)

Authors: Agreed, done. We have already commented on deleting the last sentence of the manuscript within the first revision ("This is an important sentence to prepare and guide the audience and this is why this should not be removed in our opinion. By the way, concept studies are common practice in hydrological journals."). But we will now follow the referee's opinion to delete it.

L. 37: not only: pollution and growing population are other challenges, and not the least ones...

Authors: This is why we write "One of the grand societal challenges...". No changes.

LL. 40-42: Too long. You could just mention that "even in currently water secure regions, we need to to develop a comprehensive understanding..."

Authors: We have already commented on this within the first revision ("We don't understand why we shouldn't provide such a societal motivation for our research."). We still believe that this is an appropriate first paragraph of our introduction. No changes.

L. 54: I do not understand this: what about Hammersbach, and water flowing towards Austria or Eibsee (north)?

Authors: Partnach spring catchment and Hammersbach catchment are delimited by the summit area, while ZUGOG is located on the side of the Partnach spring catchment (south), see also Fig. 1. No changes.

Fig. 1: The names in white are barely legible.

Authos: Glacier names in Figure 1 were enlarged. The colour of the alpine catchments and most of the labelling were turned from black to white for improved legibility.

L. 97: used

Authors: Agreed, done.

L. 98 crossed out text

Authors: Agreed, done.

L. 109: estimated

Authors: Agreed, done.

L. 110-113: Scandroglio et al. is just an EGU conference abstract, mentioning "A first attempt to reveal hydrostatic ..." The way you present this study is not fair: we may infer that it allowed new discoveries...it seems it is not the case, just an attempt.

Authors: Agreed. We rephrased the sentence: "Monthly RG observations have been done with a transportable spring gravimeter since 2014 by the Technical University of Munich (TUM) attempting to analyse periodic permafrost changes and detect cavities in a tunnel (Kammstollen) of Mount Zugspitze (Scandroglio et al., 2019)."

L. 117: In this study, we discuss to...

Authors: Agreed, done.

L. 126: was

Authors: Agreed, done.

L. 128, L. 131: crossed out text

Authors: Agreed, done.

L. 145: GNSS?

Authors: We think that it is a pure GPS antenna (for provision of the time stamps only). No changes.

L. 147: was

Authors: Agreed, done.

L. 154: participates to

Authors: Agreed, done.

L. 205: crossed out text

Authors: Agreed, done.

L. 205: due to an

Authors: Agreed, done.

L. 222: represents a conservative estimate of the...

Authors: Agreed, done.

L. 239: I do not understand why you include the fortnightly waves in your analyze. Why don't you use theoretical values? Fitting these long-period waves looks dangerous given the strong hydrological signals, which could partly be captured by the ETERNA process.

Authors: It is right that the large hydrological variations can influence the analysis of longer tidal waves (especially annual periods). However, the estimated results especially for the near-fortnightly wave Mf look are close to theory and thus we prefer to use these observed parameters instead of the model. By the way, the annual tidal waves do not and thus we use the ones from the model (not shown here). No changes.

L. 248: No specific effect due to the air masses below the SG?

Authors: The admittance factor of  $-3.65 \text{ nm/s}^2/\text{hPa}$  includes the maximum correlated signal between observed gravity and barometric pressure. This reduces to  $-2.92 \text{ nm/s}^2$  for the admittance between gravity residuals and local atmospheric mass redistributions probably due to atmospheric mass variations below the SG (see section 3.3). No changes.

L. 248: are those 2 last numbers really relevant?

Authors: Agreed, changed.

L. 318: crossed out text

Authors: Agreed, done.

LL. 336-338: poorly written and long sentence. Just mention that the gravity measurements are integrative.

Authors: The sentence was rephrased: "While the large complexity and variability of the hydrological parameters make the hydrological modelling very difficult, continuous gravity observations are integrative and thus should thus be highly beneficial serving as constraints for the hydrological modelling on catchment scale."

L. 340: amounts

Authors: Agreed, done.

L. 343: agreeing

Authors: Agreed, done.

L. 345-347: Crossed out text

Authors: We don't agree but think that this is a useful and exciting (while not subjective) perspective. No changes.

L. 349: crossed out text

Authors: Agreed, done.

L. 349-355: you tell a very simple story in a quite complicated way

Authors: to be rephrased

L. 366: crossed out text

Authors: Agreed, done.

LL: 369-370: I do not understand this:

Authors: We rephrased the sentence: "However, in 2020 there was no distinctive SWE peak rather a longer period with SWE values near maximum between these two dates."

L. 370: crossed out text

Authors: Agreed, done.

L. 374: Besides

Authors: Agreed, done.

L. 375: crossed out text

Authors: Agreed, done.

L. 378: how do you know this?

Authors: Simply by building the difference between gravity residuals and  $0.298 \cdot \text{SWE}$  and compare with precipitation events. We added: "Besides the high correlation between gravity and SWE from the LWD station at Zugspitzplatt, there are still significant additional signals remaining with a range of  $250 \text{ nm/s}^2$  in the differences between gravity residuals and  $0.298 \text{ nm/s}^2/\text{mm} \times \text{SWE}$ ."

L. 378: where do I see it on the figure? Elaborate, add e.g. arrows on the picture.

Authors: We added specific time periods for massive snowfalls ("e.g. from 29 Dec 2018 to mid-Jan 2019") and for rain events ("e.g. from 3 to 4 Aug 2020").

L. 380-383: long and (hence) very unclear sentence

Authors: We split and rephrased this sentence: "Second, signals from other water storage components are not considered within the regression analysis. Major remaining signals of up to  $200 \text{ nm/s}^2$  occur during the main melting periods and corresponding spring discharge from May to July (Figure 6). Moreover, rain events during the short summer season cause rapid gravity increases of up to  $100 \text{ nm/s}^2$ , e.g. from 3 to 4 Aug 2020, followed by an equally fast but only partial decrease and a slower subsequent decline due to the lagged drainage back to the gravity level before the specific rain event (Timmen et al., 2021)."

L. 385: crossed out text

Authors: Agreed, done.

L. 402: deviation from what?

Authors: We added: "deviations of 2 % and 6 % between assumption and observation."

LL: 404-405: I do not understand

Authors: Figures 5b and d shows the contributions of areas up to 99.8% and 99.9% of the total signal. The areas providing the remaining  $1 \text{ nm/s}^2$  in gravity are not shown (white). We modified and added a sentence: "Areas contributing together a remaining gravity signal of  $1 \text{ nm/s}^2$  are omitted (Table 3)."

L. 423: What about the possibilities to use remote-sensing systems (or GNSS (see Kristine Larson's work?)) to evaluate the snow thickness? You should write something about.

Authors: This is discussed in the summary and conclusions. We added to the sentence: "Still, the local snowpack distribution in the direct vicinity of the SG needs special attention due to artificial snow accumulations around the summit which are monitored by a snow scale and snow height sensors (Figure 2c)."

LL. 471-473: What is your point? What do we learn from the gravimeter?

Authors: We added at the end of the sentence: "... and allow for comparison with the water balance and karst water discharge studies at the Partnach spring."

L. 495: influence

Authors: Agreed, done.

LL. 496-497: I've quite often been disappointed by studies aiming at using spring gravimeters to look for time-varying gravity changes (hydro or volcanoes), and personally gave up with this: poor time resolution, high noise level (10  $\mu$ Gal uncertainty in the best cases...). What would be expected here? Worth elaborating.

Authors: At this point of the manuscript we don't want to specify our future work. This is done in the last chapter. Instead we deleted the last sentence and added corresponding sentences to the Summary and Conclusions.

L. 508: and...what have we learned from it here? I mean, on the gravitational point of view?

Authors: We refer to the later sentence of the last paragraph: "The overall research question to be addressed in the future is to what extent the hydro-gravimetric approach contributes to a better understanding and quantification of hydrological processes and storages in this high-alpine catchment with the insights to be transferred to other alpine locations worldwide."

L. 526: crossed out text

Authors: Agreed, done.

L. 530: do you monitor this (e.g., using thermometers at different depths?)

Authors: We modified the sentences: "Glaciologists of the Bavarian Academy of Sciences and Humanities map the glacier areas and volumes since the 1960s (Timmen et al., 2021, Mayer et al., 2021, Hagg et al., 2012). Since 2007, the Bavarian Environmental Agency permanently monitors the permafrost degradation within Mount Zugspitze in a borehole equipped with temperature sensors (Gallemann et al., 2017 and 2021)." Along with adding to the reference list:

Gallemann, T., Haas, U., Teipel, U., von Poschinger, A., Wagner, B., Mahr, M., and Bäse, F.: Permafrost-Messstation am Zugspitzgipfel: Ergebnisse und Modellberechnungen, UmweltSpezial, Geologica Bavaria 115, Bayerisches Landesamt für Umwelt (LfU), Augsburg, Germany, 2017.

Gallemann, T., Wagner, B., Foltyn, M., Mahr, M., and Jerz, H.: Permafrost und Böden im Bereich der Zugspitze, UmweltSpezial, Geologica Bavaria 120, Bayerisches Landesamt für Umwelt (LfU), Augsburg, Germany, 2021.

Mayer, C., Hagg, W., Weber, M., and Lambrecht, A.: Zukunft ohne Eis, Zweiter Bayerischer Gletscherbericht: Klimawandel in den Alpen, Bayerische Akademie der Wissenschaften (BAW), München, Germany, 2021.

L. 543: improve

Authors: Agreed, done.

L. 549: At which level? Which sampling rate?

Authors: We added: "...at least 4 times per year with a target uncertainty of 10 nm/s<sup>2</sup> (1 $\sigma$ )..."

L. 554-555: I do not agree. Today, a major challenge is to fill the gap between local-scale measurements with terrestrial instruments, at say, the 1 km<sup>2</sup> scale, and the regional-scale of GRACE. I've no answer to this. Maybe, by comparing this experiment with other ones in similar Alpine environments?

Authors: The sentence was rephrased: "Finally, an improved knowledge of hydrological variations model parameters on catchment scales and possible similar installations in high-alpine catchments enhances the resolution of large-scale hydrological variations and reduces the spatial and temporal gap to the satellite mission GRACE-FO (Gravity Recovery and Climate Experiment – Follow On), launched in May 2018, which provides gravity variations with a spatial resolution of 300 x 300 km<sup>2</sup> and a temporal resolution of 1 month."

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**Comment on revised hess-2021-78  
Anonymous Referee #2**

Referee comment on the revised version of "Introduction of a Superconducting Gravimeter as Novel Hydrological Sensor for the Alpine Research Catchment Zugspitze" by Christian Voigt et al., Hydrol. Earth Syst. Sci. Discuss., <https://doi.org/10.5194/hess-2021-78-RC2>, 2021

This manuscript presents a description of the superconducting gravimeter installation at Zugspitze and some preliminary data. The authors have responded thoroughly and adequately to the many review comments. I agree with the decision to publish as a Technical Note. The major shortcoming of the paper is the lack of overlapping spring discharge and gravity signal, but I don't think that should prevent publication at the present time.

I find the discussion of instrumental problems to be useful, as we all know these installations each have unique problems, but it also has the effect of scaring away those not already familiar with superconducting gravimeters. I might caution that many of the issues present with older OSGs may not be present in the newer iGravs.

Authors: We agree with this opinion and hope that all our iGravs will perform stable in the long term.

**Minor comments follow.**

It may be worth mentioning the significant primary limitation of superconducting gravimeters, the requirement for AC (mains) power.

Authors: We added one sentence: "AC (mains) power is available throughout the lab."

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L27: Should "gravimetric methods" be "gravity residuals"? I think you can delete this sentence altogether.

Authors: We wouldn't like to delete this sentence. In our opinion, it is necessary to guide the reader what can be expected from the gravimetric part of this manuscript. We modified: "Besides the experimental setup and the available datasets, the gravimetric methods and gravity residuals based on the first 27 months of observations are presented."

L33: What are "integral insights"?

Authors: "This shows that the hydro-gravimetric approach delivers representative integral insights into the water balance of this high-alpine site."

L52: change "regarding" to "during"

Authors: Agreed, done.

L54: Does "special geological karst situation" mean that there is an impermeable layer below the karst that forces groundwater discharge at the spring? That would be worth mentioning. If there is significant subflow not discharging at the spring.

Authors: We specified and rephrased: "The Partnach spring drains the entire RCZ due to a synclinal geological structure with impermeable claystones underlying the highly karstified Wetterstein limestone,..."

Fig. 1 caption: It looks like the alpine catchments are delineated by black lines, not white?

Authors: We changed the colours from black to white for improved legibility.

L150: delete "after abnormal drift was observed"

Authors: Agreed, done.

L154: What does "nominal" mean here?

Authors: The SG operates as it is supposed to. No changes.

L156: I see the absolute-gravity measurements are in the AGrav database, is that worth mentioning?

Authors: Thank you. We added one sentence: "Absolute gravity values from FG5X-220 measurements by LUH at ZUGOG can be found in the Absolute Gravity Database (AGrav) hosted by International Gravimetric Bureau (BGI) and the German Federal Agency for Cartography and Geodesy (BKG) (Wilmes et al., 2009)."

Along with this, we added to the reference list: "Wilmes, H., Wziontek, H., Falk, R., and Bonvalot, S.: AGrav—The New International Absolute Gravity Database of BGI and BKG and its benefit for the Global Geodynamics Project (GGP), *J. Geodyn.*, 48, 305-309, doi:10.1016/j.jog.2009.09.035, 2009."

L188: Throughout the manuscript, "has been" can be replaced by "was"

Authors: Changed throughout the whole manuscript when things happened in the past (e.g. setup of instruments) but not changed when action is still ongoing.

L200: What does "on the full signal" mean? Can it be deleted?

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Authors: We meant the full gravity signal". The sentence is not really necessary and was deleted.

L219: I don't understand "50 % overlap"?

Authors: We modified the sentence: "The best fitting solution (smallest standard deviation for the amplitude factor) is found for blocks of 3 days, polynomials of degree 3 and 50 % overlap of the blocks."

L230: should be "estimated to be"

Authors: Agreed, done.

L230: The very low drift is a nice result. At that level of drift probably uncertainty in the scale factor also limits the ability to estimate drift.

Authors: We modified the sentence: "Additional absolute gravity measurements including amplitude calibrations will stabilize improve the SG drift estimation..."

L240: Although I realize this section and Table 2 were added in response to reviewer comments, I find the tide analysis to be unimportant for a hydrologic audience.

Authors: We can follow this argumentation. Nevertheless, the manuscript is not only for hydrologists but e.g. also for other gravimetry groups active in this area. And for them, this information is really important. No changes.

L256: The barometric admittance factor doesn't come from tidal analysis, does it?

Authors: The sentence was modified: "The signal admittance factor of  $-3.6506 \text{ nm/s}^2/\text{hPa}$  estimated together with the from the tidal analysis of  $-3.6506 \text{ nm/s}^2/\text{hPa}$  includes..."

L320: "significant" and "only a fraction" contradict each other. Seems like a fairly small effect given the amount of snow.

Authors: Not necessarily. The gravity effect is  $25 \text{ nm/s}^2$  and thus significant with regard to the uncertainty of  $1 \text{ nm/s}^2$ . However, the total range of the gravity residuals is  $750 \text{ nm/s}^2$ , this is only a fraction of 1:30 and thus not the major issue at this stage. No changes.

Fig. 3: Panels a and b could be deleted to save space if needed.

Authors: The original observations and tidal effects are of interest with regard to the ratio of original gravity signal to gravity residuals for hydrology. No changes.

L338: constraints

Authors: Thank you. Done.

L376: On line 357 you state the SWE measurements are representative.

Authors: Representative observations of the snow water equivalent (SWE) **for the Zugspitzplatt are not fully representative at catchment scale.** No changes.

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Fig. 5: This figure is much improved and responds to my comments in the original manuscript.

Authors: Thank you for your recommendation. Highly appreciated.

L399: SWE, not snowpack

Authors: Agreed, done.

L402: Regarding the 393 nm/s<sup>2</sup> observed gravity signal: because the gravity residual doesn't go to zero in fall 2019 (presumably because of groundwater/soil water storage), the observed SWE gravity change would be about 30 nm/s<sup>2</sup> less (i.e., the wintertime maximum minus the fall (snow-free) minimum)

Authors: That's right. The gravity minimum in fall 2019 is 24 nm/s<sup>2</sup>, while the overall gravity minimum in fall 2020 was set to zero. This should reflect the long-term trend due to glacier mass loss and mountain uplift (Timmen et al., 2021). But at this point in the manuscript, it is not clear how the gravity signals are composed and if you look at the period from spring 2020 to fall 2020, then there is the gravity range of 393 nm/s<sup>2</sup>. Finally, we wanted to show if the observed gravity signals (whether it's 393 or 369 nm/s<sup>2</sup>) can easily be explained by a simple assumption of the snowpack distribution. And this was successful. No changes.

L456: If the spring is at 1430 m, what is significant about the 1440 m elevation? Interesting to note during this early snowmelt period that most of the water isn't leaving the catchment, but is leaving the gravimeter's region of sensitivity.

Authors: 1440 m altitude was a mistake. It is also 1430 m. Thus, when snow melts, water immediately runs out of the spring. There is **no** 10 m storage. We deleted: "...down to an altitude of 1440 m..."

L470: Suggest "water storage changes" instead of "water level changes". If it is purely karstic and storage changes are happening in large voids, it may not make sense to discuss groundwater-level changes and aquifer porosity (i.e., it's not the matrix porosity that's significant but rather the secondary karst porosity)

Authors: Agreed, done.

L474: suggest groundwater storage, not groundwater height.

Authors: Agreed, done.

L519: In addition to more sophisticated modeling, which is useful, I think it would also be useful to look at the nonlinear nature of the SWE admittance factor – does it change with depth of snowpack? Presumably as SWE increases, the gravitational effect of additional snow likely increases as there is less runoff/ET.

Authors: Thank you for the tip. We added two sentences: "Gravity residuals from the OSG 052 and the SWE measured with a snow scale at an altitude of 2420 m are highly correlated (0.963) and reveal a regression factor of 0.298 nm/s<sup>2</sup>/mm ( $1\sigma = 0.003$  nm/s<sup>2</sup>/mm)." and in the next paragraph: "Based on this concept study, it is certainly useful to study also the non-linearity of the relationship between gravity residuals and SWE – is there a significant dependence on snow height? Moreover, the description of the snowpack distribution will be refined..."

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Christian Voigt on behalf of the team of authors (16 Aug 2021)