Dear colleague,

Thank you for this comment. We found this discussion very interesting and fruitful for us.

You find my responses below.

Sincerely yours,

Anatoly Legchenko

Comments on "Monitoring water accumulation in a glacier using magnetic resonance imaging", by Legchenko et al.

I think this could be a nice and informative paper that demonstrates the applicability of a promising geophysical technique in glaciology. I agree with the authors that it's among the first places that I have seen glaciological 3D-NMR imaging – but glaciological NMR papers do exist (e.g., http://geoinfo.amu.edu.pl/sgp/LA/LA21/LA21_057-074.pdf),

Yes use of SNMR in ice is not new, but "geoinfo.amu.edu.pl" report is on 1-D SNMR and not about caverns in ice, it is 3-D neither. More pertinent is this paper cited in the article (2-D survey):

Lehmann-Horn, A., Walbrecker, J. O., Hertrich, M., Langston, G., McClymont, A. F., and Green, 5 A. G.: Imaging groundwater beneath a rugged proglacial moraine, Geophysics, 76, B165–B172, 2011.

and this group did publish a multidisciplinary study of this site, which included some of the SNMR results presented here, together with its theory in an appendix (Vincent et al., 2012, Journal of Glaciology, v58, 211, doi: 10.3189/2012JoG11J179). This leads me to question the value that this paper adds, but I will return to this issue later in the review.

"Vincent et al., 2012 et all" is our team working in the same Tête Rousse glacier. This paper reports only detection of the cavern with 3-D SNMR and different aspects of management of the glacier related hazard.

Paper under reviewing report the following new values:

1) demonstration of the monitoring of the glacier using 3-D SNMR;

2) verification of SNMR estimates of the volume of accumulated water by pumping water out the cavern;

3) estimating the recharge rate;

4) evolution of the cavern size after each drainage-refilling cycle.

General Comments

While I am not an expert in SNMR techniques, and there are admittedly few glaciological precedents to compare this work with, I would appreciate more information about constraints on the interpretation that has been made. While there is some discussion of the limitations and resolution of the SNMR technique, these do not seem to be acknowledged in later discussions about cavity size and water content, which leads me to the following concerns. These should at least be acknowledged, and preferably explained and quantified, in a resubmission of the paper.

Details of 3-D SNMR interpretation have been reported in:

Legchenko, A., Descloitres, M., Vincent, C., Guyard, H., Garambois, S., Chalikakis, K., and Ezerski, M.: Three-dimensional magnetic resonance imaging for groundwater, New J. Phys., 13, 025022, doi:10.1088/1367-2630/13/2/025022, 2011.

This reference was done in the article. We think that the repetition of technical details might render reading less fluent. Indeed, this paper is not about 3-D SNMR technical details, but about experimental verification of the method described in another paper and about glacier reaction on the drainage-refilling cycles.

We continue to think that in the paper under reviewing details on the inversion should not be added.

a) On Page 2124, the authors state that “SNMR cannot resolve small targets, and provides only results averaged over a volume larger than the target-volume.” However, the cavern does not appear small with respect to the survey loops (see Figure 2) therefore what is the real influence of the cavern size?

SVD analysis confirmed by spike tests and by numerical modeling shows that 3-D SNMR is able to resolve targets of about 40x40x10 m^3. So, smaller cavern will have a size comparable with the resolution limit, but water content will be smaller. It is because SNMR is sensitive to the volume of water even when geometry is not well resolved.

Sonar measurements showed that indeed the cavern is smaller than shown on SNMR image, but is filled with bulk water (w=100%). But sonar is not able to see all the volumes and for example, sonar-derived volume was about 25,000m^3 instead of 48,000 m^3 pumped in 2010 when the cavern was the largest (55,000 with SNMR) and in the following years when the cavern become smaller sonar have seen only 3000 instead of 17000 m^3 pumped out.

At what dimension does this condition become a concern?

There is also discussion of quantifying uncertainties and sensitivities (Page 2125); these concepts are then not developed in the paper.

These subjects have been treated using numerical modeling and reported in Legchenko et al, 2011

b) I appreciate that the water content from the SNMR is a volume-averaged quantity, but at what fractional water content is the ‘edge’ of the cavern defined? There is some use of the term “3D-SNMR estimates of the water volume” but elsewhere, the reader is led to believe that the geometry imaged in the SNMR survey is the geometry of the cavern. It must be explicitly stated that (e.g.), the SNMR-implied volume is the maximum possible extent of the real cavern. Indeed, SNMR over-estimated the water content by 3100m3 (Page 2127, also Figure 4); how much of this is an artefact of the resolution of the technique, vs. the glaciological processes (e.g., hydraulically connected channels, interstitial water) that are quoted?

In fact, SNMR estimates volume of water and not the size of the cavern. Reviewer is right, water in surrounding channels is not the cavern but contributed to the total volume.

This subject will be précised in the revised version of the paper.

c) The follow-on from this is: if the quantity measured is a volume average, then there must be some amount of lateral smearing taking place and the true cavern must be smaller than the size that is implied in the data. How much smaller is it? The error +/- 20 m is stipulated (Page 2126), but I don't see how the size of the cavern could be larger than the non-zero cell volume implied by the SNMR. Equally, the water content implied is given error bounds of +/- 20%... Is this total water content, or the water content for any one cell? If it's the latter, what does this imply when the water content of a cell is 5%, as was the maximum measured in 2012 (Figure 11)?

It has been shown in (Legchenko et al, 2011) that 3-D SNMR inversion has not sufficient resolution for reliably estimating water volume. The reason is that the sensitivity inside the loop is different, but inversion cannot locate water precisely. For estimating water volume we use the forward modeling carried out so that: 1) experimental data are fitted within experimental error (noise); 2) we select the min number of blocks necessary for that; 3) placing blocks with water at the positions with min and max sensitivity of the loop we obtain the min and max estimated volumes.

d) Can you also be sure that the cavern is entirely water-filled during the SNMR survey?

Yes, because of water level measurements in boreholes. The water level was close to the glacier surface.

e) You also mention that the temperate glacier may contain 2% water content, so how do you resolve this background from the cavern wall? Essentially, what water content marks the transition from wet ice into an open cavern? – many of the cells in the 2012 dataset, for example, could be interpreted as just showing interstitial water.

1) We have measurements around the glacier outside the cavern affected area and we estimated small amount of water in ice. 2) Water volume in the cavern is much larger than in ice and we cannot resolve this water; 3) We include water in ice in the general uncertainty.

I know that sonar and radar measurements exist for Tête Rousse, and I find it surprising that these have not been incorporated into this work (e.g., as this group did in their Journal of Glaciology paper). It seems that it would be possible to reduce uncertainties in the volume averaging if certain constraints (e.g., the depth to the cavern roof from GPR/sonar? The cavern thickness from sonar?) were applied.

Yes, if the geometry was be constrained SNMR results would be more accurate. The problem is that neither sonar ni GPR did not allow to see the entire cavern. Sonar has seen only the main "tower" and GPR the celling of the cavern. We preferred to report results obtained with only SNMR.

However, we observed a very good complementarity of GPR and SNMR and we prepare an article on this subject. To add these results to the paper under reviewing would make it too big.

This brings me on to my over-riding concern with the paper. All this said, the data do convince me that SNMR detects an evolving cavern within Tête Rousse glacier and I think that this is a neat timelapse experiment; furthermore, it is glaciological significant as an extension to 2012 of the work published in Vincent et al. (2012). My major concern is, though, without evidence from those other data sources, could these results have been interpreted from SNMR alone, with all of its apparent ambiguities?

If not, to say that results in this paper are derived from SNMR without acknowledging the other data sources, is somewhat misleading.

There is no significant acknowledgment that much of the foundation work in this research was established in the Vincent et al. (2012) publication, and a reader may be led to believe that these observations were derived from SNMR alone. This is not by any means to suggest that SNMR is a flawed technique, but that it suffers from uncertainties and limitations just like any other geophysical method. Therefore, the best way to use it is in conjunction with other techniques – and the paper should acknowledge this too.

All the results have been obtained from SNMR data only. All the SNMR interpretations have been made before drilling and pumping. GPR and sonar data were not used. The drilling program and decision making process were strongly based on SNMR results.

Furthermore, when the cavern became smaller only SNMR was able to produce reliable information on the cavern dynamics. Pumping results were used only for comparison with SNMR estimates and SNMR results were not modified after pumping. In fact it was even impossible because 2M€ pumping operation was formally based on SNMR results and if were modify something after pumping it would not be seen well by the authorities.

Specific Comments

Page 2128, Line 4: How did you estimate the temperate ice water volume as 2%?

We performed SNMR measurements out the cavern affected area and we estimated that it is impossible to have more than 2% (averaged over the loop size).

Page 2129, Line 12: You say that the larger cavern is associated with better correlation given a complex geometry thereafter; is it not possible that the water in the larger cavern represents a greater proportion of a volume average, and can therefore be measured more accurately?

Yes, it is also the point. We will add this comment in the revised version.

But more complex cavern geometry also means that the cavern may be composed of different hydraulically separated volumes. Consequently, SNMR and pumping "see" not the same volumes.

Page 2131, Line 11: "SNMR is cost-effective and reliable", but in comparison to what? Do you expect that you could have placed initial constraints on (e.g.) temperate ice water content without other techniques? I think it would be better to suggest that SNMR is highly complementary to established glaciological techniques; clearly the best results will come where multiple methods are combined (i.e., in Vincent et al., 2012).

Yes, of course, more information will always render results more reliable, but also more expensive and time consuming. We compared SNMR with pumping. Other methods did not produce any estimate of the volume of accumulated water. For the sonar (50% error in the volume estimate in 2010, and misleading results in 2011) borehole was also necessary.

Temperate ice water content was estimated with SNMR and literature data. GPR was useful for fast entire scanning of the glacier and for bedrock location (out of the cavern occupied area).

Thus, for the entire study of the glacier the use of different methods is necessary, but for the water volume monitoring SNMR was sufficient.

We will make corrections on this point.

Page 2132, Line 2: Define 'large'. Is it not possible that water could flow between the two reservoirs through a conduit that is not resolvable with SNMR (i.e., 'small')?

OK, will be precised

Page 2132, Line 22: "Despite of" should just be "Despite".

OK

Page 2133, First paragraph: This reads like a new concept in this paper, and is therefore not suited to conclusions. Better-placed in the discussion.

OK, will be replaced

Page 2133, Line 10: Unless I'm mistaken, there were only two storage areas observed in the 2012 acquisition (Figure 11). Given that you have three SNMR snapshots, it would seem that having one cavern is the 'norm', and imaging two is an anomaly.

I am not sure that I understand this question. The principal difference between three images is that before 2012 we had not measurements in the eastern edge of the glacier and hence we did not see the upper cavern. But of course we observe that the cavern is shrinking.

We will try to precise this point.

Page 2133, Line 14: You did not explicitly invoke creep closure as 'the' method of reducing the cavity volume in the discussion, and nor was the viability of this thoroughly discussed. My gut feeling is that it seems like a large volume to close up, but I'm not a modeller… nonetheless, it seems like some basic quantification of this would be required to back up the SNMR observations.

In fact, we do not know exactly the mechanisms of the ice deformation in this glacier. We just mentioned some generally existing mechanisms. We did not model yet this phenomenon and we do not know what the modeling will provide.

In this paper we report just the observations that can be used for modeling. I do not think that to extend the paper towards this subject would be a good idea.

We will precise this sentence.

Figure 2: Is it significant that certain areas that are marked as cavity abut against the acquisition grid? (i.e., the north and south boundaries?) Does this not suggest that there is an inherent acquisition effect in play, in the estimation of cavern volume?

SNMR "see" about half of the loop side out of the loop position. Inversion cells are located in the area 60 m away from the loop wire So, it is just coincidence. However, as it was explained before, water volume was not estimated from inversion results (only position of the cavern).

Figures 5,6, and 11: What are the grey meshes around the cavern volume? As impressive as they appear, these figures do not serve any useful comparative purpose because they are in different orientations; they do give some indication of the shape of the cavern, but not as a means of comparing its changing volume. To be useful to this end, they must be viewed from the same angle and preferably with the same colour bar. Even then, I question their value and it seems to me that a simple plan-view map and a cross-section would serve the desired purpose.

The grey meshes show the isosurface of the cavern cut at the lowest reliable water content.

The best way to present 3-D images would be rotating the image with for example Voxler software. It is obviously impossible in the paper.

We just tried to show the cavern and we did not find better way we did. When presenting cross sections or plans, comparison can be done only if many of them are available at different levels.

Anyway, inversion results cannot be used for computing water volume. Modeling results showed that inversion of synthetic data (so, the model and the volume are known exactly) provided about twice larger volume. This effect is explained in (Legchenko et al, 2011).

Well, we do not know how to improve this 3-D presentation with respect of the article figures. If it would be acceptable we prefer to keep these figures as they are. It is not difficult to make other figures; it is difficult to make good figures. Would you suggest?