

# ***Interactive comment on “The role of electrical conductivity in radarwave reflection” by Slawek M. Tulaczyk and Neil T. Foley***

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I thank RC1 for taking the time and reading our manuscript and for providing comments on it. In particular, I value the detailed feedback on other past publications, which incorporated the impact of electrical resistivity on radar wave reflection from glacier beds (e.g., Berry, 1975).

However, I am surprised, and deeply disappointed, by the conclusion of this reviewer that our manuscript is not suitable for publication in The Cryosphere. The Cryosphere, and similar journals like J. Glac., published recently a number of radioglaciology papers, which make the assumption that glacier bed reflectivity depends solely on relative permittivity, and hence water content, and make no mention of the fact that electrical

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resistivity of subglacial clays and fluids may also play a role (e.g., Jordan et al., 2018; Oswald et al., 2018; Passalacqua et al., 2017). This assumption is most often not even stated in these papers, it is just taken as factual truth that bed reflectivity is simply a function of subglacial water content, through its impact on relative permittivity. Yet, RC1 is telling us that our manuscript is not worth publishing because it is basically old news, since the influence of electrical resistivity on glacier bed reflectivity has been considered by Berry (1975).

Well, if our message about the need to consider electrical resistivity in interpretations of radar bed reflectivity is old news, it is old news that few in the radioglaciology community seem to be hearing. This problem is illustrated by the fact that the paper of Berry et al. (1975) has been cited only 43 times since 1975 (less than once per year) and seemingly dropped off the 'radar' of the community since it only got two citations since 2016 (based on Google Scholar). In contrast, the paper of Oswald and Gogineni (2008), which is based on the assumption that bed reflectivity has a one-to-one relation to bed wetness (their figure 3) and makes no mention of either electrical resistivity or conductivity of subglacial materials, has been cited 93 times in the 12 years since its publication and 42 times since 2016 (again, based on Google Scholar). It seems to me that the radioglaciology community is in a dire need of a reminder that electrical conductivity, in addition to relative permittivity, influences radar reflectivity of glacier beds.

We make no claims in our manuscript that we derive a new relationship for radar reflectivity of glacier beds. Clearly, we go back to a textbook from 1941 to show that such an expression can be easily obtained from Stratton's theory of radar wave reflection. However, what we do offer in our manuscript is an analytical expression for radar reflectivity as a function of permittivity and conductivity that is not wrapped up in complex numbers and abstract concepts such as the loss tangent. Clearly, some in the radioglaciology community (e.g., Berry, 1975 and Peters et al., 2005) have considered the impact of electrical conductivity on bed reflectivity, but the complex math associated

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with these treatments has been a barrier to a general uptake of this approach in the community. Instead, even the recent relevant publications make statements like: "... the reflection coefficient, which varies with the relative permittivities above and below the interface ..." (Oswald et al., 2018), and "The relative (real) part of the permittivity is the primary control on [R]." (Jordan et al., 2018), where [R] in the latter is the reflection coefficient. I can easily provide dozens of examples of radioglaciology papers in which their authors make zero mention of the fact that electrical conductivity/resistivity may have an impact on radar reflectivity, in addition to the relative permittivity. But I know of only a handful of papers that do consider electrical conductivity/resistivity when radar bed reflectivity is interpreted (e.g., Peters et al., 2005). So, I challenge RC1 to provide supporting evidence of her/his contention that our analysis is basically old news that is not worth publishing because the radioglaciology community already knows about it.

Our manuscript provides an approachable formulation for the radar reflectivity that does not require users to deal with complex and imaginary numbers. Anybody with an Excel spreadsheet or rudimentary coding skills can use our work to quickly get at the dependence of glacier bed reflectivity on permittivity and electrical conductivity/resistivity. Effective communication of quantitative concepts is as important as the concepts themselves. It is not a coincidence that radioglaciologists prefer to interpret bed reflectivity in terms of relative permittivity and wetness, it is simply because they are avoiding having to deal with the complex math concepts involved in the past formulations that included electrical conductivity. In this manuscript we remove this barrier to considering electrical resistivity in interpretations of radar bed reflectivity.

We also provide graphical illustration of the dependence of radar reflectivity on electrical conductivity (our figure 4). I am pretty familiar with dozens of papers in the radioglaciology literature and I do not recall that anybody before has produced a figure even similar to ours. Contrast our figure 4 with the figure 3 in Oswald and Gogineni (2008) where bed reflectivity is simply plotted as a single line expressing the assumed one-to-one relationship between bed reflectivity and relative permittivity (i.e., bed wetness). In

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our manuscript we carefully consider the criteria under which one is, or is not, justified to ignore electrical conductivity of subglacial materials (the low-loss and high-loss conditions). We also point out that many geologic materials, particularly clay-bearing rocks and sediments, have high enough electrical conductivity for their conductivity to matter in determining the radar reflection coefficient. Our manuscript points out that high conductivity subglacial materials (e.g., clays, brines, conductive minerals), can produce some of the brightest radar reflections (>90% amplitude reflection), which are brighter than the ca. 67% amplitude reflection from ice-water interface in the high-loss assumption. I have seen many examples, in literature and during conference presentations, of radioglaciologists claiming that ice on top of water bodies (e.g., subglacial lakes) should produce the strongest radar reflection. We point out that a patch of wet clay-bearing sediments can be brighter than a subglacial lake with fresh meltwater.

We also point out in our manuscript that the dependence of radar reflectivity on electrical conductivity can actually be useful in practical applications. For instance, under the common, low-loss assumption there should be no difference in radar reflection from ice overlying a freshwater lake versus a high salinity, briny lake. However, when electrical conductivity is taken into account, the radar reflectivity of the latter can be as much as 30% higher than that of the former. I have recently had a discussion with a pair of experienced Europa researchers and they were surprised to find out that a future radar mission to Europa may be able to provide constraints on the salinity of Europa's ocean, due to the sensitivity of radar reflectivity to electrical conductivity. This is because they, just as most of the terrestrial radioglaciology community, were under the assumption that only contrasts in relative permittivity matter in determining the strength of radar reflection from an ice-water interface.

Given all of the above, I find it surprising that the reviewer is recommending rejection of our manuscript. What we write about is not 'old news' that is well internalized by the radioglaciology community. And we clearly make contributions that have not been made by others before. It is simply unscientific to try to silence us just because we

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are trying to point out that an assumption that is commonly made in radioglaciology papers may not be justified in general. Whether the publication of our manuscript will be blocked or not, this will not change the fact that relative permittivity is, in general, not the sole control on radar reflectivity of glacier beds. It is just a convenient, but not universally applicable, simplifying assumption that has been made so many times that many in the community think that it is based on a universal law of physics.

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