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# Validation of closed-form expressions for the atmospheric altimetry correction in ground-based GNSS reflectometry based on rigorous ray-tracing

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GNSS reflectometry (GNSS-R) ability to remote sense the Earth's surface is affected by an atmospheric bias, as pointed out by several recent studies. In particular, sea level altimetry retrievals are biased in proportion to the reflector height, while by-products, such as tidal amplitudes, are underestimated. Previously, we developed an atmospheric ray-tracing procedure to solve rigorously the three-point boundary value problem of ground-based GNSS-R observations. We defined the reflection-minus-direct or interferometric delay in terms of vacuum distance and radio length. We clarified the roles of linear and angular refraction in splitting the total delay in two components, along-path and geometric. We introduced for the first time two subcomponents of the atmospheric geometric delay, the geometry shift and geometric excess. Finally, we defined atmospheric altimetry corrections necessary for unbiased altimetry retrievals based on half of the rate of change of the atmospheric delays with respect to sine of elevation angle. Later, for users without access to ray-tracing software, we developed closed-form expressions for the atmospheric delay and altimetry correction. The first expression accounts for the angular component of refraction (bending), leading to a displaced specular reflection point. The second one accounts for the linear component (speed retardation) in a homogeneous atmosphere. The expressions are parametrized in terms of refractivity and elevation bending, which can be obtained from empirical models, such as the GPT2 or Bennet's, or fine-tuned based on in situ pressure and temperature. We also provide a correction for the satellite elevation angle such that the refraction effect is nullified. We validated these expressions against rigorous ray-tracing results and showed that the discrepancy is caused by assumptions in the derivation of the closed formulas. We found the corrections to be beneficial even for small reflector heights, as approximated half of the atmospheric effect originates above the receiving antenna at low satellite elevation angles.