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Interactive comment on "Simulations of direct and reflected waves trajectories for in situ GNSS-R experiments" by N. Roussel et al.

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- ➔ Following the main point of the first reviewer, many new calculations were done, and the text of the article was supplemented by new results. As attachment you will find the modified version of the article (RousselN_new.pdf) and also a pdf file where modifications and corrections between the two versions of the article are highlighted (RousselN_corrections.pdf).

SUMMARY

The authors have developed a simulator to determine the locations of surface reflection points by modeling the transmissions from GNSS satellites. They investigate multiple approaches to modeling Earth's surface, including a digital elevation model (with potential obscuration) and incorporate a troposphere model. The latter is shown to have significant impact.
The work appears to be a very useful tool. However, some of the results are puzzling.
Some assumptions are not fully worked out. In addition, no validations are performed against prior work. These issues must be addressed prior to publication.

- ➔ Cross-comparisons have been performed between the algorithms approximating the Earth as a sphere or as an ellipsoid and between the algorithm approximating the Earth as an ellipsoid and the one integrating a DEM in a new subsection 4.2 *Validation of the surface models*, page 7, line 611.
  The one with the ellipsoid approximation is based on an iterative scheme, while the one with the sphere approximation is based on an analytical determination. Differences between both of them are sub millimetric when putting the semi-major and minor axis of the ellipsoid equal to the Earth radius.

4.2 Validation of the surface models

Simulations have been performed in the case of the Geneva Lake shore, for a 24-hour experiment, on the 4th October 2012.

4.2.1 Cross-validation between sphere and ellipsoid approximations

Local sphere and ellipsoid approximation algorithms have been compared by putting the ellipsoid semi-major and minor axis equal to the sphere radius. Planimetric and altimetric differences between both are below 6.10^{-5} m for a receiver height above reflecting surface between 5 and 300 m and are then negligible. The two algorithms we compare are totally different: the first is analytical and the second is based on a iterative scheme and both results are very similar, which confirms their validity.

4.2.2 Cross-validation between ellipsoid approximation and DEM integration

The algorithm integrating a DEM has been compared to the ellipsoid approximation algorithm by putting a flat DEM as input (i.e. a DEM with orthometric altitude equal to the geoid undulation). Results for satellite elevation angles above 5° are presented in table 1. As we can see in table 1, planimetric and altimetric mean differences are subcentimetric for a 5 and 50 m receiver height and centimetric for a 300 m receiver height. However, some punctual planimetric differences reach 70 cm in the worst conditions (reflection occurring at 3408 m from the receiver corresponding to a satellite with a low elevation angle), which can be explained with the chosen tolerance parameters but mainly because due to the DEM resolution, the algorithm taking a DEM into account approximating the ellipsoid as a broken straight line, causing inaccuracies. For a 50 m receiver height, planimetric differences are below 10 cm (reflections occurring until 573 meters from the receiver). With regards to the altimetric differences, even for reflections occurring far from the receiver, the differences are negligible (submillimetric).

Table 1. Cross-validation between ellipsoid approximation and DEM integration

		Receiver height (m)		
		5	50	300
Distance to the specular reflection point with respect to the receiver: arc length (m)	Mean	13	122	730
	Maximum	58	573	3408
Position differences (m) (planimetric / altimetric)	Mean	**0.007/0**	**0.008/0**	**0.04/0**
	Maximum	0.1/0	0.1/0	0.7/0

DETAILED COMMENTS

Abstract: “DEM” is used before it is defined

- ➔ Corrected → page 1, line 43.

p.1009, Line 23 (1009-23): This assumption is not justified, particular when a DEM is used. The authors should at least justify this assumption and have some quantitative estimate as to the error made by this assumption, and understand the implications of this assumption.

- ➔ Indeed, this assumption is only relevant for the local plane, sphere or ellipsoid approximation and not when integrating a DEM.
  In the plane, sphere and ellipsoid approximations, the specular reflection point of a given satellite is contained within the plane defined by the satellite, the receiver and the center of the Earth. With regards to the DEM integration, reflection can occur everywhere, but I only consider those contained in the plane: first because considering all the potential reflections would take a huge calculation time, and secondly because I consider the DEM integration as a way to have positions closer to reality w.r.t the sphere, plane or ellipsoid approximations, i.e. as a correction to the other algorithms, where reflections occur only within the plane.
  Please see subsection 3.4 Ellipsoid reflection approximation combined with a DEM, page 6, line 440.

3.4 Ellipsoid reflection approximation combined with a DEM

The two first approaches presented above are well adapted in the case of an isolated receiver, located on the top of a light house, for instance. In most of the cases, the receiver is located on a cliff, a sand dune, or a building overhanging the sea surface or a lake. It can however be really appropriate and necessary to incorporate a Digital Elevation Model (DEM) into the simulations, in order not to only take the mask effects (e.g., a mountain occulting a GNSS satellite) into account, but also to get more accurate and realistic positions of specular reflection points. The method we propose here consists of three steps later detailed in subsections 3.4.1, 3.4.2 and 3.4.3.

1. A ”visibility” determination approach to determine if the receiver is in sight of each GNSS satellite.

2. A determination of the specular reflection point position.

3. A ”visibility” determination approach to determine if the determined specular point is in plane of sight receiver/satellite.

We have to keep in mind that a DEM gives altitudes above a reference geoid. For consistency purpose, the positions of the receiver and the transmitter, and the DEM grid points have all to be in the same reference system. So it is absolutely mandatory to convert the altitudes of the DEM grid points into ellipsoidal heights by adding the geoid undulation. To do so, a global grid from the EGM96 geoid undulation model with respect to the WGS84 ellipsoid was removed from SRTM DEM grid points.

3.4.1 Visibility of the GNSS satellite from the receiver

This algorithm aims to determine the presence of mask between the receiver and the satellite. The visibility of the satellite and of the receiver, both from the specular point will be checked once the potential specular point position will be found.
Let R, S, and T be the locations of the receiver, the specular point and the satellite/transmitter on the ellipsoid. We interpolate the ellipsoidal heights along the path [TSR] with a step equal to the DEM resolution, with a bivariate cubic or bilinear interpolation. Cubic interpolation is used when the gradient is big, linear interpolation otherwise. Tests show millimetric differences between cubic and linear interpolation for flat zones but can reach one meter for mountainous areas. We thus obtain a topographic

profile from R to T. For each segment of this topographic profile, we check if it intersects the path [TR]. If it does, it means that the satellite is not visible from the receiver. If not, we check the next topographic segment, until reaching the end of the path (i.e. T).

3.4.2 Position of the specular point

Once the satellite visibility from the receiver is confirmed, the next step consists in determining the location of the specular reflection point S along the broken line defined as in subsection 3.4.1. In order to simplify the process, we only consider the specular points located into the plane formed by the satellite, the receiver and the center of the Earth. The algorithm is similar to the one used for the ellipsoid approximation and is based on a dichotomous iterative process. The segments formed by the points of the 2D DEM (see figure 6) are all considered susceptible to contain a specular reflection point. For each of this segment, we check the sign of the correction to apply for the two extremities of the segment with the same principle that for the ellipsoid approximation (see subsection 3.3), but with a local vertical component defined as the normal of the considered segment. If the signs are equal, no reflection is possible on this segment. Otherwise, we apply the dichotomous iterative method presented in subsection 3.3 until convergence with respect to the tolerance parameter (fixed to 1e-7°).

3.4.3 Visibility of the determined specular reflection point from the satellite and the receiver

Once the position of the specular reflection point is determined, we check if it is visible from the satellite and the receiver thanks to the algorithm presented in subsection 3.4.1.

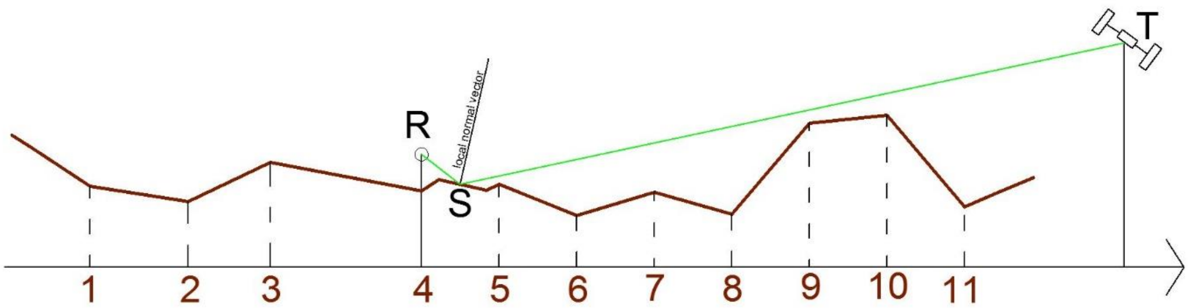

Fig. 6. Determination of the specular reflection point integrating a DEM
S: specular reflection point position. R: receiver position. T: transmitter/satellite position. A dichotomous process is applied for each topographic segment of the DEM to find if there is a point where the bisecting angle (equal to the sum of the anti-incident and scattering vectors) is colinear with the local normal vector.

p. 1015-18: There is something wrong with this sentence.

- ➔ The sentence has been deleted because a new algorithm has been developed (due to comments from the other referee).

p. 1015-22: Was it not stated earlier that a 2D coordinate system does not always apply? This should be clarified if needed.

- ➔ The sentence has been deleted because a new algorithm has been developed (due to comments from the other referee).

p. 1021-5: Do not use the word “important” here.

- ➔ Corrected. Page 8, line 687: “an important receiver height” → “A big receiver height above the reflecting surface”

p. 1023-17: The 8 cm difference seems much too large for the 5 m receiver height, comparing the sphere versus ellipsoid. 8 cm is 0.27% of the maximum reflection point distance from the receiver of 30 m. Distances from the receiver reach up to 30 m for the 5 m altitude antenna. It is hard for me to believe that the difference between sphere and ellipsoid over a 30 m distance approaches 8 cm. 30 m is a small fraction (5x10ˆ-6) of the Earth radius. I do not see how differences of nearly 0.3% are possible over 30 m.
An independent validation or cross check of this code is warranted, to establish there is not an error.

- ➔ In the new subsection 4.2 *Validation of the surface models,* the spherical model algorithm (analytical with an iterative procedure based on the Newton method to determine the roots of a fourth order polynomial) is compared to the ellipsoid algorithm, which is a pure iterative procedure (close to the algorithm presented in (Kostelechy et al 2005)). By putting the semi-major and –minor axis of the ellipsoid equal to the radius of the sphere, differences are sub-millimetric. The 8 cm difference is the geometric distance between the two determinations of the specular reflection points and is not the difference between the sphere and the ellipsoid.
  If the difference between the sphere and the ellipsoid at 30 m is about X cm, the difference between the two determinations of the specular reflection point positions will be far greater than X cm.

4.2.1 Cross-validation between sphere and ellipsoid approximations

Local sphere and ellipsoid approximation algorithms have been compared by putting the ellipsoid semi-major and minor axis equal to the sphere radius. Planimetric and altimetric differences between both are below 6.10^{-5} m for a receiver height above reflecting surface between 5 and 300 m and are then negligible. The two algorithms we compare are totally different: the first is analytical and the second is based on a iterative scheme and both results are very similar, which confirms their validity.

p.1026-5: integration of a DEM must consider the lack of co-planarity is possible between transmitter, receiver and Earth center

- ➔ You are perfectly right. But same answer as for your first detailed comment. We must precise clearly in the article that we only consider the reflections occurring in the plane defined by the transmitter, the receiver and the Earth center, which is done page 4, line 312.

In the plane, sphere and ellipsoid approximations, the specular reflection point of a given satellite is contained within the plane defined by the satellite, the receiver and the center of the Earth. With regards to the DEM integration, reflection can occur everywhere. In order to be able to compare the specular reflection point positions obtained by integrating a DEM, and to simplify the problem, we will only consider the reflections occurring within the plane, even while integrating a DEM.