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Atmospheric Measurement Techniques Discussions

Interactive comment on "Information content in reflected signals during GPS Radio Occultation observations" *by* Josep M. Aparicio et al.

Anonymous Referee #1

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The paper presents an overview of the impact and potential of using reflections in Radio Occultation observations; from their detectability to their "possible" use in the retrieval of bending angles. It is nicely organized, complete, and the topic is explained thoroughly, including correlations to several other parameters. It is appreciated to finally have a "reference" paper describing the state-of-the-art of reflection in RO. The paper is clearly written for a wider audience than just the RO community, since it provides also basics of the radio occultation theory. These basics are however nicely in context to improve understanding the extension of this theory (which is normally applied to retrieve bending angles from the direct rays) to reflected rays. Future work on this, where the information in the reflected ray is further investigated, is encouraged.

All in all, this paper should be published after a minor revision. Some specific com-

ments to improve the clarity of the manuscript are the following:

- Several times reference is made to the coherence of the "reflected" signal. Could you please add further information in the introduction in order to better address this concept (the first reference to the coherency is made at Page 2, row 30 and then again at page 3, row 18)? It would also be nice to explain why the receiver might lose tracking in case of lost coherency (assuming phase coherency... which is basically a phase which is varying randomly, because of complex scattering happening around the reflection point). Finally, it would be nice to also explain why a RO receiver can potentially track reflected signals only at very low grazing incidence (because of polarization, see first comment in the technical corrections below, but likely also because of the "phase/range" difference between direct and reflected paths that does not allow the PLL/DLL to be locked on both - but this is valid for standard closed loop and open loop using only a Doppler model like the one adopted on GRAS. It would be helpful in that context to clarify whether the COSMIC receiver has a full code/phase open loop tracking).

- Page 2, row 30: here the concept of "interferometric" phase is introduced. This is a crucial step of the processing - it is worth to provide an explanation of what it is and why it is used.

- Page 10, row 19-21: super refraction is, in general, not ducting or, in other words, ducting is the upper boundary of super refraction and is normally defined as "anomalous propagation". The electromagnetic propagation phenomenology is different between the two. In case of super refraction (when the refractivity gradient is between ∼-87 and -157 kmˆ-1) you still have "rays" bending towards the Earth's surface, with a bending angle which is increasing with the magnitude of the gradient (associated with a "signal" power which is decreasing with the square of the distance). In case of ducting (refractivity gradient < -157 kmˆ-1) rays are trapped like in a waveguide, with very small decrease of power while they propagating. Rays may or may not enter the duct, depending on the incidence angle, and if they enter, may exit very far away from the point where they entered.

- In the manuscript it is unclear when it is referring to super refractivity or to ducting. Depending on the refractivity gradient, on the ducting length, on the geometry (rays are in any case grazing the ducting layer, so they can theoretically enter the duct), rays might not be reflected from the surface closer to the expected specular point (if they are entering the ducting they will propagate along the duct before exiting). I guess that

1) trying to compute the correlation between maps of reflections and duct maps would be a good exercise and maybe can show some interesting features

2) moreover, could you please add in Figure 12 (as a legend or in the caption) the refractivity gradient magnitude and also add a third panel with the actual direct bending angles?

In this "family" you likely have both cases of super refraction and ducting (in particular the profile shaped as error function. Is what you wrote at Page 15, row 20 is true? First, propagation is also defined by the refractivity gradient, not by the surface refractivity value. Moreover, being a simulation (or application of forward model, which does not model at all the propagation within a duct), the "ray" maybe cross the duct because the incident angle (the angle with the normal to the duct) is small enough and it is "refracted" into the duct. As a first thought, in this case one might expect bigger bending angles for the same impact parameter (or smaller impact parameters for the same bending). But, looking at the family of bending angle profiles in Figure 12, right panel, this is showing exactly the opposite. The second thought is one the incidence angle, which is decreasing with increasing N gradient (more bending towards the surface), thus the overall bending angle defined by equation 3 is becoming smaller and smaller because the second term in this equation is increasing. Is it correct? Could you please add a sentence on this?

- Page 12, row 13: if taking the fR from the interferogram shown for example in Figure 9, fD is always zero and thus fR = fI? If this is true, where is the fD taken from? From

the measurements on the direct link (thus from the original carrier phase of the signal)? Taking simply the time derivative of the carrier phase? But it is well known that, in the lower troposphere and in particular in the sub- and tropical regions, atmospheric multipath often occurs. This means that the instantaneous (excess) Doppler components cannot be estimated by the carrier phase time derivative. Wave optics techniques (FSI for example) should then be applied. Thus is the fD(t) for a particular time t when the fI(t) of the reflection is also present, computed with a wave optics approach? Could you please clarify this in the paper?

- Page 16, row 20: Somehow doubting that the reflected beam will allow extracting information if the direct one is lost. This would be a "nice" case, but in reality the receiver will encounter low SNR in the lowest part of the atmosphere, is unable to track the direct beam, so why should the reflected one (which encountered even more of that lowest, variable part of the atmosphere) still be present?

- General: it might be worthwhile to also think about corrections/removal that can be applied based on knowledge of the reflected beam. This could be very valuable for all the situations where the direct beam is already very noisy (and no reflected one is easily identifiable). Can you include a few words on this option?

- General: would be nice to include some general statement on what to expect from e.g. COSMIC-2 with its high gain occultation antennas.

"Technical corrections"

Page 2, row 22: "either by polarization". This is not strictly true. The signal is right hand circularly (RHCP) polarized. The receiver antenna onboard the LEO must be sensitive to the RHCP polarization only, with a very low sensitivity to the cross-pol component (the left hand one). GPS receiver cannot separate the two components at all. The remaining energy in the LH component is something like a noise. In case of reflection with low incidence angles (∼nadir reflections, typical for a GNSS-R receiver), the polarization of the reflected signal will be LH. Thus to make the receiver "sensible" to such signals, the antenna should be a LHCP one. Again the receiver is not separating anything.

Page 2, row 26: what does it mean that the spectral distribution is compact? Maybe that the spectral components are within a small bandwidth? Use another adjective than compact...

Page 3, row 3: "signals" instead of "profiles"

Page 3, row 4: "observations to be inverted to estimate the profile of..." instead of "measurements of the profile..."

Page 4, row 2: it is certainly worth to cite ESA's plans on this, but maybe investigating is better than planning? And there is an Eart instead of Earth in previous line.

Page 4, row 6: grazing "observations" instead of grazing "angles"

Page 4, row 28: "by a PRN code" instead of "by the PRN".

Page 4, row 33: what does it mean "orbital Doppler"? Is the Doppler experienced by the signal due to the relative radial movement between GNSS and LEO considering vacuum propagations? Please specify.

Page 5, row 1-2: what are you referring with "electromagnetic noise"?

Page 5, row 3: again, is the Doppler subtraction referred to the "orbital Doppler" not better defined at Page 4, row 33? please clarify.

Page 5, row 4: what do you refer with "frequency broadening"? please clarify.

Page 5, row 12: what about L2C tracking, which might be better than L1C/A?

Page 5, row 20-21: this is the standard frequency beating phenomenon. Such details can be avoided.

Page 6, row 22: you are naming the threshold you need to define simply as SVM (also later on in the paper) Could you please find another acronym/name to such thresh-

old? SVM refers to "Support Vector Machine" which is a method, not a numerical value/threshold (see for example row 27 same page).

Page 7, row 22: reference to a supplementary movie. If you think it is ok, discard this comment. People will mostly download the paper and simply read it. Is it potentially worth to put the movie somewhere in an open repository (e.g., DropBox, Google cloud, ...) and make reference to the repository? See also Page 8, row 29

Page 8, row 10: I think that Ulaby could also be referenced well before. Probably in discussing coherency, or simply when you talking about electromagnetic reflection.

Page 8, row 28: Looking at Figure 7, I'd say that the fraction of reflections at lat > 45deg is always large, but between 45% and 65%. Unfortunately the figure uses grey levels, so it is not very clear. I suggest to use also different line styles, in order to better show the seasonal similitude (if I'm not wrong, in summer/winter there are always more/less reflections in both hemispheres). Maybe it is worth to point it in the paper also discussing figure 7.

Page 8, row 35: "opposite" instead of "contrary"?

Page 11, row 33: Could you better define the 2D template used to cross-correlate the radio-holographic image?

Page 12, row 5-9: Could you please specify as a further detail for a more generic audience why the reflected signal is always going from -25 Hz to 0 in an interferogram like the one shown in Figure 2? Or at least provide a reference for this (I guess that there is a theoretical explanation here : Beyerle, G., K. Hocke, J. Wickert, T. Schmidt, C. Marquardt, and C. Reigber, GPS radio occultations with CHAMP: A radio holographic analysis of GPS signal propagation in the troposphere and surface reflections, J. Geophys. Res., 107(D24), 4802, doi:10.1029/2001JD001402, 2002.)

Page 12, row 19-21: this is unclear. What is this formal precision of the inversion? And where is the evidence that the "thickness" of the "line" is larger than the precision? Is this because no noise is visible? This is also repeated at page 14, row 10-11.

Page 12, row 25-27: unclear. Are you inferring that atmospheric multipath is neglected (or rays are disentangled after some preprocessing)? Why are you talking about "diffraction" here? Diffraction from what? Earth's surface?

Page 13, row 10: smaller typo

Page 13; row 18: "by twice the incident angle" instead of "... grazing angle".

Page 12, row 29-31: I guess that the wording "local spherically distributed" refracted field can be used instead of its explanation.

Page 16, row 21: If you have a loss of track, you are loosing both the information carried by the direct and the reflected signal. Instead if I well understood, in the time series of observations, the reflected contributions to the bending angle characterizing the lower impact parameters come before the direct contribution. In this case it makes sense that in case the signal is lost and, if any, reflections are "tracked" they can be used to eventually fill in the gap. Not sure but if you have pure open loop data, you can always reconstruct both (if SNR allows it). Could you please better address this?

Page 16, row 24-27. Not clear. Please, rephrase it.

Table 2, caption: "surfaces typologies". Again the reference to SVM value (see comment to Page 6, row 22)

Figure 1, caption: GNSSR at higher elevation (strictly speaking in this case the elevation angle is smaller...)? What does it mean? I'd use nadir looking. Also, here you use GNSSR, while otherwise you use GNSS-R.

Figure 2, caption: "setting" instead of "descending". What does it mean "winding"?

Figure 3: with the uncertainty of the tangent point being a few km, are land reflections over small islands truly land ones, or could also be sea ones? Maybe add a pre-caution.

Figure 3, 4: it seems the Arctic is neither land nor sea. Are there no reflections observed there?

Figure 4, caption. You are referring to COSMIC here. Not sure in the text this is made. And, for instance, it is not made in Fig 3, caption, but it is made in the caption of Figure 7. Again also here is made reference to the "supplementary movie.."

Figure 8: at 50% ref, there seems to be a vertical line for all cwv, is this some threshold trigger?

Figure 10: might be better in impact height (IP - RoC)

Figure general: they need to be made more coherent, font sizes are sometimes very large, sometimes okay, sometimes small. Units missing, etc.

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