Review of the manuscript amt-2014-237

A perspective on the fundamental quality of GPS radio occultation data

by T.-K. Wee and Y.-H. Kuo

The authors use radio occultation (RO) excess phase data to determine the quality of RO data with respect to operational analysis and reanalysis data. The use of excess phase data for this purpose is a new approach, and the paper deserves to be published after revision.

General comments:

(1) The structure of the paper is somewhat odd. The introduction is quite long, and the general part is literally loaded with references (there are, e.g. not less than ten references backing the argument that reanalyses are susceptible to deficiencies of the observations (page 9484)). The reference section is therefore almost as long as the paper itself. Compared to the introduction the results (and discussion) section is surprisingly short and the results are just illustrated with three figures.

(2) In contrast to the wealth of citations in the general part of the introduction there are comparatively few references to previous work on the climate quality of RO data (some examples can be found in my specific comments).

(3) I agree with the comments of referee # 2 and repeat (for the sake of brevity) only those points, which I regard as particularly important.

(4) The discussion and the conclusions are based on a comparatively short data period: May – August 2002. This is fine for a demonstration of the new approach, but the conclusions are way too general. It should also be mentioned that the quality of operational analyses has considerably increased since 2002 – in particular in the Southern Hemisphere.

Specific comments:

(1) Page 9842, line 5/6: “This study assesses the fundamental quality of RO data, by modeling the “raw” measurements “ This formulation is somewhat misleading, since it suggests that you (just) used modeled data – in fact you compared measured phase data with modeled ones (Later on it becomes clear what you mean).

(2) Page 9842, line 7: “Center” should be “Centre” (British English).

(3) Page 9842, line 8: Instead of “that the RO measurement is ..” I would suggest using “that RO measurements are ..”

(4) Page 9842, line 15: “.. showed a close agreement in the standard deviation. This confirms the high accuracy ..” Why? High accuracy is usually understood as “small systematic error”.

(5) Page 9483, line 4: “.. in the data records ..”. Please specify which records you mean – some of the cited references refer to radiosonde data, some to (A)MSU data.

(6) Page 9485, line 29: “The data close to raw measurement ..” should read “Data close to raw measurements ..”

(7) Page 9485: This paragraph leaves the impression that “raw” data are essentially free of systematic errors, but excess phases are not really “raw” – they have already received quite some processing. Any systematic error in the orbit determination will lead to systematic errors in the excess phase data. Furthermore, the applied ionospheric correction does not remove the

entire influence of the ionosphere and leaves a (small) ionospheric residual that increases with increasing electron density (see Danzer et al., 2013).

(8) Page 9486, line 4/5: ".. assumption of spherically symmetric atmosphere." should be ".. assumption of spherical symmetry." or ".. assumption of a spherically symmetric atmosphere."

(9) Page 9486, line 9: Here you should also cite the paper by von Engeln (2006), who first reported on structural uncertainty in RO data.

(10) Page 9486, line 21: "the retrieval uncertainty in RO is avoidable by using unprocessed "raw" data". This is not entirely true, since excess phase data are not really "raw" (see specific comment 7).

(11) Page 9486, line 21: " by modeling L1 and L2 phase measurements directly and compare them with NWP analyses in the observation space." Is this really correct? I understood that you compared measured excess phases (after ionospheric correction) with modelled excess phase data based on ECMWF/ERA fields.

(12) Page 9487, line 4: Later on you will explain it in detail, but at this point of the paper the reader wonders why you chose the time period May-August 2002. At some point you should also mention that solar activity was pretty high during this period.

(13) Page 9487, equation 1: You should definitely indicate the values of the coefficients (k_1 – k_3) you employed, and you should mention the uncertainty of the coefficients – in addition to the reference proposed by referee # 2 (Aparicio and Laroche, 2001) I would suggest citing the paper by Healy (2011). Furthermore you need to write that there are also higher ionospheric terms.

(14) Page 9487, line 23: "source error" should be "error source"

(15) Page 9487, line 25: Here you should consider citing the ray tracing study by Foelsche et al. (2011).

(16) Page 9489, line 1: If you specifically mention the Frenet-Serret formula(s) you could consider including it/them in the manuscript.

(17) Page 9489, line 14: Why did you use ECMWF analyses just on 26 pressure levels? In 2002 they have already be available on 60 vertical levels.

(18) Page 9489, line 20: Did you use SMI just for the Plasmasphere, or did you use both models as alternatives – in the latter case it would be very interesting to show how the ray tracing results differ when using the different ionospheric models.

(19) Page 9489, line 29: "36512" Shouldn't the sum of 23563 and 18846 be more like 42409? Or was this meant in a different way?

(20) Page 9490, line 3: Please provide the equation for the ionosphere-free linear combination – and a reference.

(21) Page 9490, line 9: This would be another option to cite the paper by Danzer et al. (2013).

(22) Page 9490, line 11/12: "..a low-pass filter, fourth-order Butterworth filter .." There is a duplicate "filter".

(23) Page 9490, line 21: Ionospheric residual errors in 2002 have been higher due to higher solar activity.

(24) Page 9491, line 5: You mention the degradation of ERA40 forecasts in 2002. Differences between operational ECMWF analyses and RO-derived temperatures during Jun-July-August

2002 are, however, smaller than differences in JJA 2003 (Foelsche et al., 2008), though showing a similar wavelike bias structure (as reported for JJA 2003 by Gobiet et al. (2005)).

(25) Page 9491, line 23: “As can be inferred from Eq. (1), the excess phase in the stratosphere inversely relates to the temperature.” This is not always true – e.g. during an SSW the thermal expansion of the stratosphere will lead to an increase in temperature and density (and therefore also refractivity) at a given altitude, thereby causing an increase in excess phase.

(26) Page 9492, line 15: “Data from CHAMP and SAC-C are largely independent from each other” This is essentially right, but it should be noted that both datasets have similar systematic residual errors due to the same (incomplete) ionospheric correction applied.

(27) Page 9493, line 10: “..OP and RA are significantly biased, and RO data are able to quantify their systematic errors.” But this does not necessarily mean that RO data are unbiased (see comment 26).

(28) Page 9493, line 18/19: “Our study finds that the oscillation is pervasive without being confined in the SH.” This is not new: Foelsche et al. (2008) found wavelike bias structures in dry temperature also in the Northern Hemisphere – they were just most pronounced in Antarctic winter. In Northern summer 2006 they appeared with a similar magnitude in the Arctic.

(29) Page 9494, line 17: “..without the involvement of RO retrieval uncertainties”. This is too optimistic – you ignore all the uncertainties in the level 1 processing.

There are several minor issues (use of articles …), which can be solved in a later stage of the review process (I have just commented one some of them).

References:

Danzer, J., B. Scherllin-Pirscher, U. Foelsche (2013) Systematic Residual Ionospheric Errors in Radio Occultation Data and a Potential Way to Minimize them, *Atmos. Meas. Tech*., 6, 2169-2179, doi:10.5194/amt-6-2169-2013

von Engeln, A. (2006) A first test of climate monitoring with radio occultation instruments: Comparing two processing centers, *Geophys. Res. Lett*., 33, L22705, doi:10.1029/2006GL027767

Foelsche, U., S. Syndergaard, J. Fritzer, and G. Kirchengast (2011) Errors in GNSS radio occultation data: relevance of the measurement geometry and obliquity of profiles, *Atmos. Meas. Tech*., 4, 189–199, doi:10.5194/amt-4-189-2011

Foelsche, U., M. Borsche, A.K. Steiner, A. Gobiet, B. Pirscher, G. Kirchengast, J. Wickert, and T. Schmidt (2008) Observing Upper Troposphere–Lower Stratosphere Climate with Radio Occultation Data from the CHAMP Satellite, *Climate Dynamics*, 31, 49-65, doi:10.1007/s00382-007-0337-7

Healy, S. B. (2011) Refractivity coefficients used in the assimilation of GPS radio occultation measurements, J. *Geophys. Res*., 116, D01106, doi:10.1029/2010JD014013.