Interactive comment on "A novel technique including GPS radio occultation for detecting and monitoring volcanic clouds" by Riccardo Biondi et al.

<u>Response to Anonymous Referee #1</u> (interactive comment received and published: 13 February 2016)

>>> We thank the reviewer for the thorough review of our paper and for the constructive comments. Please find below our point by point response (in italics).

This is an interesting and provocative paper that should be published after careful consideration of the reviewers' comments. This reviewer is convinced that there is a volcanic signal in the RO anomaly profiles after the Puyehue (2011) and Nabro (2011) eruptions. The warming signature associated with the Nabro eruption, presumably due to the SO2 content of the plume, is especially convincing. The agreement of the RO estimated plume tops with the CALIOP measurements (Fig. 1) and the comparison of the anomaly profiles in the several months following the eruptions (Fig. 2) with the anomaly profiles in the same regions in the same months in years without eruptions (Fig. 3) support the claim that the RO anomaly profiles are providing evidence of the plumes.
While the results from two cases may not be 100% convincing, they are original and are compelling enough to be published in hope of stimulating further studies on other volcanoes.

My biggest concern is how soon after the eruptions do the horizontal scales of the plumes become large enough to produce atmospheric effects that are large enough to be detected by RO observations. With an RO observation horizontal averaging length scale (footprint) of 150 to 300 km, the scale of the plume would have to grow to at least 500-1000 km before RO observations would be likely to occur within the plume and detect its effects. The question is how long does it take for the plume to advect and disperse over a band 1000 km or greater in width (latitudinal extent)? A MODIS photograph taken 13 June, 2011, the day after the NABRO eruption, shows a plume spreading downwind towards the northwest with a width approximately 300 km 900 km downwind from the eruption.
http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=50988
This suggests that the plume would be difficult to detect by RO the first day after the eruption, but would be detectable by RO within a few days after the eruption. A modeling study by Timmrect et al. (2003), as discussed in the modeling review paper by Textor et al. (2005) see Fig. 5, gives an indication of the rate of spread of the Pinatubo eruption (1991). By 9 days the plume is approximately 30 latitude wide (more than 3,000 km). By 16 days the plume covers much of the atmosphere between 30 S and 30 N, or more than 6,500 km wide. To the extent that these figures are representative, one would expect RO to be able to sample the plume starting a few days after the eruption, certainly after a week. This paper considers perturbations through 20 days after the eruptions, so I think there should be sufficient RO observations to detect the perturbations.

>>> We thank the reviewer for this valuable comment. We added further information on the RO measurement method, resolution, and RO sampling related to volcanic clouds. As discussed by the reviewer, the scale of 1000 km dispersion in 1 day is reasonable and confirmed by several works on different eruptions, e.g., Bignami et al.: Multisensor satellite monitoring of the 2011, Puyehue-Cordon Caulle eruption, Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 7(7),

2786–2796, doi:10.1109/JSTARS.2014.2320638, 2014. Fig. 1 (upper left panel) of the manuscript shows that we found RO observations within the cloud from day 0 onward after the volcanic eruptions, based on the pre-defined cloud information from the radiometric data (OMI, AIRS). Whenever an RO observation is co-located with the cloud it will be possible to determine a signal of the cloud, with intrinsic horizontal averaging though. The larger the spread of the cloud and the longer its duration, the more RO observations will be co-located with the cloud.

We added the following sentence in section 4.1:
"Spreading about 1000 km in one day (Textor et al., 2005; Bignami et al., 2014), the extension of the volcanic cloud is well covering the scale of the GNSS RO horizontal resolution (about 200 to 300 km at the cloud altitudes) and atmospheric signals are large enough to be detected by RO observations."

In order to aid the understanding of relevant RO properties in a concise way, we included the following short description of the RO method and the resolution of RO observations in section 3.1, as follows:
"GNSS RO is an active limb sounding method using a satellite-to-satellite link. GNSS satellites transmit radio signals which are influenced by the Earth's refractivity field along their propagation path to a receiver on a Low Earth Orbit (LEO) satellite. Movement of the satellites leads to vertical scanning of the entire troposphere and stratosphere within about one minute and provides measurements with high vertical resolution but inherent along-ray horizontal averaging. The horizontal resolution across-ray is about 1.5 km and the along-ray resolution ranges from about 60 km in the lower troposphere to about 300 km in the stratosphere (Melbourne et al., 1994; Kursinski et al., 1997). The vertical resolution ranges from near 100 m in the lower troposphere to about 1 km in the stratosphere (Gorbunov et al., 2004). …
Data from the following RO missions were used: CHAllenging Minisatellite Payload (CHAMP) (Wickert et al., 2001), Satélite de Aplicaciones Científicas (SAC-C) (Hajj et al., 2004), Gravity Recovery And Climate Experiment (GRACE-A) (Beyerle et al., 2005), FORMOSAT-3/COSMIC (Anthes et al., 2008), altogether comprising about 2000 globally distributed RO profiling measurements per day."

The Pinatubo case is mentioned in the paper (Lines 186-188), but please clarify which volcano you are referring to that sentence "spreading SO2 in the atmosphere more than 60 degrees in latitude. ". I think you are referring to Pinatubo not Nabro.

>>> We are referring to the Nabro eruption here. To make this clear we improved the wording to:
"The Nabro eruption has been recognized as the largest stratospheric sulfur injection since Pinatubo in 1991 …, injecting mainly SO2 into the atmosphere, which spread…"

This sampling issue should be discussed by the authors.

>>> Please see the discussion above on the sampling issue; as explained there we have improved the text accordingly.

The review article by Textor et al. (2005) discusses the spreading of volcanic plumes and should be referenced (the current draft has no references to modeling studies.)

>>> We included this reference and cite Textor et al. (2005) in section 1 and section 2.

In the future, studies of this type would be greatly strengthened by model simulations of the volcanoes being studied. Of course this is beyond the scope of this initial paper.
Related to the sampling and scale issues are the photographs in Fig. 1. They are too small to be effective and there are no horizontal scales on them. I suggest replacing them with much larger, clearer photographs with a scale indicated (a 5 x5 grid superimposed would be very useful). Some NASA photos of Puyehue are available at http://www.nasa.gov/topics/earth/features/20110606-volcano.html. The one at 15:37 UTC June 6 (the day after the eruption is a good one).
>>> We thank the reviewer for this suggestion and for the provision of the links.
The purpose of Fig. 1. (left panels) is to show the reader an example of the radiometric measurements used in this study for supporting the co-location of RO profile observations with the volcanic plumes. We show SO_2 observations for Nabro and ash observations for Puyehue. After careful consideration we finally decided to keep these figures instead of showing images in visible channels, which are more easily available to readers anyway. However, we improved the two figures by enlarging them and by indicating latitude and longitude information.

Related to the sampling issue, the authors should explain what is meant by "co-located" (Lines 194-194). For determining the co-located RO points, how are the Puyehue and Nabro clouds defined?

>>> We reformulated the respective paragraph for better explanation and clarity. It now reads:
"For the selected eruption cases (Puyehue and Nabro) we used basic geographic areas of size 10° x 10° in latitude and longitude, centered at the volcano location. In a first step, we located the ash and SO2 clouds within these areas, using the AIRS ash index data for Puyehue (considering high level of confidence only) and the OMI SO2 data for Nabro, respectively, as illustrated in Fig. 1 (left panels). Spreading about 1000 km in one day (Textor et al., 2005; Bignami et al., 2014), the extension of the volcanic cloud is well covering the scale of the GNSS RO horizontal resolution (about 200 km to 300 km at the cloud altitudes) and atmospheric signals are large enough to be detected by RO observations.
In a second step, we screened all RO profiles at mean tangent point locations and selected those located within the region of the volcanic cloud as defined from AIRS and OMI data for each day after the eruption. Over a time period of 20 days from the eruption we found a total of 1109 profiles co-located with the Puyehue cloud, and 248 profiles co-located with the Nabro cloud, respectively. These cloud-collocated datasets were used as core RO datasets for exploring potential cloud-induced signatures. We complemented them by RO datasets from the same geographic areas outside clouds and during other time periods, in order to put the anomaly signature results from the cloud-collocated datasets into context."

For the reviewer's convenience we show below an example of a temperature profile and a bending angle profile (Figure 1r - left) located within the region of the Puyehue volcanic cloud as defined with AIRS ash observations (Figure 1r - right).

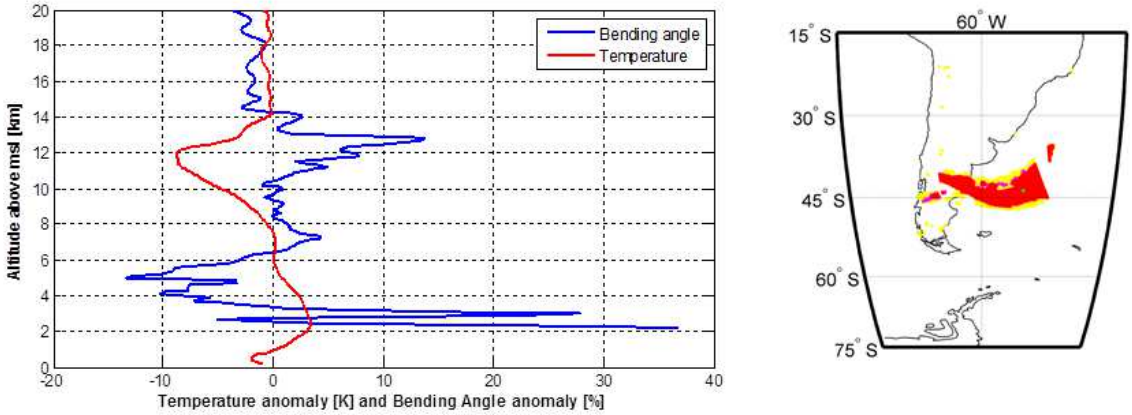

Figure 1r. (left) RO temperature anomaly profile (red) and bending angle anomaly profile (blue) co-located with (right) the Puyehue ash cloud on June 5, 2011. The ash cloud index is based on AIRS data with pixels of high confidence (red), medium confidence (magenta), and low confidence (yellow) (Clarisse et al., 2012). The green dot (right, within the cloud) indicates the location of the RO mean tangent point.

<u>A few specific suggested edits:</u>

Line 197 Add “with RO” after “. . ..cloud structure” *>>> Done.*

Line 266 - I am not sure that “primary” is the best word to describe the first (lowest) tropopause, which is thought to be caused by the volcanic cloud, and “secondary” to describe the original or main tropopause. I would suggest something like “lower tropopause (pink area) and original (main) tropopause (cyan area).”
>>> This notation is usual one used for describing double tropopause features (e.g., Randel, W. J., D. J. Seidel, and L. L. Pan, 2007: Observational characteristics of double tropopauses. J. Geophys. Res., 112, D07309, doi:10.1029/2006JD007904). We therefore preferred to keep this notation.

Line 281 – I suggest replacing “climatological” with “non-volcano” In this same paragraph, was the reference climatology from which the anomalies were computed the 2001-2012 mean (same as for the volcano anomalies)? If so, please say this.
>>>We reformulated this paragraph for better clarity. It now reads:
“Inspecting for reference normal climatological background variability for May and June months without volcanic eruptions, Figure 3 provides an overview on the atmospheric anomaly structure under such climatological conditions. It shows the monthly mean temperature and bending angle anomalies averaged over May 2007–2013 and June 2007–2013 (excluding the month of eruption June 2011), and their estimated inter-annual variability during these years, for the areas of Puyehue and Nabro.” …

Lines 335-336- I suggest rewording “RO observations can contribute to improved detection and monitoring. . .” *>>> Done.*

The paper has very few typos-I found one in line 501 (“Determination”). *>>> Done.*