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 #3</u> (interactive comment received and published: 1 February 2016)

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

In this paper the author describe results on ash cloud detection as well as volcanic ash cloud top height determination using GPS radio occultation measurements of two volcanic eruptions (Puyehue and Nabro) in 2011. This is a well written and convincing study using two quite different eruptions, one being rich in ash and no SO2 the other being very SO2 rich. The paper however falls short in convincing me if this technique would also be applicable to eruptions including lower ash or SO2 content. Admittedly, this was not the main aim of this work but the introduction builds on this argument (L36 and following), plus smaller eruption do threaten airways also considerably and techniques to monitor those are also necessary. The ability to detect smaller eruptions should in some way be addressed in the paper, the best place being most likely the discussion section.

>>>We performed some testing with smaller eruptions of Eyjafjöll and Etna, and found that the method works also for these cases. However, for these cases we did not find a statistically relevant number of GPS RO observations co-located with the volcanic clouds for more detailed analyses. This is the reason why we focused our feasibility study on the 2 largest eruptions occurring in the RO period since 2006. We added the following statement in section 6:
"We showed the feasibility for the two largest eruptions (Puyehue 2011, Nabro 2011) in the RO data period since the FORMSAT-3/COSMIC launch in 2006, where we analyzed about 1300 RO profiles for the two cases. We also found that the method works for smaller eruptions such as the Eyjafjöll eruption in Iceland in 2010 (Stohl et al., 2011). However, the number of cloud-collocated profiles was too small for a more detailed analysis, a situation that will drastically improve with the increased number of GNSS RO observations becoming available in future."
For the reviewer's convenience we show an example of cloud top results for Eyjafjöll in Fig.1r below. Evidently only 13 co-located RO profiles were available in this case, wherefore we did not include it as an extra example case; also CALIOP co-locations have not been available for this case.

As we briefly point out now more explicitly, this RO data coverage situation will drastically improve in the future with the increased number of RO constellation missions and other GNSS systems providing radio occultation signals in addition to the GPS. Motivated by this comment, we also included another brief paragraph now in the conclusions, pointing to the emerging Low Earth Orbit microwave and infrared-laser occultation methods, which are next-generation GNSS RO techniques that will enable a further drastic improvement of the characterization of volcanic clouds, as follows:
"Beyond the RO technique using the decimeter-wave GNSS signals, next-generation occultation techniques between Low Earth Orbit satellites are emerging that use centimeter- and millimeter-wave microwave signals (Kursinski et al., 2002; Kirchengast and Hoeg, 2004; Kursinski et al., 2009; Schweitzer et al., 2011a) and also micrometer-wave infrared laser signals (Kirchengast and Schweitzer, 2011; Schweitzer et al., 2011b; Proschek et al., 2011, 2014; Plach et al., 2015; Syndergaard and Kirchengast,

2016). These can simultaneously measure the thermodynamic structure, water and ice cloud structure, aerosol layering, and wind conditions and will therefore allow another drastic advancement of detecting and monitoring volcanic clouds by occultation methods in the future."

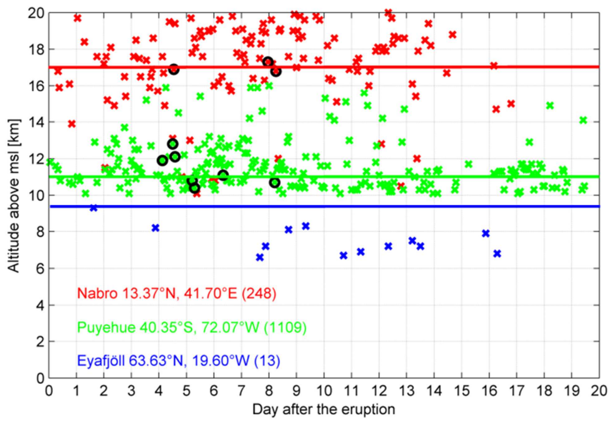

Figure 1r. Cloud top altitudes of volcanic plumes (cross symbols) for Nabro (red), Puyehue (green), and Eyjafjöll (blue) derived from RO data. Co-located CALIOP data are indicated (black circles). Numbers in brackets denote the number of RO profiles. Horizontal solid lines denote the respective monthly climatological tropopause altitudes for the three volcano locations.

As mentioned by the authors the ash of the Puyehue eruption circled the earth leading to airspace closure quite far away from the eruption. It would be of particular interest up to what distance from the volcano RO techniques could be used to detect ash. This should also be addressed in the paper.

>>> The presence of the cloud in general changes the atmospheric refractivity, which is the parameter influencing the GPS signal; this makes GPS RO observations useful and independent of the distance from the volcano. In this initial study we do not detect the presence of ash or SO_2 itself with RO; we rather use radiometric measurements first to obtain the cloud coverage knowledge. In a second step we then sample RO profiles co-located with the cloud and determine the cloud top altitude and the effect that different type of clouds have on the atmospheric thermal structure.

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 …comprising about 2000 globally distributed RO profiling measurements per day."

And we added the following explanation on plume spreading and related sampling 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."

I have listed several references which should be included in this paper to give better credit to other work which has been done in this field. Overall I feel this is an interesting paper and should be published after moderate to major revisions. Please find more specific comments below.

Specific comments:

L27: These references are ok, but there are some better ones for volcanic plumes reaching the stratosphere. A good reference could be the book by Sparks et al (1997) on Volcanic Plumes.

>>> We included this reference and cite Sparks et al. (1997) in section 1.

L31: The Pinatubo effect was as far as I know first published by MacCormick et al 1995, Nature, 373:399-404 and should be referred to in addition to the Robock paper.

>>> We included this reference and cite McCormick et al. (1995) in section 1.

L48: It is not the total ejected mass, but the mass flux which controls the height of the eruption cloud (see e.g. Woods, 1988, Bull. Volcanol, 50: 169-193). Furthermore eruption clouds typically overshoot the level of neutral buoyancy so there are certainly different height levels at which ash and aerosols are injected into the atmosphere during a single eruption.

>>> We corrected the sentence which now refers to Woods (1988) and reads:
"The mass flux of the eruption is fundamentally related to the maximum height reached by a volcanic plume (Woods, 1988)."

L87: There is a quite comprehensive paper on observation of ash clouds using radar by Sawada 2004 (http://www.ofcm.noaa.gov/ICVAAS/Proceedings2004/pdf/entire-2ndICVAAS-Proceedings.pdf) that summarizes all observations of ash clouds with radar until 2004. This could be referenced here.

>>> *Done.*

L99: From here on you refer only to RO techniques. Goals of your study are a) the detection of volcanic clouds and b) the determination of cloud top height.

>>> Yes, the goals is as concisely summarized in the final sentence of this section (section 2).

L89-98 summarize briefly what has been done on the detection of ash clouds. Previous work on the determination of cloud top heights are missing however completely and there have been other approaches to determine cloud top height which should also be referenced here. Following is a list of papers which I feel should be included in your summary of the state of the art, as some techniques referred to in those papers (e.g. reflectance ratio measurements, photogrammetry) have not been referred to. (Chang, F.-L., et al., 2010. J. Geophys. Res. 115, D06208. doi:10.1029/2009JD012304; Dubuisson, P., et al., 2009. Remote Sens. Environ. 113, 1899–1911. doi:10.1016/j.rse.2009.04.018; Frey, R.A., et al., 1999. J. Geophys. Res. Atmospheres 104, 24547–24555. doi:10.1029/1999JD900796, Poulsen, C.A., et al., 2012. Atmos Meas Tech 5, 1889– 1910. doi:10.5194/amt-5-1889-2012; Stohl, A., et al., 2011. ACP, 11, 4333-4351. doi:10.5194/acp-11-4333-2011)

>>> We thank the reviewer for this information; we included also these references at this location in section 2 in our summary of the state of the art.

L 214: I am not sure if I understand this correctly. For the reference climatology you average all profiles in an area of 5 x 5. Here you are referring to the climatology for the eruption in line 213 which is now sampled at 1 x 1 . In case this is the eruption climatology than what is the possible error by subtracting the average taken over 5 x5 which is a much larger area. But maybe I am misunderstanding this paragraph.

>>> The reference climatology is provided at a 1° x 1° grid, based on averaging around each grid point over a cell size of 5° x 5° in latitude and longitude, to ensure a robust average and being representative for large-scale background field resolution.
We do not compute an "eruption climatology" but compute the difference of individual RO profiles (within volcanic clouds) minus the profile from the reference climatology, as described in section 4.2:
"We computed the bending angle anomaly by comparing each selected RO bending angle profile in the volcanic cloud area to the monthly RO reference climatology profile extracted for the same location, i.e., subtracting the RO reference climatology profile from the individual RO profile ..."

L215: Considering a spatial distance of 200 km between the CALIOP data and the volcano, can those profiles be considered representative for the cloud top, especially because the plume may have overshooted significantly near the vent. I note, for the main cloud at the neutral buoyancy level, though, this may be valid verification.

>>> This is right, but there is a typical cloud extension of several 100 kms for the main cloud so it is basically reasonable. And unfortunately we did not have any other more strictly co-located data option for independently validating our top estimation, since even with this 200 km criterion we could not get only a small number of co-locations. While we nevertheless consider the limited CALIOP results of Fig. 1 quite convincing in their consistency, this co-location issue of course leaves some "space-time representation uncertainty", which can hopefully be improved with more dense data in future.

Fig1: Legends are missing on both maps.

>>>*We improved the two figure panels by enlarging them and by indicating latitude and longitude information.*

L555 there are no numbers in brackets. What are the black circles in the top right diagram?

>>> *We improved the caption of Fig.1 (top right panel). It now reads:*
"Figure 1….(top-right) Cloud top altitudes of volcanic plumes (cross symbols) for Puyehue (green) and Nabro (red), derived from RO data over the first 20 days from the eruption; co-located CALIOP data are indicated (black circles). Numbers in brackets denote the number of RO profiles. …"

Fig2c,d,e,g: From this figure it is very hard to see how often e.g. a certain bending angle has been measured in the individual profiles. Instead of plotting each single profile on top of each other, maybe a kind of density plot would be better in this case indicating how often a certain bending angle has been observed at what height. This would also apply to Fig4bcd as well as to all panels in Fig5.

>>> *We thank the reviewer for this suggestion. We discussed and tested possibilities of alternative presentations, such as density plots. We then considered we will lose the height resolved amplitude information which is essential to show. We finally preferred to rather keep the present plot style. We inserted the information on the number of profiles before-eruption and after-eruption into the caption of Fig. 2, however.*

L230: It is worth to note that the RMSE of RO is comparable to the estimated ash cloud photogrammetry (see Genkova, I., et al, 2007. Remote Sens. Environ. 107, 211–222. doi:10.1016/j.rse.2006.07.021; Virtanen, T.H., et al., 2014. Atmos Meas Tech 7, 2437–2456. doi:10.5194/amt-7-2437-2014; Zakšek, K., et al., 2013. ACP. 13, 2589–2606. doi:10.5194/acp-13-2589-2013) Those should be referenced.

>>> *Done. We added the following sentence in section 5:*
"These values also agree with estimates obtained with photogrammetry techniques (e.g., Genkova et al., 2007; Zakšek et al., 2013; Virtanen et al., 2014)."

L239: The references to the work of Woods et al. are somewhat confusing. Woods and Self in their 1992 paper refer to studies by Maston as well as Harris et al. regarding the cooling effect, they only use this observation to state that this is also observed in their model. The way this paper is cited here one thinks Woods and Self did those observations which they did not. The same is actually true for the reference to the Woods et al, 1995 paper. Again this paper only used observations made by others, so again this reference should be removed and replaced by references to those papers where the processed the satellite data have been published first.

>>> *Done. We now cite Harris et al. (1981) and Matson (1984) instead.*

L 258: I am a bit confused, here it's a 10 x10 area, above it's a 1 x1 area (L214 and above).

>>> Here we are specifically referring to the selection of the eruption cases where we investigate a 10° x 10° area around the volcano for volcanic clouds to sample a relevant number of individual RO profiles within the clouds.
We included an improved explanation at the beginning of the method section 4.2:
"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."

L270: Instead of strength I would write buoyancy flux because the strength of an eruption is not well defined.
>>> Done.

L317: Please provide a figure similar fig5 for the Puyehue eruption to see how this eruption evolved over time, especially because the eruption of Puyehue contained only volcanic ash.

>>> We included this figure as new Figure 5 and included the following discussion in section 5:
"The further evolution of the atmospheric structure in the Puyehue area is presented in Fig. 5 until August 2011. It shows that the cooling after the volcanic eruption persisted for about two months into July 2011, whereas in August 2011 and subsequent months (no longer shown) the thermal structure had recovered and was back to normal climatological conditions (cf. Fig. 3a and Fig. 4a)."

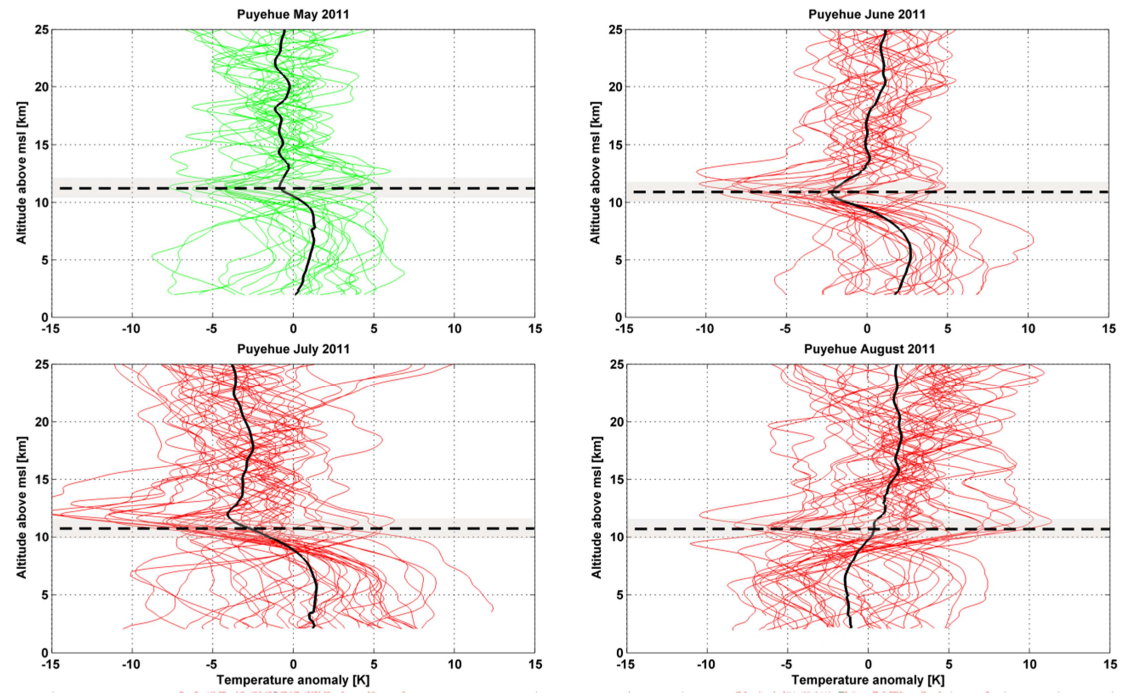

Figure 5. Individual temperature anomaly profiles before the eruption (green) and after the eruption (red) with mean anomaly profile (black) in the area of the Puyehue volcano (10 x 10 degrees box in latitude and longitude), showing the evolution of the thermal structure from May 2011 to August 2011 (Puyehue eruption early June 2011). Climatological tropopause altitude for each month (black dashed line) with its standard deviation (shaded grey).

L334: Is this method fast enough to be used as a real time monitoring system. Could it be used in a similar way as MODVOLC (doi:10.1016/j.jvolgeores.2003.12.008) from HIGP (http://modis.higp.hawaii.edu/) which is used to detect hotspots?

>>> *RO data are available in near real time, within about 3 hours, as needed and currently used for data assimilation in numerical weather prediction. In principle they could therefore be used in near real time to try getting earliest possible detection of volcanic cloud-induced anomalies in the atmospheric structure. At Wegener Center we intend to apply the detection and monitoring technique not in near-real-time but at a so-called fast track, on follow-on day of the observations. This still enables fast day-to-day tracking of emerging and evolving atmospheric volcanic effects, with one day latency but with climate-quality RO data processing with integrated uncertainty estimation and associated more robust diagnostics already (compared to near-real-time).*

Fig4: In that figure you show one mean value (at least that how it looks like). Is that the one for the deep or non-deep convective environment?

>>> *It is the mean anomaly profile for the whole dataset (convective + non convective). We corrected the caption of Fig.4 accordingly.*

Fig5: Why are there 2 black lines in the upper right panel. I assume it is the average for the profiles before and after the eruption but this should be stated somewhere in the caption.
>>> *We updated the caption (of Fig.6 in revised manuscript) accordingly: "Figure 6. … For June 2011 mean anomaly profiles are shown for pre-eruption and for post-eruption cases. …."*