THE 2015 CALBUCO VOLCANIC CLOUD DETECTION USING GNSS RADIO OCCULTATION AND SATELLITE LIDAR

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ABSTRACT

Explosive volcanic eruptions can generate ash and gas clouds rising to the stratosphere and dispersing on a global scale. Such volcanic features are at the origin of many hazards including aircraft engine damages, ash fallouts and health threats. It is thus crucial, to mitigate such hazards, to monitor volcanic clouds dispersion and altitude. In this study, we use the Global Navigation Satellite System (GNSS) Radio Occultation (RO) technique to assess the volcanic cloud altitude resulting from the 2015 Calbuco's eruption. We find volcanic cloud altitude estimations based on RO data in good agreement with the collocated Cloud-Aerosol LIdar with Orthogonal Polarization (CALIOP) and the Infrared Atmospheric Sounding Interferometer (IASI). The preliminary results of this study confirm that automatized RO profiles processing has great potential in the field of volcanic clouds monitoring.

Index Terms— Volcanic clouds, GNSS, Radio Occultation, CALIOP, Calbuco

1. INTRODUCTION

Explosive volcanic eruptions can generate ash and gas clouds rising to the stratosphere and dispersing on a global scale. Such volcanic features are at the origin of many hazards including aircraft engine damages, ash fallouts, acid rains, short-term climate changes and health threats. The ever-growing number of airplanes poses one of the main hazards related to volcanic eruptions. Recent studies have shown the impact of volcanic ash on engines and the need to reroute flights to avoid potentially dangerous areas [1].

Hence, it is crucial to monitor volcanic clouds altitude and dispersion over time in order to prevent these hazards. The past decades have seen significant technological development allowing faster and more accurate volcanic features monitoring e.g. ground-based high-speed and high-resolution cameras [2, 3], airborne aerosols measurements [4] and satellite imaging using different spectral range [5, 6, 7]. Amongst those new techniques, the satellite-based are the ones offering the best coverage of the Earth and thus are the most efficient to study very large volcanic clouds. However, volcanic clouds characterizations still display significant discrepancies depending on the used approach, e.g. up to 4 km in cloud altitude measurements.

In this study, we confirm the ability of Global Navigation Satellite System (GNSS) Radio Occultation (RO) technique to detect and parameterize volcanic clouds. Originally, developed to analyze the atmospheric structure and to perform climatological studies [8], the GNSS RO technique provides atmospheric properties at high vertical resolution (up to 0.1 km) in all weather conditions and over both land and oceans. This technique has been used to characterize the effect of the eruptions of Eyjafjallajökull (Iceland) in 2010, Puyehue-Cordón Caulle (Chile) and Nabro (Eritrea) in 2011 on the thermal structure of the atmosphere [9, 10]. More recently, a study used the GNSS RO approach to precisely estimate the volcanic cloud altitude produced by the Kasatochi eruption in 2008 [11].

In this study, we use the GNSS RO to analyze the 2015 eruption of Calbuco volcano. To enhance control on our results, we use an updated automated algorithm to detect the volcanic clouds from the Cloud-Aerosol LIdar with Orthogonal Polarization (CALIOP) onboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite. Finally, we use Infrared Atmospheric Sounding Interferometer (IASI), onboard the satellites Metop-A and Metop-B, as a second result control of cloud altitude estimations.

2. METHODOLOGY

2.1. Volcano

We focus our analysis on the 22-27 April 2015 Calbuco's eruption. Calbuco is a 1974 m high andesitic stratovolcano located North-East of Puerto Montt city in Chile. The April 2015 eruption was classified with a Volcanic Explosivity Index (VEI) of 4 according to the Global Volcanism Program [12]. The eruption was subdivided into three main phases: 1) occurrence on 22nd of April of a large explosive phase generating an ash plume that rose to 15 km; 2) on 23rd of April stronger activity with an ash plume rising higher than 15 km; 3) lower activity from 23rd to 28th of April with ash plumes rising to 2 km. This eruption was selected in this study for its large VEI and ash plume, ensuring the injection of volcanic aerosols into the stratosphere. In fact, water vapor content of the atmosphere below 10 km altitude is large and generate a significant amount of noise in the RO signal, and there is a higher probability to find meteorological clouds below this altitude which can be mistaken with the volcanic ejected material.

2.2 GNSS RO data

The GNSS RO profiles used in this study have been processed by the Wegener Center for Climate and Global Change (WEGC) with the Occultation Processing System (OPS) version 5.6. In our case, the bending angle of RO data is the parameter we elected to use. The bending angle (BA) profiles provide information about the refraction of the GNSS radio signals in the atmosphere due to variations of atmospheric properties [13, 14] and can provide accurate information on cloud top altitude [9]. In this study, we retrieve the BA anomalies from the RO profiles by using the BA reference climatology for the area of interest calculated based on 5° latitude bands around the Tropics latitude and 10° latitude bands above and below the Tropics, using the whole dataset of RO available from 2001 to 2017 [11].

To obtain an anomaly expressed in percentages each RO BA profile collocated with a volcanic cloud is subtracted with the reference climatology, and the result is normalized by the reference climatology profile [11]. In our case, we used automatic peak detection on our RO BA anomaly profiles and selected peaks displaying a prominence higher than 5%. The presence of volcanic cloud is ensured through the collocation at +/-0.2° and +/- 12h of our RO profiles with volcanic aerosol maps provided by the Atmospheric InfraRed Sounder (AIRS) [15], the Infrared Atmospheric Sounding Interferometer (IASI) [16] and the Global Ozone Monitoring Experiment (GOME) [17]. Collocations of RO BA profiles with other instruments are crucial since the RO is a blind technique as it detects atmospheric anomalies without distinction of the type of cloud responsible for it (e.g. volcanic, meteorological).

2.3 CALIOP data

We have used CALIOP backscatter data to assess the volcanic cloud height and confirm the estimations from the GNSS RO technique. The CALIOP data have been processed using both a manual contouring approach and an automatic customized Matlab algorithm. This algorithm consists of two stages. The first stage consists of applying a succession of filters highlighting the main features visible on the backscatter image while removing noise. The second stage focuses on extracting the identified structures and calculating their respective average altitude.

2.4 IASI data

IASI cloud altitude data were also used to confirm RO altitude estimations. IASI SO_2 retrieval is based on a brightness temperature difference in the SO_2 ν_3 band [18]. The retrieved Vertical Column Density assumes that all SO_2 is located at given atmospheric layers (5, 7, 10, 13, 16, 19, 25 or 30 km a.s.l) providing different estimations at different altitudes. Then the SO_2 cloud altitude is computed with an accuracy of about 2 km for plumes below 20 km [19].

3. DISCUSSION

Figure 1 shows an example of bending angle anomaly profile related to the eruption of Calbuco volcano and displaying a significant peak at 13.4 km altitude, which is close to the average volcanic cloud altitude also detected by CALIOP. This figure highlights how sensitive the GNSS RO data can be to volcanic clouds.

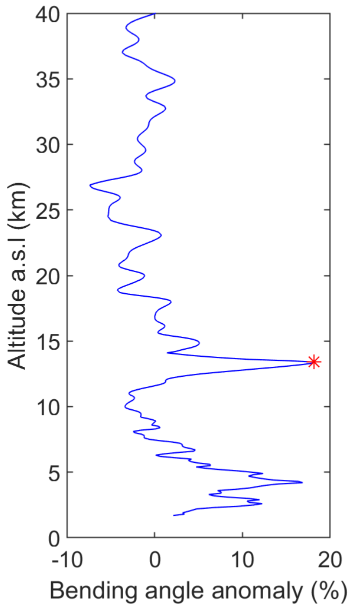

Figure 1: Bending angle anomaly profile taken on 7th of May 2015 at 08:17:43 over the Indian ocean. The red star indicates the maximum value reached by the anomaly 18.2% at an altitude of 13.4 km.

By processing the 5552 RO profiles at our disposal covering the period 22nd of April to 24th of May 2015, we have been able to retrieve the Calbuco's volcanic cloud top altitude over the eruptive period and to compare them to the estimations from CALIOP (62 co-locations) and IASI. Figure 2 shows the scatter plot between the RO cloud top altitudes and the CALIOP cloud top altitudes from manual (blue dots) and automatic (red dots) approaches. The automatic retrieval shows a better agreement with the RO data, Root Mean Square Error (RMSE) 4.28 km, than the manual approach (RMSE 5.21 km). The RMSE is much larger than other eruptions we have analyzed (e.g. [11] and [20]) and this could be explained by the wider vertical and horizontal spread of Calbuco cloud with consequent lower density to which the RO may be not sensitive. The difference between the manual and automatic approach can be instead explained with the involved filters removing the smallest features from the CALIOP image.

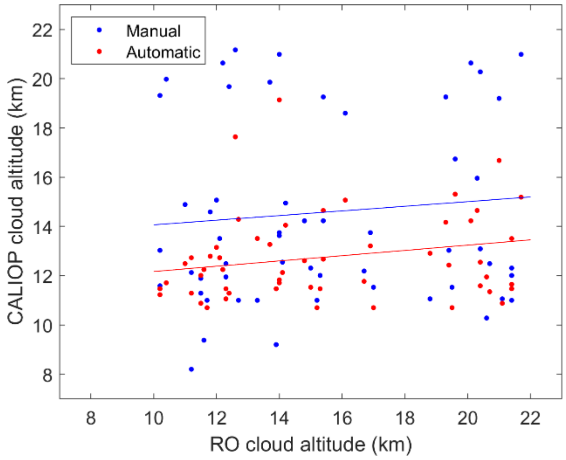

Figure 2: Top cloud altitude manually (blue) and automatically (red) estimated from CALIOP total attenuated backscatter compared to RO BA anomalies.

To control the validity of altitude estimations based on RO data we processed CALIOP backscatter images collocated with the RO profiles and IASI data. For each of the CALIOP backscatter images, our customized Matlab algorithm was used to extract volcanic cloud altitude.

We show in Figure 3 the comparison of daily cloud top height estimation from CALIOP (blue) together with the daily standard deviation (shaded area), the cloud top height from RO (black) and from IASI (green). The average cloud top altitude from RO during Calbuco's eruptive period is 14.8 km a.s.l in good agreement with the Global Volcanism Program report on Calbuco [12] and with the IASI estimations average of 16.4, while the CALIOP automatic algorithm shows an average of 12.0 km. The RMSE between IASI and RO daily estimations is 2.5 km, while the RMSE between the CALIOP and RO is 3.4 km.

Interestingly, CALIOP cloud altitude estimations agree with RO and IASI data for specific days (e.g. 24th of April, 8th and 11th of May) while remaining significantly lower for the rest of the eruptive period. This may be explained by the fact that the retrieval algorithm used here for CALIOP data catches some lower meteorological features and not systemically the volcanic cloud.

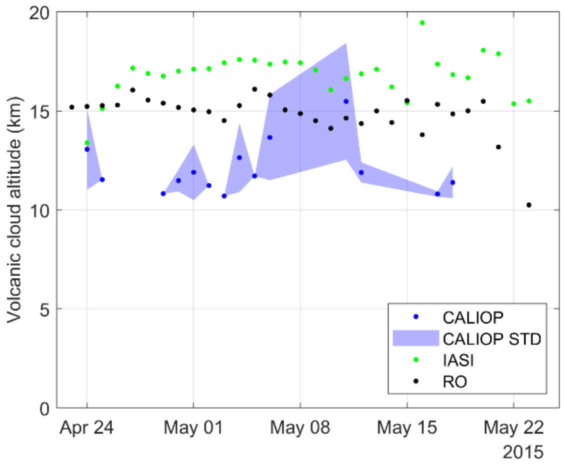

Figure 3: Calbuco's daily volcanic cloud top altitude estimates from GNSS RO BA (black), CALIOP (blue) and IASI (green) during the eruptive period. The shaded area shows the CALIOP cloud top altitude standard deviation (STD) computed on daily temporal range (no shaded area shows a single CALIOP track for the day).

4. CONCLUSION

In this study, we show that RO anomaly technique originally developed for detecting convective cloud tops can be applied in the context of volcanic plumes to estimate their maximum height with a much higher vertical resolution and coverage than other techniques. However, the performances of different techniques can change according to the volcanic eruption. Cigala et al., [11] show a RMSE between RO and CALIOP cloud top estimations of 2 km for the Kasatochi eruptive cloud at ±12h and 1 km at ±4h collocation.

In this study we found a higher discrepancy between the two estimations (4.28 km) probably due to the different density of the volcanic plumes and the higher amount of measurement available in the case of Calbuco. It is important to also notice that daily averaged data between CALIOP and RO collocated at ±12h have a RMSE of 3.4 km while when collocated at ±4h their RMSE goes down to 2.8 km.

We performed this type of analysis for each volcanic eruption with a VEI of 4 that occurred since 2006 and we built a whole new database [20] gathering, for each of those eruptions, several of the primary sensors used to monitor volcanic clouds (e.g. AIRS, IASI, GOME) and new ones (GNSS RO). The new database provides direct access to the volcanic clouds data and enables to perform original analysis and comparisons between different techniques.

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6. REFERENCES

[1] E. I. Gordeev and O. A. Girina, "Volcanoes and their hazard to aviation," *Herald of the Russian Academy of Sciences*, *84*(1), 1–8, 2014.

[2] J. Taddeucci, P. Scarlato, A. Capponi, E. Del Bello, C. Cimarelli, D. M. Palladino and U. Kueppers, "High-speed imaging of Strombolian explosions: The ejection velocity of pyroclasts," *Geophysical Research Letters*, *39*(2), L02301, 2012.

[3] P.-Y. Tournigand, J. Taddeucci, D. Gaudin, J. J. Peña Fernández, E. Del Bello, P. Scarlato, et al., "The Initial Development of Transient Volcanic Plumes as a Function of Source Conditions," *Journal of Geophysical Research: Solid Earth*, *122*(12), 2017JB014907, 2017.

[4] A. Spanu, M. Dollner, J. Gasteiger, T. P. Bui, and B. Weinzierl, "Flow-induced errors in airborne in-situ measurements of aerosols and clouds," *Atmospheric Measurement Techniques Discussions*, 1-46, 2019.

[5] S. Corradini, L. Guerrieri, V. Lombardo, L. Merucci, M. Musacchio, M. Prestifilippo, et al., "Proximal Monitoring of the 2011–2015 Etna Lava Fountains Using MSG-SEVIRI Data," *Geosciences*, *8*(4), 140, 2018.

[6] F. S. Marzano, S. Corradini, L. Mereu, A. Kylling, M. Montopoli, D. Cimini, et al., "Multisatellite Multisensor Observations of a Sub-Plinian Volcanic Eruption: The 2015 Calbuco Explosive Event in Chile," *IEEE Transactions on Geoscience and Remote Sensing*, *56*(5), 2597–2612, 2018.

[7] N. Theys, R. Campion, L. Clarisse, H. Brenot, J. Van Gent, B. Dils, et al., "Volcanic SO2 fluxes derived from satellite data: a survey using OMI, GOME-2, IASI and MODIS," *Atmospheric Chemistry and Physics*, *13*(12), 5945–5968, 2013.

[8] R. A. Anthes, P. A. Bernhardt, Y. Chen, L. Cucurull, K. F. Dymond, D. Ector, et al., "The COSMIC/FORMOSAT-3 Mission: Early Results," *Bulletin of the American Meteorological Society*, *89*(3), 313–334, 2008.

[9] R. Biondi, A. K. Steiner, G. Kirchengast, H. Brenot and T. Rieckh, "Supporting the detection and monitoring of volcanic clouds: A promising new application of Global Navigation Satellite System radio occultation," *Advances in Space Research*, *60*(12), 2707–2722, 2017.

[10] I. Okazaki and K. Heki, "Atmospheric temperature changes by volcanic eruptions: GPS radio occultation observations in the 2010 Icelandic and 2011 Chilean cases," *Journal of Volcanology and Geothermal Research*, *245–246*, 123–127, 2012.

[11] V. Cigala, R. Biondi, A. J. Prata, A. K. Steiner, G. Kirchengast and H. Brenot, "GNSS Radio Occultation Advances the Monitoring of Volcanic Clouds: The Case of the 2008 Kasatochi Eruption," *Remote Sensing*, *11*(19), 2199, 2019.

[12] Global Volcanism Program, Report on Calbuco (Chile) (Venzke, E., ed.). *Bulletin of the Global Volcanism Network*, 40:6. Smithsonian Institution, 2015.

[13] E. K. Smith and S. Weintraub, "The Constants in the Equation for Atmospheric Refractive Index at Radio Frequencies," *Proceedings of the IRE*, *41*(8), 1035–1037, 1953.

[14] E. R. Kursinski, G. A. Hajj, J. T. Schofield, R. P. Linfield and K. R. Hardy, "Observing Earth's atmosphere with radio occultation measurements using the Global Positioning System," *Journal of Geophysical Research: Atmospheres*, *102*(D19), 23429–23465, 1997.

[15] A. J. Prata, G. Gangale, L. Clarisse and F. Karagulian, "Ash and sulfur dioxide in the 2008 eruptions of Okmok and Kasatochi: Insights from high spectral resolution satellite measurements," *Journal of Geophysical Research: Atmospheres*, 2018.

[16] E. Carboni, R. Grainger, T. A. Mather, D. M. Pyle, A. Dudhia, G. Thomas, et al., "The vertical distribution of volcanic SO2 plumes measured by IASI," *Atmospheric Chemistry and Physics*, *16*, 2016.

[17] R. Munro, M. Eisinger, C. Anderson, J. Callies, E. Corpaccioli, R. Lang, A. Lefebvre, Y. Livschitz, A. Pérez Albiñana, GOME-2 on MetOp. In Proceedings of the 2006 EUMETSAT Meteorological Satellite Conference, p. 48, Helsinki, Finland, 12–16 June 2006.

[18] Clarisse, L., Hurtmans, D., Clerbaux, C., Hadji-Lazaro, J., Ngadi, Y., and Coheur, P.-F.: Retrieval of sulphur dioxide from the infrared atmospheric sounding interferometer (IASI), in: Atmos. Meas. Tech., 5, 581–594, https://doi.org/10.5194/amt-5-581-2012, 2012.

[19] Clarisse, L., Coheur, P.-F., Theys, N., Hurtmans, D., and Clerbaux, C.: The 2011 Nabro eruption, a SO2 plume height analysis using IASI measurements, in: Atmos. Chem. Phys., 14, 3095–3111, https://doi.org/10.5194/acp-14-3095-2014, 2014.

[20] Tournigand, P.-Y., Cigala, V., Lasota, E., Hammouti, M., Clarisse, L., Brenot, H., Prata, F., Kirchengast, G., Steiner, A., Biondi, R.: A comprehensive archive of large SO2 volcanic clouds in 2000s. GFZ Data Services. http://doi.org/10.5880/fidgeo.2020.016, 2020.