Introduction. Ground deformations observed in volcanic areas reflect physics processes that develop at depth and are transmitted to the surface through the mechanical properties of the crust (Dzurisin, 2003). For this reason, monitoring of deformation by Global Positioning System (GPS) and its analysis - together with other geophysical and geochemical monitoring data - are essential to assess the volcanic hazard of a specific area. In this work we present the deformation data recorded at Nevado del Ruiz volcano (Colombia) from 2010 to present and their interpretation.

The Nevado del Ruiz Volcanic Complex (NRVC) is part of the North Volcanic Segment of Colombia, a group of eleven volcanoes aligned N-S and extended for 137 km along the highest part of the Central Cordillera of Colombia (San Diego, El Escondido, Romeral, Cerro Bravo, Nevado del Ruiz, Paramillo del Cisne, Nevado de Santa Isabel, Paramillo del Quindio, Paramillo de Santa Rosa, Nevado del Tolima and Cerro Machin). The NRVC has 4 geological stages: the Pre Ruiz effusive volcano 1.8 m.y.b.p.; the 1st Ruiz effusive stage 1.2 m.y.b.p. with the Rio Claro ignimbrite eruption and a caldera formation; the intermediate stage 89,000 y.b.p with the formation of the La Olleta, La Piraña and Nereidas volcanoes; and the actual Nevado del Ruiz stratovolcano 10,000 y.b.p. with explosive eruptions of a central vent that produced pyroclastic flows and surges, debris avalanches, ash falls and lahars (Martinez, et al., 2014).

Nevado del Ruiz is a 5321 m high dacitic stratovolcano, one of the most active volcanoes of the North Volcanic Complex of Colombia. It is located at 4°53’43”N, 75°19’21”W, near the limits of the departments of Caldas and Tolima, approximately 140 km NW of Bogotá (Capital of Colombia) and 28 km SE of Manizales.

On its flat summit lies the main crater called “Arenas” (870 m in diameter and 250 m deep), crowned by an ice cap of about 12 km² from where are born the rivers Lagunilla, Azufrado, Guali and Recio that drain into the Magdalena river to the East, and the Molinos, Nereidas and Alfombrales that drain into the Cauca river to the West. Nevado del Ruiz is built on the complex intersection of four fault groups, where the most significant are the Palestine and Termales-Villamaría faults.

Fig. 1 - The GPS monitoring network of Nevado del Ruiz Volcano is defined by eight stations (BIS, BLLR, GUAL, NERE, OLLE, RUBI, PIRA and SINN) located around the Volcano.
The eruption of 13 November 1985 caused a major disaster in Colombia because the ash fall from a modest explosion in the Arenas crater led to the sudden melting of the volcano ice-cap and the formation of a lahar that reached and destroyed the town Armero and some neighborhoods of the town of Chinchina, causing 25,000 dead. Due to its past eruption history, studying this volcanic complex using ground deformation data has a considerable value for understanding the physical processes controlling its behavior. Furthermore, there is a real need to use this information to serve the communities around the volcano and reduce the volcanic risk.

The volcano has an efficient seismological, geodetic and geochemical monitoring network run by the Colombian Geological Survey by the Volcanological and Seismological Observatory of Manizales. The deformation of Nevado del Ruiz has been monitored since 1985 and in the last years the geodetic network has been enhanced with electronic tiltmeters (since 2007) and permanent GPS stations (since 2011) (Ordoñez et al., 2015). To the present day the GPS monitoring network of Nevado del Ruiz Volcano is defined by eight stations (BIS, BLLR, GUAL, NERE, OLLE, RUBI, PIRA and SINN) located around the Volcano (Fig. 1).

The monitoring record shows that Nevado del Ruiz has been continuously active since 2010 (Fig. 2). This activity includes an increase in seismicity, large gases and ash emissions, deformation and moderate explosive eruptions (VEI = 2) such as those in May and June 2012.

**GPS Monitoring network and data processing.** GPS is a system of military origin, used since the second half of the eighties also for the study of the Earth’s shape (Geodesy). The three-dimensional nature of GPS measurements allows to record vertical as well as horizontal displacements at benchmarks of a monitoring network with extremely high accuracy (error less than 1 cm).

The receivers installed at the permanent GPS sites (CGPS) monitoring Nevado del Ruiz are Trimble Model NetR9, configured to be operated as a continuous operation reference station (CORS) with recording and data storage every 30 seconds and daily file generation. The receivers can acquire satellite signals from the GPS system (L1, L2, L2C and L5) and the GLONAS system (L1 / L2). Additionally, they can acquire signals based on the SBAS (Space Based Augmentation System) technology of both American WAAS signals, as well as EGNOS.
from Europe and Japan MSAS and has 440 channels available to receive satellite signals. The receiver allows nominal accuracies of ± 5 mm in the horizontal and ± 7 mm in the vertical. The antennas installed are Trimble Zephyr Geodetic II, “Ground Plane” type, which are designed to reduce the effect of Multipath and offers sub-millimeter precision in the centering phase.

Daily GPS solutions are processed with GAMIT/GLOBK version 10.61 (Herring et al., 2015). GAMIT/GLOBK is a comprehensive suite of programs for analyzing GPS developed at MIT, the Harvard-Smithsonian Center for Astrophysics (CfA), and the Scripps Institution of Oceanography (SIO) for estimating GPS station coordinates and velocities, stochastic or functional representations of post-seismic deformation, atmospheric delays, satellite orbits, and Earth orientation parameters. GAMIT is collection of programs to process phase data to estimate three-dimensional relative positions of ground stations and satellite orbits, atmospheric zenith delays, and earth orientation parameters. The software is designed to run under any UNIX/LINUX operating system. GLOBK is a Kalman filter whose primary purpose is to combine geodetic solutions (GPS, VLBI, SLR) of different epochs in a unique solution. The input data are the covariance matrices for station coordinates, earth-orientation parameters, orbital parameters and relative positions constrain in a reference frame (coordinates and velocities of reference frame); the results are the estimation of precise coordinates and velocities.

We use several GPS stations from the International GNSS Service (IGS) located in the stable South American plate and 18 stations of the Geodetic Colombian Network GEORED (Geodesia: Red de Estudios de Deformación - https://geored.sgc.gov.co/) to define regional (South America) and local (North Andes block) reference frame.

**Results and modelling.** The 2010-2015 GPS time series show a constant inflation trend and the tilt data shows different inflation periods (Fig. 2). To interpret the cause of ground deformation and understand the source characteristics we inverted the GPS displacements using dMODELS. dMODELS is a MATLAB software package for modeling crustal deformation near active volcanoes that model physical characteristics of a source (location, depth, radius, pressure and volume change) and compute the best-fit between observed and modeled data (Battaglia et al., 2013). The best-fit for the GPS data of NRV between 2012 and 2015 is represented by a spherical source (McTigue, 1987) located 8 km SW from the main crater (Fig. 3). This source ascended between June 2012 and December 2015 from a depth of 17 to 7 km,
with a volume change of approximately $1.5 \times 10^6$ m$^3$. This solution is consistent with the source, located midway between Nevado del Ruiz and Nevado de Santa Isabel volcanoes inferred by InSAR (Lundgren et al., 2015). Analysis of tilt recorded between 2007 and 2012 suggested the accumulation of magma in the shallower reservoir that is feeding the gas release and ash emissions (Ordoñez et al., 2014).

**Conclusions.** Nevado del Ruiz is one of the most active volcanoes of the North Volcanic Complex of Colombia and the GPS data shows that the volcano has had a continuous deformation since 2010. The main activity includes an increase in seismicity, continuous gas (SO$_2$) release, frequent ash emissions, surface deformation and two moderate explosive eruptions (VEI = 2) in May and June 2012. The present volcanic unrest is controlled by two sources:

- **a deep magma reservoir located between Nevado del Ruiz and Santa Isabel volcano (depth $\sim 15$ km, volume change $\sim 10^6$ m$^3$)**, inferred from the inversion of InSAR (Lundgren et al., 2015) and GPS displacements (Fig. 3); analysis of GPS time series suggest that a batch of magma from this source may have moved from a depth of 15 km to a depth of 7 km between 2012 and 2015;
- **a shallow reservoir, inferred from the inversion of tilt data, that is feeding the gas release and ash emissions (Ordoñez et al., 2014).**

**References**


