

# **A new satellite-based method to measure the Volcanic Cloud Top Height: the Plume Elevation Model. Examples on Holohraun (Iceland) and Mount Etna (Sicily).**

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The retrieval of both height and velocity of a volcanic plume is an important issue in volcanology. As an example, it is known that large volcanic eruptions can temporarily alter the climate, causing global cooling and shifting precipitation patterns; the ash/gas dispersion in the atmosphere, their impact and lifetime around the globe, greatly depends on the injection altitude. Plume height information is critical for ash dispersion modelling and air traffic security. Furthermore, plume height during explosive volcanism is the primary parameter for estimating mass eruption rate. Knowing the plume altitude is also important to get the correct amount of SO<sub>2</sub> concentration from dedicated spaceborne spectrometers. Moreover, the distribution of ash deposits on ground greatly depends on the ash cloud altitude, which has an impact on risk assessment and crisis management. Furthermore, a spatially detailed plume height measure could be used as a hint for gas emission rate estimation and for ash plume volume researches, which both have an impact on climate research, air quality assessment for aviation and finally for the understanding of the volcanic system itself as ash/gas emission rates are related to the state of pressurization of the magmatic chamber. Today, the community mainly relies on ground based measurements but often they can be difficult to collect as by definition volcanic areas are dangerous areas (presence of toxic gases) and can be remotely situated and difficult to access. Satellite remote sensing offers a comprehensive and safe way to estimate plume height. Conventional photogrammetric restitution based on satellite imagery fails in precisely retrieving a plume elevation model as the plume own velocity induces an apparent parallax that adds up to the standard parallax given by the stereoscopic view. Therefore, measurements based on standard satellite photogrammetric restitution do not apply as there is an ambiguity in the measurement of the plume position. Standard spaceborne along-track stereo imagers (e.g. SPOT 5, ASTER or Quickbird among the others) present a long temporal lag between the two stereo image acquisitions. It can reach tens of seconds for baseline-to-height ratios (B/H) between 0.2 and 0.5, during which time the surface texture of the plume may have changed due to the plume fast displacement (i.e. velocities larger than 10 m/s) biasing automatic cross correlation offset measurements. For the purpose of the plume surface elevation model extraction, the ideal is as small as possible time lag, with still a B/H ratio large enough to provide a stereoscopic view for restituting the height.

In this study we present a method to reconstitute a detailed map of the surface height of a volcanic eruptive column from optical satellite imagery. We call it the volcanic Plume Elevation Model (PEM). As the volcanic plume is moving rapidly, conventional satellite based photogrammetric height restitution methods do not apply as the

epipolar offset due to plume motion adds up to the one generated by the stereoscopic view. This is because there are time-lags of tens of seconds between conventional satellite stereoscopic acquisitions, depending on the stereo acquisition mode. Our method is based on a single satellite pass. We exploit the short time lag and resulting baseline that exist between the multispectral (MS) and the panchromatic (PAN) bands to jointly measure the epipolar offsets and the perpendicular to the epipolar (P2E) offsets. The former are proportional to plume height plus the offsets due to plume velocity in the epipolar direction. The latter, are proportional to plume velocity in the P2E direction only. The latter is used to compensate the effect of plume velocity in the stereoscopic offsets by projecting it on the epipolar direction assuming a known plume direction, thus improving the height measurement precision. We apply the method to Landsat 8 data taking into account the specificities of the focal plane modules. We focus on the Holuhraun 2014 fissure eruption (Iceland) and on Mount Etna 2013 episode. We validate our measurements against ground based measurements. The method has potential for detailed high resolution routine measurements of volcanic plume height/velocity. The method can be applied both to other multi focal plane modules push broom sensors (such as the ESA Sentinel 2) and potentially to other push-broom systems such as the CNES SPOT family and Pléiades.