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Volcanic Eruptive-Column(Plume)Elevation Model and its Velocity Derived From Landsat 8

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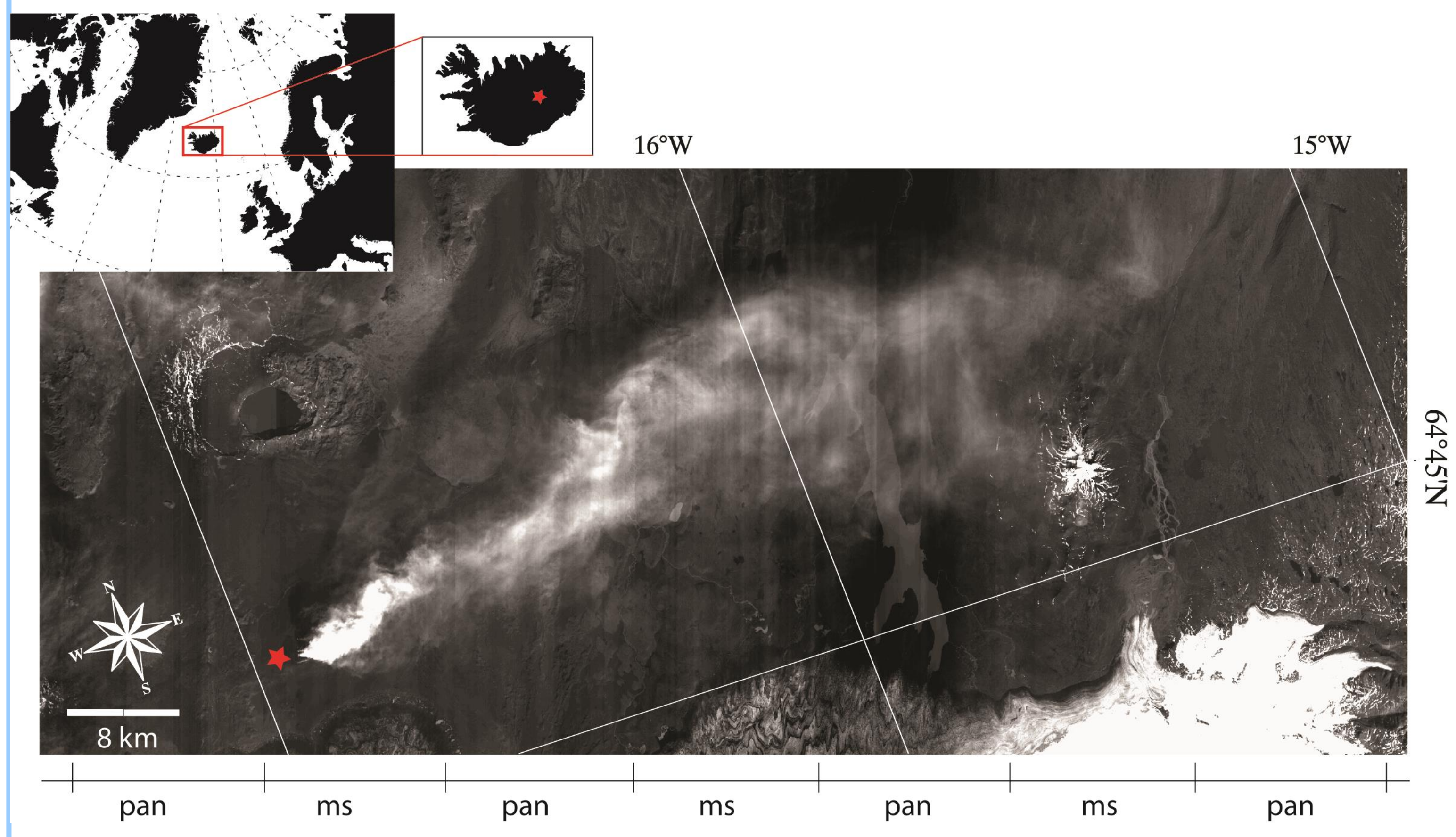
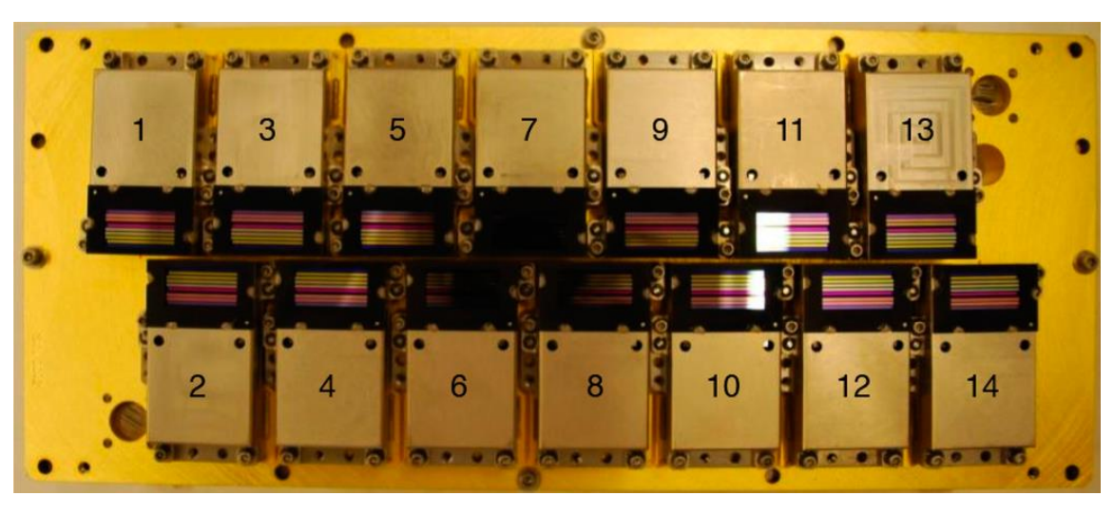
The retrieval of both height and velocity of a volcanic plume is an important issue in volcanology. As an example, it is known that large volcanic eruptions can temporarily alter the climate, causing global cooling and shifting precipitation patterns; the ash/gas dispersion in the atmosphere, their impact 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_2 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 photogrammeric 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 restitute 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.



LANDSAT 8 IMAGES acquisition on **Holuhraun** Eruption

Figure 1. The study area. Holuhraun (Iceland) eruption site (red star) and the volcanic plume from Landsat 8. The data were acquired on 6 September 2014 at 12:25 UTC. We reconstructed this image from raw Landsat 8 data (courtesy of USGS). The image is made of alternate PAN-MS stripes from adjacent FPMs.

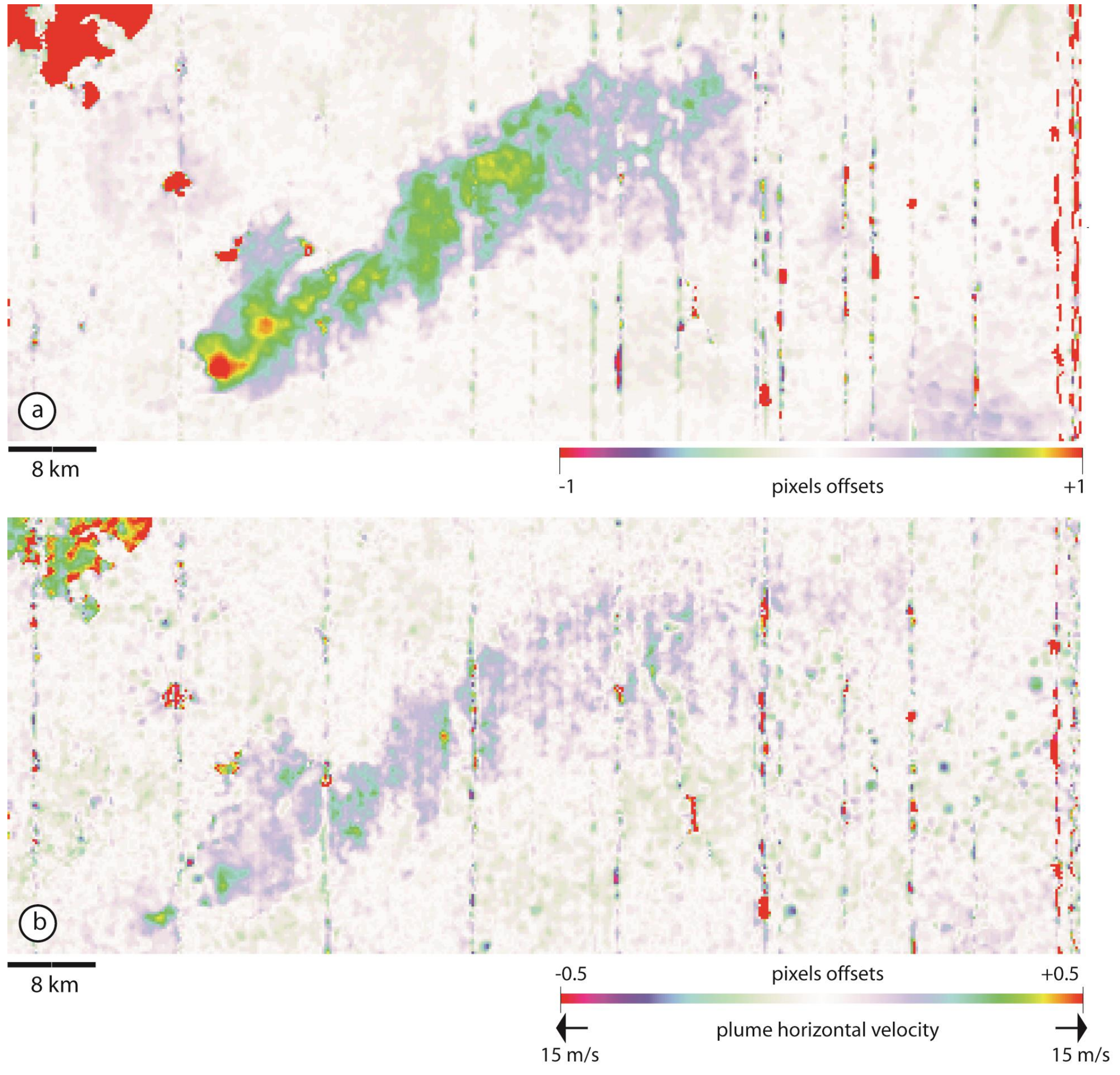


LANDSAT focal plane geometry

Figure 2. The Landsat 8 Operational Land Imager (OLI) is a push-broom (linear array) imaging system that collects visible, Near-InfraRed (NIR), and Short-Wavelength InfraRed (SWIR) spectral band imagery at 30-meter (15-meter panchromatic) ground sample distance (Storey et al., 2014). It collects a 190-kilometer-wide image swath from a 705-kilometer orbital altitude. The OLI architecture is described as follows by Knight et al. (2014) and Storey et al. (2014). The OLI detectors are distributed across 14 separate Focal Plane Modules (FPMs), each of which covers a portion of the 15-degree OLI cross-track field of view

Cross correlation between PAN and MS bands

Figure 3. Pixel offsets from correlation analysis. a) offsets in the epipolar direction due both to parallax and plume velocity in the along-track direction. b) P2E offset due to horizontal plume velocity in the P2E direction.



Results: The Plume Elevation Model (PEM)

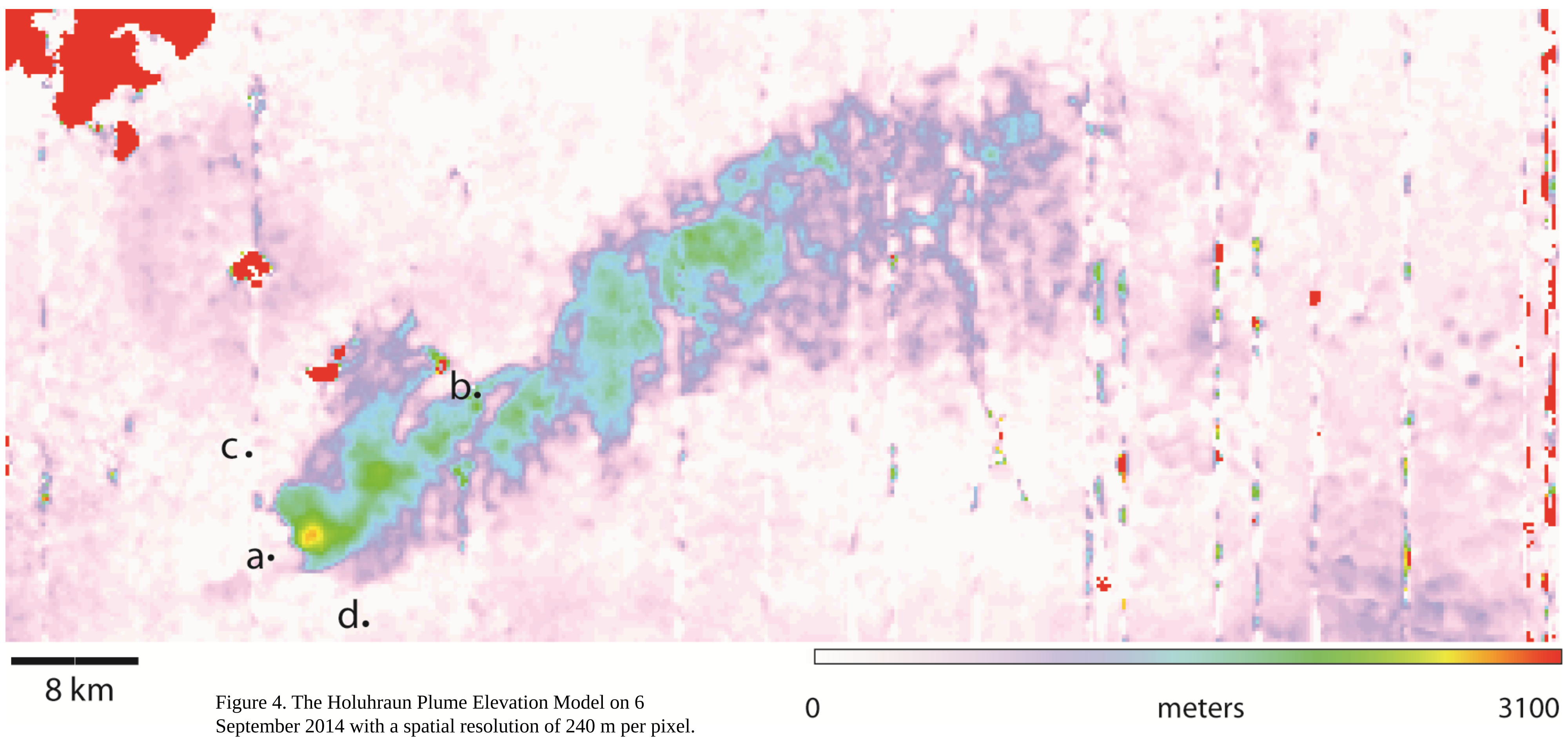
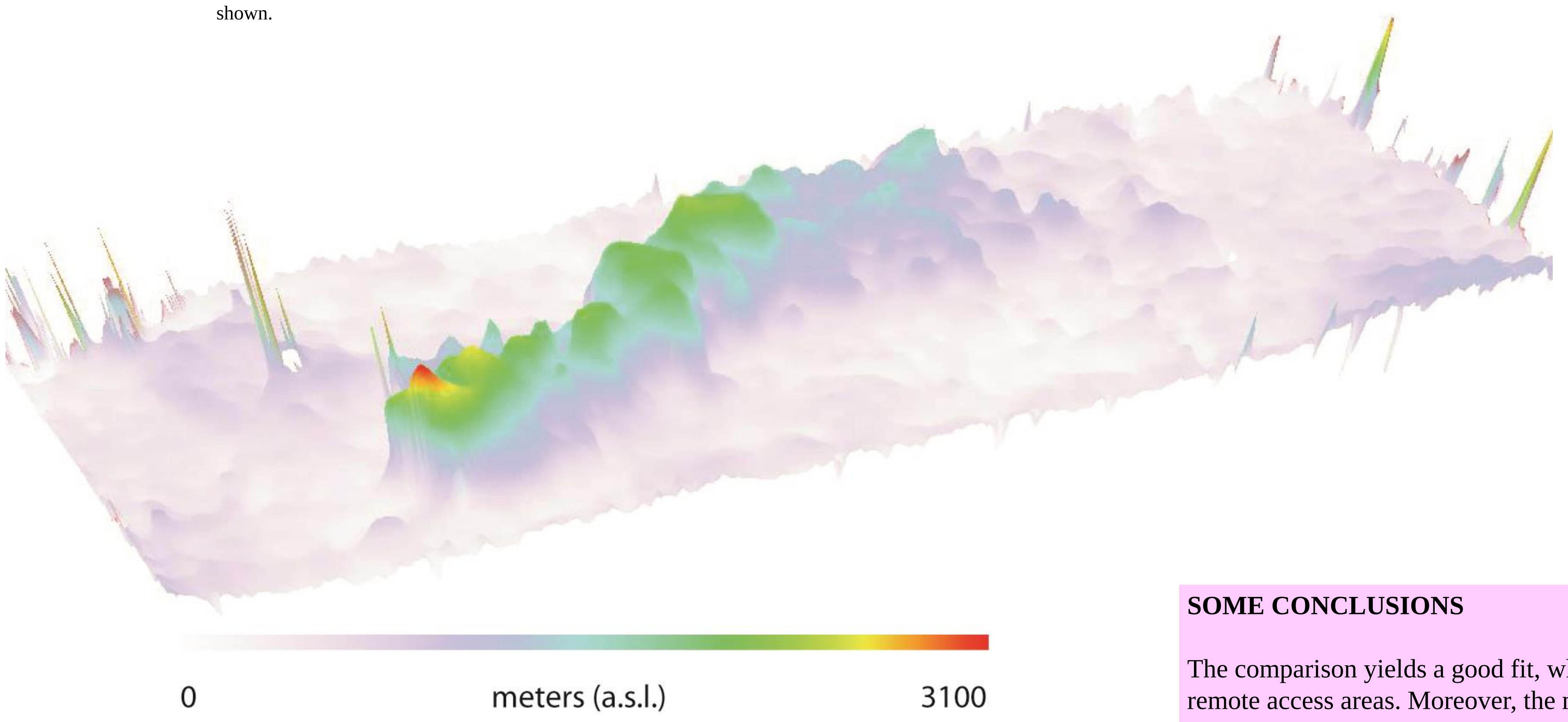


Figure 4. The Holuhraun Plume Elevation Model on 6 September 2014 with a spatial resolution of 240 m per pixel. Location of the a-b and c-d elevation profiles in Fig. 5 are shown.



Volcanic Plume Elevation

Comparison with field measurements

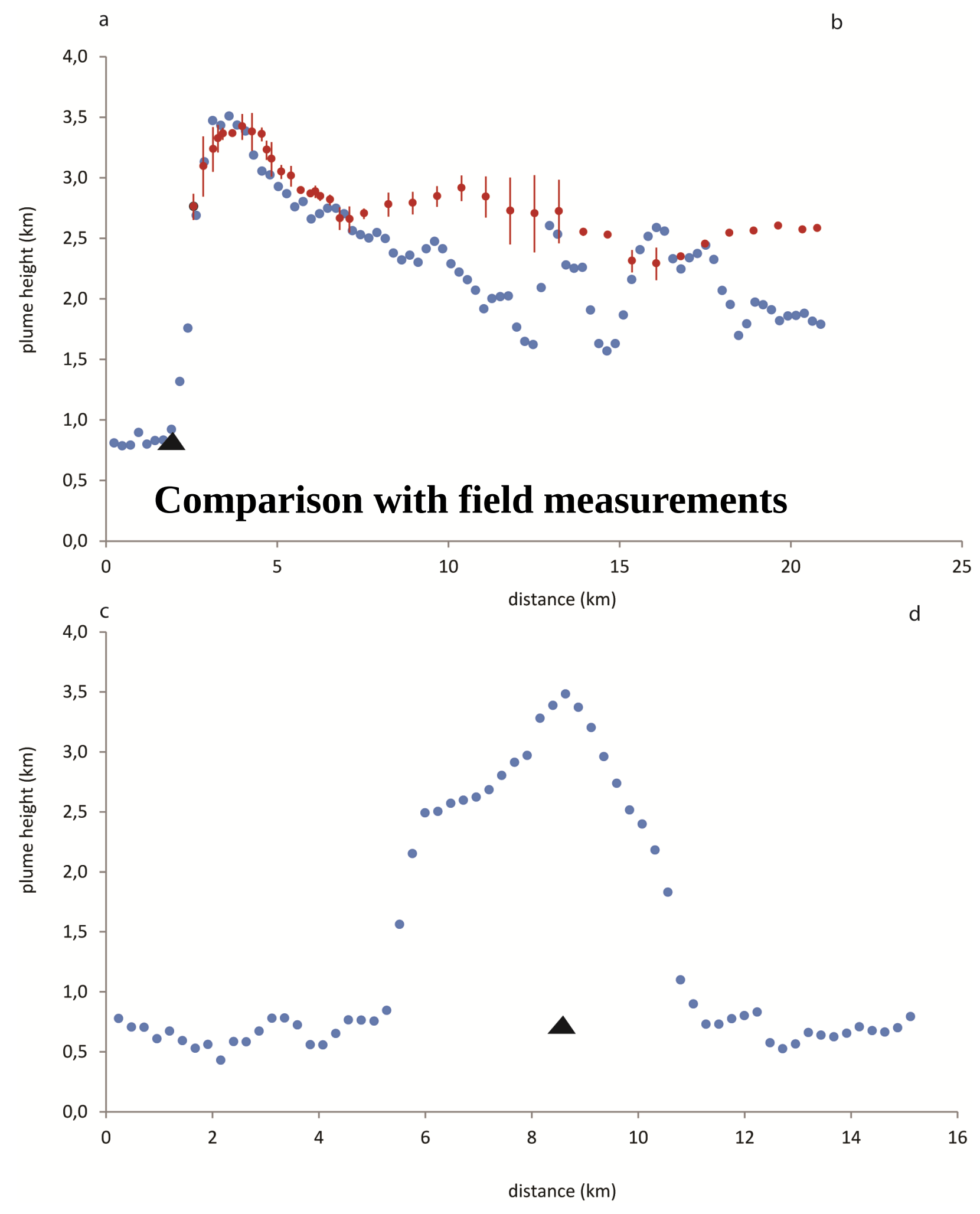


Figure 5. Along-plume elevation profile a-b (top) and across-plume elevation profile c-d (bottom) (see location in Fig. 3). The red circles represent the average of two ground camera measurements at 12:20 UTC and 12:30 UTC that we use for validation. The red bars indicate the difference between the two ground observations. The black triangles represent the location of the eruption site.

SOME CONCLUSIONS

The comparison yields a good fit, which makes us confident about the potential use of our method in remote access areas. Moreover, the method has potential for automation given that the procedure is relatively straight forward and the only input is the spaceborne imagery and associated metadata. The produced PEM is consistent with ground observations for the first 7 km of the profile from the eruption site. The discrepancies are less than 150 m indicating that, in a range of a few km from the eruption site, our method appears to be accurate.

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