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## Sounding the plume of the 18 August 2000 eruption of Miyakejima volcano (Japan) using GPS

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[1] We processed 79 days of GPS data collected at four stations on Miyakejima volcano (Japan) before and during its eruption in 2000. This period includes a strong seismic swarm (27 June to 8 July) followed by five eruptions (8 and 14–15 July, 10, 18, and 29 August). Surface motion is strong during the seismic swarm, then remains almost steady during eruptions. However, during each eruption, we found anomalous values of the LC (ionosphere free) double differences, especially on 18 August, with a peak of 0.6 cycles (i.e., an apparent 290 mm increase of the satellite-station range). We cannot explain these anomalies by temporary ground displacements during the events. Instead, we propose that they are due to path delay effects in the hot volcanic plume. By adapting a seismic tomography algorithm, the refractivity anomaly and the inferred temperature in the plume is mapped in time and space.

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### 1. Introduction

[2] Miyakejima volcano forms a small island ( $\sim 9 \times 9$  km) located 180 km south of Tokyo (Figure 1). On 8 July 2000 after 17 years of rest and 1 week of strong seismicity, a new eruption started [*Japan Meteorological Agency*, 2000; *Shirao et al.*, 2000; *Fujita et al.*, 2001; *Nakada et al.*, 2001; *Sakai et al.*, 2001]. This event dispersed ash over the whole island and triggered formation of a caldera about 1 km in diameter that grew in the following 2 months [*Hasegawa et al.*, 2001], especially during four other eruptions on 14–15 July and 10, 18, and 28 August. Continuously recorded GPS data were collected during that period at four permanent stations (Figure 1) operated since 1996 by the Geographical Survey Institute (GSI) in the framework of the “GEONET” array [*Hatanaka et al.*, 2003]. Here we examine the GPS data of 18 August, when a large plume reached 10 km above sea level (a.s.l.) [*Geshi et al.*, 2002]. On that day, as for the other episodes, we found large residuals in the GPS data at the time of the event. We show here that these residuals cannot be due to a deformation transient, and we interpret them as anomalous GPS path delays through the hot volcanic plume.

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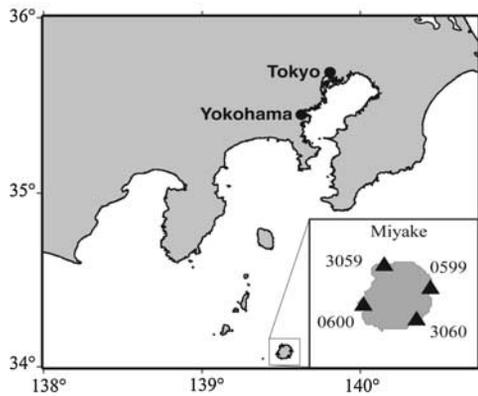
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### 2. GPS Data Analysis

[3] Seventy-nine days (20 June 2000 to 5 September 2000) of data from the four stations were processed using GAMIT software [*King and Bock*, 2001] and precise IGS (International GPS Service) orbits. To obtain coordinates in the International Terrestrial Reference Frame 2000 (ITRF2000) [*Altamimi et al.*, 2002], these data were processed together with data from four IGS stations (TSKB, YSSK, PIMO, KAYT) whose coordinates were fixed at their official ITRF2000 values. Two other GSI stations located on surrounding islands (station 0602 at N32.289, E139.765 and station 3086 at N34.430, E138.838) were also used in the processing to detect any possible global motion of the island. Figure 2 shows the coordinate time series of the four GPS stations. Most of the ground motion occurs during the earthquake swarm before the first eruption, corresponding to a large dyke intrusion mostly offshore to the west of the volcano, as already shown by *Nishimura et al.* [2001]. In the following period, the deformation rate is relatively steady and the changes during eruptions never exceed 50 mm.

[4] However, looking at the post-processing residuals, we found large misfits between observed and modelled LC (ionosphere free) phase double differences during eruption activity. The strongest case is on 18 August with misfits reaching 290 mm (the wavelength of LC is 480 mm). We then discovered that only the double differences with at least one ray crossing the volcano summit area were anomalous. In total, six satellite-station pairs were anomalous on that day (Figure 3).

[5] To obtain the least noisy estimate of the anomalous time series, we averaged for each of the six “anomalous” satellites all the available double difference residuals (typically seven) formed with the GPS station YSSK (located far from Miyakejima on Sakhalinsk island), the local site, the “anomalous” satellite and all the other available satellites. Figure 4 shows that the anomalies start after 0800 UT, 18 August, culminate between 0830 and 0900 UT, and disappear before 1000 UT. This is very close to the timing of the eruption which started at  $\sim 0800$  UT according to field observations, suggesting that the phenomena are linked. Furthermore, the absence of any anomalous signals on paths not passing over the summit area strongly implies that the anomalies are not the consequence of a deformation transient since this would affect all GPS signals. An independent test was made by processing the GPS data epoch by epoch in kinematic mode using the Ashtech Prism software, which showed no significant deformation at the time of the eruption (within  $\pm 20$  mm noise). A local ionospheric anomaly can also be excluded because the LC (ionosphere free) combination is essentially not a function of the ionosphere. We therefore propose that



**Figure 1.** Location of Miyakejima and the four GPS sites (triangles).

the observed anomalies are a signature of the hot volcanic plume, and thus not modelled by the standard GPS processing software (which assumes a laterally homogenous troposphere). The amplitudes of the anomalies, an order of magnitude greater than the noise, show that the detection by GPS of large volcanic plumes is achievable and technically simple.

### 3. Mapping the Refractivity Anomaly in the Plume

[6] We have developed a time-dependent tomographic algorithm by adding time dependence to an algorithm already developed for 3D seismic tomography by *Tarantola and Necessian* [1984] and *Necessian et al.* [1984]. Following these papers, the a priori covariance function  $C_{m_0}$ , including an additional exponential term for the time dependence, becomes

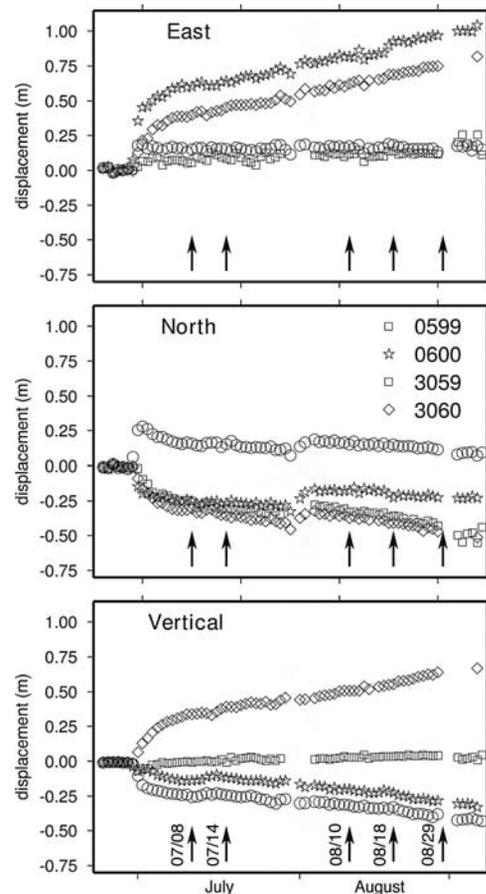
$$C_{m_0}(r, r', t, t') = \sigma_m^2 \exp\left(-\frac{1}{2} \frac{\|t - t'\|^2}{T^2}\right) \exp\left(-\frac{1}{2} \frac{\|r - r'\|^2}{L^2}\right), \quad (1)$$

where  $\sigma_m$  is the a priori uncertainty of the observations,  $t, t'$ ,  $r, r'$  the temporal and spatial coordinates, and  $T$  and  $L$  the temporal and spatial correlation lengths, respectively.

[7] The anomaly is

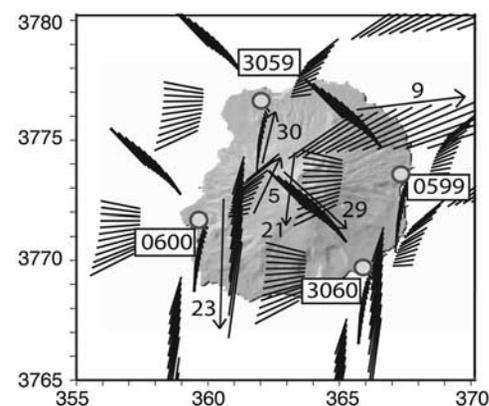
$$\Delta n(r, t) = \sum_i \sum_j (S_{ij}^{-1}) \Delta t_j^{obs} \int ds_i C_{m_0}(r, r_i, t, t_i), \quad (2)$$

with  $S_{ij} = \sigma_r^2 \delta_{ij} + \int ds_i \int ds_j C_{m_0}(r_i, r_j, t_i, t_j)$ .  $L$  and  $T$  are critical to solve the inverse problem. They are a compromise between the true dimensions of the phenomenon and the density of available data. After various trials, we adopted  $T = 15$  min and  $L = 1$  km. Given the apparent velocity of motion of the satellite through the plume, this corresponds to comparable resolutions in space and time. These values are also of the order of one tenth of the size and longevity of the plume, which is sufficient to provide a reasonably detailed description of the phenomenon. In order to improve the computational stability of the inversion, since two consecutive GPS residuals are very close spatially, and appear as very similar rows in the computation matrix, we

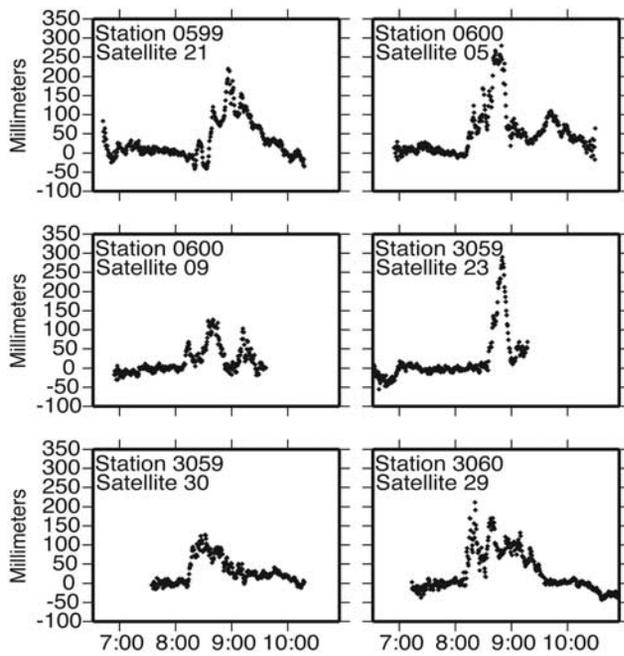


**Figure 2.** Displacement time series of east, north, and vertical components for the four GPS sites. Arrows indicate the dates of the five eruptions. Errors bars are smaller than the symbols.

used a jack-knife mechanism (in which several independent subsets of data are inverted and the results are averaged). Figure 5 displays the non-dimensional results of the inversion (horizontal and vertical cross sections) that



**Figure 3.** Projection of the raypaths at the Earth's surface. The lower and upper altitude cutoffs are 4 and 6 km a.s.l. A line is drawn each 15 min (every 30 data points). Arrows indicate the projection of the trajectory of the six satellites (numbers refers to PRN). Grid is in units of kilometers (UTM54).



**Figure 4.** Residuals on LC (ionosphere free) frequency in millimeters for the six anomalous satellites on 18 August. The eruption as well as the anomalies start at 0810 UT, culminate around 0900 UT, and cease around 1000 UT. These residuals correspond to the heterogeneous delay, the homogenous one being modelled by the software.

correspond to anomalous phase delay length per unit length, expressed in parts per million (ppm). Each image is a map of the troposphere refractivity anomalies integrated over a 15 minute time window. The inferred plume is located above the western part of the island, slightly shifted with respect to the summit of the volcano. This is consistent with the observed distribution of tephra fall deposits which were much thicker in the west of the island (observations made by the Joint university Research Group, Geological Survey of Japan). The refractivity anomaly is larger in the central part of the plume, which is denser and hotter. Its maximum is  $\sim 200$  ppm at 4 km elevation and at 0850 UT. At the same time and elevation, its mean value in a 3-km-diameter cylinder is  $80 \pm 20$  ppm.

#### 4. Interpretation

[8] Several factors can affect the velocity of radio waves in a volcanic plume: temperature, pressure, water vapor, volcanic gases (e.g.,  $SO_2$  or  $H_2S$ ), solid particles (tephra of various sizes). Neglecting the effect of the last two factors according to the study of *Solheim et al.* [1999], the refractivity,  $N$ , of the troposphere is given by the formula of *Thayer* [1974],

$$N = k_1 \frac{P - e}{T} + k_2 \frac{e}{T} + k_3 \frac{e}{T^2}, \quad (3)$$

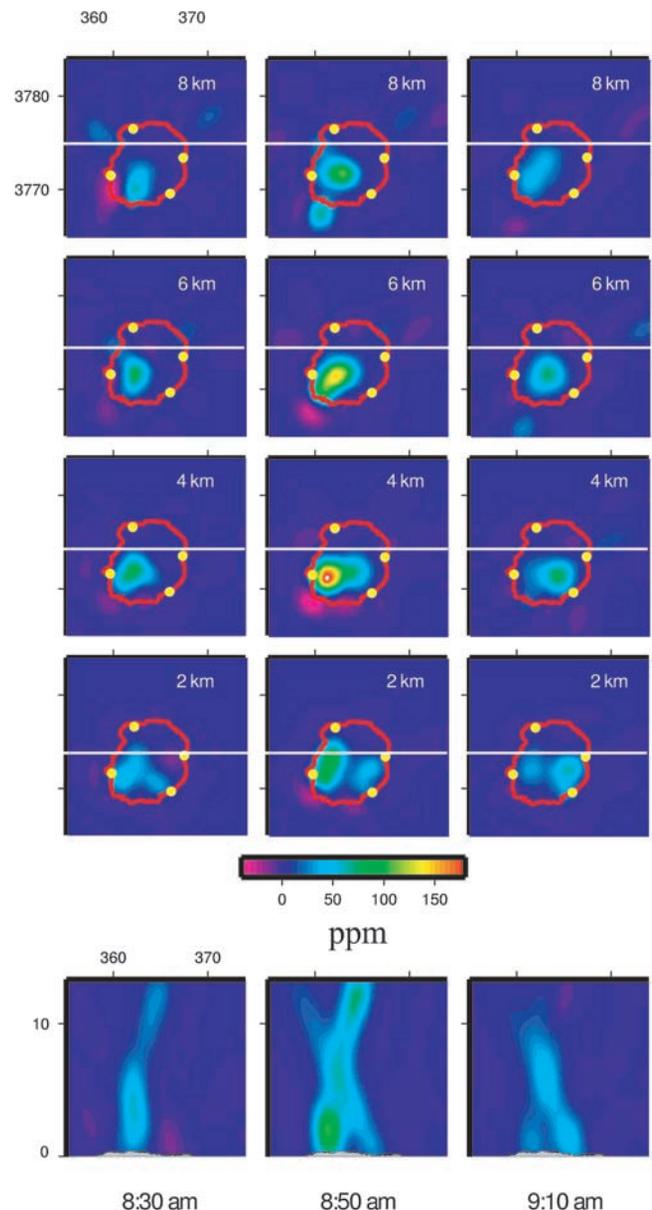
where  $e$  is partial water vapor pressure (hPa),  $T$  is the temperature (Kelvins),  $P$  is the total pressure (hPa), and  $k_1, k_2, k_3$  are three constant parameters ( $k_1 = 77.60 \pm 0.009$  K/hPa,

$k_2 = 69.4 \pm 2.2$  K/hPa,  $k_3 = 370100 \pm 1200$  K/hPa).  $T$  and  $P$  are functions of the elevation  $z$  (km),

$$T = T_{(z=0)} - 0.006z, \quad (4)$$

and, according to *Triplet and Roche* [1983],

$$P = P_{(z=0)} \left( 1 - \frac{6.5 * 10^{-3} z}{288.15} \right)^{5.256}. \quad (5)$$



**Figure 5.** Top: Refractivity anomaly (ppm) maps for different heights and times obtained by time-dependent inversion. (right) For 0830 UT, elevations above sea level (from bottom to top: 2, 4, 6, and 8 km for each map). (center and left) Same elevations at 0850 UT and 0910 UT. The time stamp is the center of the time window. Coordinates are kilometers in UTM54. (bottom) East-west vertical cross sections along the white lines in top images at the same time.

[9] Following *Hanssen* [1998], we use the Clausius-Clapeyron equation to estimate the saturation water vapor pressure  $e_s$ , as a function of temperature  $T$ , the freezing point temperature  $T_0$  and the corresponding partial water vapor pressure  $e_0$ ,

$$e_s = e_0 \cdot \exp\left(\frac{L}{R_e} \left(\frac{1}{T_0} - \frac{1}{T}\right)\right), \quad (6)$$

where  $L$  (latent heat of vaporization of water) =  $2.83 \cdot 10^6$  J/kg,  $R_e$  (specific gas constant for water vapor) =  $461 \text{ JK}^{-1}\text{kg}^{-1}$ ,  $T_0$  (freezing point temperature in K) =  $273.15^\circ\text{K}$  and  $e_0$  (partial water vapor pressure corresponding to  $T_0$ ) =  $6.11$  hPa.

[10] In the plume we expect a higher than ambient temperature, a possible increase of pressure, and an increase of the partial water vapor pressure (which does not imply an increase of the relative humidity  $H = \frac{e}{e_s}$  since  $e_s$  is a rapidly increasing function of  $T$ ). To estimate the effect of each of these parameters, we calculated the partial derivatives of  $N$  with respect to  $T$ ,  $P$ , and  $H$  at an elevation of 4000 m, assuming  $T_{(z=0)} = 298$  K (i.e.,  $T_{(z=4000)} = 274$  K),  $P_{(z=0)} = 1013$  hPa, (i.e.,  $P_{(z=4000)} = 616$  hPa), and  $H_{(z=4000)} = 100\%$ . Around those values of  $T$ ,  $P$ , and  $H$ , the function  $N = f(T, P, H)$  has the following partial derivatives:  $\frac{\delta N}{\delta P} = 0.3$ ,  $\frac{\delta N}{\delta T} = 10$ ,  $\frac{\delta N}{\delta H} = 0.15$ . When  $H = 50\%$ , the partial derivatives are almost unchanged, except  $\frac{\delta N}{\delta H} = 0.3$ . This shows that  $N$  is most sensitive to  $T$ , by more than an order of magnitude compared with  $P$  and  $H$ . In the case of the 18 August eruption, assuming  $H = 100\%$ , the increase of  $N$  to 200 ppm can be explained by an increase of temperature of only 40 K in the central part of the plume, averaged over a volume of  $1 \text{ km}^3$ . Much higher temperatures can exist in the central parts of some volcanic plumes [e.g., *Kienle and Shaw*, 1979; *Woods and Kienle*, 1994]. This apparent discrepancy could be explained if the very hot part of the jet has a cross-sectional area at least 10 times smaller. In such a case the maximum temperature inferred from the 1-km cells of the tomographic analysis is more than 10 times less than the expected temperature in the jet.

## 5. Conclusions

[11] We have shown that it is possible to detect and map the temperature of volcanic plumes using GPS data from nearby stations. In the case of the 18 August 2000 eruption of Miyakejima, the four available GPS sites limit the spatial resolution of the tomography to about  $1 \text{ km}^3$ . Our method could be applied to routine detection and quantification of plumes of other volcanoes equipped with permanent GPS stations. At present, the management of aviation hazard is addressed in large part by the international consortium of Volcanic Ash Advisory Centers (VAAC) using meteorological and environmental satellites. One of the main shortcomings of this method is that it fails in the presence of intermediate and high altitude clouds and is also not operational at night. An independent method based on the real time analysis of permanent GPS data could therefore enhance such an alert network.

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## References

- Altamimi, Z., P. Sillard, and C. Boucher (2002), ITRF2000: A new release of the International Terrestrial Reference Frame for earth science applications, *J. Geophys. Res.*, *107*(B10), 2214, doi:10.1029/2001JB000561.
- Fujita, E., M. Ukawa, E. Yamamoto, Y. Okada, and M. Kikuchi (2001), Volcanic earthquakes and tremors associated with the 2000 Miyakejima volcanic eruptions (in Japanese with English abstract), *J. Geogr.*, *156*, 191–203.
- Geshi, N., T. Shimano, T. Chiba, and S. Nakada (2002), Caldera Collapse during the 2000 eruption of Miyakejima Volcano, Japan, *Bull. Volcanol.*, *64*, 55–68.
- Hanssen, R. (1998), Atmospheric heterogeneities in ERS tandem SAR interferometry, in *DEOS Report Number 98.1*, chap. 2, pp. 8–24, Delft Univ. Press, Delft, Netherlands.
- Hasegawa, H., M. Murakami, and K. Matsuo (2001), Caldera subsidence measurement at Miyakejima summit (in Japanese), *J. Geogr. Surv. Inst.*, *95*, 121–128.
- Hatanaka, Y., T. Iizuka, M. Sawada, A. Yamagiwa, Y. Kikuta, J. M. Johnson, and C. Rocke (2003), Improvement of the analysis strategy of GEONET, *Bull. Geol. Surv. Inst.*, *49*, 11–38.
- Japan Meteorological Agency (2000), Recent seismic activity in the Miyakejima and Nijima-Kozushima region, Japan—The largest earthquake swarm ever recorded, *Earth Planets Space*, *52*, i–viii.
- Kienle, J., and G. E. Shaw (1979), Plume dynamics, thermal energy and long-distance transport of vulcanian eruption clouds from Augustine volcano, Alaska, *J. Volcanol. Geotherm. Res.*, *6*, 139–164.
- King, R. W., and Y. Bock (2001), Documentation for the GAMIT Analysis Software version 10.0, report, Mass. Inst. of Technol., Cambridge.
- Nakada, S., M. Nagai, A. Yasuda, T. Shimano, N. Geshi, M. Ohno, T. Akimasa, T. Kaneko, and T. Fujii (2001), Chronology of the Miyakejima 2000 eruption: Characteristics of the summit collapsed crater and eruption products (in Japanese with English abstract), *J. Geogr.*, *110*, 168–180.
- Nercessian, A., A. Hirn, and A. Tarantola (1984), Three-dimensional seismic prospecting of the Mont Dore volcano, France, *Geophys. J. R. Astron. Soc.*, *76*, 307–315.
- Nishimura, T., O. Shinzaburo, M. Murakami, T. Sagiya, T. Tada, M. Kaidzu, and M. Ukawa (2001), Crustal deformation caused by magma migration in the northern Izu Islands, Japan, *Geophys. Res. Lett.*, *28*, 3745–3748.
- Sakai, S., et al. (2001), Magma migration from the point of view of seismic activity in the volcanism of Miyake-Jima island in 2000 (in Japanese with English abstract), *J. Geogr.*, *110*, 145–155.
- Shirao, M., et al. (2000), Submarine observation of undersea craters in Miyake-Jima 2000 eruption (abstract in Japanese), *Prog. Abstr. Volcanol. Soc. Jpn.*, *5*.
- Solheim, S., J. Vivekanandan, R. H. Ware, and C. Rocken (1999), Propagation delays induced in GPS signals by dry air, water vapor, hydrometeors, and other particulates, *J. Geophys. Res.*, *104*, 9663–9670.
- Tarantola, A., and A. Nercessian (1984), Three-dimensional inversion without blocks, *Geophys. J. R. Astron. Soc.*, *76*, 299–306.
- Thayer, G. D. (1974), An improved equation for the radio refractive index of air, *Radio Sci.*, *9*, 803–807.
- Triplet, J. P., and C. Roche (1983), *Météorologie Generale*, 300 pp., Météo-france, Toulouse, France.
- Woods, A. W., and J. Kienle (1994), The dynamics and thermodynamics of volcanic clouds: Theory and observations from April 15 and April 21, 1990 eruptions of Redoubt Volcano, Alaska, *J. Volcanol. Geotherm. Res.*, *62*, 273–299.

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