Remote Sensing

Supporting Material for

GNSS radio occultation pushes forward the monitoring of volcanic clouds: The case of the 2008 Kasatochi eruption

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Introduction

The file uploaded as Supplementary Material consists of 1) one figure where the bending angle anomaly calculated from the 10° latitude band climatology and the 2.5°x2.5° grid climatology; 2) three Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) backscatter images of the outlier data points, collocation number 5, 22, and 23, the related bending angle anomaly profiles are superimposed on the images. In these cases, the automated peak detection algorithm does not estimate the right volcanic cloud altitudes. A non-perfect spatial and temporal collocation between the volcanic cloud and the radio occultation (RO) profile is the main reason for the wrong estimation. To that, it adds the case where the volcanic aerosol is not widely extended spatially. 3) the altitude estimation table summarizing the volcanic cloud altitudes estimated from the Global Navigation Satellite System (GNSS) RO bending angle anomaly and CALIOP backscatter; 4) a table summarizing the date and time of each collocation; and 5) a table summarizing the error estimations as presented in Figure 3 in the main text.

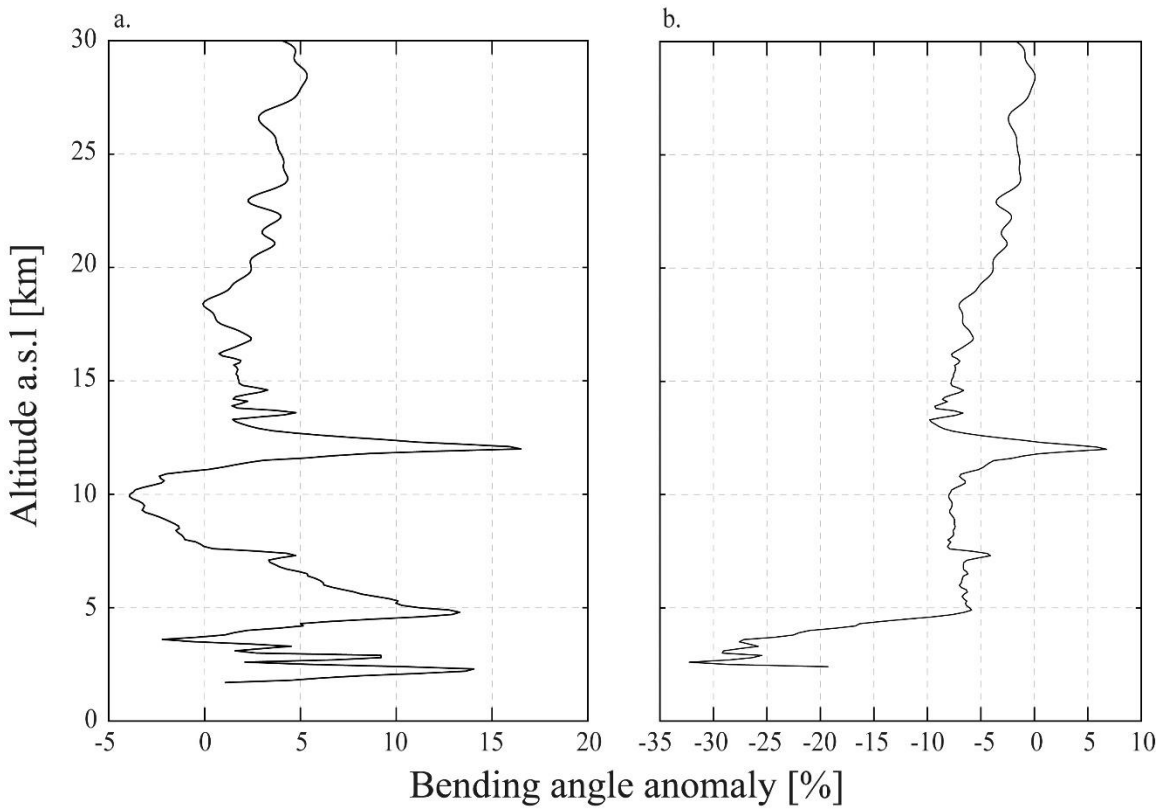

Figure S1. Plot a. shows the banding angle anomaly calculated as described in the main text using a 10° latitude band climatology and shows the same example (collocation number three) as in Figure 1 in the main text. Plot b. shows the banding angle anomaly for the same collocation but calculated using a 2.5°x2.5° grid climatology. The peak corresponding to the volcanic cloud is present in both cases, in plot a. the peak is more prominent than in plot b. The same was seen for all the collocated profiles; thus, we have decided to use the 10° latitude bands.

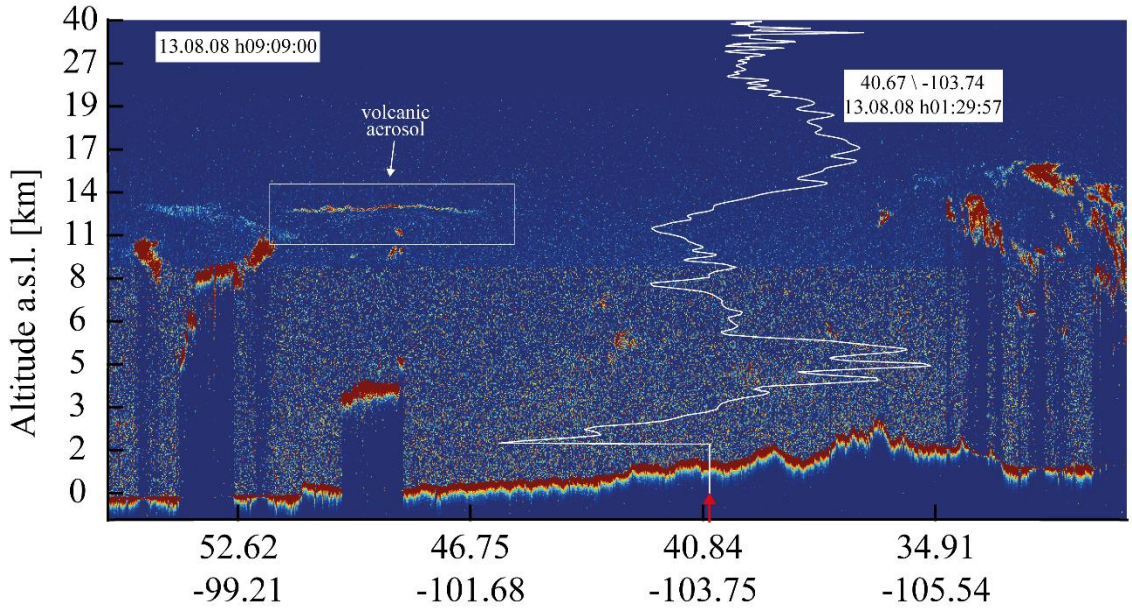

Figure S2. Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) backscatter image (product of level 1) acquired on 13.08.08 with superimposed the collocated bending angle anomaly representing collocation number 5. The radio occultation (RO) profile is not well collocated with the volcanic cloud, and it is also noisy. The automated peak detection detects a peak at about 16 km, while here the volcanic cloud is at about 12 km. The red arrow represents the zero in the bending angle anomaly.

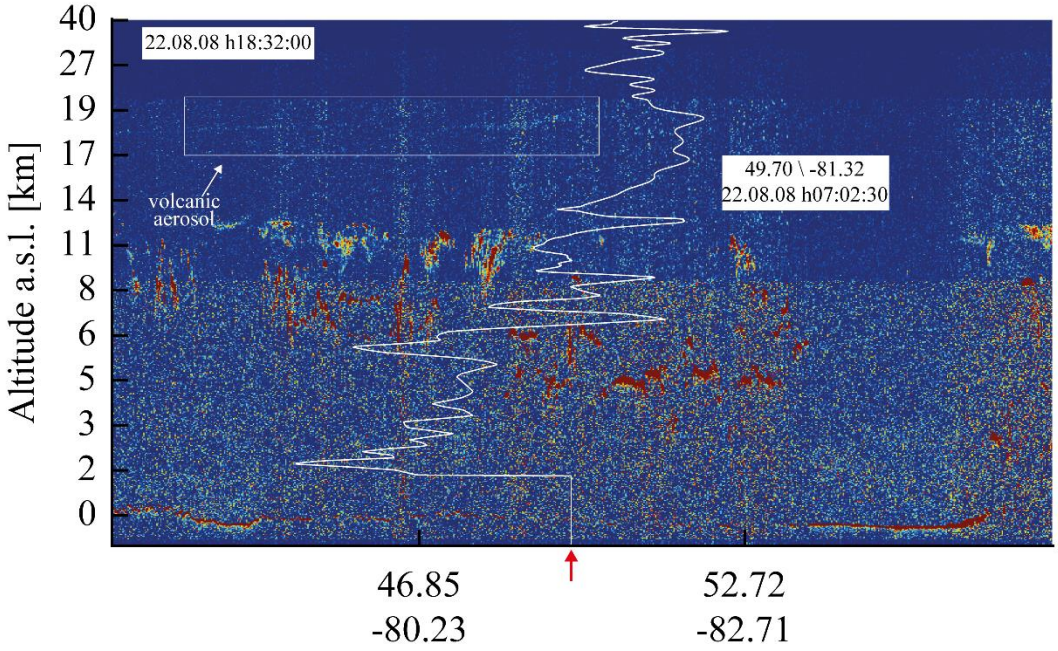

Figure S3. CALIOP backscatter image (product of level 1) acquired on 22.08.08 with superimposed the collocated bending angle anomaly representing collocation number 22. The RO profile is spatially well collocated with the volcanic cloud. However, the automated peak detection detects a peak at about 12 km, while the volcanic cloud is at about 18 km. The red arrow represents the zero in the bending angle anomaly.

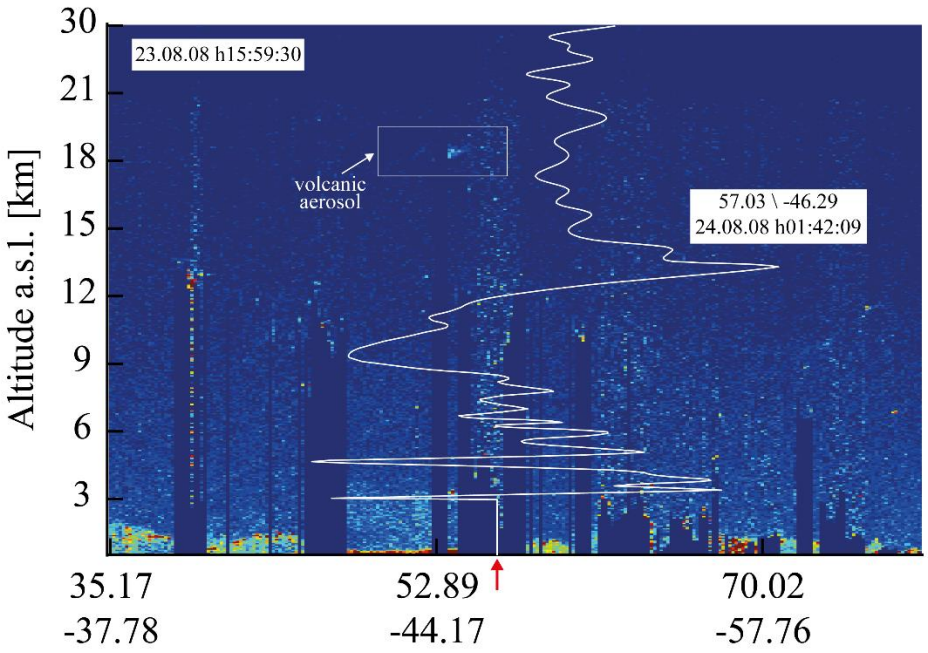

Figure S4. CALIOP backscatter image (product of level 1.5) acquired on 23.08.08 with superimposed the collocated bending angle anomaly representing collocation number 23. The RO profile is spatially well collocated with the volcanic cloud, which is not largely extended, and in the 12 hours range. The automated peak detection detects a peak at about 12 km, while the volcanic cloud is at about 18 km. The product of level 1.5 is a new type of product available from NASA. It is in the 532 nm wavelength, as the product of level 1, however, in this case, meteorological clouds are cleared out and only the aerosol is left. The pixel resolution is also coarser than in level 1. The red arrow represents the zero in the bending angle anomaly.

Table S1 Altitude estimations table. The table summarizes the collocations altitudes estimated from the Global Navigation Satellite System (GNSS) RO bending angle (BA) anomaly and CALIOP backscatter. This data has been used to create Figure 2. Furthermore, the latitude (Lat) and longitude (Lon) of the collocated RO profiles are reported.

	RO cloud altitude [km]	*Lat RO*	*Lon RO*	*CALIOP cloud top [km]*	*CALIOP cloud average [km]*	*CALIOP cloud bottom [km]*
1	10.9	53.678	-168.259	12.07	10.13	8.19
2	12.2	50.231	-163.291	13.09	12.43	11.77
3	12	47.431	-134.352	13.68	12.725	11.77
4	10.4	68.851	-62.485	12.61	12.28	11.95
5	16.6	40.657	-103.740	12.55	12.31	12.07
6	10	59.239	-18.441	12.01	10.19	8.36
7	10.2	68.069	-35.778	12.25	10.96	9.67
8	12.8	49.909	-97.222	13.09	12.16	11.23
9	18.1	46.500	-123.347	17.76	17.31	16.86
10	11.7	67.534	153.773	12.07	11.50	10.94
11	18	39.265	-97.679	18.54	17.88	17.22
12	11.2	59.653	-25.923	12.55	12.01	11.47
13	11	72.446	-23.219	12.43	11.11	9.79
14	15.5	56.899	-87.943	18.12	17.88	17.64
15	10.6	64.834	19.158	13.51	12.07	10.64
16	10	76.959	-27.592	11.24	10.94	10.64
17	12.3	70.498	139.208	12.37	10.58	8.78
18	12.6	46.127	97.335	12.25	10.58	8.90
19	11.9	72.890	146.049	12.07	10.79	9.50
20	11.5	72.770	71.836	12.37	11.24	10.10
21	11.3	64.633	-164.266	11.59	10.28	8.96
22	12.1	49.699	-81.321	19.14	18.27	17.40
23	12.8	57.032	-46.285	18.12	17.76	17.40
24	13.4	62.385	151.075	12.97	12.07	11.17
25	12.6	61.624	165.281	13.09	11.21	9.32
26	10.1	75.323	124.855	11.65	10.37	9.08
27	11.7	79.640	-29.009	12.85	11.29	9.74
28	11.2	71.802	-131.622	12.85	11.29	9.74

Table S2. Table summarizing the date and time of each collocation for the RO profiles, CALIOP, atmospheric infrared sounder (AIRS), infrared atmospheric sounding interferometer (IASI), and Global Ozone Monitoring Experiment-2 (GOME-2). In a few cases, the same RO profile is collocated with two satellite sensors between AIRS, IASI, and GOME-2 at a different time thus giving additional confidence that the volcanic cloud (VC) was present at the time of the RO profile acquisition. Time is in UTC.

	Date RO	*Date CALIOP*	*Date AIRS*	*Date IASI*	*Date GOME*
1	8 August 2008 03:56:53	8 August 2008 13:43:30	8 August 2008 13:42:00		
2	9 August 2008 21:09:31	9 August 2008 23:59:30	9 August 2008 12:48:00		
3	12 August 2008 00:24:00	11 August 2008 22:07:30	11 August 2008 22:06:00	11 August 2008 18:42:16	
4	13 August 2008 17:15:58	13 August 2008 07:22:10	13 August 2008 07:18:00	13 August 2008 14:31:19	
5	13 August 2008 01:29:57	13 August 2008 09:09:00	13 August 2008 09:06:00		12 August 2008 16:41:49
6	14 August 2008 16:37:45	15 August 2008 03:54:50	14 August 2008 12:48:00	14 August 2008 12:30:51	
7	15 August 2008 10:33:27	15 August 2008 05:31:10	15 August 2008 05:30:00		
8	14 August 2008 22:27:25	15 August 2008 08:54:10	15 August 2008 08:48:00	15 August 2008 03:24:14	
9	15 August 2008 12:37:43	15 August 2008 10:34:00	15 August 2008 21:36:00	15 August 2008 05:04:45	
10	17 August 2008 09:09:24	17 August 2008 16:51:10		17 August 2008 01:17:32	
11	18 August 2008 03:19:32	17 August 2008 19:49:20		17 August 2008 16:38:20	
12	17 August 2008 16:38:26	18 August 2008 04:25:40	17 August 2008 13:18:00		
13	18 August 2008 17:39:33	19 August 2008 05:05:10	18 August 2008 05:54:00		
14	20 August 2008 14:28:57	20 August 2008 18:46:20	20 August 2008 18:42:00		
15	21 August 2008 22:21:36	21 August 2008 11:17:30		21 August 2008 18:17:06	
16	21 August 2008 01:35:36	21 August 2008 13:00:10		20 August 2008 18:42:59	
17	22 August 2008 00:51:43	21 August 2008 18:04:30			22 August 2008 00:21:27
18	21 August 2008 19:29:51	21 August 2008 19:50:20		22 August 2008 03:02:30	
19	22 August 2008 04:54:05	22 August 2008 02:09:50		22 August 2008 01:13:09	
20	22 August 2008 02:57:40	22 August 2008 07:06:30			22 August 2008 05:24:45

21	22 August 2008 04:41:36	22 August 2008 13:52:50	21 August 2008 20:11:51	
22	22 August 2008 07:02:30	22 August 2008 18:32:00	22 August 2008 02:38:38	
23	24 August 2008 01:42:09	23 August 2008 15:59:30		23 August 2008 13:55:24
24	24 August 2008 23:57:44	25 August 2008 02:37:40		25 August 2008 00:23:25
25	25 August 2008 18:35:00	26 August 2008 01:41:50		26 August 2008 00:22:53
26	28 August 2008 03:38:17	28 August 2008 03:12:30	28 August 2008 02:29:32	
27	29 August 2008 00:13:24	29 August 2008 12:11:50		28 August 2008 17:09:42
28	29 August 2008 08:43:45	29 August 2008 12:18:00		28 August 2008 22:43:57

Table S3. Error estimation table. The table summarizes the correlation coefficient (R^2), the root-mean-square error (rmse) and standard deviation (std) of the estimation between the RO BA anomaly profiles and the CALIOP backscatter images.

	Correlation coefficient (R^2)	*Root mean square error (rmse) [km]*	*Standard deviation (std) [km]*
RO – CALIOP top	0.65	2.25	1.62
RO – CALIOP average	0.67	1.98	1.51
RO – CALIOP bottom	0.67	2.36	1.42
RO – CALIOP top w/o outliers	0.90	1.38	0.81
RO – CALIOP average w/o outliers	0.88	1.08	0.66
RO – CALIOP bottom w/o outliers	0.83	1.86	1.04
RO – CALIOP top 4h range	0.93	1.07	0.65
RO – CALIOP average 4h range	0.92	1.02	0.65
RO – CALIOP bottom 4h range	0.90	1.92	1.15