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Assessing the solution quality of the earthquake location problem

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1 Introduction

1.1 Motivation

In local earthquake tomography, using precise earthquake hypocenter locations is crucial for obtaining reliable results. Location errors propagate into the derived velocity models due to hypocenter-velocity structure coupling (Thurber, 1992). This coupling results in a trade-off between seismic velocities, epicenter and focal depth due to the dependence of traveltimes on on both distance and wave-speed, therefore, a reliable model of subsurface velocity structure can only be obtained by using well locatable hypocenter locations.

Apart from errors that result from picking the seismic phases, the biggest constraint on location precision is given by the seismic network observing the event. (Bondár et al., 2004) identified four main network criteria for epicenter accuracy: The number of observations, the distance to the nearest station, the azimuthal GAP, and a so-called secondary azimuthal GAP that only contains one station. I take a look at the influence of station geometry, namely the seismic GAP and the number of observations per event on the associated location uncertainties.

1.2 Aim

This Semesterabeit will focus on the influence of the size of the azimuthal gap and the number of observations per event on the properties of the resulting hypocenter location uncertainties. To study these effects, I compute probability density functions for the hypocenter locations in three dimensions with the same dataset for different station geometries. The spatial distribution of hypocenter location probability can be visualized with a point cloud and studied from all directions. It is also helpful to look at the shape, size and position of the 68% confidence ellipsoid that can be calculated from the PDF to track changes in the distribution of the PDF with changing station geometry.

Here, I look at the effects the azimuthal GAP and the nearest station distance have on the location uncertainty of three earthquakes in Switzerland. The seismic network in Switzerland is very dense, and seismicity is constantly monitored by the Swiss Seismologic Survey (SED). These three earthquakes located at different depths and in different tectonic settings are all well observed at a large number of stations. I examine the criteria for reliable earthquake location by changing the station geometry and analyzing the resulting probability density functions for the hypocenter to try and reproduce the findings of (Bondár et al., 2004) and others on real data in a dense network.

My objective was to show the strong dependence of the accuracy of probabilistic hypocenter relocation on event observation, i. e. the seismic network geometry. This dependence should be clearly visible in the spatial distribution of the posterior probability density functions. The results will influence my Master's Thesis, where I will investigate the impact of location uncertainties on local earthquake tomography and on the resulting subsurface velocity structure.

2 Approach

2.1 Non-linear probabilistic earthquake location

The location of an earthquake hypocenter is usually determined by analyzing the misfit between observed arrival times of a seismic phase at a station, and predictions of these arrival times using a given elastic-wave speed model. This inverse problem can be solved iteratively or directly, and the minimum misfit solutions are retained as best estimates of the true location. Numerically, this is often done iteratively with linearized equations (e.g. by using Taylor expansion) but the non-linear problem can also be solved directly by a range of different algorithms (Lomax et al., 2007).

One possibility is the use of posterior probability density functions $\sigma_p(\mathbf{p})$, determined for the model parameters. This function represents a complete probabilistic solution for the earthquake location problem (Lomax et al., 2000).

For the general inverse problem

$$\mathbf{d} = \theta(\mathbf{d},\mathbf{p})\mathbf{p} \tag{1}$$

With data vector $\mathbf{d}$, vector $\mathbf{p}$ for the model parameters and the relationship $\theta(\mathbf{d},\mathbf{p})$, the probabilistic solution for the parameters is expressed as the probability density function

$$\sigma_p(\mathbf{p}) = \rho_p(\mathbf{p}) \int \frac{\rho(\mathbf{d})\theta(\mathbf{d}|\mathbf{p})}{\mu_d(\mathbf{d})} d\mathbf{d} \tag{2}$$

where $\rho_d(\mathbf{d})$ and $\rho_p(\mathbf{p})$ are density functions containing prior information on the data and the model parameters, $\mu_p(\mathbf{p})$ is the density function of null information on the model parameters and the theoretical relationship $\theta(\mathbf{d},\mathbf{p})$ can be expressed as $\theta(\mathbf{d}|\mathbf{p}) * \mu_p(\mathbf{p})$. For complete derivation of the probability density function, see (Tarantola & Valette, 1982).

For the earthquake location problem, the model parameters are the x, y and z coordinates of the hypocenter location, and the origin time. They are an expression of the probability with which the observed event occurred at any point in space and time. By definition, the PDF has unit integral over the entire space of possible locations and times. If we are only interested in the spatial location of the source and not its temporal location, the density function for the spatial coordinates can be obtained by the marginal density function

$$\sigma(x, y, z) = \int_{-\infty}^{+\infty} \sigma(x, y, z, T) dT \tag{3}$$

where the posterior density function is integrated over the range of the origin time T (Tarantola & Valette, 1982).

In the inversion for event hypocenter location, the observed data are arrival times measured at seismic stations and the model parameters are the three spatial dimensions and time. To relate data to parameters, theoretical travel times are calculated (Husen et al., 2003). Prior probability density functions contain what information on the spatial and temporal distribution of the event is available before the inverse problem is actually solved, while posterior probability density functions are calculated for the resulting model parameters. The topography of these functions reflects information on picking uncertainties, the quality of the applied velocity model, the number of stations and network geometry.

The resulting hypocenter location is then given by its maximum likelihood value, which corresponds to the global maximum of the PDF (Lomax et al., 2007). The determination of the maximum likelihood hypocenter in probabilistic earthquake localization is conducted by algorithms sampling the probability density function to find its global maximum. Algorithms used to sample the function might converge on a local maximum, rather than detecting the location of the global maximum likelihood value for the hypocenter location. The choice of the sampling algorithm needs to be evaluated carefully, since any error introduced at this stage will largely influence the location of an event, and thus propagate into all inversions that are conducted on this data. To efficiently locate the maxima of the PDF, NonLinLoc contains, among others, an OctTree importance sampling algorithm that I will use for this report. This method is about 100 times faster than the grid-search that is also built into NonLinLoc, and it generates a cascade of sampled cells that are assigned the PDF values of the cell centers (Husen et al., 2003).

2.2 Application

I use the NonLinLoc software package developped by A. Lomax for probabilistic earthquake location. With this approach, uncertainties of the observed arrival times and their relationship with the predicted travel times are assumed to be Gaussian, and are incorporated into the a priori PDF using covariance matrices for observations (data) and model calculations (Lomax et al., 2000). NonLinLoc is also used by the Swiss Seismologic Survey to routinely locate earthquakes. The posterior probability density function represents the complete probabilistic solution to the earthquake location problem, including information on the uncertainties due to Gaussian picking and travel-time calculation errors, the network geometry, and picking uncertainties (Lomax et al., 2000).

The inversions are run using an OctTree sampling algorithm included in the NonLinLoc software package. This procedure samples 20’000 points of the PDF and draws 5’000 scattered samples from the results of the OctTree search to plot the spatial distribution of the function. The aim of the study is to see the effects of different network parameters on the location uncertainty. The probabilistic approach is especially appropriate here not only because it represents a complete solution to the problem, but also because the three-dimensional point cloud representation facilitates visual interpretation of the uncertainties and their changes with changing network geometry.

2.2.1 Case description

The data for the inversion (Table 1) is a subset of the dataset used in a study by (Husen et al., 2003) on probabilistic earthquake location in Switzerland. I calculate hypocenter location PDF’s with NonLinLoc for a group of events with changing station geometry. The aim of the study is especially to see the effects of an azimuthal GAP >180° on the properties of the resulting PDF.

I study the effects of large GAP on the distribution of the posterior PDF on the example of three earthquakes in different settings very typical for Switzerland 1. These events are observed by a large number of stations and well located 2. The first event lies in the Fribourg region in the western part of central Switzerland. It was recorded on February 14th, 1999 with a moment magnitude of 4.3 and observed by 52 stations in the Swiss seismic network. The north-south distribution of observations for this earthquake was very even, however, due to its western location there was a lack of seismic stations east of the event. The second earthquake happened on the 13th of July 1999 in Pratteln in the Basel area, one of the most active seismic regions in Switzerland due to its location on the Rheingraben fault system. The magnitude of this rather small event was calculated to be 2.7, but due to the spatial density of the seismic network in this area of high seismic hazard, the event was still registred by 36 stations. A spatially uneven distribution of observations of this event results from its location in the network boundary region. The third earthquake is located in

Bad Ragaz, near the Austrian border, in the east of Switzerland. It occurred on February 23rd, 2000, with a moment magnitude of 3.6. Most stations of the Swiss network lie to the west of the epicenter, which again will affect the spatial distribution of the probability density function.

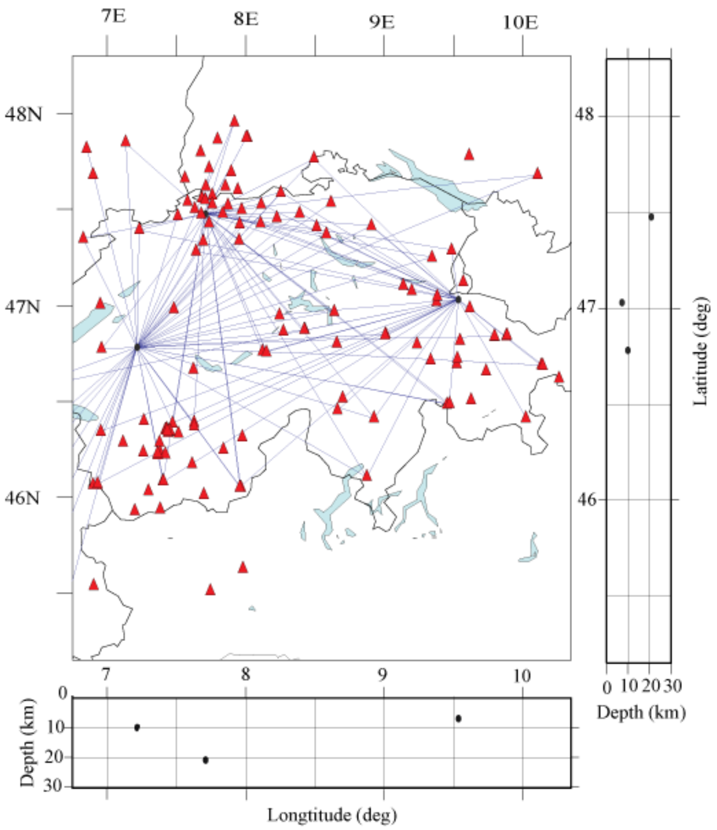

Figure 1: Hypocenter distribution of the three earthquakes used for this study.

Event	Date	M	z [km]	N_obs
Fribourg	1999-02-14	4.3	10.01	52
Pratteln	1999-07-13	2.7	20.97	36
Bad Ragaz	2000-02-23	3.6	7.21	32

Table 1: Name, date of occurrence, moment magnitude, depth obtained from routine location and number of observations for the three events in the dataset.

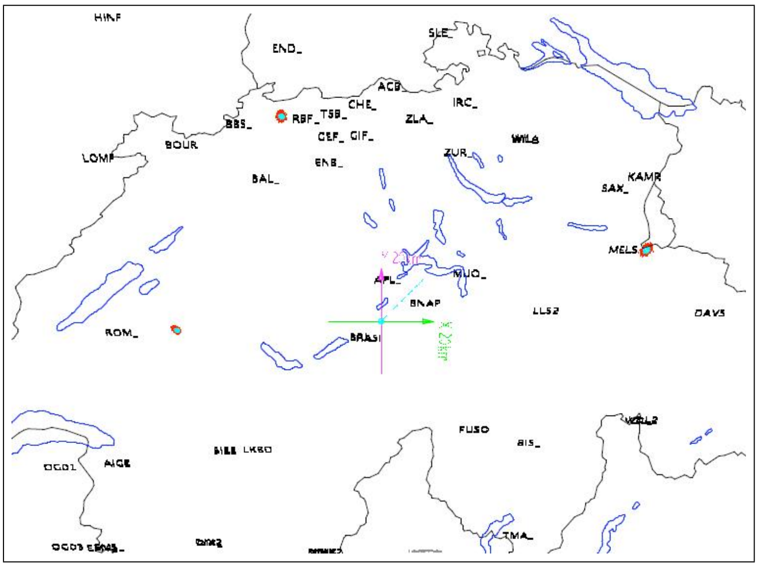

Figure 2: Probabilstic epicenter locations of the three selected events using all available data.

3 Results

3.1 Azimuthal GAP

3.1.1 Effect of azimuthal GAP on epicenter location

The influence of an increase in azimuthal GAP to more than 180° can be observed very well on the case of the Pratteln earthquake in the Basel region. For this event, stations situated northwest of the event were removed from the data, resulting in a small decrease in the number of observations from 36 to 30, and an increase in seismic GAP from 57° to 209°. Figure 3 illustrates the change in the distribution of the posterior probability density function on the surface plane, from a small and more or less circular shape to an ellipse of about twice the size with elongation in NW-SE direction.

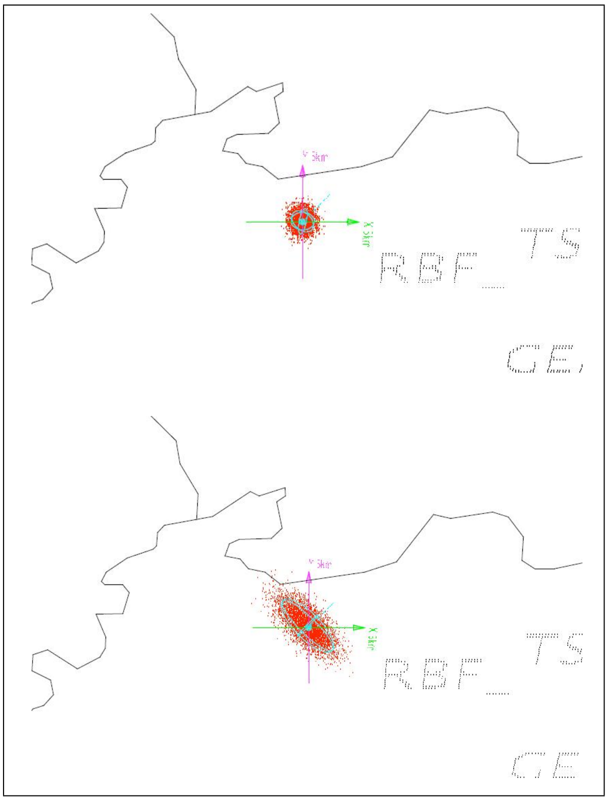

Figure 3: Probability density function on the x-y plane for the hypocenter of the event in Pratteln with GAP=57° (above) and GAP=209° (below). Arrow length is 5 km for both cases.

The GAP of the alpine event near Bad Ragaz was with 134° already quite large with the original data due to its location in eastern Switzerland, where the station array east of the epicenter is sparse. As can be seen in Figure 4, the probability density function of the epicenter location is slightly more elliptic in contrast with the circular shape of the distribution for the Pratteln earthquake in Figure 3. The GAP was increased to 222° by neglecting only 3 stations east of the event, reducing the number of observations from 32 to 29. Figure 4 again shows the surface projection of the posterior probability function, the probability distribution of the epicenter. Like the Pratteln earthquake, the PDF of the Bad Ragaz event grows to about double the size, and ellipticity increases due to elongation in NE-SW direction perpendicular to the remaining seismic network.

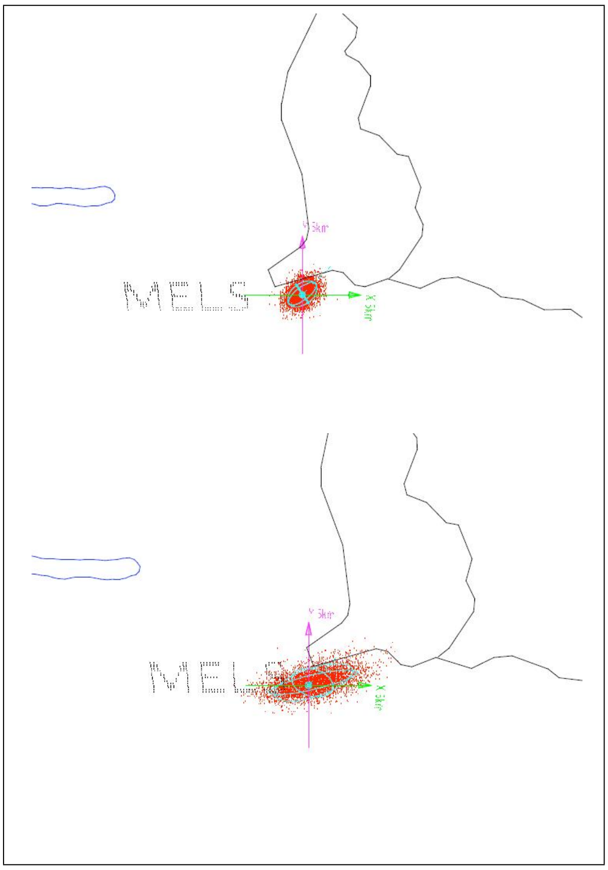

Figure 4: Probability density function on the x-y plane for the hypocenter of the event near Bad Ragaz with GAP=132°(above) and GAP=222° (below). Arrow length is 5 km.

In results from the Fribourg event, the effect of increasing the azimuthal GAP from 69° to 194° by using only 23 of 50 observations can be observed as an increase in the area of the probability distribution for the epicenter location

(Figure 5). The ellipticity of the PDF is slightly larger, and the ellipse is rotated with the longest axis again pointing approximately perpendicular to the closest group of stations.

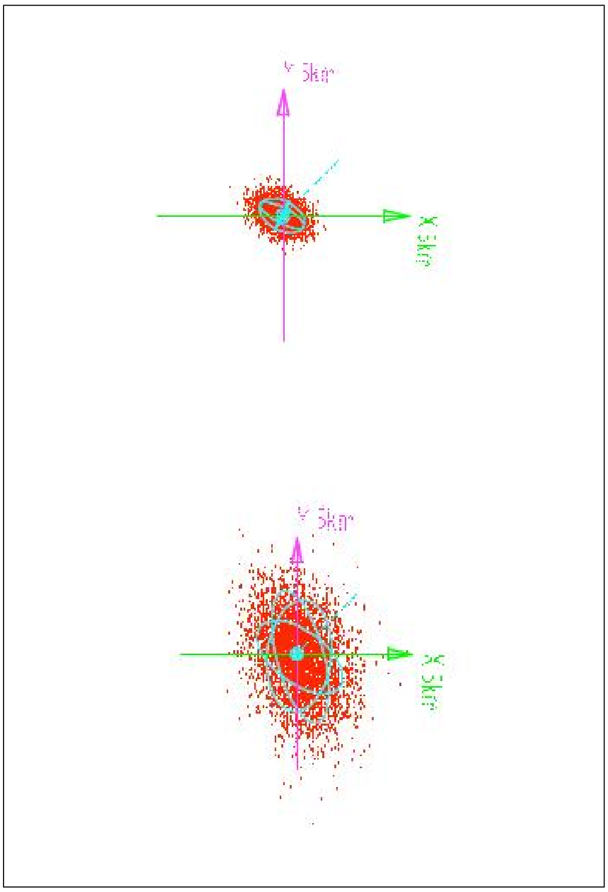

Figure 5: Probability density function on the x-y plane for the hypocenter of the event near Fribourg with GAP=69° (above) and GAP=194° (below). Arrow length = 5 km.

3.1.2 Effect of azimuthal GAP on focal depth

Figure 6 illustrates the depth distribution of the posterior PDF for the Pratteln earthquake both in the x-z and the y-z plane. It is shown that the large increase in GAP from 57° to 209° mostly decreases location accuracy in x (E-W) and y (N-S) directions, while the depth remains relatively well constrained 2. The largest increase of ellipticity in x direction was already seen in the probability distribution for the epicenter in Figure 3.

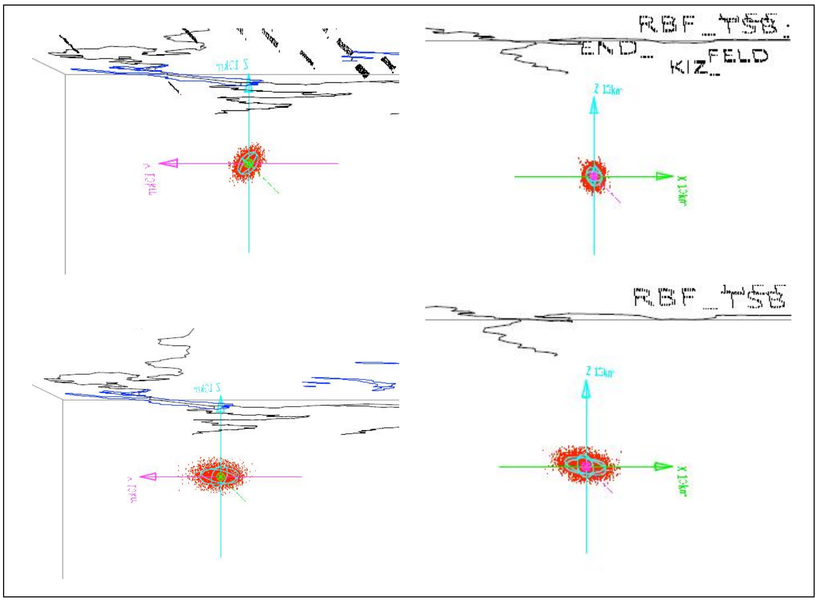

Figure 6: Probability density function on the y-z plane (left) and the x-z plane (right) for the hypocenter of the Pratteln event with GAP=57° (above) and GAP=209° (below). Arrow length is 10 km for all cases.

Similar behaviour can be found for the Bad Ragaz event (Figure 7). Although depth was not constrained very well for this case to begin with, the PDF mainly shows increasing uncertainty in the horizontal directions, going from a highly elliptic to an almost circular shape in the x-z plane. The uncertainty in focal depth basically remains the same for GAP=132° and GAP=222°.

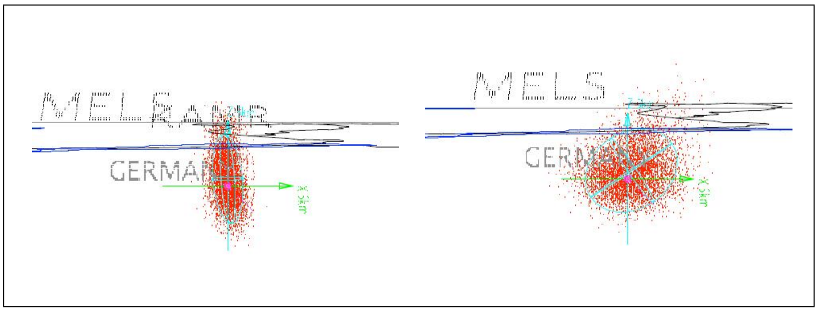

Figure 7: Probability density function on the x-z plane for the hypocenter of the event near Bad Ragaz with GAP=132° (left) and GAP=222° (right). Arrow length is 5 km.

Contrary to the other two cases, in Figure 8 the posterior probability density function for the Fribourg earthquake clearly shows decreasing accuracy for

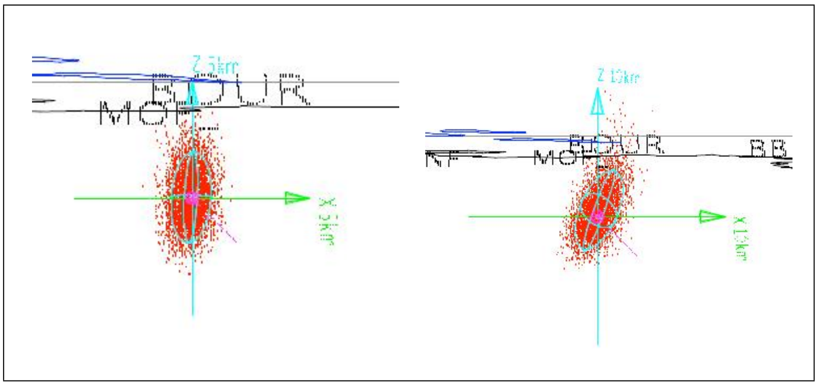

Figure 8: Probability density function in the x-z plane for the hypocenter of the event near Fribourg with GAP=69° (above, arrow length=10 km) and GAP=194° (below, arrow length=5 km).

the focal depth determination. The PDF still grows in size mostly in x (E-W) direction, but there is also a significant increase in the depth component. Whether this phenomenon is a direct consequence of the increase in azimuthal GAP or rather related to the large number of stations that were neglected, leaving only one station in a radius of 56.8 kilometers remains to be determined.

3.2 Nearest station distance

3.2.1 Effect of nearest station distance on epicenter location

Figure 9 shows nicely the effect of neglecting the station closest to the epicenter on the distribution of the posterior location PDF on the surface plane for the alpine Bad Ragaz event. The distribution does not vary significantly and the azimuthal GAP remains 222° when leaving out the station in Mels. The axes of the 68% confidence ellipsoid give a quantitative measure to the distribution, and it can be seen from table 2 that leaving out the nearest station mainly elongates one axis and has little effect on the others.

The inversion for the Pratteln earthquake results in a probability density function that is very similar to the one for the Bad Ragaz event (Figure 10). This result is important, since the GAP is not changing at all without the nearest stations for both cases, and the nearest station distance is the only factor differing in the two images.

The largest changes in the posterior probability density function of the epicenter due to the nearest station distance can be observed in the Fribourg event (Figure 11). Here, the distance to the nearest station is almost tripled from 19.8

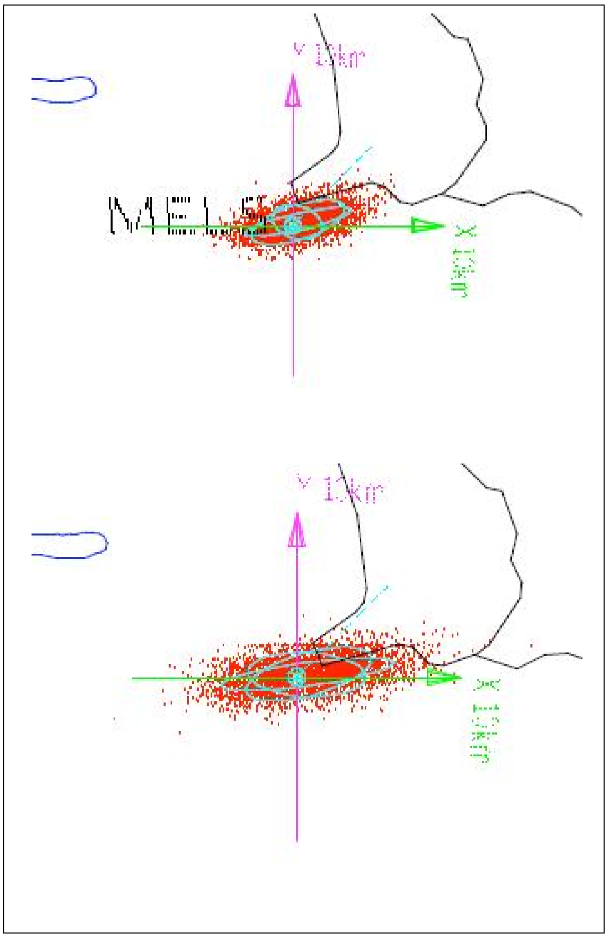

Figure 9: Probability density function on the x-y plane for the hypocenter of the Bad Ragaz event with GAP=222° (above) and GAP=245° (below). Arrow length is 10 km.

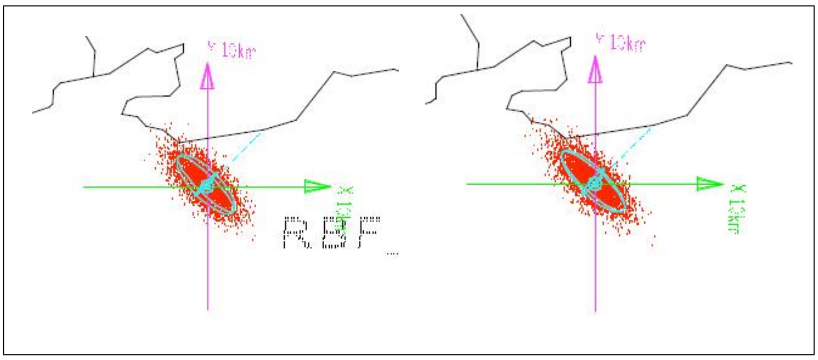

Figure 10: Probability density function on the x-y plane for the hypocenter of the Pratteln event with GAP=209° for both cases. Arrow length is 10 km.

km to 56.9 km, and the azimuthal GAP increases from 194° to 256°. These changed parameters increase the ellipticity of the PDF surface projection, as well as increasing the depth of the maximum likelihood hypocenter from 7.4 to 10.8 kilometers 2.

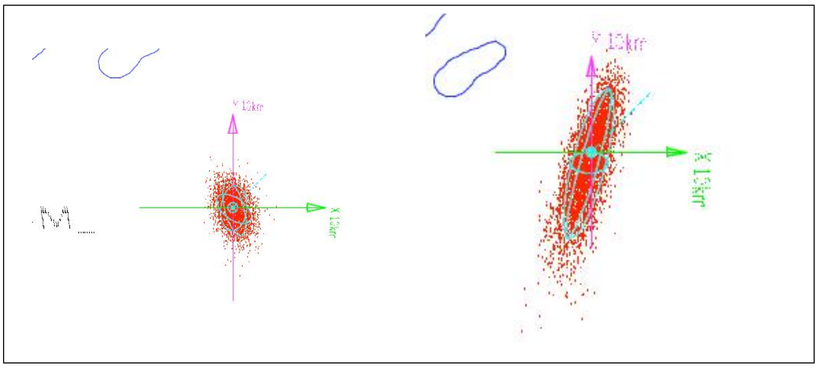

Figure 11: Probability density function on the x-y plane for the hypocenter of the Fribourg earthquake with GAP=194° (left) and GAP=256° (right). Arrow length is 10 km.

3.2.2 Effect of nearest station distance on focal depth

The effect of the epicentral distance to the nearest station in the seismic network on the focal depth can be seen very nicely on the example of the Fribourg event (Figure 12). Here, neglecting the nearest station of the seismic network in combination with a large azimuthal GAP leads to an elliptic shape in the y-z plane, directed away from the remaining stations. Without the station near the seismic source, the network can no longer separate depth from horizontal distance, resulting in a trade-off between the y coordinate (N-S) and depth that can be observed in the curved distribution of the sampled PDF. Focal depth of the maximum likelihood hypocenter increases largely from 7.4 to 10.8 kilometers.

Figure 13 shows the PDF of the Bad Ragaz earthquake on the y-z plane. Focal depth was not very well constrained for this event to begin with, and leaving out the MEL seismic station in the inversion results in an even bigger ellipsiod that is directed towards the surface away from the observing network. In this case the posterior probability density function for the hypocenter is cut off by the intersection with the surface, a consequence of the large uncertainty for an earthquake at relatively shallow depth. The depth location of the maximum likelihood hypocenter decreases sharply from 5.8 to 1.9 km, and the growing

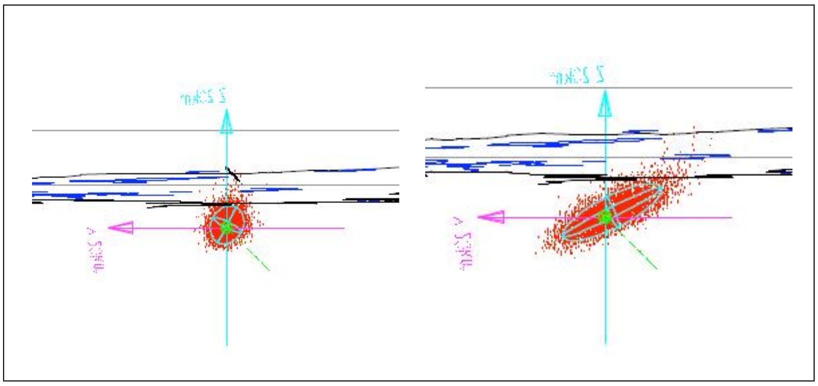

Figure 12: Probability density function on the y-z plane for the hypocenter of the Fribourg event with GAP=194° (left) and GAP=256° (right). Arrow length is 20 km.

size of the PDF can be attributed to the effect of the epicentral distance to the nearest station on the focal depth uncertainty.

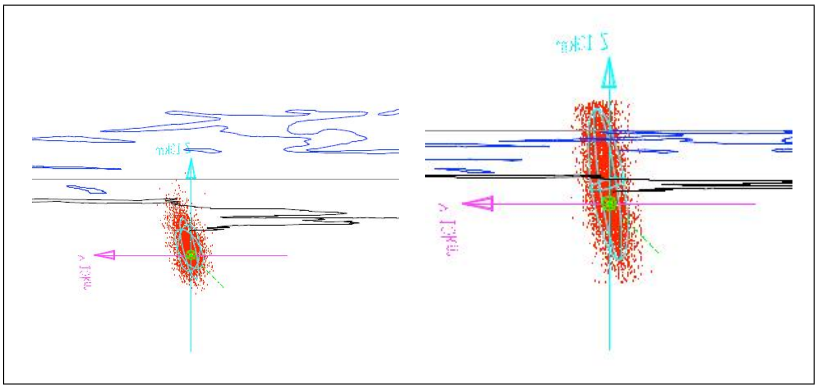

Figure 13: Probability density function on the y-z plane for the hypocenter of the Bad Ragaz event. Arrow length is 10 km.

The event in Pratteln (Figure 14) is a special case regarding the influence of nearest station distance on the probability density funciton for the hypocenter. With a routine location depth of 20.97 km it is the deepest of the three events, while the seismic network is very dense due to the increased seismic hazard in this region, so the focal depth of the Pratteln earthquake is still well constrained without the nearest station. In fact, the y-z distribution of the posterior probability density function shows no significant changes in shape or size without the data of the station nearest to the event.

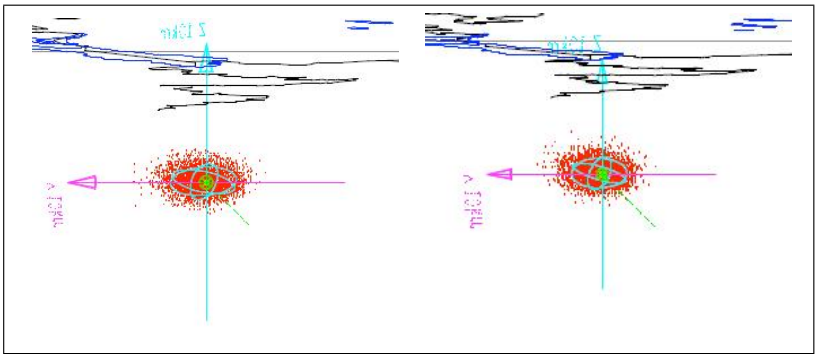

Figure 14: Probability density function on the y-z plane for the hypocenter of the Pratteln event with distance to the closest station equal to 10.7 and 20.3 kilometers. Arrow length is 10 km.

Run	Epicenter	z[km]	GAP	N_obs	Ellipsoid	Dist
Fribourg 1	46.78N 7.21E	7.02	69°	50	0.59 0.96 1.97	19.77
Fribourg 2	46.79N 7.22E	7.40	194°	23	1.49 2.69 3.60	19.77
Fribourg 3	46.85N 7.25E	10.76	256°	22	1.85 2.80 8.95	56.86
Pratteln 1	47.51N 7.70E	17.95	57°	36	0.96 1.05 1.42	10.74
Pratteln 2	47.51N 7.70E	18.06	209°	30	1.11 .153 3.16	10.74
Pratteln 3	47.51N 7.70E	18.03	209°	29	1.14 1.63 3.33	20.33
Bad Ragaz 1	47.05N 9.51E	4.81	132°	34	0.90 1.41 3.50	9.29
Bad Ragaz 2	47.05N 9.47E	5.81	222°	29	1.17 2.53 3.84	6.68
Bad Ragaz 3	47.05N 9.47E	1.93	222°	28	1.15 3.26 5.29	41.91

Table 2: Name, maximum likelihood epicenter location and focal depth, GAP, number of observations, lengths of the three main axes of the 68% confidence ellipsoid, and distance from the closest station to the epicenter for every run with the original data (1), increased azimuthal GAP (2) and with increased azimuthal GAP and nearest station distance (3).

4 Discussion

4.1 The influence of azimuthal GAP on epicenter location

For a dense and well-distributed network with a small seismic GAP like in the situation of the Pratteln earthquake, the epicenter is well constrained with probabilistic earthquake location. The probability density distribution on the surface plane is circular with a small radius of a few kilometers. In the other two cases, where the events lie near the boundaries of the Swiss seismic network and there are only few stations to one side of the event, the initial distribution of the PDF on the x-y plane is already slightly elliptic. The GAP of 132° for the Bad Ragaz earthquake is already above the value stated by (Bondár et al., 2004) for accurate hypocenter location, but the axis lengths are still small.

It can be seen clearly from the plotted results that the probability density functions of epicenter locations for all events change both in size and geometry when the azimuthal GAP is increased above 180°. Ellipticity increases in the direction perpendicular to the remaining observation network, or, in the case of the Fribourg event, the portion of the remaining network that is close to the event. Since the length of the short axis of the ellipse remains more or less constant, the area of the surface projection of the posterior probability density function, which represents the total uncertainty of the epicenter location, increases.

4.2 The influence of azimuthal GAP on focal depth

Focal depth accuracy seems to be unaffected by a large increase in GAP when looking at the Pratteln and Bad Ragaz events. The plotted PDF's again show the increase of uncertainty in the horizontal direction perpendicular to the network, but no changes on the depth axis. While the Pratteln earthquake is quite deep (approximately 20 km), and situated in a dense network, the Bad Ragaz event was originally located at about 7 km and lies in the network boundary region. Consequently, the focal depth PDF's calculated with the original data are very different, with a very well constrained hypocenter at large depth for the Pratteln (Figure 6) and a shallow hypocenter with large uncertainty for the Bad Ragaz event (Figure 7). Since there is no visible change in the accuracy of the focal depth determination, and little change in the depth of the maximum likelihood hypocenter especially for the Basel event, it is reasonable to assume that focal depth is constrained by some other parameter, probably the epicentral distance to the closest station, for these two events.

Different behaviour is observed for the Fribourg earthquake (Figure 8). Although the shape of the probability density function in the x-z plane remains quite similar, lenght of the axes of the ellipse, and therefore the area increase. Special in terms of the station geometry for the Fribourg event is the distance from the maximum likelihood epicenter to the smaller seismic network (Figure 15). Without station ROM at 20km, the nearest station to the event (BAL) lies at a distance of more than 60 kilometers, while the original estimate of focal depth was only 10 km. As a rule of thumb the nearest station distance should be approximately in the range of 1* the focal depth to impose a good depth constraint. Stations at distances from a few to over 100 kilometers contain information for different ray take-off angles, and are needed to constrain the focal depth. To reach an azimuthal GAP>180° for this event, 3 stations in 20 to 60 km distance were excluded from the inversion. In this case, the increasing focal depth uncertainty can probably be explained not as a direct consequence of the increase in seismic GAP, but to be caused by the geometry of the new observation network, where close stations are sparse and the nearest station distance is twice the focal depth.

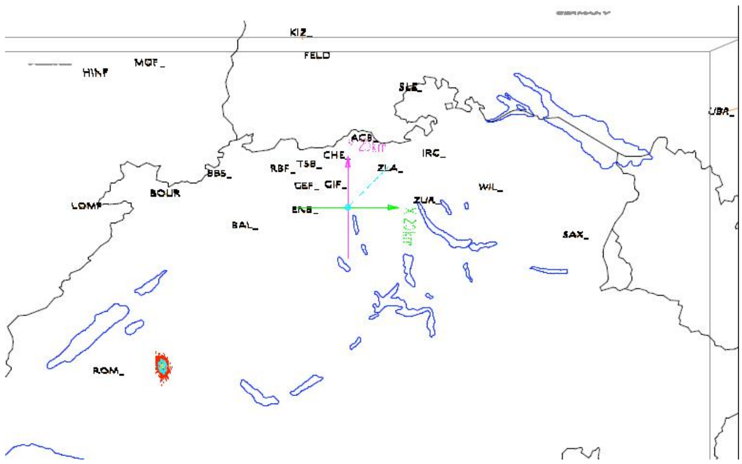

Figure 15: Seismic network for the Fribourg event with GAP=194.

4.3 Influence of nearest station distance on epicenter location

Neglecting the station closest to the epicenter leaves the GAP constant for the Pratteln and Bad Ragaz events. The PDF's show no significant change in size or geometry for these two cases. The Bad Ragaz event is a very good case study for the influence of the distance to the nearest station on epicenter location, since this distance increases about sixfold from 6.7 km to 41.7 km, while the GAP remains constant and therefore cannot influence the result. The distance to the nearest station only doubles without station RBI for the Pratteln earthquake, and is with 20.3 km still in the range of the focal depth for this event.For both events, no dependence of the epicenter location uncertainty on the epicentral distance to the closest station can be observed.

In the case of the Fribourg event, the nearest seismic station ROM is important for the GAP, and removing it increases the azimuthal GAP by more than 50°. As seen before, seismic GAP is an important parameter for the horizontal distribution of the posterior location PDF, and interpreting the results of the surface distribution of the Fribourg case for the effect of nearest station distance is bound to contain large uncertainty. Leaving the station nearest to the Fribourg event out of the inversion invokes large changes in its epicenter location probability distribution (Figure 11). Ellipticity and area increase, and the maximum likelihood epicenter is shifted to the northeast. The larger, elliptic PDF is also rotated slightly, again in a direction perpendicular to the remaining station network, implying that the changes are caused by the increase in azimuthal GAP by 62° without the closest station.

4.4 Influence of nearest station distance on focal depth

As mentioned before, the epicentral distance to the nearest station should not exceed the focal depth to ensure accurate hypocenter location. Neglecting the network station closest to the earthquake theoretically should increase the uncertainty in focal depth, but the density of the network in the area around Pratteln is very high relative to the large depth of about 20 kilometers for the earthquake, so the hypocenter depth location PDF does not change and focal depth is still well constrained with one less observation in the inversion (Figure 14).

Neglecting the nearest station only increases the azimuthal GAP by 62° for the Fribourg earthquake, while there is no change in GAP for the other two events. The best case to look at the influence of the distance from the epicenter to the nearest seismic station is the Bad Ragaz event. The distance to the closest station increases from 6.7 to 41.9 kilometers, and the resulting probability density distribution shows large uncertainties for the focal depth. The PDF has the form of a very elongated ellipsoid, pointing towards the surface away from the remaining network to the east, and even cut off by the surface due to the shallow hypocenter of the Bad Ragaz event (Figure 13). The curved distribution of probability density function samples is the visual expression of the trade-off occurring between horizontal and vertical distance of the hypocenter when neither depth nor epicenter location is well constrained. Focal depth of the maximum likelihood hypocenter of the Pratteln event decreases from 5.8 to 1.9 kilometers, where the estimate of the routine location was a depth of 7.2 km. This behavior reflects the large uncertainty associated with earthquake focal depth determination, especially in a sparse seismic network that will be the standard in most parts of the world. Similar behaviour can be seen for the Fribourg event, where an increase in azimuthal GAP and in the nearest station distance result in an elongated ellipsoid that points toward the surface perpendicular to the remaining stations (Figure 12).

5 Conclusions

The azimuthal GAP and the epicentral distance to the closest station both largely influence the quality of the hypocenter location. The GAP affects the probability distribution of the epicenter location, and a large GAP results in a PDF surface distribution ellipse with the long axis aligned perpendicular to the nearer portion of the remaining network. The short axis of the ellipse remains unaffected by the change in GAP, which means the area of the probability distribution and the epicenter location uncertainty grows larger. A very large azimuthal GAP may also shift the maximum likelihood hypocenter. To accurately locate earthquake epicenters, it is therefore important to keep the GAP small. (Bondár et al., 2004) set the boundary value for the azimuthal GAP to 110° for accurate earthquake location, a value that agrees well with the results of this report.

The nearest station distance is an important constraint for the accuracy of the focal depth, and it should be in the range of 1* the focal depth for a good depth location of the hypocenter. Increasing the nearest station distance therefore leads to larger uncertainties for the focal depth and an ellipsoid that is elongated in the z direction. As seen from the Pratteln earthquake, the near stations can constrain the focal depth very well also for a large azimuthal GAP, and the rule of thumb that the closest station should lie within a distance in the range of the focal depth from the epicenter is an ideal situation. (Bondár et al., 2004) found the maximum value for the nearest station distance to be 30 km for accurate focal depth location. This is again in agreement with the inversions in this study, although the deepest earthquake in the dataset was only 20 km, and this constraint needs to be tested for deeper events.

A combination of the two effects, large azimuthal GAP and a large distance from the epicenter to the nearest station, leads to an elongated ellipsiod and a distribution of the sampled probability density function that points to the surface in the direction perpendicular to the remaining seismic network and illustrates the trade-off between horizontal and vertical distance. When neither depth nor epicentral distance is well constrained anymore, the location uncertainty becomes very large and the maximum likelihood hypocenter can be shifted by several kilometers.

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