T2.1-P3

Absolute and relative location at the IDC: five DPRK events

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Abstract

The International Data Centre (IDC) determines various types of seismic magnitudes. Estimation of body wave magnitude m_b is based on P-waves measured at stations of the International Monitoring System (IMS). Because of the CTBT-related monitoring requirements signal amplitude and corresponding period are measured within a 6 s window, including 5.5 s after arrival time. This is approximately the same time window as used in the waveform cross-correlation (WCC) method, which is under development at the IDC. The WCC method is applicable only to spatially close events generating similar signals as observed at IMS stations. We proposed to use the ratio of RMS amplitudes in cross-correlation windows for relative magnitude estimation of two close events. Five DPRK tests were conducted within a few km from each other and represent an important case for relative magnitude estimation and comparison with the network m_b estimates. Stations of the IMS seismic network are well distributed over azimuth and take-off angles for the DPRK test site. Thus, the ratios of RMS amplitudes are tested for the use in the relative moment tensor inversion.

Conclusion

Five DPRK events were conducted within a few kilometers from each other and had sizes within 1.3 units of magnitude. The IDC has automatically detected all five events and, after thorough interactive analysis, estimated their principal characteristics as seismic sources. Since the ground truth information about yields, depths and locations of these events is not available several advanced methods were applied to accurately estimate the observed differences in seismic wave-fields from these events.

Waveform cross correlation allows to precisely estimate relative locations between all pairs of events and then in a joint procedure. The relative locations of the 2009, 2013 and two 2016 DPRK events can be placed within the same mountain. The 2006 event is located at a distance of approximately 2.3 km to east from the January 6, 2016 explosion.

Automatic and interactive IDC solutions

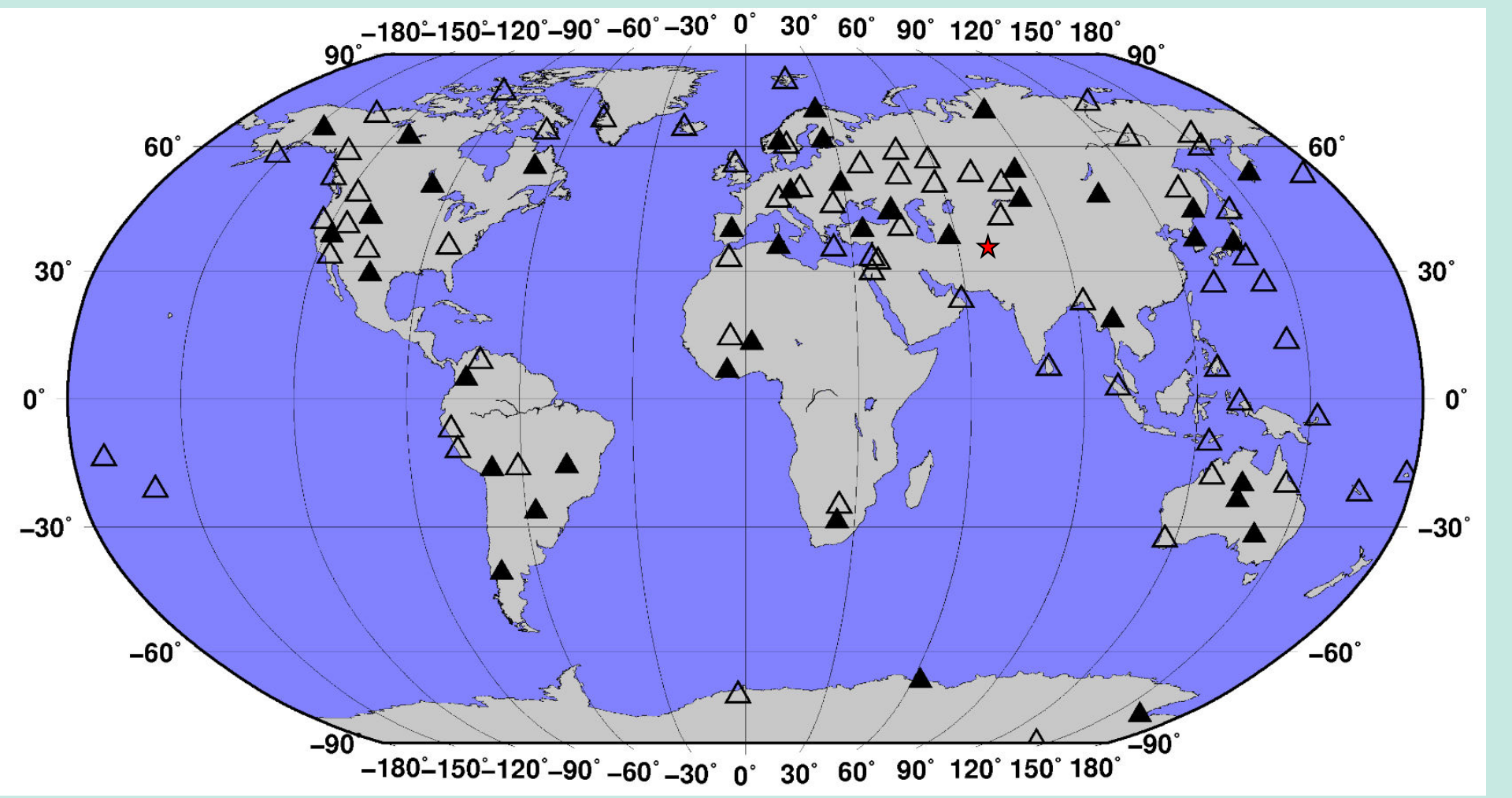

Figure 1. Primary station locations are shown in black, auxiliary station locations are shown as open triangles, the 9 SEP 2016 event location is shown in red

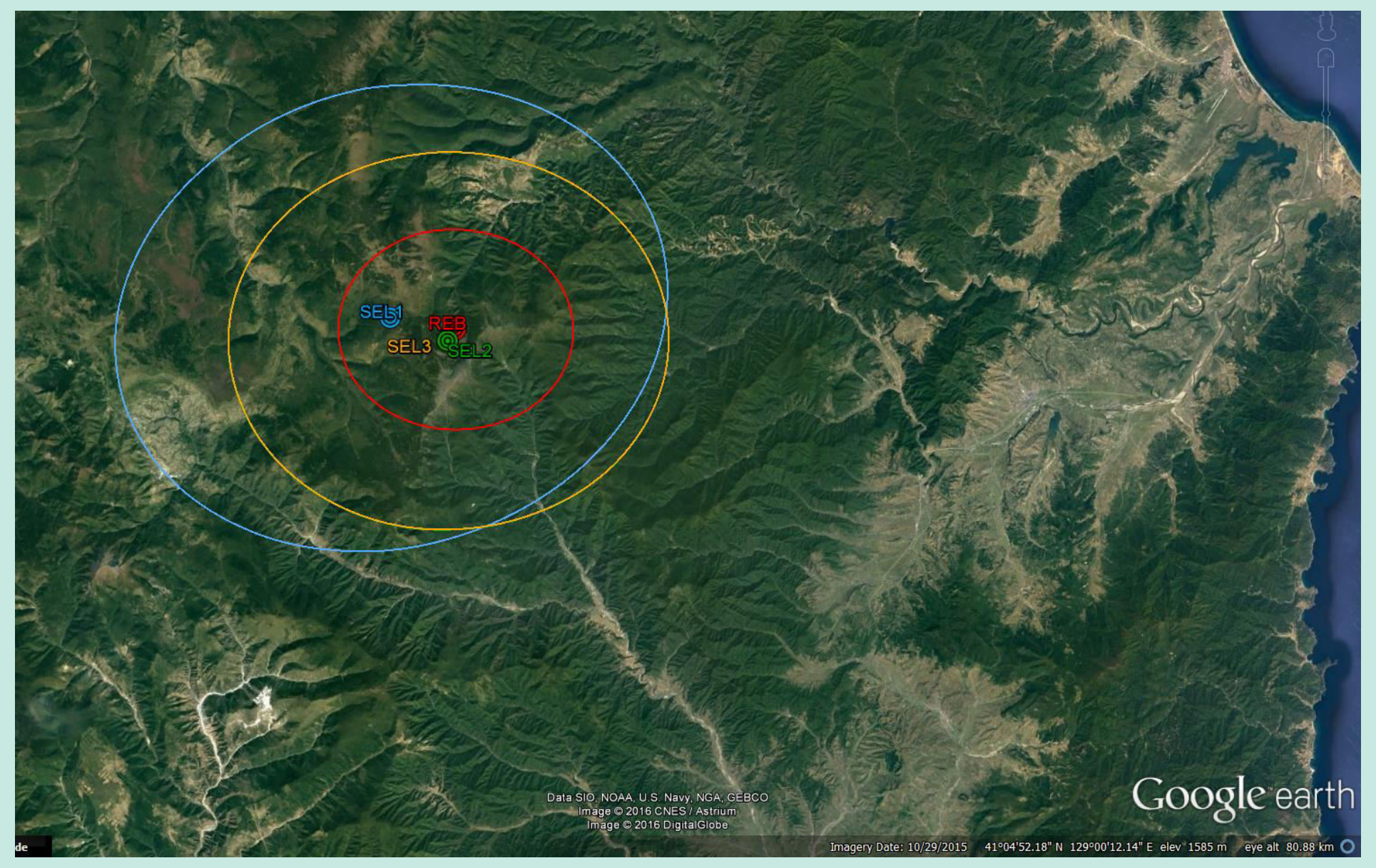

Figure 2. Locations and confidence ellipses of three consecutive automatic solutions (SEL1, SEL2 and SEL3) and the final interactive solution (REB) for the 9 SEP 2016 event.

The DPRK announced and conducted five underground explosions: 2006, 2009, 2013, and two (January and September) in 2016. The International Data Centre carried out automatic and interactive analysis of seismic data measured by primary and auxiliary seismic stations (see Figure 1) of the International Monitoring System.

Table 1 lists some principal characteristics of seismic sources as estimated by the IDC. Figures 2 illustrates progressive improvements in the accuracy of epicenter location and confidence ellipses of the DPRK5 (September 9, 2016) as obtained in three stages of automatic processing - from SEL1 (Standard Event List) to SEL3 and then after interactive processing (REB – Reviewed Event Bulletin) by experienced IDC analysts.

Figure 3 presents five epicenters and their respective confidence ellipses. Shape and size of confidence ellipses depend on the number and distribution of seismic stations used in location as presented in the panel below. In order to obtain unbiased locations for events with small number of stations (the lowest allowed number if 3) the IDC replaces actual travel time residuals with modelling errors fixed for all regular phases and distances. This means that the confidence (coverage) ellipses never decrease below certain value even if all travel time residuals at all IMS stations were zero.

All five seismic DPRK sources were close in space, and thus, produced similar seismic wave-field at regional and teleseismic distances. This similarity creates a basis for application of advanced methods of data processing like waveform cross correlation for estimation of relative location, magnitude and the depth of burial.

The success in application of several techniques proving higher similarities between close sources makes it important to estimate and understand the level of difference between the DPRK tests. First of all, observations at the IMS seismic network demonstrate clear differences in the estimated magnitudes based on body and surface waves as well as local magnitudes, as Table 1 shows. There are several potential sources of these differences: yield, depth of burial, rock type, and local geological structure, which also may affect signal complexity.

The use of the matched filter technique significantly reduces detection threshold. Therefore, it is possible to detect signals from very weak events if they are close to the known seismic sources serving as master events. However, only one small seismic event was found by cross correlation near one of the DPRK tests since the start of continuous testing of matched filter in 2011.

The IMS seismic data from the DPRK 2006, 2009, 2013, 2016_1 and 2016_2 allow accurate relative location using waveform cross correlation. Figure 4 presents typical waveform templates. The length of templates and their spectral content are varied to obtain the largest signal-to-noise ratio. Regional templates (*e.g.*, KSRS and SONM) are usually longer than those for teleseismic stations (*e.g.*, WRA). For detection, we use traces of cross correlation coefficient and standard STA/LTA detector.

WAVEFORM TEMPLATES

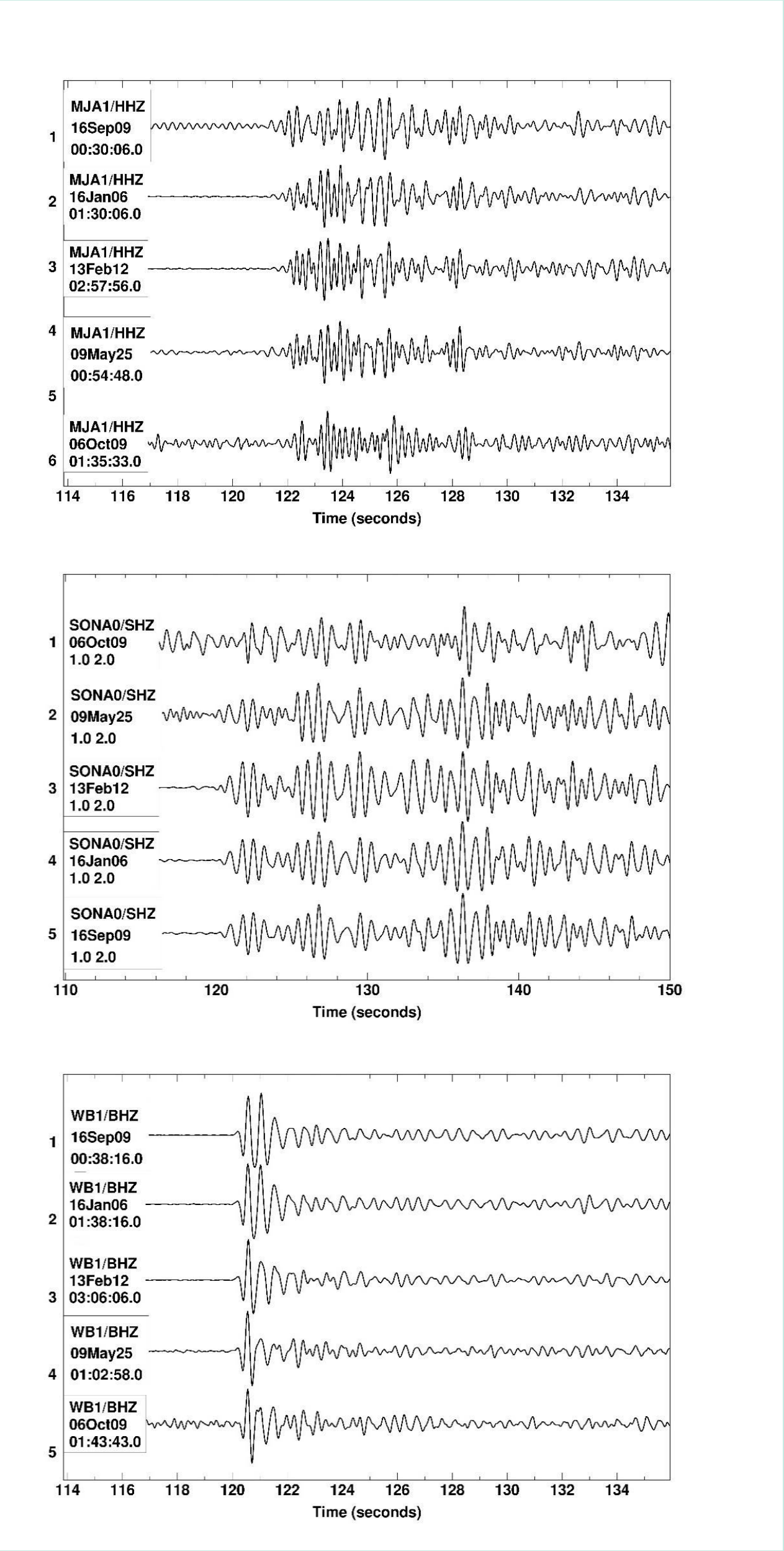

Figure 4. Waveform templates for five DPRK master-events at two regional array stations (KSRS and SONM) and teleseismic array WRA

Relative location using cross correlation

For all detected signals generated by a slave event (*i.e.*, one of five DPRK events), we calculate the empirical travel time residuals, i.e. the travel time residuals relative to the empirical travel times between the master events (other four DPRK sources) and IMS seismic stations instead of theoretical travel times.

We use the grid search algorithm and calculate travel time residuals for all IMS stations in each node of a grid with a 10 m spacing. Figure 5 presents the distribution of the RMS empirical travel time residuals over the grid as obtained using four regional array stations USRK, KSRS, MJAR, and SONM for the DPRK 2016_1 as a master and the 2016_2 DPRK as a slave. These stations are characterized by different sampling rates: 20 Hz at KSRS, 40 Hz USRK, 50 Hz at SONM, and 80 Hz at MJAR. In order to make the sampling rate, and thus, the distance uncertainty associated with discrete timing, uniform over stations as well as to improve the accuracy of onset time estimation with cross correlation we resample all waveforms to 200 Hz. This rate provides the onset time uncertainty of 0.0025 s, which is equivalent to the source-station distance uncertainty of 20 m for P_n-wave with 8 km/s velocity.

Having 4 stations, one can determine the relative location with 10 m to 20 m uncertainty. For poor slave/master signals (*e.g.*, the signals from the 2006 DPRK), however, the uncertainty increases since the onset time can be biased by the ambient microseismic noise. In order to retain high quality of signals and to improve SNR we use only IMS array stations in the relative location of the DPRK events. Figure 5 shows that the 2016_2 DPRK test was conducted **500** m to north-east-east from the 2016_1 event. For the original sampling rates at the same stations the estimated distance was **450** with a 100 m accuracy.

Figure 6 depicts location of 5 DPRK events relative to 4 biggest events. The distances between pairs of events are changing with the reference event due to different number of waveforms templates used in cross correlation.

Figure 7 presents the joint relative locations of all five events. The distance between the 2006 DPRK and the 2016_1 DPRK and is **2.32** km. Hence, the relative location is effective even at ranges of a few km since the level of cross correlation allows precise onset time estimates.

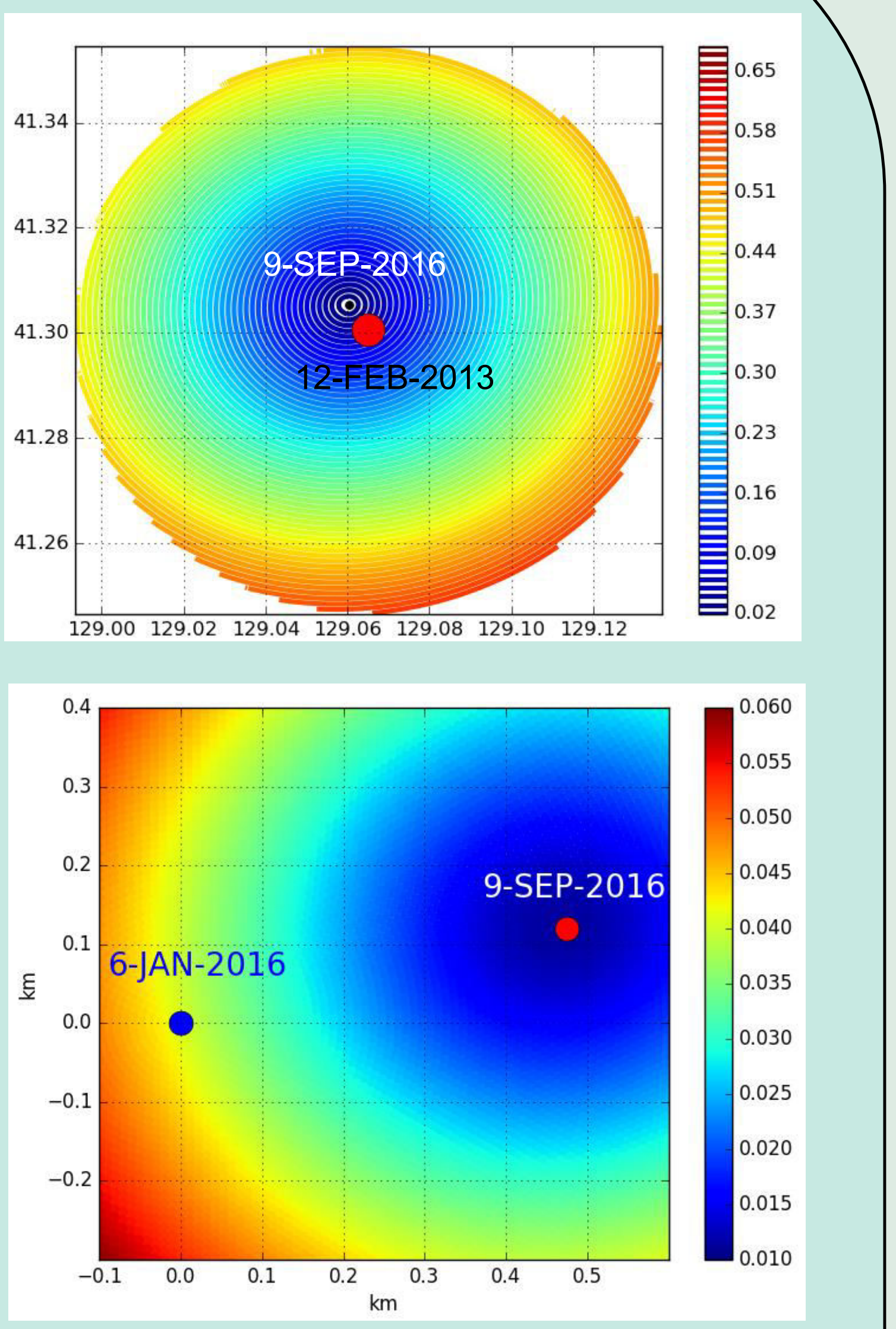

Figure 5. Examples of relative location: Upper panel: the position of the 9-SEP-2016 DPRK event (dot in centre of blue circles) relative to the DPRK3 (REB location). Lower panel: the same event relative to the DPRK4 (6 January, 2016) (dark blue). The distribution of the RMS travel time residual is shown by colour, scale in seconds.

IDC location algorithm

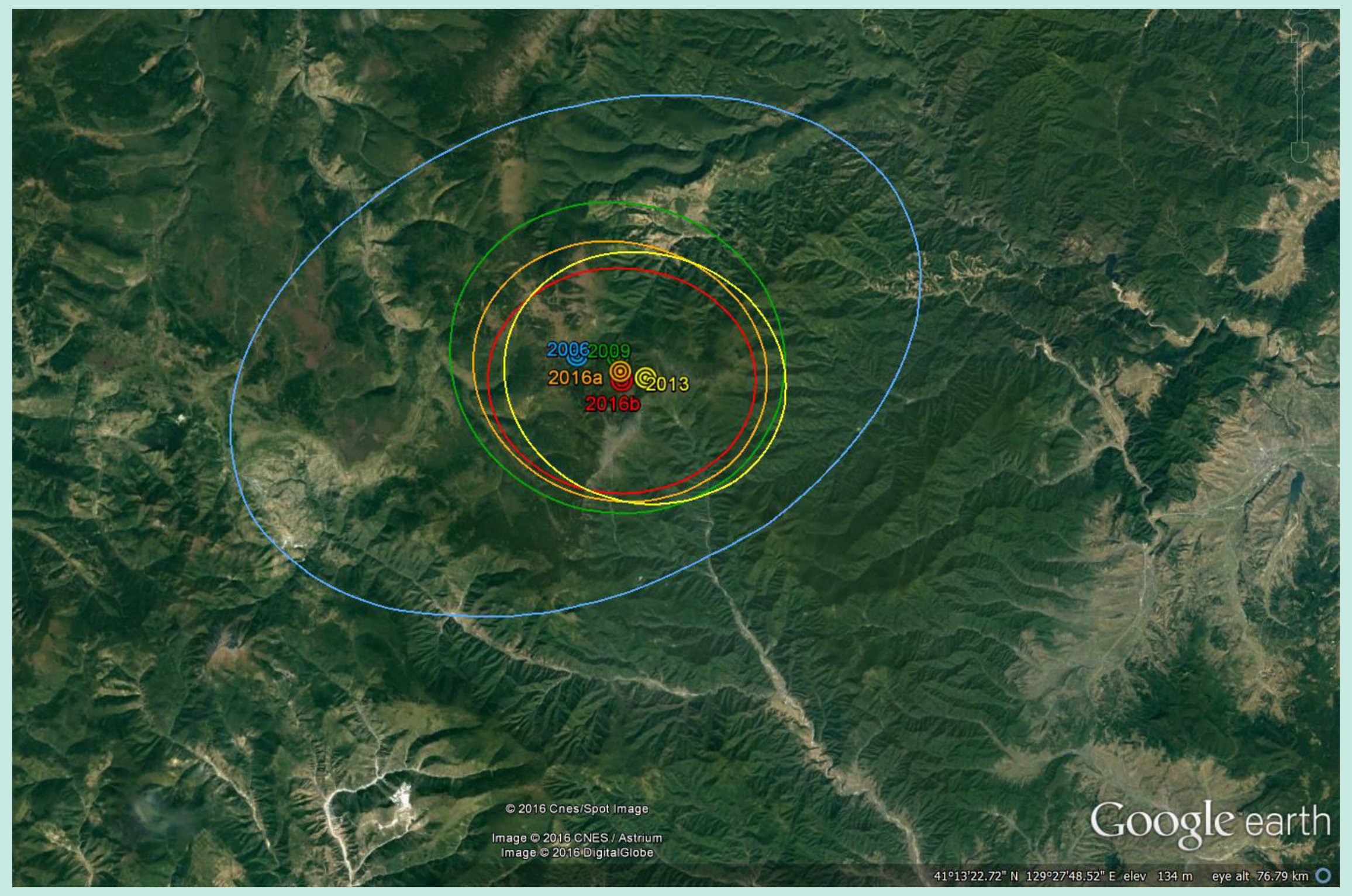

Figure 3. Locations and confidence ellipses of interactive solutions for 5 DPRK events.

Table 1. Final and preliminary (SEL3) m_b magnitudes, Ms, ML, the number of stations used in location and confidence ellipses for 5 DPRK events

Date	m_b, Final (Preliminary)	M_s	ML	Stations Detecting (Used in Location)	Confidence area Smaj, Smin (area km^2)
09-Oct-06	4.08 (4.04)	-	3.89	22 (22)	20.6, 13.6 (880)
25-May-09	4.51 (4.53)	3.56	4.27	61 (59)	9.6, 8.8 (265)
12-Feb-13	4.92 (4.96)	3.94	4.51	96 (88)	8.1, 7.1 (181)
06-Jan-16	4.82 (4.88)	3.91	4.60	102 (83)	8.4, 7.3 (193)
09-Sep-16	5.09 (4.90)	4.17	4.29	108 (97)	7.6, 6.4 (153)

$$\mathbf{r} = \mathbf{A}\Delta\mathbf{x}_e$$

A - sensitivity matrix, **r** - data residual vector. **A** is a partial derivative matrix of N data by M parameters that links the data residuals to an adjustment correction) solution vector, $\Delta\mathbf{x}_e$

Before solving for $\Delta\mathbf{x}_e$ the derivative matrix, **A**, and the residual vector, **r**, are row ***normalized (weighted)*** by their pre-determined errors (an inverse ***rms*** combination of measurement and modelling errors). **A** is also column normalized (every column is made to sum, in an ***rms*** sense, to 1.0). This normalization numerically conditions the matrix so that each model parameter is treated equally.

$$\Delta\mathbf{x}_e = (\mathbf{A}_w^T\mathbf{A}_w)^{-1}\,\mathbf{A}_w^T\mathbf{r}_w$$

$$\mathbf{C}_m = (\mathbf{A}_w^T\mathbf{A}_w)^{-1}$$

$\mathbf{C}_m$ **-** covariance matrix

$$(\mathbf{x}_{ellip} - \mathbf{x}_{final})^T\,\mathbf{C}_m\,(\mathbf{x}_{ellip} - \mathbf{x}_{final}) = k_p$$
2

the confidence coefficient, $k_p^2 = Ms^2F_p[M, N - M]$, F_p defines a *p* percentile F-statistic distribution with M and N – M degrees of freedom; s^2 is the variance scale factor

$$s^2 = [K(sK)^2 + \mathbf{r}^2] / [K + N - M]$$

sK is a priori estimate for the variance scale factor. At IDC, K = 99999 and $s^2 = 1$. IDC uses “coverage ellipses”, data variances are known **exactly**.

Joint relative location of 5 DPRK events

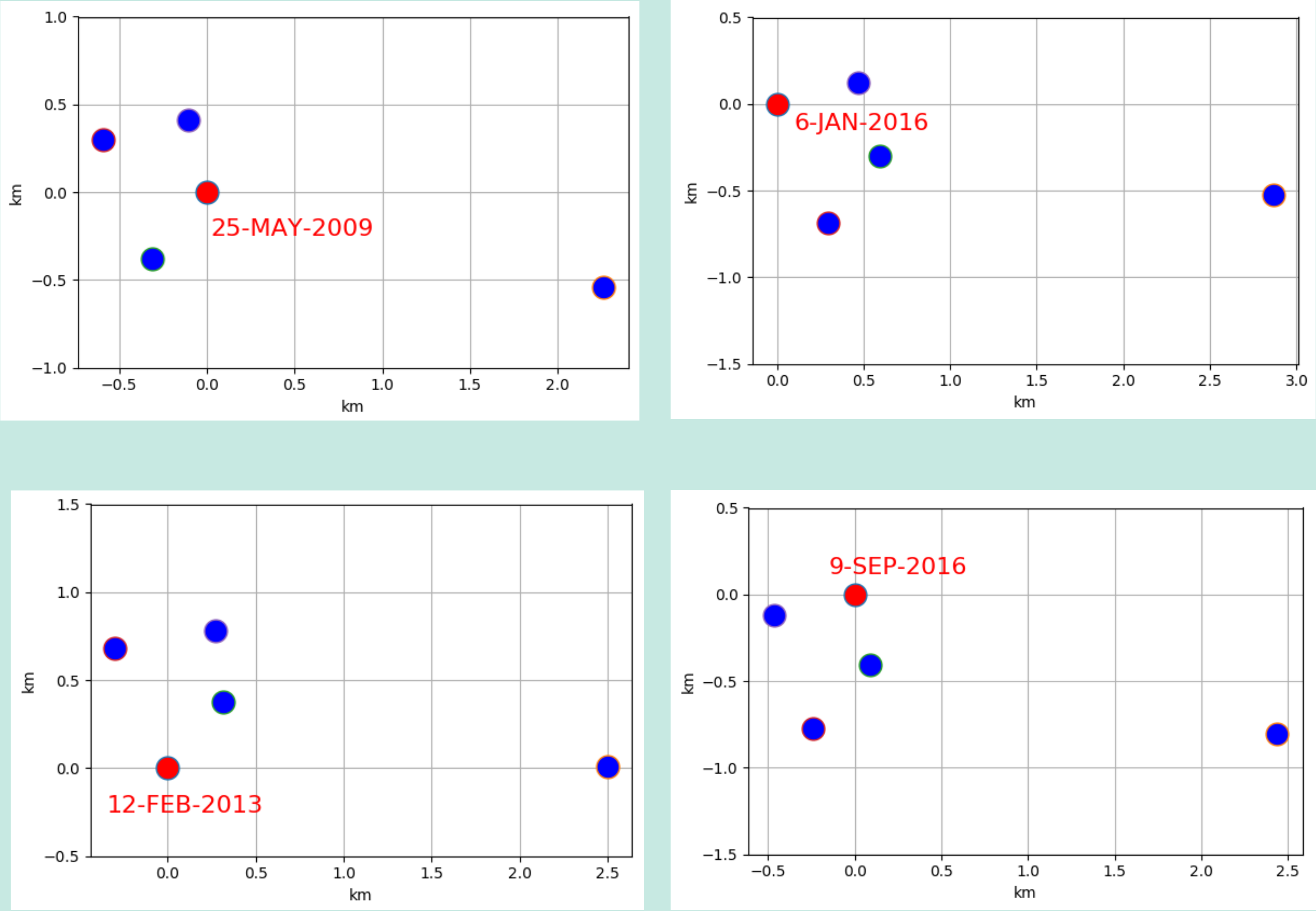

Figure 6. Location of 5 DPRK events relative to 4 biggest events. The distances between pairs of events are changing with the reference event due to different number of waveforms templates used in cross correlation.

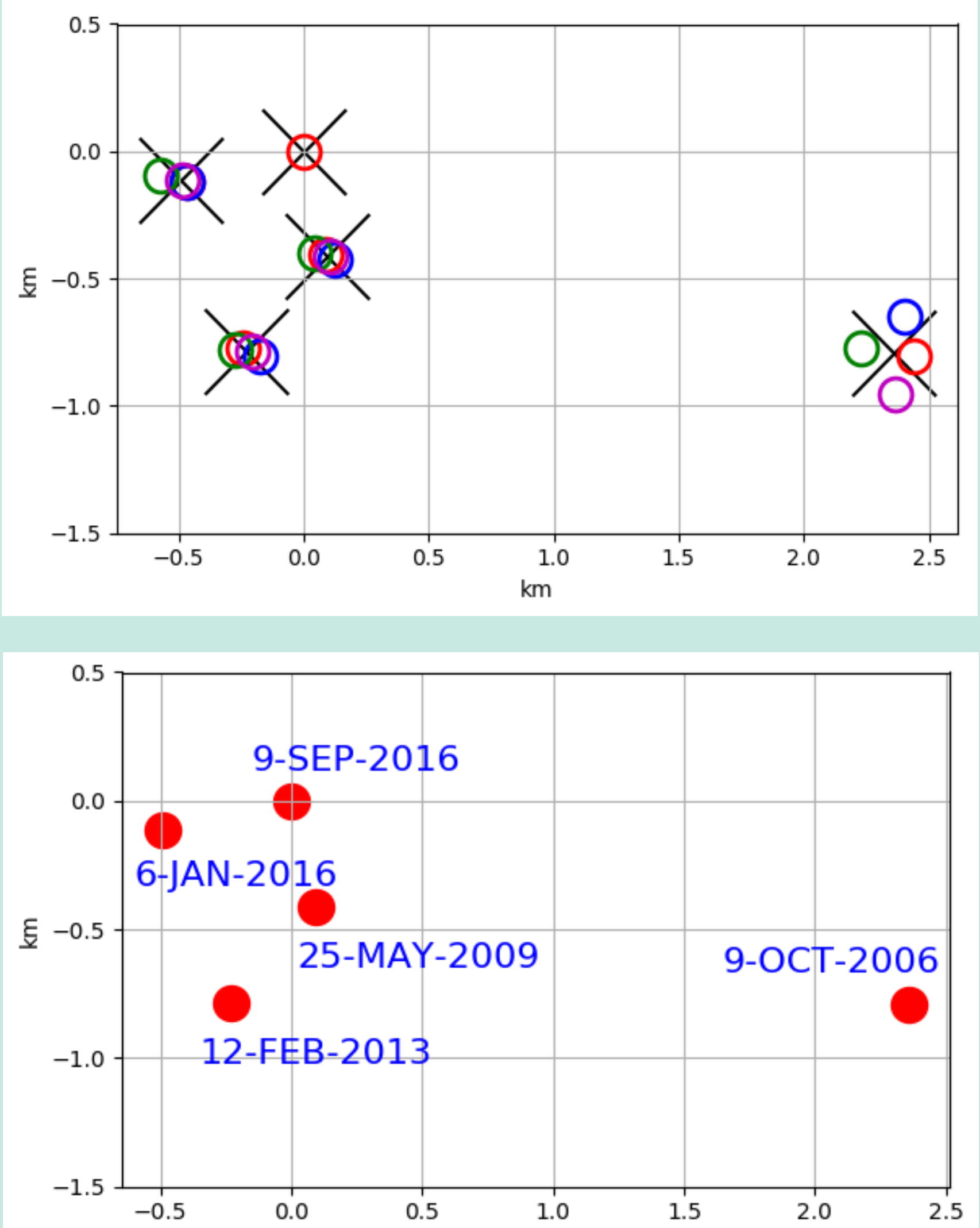

Figure 7. Joint relative location of five DPRK explosions conducted in 2006, 2009, 2013 and 2016. Only regional stations are used. In the upper panel, the SEP-9-2016 event is always fixed and the relative locations of other events accommodates the difference seen in Fig. 6. The location of 2006 event has lower precision due to poor signals.

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