GROUND-TRUTH EVENT LOCATIONS USING CROSS-CORRELATED SEISMIC PHASES AND SATELLITE IMAGERY

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ABSTRACT

Efforts are described to establish ground-truth (GT) locations of industrial blasts in South Korea that can be used to calibrate seismic travel times. Our approach is to apply waveform cross-correlation and master-event location techniques to obtain precise relative locations of event clusters, and use high-resolution satellite imagery to associate the clusters to observed surface features of blasting activity. Currently, eight clusters of blasts have been analyzed using cross-correlated seismic phases (Pn, Pg, and/or Lg), mainly recorded by KSRS and INCN, to estimate relative locations of events within each cluster. Seven clusters have been fixed to specific sites, based on examination of surface features in IKONOS satellite imagery. Another cluster has been located relative to a nearby fixed cluster, but has not yet been associated with surface features in imagery. Efforts so far have resulted in 133 GT events. Four events are categorized as GT0, 100 as GT1, 18 as GT2, and 11 as GT5 or better. An important ramification of this research is that very precise relative location estimates (i.e., within hundreds of meters) can be obtained for small explosions using as few as three seismic phases recorded by only two stations, if the phases are aligned properly, despite very large azimuthal gaps (e.g., 290 to 340 degrees) for most of these events. Implications of these results are discussed with regard to (1) location performance for small explosions using limited seismic data; and (2) extensive applicability of this technique to establish valuable ground-truth location information for clusters of surface blasts in many other regions.

OBJECTIVE

The objective of this effort is to establish ground-truth (GT) locations of industrial blasts on the Korean Peninsula and in China that can be used to calibrate seismic travel times and thereby improve the accuracy of location estimates in such regions. This is difficult (or impossible) to accomplish using seismic data alone, since international stations are very sparse and relevant local networks generally do not provide data to foreign researchers. Thus, additional information, such as space-based imagery, must be used to ascertain GT locations. Our approach is to collect seismic data for relevant blasts, apply waveform cross-correlation and master-event location techniques to obtain precise relative locations of event clusters, and use high-resolution satellite imagery to associate these clusters to visible surface features of blasting activity.

RESEARCH ACCOMPLISHED

As part of previous research and development efforts by Science Applications INternational Corporation (SAIC) and ATK/MR (Barker et al., 2004; Kohl et al., 2004), 219 seismic-acoustic (SA) events, presumably blasts in a larger listing by Che (2002, personal communication), were processed to automatically cross-correlate Pg and Lg phases among the events at KSRS (Wonju seismic array, Republic of Korea). Nearest-neighbor cluster analysis was applied to the geometric mean of Pg and Lg maximum cross-correlation values to form 10 main clusters from 195 of the 219 events. Eventually, the cross-correlation and cluster analyses were applied to 628 events on the Korean Peninsula, of which 408 events were formed into 28 clusters, the first 10 correspond to the initial set of clusters. All but 4 of these 28 clusters include at least one member listed as an SA event by Che (2002, personal communication). These data were used as a starting point for this effort.

Currently, eight clusters of industrial blasts on the Korean Peninsula have been analyzed using cross-correlated Pn, Pg, and/or Lg phases mostly recorded by KSRS and INCN (seismic station near Inch'on, Republic of Korea) to estimate relative locations of events in these clusters. Seven of these clusters have been fixed to specific sites, based on surface features in IKONOS imagery. Another cluster has been located relative to a nearby fixed cluster, but surface evidence of these blasts has not yet been found in imagery. The analyses and results are illustrated below for a couple of cases in South Korea, and some concluding remarks are provided. Other clusters have also been analyzed partially; however, due to limited signal-to-noise ratio (SNR) mainly at INCN, seismic data from one or more additional stations are needed in order to obtain locations estimates using cross-correlated arrival times.

Master-Event Location Analysis

As a starting point for this work, the small stars in Figure 1 represent preliminary location estimates of events in South Korea from Barker et al. (2004), color-coded by membership in a given cluster. The circles correspond to additional events that were not assigned to any of the 28 clusters. Note that cross-correlated arrival times were not used to estimate these locations. Spatial dispersion within clusters is mostly due to variations of automatic phase picks and/or phase identification errors for the more obvious outliers. A significant number of these events were located using arrival time, azimuth, and slowness data from KSRS only. The large stars in Figure 1 correspond to location results obtained under this effort, using cross-correlation and master-event analyses, and shifted to GT locations, based on examination of satellite imagery.

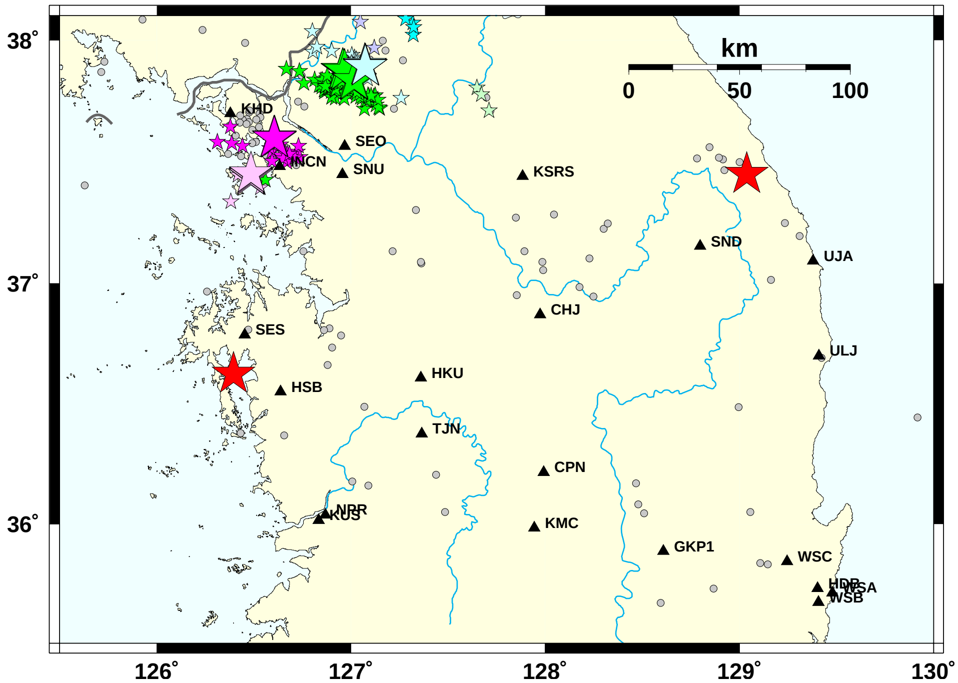

Figure 1. The small stars depict preliminary location estimates of events in South Korea from Barker et al. (2004) that were assigned to a cluster, based on nearest-neighbor cluster analysis of Pg and Lg cross-correlations. The large stars represent the GT location results obtained thus far under this effort. Stars are color-coded by membership in a given cluster.

In the analyses below, the cross-correlated arrival time offsets for Pg and Lg at KSRS were used to automatically align relative phase picks among events. All picks were reviewed and refined interactively in *geotool* and additional arrivals at KSRS and INCN were picked. Data from CHNAR and some Korean Meteorological Agency (KMA) stations are available for some events, but presently not for enough events at common stations to be very useful in the following analysis. As an example, Figure 2 (left) shows KS31/bz seismograms, filtered in the 2-8 Hz band, for four events. Figure 2 (right) illustrates the similarity of Lg phases for two of the events. This allows for very precise relative phase picks, which lead to precise relative locations of the events.

A master event was then selected for each cluster and their epicenters fixed, based on surface evidence of blasting activity in IKONOS satellite imagery and other considerations, discussed below. Fixing the epicenter and depth, *LocSAT* was used to estimate the origin time and travel-time residuals (relative to IASPEI91) of each master event. These residuals were then used to correct the travel times of corresponding phases/stations for the other events in the same cluster and *LocSAT* was used to estimate their epicenters and origin times, with all depths fixed at the surface. This is the same procedure that was used by Fisk (2002) to obtain very accurate locations of underground nuclear explosions at the Lop Nor test site. Case-specific details are described below.-

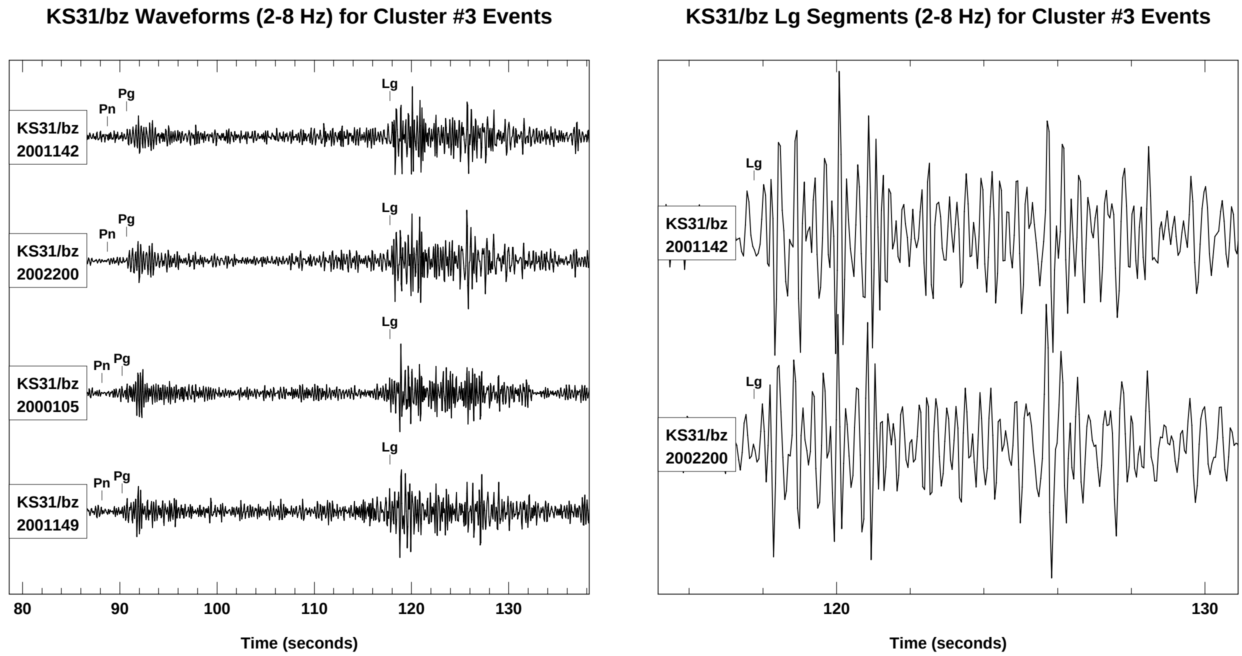

Figure 2. Example of KSRS (KS31/bz) waveforms filtered in the 2 to 8 Hz band for four selected mining blasts (left) and Lg waveform segments for two of the mining blasts (right), showing the similarity of Lg phases.

Example #1: Quarries in South Korea

As noted by Stump et al. (2002), numerous blasts to the south of CHNAR correspond to hard rock mines (quarries) in South Korea, and most of these shots use modest amounts of explosives and are delay-fired. Seven main clusters of seismic-acoustic events were formed by Barker et al. (2004) for this general area, although only two clusters (#2 and #4) currently include enough events with sufficient SNR at two or more stations (mainly KSRS and INCN) to allow application of the master-event analysis. Access to CHNAR data for these events would allow improved accuracy of the solutions and application of the analysis to additional clusters. Figure 3 shows the preliminary locations estimates of these events (small stars), the GT solutions obtained (large red stars), and footprints of satellite imagery used. Since clusters #2 and #4 are separated by less than about 10 km, both clusters were analyzed simultaneously to ensure consistent seismic phase picks (Pg and Lg at KSRS and INCN) and relative locations among the events in the two clusters. Matching the pattern of relative locations of these clusters to a pattern of surface features in the satellite imagery also helps to confirm the uniqueness of the absolute locations.

Figure 4 shows a dendrogram of the nearest-neighbor linkage for 123 events in clusters #2 and #4, using the geometric mean of Pg and Lg maximum cross-correlation values at KSRS as a similarity measure. The analysis forms two to four subclusters of events, depending on the similarity value at which the dendrogram is cut. It is not clear how much the variations in cross-correlations are due to spatial separation, variations in blasting practices, and/or SNR, but the cross-correlations for all combinations of these event pairs range from less than 0.05 to greater than 0.86.

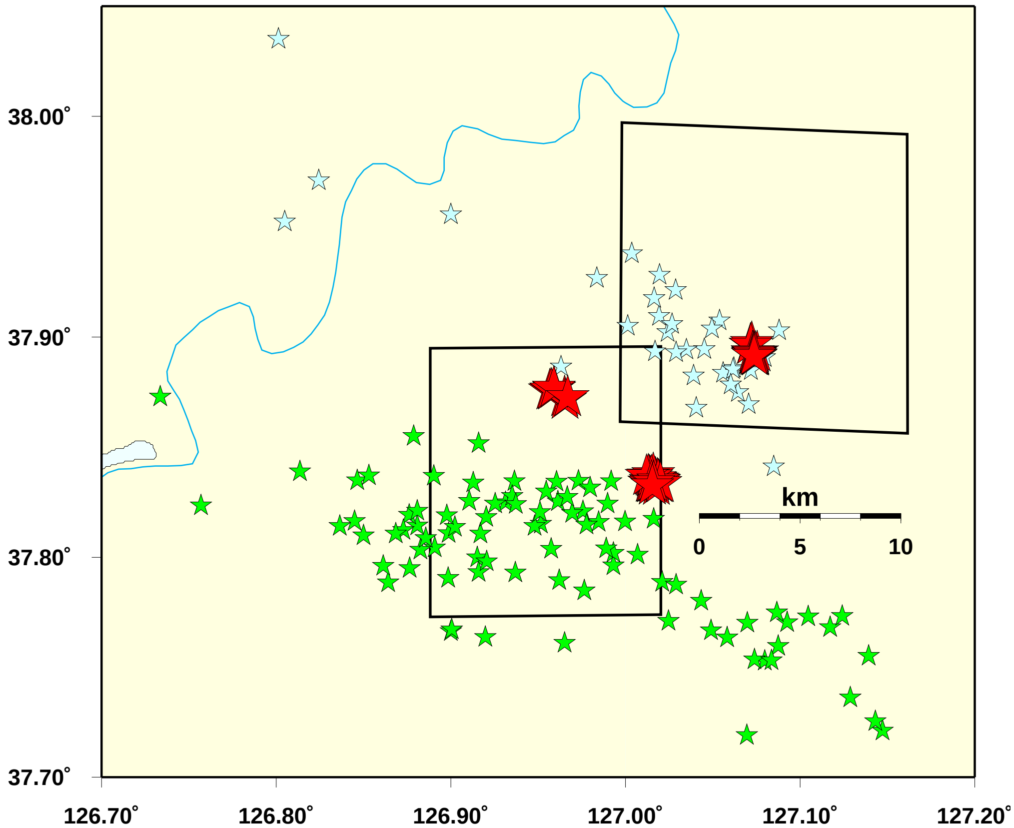

Figure 3. Preliminary location estimates of events assigned to clusters #2 (green stars) and #4 (blue stars), as in Figure 1. The large red stars represent the GT location results obtained for these events. The two rhombi indicate the footprints of satellite imagery that are shown in Figures 5 and 6.

Stump (2004, personal communication) provided the GT location and origin time for a shot on September 26, 2000. However, available data for this event are currently limited to KSRS. In order to utilize the GT0 information, the location and origin time of the 2000/09/26 shot were fixed and the travel time residuals for Pg and Lg at KSRS were computed. Another event on 23 June 2001 was found with high waveform cross-correlation at KSRS to the GT event. Making the assumption that these events are closely located, the epicenters of both events were fixed at the same location and the relative Pg and Lg arrival times at KSRS were used to estimate the origin time of the June 23, 2001, shot. With depth, epicenter, and origin time of this event fixed, this allows the travel time residuals for Pg and Lg at KSRS and INCN to be computed. Based on this procedure, the June 23, 2001 shot was then used as the master event to locate the other events in clusters #2 and #4. Note that the GT information could be used more straightforwardly if CHNAR data become available for the September 9, 2000, GT event and one or more of the other events. Nevertheless, the absolute location accuracy of the master event is well within one km and the origin time is estimated to be consistent relative to the GT information provided by Stump (2004).

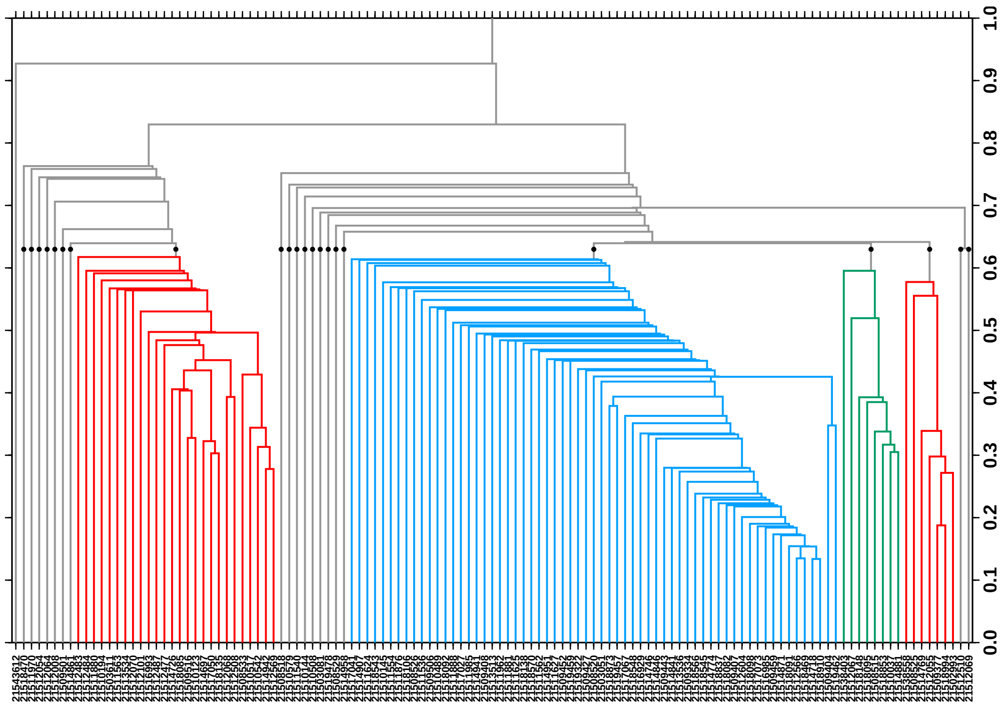

Figure 4. Dendrogram of nearest-neighbor cluster analysis for clusters #2 and #4, showing distinct subclusters. The axes represent the orid and one minus the maximum cross-correlation.

Origin times and epicenters were estimated for 41 blasts of cluster #2, using mostly arrival times of Pg and Lg at KSRS and Lg at INCN (some larger blasts also have Pg picks at INCN), relative to the June 6, 2001, master event. Figure 5 depicts these location estimates (red stars) on an IKONOS image containing a prominent quarry in South Korea. The majority of blasts are associated with this quarry. Eight of the events form two small subclusters of blasts that appear to be associated with a water reservoir approximately six km to the northwest of the quarry. The locations of these eight events are within one km of apparent dam-like features at two ends of the reservoir. The reliability of these solutions is still being investigated. The solutions of the other 32 quarry blasts are well within one km of the master event and visible quarry features, and their origin times are also fairly well constrained by the GT information and procedure above. Thus, these events are categorized as GT1.

Origin times and epicenters were also estimated for 25 blasts of cluster #4, using arrival times for Pg and Lg at KSRS and Lg at INCN and the June 6, 2001, shot of cluster #2 as the master event. Figure 6 depicts these location estimates (red stars) on an IKONOS image containing a small quarry about 8 to 9 km to the northeast of the quarry seen in Figure 5. Location estimates of 22 blasts are within 135 meters of each other and three other blasts are located about 500 meters to the north. These latter three blasts also appear as a fairly distinct subcluster in the dendrogram of the cluster analysis. The location estimates of all 25 blasts are well within one km of the quarry, and their origin times should also be fairly well constrained by the GT information and procedure described above. Thus, these events are also categorized as GT1. It is remarkable that the precise relative locations for these events in clusters #2 and #4 were estimated using only 3-4 phases at 2 stations with azimuthal gaps greater that 260 degrees.

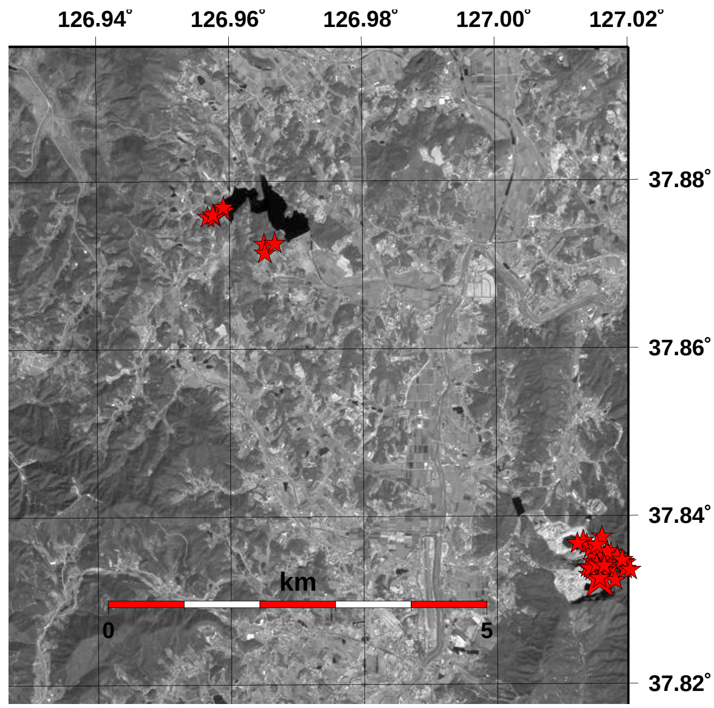

Figure 5. Location estimates of cluster #2 blasts (red stars) on an IKONOS image containing a quarry in South Korea. The main cluster of blasts is associated with the quarry and two small subclusters of blasts appear to be associated with a water reservoir about 6 km to the northwest of the quarry.

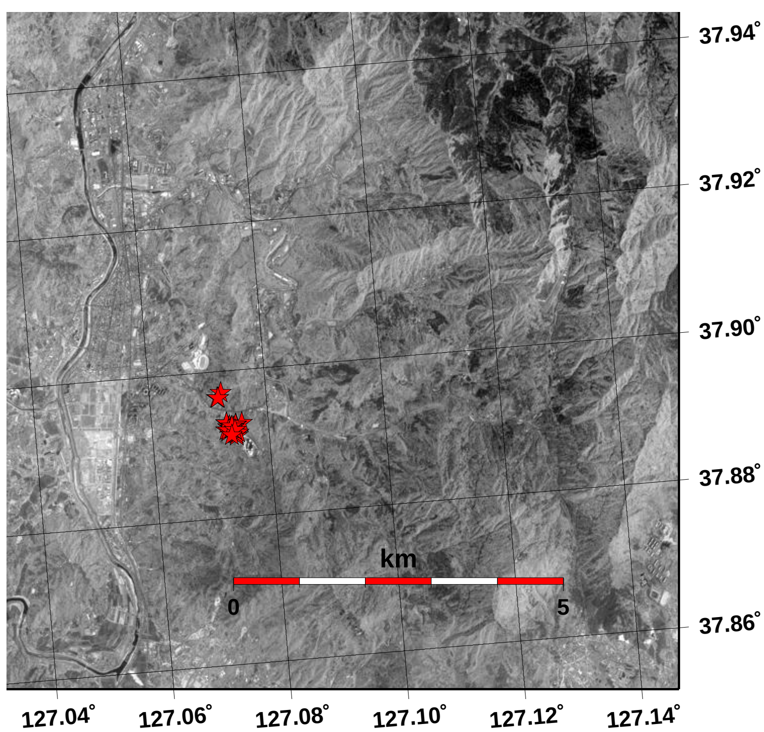

Figure 6. Location estimates of cluster #4 blasts (red stars) on an IKONOS image containing a small quarry in South Korea about 8 to 9 km northeast of the quarry shown in Figure 5.

Example #2: Inch'on International Airport

Numerous blasts were used in the construction of an international airport near Inch'on, Republic of Korea (e.g., Stump et al., 2000, 2001, 2002), such as to flatten topographic features. Many of these blasts produced clear seismic signals at KSRS, INCN, CHNAR, and other stations, and infrasonic signals at CHNAR. In this analysis, two clusters of events were located using Pg and Lg phases at KSRS and INCN (3-4 defining phases with azimuthal gaps of 289 to 343 degrees). Seismic and GPS instruments were deployed locally to record two blasts on April 6 and 7 2000. Stump (2004, personal communication) provided their GT locations and origin times. The blast on April 7, 2000, is used as the master event, with its epicenter, depth, and origin time constrained to the GT information provided. Epicenters and origin times were estimated for eight blasts that are part of a cluster of shots used to level an island at the airport and for nine additional blasts located relative to the April 7, 2000, master event at the airport site.

Figure 7 shows the location estimates of the events in both clusters and an IKONOS image of the airport that provides visible evidence of surface blasting slightly west of the estimated epicenters (red stars). In fact, the entire image is shifted slightly west relative to the event locations and coastline data, presumably due to a minor image registration error of ~200 meters. Regardless, the two blasts on 6-7 April 2000 are categorized as GT0, based on information from Stump (2004), and the location estimates of the other six nearby events are within 535 meters and are considered to be GT1. The other nine events form a relatively tight cluster about 20 km to the northeast of the cluster at the airport (blue stars in Figure 7). IKONOS imagery have been examined to find surface features associated with these blasts on the mainland, but unsuccessfully so far. Independent analysis of backazimuth estimates from two infrasound arrays (Barker *et al.*, 2004) corroborates the relative location of this cluster obtained here using cross-correlated seismic data. The GT quality of these solutions is still under investigation, but appears to be GT5 or better.

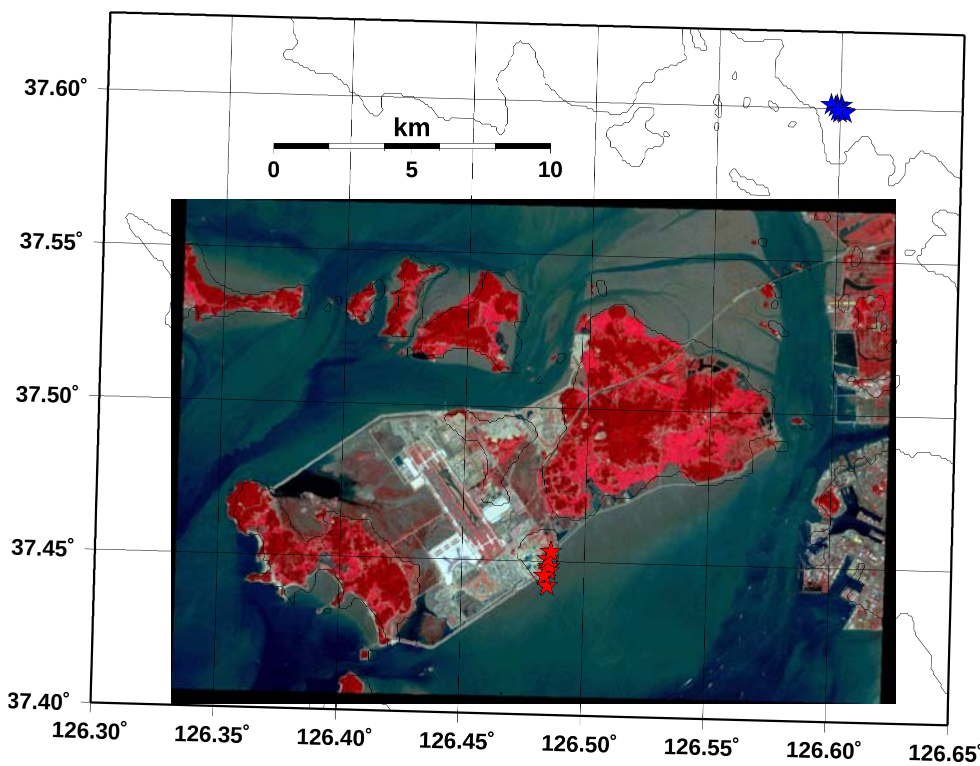

Figure 7. Location estimates of two clusters of blasts, separated by about 20 km, near the Inch'on International Airport, Republic of Korea, using a master event (7 April 2000) at the airport.

CONCLUSIONS AND RECOMMENDATIONS

Efforts thus far have produced 133 GT events for the Korean Peninsula. Four events are categorized as GT0, 100 as GT1, 18 as GT2, and 11 as GT5 or better. The examples shown above illustrate the analysis procedures and typical results, although the other cases do not have *a priori* GT information. Although further work is being pursued to improve the GT quality of some of these solutions, the existing results are suitable to help calibrate travel times of seismic phases for this region and to evaluate the performance of location capabilities. Dr. Myers has independently reviewed these results and reproduced location estimates to within the stated accuracies of the solutions.

Figure 8 shows histograms of the number of defining phases and azimuthal gaps for the 133 event locations obtained in this study. Most of the solutions used four or fewer defining phases at two stations with almost all azimuthal gaps greater than 260 degrees. (Solutions for five events also included cross-correlated seismic phases recorded by numerous KMA stations.) Indeed, a remarkable outcome of this study is that very precise relative location estimates (i.e., within hundreds of meters) can be obtained for small blasts using only 3 to 4 seismic phases recorded by as few as 2 stations, if the phases are properly aligned (i.e., cross-correlated), despite very large azimuthal gaps of 260 to 340 degrees for most of these events, using only KSRS and INCN. A couple of clusters were located relative to master events that were 8 to 20 km away and the relative location estimates were found to be within 1 to 2.5 km from evidence of blasting in IKONOS imagery. This surprisingly high degree of accuracy for locations relative to more distant master events may be due to the fairly homogeneous geological structure of the Korean Peninsula (e.g., Stump et al., 2002), and is not expected to be as good in more heterogeneous regions.

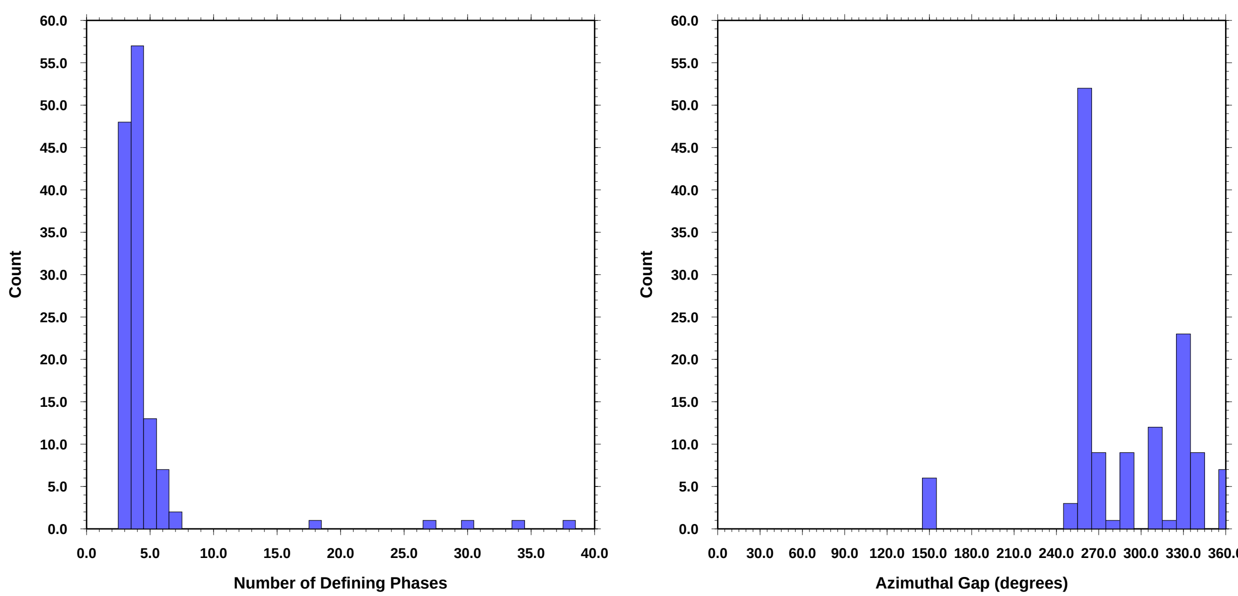

Figure 8. Histograms of the number of defining phases (left) and azimuthal gaps for the relative event locations estimated for the 133 GT events.

Preliminary examination of location performance, based on *default* processing methods using *LocSAT* and IASPEI91 travel time curves, and comparison to the GT solutions, indicates mislocations up to 35 km, median mislocation of about 8 km, median error ellipse area of about 1400 km^2, and coverage of the GT epicenters by about 90% of the error ellipses. These results are probably biased better than might be expected for a broader set of typical events on the Korean Peninsula because the 133 events with GT solutions that were used in this assessment were typically ones with the highest SNR. Future plans include assessing location performance for all events in the various clusters (regardless of whether they were relocated by the methods described above), evaluating the performance of regional travel time curves, and separating the contributions to location errors that come from arrival time measurement errors and those that are due to travel time biases.

This study also demonstrates that high-resolution satellite imagery is very useful to obtain accurate absolute locations in the absence of other GT information or other forms of data to constrain the true locations. These results are very encouraging for continued successful and extensive application of these techniques to many other clusters of mining and other industrial blasts to establish valuable GT information. Future plans include applying these procedures to clusters of mining blasts in China.

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