OPTIMIZING RECORDING EFFICIENCY OF A NEW STRONG-MOTION ARRAY (ICEARRAY) USING COMMON-TRIGGERING

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ABSTRACT

Traditional arrays using a central recording facility and dedicated communications channels to continuously record data are expensive to deploy and maintain. A lower cost alternative is to install a network of low-cost stand-alone instruments, each operating in a 'triggered recording' mode with local storage and near-real-time generic communications. Natural and cultural conditions generally result in varying background noise levels across the sites of a given network. Therefore, event detection and recording should be optimized to produce complete data sets, even for frequent small and local earthquakes, without creating masses of spurious records at individual nodes. We achieve this by employing a tuned "common-triggering" (CT) scheme, effectively converting a network of isolated instruments into an array. Selected instruments are configured to send trigger notification messages over the Internet to one or more central hubs, each running a CT detection algorithm. Within the CT detection algorithm, each received trigger notification message results in a preset number of 'votes' being added to a tally. The number of votes being added depends on the known triggering quality of the node sending the alert package. Whenever a preset number of votes are received within a moving time window, a global trigger command is issued to all instruments within the network. This system was implemented for the ICEARRAY, the first small-aperture, strong-motion array in Iceland, consisting of 14 CUSP-3Clp broadband, triaxial, strong-motion accelerographs equipped with GPS based timing and perpetual GPRS Internet communications. We show that the CT-scheme maximizes the array's efficiency in recording real events while minimizing the analyst's efforts in reviewing data. This system markedly improves the usefulness of a network of stand-alone instruments by converting them into an array with little or no additional cost and allows sites with marginal triggering suitability to be effectively incorporated as slave instruments.

KEYWORDS: Array, ICEARRAY, Iceland, CUSP, optimization, triggering, earthquake, network, accelerograph, instrumentation

1. INTRODUCTION

Small-aperture, strong-motion arrays are of great importance for earthquake and engineering seismology. Their capabilities of recording broad-band ground motions over a wide dynamic range can provide insight into details of fracture processes at the earthquake source (Spudich & Cranswick, 1984), the heterogeneity levels of the medium (Sato & Fehler, 1998), site effects (Ansal, 1999) and the spatial variability of ground motions (Abrahamson & Bolt, 1987). In addition, their wide dynamic range provides the opportunity to investigate the transition of strong-to-weak-motions e.g., earthquake source and ground motion scaling over a wide magnitude range. The sensitivity of the strong-motion instruments generally controls how far this range extends to smaller magnitudes. When the waveform correlation is sufficient over the aperture of a group of instruments operating in an array configuration, the sensitivity can be increased beyond that of the individual instruments (Steinberg, 1965). Therefore, it is essential that as many instruments as possible within the array capture any earthquake disturbances, even weak motions, as the application of array processing techniques can produce good datasets from otherwise useless data. While it may seem straightforward to capture a complete set of earthquake recordings, in practice it is difficult due to the variability of ground motions and noise levels across even a small-aperture array, especially when using adaptive triggers such as STA:LTA triggers, whose sensitivity is dependent on the current background noise levels. This is particularly problematic with deployment in an urban setting as noise levels are generally both time and site dependent and site-to-site variations can change significantly within a very short time. The fact that one gains dynamic range across an array by applying array processing techniques such as beamforming (Gibbons and Ringdal, 2006; Almendros et al., 1999), used to retrieve useful information even from noisy datasets, is an important consideration when choosing the sensors for a network. Strong-motion (accelerometer) sensors that are capable of capturing the largest ground motions, even in the near-fault region, generally have a high noise floor, while the high-sensitivity velocitymeters trade off high-amplitude response for a low noise floor. The application of array processing techniques can thus allow the noise floor of a strong motion network to be extended downwards to capture a wider range of ground motions than either sensor can provide on their own. Thus, a strong-motion array is able to capture complete ground motions while velocitymeter array runs the risk of clipping large amplitude motions. This is especially true when a strong-motion network is equipped with a *common-triggering* (CT) scheme that ensures complete event capture across the entire network, effectively becoming an array capable of recording both weak and strong ground motions. When the CT scheme also sifts out natural or cultural disturbances that are site-specific i.e., those affecting only one or very few array stations, there is the added benefit of needing to analyze *only* those ground motion recordings that contain events that affect the entire array region. In the vast majority of such cases, the disturbance is caused by an earthquake. Thus, such a scheme markedly improves the usefulness of a network of stand-alone instruments and minimizes the analyst's efforts in reviewing data. Such a scheme has been developed and implemented on a central hub monitoring a newly installed small-aperture strong-motion array in Iceland, the ICEARRAY. Moreover it has been tested during a recent M6.3 earthquake for which the ICEARRAY was in the near-fault region. The results exemplify the considerable advantages of the CT.

2. THE ICEARRAY NETWORK IN SOUTH ICELAND

The Earthquake Engineering Research Centre (EERC) at the University of Iceland operates the Icelandic Strong Motion Network (IceSMN), the only accelerograph network in Iceland. The network has been in operation for over a quarter of a century and its largest part is located in the South Iceland Seismic Zone (SISZ, see Figure 1), a transform zone of high seismicity and a history of destructive earthquakes. The largest events recorded by the IceSMN are the two $M_w 6.5$ earthquakes that occurred in June, 2000 (see Figure 1) (Halldórsson et al., 2007) and the $M_w 6.3$ earthquake of May 2008 (Sigbjornsson et al, 2008). The latest addition to the IceSMN is the ICEARRAY, the first small-aperture strong-motion array in Iceland, installed in the SISZ for the specific purpose of establishing quantitative estimates of spatial variability of strong-motions, and investigating earthquake rupture processes and source complexities of future significant earthquakes in the region (Halldorsson et al., 2008). The ICEARRAY has been in operation since October 2007 and was installed in the village of Hveragerdi on the western edge of the SISZ (see Figure 1). The SISZ is collocated with high population densities in numerous towns and villages along with the infrastructure essential to a modern society. As a consequence, the seismic risk in Iceland is highest in the SISZ.

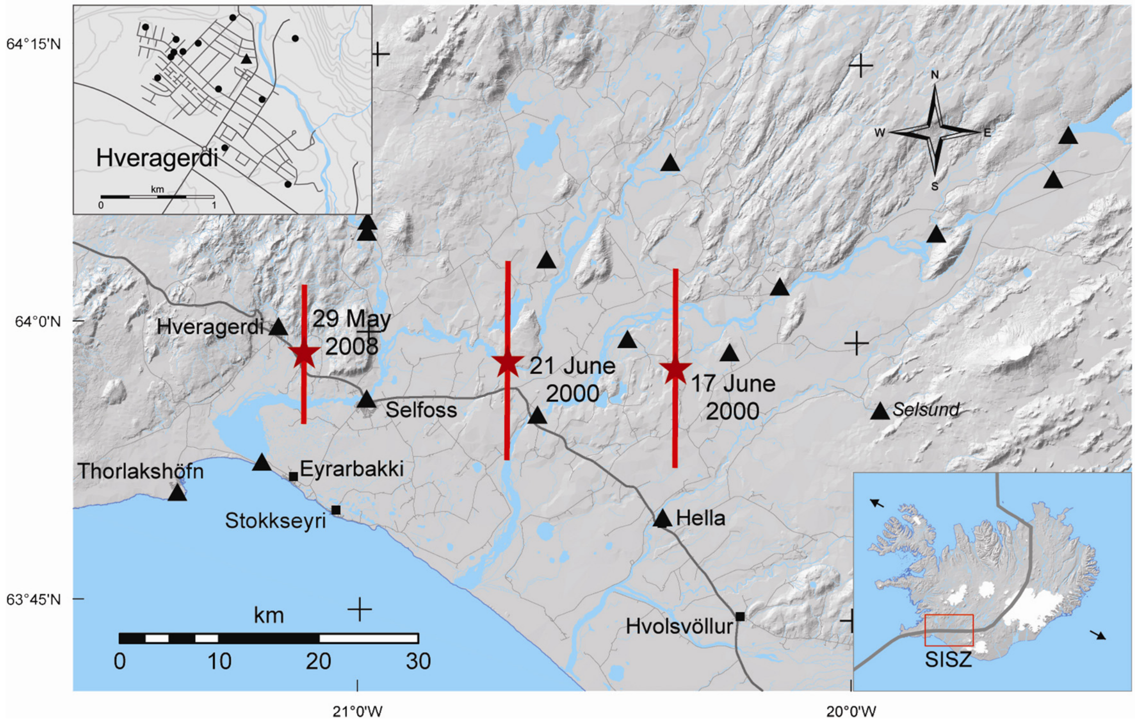

Figure 1 The small map inset at bottom right shows Iceland, an island in the North Atlantic Ocean (blue), with glaciers in white, in reference to the present-day boundary of the Eurasian and North American tectonic plates (thick line, Sigbjörnsson et al, 2006). Their relative motion is ~2 cm/year, in the direction indicated by the bold arrows (Stefánsson et al, 1993). The rectangle indicates the area of the SISZ, shown in the larger map along with the main roads, villages, rivers and lakes. The fault planes and epicenters (stars) of the earthquakes of June 2000 and May 2008 are shown in reference to the recording sites of the IceSMN (triangles). The small map inset at top left shows the ICEARRAY recording sites (dots) on a street map of Hveragerdi village, with the single IceSMN station shown as a triangle.

The optimal ICEARRAY geometry and number of stations was attained via analyses of the corresponding array transfer functions and their properties (Halldorsson et al., 2008). The final layout of the array, shown in Figure 1, comprises N = 14 stations (one of which is shown in Figure 2) over an area of aperture D = 1.9 km with the smallest inter-station distance of d = 50 m. The distribution of stations ensures sufficient resolution for establishing a smooth spatial coherency function vs. distance.

The recording system at each ICEARRAY station consists of a single CUSP-3Clp strong-motion accelerograph unit manufactured by Canterbury Seismic Instruments Ltd. The units are equipped with triaxial low-noise (~70 μg rms) Micro-Electro-Mechanical (MEM) accelerometers with a high maximum range (± 2.5 g) and a wide frequency passband (0-80 Hz at 200 Hz sampling frequency). Such setup ensures the recording of complete waveform information (body and surface waves) at all frequencies of interest in engineering seismology. Each unit possesses a continuous GPS timing system, acts in triggered mode and saves data files directly to solid state memory. The units draw their power from the mains supply of the respective building, although a backup battery ensures up to a week's worth of functionality in case of power failures. The communications system consists of standard TCP/IP protocols (https, sftp, rsync, email etc.) connected wirelessly using perpetually-connected GPRS data modems. This system provides reliable connectivity for remote maintenance, control, and for near-realtime transfer of recordings to a central server after recording an event. The latter is especially useful as it provides near-realtime access to the complete data set from a single collection points.

Figure 2 Sites IS608 and IS608b of the ICEARRAY network, serving a dual purpose. In this case an earthquake fault in the bedrock underneath the service center building in Hveragerdi, South Iceland, is monitored by two CUSP-3Clp units. One unit is a part of the ICEARRAY network and the other has the purpose of monitoring the differential motions across the fault during other earthquakes. The gray boxes on the base walls contain the auxiliary power and modems for the CUSPs.

Because the CUSP-3Clp instruments use standard TCP/IP no special requirements exist for the central server to receive data events other than an sftp server. For ICEARRAY, the central server used is a CUSP-HUB smart network manager from Canterbury Seismic Instruments. This was developed in conjunction with the EERC to include support for the CT system. The CUSP-HUB consists of a large storage repository connected to https, rysync and sftp servers to allow the collection, storage, management and dissemination of data. The CUSP-HUB also provides trigger alerts in the form of emails and/or text messages to mobile devices. The CUSP-3Clp instruments can also issue such alerts to the administrator.

Prior to the application of the CT scheme ICEARRAY operated as a network of stand-alone stations with very similar triggering criteria and levels. Two issues were apparent from the outset:

1. Earthquakes producing weak-ground motions (local, small and nearby earthquakes) were not picked up by all stations.
2. The low triggering levels in the urban area resulted in a large number of individual triggers at different stations that were not associated with real earthquake events.

Both of these issues stem from the collocation of ICEARRAY with an urban area and somewhat non-uniform setup conditions from site-to-site, which result in variable and time-dependent noise levels across the array. The resulting incomplete event captures and the masses of useless data provided the motivation for developing the CT scheme.

3. THE COMMON TRIGGERING SYSTEM

Traditional arrays using a central recording facility and dedicated communications channels to continuously record data are expensive to deploy and maintain. A lower cost option is to install stand-alone instruments operating in a triggered mode with local storage and near-real-time generic communications, reducing both deployment and communications costs. For such a network, it is important to optimize the detection consistency and recording completeness for frequent small and local earthquakes, especially when the network is of a small-aperture. This task is in many cases hampered by complex path effects, local site effects, and localized cultural noise within the network, resulting in low signal levels at some sites and requiring others to be configured with a high triggering thresholds. The use of adaptive triggering schemes such as STA:LTA reduces the number of false records at the risk of losing small, yet genuine, events that coincide with a period of high cultural noise.

Both of these problems result in incomplete data sets from small events, despite the data from the missing sites being useful in an array application. The issue can be solved and record completeness attained through the application of a "common-triggering" system on the array, implemented as follows (see also Figure 3);

- within the CT hub's database each instrument in a defined "common-triggering" network is assigned a number of votes that are to be generated when that instrument triggers
- whenever a triggering event is encountered on an instrument within the defined "common-triggering" network, the instrument begins recording data and sends a small TCP/IP data packet over the Internet to the central CT hub
- the CT hub receives the trigger notification messages and determines the source of the trigger for each notification message received
- once the source has been determined the number of votes assigned to that source are added to a vote tally within a moving time window
- once a preset number of votes, n_{tol}, are received within a preset time window a global triggering event is determined and small TCP/IP packets are sent to all instruments within the triggering network telling them to begin recording
- each instrument will then begin recording (if not already recording) and respond with trigger-acknowledge TCP/IP packets

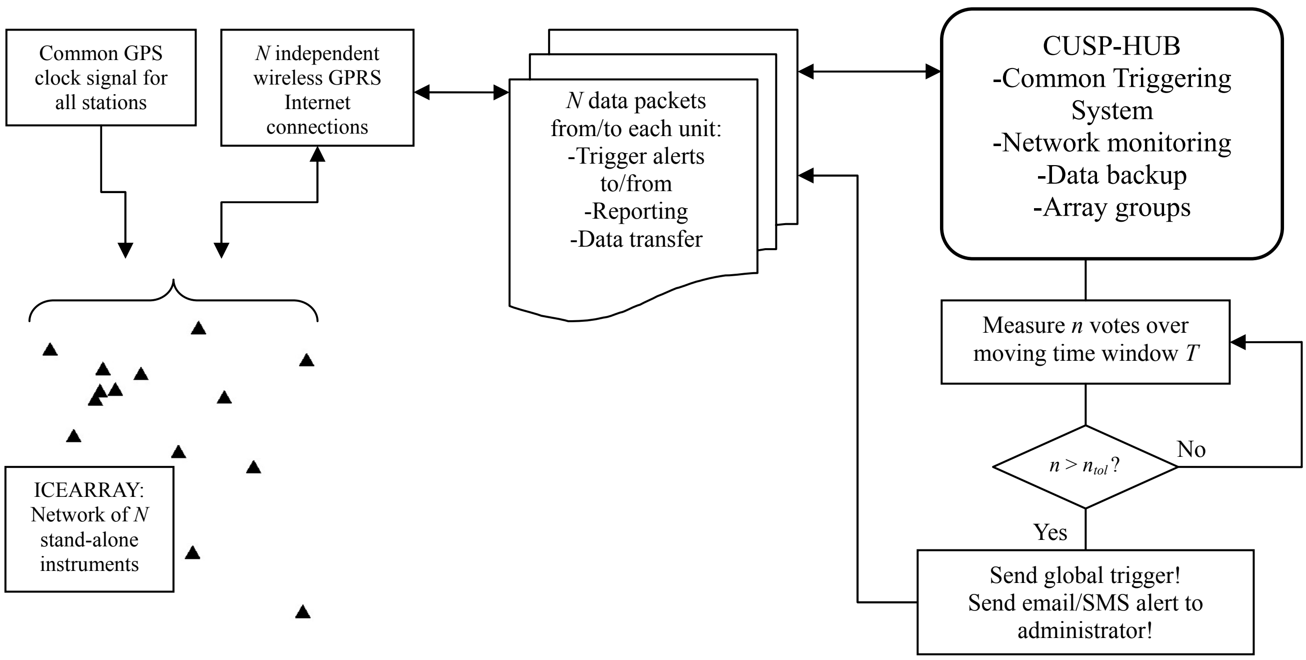

Figure 3 A schematic view of the information flow to/from a network (ICEARRAY) of N stand-alone instruments, perpetually connected to the Internet and monitored by a central hub running a Common Triggering System. The instruments send trigger notification messages to the central hub and then upload the data to it after recording. The central hub determines the incoming trigger alert's source and according to this adds a preassigned number of votes to a tally. Once n_{tol} votes are accumulated within a moving window of duration T, the "common-triggering" system issues a global trigger to all instruments and alerts an administrator.

The use of the voting scheme allows the CT to be tuned according to each sites triggering reliability (i.e., noise level). This ensures effective redundancy, as, at times when the best sites are inoperative (communications or other failure), sites that typically experience too many false triggers (and thus have a low vote number) can still be useful because many unreliable sites triggering at one time will give a cumulatively high vote, yet the chance of so many instruments falsely triggering at the same time is very low.

The use of TCP/IP packets allows the CT trigger notification messages to be transferred over the public Internet.

This provides some degree of data-path reliability with the diverse network paths possible. However, the localized deployment range may negate this benefit to a large degree as the communications path may be almost direct. The use of the Internet with TCP/IP packets also permits simple incorporation of other sources to act as voting members in the CT scheme. For instance, with a sufficiently long pre-event recording length within each instrument, useful data could be captured from triggers originating from remote networks or other, more reliable, local sources e.g. sources not prone to cultural noise triggers, such as bore-hole sensors, which should be given a high number of votes.

Though the CT was developed by the EERC in conjunction with a commercial entity, it is hoped that this triggering system's packet structure could form the basis of an open and manufacture-independent protocol allowing a diverse range of instruments and sensor types to be incorporated into the CT scheme.

At present the ICEARRAY is monitored by a CUSP-HUB installed at the EERC headquarters. The ICEARRAY CT scheme is yet to be fine-tuned, as the instruments within the network have simply been assigned 1 vote each, excepting known-bad sites which have been assigned 0 votes. The number of votes, the detection time window and the instrument pre-event recording period are all set to initial estimates; 3 votes tally, 10 s detection window and 15 s pre-event recording length. This crude approach has been very useful for developing a map of the instruments triggering reliability and has provided considerable amounts of data on the exact values each site should be given when the final votes are determined. It is hoped that this information will enable inference of the optimal balance between maximum redundancy in the system and minimum false triggers.

4. ANALYSIS OF CT SYSTEM PERFORMANCE

At 15:45 on May 29th, 2008, a M_w 6.3 earthquake struck in the Olfus lowland between Hveragerdi and Selfoss (see Figure 1) (Sigbjornsson et al, 2008). The ICEARRAY recorded the main shock on 11 stations and the vast majority of its aftershocks. At present, this data comprises the largest part of ICEARRAY's dataset of 2933 recordings since October 1st, 2007 However, when including only triggers on three stations or more the ICEARRAY has recorded 1046 datafiles since October 1st 2007 until June 5th 2008.

Shortly after the main shock the CT scheme on the CUSP-HUB ceased operation for unforeseen technical reasons, specifically between 2008/05/29 16:01 to 2008/06/01 08:35, during which period 1055 triggers were issued to the central hub. While this was unfortunate in terms of data capture, the failure period has allowed the effectiveness of the CT scheme to be analyzed. The result is shown in Figure 4a, where, to achieve consistency over the analysis period, we have removed sites that were non-operational or that suffered from intermittent communication related problems within the period, leaving 7 stations with 100% uptime. Figure 4a shows the number of recordings captured simultaneously (start-time within 10s from first to last record) and indicates clearly that the number of stations capturing any particular event varied greatly. On the other hand, once the CT scheme had been reinstalled, complete station coverage for each event was nearly achieved, as can be seen from Figure 4b which covers the time period of 2008/06/01 08:42 to 2008/06/03 11:40. As in Figure 4b stations have been removed leaving 8 instruments with 100% uptime over the period. The few incidences of 6 and 7 station datasets in Figure 4b are caused by the failure of the global trigger message to be received in time, creating one or two late records e.g., a 7-instrument dataset plus a late single recording. In one case, the trigger message was never received by one instrument. The delays introduced by the communications network are therefore of considerable importance when implementing a CT scheme over the public Internet, which introduces a further consideration in order for the CT scheme to function correctly; to characterize the communication network's worst-case latencies. Once this has been determined, the CT scheme's window size and each instrument's pre-event recording period can then be adjusted. Analysis of the source data from figure 4b shows that extending the instrument pre-event recording length from 10s to 45s would have resulted in the loss of just one station's records in one of the 86 global events captured over the time period figure 4b's data came from.

Figure 5 shows the number of global triggers that the CT has issued on the ICEARRAY over a period of 6 weeks from 15/06-29/07/2008, along with the number of additional, isolated, trigger alerts for each instrument. All the instruments have similar triggering criteria and levels, and it is clear that some sites are noisier than others. The alerting system of the CUSP-HUB running the CT scheme has resulted in the analyst viewing only those recordings that were associated with global triggers. The other triggers can be discarded and therewith the data. Even with the present non-optimized setup of the CT system, considerable data-reviewing effort on behalf of an analyst has been saved. Spot-checking of a number of those additional triggers revealed no real events. The bar-plot also indicates that sites IS602, 603, 608, 609 and 613 are the most reliable sites i.e., have the smallest number of false triggers, and in future these sites should be assigned a high number of votes.

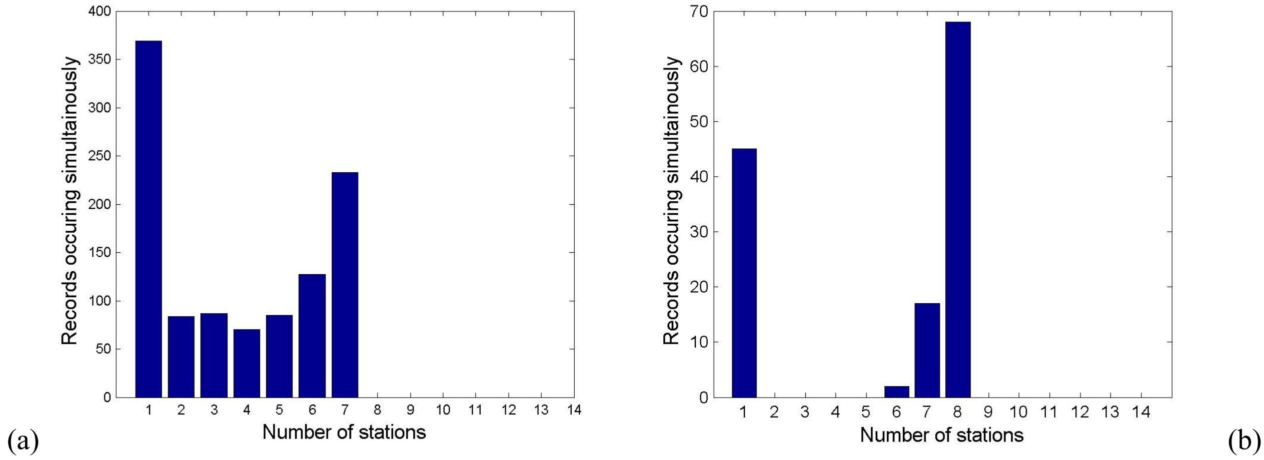

Figure 4 The number of ICEARRAY stations simultaneously recording (starting within a 10 second moving time window) aftershocks of the 15:45 May 29, 2008, M6.3 earthquake near Hveragerdi, South Iceland, and had 100% uptime status during (a) 2008/05/29 16:01 to 2008/06/01 08:35 *without CT*; and (b) 2008/06/01 08:42 to 2008/06/03 11:40 *with CT*.

5. CONCLUSIONS

The ICEARRAY network of accelerographs has been deployed in the in the South Iceland Seismic Zone, a region known to produce strong and destructive earthquakes. The ICEARRAY consists of 14 stations each equipped with a stand-alone triaxial accelerograph of the type CUSP-3Clp produced by Canterbury Seismic Instruments. The aperture of the network is 1.9 km and the smallest inter-station distance is 50 m. Each instrument is equipped with a perpetual GPRS link and the sensor is run in triggered mode and saves recordings to a local disk repository with a sampling rate of 200 Hz. Each record is time-stamped with a GPS clock enabling the application of array processing techniques on the network recordings provided complete data sets are acquired.

The ICEARRAY's deployment has led to the development of a "common-triggering" scheme, in which the instruments are configured to send trigger notification messages to one or more central hubs running a common-triggering algorithm that accepts the trigger notification messages. Each trigger notification message is decoded to find its source and based on this a preset number of votes are added to a tally. Whenever a preset number of votes have accumulated within a specified moving time window a global triggering command is issued to all instruments within the network. Thus, the "common-triggering" scheme operating over the Internet maximizes the efficiency of the triggering system of a network, effectively converting it into a triggered array, recording significant (real) events only, with the added benefit of significantly minimizing the analyst's efforts in reviewing recorded data by separating earthquake recordings from noise. This system markedly improves the usefulness of a network of stand-alone instruments with little or no additional cost and allows sites with marginal triggering suitability to be effectively incorporated as slave instruments.

6. ACKNOWLEDGEMENTS

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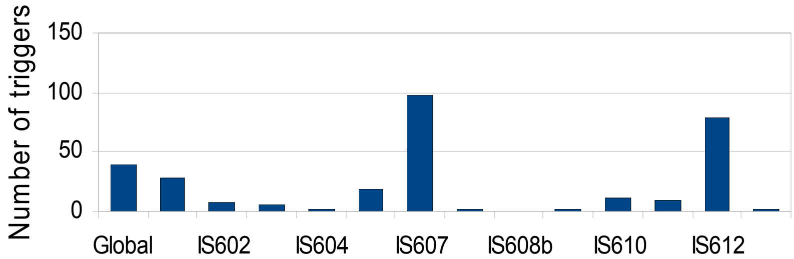

Figure 5 The number of triggers on ICEARRAY from 15/06-29/07/2008. The column at left shows the number of global triggers issued by the CT scheme, while the other columns show individual triggers from each instrument of the ICEARRAY that did not cause a global trigger. Site IS608b is not included in the array (see Figure 2).

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