The Role of non-IMS Stations in Explosion Monitoring

Ray Willemann's talk at the Vertic seminar
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Seismology has always required sharing data across broad geographical regions. Indeed, some people assert that British seismologists from the early part of the 20th century were outstanding in the field partly because demanding data from various parts of the British Empire was quicker than negotiating data exchange agreements.

The International Seismological Centre was created in 1970. Part of its original mission was to take full advantage of the then new World Wide Standardised Seismograph Network (WWSSN). But the ISC was also charged with collecting data from other seismic observatories that collected data relevant to global earthquake monitoring, and creating an integrated analysis of all WWSSN and other available data. The ISC's structure is very different than the IDC's. The ISC relies heavily on the work of individual observatories and regional networks, and principally integrates their regional or preliminary analyses into a coherent global summary.

The ISC's work has grown over time, as technology has made it straightforward to share an ever-growing volume of data and as more regional seismic networks have been installed. The growth also shows that seismologists have remained true to their original ideal of generously sharing data. Rather than try to pick out individual periods of rapid growth, I tend view this figure as generally exponential growth, followed by almost no growth at all from 1994 to 1998. The lack of growth in those years reflects the limited capability of the ISC; there was no slow down in either the volume of data collected or the willingness of seismologists to share their data.

prev next

In adding data for further years, I have changed vertical the scale in order to show the much larger number of events for which the ISC has collected data in recent years. The red bars in this chart for 1965 to 1998 represent the same numbers as in the previous chart.

The change from 1999 onward is that the ISC has re-organised its own system, so that we can collect information and re-distribute it to seismologists while manually reviewing data for only selected events. The points of this chart are that seismologists continue to share data freely and that the volume of data continues to grow exponentially. The ISC now bases its analysis on data contributed each year from more than 2000 seismic stations. Based on my regular discussions with seismologists around the world, I believe that at least twice that many seismic stations are operating. Some seismologists reckon that within a few years there might be 10,000 seismic stations operating all around the world.

Apart from the CTBT International Monitoring System, a large majority of seismic stations are installed as part of seismic hazard analysis and mitigation programmes. (A few hundred are installed in global networks for academic studies of earth structure, and these networks include stations in aseismic, unpopulated regions.) The rise in the number of mega-cities in seismically active areas is startling, accelerating, and likely to compel further advances in collecting and analysing seismic data.

How useful are all of these seismic stations in monitoring for covert underground nuclear explosions? To put the question very provocatively, does the enormous growth in the number non-IMS seismic stations make the IMS pointlessly redundant?

prev next

The question should not be answered simply yes or no, because seismic monitoring has several purposes. We want to know whether or not "something happened", where the something was, what the something was, and how big the something was.

This division is somewhat arbitrary. Knowing that something happened implies at least a general idea of where and how big it was, and knowing just where and how big it was is often useful in know what it was. Still, breaking things down like this helps to answer questions about the monitoring roles of seismic data from various stations.

prev

next

Those of you who have been involved in CTBT affairs may have seen maps of global detection thresholds, which show the size of the largest earthquake or explosion that might not be detected. Non-IMS stations can improve detection thresholds in an obvious way: near a seismic station an explosion must be smaller to evade detection.

I want to describe a different sort of contribution that non-IMS data can make to detection. One of the first steps, and it is a very crucial step, is recognising that signals at several different seismic stations all come from a common source. This step is challenging partly because a small earthquake that happens to be near an IMS station can produce a signal at that station, even though it is smaller than the detection threshold, and so fails to produce a visible signal at any other IMS station.

In analysing IMS data, computer programs and human analysts at the IDC might incorrectly suppose that signals at several different stations come from one common source when, in fact, the come from various small sources near each of the stations. This is a problem for any seismic network with a limited number of stations spread across a wide area. IDC seismologists are alert to this problem, but in some cases the only way to recognise such an error is to have more data from stations near the source that has supposedly been detected.

This is not simply a theoretical problem. There are 44 earthquakes in REBs of year 2000 that the ISC later concluded did not exist. ISC seismologists found that when they reviewed data from, say, numerous stations of the Japan Meteorological Agency, there were no signals from an earthquake that the IDC said was near to Japan. There are grounds for discussion among seismologists about the correct interpretation of the data in some cases. But in a co-operative project between the IDC and the ISC has concluded that at least a dozen of them are truly "phantom" earthquakes.

prev next

Methods for computing locations that were widely used in the 1960's are still the methods used most often today, even (with some modifications) at the IDC. Among other things, this means that data from less advanced seismic stations can contribute to a computed location.

Locations computed using these standard methods in a routine way are likely to be much more in error than locations based on a great deal of very careful work. This means not that seismologists are lazy, but that there has been insufficient motivation to automate the sophisticated analysis that can give more accurate locations. The requirements of CTBT monitoring are among the motivations that are pushing seismologists to improve their methods. I am hopeful that within 5 to 10 years, much of what I say about this slide will be completely out of date.

Where more accurate locations for many earthquakes have been required, seismologists have usually overcome the limitations of their methods by using an overwhelming amount of data. If we have data from stations from stations that are close to an earthquake and surround it (2 stations to the north, 2 to the south, 2 stations to the east, and 2 to the west), then even the crudest of our methods will almost always produce a location that is close to the true location.

This map shows the regions with stations from which the ISC receives enough data to compute reliable locations using the standard methods. The regions shaded yellow are surrounded by stations within 1000 km. Even moderately small earthquakes or explosions in these regions will be produce recognisable signals at stations all around the source, and any seismologist can easily compute a reliable location. The regions shaded orange are not as good; only earthquakes big enough to produce large signals out to 2000 km will be detected at surrounding stations. Red is even worse, while green is better.

The situation is actually better than this maps shows. In Peru, Algeria, Central Asia and western China, for example, I know that networks of tens of seismic stations are operating. Unfortunately, I have not yet succeeded in concluding arrangements for data from these networks to be contributed to the ISC.

Non-IMS stations are concentrated in regions where there is concern about seismic hazard. This can be seen clearly in Africa, where both earthquakes and non-IMS seismic stations are unusually sparse except in the East African Rift Zone. Nevertheless, even by this is very demanding standard for sufficient data, there are enough non-IMS stations in almost all continental regions to improve locations using our existing methods.

The other way in which standard location methods are unsatisfactory is the error estimates. It is quite routine for seismologists to be faced with evidence that an earthquake was, say, 20 kilometres from their computed location when they calculated a location uncertainty only 10 kilometres. In fact, many seismologists regard as evidence that the "whistle-blower" is ignorant. That is, the person pointing out the discrepancy simply has shown that he or she does not understand what location uncertainty means. As with the locations themselves, active research programmes motivated partly by CTBT requirements show promise of correcting this.

prev

next

Determining whether the source was an earthquake or an explosion is more challenging than detecting the event and computing its location. Partly for this reason, discrimination is beyond the mission of the IDC. Nevertheless, data from IMS and other seismic stations still can be used in discrimination.

This figure, from a report by the U.S. National Academy of Sciences, demonstrates two of the principles of discrimination. Explosions and earthquakes each produce compressional waves and shear waves, but with different relative sizes. At the bottom left, we see a record from an earthquake in which the early, compressional waves are small compared to the shear waves, which arrive later. At the bottom right, we see the record from an explosion with the opposite pattern; the early compressional waves are large compared to the later shear waves. The pattern is sometimes not so clear, partly because jagged boundaries between different types of rock within the earth sometimes convert compressional waves from explosions into shear waves, making their seismic records look like earthquake records.

The upper frames show the same records as the lower frames, but with the high frequencies filtered out. Low frequency waves travel along the surface of the earth and arrive later than the high frequency waves. But please notice that the amplitude of the low frequency wave from the earthquake is greater than the amplitude of the low frequency wave from the explosion. This happens because it takes time for earthquake rupture to propagate along the fault, while the explosion happens very quickly. To use this method requires modern "broadband" seismic stations that are carefully sited to avoid low-frequency noise. Even with the best seismometers, this method is less effective for smaller earthquakes and explosions; small earthquakes rupture shorter fault segments, so they are over more quickly and produce less low frequency energy.

I list, but do not show figures for, other discrimination methods. Waves from explosions often are radiated with similar amplitudes in all directions, while waves from earthquakes radiate with larger amplitudes in some directions than in others, depending on the orientation of the fault. Comparing amplitudes at stations in different directions can reveal a radiation pattern that is characteristic of an earthquake, suggesting that that particular source is not an explosion.

If the seismic waves show that the source was more than a few kilometres deep then it was surely not a man-made explosion. Studying the reverberations of the ground between the source and the surface can tell us the depth quite accurately, but only if we have high quality records from a station relatively close to the source.

For each of these methods, broadband stations near the source will provide the best evidence for discrimination, regardless of whether the station is part of the IMS or not.

prev next

Finally, I want to consider the properties of non-IMS stations in the context of the goals of explosion monitoring.

Are there likely to be non-IMS stations near the source? Yes. With just a few exceptions earthquake-monitoring stations cover almost all land areas.

Is a non-IMS stations likely to have a digital recorder? Yes. Ten years ago a seismologist from a small network might have talked proudly about the imminent upgrade of his or her network to digital recording. Now, digital recording is cheaper and more reliable than recording on paper, so it is the nearly universal standard.

Is a non-IMS station likely to be broadband? Not yet. Regional networks in wealthy countries generally have broadband seismometers and a few hundred stations in global networks are broadband. But across large swaths of the earth, the local and regional networks are still primarily short period. This probably will change within ten years, but right now the most common type of non-IMS stations could make only a limited contribution to discrimination. By the way, the relative sparseness of broadband stations is why so many seismologists are so keen for the CTBT Organisation to make IMS data freely available.

Are data from most non-IMS stations available in near-real-time? Locally, yes. Most networks have a central site to which data are transmitted. And, usually, each network centre has a connection to the Internet. But in most cases there has been no motivation (or funding) to build a system that routinely transmits the data on from the regional network centre.

Are most non-IMS stations at low-noise sites? Not as low-noise as IMS stations, which are very carefully sited. But most broadband stations have been well enough sited (or have been moved to sufficiently good sites, if there were problems initially) that they could make a very useful contribution, even to discrimination.

Are most non-IMS stations secure? No. IMS data include the digital signatures based on securely held private keys to guard against spoofing, i.e., replacing real data with data recorded somewhere else or at some other time. All seismologists guard against technical failures and vandalism, of course. But I would regard an earthquake-monitoring seismologist concerned that somebody might try to spoof his or her data as clearly paranoid. I know of no records from non-IMS seismic stations with digital signatures.

prev ----

In this slide I have supplemented my concluding remarks with some graphics that I hope will help to make my statements more clear. The graphics are not quantitative. There is no scale and if another seismologist argued with me that some of these bars should be a bit taller or shorter, then after some discussion I might well agree with him or her.

At this time, non-IMS seismic stations do not contribute nearly as much to Detection as IMS stations. This is not due to any limitation of the stations, but due to the lack of using the data in an effective way for global monitoring. It is possible to conceive of ways to use these stations for global monitoring; I represent this possibility with an outlined green bar. Since even short period stations are effective for detection and there are so many of them, in almost all land areas, non-IMS stations could (in principal) collectively provide a better detection threshold than the IMS.

At this time, non-IMS stations contribute more to earthquake and explosion accurate Location than the IMS. The short period instruments at most non-IMS stations are perfectly good for computing locations, and their greater numbers are essential for achieving accuracy. One word of caution: without a global communication system to routinely and securely transmit data, there could be a delay of a few days in collecting data from some non-IMS stations even when they are most urgently required.

New location methods that seismologists are developing will reduce the gap between accuracy from the sparse IMS and the dense networks of non-IMS stations, but even earthquake-monitoring seismologists will take advantage of these new methods, so the greater density of their stations will always give them some advantage.

At this time, the contributions to Discrimination from the IMS and from non-IMS seismic stations are about the same. Very high quality stations with well-known broadband response functions are important for discrimination, especially for relatively small events, and the 170 seismic stations of the IMS are among the best in the world.

But a growing number non-IMS stations have modern instrumentation, and within five to ten years IMS stations are likely to become a small minority of broadband instruments in almost all land areas. It seems obvious to me that the States Parties, who are responsible for discrimination, will use data from the numerous non-IMS seismic stations in discrimination.