A COMPARATIVE STUDY OF TWO AZIMUTH-BASED NON-STANDARD LOCATION METHODS

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ABSTRACT

In this study, two non-standard location procedures are reviewed, implemented and evaluated. Though independently developed, these two methods appear to be extremely similar in concept. Through azimuthal triangulation, Asian seismic network operators have been locating earthquakes for several decades using the "Induced Perpendicular Bisectors" (IPB), long before computers were invented and introduced to seismologists. The underlying simple principle can be best illustrated with the following extreme case. If two seismographs happen to record identical arrival times of the same seismic phase, then to the extent the 1-D structure applies to the region, the hypocenter should lie on the perpendicular bisector of the line segment or the great circle which connects these two specific seismographs. Depending on the epicentral distances, the perpendicular bisector itself could be a great circle along the Earth's surface or a normal section cutting through the Earth. If two or more such perpendicular bisectors are available, then the hypocenter or epicenter can be determined via triangulation. The merit lies in how the perpendicular bisector is derived in a more general setting, when the arrival time varies from station to station, which is typically the case in reality; and when waveform data are not available, which renders techniques based on full waveforms (such as polarization analysis and frequency-wave number (FK) technique) not applicable. The so-called "Yin Zhong Xian" algorithm, hereafter the YZX method, is an Oriental version of IPB-based procedure. It computes one IPB (via interpolation) for each group of three seismographs.

Also relying on the azimuthal triangulation for seismic location, Jih (1999) proposes a procedure, J0, to derive the back azimuth with a large-aperture network where all seismographs are on one side of the event. Any standard Geiger-type of least-squares inversion routine can be applied to determine the back azimuth easily. Two or more such skewed networks would suffice to derive two back azimuths for triangulation purpose. It has been demonstrated in Jih (1999) that this simple, hybrid procedure is particularly suitable for the seismic location problem at regional distances when [1] the crustal model is not known, [2] the seismic network is not calibrated, and [3] the azimuthal coverage of recording stations is poor. In this paper the procedure J0 is compared against the YZX method, to relocate earthquakes and explosions of known or well-constrained locations. It is shown that, at regional distances, the J0 algorithm performs better than does the YZX method, because the back azimuth derived with J0 is more reliable and stable. This is not surprising, as the YZX tends to be more susceptible to the small-scale lateral heterogeneity, which is often present in the crust. At local distances, however, the two methods seem to perform equally well.

Key Words: location, triangulation, back azimuth, calibration.

OBJECTIVE

To develop *ad hoc* algorithms which can effectively tackle the seismic location problem under the following difficult yet realistic situations often encountered in earthquake monitoring for the purposes of hazard reduction as well as for the CTBT verification: [1] the crustal model is not known, and hence an arbitrary global model (such as IASP91) will be sued; [2] the seismic network is not calibrated, and hence the phase arrivals will be used as they are - without any correction; and [3] the azimuthal coverage of recording stations is poor.

RESEARCH ACCOMPLISHED

1 Background

Epicenter remains as one of a few important source parameters that need to be promptly determined with sufficient accuracy and confidence whenever a natural - or man-made - seismic event of concern occurs. Over the years the computer-based Geiger-type least-squares inversion and its variations have become the standard means in solving the location problem.

If the ground-truth location of a nearby seismic event is known, the arrival readings of the new event at each seismograph can be individually "calibrated" to match the predicted travel-time curves of some pre-selected velocity model. It has been long established that, with the station corrections, locations of new seismic events in the vicinity around the ground-truth event can be significantly improved. This is the standard approach of ``calibration''. In a special application of this technique, travel-time residuals are obtained from a least-square location routine which is run with the depth constrained to the known ``true'' value. When these residuals are used as travel-time corrections in the same program run depth-free, nearby events can be located with smaller errors in depth. An elaboration of this specific application has been denoted the SRST (Source-Region-Station-Time) technique by Veith (1975) (see also Blandford, 1975). Alternatively, a postulated 1D crustal velocity model can be adjusted so that the estimated hypocenter would perfectly match the ground-truth event. Thus, the fine-tuned velocity model can be used to determine the location of nearby events without the need of establishing residual corrections for individual stations. Both the SRST and the model-tuning procedures require at least one ground-truth event.

There are cases where no nearby event of known location is available. Furthermore, there are cases where not only the crustal model is not well known, the seismic stations could be sparse or even spread in a very skew geometry. Jih (1999) presents a procedure, J0, which could be particularly suitable for these disadvantageous situations. In this study, J0 and another azimuth-based non-standard location procedure are reviewed and compared.

2 Adaptive Location Methods J0 and YZX

The most commonly used triangulation procedure for location is the "radial triangulation" which is based on intersection of several arcs drawn at respective epicentral distances. The epicentral distances can be individually estimated at each seismograph if, for instance, [1] the differential arrival (such as S-P) is available and [2] the P- and S-wave velocity structure around the seismograph is known. In the case only one common phase, say, the initial P, is available, then each pair of seismographs can jointly determine a hyperbola which passes through the epicenter – provided that, again, the P-wave velocity is known. Lacking the knowledge of the crustal structure, the location derived from radial triangulation could be severely biased when the number of seismograph is limited. The Geiger-type least square inversion using arrival times would inherently suffer from the same drawback and limitations.

Through "azimuthal triangulation", Asian seismic network operators have been locating earthquakes for several decades using the "Induced Perpendicular Bisectors" (IPB), even before computers were introduced to seismologists. The underlying simple principle can be best illustrated with the following extreme case. If two seismographs happen to record identical arrival times of the same seismic phase, then to the extent the 1D structure applies to the region, the hypocenter should lie on the perpendicular bisector of the line segment or the great circle which connects these two specific seismographs. Depending on the epicentral distances, the perpendicular bisector itself could be a great circle along the Earth's surface or a normal section cutting through the Earth. If two or more such perpendicular bisectors are available, then the hypocenter or epicenter can be determined via triangulation. The merit lies in how the perpendicular bisector is derived in a more general setting when the arrival time varies from station to station, which is typically the case in reality; and when waveform data are not available, which renders techniques based on full waveforms (such as polarization analysis and frequency-wavenumber (FK) technique) not applicable.

The so-called "Yin Zhong Xian" algorithm, hereafter the YZX method, is an oriental version of IPB-based procedure. Given three arrivals, t1 < t2 < t3, at three seismographs S1, S2, and S3, respectively, the YZX method finds a point S4 which lies on the great circle connecting S1 and S3 such that the arrival time at S4 would be approximately t2. S2 and S4 then determine one IPB. The search of S4 (through interpolation) requires a priori knowledge about the velocity structure. In reality, simple interpolation procedures are often used, which inevitably introduce additional uncertainty into the derived back azimuth, and hence the location would be affected as well.

Also relying on azimuthal triangulation for seismic location, Jih (1999) proposes a procedure J0 to derive the back azimuth with a large aperture network where all seismographs are on one side of the event. The basic idea of J0 method is to decompose the recording network into (at least) two sub-networks so that each sub-network is comprised of stations spread over only one side of the postulated epicenter. That is, each sub-network should have a very large azimuthal gap and preferably a large aperture as well. Any standard Geiger-type of least-squares inversion routine can be applied to determine the bac kazimuth easily. Two or more such skew networks would suffice to derive two back azimuths for triangulation.

In this paper the procedure J0 is compared against the YZX method, to relocate earthquakes and explosions of known or well-constrained locations. It is demonstrated that, at regional distances, the J0 algorithm performs better than does the YZX method, because the back azimuth derived with J0 is more reliable and stable. This is not surprising, as the YZX tends to be more susceptible to the small-scale lateral heterogeneity which is often present in the crust. At local distances, however, the two methods seem to perform equally well (not shown).

3 Example 1: The Salmon Explosion of October 22, 1964

Salmon, an underground nuclear explosion in Mississippi, was seismically recorded throughout North America and at some teleseismic stations. The 5-kt explosion was detonated at 16h 00m 00.0s UT on October 22, 1964, at a depth of 828.1 meters. The epicenter is 31°08'31.57"N, 89°34'11.8"W, in the Taut salt dome in Hattiesburg, Southern Mississippi. Extensive studies have been conducted for this event to validate crustal profiles toward different directions (Jordan *et al.,* 1966; Springer, 1966; Warren *et al.,* 1966). Jordan *et al.* (1966) published phase picks recorded at 143 stations for Salmon explosion. Thirty six arrivals from those stations within 10º are used in this example.

Figure 1 shows 21 "induced bisectors", each derived with the YZX method from three sites of the 36-station regional network. Figure 2 is the same as Figure 1, except that 25 back azimuths are determined using the method J0 in conjunction with a global continental average model, IASP91 (Kennett, 1991). The IASP91 model is arbitrarily chosen to mimic the situation where the true crustal structure of a region of interest may not be available, and seismic analysts would have to use a possibly erroneous crustal model to start with (Figure 2). The method J0 gives tightly converged rays, with the majority intersecting in the vicinity of the ground-truth location. The dashed circle in Figures 1, 2, 3, 4, and 6 has a radius of 18.73 km, which encircles an area of 1,000 km_ .

4 Example 2: The Taiwan Strait Earthquake of September 16, 1994

The September 16, 1994, Taiwan Strait earthquake caused significant damages to southeast China. Though at equal distance to Taiwan, its damage to Taiwan was relatively minor. Paths to the mainland China apparently had a weaker attenuation in ground motion. Fifteen pairs of Pn and Sn arrival times have been published by the Fujian Provincial Seismological Bureau [FSB], China (Yeh, 1995; Huang et al., 1998.) Yeh (1995) selected five sets of IPBs and suggested that YZX would lead to a solution consistent with the conventional triangulation results using solely S-P times (c.f. Figures 2 and 3 of Yeh, 1995). In an attempt to duplicate Yeh's result, it is found that the YZX method degrades somewhat as additional IPBs are drawn from different combinations of FSB seismographs (Figure 3). It should be noted that, however, the station coordinates of FSB seismographs used in this re-location exercise are not exact, as they were digitized from geographic maps, which certainly have added extra random errors to the location, with an effect equivalent to those of larger phase picking errors or stronger lateral heterogeneities in the crust.

If the same 1-dimensional model is assumed for paths to Taiwan and mainland China, then combining FSB phase picks with those measured at Taiwan's Central Weather Bureau [CWB] leads to a location with large offset (See the yellow diamond in Figure 4). The 1-second difference between FSB and CWB clocks, as speculated by Huang *et al.* (1998), can not count for this dramatic shift of location. It appears that paths to Fujian region may have a velocity faster than that of the IASP91model, whereas paths to Taiwan may be much slower. This is evidenced by Figure 4 (bottom) in which FSB and CWB underestimate and overestimate, respectively, the epicentral distances when the IASP91 model is used. Nevertheless, the individual back azimuths determined by FSB and CWB networks are not severely biased in direction. Thus applying the adaptive method J0 would lead to a triangulation result extremely close to the ISC and USGS/NEIC solution, which are based on hundreds of stations spread over all directions. The adaptive method is less sensitive to the choice of crustal model. Changing the crustal model from IASP91 to the southeast China model, which is in routine use at FSB (Fan *et al.,*1989; see also Jih, 1998), does not seem to affect the triangulation result (Table 1). This is yet another indication that the adaptive method J0 is robust.

Table 1. Comparison of Epicenters of September 16, 1994 Event

Network/Bulletin	ϕ° (N)	λ° (E)	Remark
Fujian Network	22.60	118.68	Yeh (1995), Southeast China model
Fujian + Canton	22.70	118.75	Yeh (1995), Southeast China model
CSB Preliminary	22.60	118.73	(China Seismological Bureau)
CSB RRSN	23.00	118.50	(CSB Rapid Reporting Seismograph Network)
Taiwan CWB	22.43	118.47	(Taiwan Central Weather Bureau)
USGS / NEIC	22.53	118.71	
ISC	22.52	118.75	
Adaptive Method J0	22.48	118.73	This study: Fujian+Taiwan, SE China model
Adaptive Method J0	22.48	118.72	This study: Fujian+Taiwan, IASP91 model

5 Example 3: The Kara Sea Event of August 16, 1997

Figure 5 illustrates how the method J0 can be applied to derive the location of Kara Sea event of August 16, 1997. A sub-network "A" comprised of 6 stations (KBS, SPITS, KEV, SDF, KAF, and FINESS), 11 phase picks, are fed into the LocSAT program (Figure 5, top) as described in Jordan and Sverdrup (1981) and Bratt and Bache (1988). The semimajor axes of the seven error ellipses are nearly the same, all pointing to the east – roughly 100º from the north (Figure 6). A second sub-network ``B'' is formed with 7 stations all spread to the south of Novaya Zemlya, which includes NRI, ARU, PKK, JOF, VAF, SUF, and KJN. There are 10 phase picks reported by these stations. Seven different continental crustal models produce nearly identical "optimal" back azimuths, pointing to the north (Figure 5, bottom). Using the IASP91 model, the two rays intersect at a location 11 km to the west of pIDC's REB location published in Israelson *et al.* (1997) (Figure 6). If the two networks were combined and the conventional location algorithm applied, the resulting location is 24 km to the south of the REB location (unfilled star in Figure 6). In-depth reviews addressing both the technical and political aspects of this event can be found in Sykes (1997) and Richards and Kim (1997).

DISCUSSION AND CONCLUSIONS

Two azimuth-based location techniques, J0 and YZX, have been implemented and tested to relocate earthquakes and explosions of known or well-constrained locations. It is shown that, at regional distances, the J0 algorithm performs better than does the YZX method, because the back azimuth derived with J0 is more reliable and stable. This is not surprising, as the YZX tends to be more susceptible to the small-scale lateral heterogeneities which are often present in the crust. At local distances, however, the two methods seem to perform equally well.

An interesting question raised by Prof. Thorne Lay at the 1st Event Screening Workshop (November 1997, Beijing) was that, if both the staged location procedure (like J0) and the conventional Geiger inversion are using virtually the same amount of information, would the staged approach offer advantages over the conventional procedure? In the case of simple crustal structure, indeed both methods could perform equally. Figure 2 exhibits a tight clustering of back azimuths derived from the adaptive method J0, resulting a well-constrained epicenter. This can certainly be achieved with all the phase picks lumped in one single Geiger inversion. This is not the case in general, however. As shown in Figure 4, lumping phase picks from Fujian and Taiwan seismic networks into one least-squares inversion would lead to a disastrous location, unless the difference in lateral difference in crustal velocities is accounted for. This is the intrinsic drawback of the conventional location procedure. In the case of staged procedure such as J0, each back azimuth is determined with a skew sub-network. The skew geometry of the sub-network would inevitably lead to large uncertainty in location and large error in epicenter. However, the method J0 does not use the epicenter information in the second stage of the process. The only piece of information – which is the best constrained piece – utilized by J0 is the semi-major axis, or equivalently, the back azimuth. As a result, the J0 method is practically using several back azimuths – each one being better constrained in the process - for triangulation. This explains why J0 is not equivalent to the conventional Geiger inversion.

A side remark on seismic data should be made. Seismic data have multiple uses – quick and accurate location of damaging earthquake so as to permit rapid emergency response, studies of the interior of the earth and the physics of the earthquake source, and nuclear test verification (Sykes, 1997). The field of seismology, which has been involved in earthquake studies for nearly 100 years, has a long tradition of international data exchange, much like that for weather information. It would be a tragedy if a major earthquake disaster strikes and response to the disaster were delayed because seismic data were not available. Example 2 clearly illustrates the advantages and importance of sharing the phase readings between China and Taiwan. China Seismological Bureau [CSB] has been promptly sharing phase readings of large earthquakes with Russia and Cuba. It is not surprising that the performance of CSB's RRSN [Rapid Reporting Seismograph Network] in earthquake location has greatly benefited from the data exchange. News has it that CSB and the Central Weather Bureau [CWB] of Taiwan have recently started negotiating a possible “seismic cooperation”, hopefully that could lead to an agreement on routine seismic data exchange between the two sides of the Taiwan Strait.

A lesson learned from Example 2 (Figure 4) is that phase picks from different tectonic regions must be combined in a judicious manner, if the conventional Geiger inversion is to be applied. One way to do so is to take into account the difference in crustal structures and apply the path-dependent travel-time tables - or equivalently, path-dependent corrections - prior to lumping the phase picks together for inversion. If adaptive methods (such as the method J0) are utilized, however, then the improvement in location can be immediately achieved without the need to wait for the time-consuming ``calibration research" is conducted. This can be regarded as an *ad hoc* measure.

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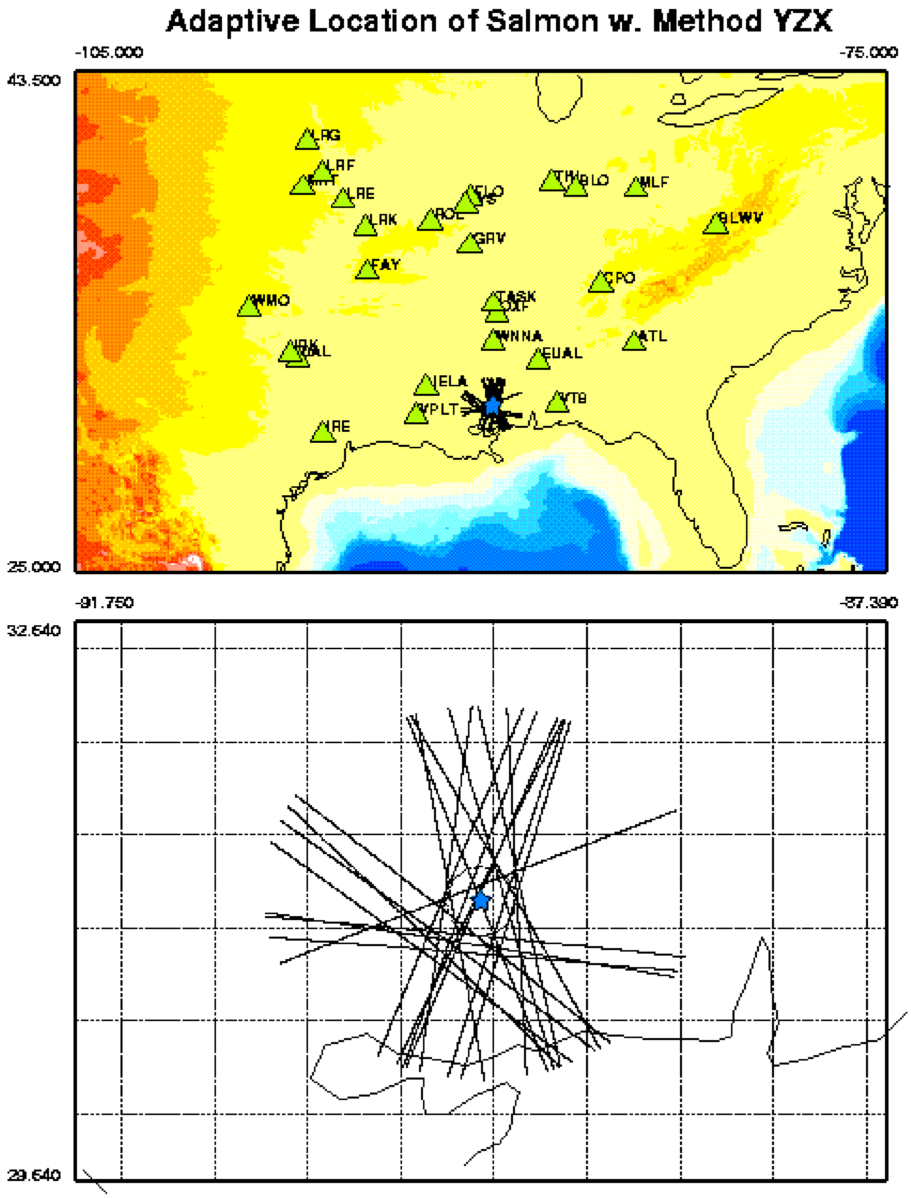
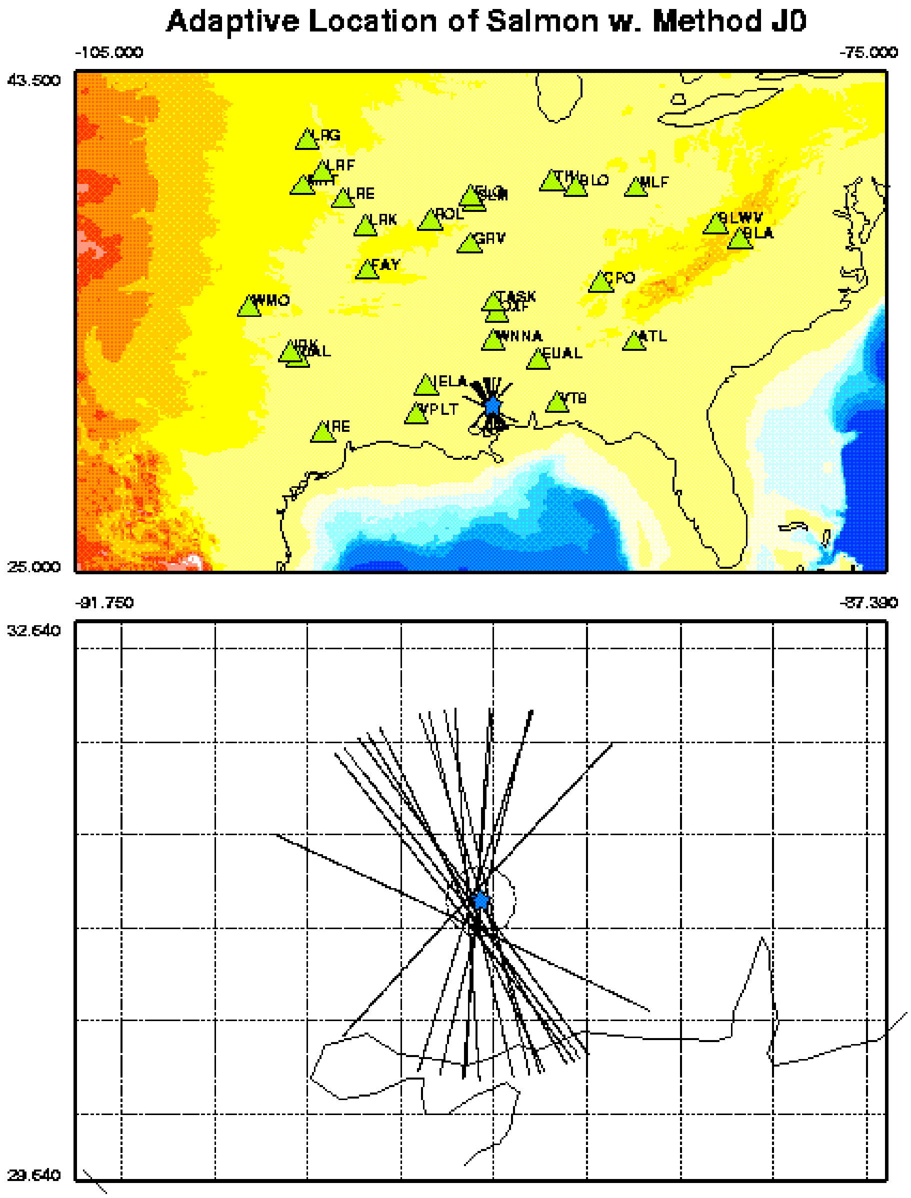


G.T. location= 31.142N -89.570W 0.828
21 "induced bisectors" used, each derived from a 3-station subnetwork

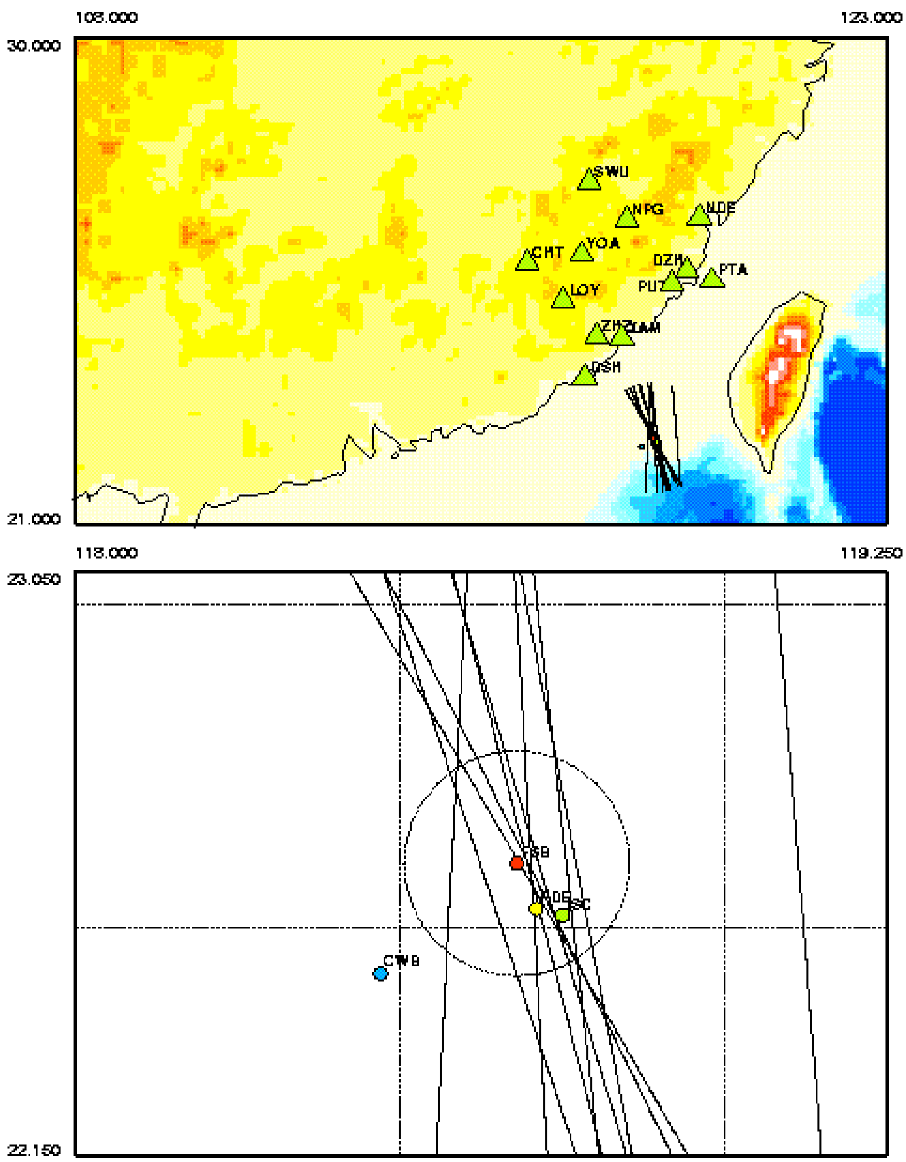
Figure 1



G.T. location= 31.142N 89.570W 0.828km
IASP91 model used for all subnetworks

Figure 2

Adaptive Location of 940916 w. Method YZX



10 "induced bisectors" used, each derived from a 3-station subnetwork
NEIC = 0620 18.7 22.53N 118.71E 13km, ISC = 22.52N 118.75E 13km
CWB = 0620 15.62 22.43N 118.47E 19km; FSB = 22.60N 118.68E 10km

Figure 3

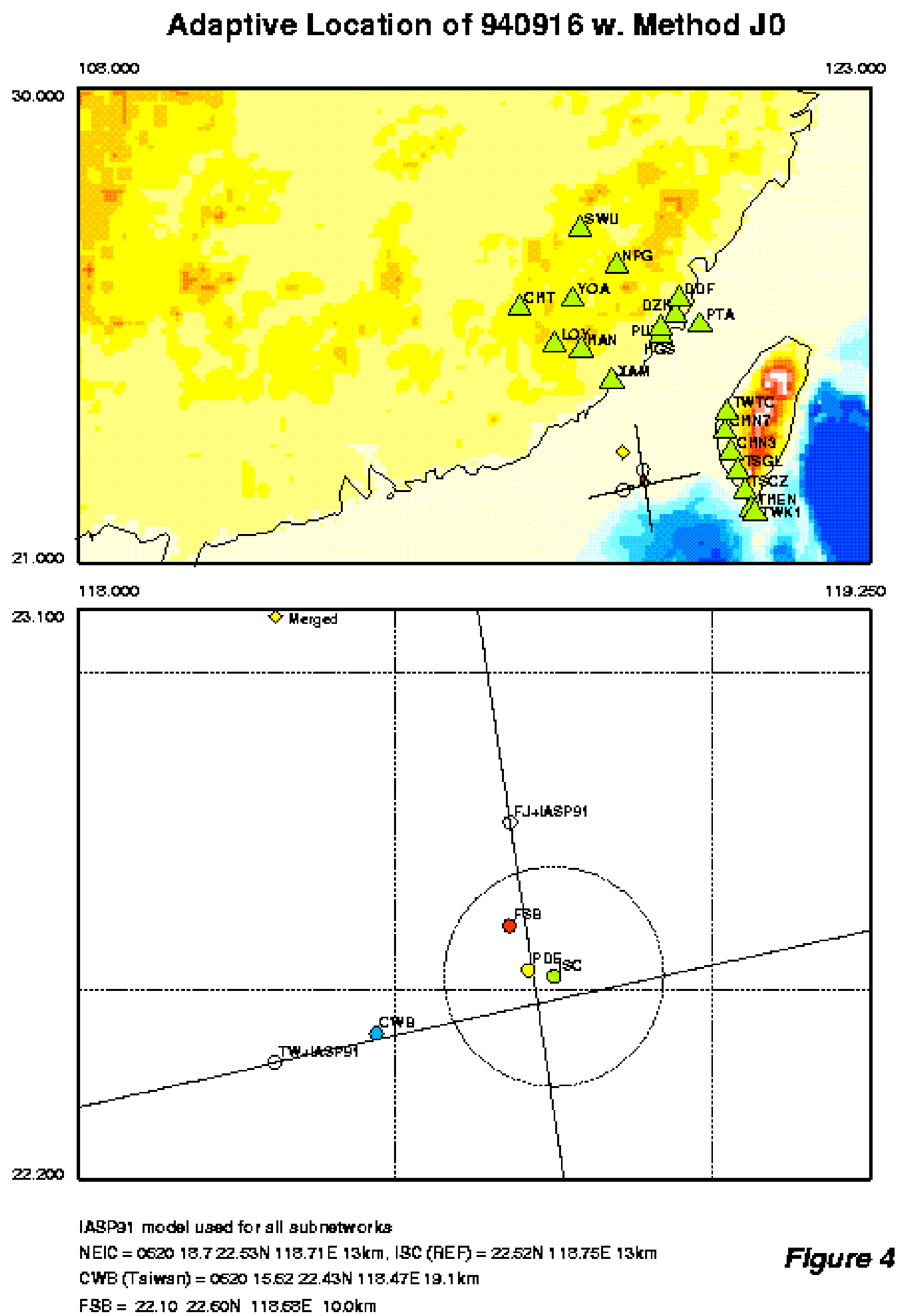

Adaptive Location of 940916 w. Method J0
108.000
123.000
30.000
21.000
SWU
NPG
YOA
CHT
PTA
XAM
118.000
119.250
23.100
22.200
Merged
FJ+IASP91
FSB
PDE
ISC
CWB
TW+IASP91
IASP91 model used for all subnetworks
NEIC = 0620 18.7 22.53N 118.71E 13km, ISC (REF) = 22.52N 118.75E 13km
CWB (Taiwan) = 0620 15.62 22.43N 118.47E 19.1km
FSB = 22.10 22.60N 118.68E 10.0km

Figure 4

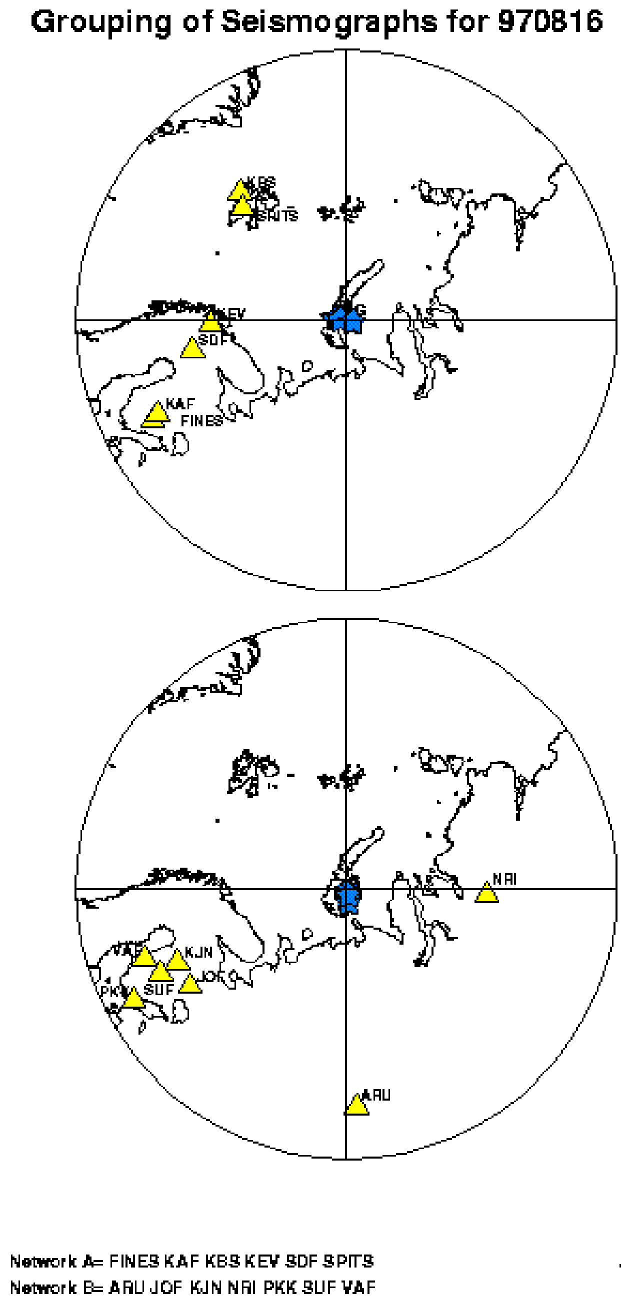
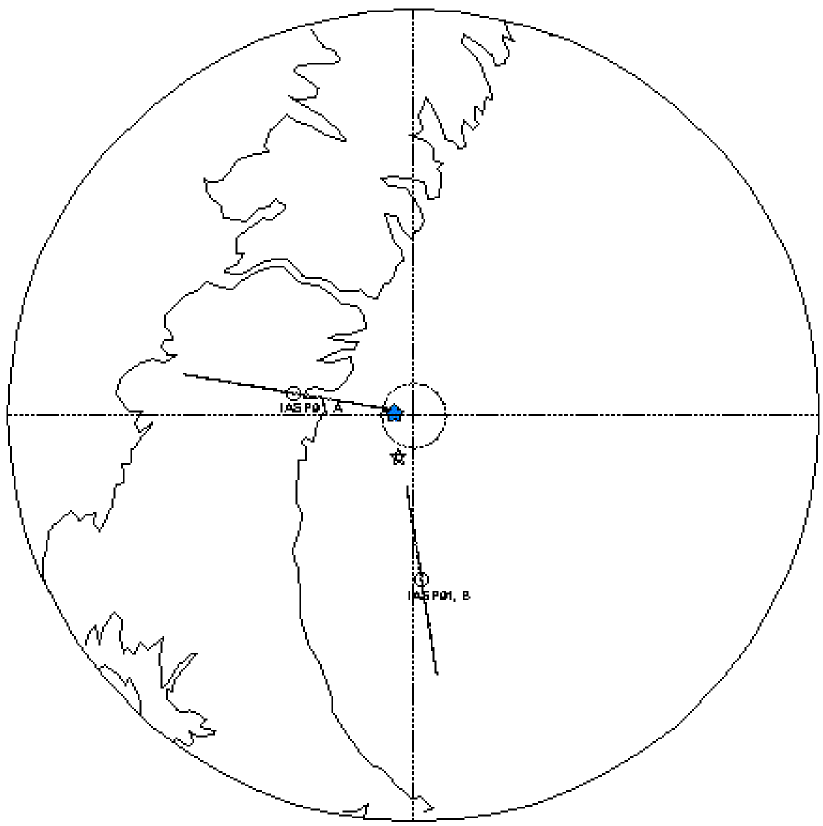

Grouping of Seismographs for 970816
KBS
SPITS
KEV
SDF
KAF
FINES
NRI
VAF
KJN
JOF
PKK
SUF
ARU
Network A= FINES KAF KBS KEV SDF SPITS
Network B= ARU JOF KJN NRI PKK SUF VAF

Figure 5

Locations of 970816, Conventional vs. Adaptive [J0]



REB location = 72.6484 57.3517 [depth set to 0]

IASP91, 11 picks ==> OT=2:11:5.281, 72.750 55.358 0.000, Offset= 67.2
(Network A=FINES KAF KBS KEV SDF SPITS)
IASP91, 10 picks ==> OT=2:11:4.357, 71.839 57.472 55.559, Offset= 90.4
(Network B=ARU JOF KJN NRI PKK SUF VAF)

IASP91 + J0 method => 72.657 57.033, Offset=10.7, Ang=71.29
IASP91 + all picks combined => 72.445 57.104, Offset=24.2

Figure 6