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Franco Pettenati
National Institute for Geophysics (I.N.G.), Italy

Livio Sirovich
The National Institute for Oceanography and for Experimental Geophysics (O.G.S.), Italy

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NEW-GENERATION OBJECTIVE AND REPRODUCIBLE ISOSEISMALS, AND TESTS OF SOURCE INVERSION OF THE USGS "FELT REPORTS"

Franco Pettenati
The National Group for Defence Against Earthquakes
(G.N.D.T.) of the National Institute for Geophysics (I.N.G.),
Rome, Italy, at O.G.S.

Livio Sirovich
The National Institute for Oceanography and for Experimental
Geophysics (O.G.S), Borgo Grotta Gigante, 42C,
34010 Sgonico, Trieste, Italia

ABSTRACT

We present two new techniques for treating earthquake intensity data objectively and reproducibly. First, our natural-neighbor, n-n, isoseismals (program: ConVor) are used to draw objective and reproducible isoseismals of the Whittier Narrows M_L=5.9, 1987 earthquake from the earthquake damage ("felt reports") sparsely observed in the region by the U.S.G.S.. ConVor uses the n-n coordinates to weight and interpolate the observations; thus, the weights of the experimental sites which are natural neighbors to a new point are proportional to the areas of the intersections of their Voronoi polygons. It is shown that the n-n isoseismals: 1) honour the experimental data completely, and are, thus, frequency-complete representations; 2) are easy-to-grasp and reliable overviews of regional earthquake damage; 3) do not ballast any subsequent quantitative treatment, because they do not introduce new (contouring) parameters. Secondly, we demonstrate that the approximate source geometry and kinematics of this earthquake can be back-predicted by inverting its intensity data automatically. The inversion involves twelve parameters, the most sensitive of which are the epicentral co-ordinates and the fault plane solution; our trial-and-error technique minimizes the sum of the squared residuals (calculated intensity - minus - observed intensity) at the surveyed sites, and the errors of the source parameters are also estimated.

INTRODUCTION

The crux of the paper lies in the following points. We observed that in several cases the isoseismals available for some well-surveyed earthquakes bear a likeness to the synthetic isoseismals obtained from a simple kinematic model (KF) (Sirovich, 1996a, b, 1997); the model considers the body-wave radiation from a line source in an elastic half space in the distance range of approximately 10 to 100 km. This likeness left us hope of carrying out inversions, but, traditional techniques did not allow us to make this comparison objectively. So, we are presenting here a new technique for drawing isoseismals, and a new inversion strategy.

Consider that, for isoseismals, the automatic contouring techniques available up to now constitute a two-dimensional filter; this is the unavoidable effect of combining sampling with contouring (Wren, 1975). Filtering the site intensity data sets (or "felt reports"; in the following: intensities) without a statistical or physical criterion is an arbitrary choice, however. On the other hand, the subjectivity of hand-drawn isoseismals has been stressed by many authors (e.g., the more recent works by Bollinger, 1977; Hanks and Johnston, 1992; Pettenati el al., 1999; see also the international experiment by Cecic' et al., 1997). Rather, we produce easy-to-grasp geographical representations of the regional distribution of earthquake damage (intensities) by adopting the n-n approach by Sibson (1980) and Sambridge *et al.* (1995), which is based on the Voronoi tessellation technique. In this way, we draw the new n-n isoseismals (Cavallini et al., 2000).

We have already shown that for inversion macroseismic intensities can be quantitatively treated to retrieve source information. We did this by restricting the inversions to a limited space of the parameters, and obtained results (Pettenati et al., 1999; Sirovich and Pettenati, 1999) which agree with those independently produced by other workers who treated instrumental observations. This was promising for improving the knowledge on hazard in areas with rich historical catalogues and/or low seismicity rates and rare, strong earthquakes.

The test of intensity inversion, presented in this paper, was conducted on the whole of the space of the angular parameters controlling the fault plane solution, and on a limited space of the other parameters. In this connection, note that obviously one has to adopt constraints on epicentral coordinates, depth of the line source H, shear wave velocity V_S, rupture velocity V_r, Mach number and length of rupture L. In the convention adopted here, the total length of the rupture is the sum of the absolute values of the along-strike part (which is considered positive, L+) and the antistrike (negative, L-); the same holds for the Mach number (Mach+, and Mach-).

We state that we do not want to determine "new" source parameters for the studied earthquake. In fact, it is more than evident that the solutions obtained till now by Hauksson et al. (1988), Bent and Helmberger (1989), Haukkson and Jones (1989), Lin and Stein (1989), Zeng et al. (1993) are much more reliable than ours, because those authors treated instrumental measurements which are much more reliable and easier to treat with respect to the felt reports. All we want to try and do is to see if, by using the intensities, it is possible to get an approximate idea of the source of the Whittier Narrows, 1987 earthquake. To expect anything more would be unrealistic. In other words, from the point of view of our research, this well documented earthquake is a precious opportunity to validate our techniques. But, pre-instrumental earthquakes are the strategic target of our work. We call "pseudo-intensities" the intensity values forced on a numerical axis.

THE N-N ISOSEISMALS

As known, the Voronoi tessellation solves the problem of proximity in the plane so that each surveyed site is circumscribed by a convex polygon, and all points inside that polygon are unequivocally closer to that surveyed site than to any other surveyed site that generated the neighborring polygons (see details and theorems in Preparata and Shamos, 1985).

Borrowing the n-n method from Sambridge *et al.* (1995), we represent the regional damage field by locally interpolating the intensities observed at the sites. These authors gave full details of the theory and sophisticated numerical algorithms; for simplicity, as a preliminary step, we solved this local interpolation scheme with approximate graphical means, using the screen pixel as the "infinitesimal" surface element (see also Okabe et al., 2000; page 51). Thus, the weight of the value observed at point S_I upon the value at the new point X (refer to Fig. 1), where intensity was *not* observed, is equal to the area of the polygon *a-e-f-g-h* divided by the area of the polygon *a-b-c-d-e*. In the figure, the dashed segments constitute the Delaunay triangulation that was created by adding point X to points S_i.

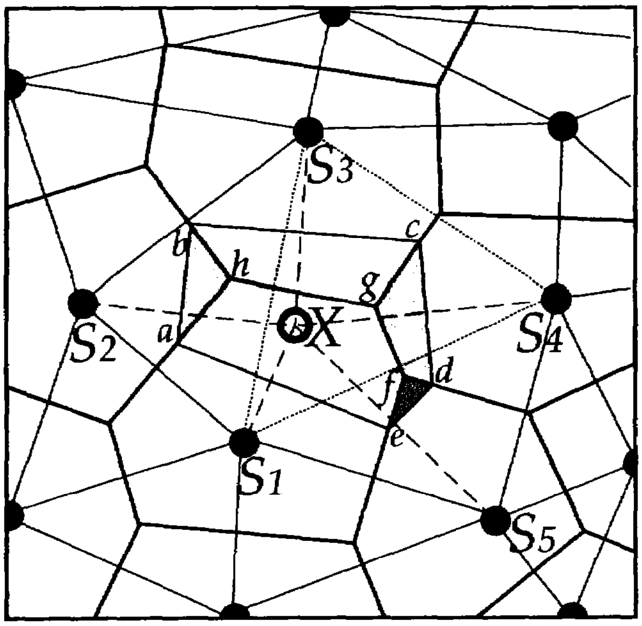

Fig. 1. Local interpolation scheme of the n-n isoseismals.

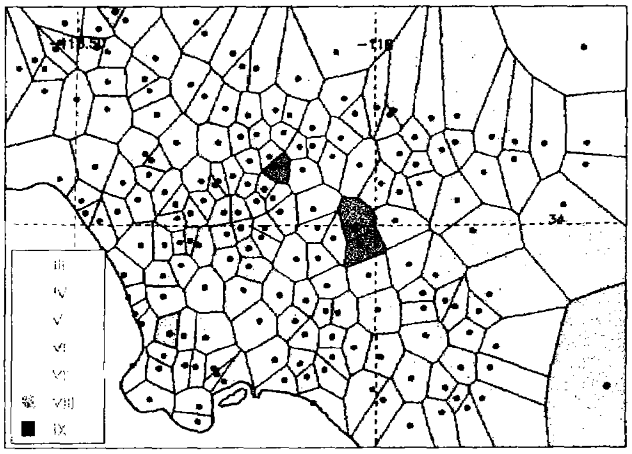

Fig. 2. Whittier Narrows, 1997 earthquake. Tessellated observed intensities.

N-n isoseismals of the Whittier Narrows, 1987 earthquake

Figure 2 shows the observed intensities of this earthquake (courtesy of J. W. Dewey, written communication, 1994) and the tessellation with Voronoi polygons. Consider that we emended the U.S.G.S. data set from the two statistical outliers: Sylmar (intensity 5 at 252km epicentral distance), and South San Gabriel (intensity 6 at 6km). Then, the intensity 8 at Rosemead Ticor Title Ins. Bldg. also is not shown in Fig. 2 because we did not use it for inversion (it is the closest site to our source, and the KF model gives unrealistic radiations close to it).

The figure allows one to consider the data from the point of view of information density and continuity; for example, there are two points with I=VIII, and one more point NW of them. To include these four points in a VIII degree meizoseismal area would be arbitrary (the same holds if the datum of Rosemead Ticor Title Ins. Bldg. is included). Then, south of the epicentral area, tessellation shows that two sites of V degree make an island inside a VI degree area. SE of the epicentral area, the abrupt passage from degrees VI to V could be due to the low information density there.

Figure 3 shows the n-n isoseismals of this earthquake, starting from the felt reports of the U.S.G.S. (total data set); in the figure, the intensity numbers are centered on the surveyed sites (courtesy of J. Dewey, written communication, 1994). A 200×150 graphical grid was used in the figure, which let the picture graphically honour all observations. Note, however, that in the n-n approach the contouring surface is univocally determined by the scheme in Fig. 1, and that the choice of the graphical sampling grid is external to the contour. The solution obtained is univocal, and no contouring parameters are needed. It is also seen that the field data are honoured completely; given the all-pass filter nature of n-n isoseismals, this is a general characteristic of this technique.

Fig. 3. Whittier Narrows, 1997 earthquake. Natural-neighbor isoseismals (see text).

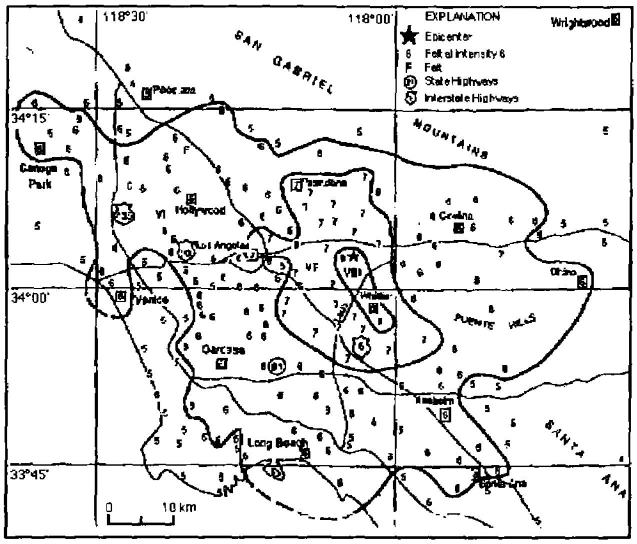

Fig. 4. Whittier Narrows, 1997 earthquake. The U.S.G.S. isoseismals (courtesy of J. W. Dewey, written communication, 2000; partly redrawn).

In this particular case, also the stochastic contouring technique called "inverse-weighted-distance-average" (IWDA) (eq. A.6 in Eckstein, 1989) is also able to acceptably honour the data after the maximum and minimum search radius, the distance exponent for interpolation weighting, the maximum number of experimental intensities considered in all directions and the minimum number per quadrant, the axes samplings for the interpolation grid, and the smoothing, are properly tuned (figure not shown). Note, however, that this choice is highly critical and strongly depends on the individual data set.

It is noteworthy that the n-n isoseismals of Fig. 3 resemble those of degrees VIII to VI hand-drawn by the U.S.G.S. (see Fig. 4), but are different from preliminary VIII and VII degree isoseismals by Hauksson et al. (1988).

INVERSIONS OF INTENSITIES

Sirovich (1996) had qualitatively compared the Whittier Narrows isoseismals by Hauksson et al. (1988) and by the U.S.G.S. (courtesy of J.W. Dewey, written communication, 1994) with the synthetic ones calculated by trial-and-error using the KF kinematic source model; in so doing, he retrieved source parameters that are compatible with those obtained from instrumental measurements. Now, we quantitatively explore the whole space of the angular parameters controlling the fault plane solution, and a limited space of the other principal source parameters.

Fig. 5. Whittier Narrows, 1997 earthquake. Example of squared pseudo-intensity residuals at the surveyed sites; whole space of the fault plane solution (see text).

For example, Fig. 5A shows the squared pseudo-intensity residuals (calculated-minus-observed at the surveyed sites, Σr^2) for the strike angle ranging from 0 to 355°, and the dip angle from 30° to 90° (5° step). In Fig. 5A, values of Σr^2 are from ≤120 (dark red) to ≥320 (blue), with a step of 20. Figs. 5B-5D show Σr^2 for the strike angle, ranging from 0° to 355°, and the rake from 0° to 180°. The dip angle is 40° in Fig. 5B, 45° in Fig. 5C, 50° in 5D; Σr^2 go from ≤120 (dark red) to ≥380 (dark blue); same step as Fig. 5A. We wish to recall that we adopt the convention of the positive direction of the strike ranging from 0° to 360°, with the plane dipping to the right, and the rake angle seen from the roof of the fault and measured counterclockwise (see Fig. 1 in Sirovich, 1997).

During this first inversion, the other parameters were kept fixed. They were: -118°.081 epicentral longitude and 34°.049 latitude from Hauksson and Jones (1989); then, depth H=12 km, |L+|=|L-|=3 km, |Mach+|=|Mach-|=0.75, V_S=3.3 km/s, M_0 1.0×10^{18}N·m. As seen from Figs. 5B-5D, we found four relative minima from the beginning, that corresponded to rake angles around 50°-130°, at approximately 90° intervals of the strike. Regarding this quasi regular recurrence, note that both "experimental" and synthetic isoseismals of degree VI (Sirovich, 1996; Fig. 4) of this earthquake show two symmetry axes approximately NE and NW oriented (the same holds for the Northridge, 1994 earthquake).

Then, we systematically explored the other parameters in the ranges shown in Table 1. More trials were also done using values outside the ranges of Table 1, but they gave higher residuals. Consider that our program lets us treat a maximum of six parameters simultaneously.

Table 1. Parameters' space.

PARAMETER	RANGE	STEP
strike angle [°]	0-355	5 (then: 1)
dip angle [°]	30-90	5 (then: 1)
rake angle [°]	0-175	5 (then: 1)
nucleation longitude [°]	-118.14 to -118.04	0.01
nucleation latitude [°]	34.03-34.07	0.01
nucleation depth H [km]	10-18	1
rupture length L* [km]	0-3	1
V_S [km/s]	3.0-3.7	0.01
Mach*	0.64-0.76	0.02
M_0 [10^{18}Nm]	1.0-6.4	0.01

* positive along-strike, negative antistrike

Results

By this trial-and-error inversion it was found that the absolute variance minimum is not far from the second minimum from right in Fig. 5C. The absolute minimum scores Σr^2=67, and the associated source parameters are in Table 2. The errors have been calculated according to the bootstrap technique, and are preliminary. We also quantified the sensitivities of the principal parameters; to do so, we assumed that an error of two degrees in the intensity estimated in the field is unlikely. Then, we progressively increased (and decreased) the parameters of the best-fitted solution, one by one, by trial-and-error, till the first site experienced a pseudo-intensity change of two degrees (see the details in Sirovich and Pettenati, 1999). These sensitivities are conservative because the allowed variation for each single parameter results in at least one site changing by the maximal assumed uncertainty of the estimates. The asymmetry of some sensitivity values in Table 2 is due both to the incomplete sampling provided by the sites, and the functional expression of equation (2) in Pettenati et al. (1999); note that the reliability of these sensitivities deteriorates at the extremes of the validity of the equation. Table 2 also reports the parameters determined by Sirovich (1996a).

Table 2. Source parameters corresponding to the absolute variance minimum in the inversion.

PARAMETER	VALUE ± error; sensitivity (+;-)	Sirovich (1996a)
strike angle [°]	260±8 +17, -32	270
dip angle [°]	44±3 +9, -10	50
rake angle [°]	100±7 +14, -27	100
nucleation longitude [°]	-118.10±0.03 +0.06, -0.09	-118.081
nucleation latitude °]	34.04±0.02 +0.03, -0.05	34.049
nucleation depth H [km]	17±2 +7, -6	10
rupture length L * [km]	|L-|=|L+|=3±** **	3
V_S [km/s]	3.31±0.2 **	3.5
Mach+ *	0.73±0.05 +0.18, -0.12	0.74
Mach- *	-0.72±0.05 +0.25, -0.16	-0.74
M_0 [10^{18}Nm]	1.9±0.5 +**, -1.85	/

* positive along-strike, negative antistrike;
** non-determined.

Then, the second relative minimum scores Σr^2=71, and is not far from the first one from left in Fig. 5D. It is worth mentioning, however, that: 1) the model of Table 2 gives positive and negative residuals sparse in the plane, and this means that this model was able to approximately reproduce the shape of the observed intensity field; 2) instead, positive residuals clearly predominate in the second relative minimum, and negative residuals concentrate N and SE of the source (figure not shown); 3) the careful exploration of the space parameters in the vicinity of this relative minimum in Fig. 5D was not able to go under the value of 71. This minimum corresponds to a dip-slip mechanism having a strike angle of 62°. In the light of the mechanism already obtained from instrumental measurements, we know that this mechanism is unrealistic; however, a blind test would discard it not only for its higher Σr^2, but also according to observations (1) and (2).

Thus, the source inversion of the intensities of the Whittier Narrows, 1987 earthquake points to reasonable source parameters; this is a striking result because it gives hope of being able to treat some pre-instrumental earthquakes successfully. We are aware, however, that the strength of our solution is not so strong.

Figure 6 shows the tessellated synthetic pseudo-intensities produced by the model in Table 2. As said, the KF model gives unrealistic radiations at distances less than approximately 10 km from the source; we think that the area of degree 6, which separates the two 'islands' of degree 7 in Fig. 6, is partly due to this deficiency.

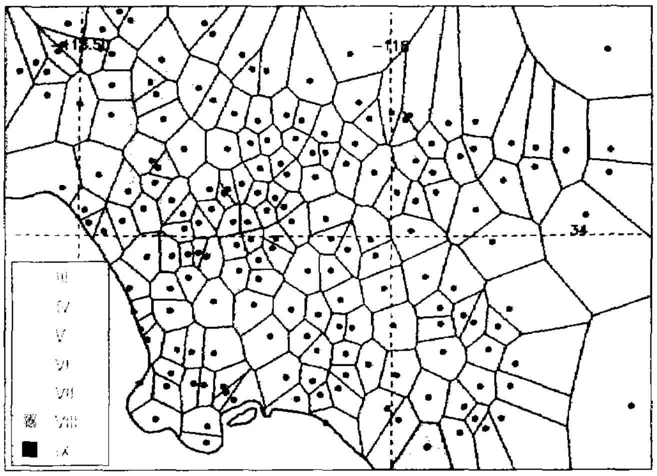

Fig. 6. Whittier Narrows, 1997 earthquake. Tessellated synthetic pseudo-intensities produced by the bestfitting model of Table 2.

COMMENTS AND CONCLUSIONS

At this stage of our research, we did not use inversion algorithms which allow the optimization of the search of the minimum variance model; in fact, we still need to know the shape of the minimum residuals surface. If the result in Fig. 5 is confirmed by more tests, then we plan to adopt such algorithms.

It is worth mentioning that the two series of parameters in Table 2 are rather similar. The qualitative comparison of "experimental" and synthetic isoseismals in Sirovich (1996a; Fig. 4) perhaps looks nicer than the comparison between Figs. 2 and 6, but the results of the present objective and quantitative analysis confirm that the U.S.G.S. felt reports of the Whittier Narrows earthquake carry information on its source.

Then, the n-n isoseismals of Fig. 3 strictly resemble the U.S.G.S. isoseismals of Fig. 4. Given some previous results on the Northridge, 1994 earthquake (Cavallini et al., 2000), this resemblance suggests that the proposed n-n isoseismals have the necessary qualities for an international standard for graphically representing regional intensity surveys. In fact, they produce pictures that are easy-to-grasp and reliable, objective and reproducible. In the case of the Whittier Narrows, 1987 earthquake the n-n isoseismals are rather smooth, and the tendency of intensity to decay with distance is clearly seen. Then, according to our inversion results, it seems that the regional shape of the intensity field is conditioned by the body waves radiation approximately within the 10-100 km distance range. In other cases, as the 1925 Charlevoix earthquake in Canada (Cavallini et al., 2000), n-n isoseismals are much more complicated, but this comes objectively from the complex distribution of the intensities surveyed in the field (or perhaps even from errors). N-n isoseismals do not apply any cosmetic treatment, and for this reason too can be used for other quantitative applications. For example, estimating the Magnitude of pre-instrumental earthquakes from intensity data is a well established (and unavoidable) practice. Usually, this is done by using the dimensions or mean radii of equal intensity areas. But the choice of areas and radii is obviously biased by the many kinds of contouring techniques used. Our technique can help define areas and mean radii objectively; we tested this in the case of the aforementioned 1925 Charlevoix earthquake in Canada (Cavallini et al., 2000).

However, for simplicity, we continue to use data sets (point-, or tessellated, intensities) for source inversion purposes. As said, the purpose of our inversion test was to repeat the analysis by Sirovich (1996) but in quantitative terms. We wanted to test if an automatic source inversion of intensities is feasible, and, if, by so doing is it possible to get an approximate idea of the source of the Whittier Narrows, 1987 earthquake. From this point of view, our test is successful, even if the absolute minimum variance is not far from that of an unrealistic model. This result encourages us to validate our regression technique with more well-documented earthquakes, and to treat intensities of pre-instrumental earthquakes, which are the principal target of our work.

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