2008 SCEC FINAL REPORT
Project Title: Modeling Short-Period Seismograms
Don Helmberger, Principal Investigator

Here we report on a detailed test of a recently developed technique, CAPloc, in recovering source parameters from a few stations against results from a large broadband network in Southern California. The method uses a library of 1D Green's functions which are broken into segments and matched to waveform observations with adjustable timing shifts. These shifts can be established by calibration against a distribution of well-located earthquakes and assembled in tomographic images for predicting various phase-delays. Synthetics generated from 2D cross-sections through these models indicates that 1D synthetic waveforms are sufficient in modeling but simply shifted in time for most hard-rock sites. This simplification allows the source inversion for both mechanism and location to easily obtain by grid search. We test one-station mechanisms for 160 events against the array for both PAS and GSC which have data since 1960. While individual solutions work well for mechanism (about 80%), joint solutions using these two stations produce more reliable and defensible results. Inverting for both mechanism and location also works well except for certain complex paths across deep basins and along mountain ridges.

Regional monitoring of seismicity is still dominated by travel time picks of short-period P-waves where ground truth estimates are defined by the azimuthal distribution of stations, *Bondar et al*. (2004). However, as short-period stations are replaced by broadband instruments, we can start using the whole waveform to invert for source excitation as well as location. Thus, fewer stations are necessary to monitor seismicity with comparable accuracy as well as retrieving source parameters. A recent feasibility study by *Tan et al.* (2006) demonstrated that using three-component waveform data from two path-calibrated stations was sufficient to retrieve results comparable to those obtained by a PASSCAL network. In this study, we will carry this approach forward by using phase-delay maps and testing two-station solutions results against the Southern California network results and discussing successes and difficulties.

The essence of "CAPloc" is to model the entire record with the differential travel times between major phase groups (the P and surface waves) adjusted from known calibration information. These travel time adjustments, either from a well-determined tomographic map (*Liu et al.*, 2004) or a calibration study are made to correct for deviations of the real crustal structure from the model. They are the prerequisites for accurate epicentral location. Compared to the traditional method of using impulsive P-waves, "CAPloc" greatly enhances sampling of the focal sphere by using the whole seismograms, so reliable source estimates can be achieved with sparse data set.

Here we briefly review the methodology of "CAPloc". Let $u(t)$ be a recorded seismogram with instrument response removed. The corresponding synthetics, $s(t)$, for a double couple source can be expressed as a summation of contributions from three fundamental faults, namely, vertical strike-slip, vertical dip-slip, and 45° dip-slip:

$$s_j(t) = M_0 \sum_{i=1}^{3} A_{ij}(\phi - \varphi(\theta,\xi), \delta, \lambda) G_{ij}(h, \Delta(\theta,\xi), t), \quad (1)$$

where j = 1, 2, 3 denotes the vertical, radial, and tangential component, respectively [*Helmberger*, 1983]. The G_{ij} 's are the Green's functions, and the A_{ij} 's are the radiation coefficients. M_0 is the scalar moment. φ and Δ are the station azimuth and distance. The unknowns, *h* (depth), ϕ(strike), δ(dip) and λ(rake), that describe the source depth and orientation, together with θ(event latitude) and ξ(event longitude) that define the epicenter location, can be obtained by solving the equation

$$u(t) = s(t). \tag{2}$$

We solve Eqn. 2 in a grid-search manner where a weighted summation of waveform misfit errors (e_{Pnl} and e_{Sur} defined in Eqn.3) plus P-wave travel time residues are minimized.

$$e_{Pnl} = \left\| u^{Pnl}(t) - s^{Pnl}(t - \Delta T) \right\|$$
$$e_{Sur} = \left\| u^{Rayleigh}(t) - s^{Rayleigh}(t - \Delta T - \delta t^{rayleigh}) \right\| + \left\| u^{Love}(t) - s^{Love}(t - \Delta T - \delta t^{Love} \right\| \tag{3}$$

Here $\| \ \|$ denotes the L_2 norm. ΔT is the time shift to align synthetics with data on the first P arrival. The $\delta t^{Rayleigh}$ and δt^{Love} stand for the path specific timing corrections for the synthetic Rayleigh and Love wave segments from calibration. We distinguish body (Pnl) and surface waves because they sample the crustal structure differently and provide independent constrain on the source parameters. To take full advantage of both Pnl and surface waves, an adaptive weighting scheme between them was developed and proved crucial when a sparse data set is used (see *Tan et al.*, 2006). The first stage in the use of Eqn. 3 is to establish the phase-delays (δt's), a calibration and mapping procedure so that these delays can be estimated for any path ending at (θ, ξ).

Phase-delay Maps

The most direct approach is to use the locations of the events displayed in Fig. 1 as given in the SCSN catalog and measure these delays for the various paths connecting the event-station pairs. However, measuring these delays requires modeling the events since the initial surface excitation phase depends on mechanism. Fortunately, the CAP method produces these delays automatically as part of the modeling process and used to construct tomographic-style models, *Wei et al.* (2009).

Generally, tomographic models are validated by performing a checkerboard test or testing how well the new model predicts the observed travel time anomalies. We have picked two stations, PAS and GSC, for this test since these stations have produced reasonably broadband records since 1960. These old records have been scanned and digitized and can be modeled as demonstrated in *Ho-Liu and Helmberger* (1989), and thus it is useful to calibrate paths for future efforts in refining historic events. It appears that travel time delays trade-off directly with source mechanism accuracy. This feature becomes particularly apparent in two-station inversions for mechanisms as can be seen for the stations GSC and PAS (Fig. 2). Here, we display the delays for a population of events, essentially a station-centered spider diagram. The first column contains the 1D delays from the network source inversions. The second column presents the predictions from the tomographic maps model with the third column indicating the residual. There are several paths that cause problems for the GSC station; one for paths towards the Brawley seismicity zone and crossing the Palm Springs Valley and the other from the western edge of the Sierra Nevada Mountains, Coso patch of seismicity. This means that mechanisms derived by these paths to GSC will probably disagree with those derived by the full array.

The results for two station solutions are included in Fig. 1 where the agreement with the full array is displayed. Most events in regions with good calibration as defined by Fig. 2 provide accurate results, although there are a few exceptions. Only two events particularly stand out, one is the 9109442 in the Hector Mine sequence and the other is the 9038699 on the northern Elsinore fault. Two- station solutions with adequate fits (cc's > .8) were obtained for over 70% of the events. Roughly 15% of the events had no solution or one station was too noisy to use. Bad solutions with good fits, unfortunately, are evident but at a small percentage. In summary, the two stations, PAS and GSC, used together can produce accurate mechanisms for events occurring between 1960-1990 when both stations produced three-component long-period records.

We conducted a test of the recently developed technique, CAPloc that uses regional waveforms to generate complete source solutions. Seven parameters are determined, the three shear dislocation orientations (strike, dip, and rake), the moment and three location coordinates. To obtain accurate results using two stations requires path calibration (delays) which in this case were derived from a large population of events with known locations, and assembled in a phase-delay map. The search for the best-fitting solution is a simple grid-search where the source can have any (θ, λ, δ) and be located at any point in a box. The phase delays from the Phase-delay map is used to correct any set of 1D Green's functions from a library. We then used this procedure to obtain the source parameters of random events and test 2 station solutions against the full array. The test proved quite satisfactory for events located in-between the two trial stations, PAS and GSC. Locations for events at obtuse angles worked less well and require calibrated P-wave travel paths to augment the surface wave control.

References

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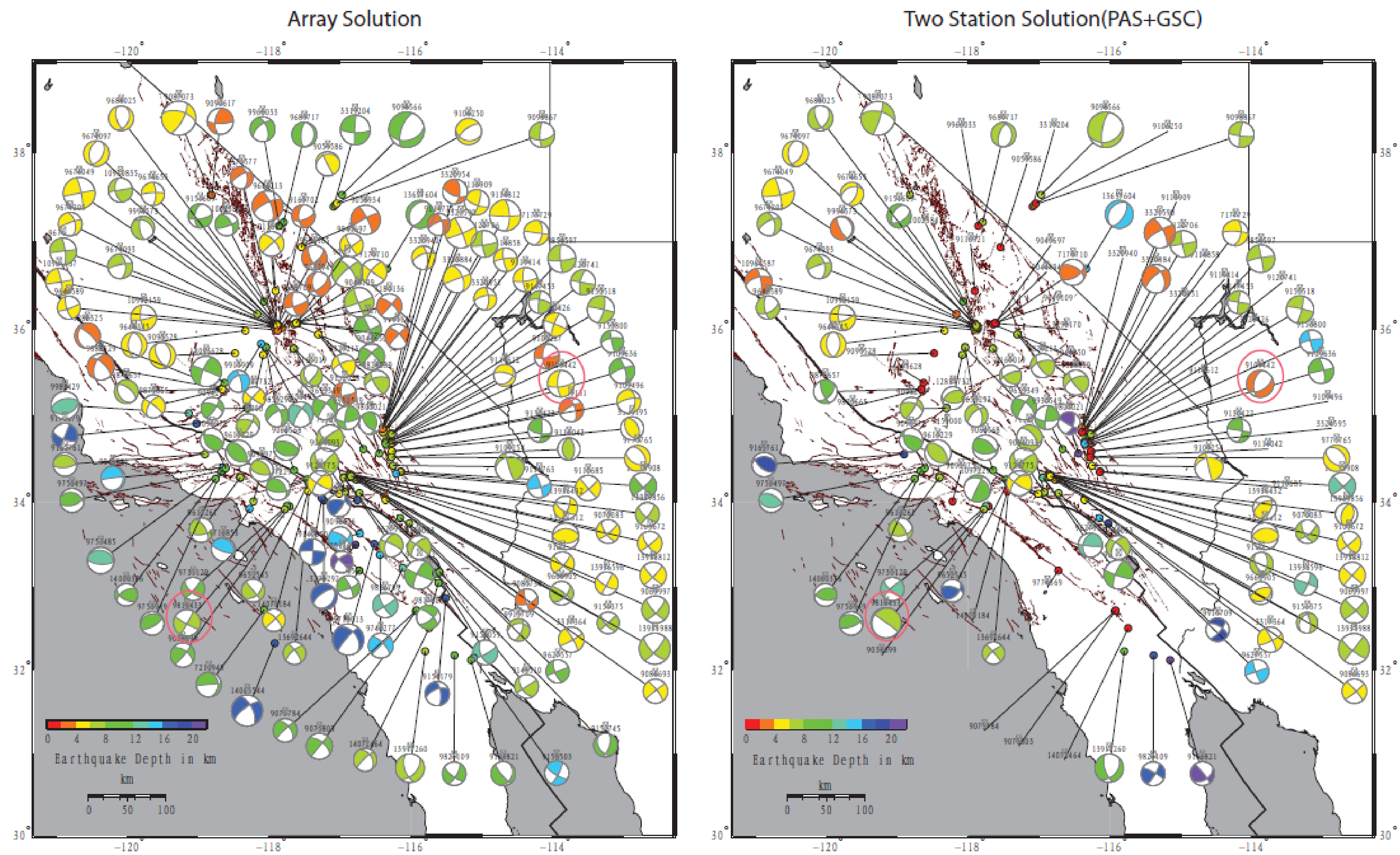

Figure 1. Source parameters of 160 Southern California events retrieved with the CAP method with source parameters are displayed on the left. Source depths are indicated by color, ranging from 3 to 20 km. Comparison of mechanisms derived by the full array vs. the two station results are given on the right. Two mechanisms with problems are circled. Events with no solutions are indicated as red dots.

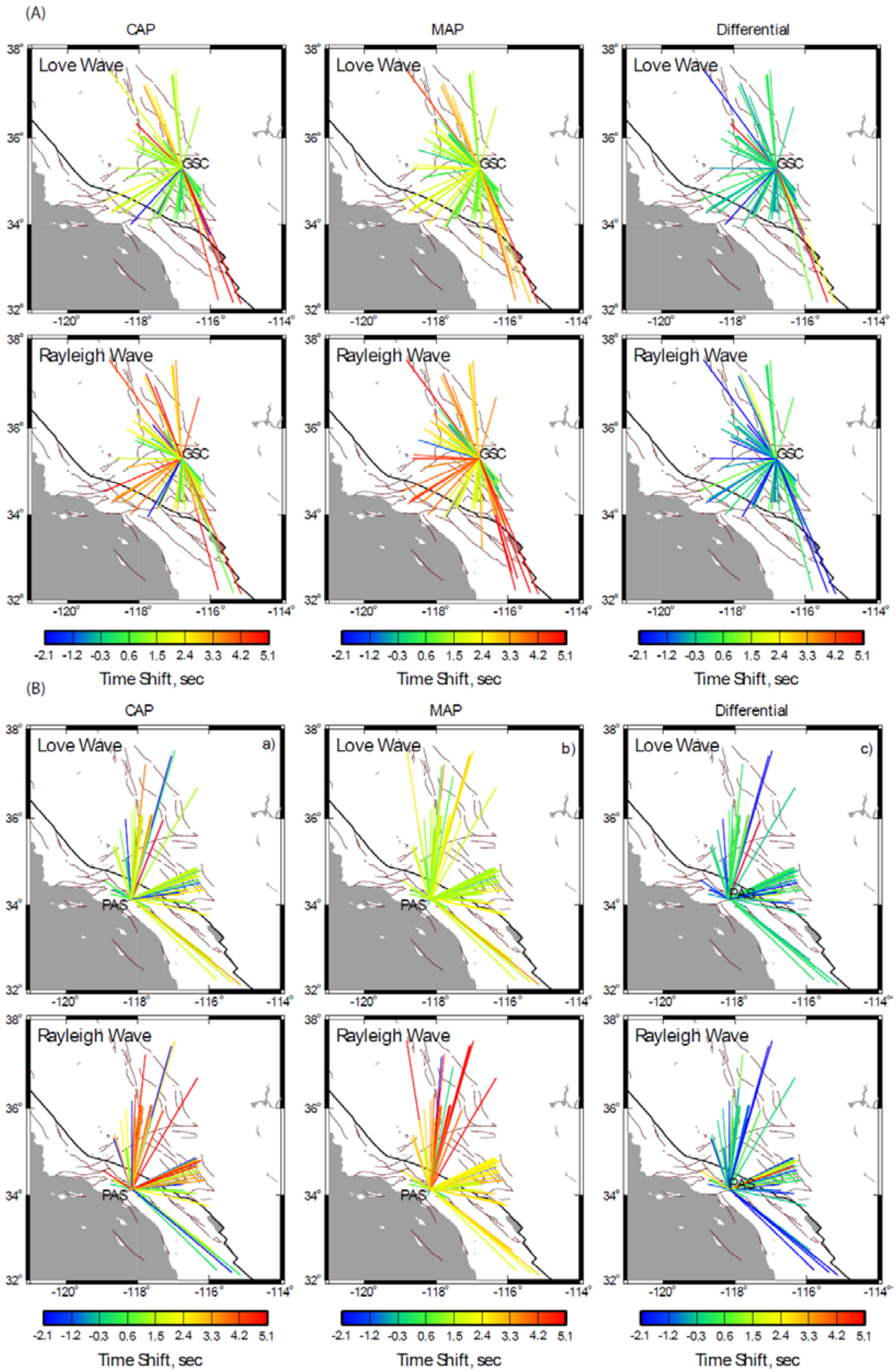

Figure 2. Station-based spider diagrams for the Love and Rayleigh phase delays at GSC and PAS are given on the right. The first column contains the CAP values, the second the tomographic predictions, and the third the residual. The latter essentially defines which paths (red) will cause difficulties when conducting two-station source inversions.