PRELIMINARY DETERMINATION OF PARAMETERS OF THE HIGH-FREQUENCY SOURCE FOR THE DEC. 5, 1997, M_w=7.9, KRONOTSKI EARTHQUAKE

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Abstract. To study high-frequency (HF) radiator of Kronotski earthquake (Dec. 5, 1997, M_w=7.9) we apply a new technique of restoration of the pulse shape of radiated power of HF body waves. To compensate the distortion of the pulse shape caused by the propagation through the real Earth, we use the power signal from an aftershock as the empirical Green's function for power. We recover power time histories of source-radiated P waves for the 0.5-2 Hz band for a few teleseismic stations. We then apply the power moment technique to determine from these data the following parameters of the HF source: temporal centroid: 22 ±2 s after the origin time; vector from the epicentre to the spatial centroid: length 87 ± 35 km, azimuth 220°±22°; the process duration and length for a linear running-point source: 47 s and 187 km; the direction of rupture propagation: SW; and its velocity: 4.0 km/s . The location and size of the HF source agree well with the distribution of aftershocks. Rupture direction and velocity agree well with very short durations (about 10 s) of strong-motion S waves radiated into the SW direction.

Introduction. Our goal is to characterize parameters of the HF radiator in a source of a recent large earthquake improving the technique after Gusev &Pavlov (1991). First, for a number of teleseismic stations we restore "true" wave power pulse (smoothed envelope of band-filtered amplitude squared) radiated by the source into the direction of a station, by means of inverse filtering of the recorded power pulse. The inverse filter is constructed from an aftershock record on the basis of the "empirical Green's function" idea. Then we determine power moments of degrees 1 and 2 of the recovered "true" source pulses. From these data we may finally determine (Gusev&Pavlov 1978, 1988, 1991) normalized spatio-temporal power moments of the HF source; we consider these as its most important parameters. The practical problem of fast preliminary determination of parameters of the recent Kronotski earthquake is a good test for the described approach.

Technique. Let $M(t)$ and $A(t)$ be smoothed squares of band-filtered body-wave record amplitude at a station for the main shock and an aftershock. The frequency band of the filter is a "high-frequency" one; practically, we use the 0.5-2 Hz band for a M_w=7.9 event. $M(t)$ represent source-radiated energy pulse distorted by propagation in the real Earth. We seek for the "ideal" signal $P(t)$ that would be recorded in a homogeneous Earth. We make two credible assumptions: (1) the "power medium pulse response function" (PMPRF) varies weakly over the epicentral area, and (2) a record of an aftershock may be used as an estimate for PMPRF. For random, noise-like, signals, power is additive; hence, $M \approx A*P$, where * denotes convolution. In the matrix notation, $\mathbf{M}=\mathbf{AP}$; so that $\mathbf{P}=\mathbf{A}^{-1}\mathbf{M}$. In practice, this inversion is not quite stable in frequency domain (Gusev&Pavlov 1991). Here we perform the inversion in time domain with positivity constraints, this improves stability. From each estimated $P(t)$ we find normalized temporal power moments: the first moment e_1, or pulse centroid, and the central second moment e_2, or mean squared duration of a pulse.

With $e_1$and e_2 values known at a number of stations, one can estimate normalized spatio-temporal moments of the source: first moments $\{N_\mathbf{x}, N_t\}$ and second central moments $\{N_\mathbf{xx}, N_{t\mathbf{x}}, N_{tt}\}$, where $\mathbf{x} = (x_1, x_2, x_3)$. The vector $N_\mathbf{x}$ defines the location of source centroid with respect to hypocentre; and N_t is the mean time delay (temporal centoid). The tensor $N_\mathbf{xx}$ defines the spatial extent of the source; the scalar N_{tt} defines its temporal extent, and the vector $N_{t\mathbf{x}}$ indicates the direction of the source growth. For HF data from a shallow event, the source moments related to the vertical (x_3) coordinate cannot be determined, so we seek only for those related to x_1, x_2, and t.

Initial data and station data processing. We collected P-wave records of the main shock and of an aftershock with similar fault plane solution (06.12.1997 at 10^h59^m) from BHZ channels of a number of GNSN stations via the "autodrm @gldfs.cr.usgs.gov" server of USGS. Data of only seven stations were found usable. The processing procedure is shown on Fig. 1 and 2. On Fig. 1a, filtered records of BHZ channel of OBN station are given; on Fig. 1b, corresponding power functions are seen, smoothed by short(0.8 s) and long (≈10 s) time windows, the latter ones (i.e., $M(t)$ and $A(t)$) are also repeated on Fig 2a. On Fig 2b, one sees the result of fitting $M(t)$ by the convolution of $A(t)$ with the estimated positive $P(t)$, and the misfit function; $P(t)$ proper is shown on Fig 2c. The complete set of $P(t)$ is shown on Fig. 3., and the station locations on the focal sphere are given on Fig.4 (top, left). From each $P(t)$ *we* calculate $e_1$and e_2.

Source moment estimation. Then we solved the least squares equations for $\{N_\mathbf{x}, N_t\}$ and $\{N_\mathbf{xx}, N_{t\mathbf{x}}, N_{tt}\}$. In these calculations, we set P-wave velocity to 7 km/s. Unfortunately, small amount of data (seven) did not permit us to obtain a meaningful solution for all six second source moments without severe additional constraints. For this reason, we consider (see the table) three separate solutions: unconstrained (A), "linear source" (B), and "running point" (C). In Solution A, first moments were estimated successfully, but the solution for the $N_\mathbf{xx}$ tensor is physically meaningless (negative eigenvalues). As the source propagation direction was successfully defined on the basis of first moments, and this direction agrees well with the orientation of the aftershock zone and to its relative location with respect to the instrumental epicentre, we constrained the source to be located on a line of this particular orientation and thus obtained the Solution B (with 3 unknown second moments). The results are better; but they still violate some physical constraints. For this reason we additionally assumed that the source may be approximately described as a running point with a constant velocity v and constant luminosity (similarly to the classical model of the low-frequency (LF) source after Ben-Menachem (1961)). The value of v, used as the constraint, may be found from Solution A as 4.0 km/s, and we arrive to the case of a single unknown, e.g., of the source length L. All other parameters may be expressed through it: $N_t=L/(2v)$, $N_1=L/2$, $N_{tt}= N_{11}/v^2$, $N_{t1}=N_{11}/v$, $N_{11}=L^2/12$. The resulting Solution C is quite acceptable.

Sol.	N_t s	$\lvert N_{\mathbf{x}}\rvert$ km	Az($N_{\mathbf{x}}$)	N_{tt} s^2	$\lvert N_{t\mathbf{x}}\rvert$ km s	Az($N_{t\mathbf{x}}$)	N_{11} km^2
A	21.6	87	220°	483	1646	170°	-
σ	(1.9)	(35)	(22°)	(97)	(470)	(27°)	
B	21.8	92	220°	313	1677	220°	2095
σ	(1.6)	(21)	(fixed)	(96)	(637)	(fixed)	(17375)
C	23.3	93	220°	181	726	220°	2904
σ	(1.2)	(4.6)	(fixed)	(18)	(72)	(fixed)	(286)

Under each tabulated solution, the row of its rms errors is given. For Solutions B and C, the real accuracy is worse; seemingly, around 30%.

Interpretation. Now let us consider the geophysical meaning of the results (see Fig. 4). Of them, the first moments, found in the unconstrained Solution A, are the most reliable. Combining the $N_{\mathbf{x}}$ vector with the instrumental epicentre (**+**) from the regional network, we can locate the centroid of the HF radiator (diamond with error bars) in the central part of the aftershock area (dots), close to the Harvard CMT (low-frequency) centroid (star). Location of the aftershock used (**x**) and nodal planes for the main shock and this aftershock are also given. From the N_t value we determine the HF temporal centroid (22 s, compare to Harvard CMT temporal centroid of 27.1 s). Judging by the orientation of both the $N_{t\mathbf{x}}$ and $N_{\mathbf{x}}$ vectors (170° and 220°), the general source growth direction is S-SW. This conclusion agrees well both with the aftershock zone orientation along the NE-SW direction, and with the location of this zone to SW with respect to the instrumental epicentre. The values of $2|N_{\mathbf{x}}|$ and $2N_t$ provide approximate estimates for L (177 km), total duration T (44 s) and the rupture velocity $v=|N_{\mathbf{x}}|/N_t = 4.0$ km/s. From Solution C, combining first and second moment data we obtain our preferred estimates for L (187 km, solid segment on fig. 4) and T (47s). Within the same constraints of Solution C, we additionally estimated L=254 km and T=63 s from second moments only; these less reliable results are somewhat larger than those from Solution C.

The value of v can be combined with the mantle c_S=4.5 km/s to yield the Mach number of 0.89, on the high end of usually observed values. (The Harvard CMT depth is 39 km, and the crust is about 30 km thick here). However, this value of rupture velocity agrees well with very short (about 10 s) durations of the *S*-wave part of accelerograms recorded in the SW direction from the source. These short durations can be associated with strong compression of the source pulse for the observation direction that is near to that of rupture propagation when the rupture velocity is near to that of S waves ("Doppler-effect").

Conclusion. The first attempt to determine power moments of a HF source from digital data proved to be successful, and yielded a reasonable gross description of the source. For the event studied, spatial and temporal parameters of the high-frequency and low-frequency sources seem almost to coincide.

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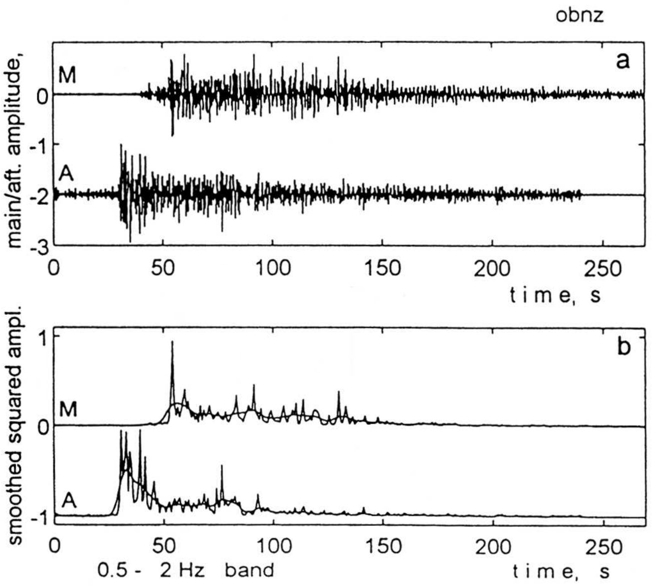

Fig.1. Example HF P-wave records and power signal.

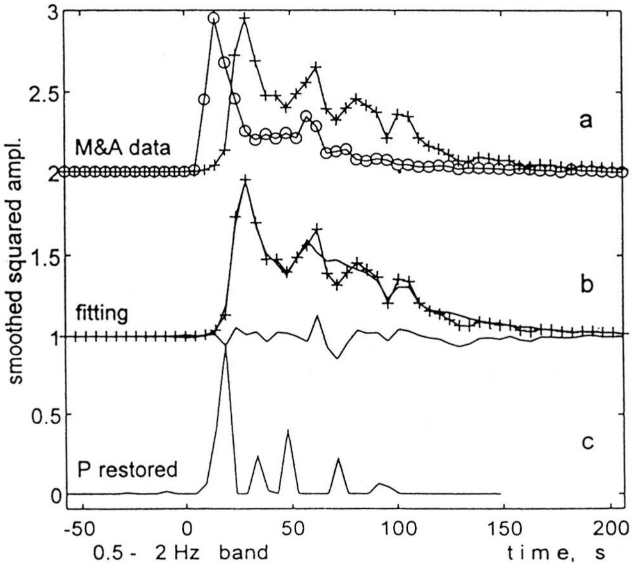

Fig.2. Restoration of source-radiated power signal for OBN.

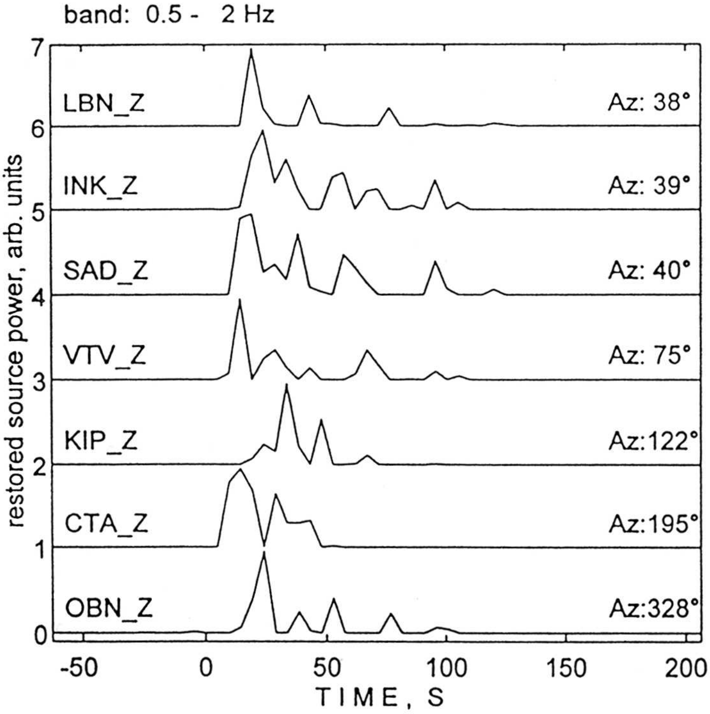

Fig.3. Recovered *P*-wave source power pulses for all the stations

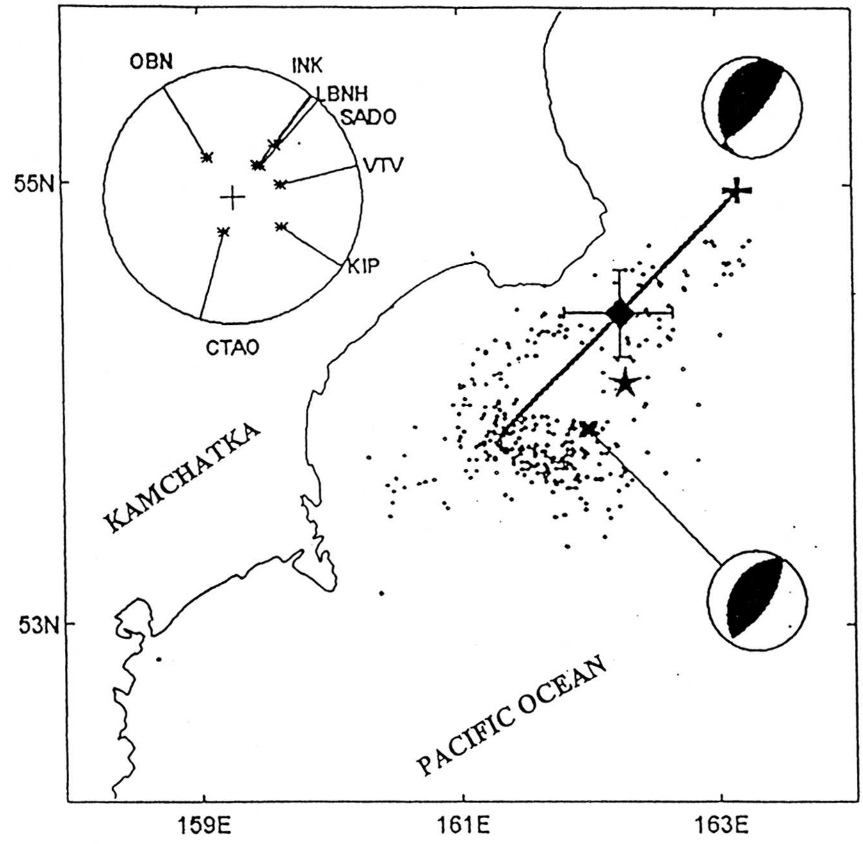

Fig.4. Epicentral region and the results of inversion.