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THE EVALUATION OF THE EFFECTIVENESS OF DISCRIMINANTS

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ABSTRACT

The quantitative evaluation of the effectiveness of seismometric discriminants by means of their identification curves is described. These curves are analogous to the receiver operating characteristics employed for similar purposes in tele-communication analysis. They display the simultaneously available combinations of the probability for correct identification of an explosion, once it has occurred, and the probability for false alarm about an earthquake, once that has occurred. Observed identification curves and their confidence limits can be significantly different between different seismometric networks observing the same source area and also between different source areas observed by the same network. In one case, where the probability for false alarms about earthquakes was kept at one in one thousand earthquakes, those having with a 99% confidence attainable probability for correct identification of explosions by m(M) discriminants changed from 12% to 78% when the observation of events in western North America was shifted from the Canadian station network to the Hagfors station in Sweden. Such regional differences obviate simple statements about global identification possibilities.

From a rather small set of m(M) data from the Lillehammer (LHN) array station in Norway the 99% confident probability for correct identification of explosions in North America was estimated as 14%, when the rate of false alarms about earthquakes there was put at one in one thousand. Such an identification probability is low but could be judged to give a sufficient deterrence against violations. For explosions in the USSR, however, and for earthquakes in south-western Asia or in the Kurile-Kamchatka arc the discrimination appeared to be much worse and quite unsatisfactory. The Lillehammer data used were few and one should therefore not stress the validity of the numerical results. However, it should be noted that similar results have been obtained from Hagfors data. The conclusion is that discrimination by Scandinavian m(M) seems to be less sharp between Asian events than between North American events.

The Lillehammer array, which sometimes was denoted the Oslo array (00 NW), was operative from 1963 to 1969. It comprised one 3-comp LP and 7 vertical SP seismometers and had a diameter of around 7 km. The Lillehammer array was located in the same general area as the NORSAR array.

THE EFFECTIVENESS OF EARTHQUAKE-NUCLEAR EXPLOSION DISCRIMINANTS

In a geophysically defined situation, where a specified network observes events in a specified source area, the discriminant values D obtained from the measurements will be distributed in a certain pattern as indicated in Fig 1. If a decision level C is selected for purpose of treating all events with D values equal to or less than C as if they were explosions and other events as earthquakes, then the probability $F_E(C)$ for correctly identifying an explosion E and the probability $F_Q(C)$ for striking a false alarm about an earthquake Q will depend on the selected decision level C as indicated in Fig 2. The probabilities apply once the events have occurred and have been properly recorded. In Fig 3 the joint occurring pairs of F_E and F_Q are plotted together. The resulting identification curve has the same meaning as the receiver operating characteristic (ROC) employed for similar purposes in the theory of telecommunications. The identification curve is the essential characteristic of a discriminant D. As the earth is inhomogeneous the unambiguous definition of such a curve requires the definition of the corresponding boundary conditions, i.e. the source areas and the location of the seismic network used.

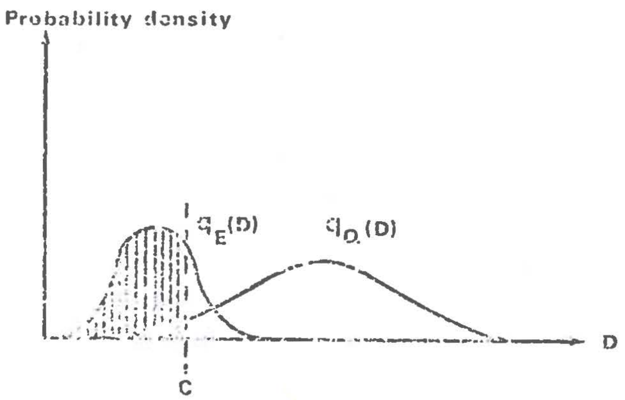


Fig 1.

Sharp discrimination means high probability F_E and low probability F_Q or an identification curve high up to the left in Fig 3. The political requirements on a test ban control operation can indeed be expressed as geometrical conditions on the identification curve (Ericsson, 1970). For the present purpose it is sufficient to consider that a politically satisfactory identification curve would have to be positioned above and to the left of some politically defined critical point. For illustrative purposes we will use the point at $F_E = 0.10$ and $F_Q = 0.001$.

The numerical treatment of identification curves is much simplified if the F_E and F_Q scales on both axes are changed into those commonly used for the display of normal distributions as straight lines, as indicated in Fig 4. In such a diagram an identification curve derived from nor-

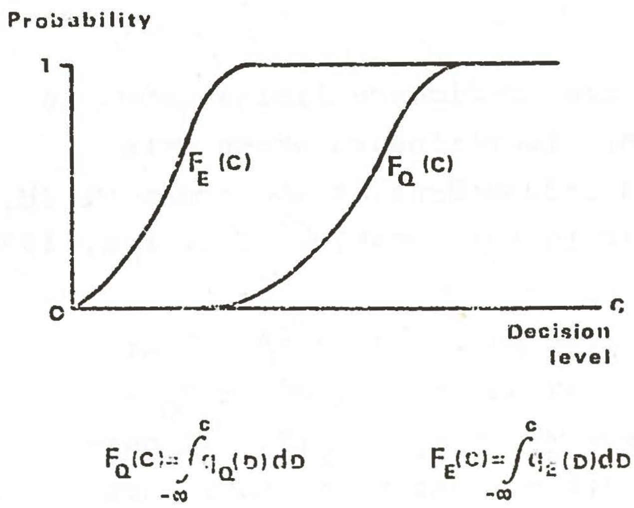


Fig 2.

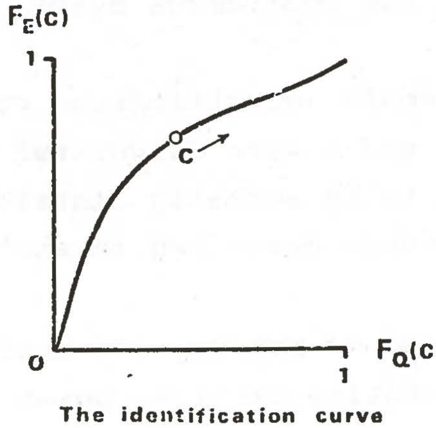


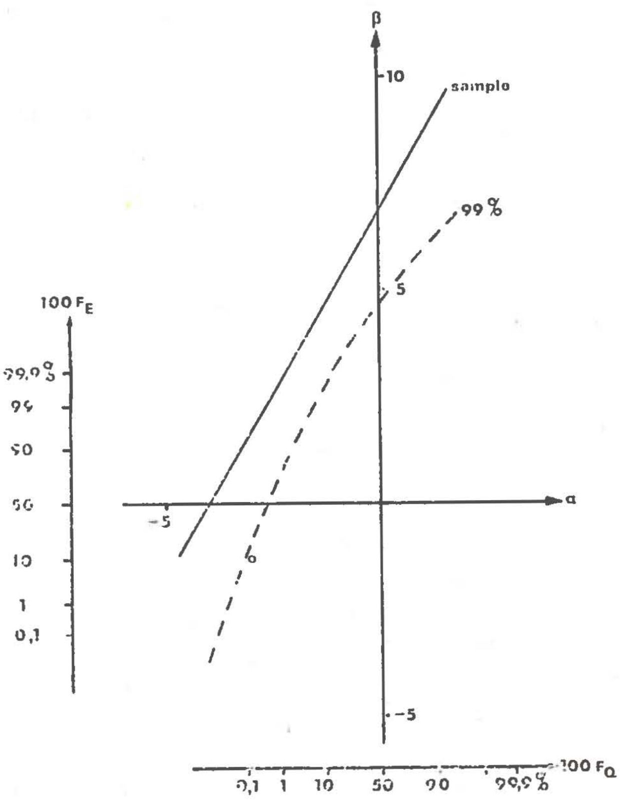
Fig 3.

mally distributed D appears as an upward sloping straight line. As the standard deviations of the earthquake and explosion populations of D generally are different, the slope of this identification line will generally be different from unity. Further simplification is obtained if the origin of the scales is shifted to the $F_E = 0.50$ and $F_Q = 0.50$ point and distances along the new axes are measured in units of standard deviations. These new units are denoted by α along the earthquake axis and by β along the explosion axis (see Fig 4). A somewhat more detailed discussion of this topic is given in a report by the author (Ericsson, 1971 d).

In terms of the α and β values an observed or "sample" identification line is defined by the intercept $(\bar{D}_Q - \bar{D}_E)/S_Q$ on the α-axis and the intercept $(\bar{D}_Q - \bar{D}_E)/S_E$ on the β-axis. The $\bar{D}_Q$ and $\bar{D}_E$ are the observed mean values of the earthquake and explosion distributions and the S_Q and S_E are the corresponding observed standard deviations. Such samples line intercepts are t-distributed along the axes and the position of a specific sample line is a matter of chance. For samples with few events J_E and J_Q the sample line can be quite different from the population line it estimates. The author therefore derived formulae for the calculation of onesided confidence limits to the identification lines (Ericsson, 1971 d). These formulae are, however, only approximate when applied to small samples. Fig 4 shows such a limit, calculated for the 99% confidence level. As expected, it is considerably below the identification line sample. Its interpretation is as follows; according to the available measurements we can be 99% confident that identification by the discriminant in question is good enough to satisfy all political requirements whose critical points fall on or below the confidence curve.

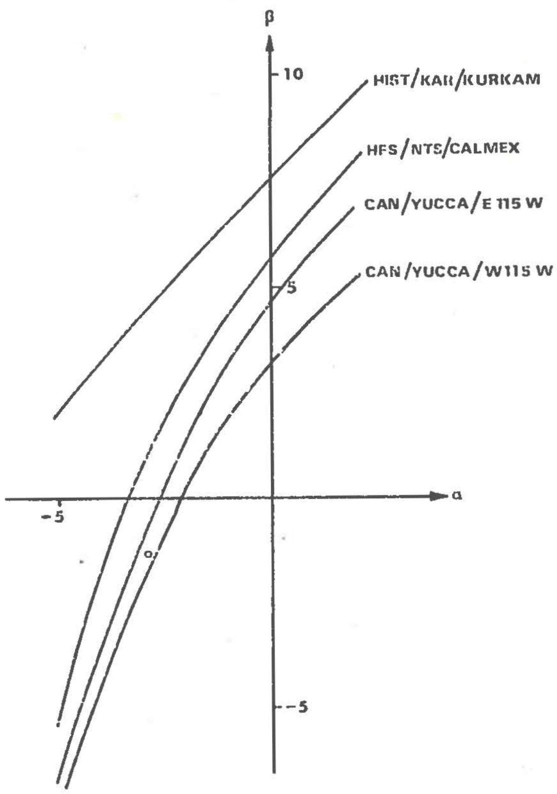
The sample identification curve and the confidence limits shown in Fig 4 and 5 were calculated from m(M) discriminants which were taken to be normally distributed and independent of the event yield, on grounds described in another paper in this booklet (Ericsson, 1972).

Fig 4 shows how the 99% confidence curve passes just above our illustrative critical point at $\alpha = -3.09$ and $\beta = -1.28$ or $F_Q = 0.001$ and $F_E = 0.10$. The curve passes where $F_E = 0.12$. It pertains to a Canadian station network discriminating by body wave magnitude m and surface wave magnitude M between nuclear explosions in the Yucca Flat area in the Nevada Test Site and earthquakes in the western United States and Mexico, east of 115°W longitude. Details are given in a report by the author (Ericsson, 1971 d) on identification by body and surface wave magnitudes. Fig 5 shows the 99% confidence limits for four different situations, selected from 24 situations treated in the mentioned report. The HIST/KAR/KURKAM curve is for a network (HIST) of four short period arrays in



Sample and 99% confidence limit for the identification curve for CAN/YUCCA/E 115°W.

Fig 4.



The 99% confidence limits for four different identification curves.

Fig 5.

Canada, Scotland, India and Australia and four long period WWSSS stations in Iran, Pakistan and India discriminating between nuclear explosions in eastern Kazakh (KAR) and earthquakes in the Kuriles-Kamchatka arc (KURKAM). The 99% confident probability for correct identification of the explosions is close to unity and is the best case so far encountered by the author. It contrasts sharply with the 99% confident value of only 0.03% obtained (Ericsson, 1971 d) for the probability for correct identification of KAR explosions among KURKAM earthquakes, when the m and M were not from HIST but from the LASA array in Montana. The numerical details of this comparison of HIST and LASA are, however, somewhat uncertain, as the HIST and LASA event sets are quite different and the LASA explosion sample is rather small. The LASA curve is therefore not shown.

The 99% confidence limit HFS/NTS/CALMEX in Fig 5 refers to the HFS station in Sweden discriminating between explosions in the Nevada Test Site (NTS) and earthquakes in California and western Mexico. At the false alarm rate of $F_Q = 0.001$ or $\alpha = -3.09$ the 99% confident probability for correct identification of the explosions is 78%. This is much higher than the 12% attained by the CAN/YUCCA/E 115^{o}W curve obtained from a Canadian network of 19 stations measuring both m and M from explosions in the Yucca Flat area in the Nevada Test Site and from earthquakes in the western US and Mexico, east of the 115^{o}W longitude. This is another illustration of the sometimes very large differences between seismic networks monitoring nearly the same areas. The fourth curve, CAN/YUCCA/W 115^{o}W, shows that US and Mexican earthquakes west of the 115^{o}W longitude are even more explosion like than those east of that longitude. The comparisons between CAN and HFS were made without overlap between the CAN and HFS event populations and should be remade with a common data base. Another interesting difference is the one between the HFS value of 78% for NTS explosions and the HFS value of about 24% derived in the above mentioned report (Ericsson, 1971 d), from rather few data on KAR explosions. The earthquakes were in Central Asia and the false alarm rate was again held at 0.001.

Similar differences between North American and Asian explosions were derived from a somewhat small set of m and M data published by Ward and Toksöz (1971) from the Lillehammer array station in Norway, (see

Tables 1, 2, 3 and 4).

TABLE 1:

Events selected from Ward and Toksöz (1971) with M from Lillehammer (LHN) and m from USCGS.

Date	Area	Lat	Long	M	m	D_{LHN}	Kind
68 01 19	NEV	38.6N	116.2W	4.6	6.0	3.44 + 0.54M m= -0.12	E
68 02 21	"	37.1	116.1	4.0	5.4	-0.15	E
68 03 22	"	37.3	116.3	3.8	5.6	0.16	E
68 04 26	"	37.3	116.5	5.1	6.0	0.16	E
68 02 06	NAM	38.0	118.4	4.0	4.6	0.96	Q
68 05 08	"	43.9	128.2	4.4	4.9	0.87	Q
68 05 08	"	43.9	128.2	4.3	4.5	1.22	Q
68 05 30	"	42.3	119.8	3.6	4.7	0.65	Q
68 06 03	"	40.3	127.1	3.6	4.3	1.05	Q
68 06 04	"	42.3	119.9	3.7	4.7	0.70	Q
68 01 26	"	24.3	111.5	5.2	5.2	1.00	Q
68 06 09	"	14.6	92.0	4.8	4.7	1.28	Q
68 06 17	"	14.4	92.9	4.5	4.8	1.03	Q

The 99% confident probability for correct identification of explosions in Nevada (NEV) was estimated as 14% when the rate of false alarms about earthquakes in North America (NAM) again was put at 0.001. An identification probability of 14% is low but could be judged to give a sufficient deterrence against treaty violations. For explosions in the Soviet Union (SOV), however, and for earthquakes in southwestern Asia (SWAS) or in the Kuriles-Kamchatka arc (KURKAM) the discrimination appeared to be much worse and indeed quite unsatisfactory. As these Lillehammer data were few, one should not stress the numerical results. The main point they make, together with the above mentioned results from HFS data, is that Asian events are harder to identify properly using Scandinavian m(M) data than North American events.

TABLE 2:

Events selected from Ward and Toksöz with M from Lillehammer and m from USCGS.

Date	Area	Lat	Long	M	m	D_{LHN}	Kind
68 01 07	SOV	49.8N	78.0E	3.2	5.5	3.56 + 0.63 M - m = 0.08	E
68 06 07	"	50.0	79.1	3.1	5.6	-0.09	E
68 07 01	"	46.9	48.9	3.9	6.0	0.02	E
68 07 12	"	50.8	79.1	3.0	5.5	-0.05	E
68 01 11	KURKAM	46.4	153.3	4.0	4.9	1.18	Q
68 02 04	"	43.2	147.2	4.6	6.1	0.36	Q
68 02 04	"	43.0	147.1	5.9	6.2	1.08	Q
68 05 20	"	48.8	150.3	5.5	5.2	1.82	Q
68 05 20	"	44.8	154.	6.1	5.7	1.70	Q
68 05 21	"	44.8	150.2	5.1	5.9	0.87	Q
68 05 21	"	44.9	150.2	5.8	5.7	1.52	Q
68 05 30	"	44.7	150.3	5.6	5.9	1.19	Q
68 06 08	"	43.4	147.0	5.4	6.2	0.76	Q
68 06 14	"	45.2	153.5	4.9	6.0	0.65	Q
68 06 14	"	51.7	159.3	4.5	6.0	0.40	Q
68 02 11	SWAS	34.2	78.6	4.4	5.3	1.04	Q
68 03 14	"	42.3	66.5	4.0	5.6	0.48	Q
68 04 26	"	35.1	50.2	4.0	5.3	0.78	Q
68 05 11	"	41.0	49.8	3.8	4.9	1.06	Q
68 05 30	"	27.8	50.4	4.2	4.8	1.41	Q
68 05 30	"	29.7	51.3	4.2	4.8	1.41	Q
68 06 04	"	32.7	48.3	3.8	4.8	1.16	Q
68 06 14	"	31.2	70.2	4.4	4.8	1.54	Q
68 06 23	"	29.8	51.2	4.9	5.2	1.45	Q
68 07 01	"	44.0	79.2	3.6	4.9	0.93	Q
68 07 08	"	38.0	67.6	3.9	5.9	0.12	Q
68 07 21	"	55.2	113.3	4.6	4.9	1.56	Q

TABLE 3

	$\bar{D}_Q$	$\bar{D}_E$	J_Q	J_E	S_Q	S_E
NEV		0.00		4		0.16
NAM	0.97		9		0.21	
SOV		0.00		4		0.08
KURKAM	1.05		11		0.74	
SWAS	1.07		12		0.43	

TABLE 4

ROCCONF estimates of the 99% confidence lower limits for β at five α-values

	α = -4	-3.09	-3	-2	-1
LHN/NEV/NAM 99%β =	-4.38	-1.02	-0.80	0.93	1.99
LHN/SOV/KURKAM	-196	-130	-124	-54	-5.68
LHN/SOV/SWAS	-72	-36	-33	-5.60	2.47

CLOSING REMARK

After the presentation of this paper on Nov 24, 1971, in Oslo, the author has published an extended summary and discussion of the here quoted papers and reports (Ericsson, 1971 e). In that paper a physical explanation was given of one of the observed regional differences in discrimination, namely the one between events east and west of longitude 115^{o}W in the US and Mexico. That explanation implies that explosions west of the longitude 115^{o}W are expected to be as well discriminated as the explosions east of 115^{o}W.

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