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A SEISMIC LOCATION STUDY OF STATION ANOMALIES, NETWORK EFFECTS, AND REGIONAL BIAS AT THE NEVADA TEST SITE

25 August 1970

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90

A SEISMIC LOCATION STUDY OF STATION ANOMALIES, NETWORK EFFECTS, AND REGIONAL BIAS AT THE NEVADA TEST SITE

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ABSTRACT

A location study is made of 28 large underground explosions detonated in the northern area of the Nevada Test Site (NTS). Recording networks were comprised of between 9 and 49 teleseismic stations having two- to three-quadrant distributions.

Errors of locations obtained without applying travel-time anomalies (relative residuals), and with depths restrained to the known values, average about 7 km but are as large as 20 km. With anomalies, the errors are consistently 2.5-3.0 km. The size of the area at NTS across which the anomalies are valid is at least 70 km by 25 km.

Depth errors average 70 km without anomalies and 15 km with anomalies. Without the anomalies, a linear relationship is observed between the least-squares standard deviation, σ, of time errors of the solution obtained when the depth is restrained to its true value and the depth errors, dz, of the corresponding unrestrained solution: dz(km)=75σ (sec).

By deliberately mislocating a calibration event approximately 140 km, it is shown that relative accuracy (precision) remains at about 2.5-3.0 km.

If a constant network is used to locate a set of events, the "bias" is a consistent and unique function of that network. The lack of a common bias among networks with similar azimuthal distributions definitely eliminates the source region as the principal cause of the anomalies.

Alternatively, the anomalies may be attributed to slight lateral and vertical inhomogeneities within the mantle between the source and receiver, the effects of which are integrated along the entire path.

Furthermore, when constant networks are used, the relative locations obtained without anomalies are identical to those obtained with anomalies, except for a bias translation appropriate for that network.

Finally, it is shown that station anomalies determined from explosions occurring in regions other than NTS do not agree with those at NTS. It is demonstrated that, in general, it is better to apply no anomalies at all rather than the wrong ones.

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INTRODUCTION

In earlier papers (Chiburis, 1968b, Evernden, 1969), it was demonstrated that a significant improvement in accuracy can be achieved when locating nuclear explosions with networks of limited azimuth aperture (single quadrant) and limited numbers of stations, if pre-determined travel-time anomalies[1] are used. The accuracy reported for some seventeen well recorded explosions in the Nevada Test Site area (NTS) was 2.5-3.0 km when the solutions were restrained to the surface. The objectives of the present study are to investigate in more detail the stability and applicability of the anomalies across and beyond NTS, the effects of location bias on anomaly solutions, unrestrained depth solutions, and constant and variable network locations.

It is important to understand the definition of the term "bias" in terms of the particular network used for any location, and to understand that the results of any solution are relatively unpredictable when no heed is taken of the anomalies. In this report, "location bias" is defined as that error obtained when anomalous travel times are used for locating teleseismic explosions, regardless of the causes of the anomalies. The travel times are termed

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[1] An anomaly is defined as the usual station residual but relative to another station in the network; that is, if the residual at station i is R_i = observed time - computed time, then the anomaly at station i relative to station j is $A_{ij} = R_i - R_j$.

anomalous in that they do not conform to those of an average earth model. It is generally agreed that the anomalies are caused by unknown inhomogeneous effects of source region geology, of the crust and upper mantle in the vicinity of the recording station, and of the total travel path in the deeper mantle. Disagreement arises as to the proportionate contribution of each of these effects. At the present time, no technique is known which can unambiguously isolate the three possible causes or quantify their respective contributions. Although the exact causes of the anomalies are not considered, it will be shown that their effects on <u>relative</u> location accuracy using a common network are negligible (within the limits of seismogram timing error), and that if one does not compensate for the existence and variability of anomalies for different stations and regions, the calculated locations may be highly variable.

DESCRIPTION OF THE DATA

A total of 28 large (M=4.8-6.4) explosions detonated within the northern portion of NTS (Figure 1) was selected for analysis on the basis of the number of recording stations and the quality of the signals received. Information pertinent to these events is given in Table I, which also includes the number and type of recording stations used for location purposes. All of the selected stations, a total of 65, were teleseismic (> 1600 km) to the explosions. Table II lists the stations, their type, distances and azimuths from the event BILBY, and whether they recorded a particular event. All time readings were made by analysts at the Seismic Data Laboratory ard are believed accurate to within 0.1 sec for most of the LRSM stations, within 0.5 sec for the USC&GS stations, and better than 0.1 sec for the one VELA Observatory (CPSO). The travel-time tables used for the locations are those of Herrin (1968), unless clearly specified otherwise.

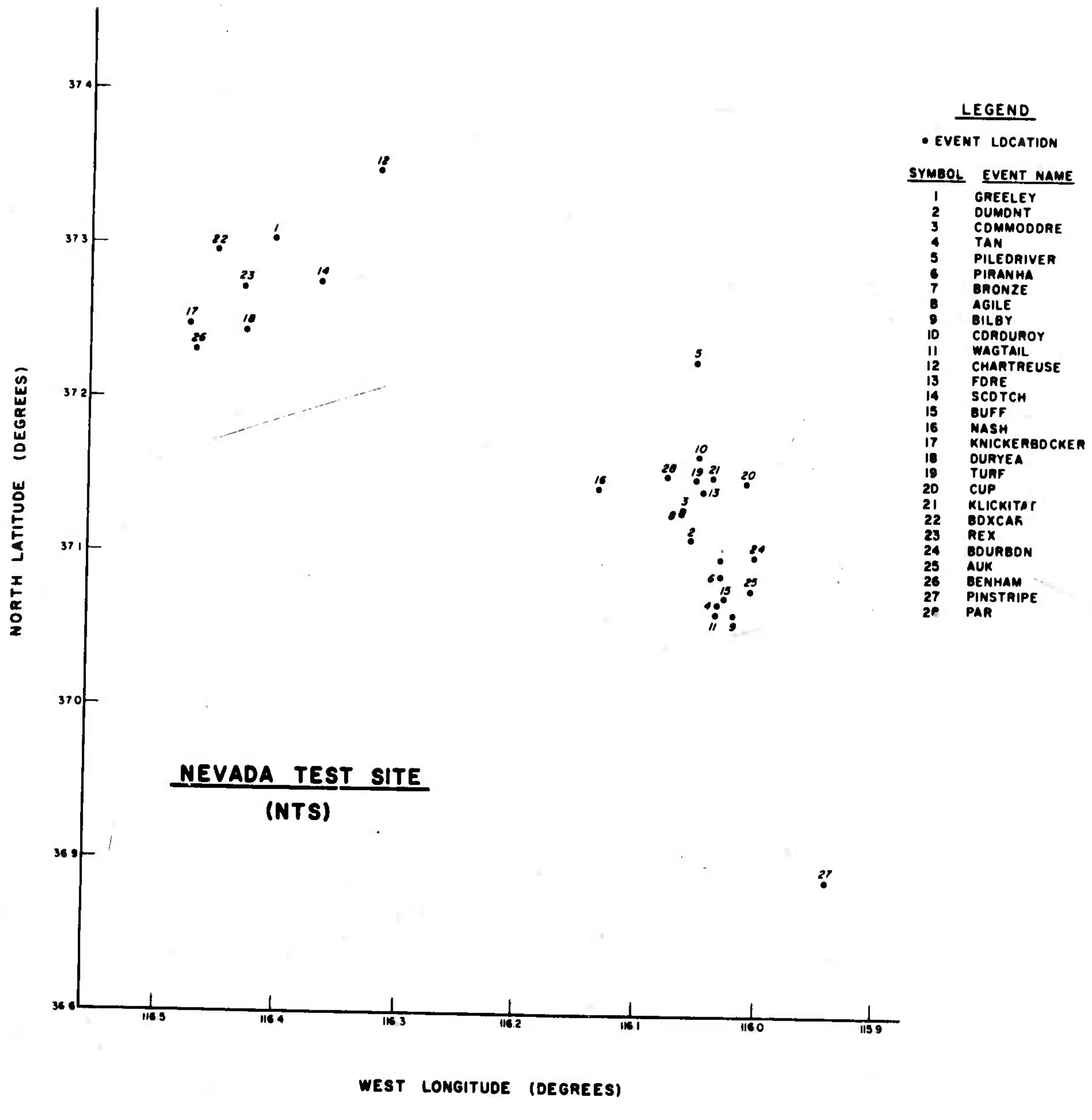


Figure 1. Nevada Test Site explosion positions.

TABLE I

EVENT INFORMATION

Event Name	Date	Origin Time	Mag	Depth (km)	Latitude (Deg-North)	Longitude (Deg-West)	Number of Stations Used VELA	C&GS	Azimuth Aperture	Event Code (Figure 1)
GREELEY	20Dec66	1530 00.1Z	6.3	1.23	37.302	116.408	12	37	194	1
CHARTREUSE	06May66	1500 00.1Z	5.3	0.67	37.348	116.322	7	21	194	12
SCOTCH	23May67	1400 00.0Z	5.6	1.00	37.275	116.370	5	21	178	14
KNICKERBOCKER	26May67	1500 00.0Z	5.5	0.63	37.248	116.480	5	17	195	17
DURYEA	14Apr66	1413 43.1Z	5.2	0.55	37.243	116.431	8	13	178	18
BOXCAR	26Apr68	1500 00.0Z	6.4	1.32	37.296	116.456	6	11	232	22
REX	24Feb66	1555 07.0Z	4.8	0.67	37.272	116.434	7	9	157	23
BENHAM	19Dec68	1630 00.0Z	6.4	1.40	37.231	116.474	4	7	201	26
DUMONT	19May66	1356 28.1Z	5.5	0.67	37.111	116.058	8	32	194	2
PILEDRIVER	02Jun66	1530 00.1Z	5.6	0.46	37.227	116.055	7	31	245	5
PIRANHA	13May66	1330 00.0Z	*	0.56	37.087	116.034	9	27	234	6
BRONZE	23Jul65	1700 00.0Z	5.2	0.53	37.098	116.033	9	26	238	7
AGILE	23Feb67	1850 00.0Z	*	0.76	37.127	116.066	7	28	238	8
WAGTAIL	03Mar65	1913 00.0Z	5.3	0.75	37.064	116.037	9	20	188	11
FORE	16Jan64	1600 00.1Z	5.2	0.49	37.142	116.049	12	14	138	13
BUFF	16Dec65	1915 00.0Z	5.1	0.50	37.073	116.029	8	17	238	15
NASH	19Jan67	1645 00.1Z	5.3	0.37	37.144	116.135	7	15	185	16
TURF	24Apr64	2010 00.2Z	5.0	0.51	37.150	116.055	8	13	157	19
CUP	26Mar65	1534 08.2Z	5.3	0.55	37.148	116.013	9	11	234	20
KLICKITAT	20Feb64	1530 00.1Z	5.0	0.50	37.151	116.040	9	9	157	21
BOURBON	20Jan67	1740 04.1Z	5.1	0.56	37.100	116.004	4	12	185	24
AUK	02Oct64	2003 00.0Z	4.9	0.46	37.078	116.009	5	6	155	25
PINSTRIPE	25Apr66	1838 00.1Z	4.5	0.30	36.888	115.941	5	6	123	27
PAR	09Oct64	1400 00.1Z	4.8	0.41	37.151	116.077	6	3	182	28
COMMODORE	20May67	1500 00.1Z	5.7	0.76	37.130	116.064	5	33	244	3
TAN	03Jun66	1400 00.0Z	5.6	0.56	37.068	116.035	8	31	244	4
BILBY	13Sep63	1700 00.1Z	5.8	0.71	37.061	116.022	13	20	237	9
CORDUROY	03Dec65	1513 02.1Z	5.6	0.69	37.165	116.052	9	24	195	10

*Magnitude unknown.

TABLE II
NETWORK/EVENT COMBINATIONS

Station	Bilby Area Distance (deg)	Bilby Area Azimuth (deg)	Number Events	GREELEY	CHARTREUSE	SCOTCH	KNICKERBOCKER	DURYEA	BOXCAR	REX	BENHAM	DUMONT	PILEDRIVER	PIRANHA	BRONZE	AGILE	WAGTAIL	FORE	BUFF	MASH	TURF	CUP	KLICKITAT	BOURBON	AUK	PINSTRIPE	PAR	COMMODORE	TAN	BILBY	CORDUROY
			[illegible]	194	194	178	195	178	232	157	201	194	245	234	238	238	188	138	238	185	157	234	157	185	155	123	182	244	244	237	195
			Number Stations	49	28	26	22	21	17	16	11	40	38	16	35	35	29	26	25	22	21	20	18	16	11	11	9	38	39	33	33
VLL																															
AD-IS	44.5	309	6												✓		✓		✓			✓					✓				✓
AXZAL	24.9	91	8	✓	✓			✓				✓	✓	✓												✓			✓		
BE-FL	29.5	96	6	✓								✓	✓	✓															✓		✓
BL-WY	27.5	78	7												✓		✓	✓			✓	✓	✓							✓	
BR-PA	29.2	72	8												✓		✓	✓			✓	✓	✓				✓			✓	
CPSO	24.6	84	22	✓	✓			✓		✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓		✓	✓	✓
DH-NY	31.9	68	7												✓		✓				✓	✓	✓		✓					✓	
EB-MT	19.4	43	4															✓			✓		✓							✓	
EN-MO	20.3	83	3							✓																					
GU-AL	23.5	92	2																											✓	✓
EUZAL	23.5	92	1	✓																											
GG-GR	81.8	32	4	✓														✓					✓								
HN-ME	36.6	60	25	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓
LV-LA	20.5	97	2															✓												✓	
NP-NT	39.3	359	24	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓		✓		✓	✓	✓
OO-NW	73.1	24	4	✓													✓	✓												✓	
PG-BC	17.2	348	11	✓		✓	✓	✓	✓	✓				✓		✓				✓						✓		✓			
PZ-PR	47.3	100	2															✓												✓	
RK-ON	21.1	43	28	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
SI-BC	19.3	340	10		✓			✓		✓		✓	✓	✓					✓							✓			✓		✓
SV2OB	37.7	46	4												✓		✓					✓					✓				
SV3OB	37.7	46	15	✓	✓	✓	✓	✓	✓			✓		✓		✓			✓	✓				✓				✓	✓		✓
WH2YK	26.5	339	8	✓		✓	✓		✓		✓					✓				✓											
CAGS																															
AAM	25.4	68	16	✓		✓	✓		✓	✓	✓		✓			✓	✓	✓			✓	✓		✓				✓	✓		✓
AKU	60.0	28	7	✓					✓				✓		✓	✓						✓							✓		
ANT	74.2	137	11		✓		✓					✓	✓		✓	✓	✓	✓	✓										✓		
ARE	67.8	133	20	✓	✓		✓			✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓				✓	✓		✓
ATL	26.1	88	19	✓	✓		✓			✓		✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓		✓	✓			✓	✓	✓
BEC	42.0	81	3		✓	✓			✓			✓		✓																	
BLA	28.3	79	13	✓	✓		✓	✓		✓		✓	✓	✓		✓												✓	✓	✓	✓
CAR	51.4	108	19	✓	✓		✓	✓	✓			✓	✓	✓		✓	✓	✓	✓	✓			✓	✓				✓	✓	✓	✓
COL	33.6	336	26	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
COP	77.6	27	2	✓																								✓			
CMC	30.8	1	18	✓	✓	✓	✓	✓				✓	✓	✓	✓	✓	✓		✓	✓		✓				✓		✓	✓		✓
ESK	71.6	34	7	✓	✓							✓	✓		✓	✓													✓		
FLO	20.3	77	20	✓	✓	✓	✓			✓		✓			✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	
GEO	30.6	74	10	✓	✓							✓	✓	✓	✓	✓	✓											✓	✓		
GOM	46.2	26	11	✓		✓						✓		✓	✓	✓	✓			✓								✓		✓	✓
GIE	44.6	142	3	✓								✓																✓			
GUA	89.0	286	6			✓			✓		✓			✓														✓		✓	
KEV	70.1	13	7	✓								✓	✓	✓	✓														✓	✓	
KIP	39.5	259	11						✓		✓		✓	✓	✓	✓			✓			✓						✓	✓	✓	
KON	73.7	25	13	✓		✓		✓				✓	✓	✓	✓		✓	✓			✓		✓		✓				✓		
KTG	56.9	24	16	✓	✓	✓						✓	✓	✓	✓	✓		✓	✓	✓			✓	✓				✓	✓		✓
LPB	69.8	131	22	✓	✓		✓	✓	✓	✓		✓		✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓		✓
LPS	33.1	126	14	✓	✓		✓	✓				✓	✓	✓	✓		✓	✓			✓							✓	✓	✓	
MAL	83.1	49	11	✓		✓			✓			✓	✓	✓	✓		✓				✓							✓	✓		
MAT	79.6	308	13	✓		✓	✓							✓		✓				✓				✓				✓	✓		
NOR	54.9	10	15	✓	✓		✓					✓	✓	✓	✓	✓	✓		✓		✓	✓						✓	✓		✓
NNA	61.1	135	7	✓									✓		✓	✓												✓	✓		✓
NUR	77.6	19	14	✓	✓	✓	✓					✓	✓	✓	✓		✓	✓	✓									✓	✓	✓	
OGO	32.2	70	11	✓		✓							✓	✓	✓	✓	✓		✓									✓		✓	✓
OXF	21.8	89	24	✓	✓	✓	✓	✓				✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓
PEL	81.7	143	3	✓	✓		✓					✓	✓															✓	✓	✓	✓
PTO	77.7	48	3	✓								✓	✓	✓		✓												✓	✓		✓
SCP	29.8	71	16	✓		✓		✓		✓	✓	✓		✓	✓		✓	✓	✓		✓							✓	✓	✓	✓
SEO	85.6	315	13	✓	✓		✓	✓				✓	✓	✓	✓	✓				✓				✓				✓			✓
SHA	24.0	97	3	✓		✓					✓	✓	✓			✓												✓		✓	
SHK	84.3	309	5	✓	✓							✓	✓																✓		
SJG	47.5	99	13	✓		✓		✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓				✓		✓					
STU	81.7	33	13	✓		✓						✓	✓		✓	✓		✓	✓	✓								✓	✓		✓
TOL	81.2	46	15	✓		✓	✓					✓	✓	✓	✓	✓	✓		✓		✓							✓	✓	✓	✓
TRN	55.6	104	13	✓	✓	✓	✓					✓	✓		✓	✓				✓								✓	✓	✓	✓
VAL	70.3	39	3	✓					✓																					✓	
WES	34.5	67	2			✓																									✓

LOCATION PROCEDURES AND RESULTS USING NO ANOMALIES

To determine the improvement in accuracy it is first necessary to locate all explosions with every available recording station, to restrain the depths to the known values, and to use no anomaly corrections. The number of stations recording each of the events varies from 9 to 49; the azimuth aperture, or quadrantal coverage, varies from 123° to 245° (two to three quadrant distribution). The location results are shown in Figure 2 both in plan view and normalized to a common origin. The numerals adjacent to the vectors in Figure 2 refer to the event identification number as given in Figure 1. In order to note any possible variations in location patterns, the southern area of NTS was split into two subregions, I and II. The location errors for the 28 events vary from 0.60 km to 18.89 km (with an average of 6.65 km) and the directions of the shifts are nearly random, although there is some suggestion that in subregion I the events shift northerly and in subregion II southwesterly. Since the networks are well-distributed, and the signal-to-noise values are high, these results are indicative of the smallest errors one can expect to achieve for the NTS region without empirical corrections.

At this point, it is of interest to compare the preceding results, obtained with the Herrin 1968 tables, with those obtained with the Jeffreys-Bullen (J-B) tables. The J-B results are shown in Figure 3 in which the errors vary from 2.69 km to 21.11 km (with an average of 7.66 km). The difference in the average error between the two tables

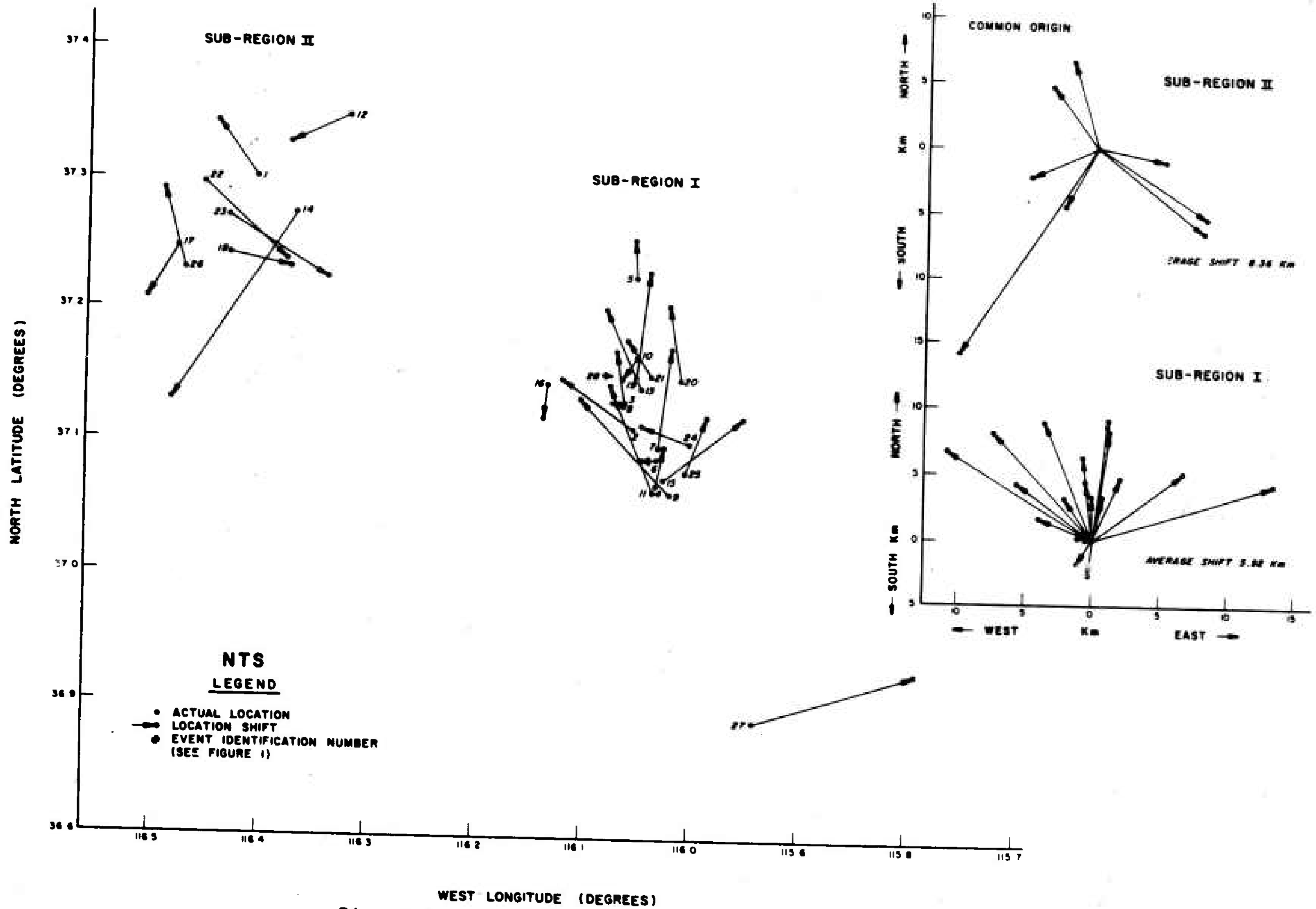


Figure 2. Restrained location shifts obtained with all available stations and without anomalies. Herrin 1968 travel-time tables.

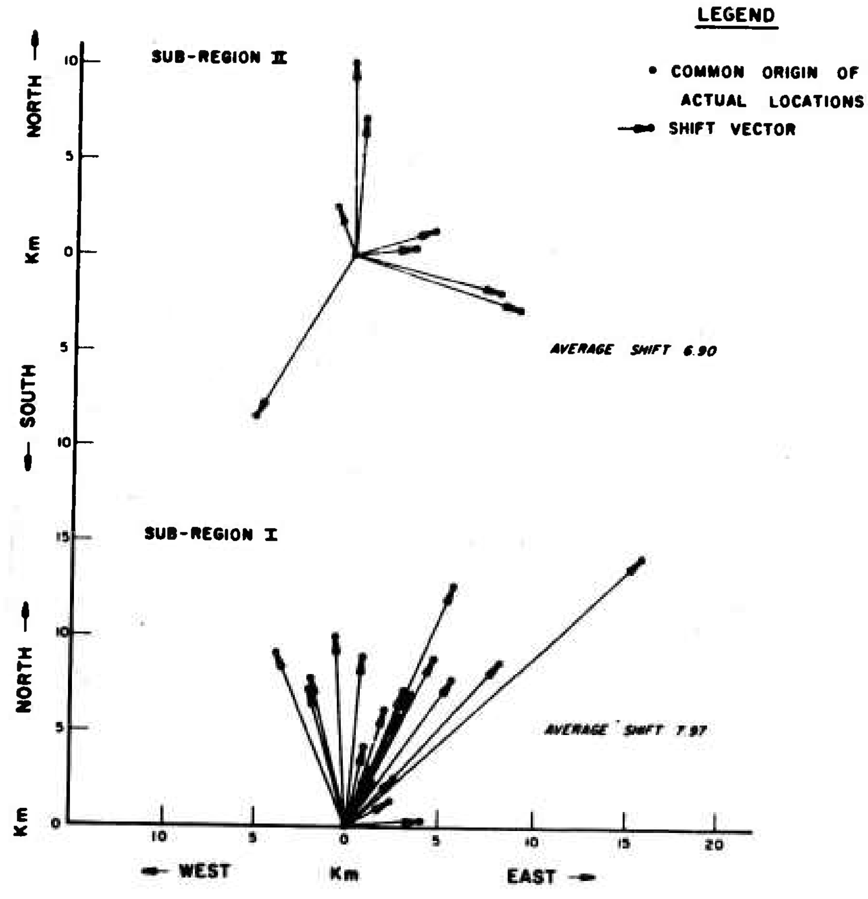


Figure 3. Restrained location shifts obtained with all available stations and without anomalies. Jeffreys-Bullen travel-time tables.

is negligible, although individual events have quite different shift magnitudes, and the normalized-origin plot is considerably changed from that in Figure 2: the events in subregion I shift nearly in one quadrant (north-north-easterly) and those in subregion II the same except for one event. The location results for both travel-time tables are given in Table III, which also includes the standard deviations of errors obtained from the least-squares solutions. The values of the standard deviations, which are general indicators of the goodness-of-fit to the least-squares regression, are of the same size as those obtained when locating events anywhere with any network (e.g., those reported by the USC&GS on PDE cards). Therefore, the times read in this study are not unusually good regarding the least-squares fits.

Generally, for the NTS region, the results indicate that when anomalies are not used, 1) restrained location errors are moderate on the average (about 7 km) but can be large (about 20 km); 2) no consistent location bias exists which can be reasonably attributed to NTS source geology alone; and 3) although both the Herrin and J-B tables yield about the same magnitude of average error, the patterns of locations are a function of the particular travel-time table used.

TABLE III

COMPARISON OF LOCATION RESULTS OBTAINED WITHOUT ANOMALIES
FOR TWO DIFFERENT TRAVEL-TIME TABLES

Event Name	Number Stations	Azimuth Aperture	HERRIN 1968 Shift (km)	HERRIN 1968 Direction of Shift (Deg)	HERRIN 1968 Standard Deviation of Errors (Sec)	JEFFREYS-BULLEN Shift (km)	JEFFREYS-BULLEN Direction of Shift (Deg)	JEFFREYS-BULLEN Standard Deviation of Errors (Sec)
GREELEY	49	194	5.74	325	1.04	7.15	5	1.11
CHARTREUSE	28	194	5.45	245	1.09	2.69	340	1.09
SCOTCH	26	178	18.89	212	1.06	9.91	212	1.12
KNICKERBOCKER	22	195	5.04	208	1.24	3.31	84	1.23
DURYEA	21	178	5.07	102	1.07	4.56	75	0.94
BOXCAR	17	232	10.07	129	1.00	9.28	108	0.86
REX	16	157	9.70	123	0.73	8.19	104	0.59
BENHAM	11	201	6.88	345	1.31	10.11	90	1.30
DUMONT	40	194	7.07	306	1.02	8.05	346	1.05
PILEDRIVER	38	245	3.34	359	1.03	6.36	18	1.06
PIRANHA	36	234	1.25	280	1.05	4.25	13	0.98
BRONZE	35	238	8.29	8	0.85	9.94	28	0.90
AGILE	35	238	0.98	300	1.15	2.82	30	1.26
WAGTAIL	29	188	9.59	338	0.55	10.04	356	0.56
FORE	26	138	13.55	299	0.49	9.86	337	0.65
BUFF	25	238	8.45	52	0.79	11.91	43	0.80
NASH	22	185	2.75	187	0.95	4.03	85	0.99
TURF	21	157	9.05	7	0.65	13.83	24	0.76
CUP	20	234	6.34	353	0.70	8.87	5	0.76
KLICKITAT	18	157	3.71	326	0.66	7.75	24	0.76
BOURBON	16	185	4.33	292	0.71	3.25	21	0.71
AUK	11	155	5.13	23	0.69	9.48	36	0.68
PINSTRIPE	11	123	13.94	72	1.04	21.11	48	0.88
PAR	9	182	0.60	278	0.71	2.69	59	0.68
COMMODORE	38	244	4.53	353	1.01	7.79	26	1.05
TAN	39	244	3.45	12	0.89	6.44	24	0.91
BILBY	33	237	10.89	317	0.96	7.35	344	1.11
CORDUROY	33	195	2.15	215	0.83	3.52	45	0.86
AVERAGE	26		6.65		0.902	7.66		0.916

LOCATION PROCEDURES AND RESULTS USING CALIBRATION ANOMALIES

Following the procedures described by Chiburis (1968b), relative travel-time anomalies were determined from the events BILBY, TAN, COMMODORE, and CORDUROY. Those stations recording more than one of these "calibration events" were accordingly assigned an anomaly based on the average of from two to all four events. The resulting anomalies, relative to station RK-ON are presented in Table IV. Assuming that the anomalies from these four events effectively correct the inadequately-known earth model appropriate to NTS, the remaining 24 events can be located using, as before, all available stations for each event. The location shifts are plotted in Figure 4 and the results given in Table V. Using anomalies, the location errors now range from 0.52 km to 6.75 km with an average of 2.81 km, an improvement factor of about three over the results obtained without anomalies. The corresponding standard deviations are significantly reduced (a necessary but not sufficient condition for the anomalies to be appropriate for the NTS region).

Although for some purposes an improvement factor of three might not appear to warrant the general use of anomalies, there are several facts to consider: 1) the locations without anomalies were made with an average of 26 recording stations which were well-distributed azimuthally such that the networks were quite stable (in fact, even nearly ideal network distributions do not guarantee more accurate locations, as Lambert et al (1969) report a 20 km error for LONG SHOT when using 329 stations at virtually all

TABLE IV

CALIBRATION ANOMALIES; HERRIN 1968 TRAVEL-TIME TABLES

Station (VELA)	Anomaly (Sec)	Source Code*	Station (C&GS)	Anomaly (Sec)	Source Code*	Station (C&GS)	Anomaly (Sec)	Source Code*
AD-IS	0.16	D	AAM	0.03	C	MAL	0.58	C
AX2AL	1.68	D	AKU	1.04	D	MAT	-0.21	B
BE-FL	1.24	C	ANT	1.16	C	NOR	-0.48	B
BL-WV	0.56	D	ARE	1.36	B	NNA	0.65	B
BR-PA	0.71	D	ATL	0.86	C	NUR	-0.31	B
CPSO	0.86	B	BEC	0.35	A	OGD	0.22	B
DH-NY	-0.02	D	BLA	0.95	C	OXF	1.73	A
EB-MT	0.09	D	CAR	0.63	A	PEL	0.12	B
EN-MO	0.68	D	COL	0.91	B	PTO	-0.54	B
EU-AL	1.98	D	COP	0.12	D	SCP	0.19	A
EU2AL	1.98	***	CMC	-0.01	B	SEO	0.01	C
GG-GR	0.96	D	ESK	-0.77	D	SHA	3.13	C
HN-ME	0.56	A	FLO	1.45	C	SHK	-0.45	D
LV-LA	1.95	D	GEO	0.29	B	SJG	0.72	B
NP-NT	-1.02	B	GDH	0.60	B	STU	0.46	A
OO-NW	-0.04	D	GIE	1.70	D	TOL	0.26	A
PG-BC	2.45	D	GUA	-1.44	C	TRN	-2.16	A
PZ-PR	1.22	D	KEV	-1.19	C	VAL	-0.66	D
RK-ON	0	**	KIP	1.64	B	WES	0.60	D
SI-BC	2.90	C	KON	0.26	D			
SV2QB	-0.42	***	KTG	0.05	B			
SV3QB	-0.42	B	LPB	0.12	B			
WH2YK	0.75	D	LPS	1.63	B			

* Code = A Anomalies are an average of BILBY, TAN, CORDUROY, COMMODORE.
Code = B Anomalies are an average of three of the above.
Code = C Anomalies are an average of two of the above.
Code = D Anomalies were determined from only one of the above.

** All anomalies are referenced to station RK-ON.

*** Used anomaly determined from EU-AL for EU2AL and SV2QB for SV3QB.

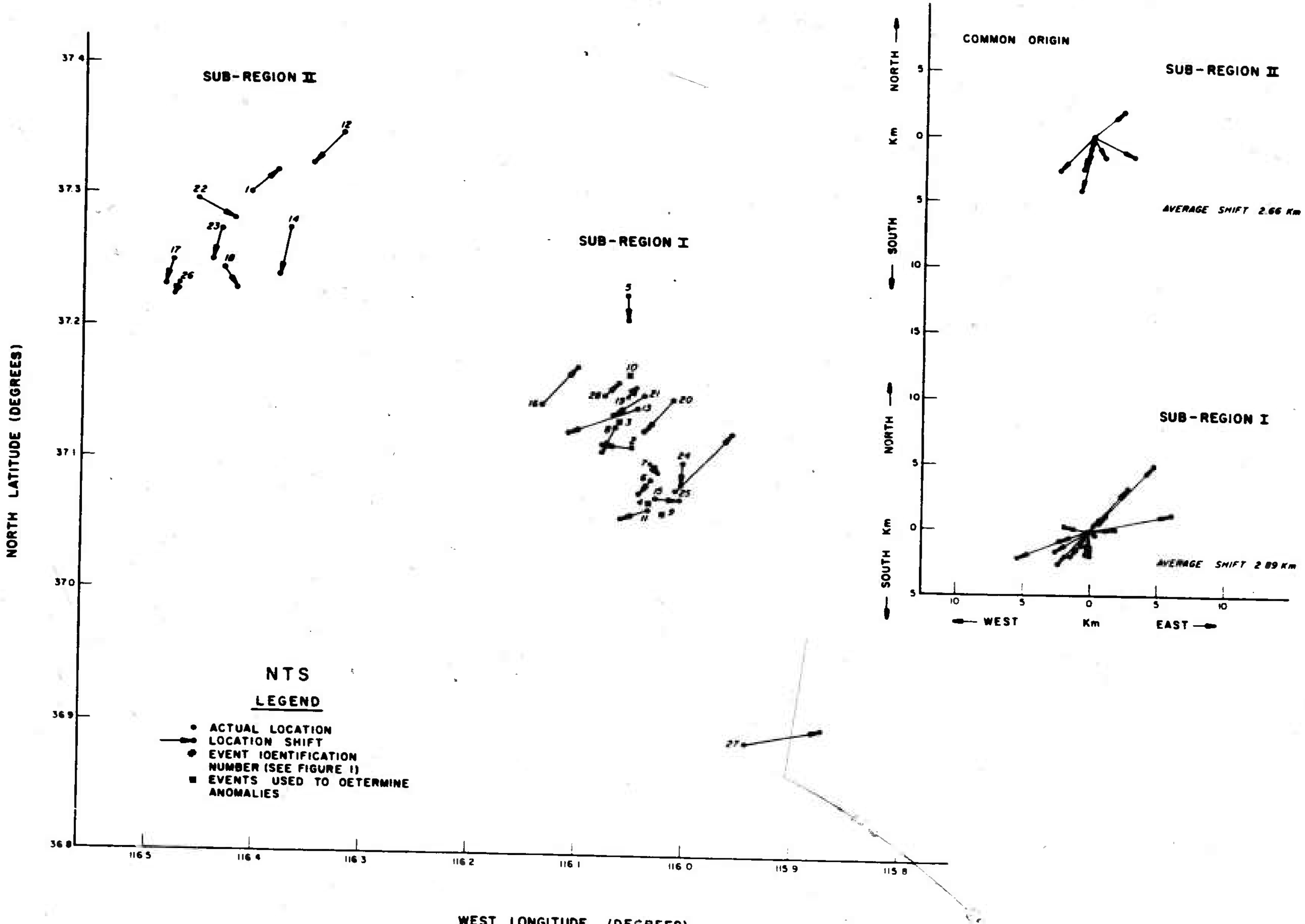


Figure 4. Restrained location shifts obtained with all available stations and with calibration anomalies.

TABLE V

LOCATION RESULTS USING CALIBRATION ANOMALIES

Event	Number Stations	Azimuth Aperture	Shift (km)	Direction of Shift (Deg)	Standard Deviation of Errors (Sec)
GREELEY	49	194	2.86	51	0.40
CHARTREUSE	28	194	3.60	225	0.31
SCOTCH	26	178	4.15	193	0.38
KNICKERBOCKER	22	195	1.94	196	0.45
DURYEA	21	178	1.83	149	0.35
BOXCAR	17	232	3.39	116	0.30
REX	16	157	2.57	197	0.40
BENHAM	11	201	0.94	192	0.32
DUMONT	40	194	1.84	275	0.22
PILEDRIVER	38	245	2.03	179	0.33
PIRANHA	36	234	1.37	210	0.41
BRONZE	35	238	0.52	136	0.36
AGILE	35	238	2.36	213	0.45
WAGTAIL	29	188	2.30	250	0.30
FORE	26	138	5.85	248	0.43
BUFF	25	238	1.85	91	0.35
NASH	22	185	4.17	43	0.39
TURF	21	157	1.06	41	0.38
CUP	20	234	3.45	222	0.29
KLICKITAT	18	157	2.99	236	0.36
BOURBON	16	185	1.93	183	0.43
AUK	11	155	6.75	44	0.35
PINSTRIPE	11	123	6.14	80	0.25
PAR	9	182	1.55	47	0.30
AVERAGE	24		2.81		0.35

azimuths and distances); 2) in a previous paper (Chiburis, 1968b), where the networks were approximately single-quadrant and had fewer recording stations, a more common situation, the location results without anomalies were 20-25 km in error; and 3) in both the previous and present studies, the location accuracies obtained using anomalies are essentially the same (2.5-3.0 km) regardless of network stability. Therefore, all locations fall in a small area around the true location with the use of anomalies, whereas otherwise the solutions cover a large area, are mislocated (in an absolute sense if the true locations happen to be known, as for explosions), and are prone to misinterpretation regarding their relationship to assumed earth models, to tectonic or explosion patterns, and to source region geophysics.

USE OF AVERAGE ANOMALIES

Seismograms of any event have some random reading errors associated with them which can affect the location of subsequent events when using the measured anomalies as corrections. The location results in Table V obtained with anomalies indicate the expected accuracy when one to four events are available for calibration purposes. To minimize these random errors, an average anomaly can be determined for each station from as many events within the same anomaly region as possible. This process will give the best correction for that region. Table VI gives such corrections and Figure 5 shows the location shifts of the 28 events obtained by using the average anomalies. The results are tabulated in Table VII, where the average error is seen to be 2.14 km, which represents perhaps the optimum accuracy for teleseismic location at NTS when the standard deviation of reading errors is on the order of 0.25 sec.

TABLE VI

AVERAGE ANOMALIES FOR NTS; HERRIN 1968 TRAVEL-TIME TABLES

Station (VELA)	Anomaly (Sec)	Number of Events*	Station (C&GS)	Anomaly (Sec)	Number of Events*	Station (C&GS)	Anomaly (Sec)	Number of Events*
AD-IS	0.01	6	AAM	0.51	16	MAL	0.55	11
AX2AL	1.85	8	AKU	1.08	7	MAT	-0.18	10
BE-FL	1.35	6	ANT	1.12	11	NOR	-0.70	15
BL-WV	0.75	7	ARE	1.30	20	NNA	0.37	7
BR-PA	1.00	8	ATL	1.00	19	NUR	-0.28	14
CPSO	0.93	22	BEC	0.65	9	OGD	0.50	11
DH-NY	0.17	7	BLA	1.38	13	OXF	1.99	24
EB-MT	0.26	4	CAR	0.83	19	PEL	-0.12	8
EN-MO	1.06	3	COL	1.34	26	PTO	-0.74	8
EU-AL	2.01	2	COP	0.13	2	SCP	0.43	16
EU2AL	2.01	***	CMC	0.24	18	SEO	0.42	13
GG-GR	0.69	4	ESK	-0.77	7	SHA	3.36	8
HN-ME	0.64	25	FLO	1.63	20	SHK	-0.10	5
LV-LA	1.96	2	GEO	0.45	10	SJG	0.71	18
NP-NT	1.05	24	GDH	0.72	11	STU	0.46	13
OO-NW	-0.07	4	GIE	2.00	3	TOL	0.17	15
PG-BC	3.06	11	GUA	-1.43	6	TRN	-2.04	13
PZ-PR	1.56	2	KEV	-1.13	7	VAL	-0.38	3
RK-ON	0	**	KIP	1.89	11	WES	0.54	2
SI-BC	3.06	10	KON	0.12	13			
SV2QB	-0.45	4	KTG	0.17	16			
SV3QB	-0.47	15	LPB	0.23	22			
WH2YK	1.25	3	LPS	1.62	14			

* The number of events refers to the number of readings used in obtaining the average anomaly for each station.

** All anomalies are referenced to station RK-ON.

*** Used the anomaly determined for EU-AL.

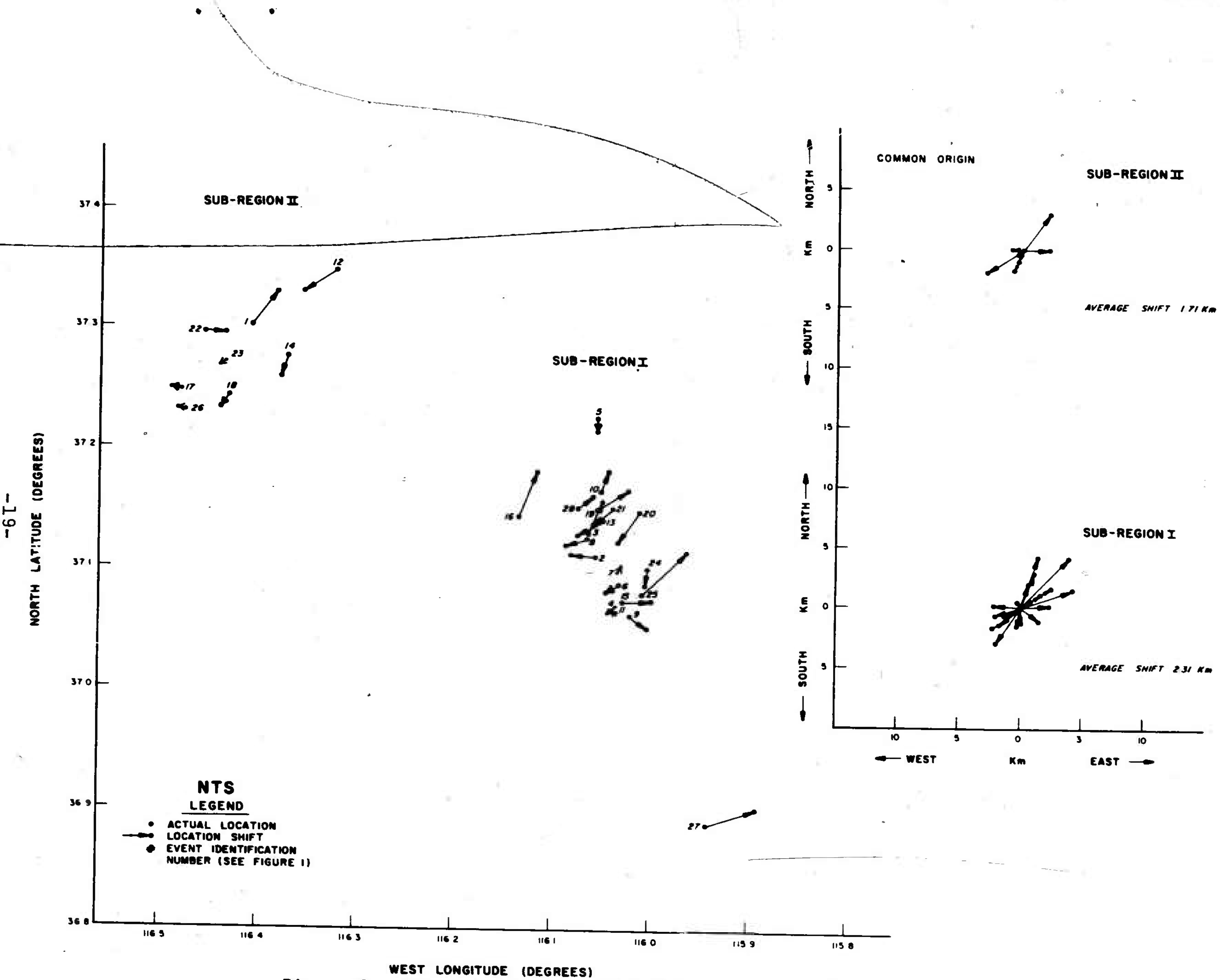


Figure 5. Restrained location shifts obtained with all available stations and with average anomalies.

TABLE VII

LOCATION RESULTS USING AVERAGE ANOMALIES

Event	Number Stations	Azimuth Aperture (Deg)	Shift (km)	Direction of Shift (Deg)	Standard Deviation of Errors (Sec)
GREELEY	49	194	3.66	37	0.28
CHARTREUSE	28	194	3.45	235	0.26
SCOTCH	26	178	1.89	199	0.32
KNICKERBOCKER	22	195	0.61	276	0.32
DURYEA	21	178	0.95	200	0.28
BOXCAR	17	232	1.91	92	0.17
REX	16	157	0.45	225	0.32
BENHAM	11	201	0.72	280	0.24
DUMONT	40	194	2.00	275	0.17
PILEDRIVER	38	245	1.19	177	0.34
PIRANHA	36	234	1.22	237	0.34
BRONZE	35	238	0.78	58	0.37
AGILE	35	238	1.89	251	0.37
WAGTAIL	29	188	0.27	339	0.24
FORE	26	138	2.71	234	0.34
BUFF	25	238	2.26	87	0.32
NASH	22	185	4.37	20	0.34
TURF	21	157	2.99	57	0.29
CUP	20	234	3.33	213	0.18
KLICKITAT	18	157	2.17	230	0.28
BOURBON	16	185	1.52	190	0.37
AUK	11	155	5.58	44	0.27
PINSTRIPE	11	123	4.47	72	0.26
PAR	9	182	1.84	55	0.18
COMMODORE	38	244	3.13	23	0.27
TAN	39	244	0.78	242	0.25
BILBY	33	237	1.78	127	0.20
CORDUROY	33	195	1.99	22	0.25
AVERAGE	26		2.14		0.28

NTS ANOMALY STABILITY

Considering the location errors in Figures 2 and 4, there appears to be no significant difference between subregions I and II when using anomalies determined from events in subregion I. The implication is that the region over which the anomalies are valid is at least as large as that shown in Figure 1, approximately 70 x 25 km. Although it is known that the anomalies vary from one region to another in an unpredictable manner (e.g., Chiburis, 1966a, b, and 1968a; Herrin and Taggart, 1968; Hales et al (1968); and others), calibrating specific regions of interest is possible if a few well-located shallow events are available. This statement must be qualified in that all of the results in this study were obtained with explosions, and, hence, perfectly-known positions, so thay are undoubtedly simpler to evaluate quantitatively than those obtained with earthquakes of unknown position, especially depth. It is certain that the anomalies change with depth as well as region, but it is uncertain how they change and how best this fact can be used to advantage. Current studies are underway which specifically address the problem of travel-time/depth.

UNRESTRAINED DEPTH SOLUTIONS

It is important at this point to investigate the P-wave solutions obtained by letting the depth parameter run free in the least-squares scheme. Using all available stations, unrestrained locations were computed both with and without anomalies determined from BILBY, TAN, COMMODORE, and CORDUROY. Table VIII gives the results for the set of events. As indicated on the table, those solutions yielding depths above the surface are restrained to zero and the epicenter recomputed. The computed above-surface values shown in parentheses (a total of four) were replaced by zeroes in forming the average. When anomalies are not used, the average depth error is 69.4 km (range: 23.0-121.0 km); with anomalies, the average depth error is reduced to 14.9 km (range: 0.4-42.3 km). The unrestrained epicenter shifts without anomalies average 16.75 km (range: 2.04-58.49 km) and with anomalies 3.90 km (range: 0.36-17.36 km). Therefore, for this set of events, the accuracy is improved by factors of about five and four in depth and epicenter respectively when anomalies are used.

These results demonstrate that if anomalies are determined from teleseismic explosions, they can be used to teleseismically locate subsequent explosions detonated within the same anomaly region with an epicenter accuracy of about 3 km and a depth accuracy of about 15 km. The same accuracy can be expected for shallow-focus (<60 km) earthquakes in the same region, because other studies (Chiburis and Ahner, 1969) show that the anomalies from explosions are approximately similar to those from nearby shallow earthquakes.

TABLE VIII

COMPARISON OF DEPTH-FREE LOCATION RESULTS OBTAINED WITHOUT AND WITH ANOMALIES

Event Name	Actual Depth (km)	Without Anomalies: Shift (km)	Without Anomalies: Depth Error (km)	Without Anomalies: Restrained σ (Sec)	With Anomalies: Shift (km)	With Anomalies: Depth Error* (km)	With Anomalies: Restrained σ (Sec)
GREELEY	1.23	18.40	78.7	1.044	7.05	24.0	0.404
CHARTREUSE	0.67	19.20	94.3	1.094	2.20	7.3	0.309
SCOTCH	1.00	2.04	67.1	1.056	1.58	17.5	0.384
KNICKERBOCKER	0.63	23.75	96.7	1.244	6.65	35.3	0.452
DURYEA	0.55	25.21	90.8	1.065	4.56	26.1	0.354
BOXCAR	1.32	10.60	67.1	0.997	3.77	22.1	0.295
REX	0.67	21.60	70.0	0.731	1.70	17.9	0.402
BENHAM	1.40	19.66	121.0	1.312	1.13	20.7	0.324
DUMONT	0.67	16.90	79.9	1.017	1.36	4.4	0.219
PILEDRIVER	0.46	12.06	71.6	1.025	2.01	0.4	0.330
PIRANHA	0.56	12.27	77.2	1.048	0.36	8.2	0.412
BRONZE	0.53	12.22	50.7	0.646	0.51	(3.2)	0.363
AGILE	0.76	10.97	66.5	1.147	1.30	8.2	0.445
WAGTAIL	0.75	14.59	51.1	0.552	0.60	16.4	0.298
FORE	0.49	10.38	23.0	0.487	5.85	(24.7)	0.428
BUFF	0.50	16.37	60.5	0.791	2.40	7.9	0.352
NASH	0.37	16.26	65.1	0.948	5.24	4.7	0.392
TURF	0.51	20.65	50.8	0.652	3.60	11.4	0.379
CUP	0.55	11.13	59.3	0.700	1.66	20.5	0.292
KLICKITAT	0.50	20.40	63.1	0.661	8.01	39.9	0.364
BOURBON	0.56	11.60	53.8	0.714	1.93	(20.8)	0.425
AUK	0.46	30.47	86.2	0.693	17.36	42.3	0.352
PINSTRIPE	0.30	58.49	114.9	1.036	11.33	21.8	0.252
PAR	0.41	5.80	33.4	0.712	1.55	(29.0)	0.301
COMMODORE	0.76	14.29	69.0	1.009	2.69**	5.9**	0.212**
TAN	0.56	11.20	63.8	0.889	1.80**	(6.7)**	0.146**
BILBY	0.71	10.76	55.1	0.959	1.23**	0.4**	0.137**
CORDUROY	0.69	11.82	63.3	0.829	1.17**	2.9**	0.151**
AVERAGE		16.75	69.4	0.902	3.90	14.9	0.355

* Depth error in parentheses indicates that solution is above the surface; zero depths were used in computing the average.

** Not used in averaging; these are calibration events from which the anomalies were determined.

Concerning the depth errors, an interesting relationship is observed between the standard deviation, σ, of least-squares time errors of the depth restrained solution without anomalies and the depth error, dz, of the corresponding unrestrained solution. Figure 6 shows the results (dot-symbols) and the linear relationship over the range of standard deviations obtained, which can be expressed as

$$dz = z - z_o = 75\sigma$$

where z_o is the actual depth and z is the unrestrained depth. The relation simply states that, for explosions at NTS, the larger the least-squares time errors (due either to anomalies, to reading errors, or to both), the greater is the depth bias in the unrestrained solutions. In Figure 6, the apparent outliers (denoted with arrows) are the four events with the least number of stations: 11, 9, 11, and 11 in order of increasing σ. The next least number of stations is 16 and is not an outlier.

When anomalies are applied to the depth-free solutions, the results are as shown in Figure 6 (x-symbols) which are clearly below the linear fit to the no-anomaly results. Therefore, the anomalies apparently remove the "depth-bias" (the functional relationship between σ and dz) for NTS. The remaining 15 km average error, corresponding to the 3 km average error in epicenter, is caused by the random errors in the calibration anomalies, and by the random errors in arrival times. Also, in the calculation of the

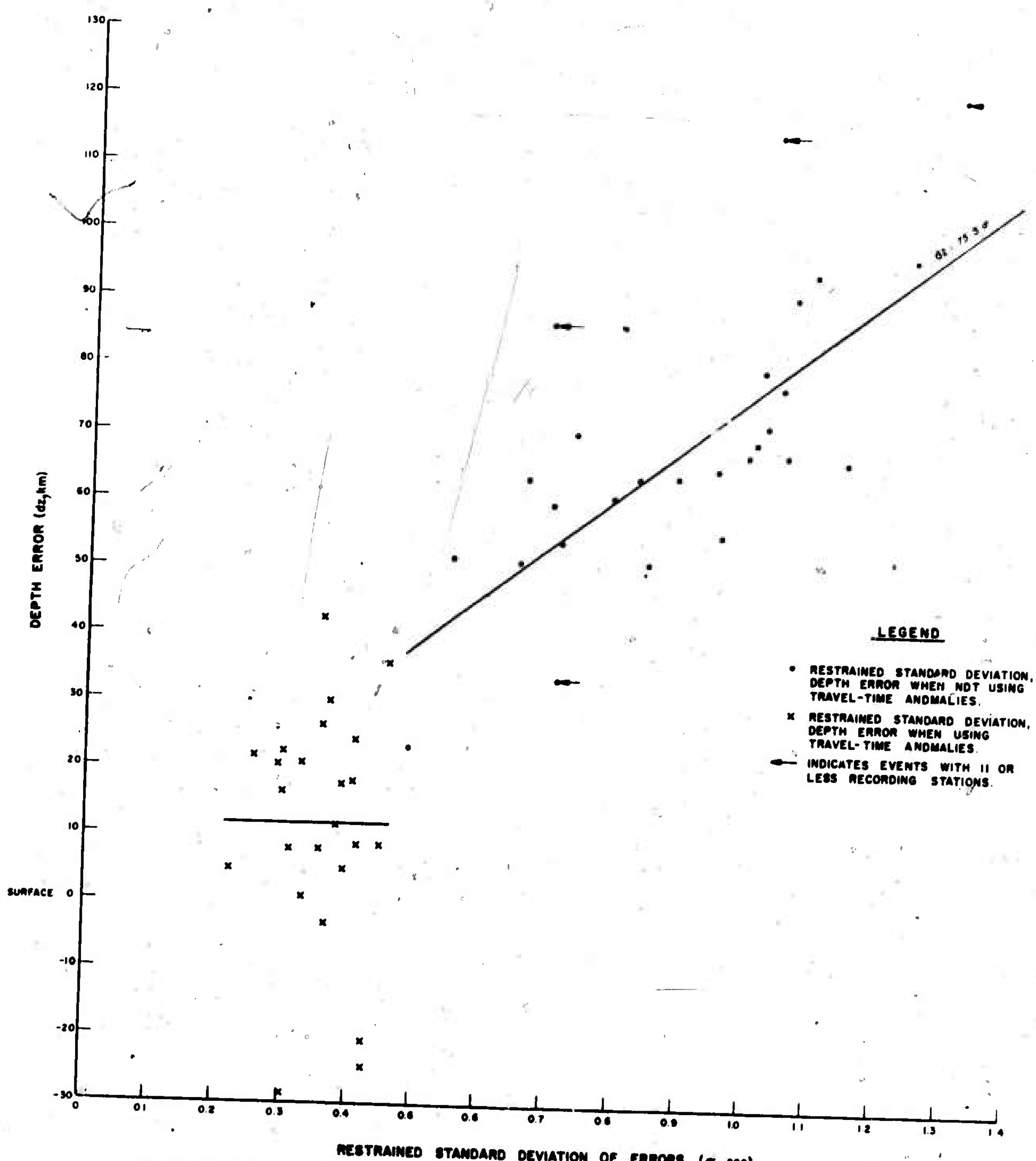


Figure 6. Relation between restrained standard deviation of time errors, σ, and the depth error, dz, of the corresponding unrestrained solution.

average, all negative depths were set to zero, although this would account for only about 20% of the remaining 15 km bias.

LOCATION BIAS EFFECTS

In the preceding analyses, known explosions comprised the data set, and errors caused by an invalid earth model are eliminated by using anomalies. One can then properly speak of location accuracy rather than precision (relative accuracy). In the case of earthquakes, there is an unknown error in the assumed position, and studies concerning locations using earthquake anomalies are always suspect. However, the question of the precision achievable by applying anomalies which are determined from an event whose location is unknown can be addressed if a calibration explosion is deliberately mislocated.

To establish a base from which a comparison can be made, true anomalies can be determined from the actual position of BILBY for a teleseismic network of 33 stations (Table II) and applied as corrections to other events occurring within the same anomaly region. Shifts for this case calculated with depth restrained are plotted in Figure 7 for the 27 events (other than BILBY) listed in Table I. The true location of BILBY is indicated on the figure. The average location error is about 5 km when using only the BILBY anomalies. (The normalized plots shown in Figure 7 suggest that there is some anomaly instability between the two sub-regions and that one should probably use slightly different anomalies when locating events in subregion II. However, as shown in a previous section, if an anomaly average of several events is used instead of an anomaly determined from a single event, the size of the anomaly region can be increased without sacrificing accuracy.)

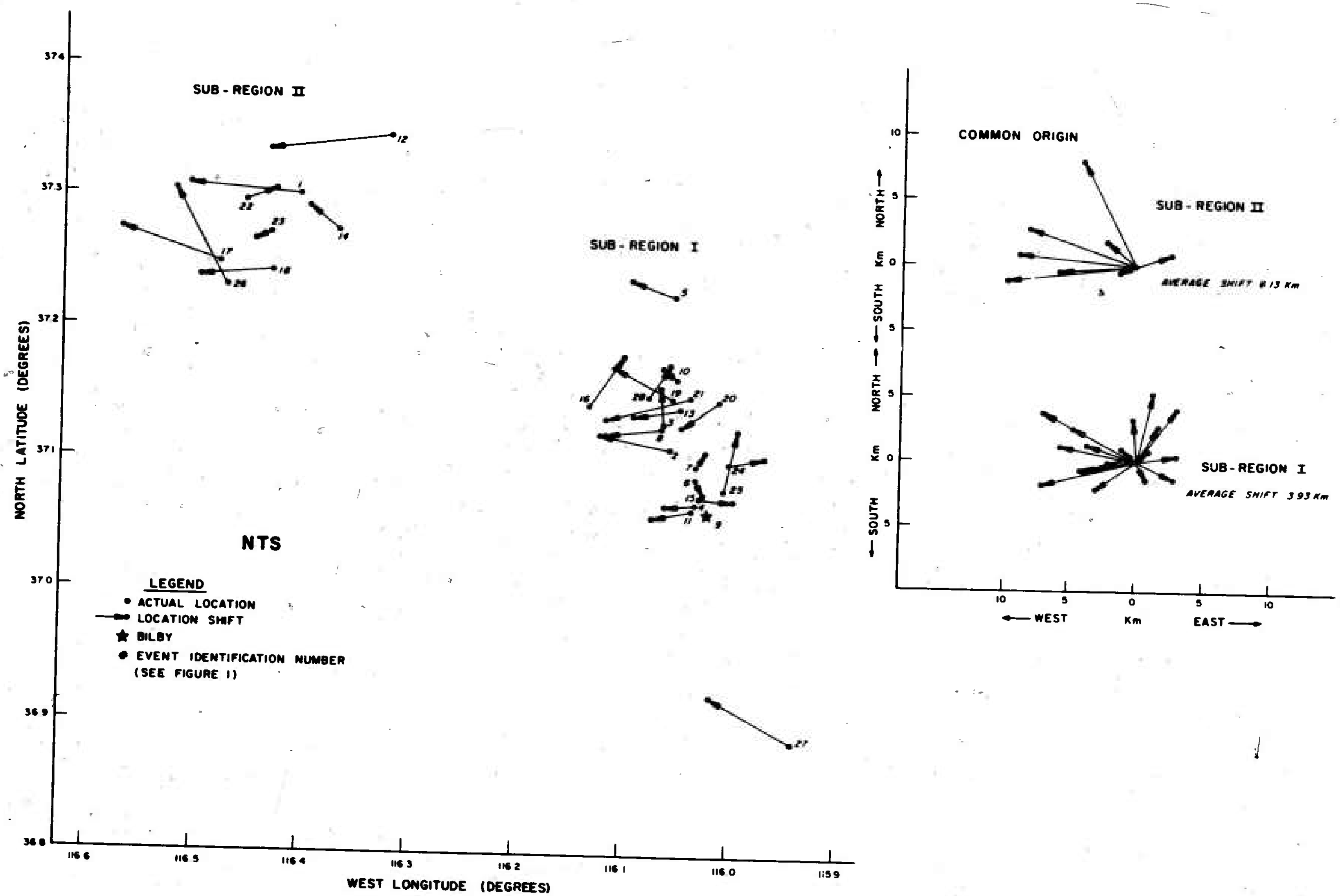


Figure 7. Restrained location shifts obtained with the BILBY stations and with anomalies determined from the true BILBY location.

If the actual location of BILBY is now deliberately given an error of +1° longitude and +1° latitude (about 140 km to the northeast), anomalies can be re-determined from this assumed-correct position and applied as corrections to subsequent events. The station anomalies that one would obtain from the displaced BILBY location are given in Table IX; teleseismic anomalies this large have never been observed, so it is safe to assume that bias effects will generally be smaller than those imposed on this example.

The results of locating events with the displaced-BILBY anomalies are shown in Figure 8. The average location precision (3.9 km) is about the same as the average location accuracy in Figure 7 (4.6 km). (The precision is actually a little better than the accuracy because the northeasterly bias given to BILBY artificially moves the event set generally closer to the networks, thereby increasing the sensitivity ($dT/d\Delta$) of the travel-time tables. Thus the solutions need to move away from their true values by a smaller amount to achieve an equivalent minimization of the residual time errors). The main point to be made is that regardless of where the calibration event is assumed to be located, the accuracy of subsequent events <u>relative to the calibration event</u> is virtually unaffected if anomalies are used. This is important, for example, in studies of nuclear test sites, of event migration in aftershock sequences, or of seismo-geologic correlation with island arcs, oceanic ridges, and major fault zones (Isacks et al (1967); Sykes et al (1969); Mitronovas et al (1969); and others), in which the pattern

TABLE IX

DISPLACED-BILBY ANOMALIES

Station (C&GS)	Anomaly (Sec)*	Station (VELA)	Anomaly (Sec)*
ARE	-13.52	BL-WV	-4.77
BEC	-6.10	BR-PA	-4.10
CAR	-10.02	CPSO	-4.91
FLO	-1.40	DH-NY	-4.37
GDH	-3.62	EB-MT	1.11
GUA	-18.10	EU-AL	-4.85
KEV	-7.90	EU2AL	-4.85**
KIP	-20.44	GG-GR	-6.40
LPB	-14.27	HN-ME	-3.44
LPS	-12.38	LV-LA	-4.99
NNA	-14.81	NP-NT	-4.70
NUR	-7.54	OO-NW	-6.75
OXF	-4.10	PZ-PR	-8.21
PTO	-7.48	RK-ON	0
SCP	-4.47		
SHA	-5.23		
STU	-7.04		
TOL	-6.86		
TRN	-12.57		
VAL	-6.83		

* All anomalies are referenced to station RK-ON.

** Used the anomaly determined for EU-AL.

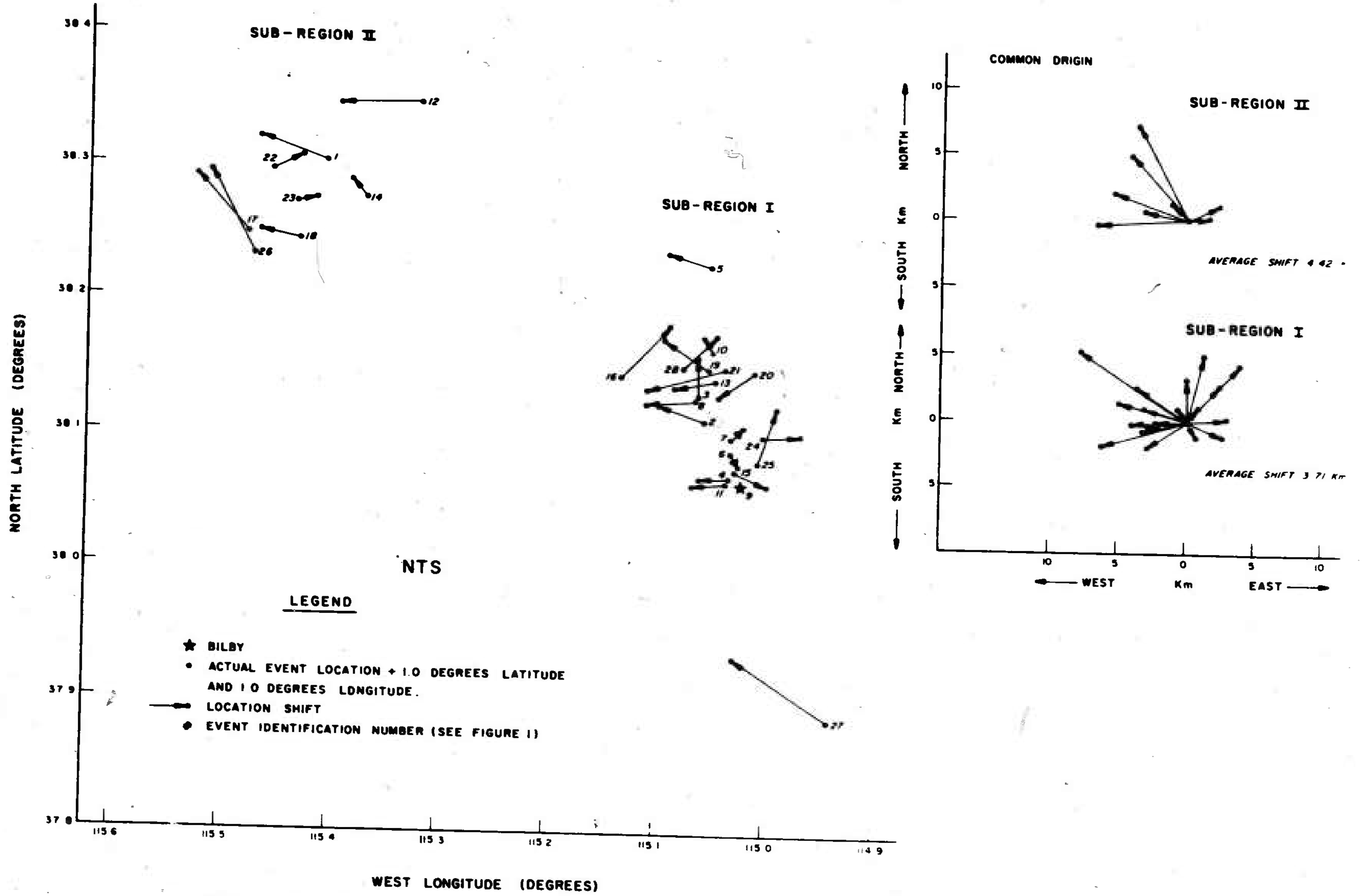


Figure 8. Restrained location shifts obtained with the BILBY stations and with displaced-BILBY anomalies.

of events (or lack of it) is contributory to the conclusions reached regarding the location of clandestine underground explosions, seismicity, or global tectonics.

LOCATIONS USING CONSTANT NETWORKS

In the previous sections of this report, the locations were made using every available recording station, the number of which varied between 9 and 49. The results obtained without anomalies (Figure 2) were seen to be variable in magnitude and direction, whereas with anomalies (Figure 4) the variability was significantly reduced. It will now be shown that by using networks composed of the same stations for a set of explosions the results obtained without anomalies are no longer variable but instead yield exactly the same precision as the results obtained with anomalies. Furthermore, it will be shown that location bias is a function of the particular network used, and, because the several networks investigated have essentially identical quadrantal distributions, that location bias cannot be attributable to source region geology alone but can be more properly understood as a function of the total travel path, including the lower mantle and the crustal and upper mantle geology in the vicinity of the stations.

First, a five-station network is selected: RK-ON, CPSO, COL, HN-ME, and NP-NT. This network has an azimuth aperture of 109° and a reasonable range in distance (21° to 39°). Using no anomalies, the results of locating 17 events recorded by these five stations are shown in Figure 9 plotted from a common origin. The average error is 22.9 km and all of the events shift northeast. Clearly, this particular network may be said to have a northeast location bias of about 23 km.

Using the same network but with the NTS anomalies as given in Table VI, the average location error is reduced to

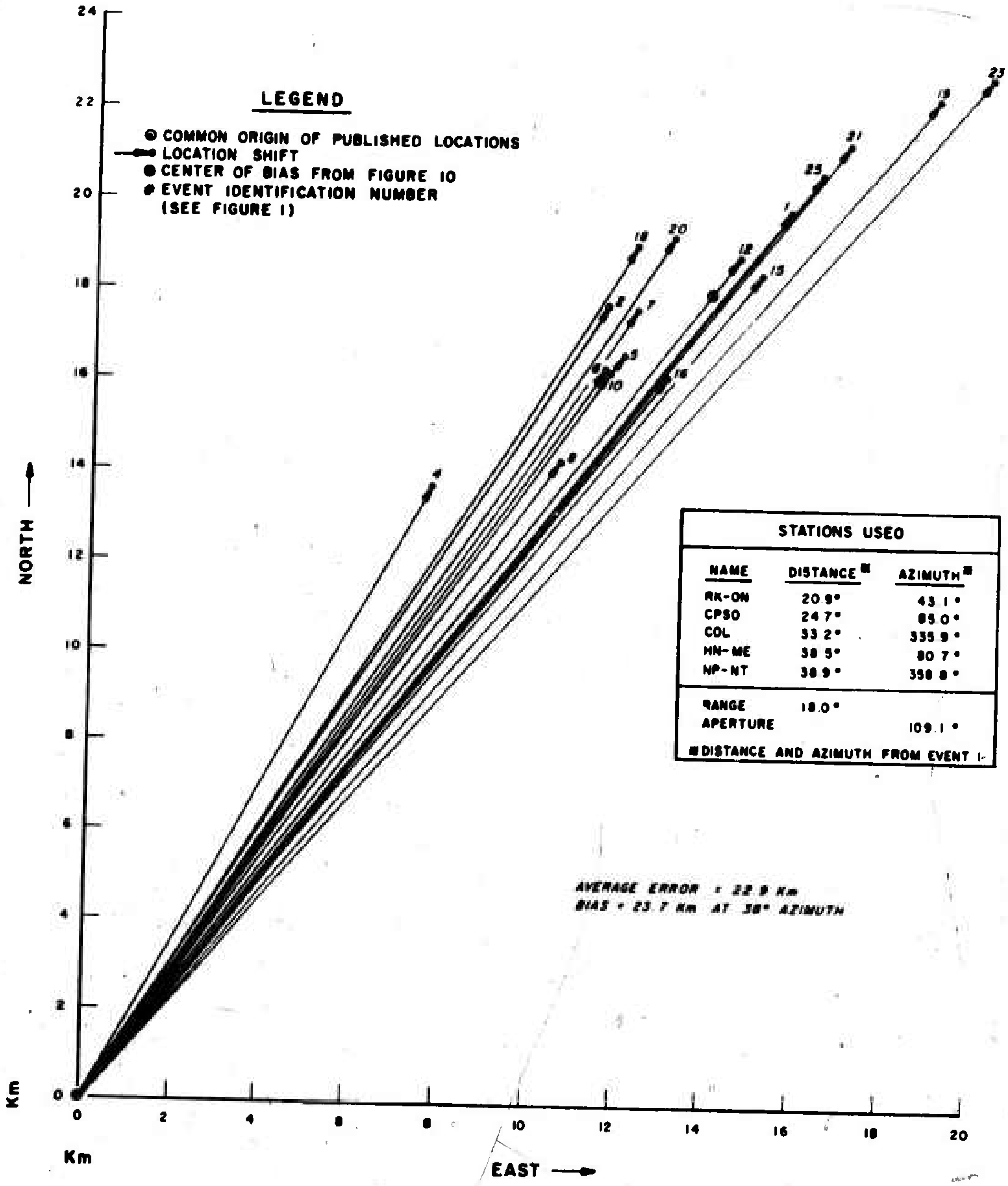


Figure 9. Restrained location shifts using a constant five-station network and no anomalies plotted from a common origin.

3.5 km and the directions are randomized. These results are plotted in Figure 10 to the same scale as in Figure 9. The vectors from Figure 9 are replotted on Figure 10 as blue lines; it is seen that the relative locations (vector terminal points) are identical in both cases.

If to the five-station network used above, a sixth station (ARE) is added, the azimuth aperture is increased to 157°. The results without anomalies are shown in Figure 11a; the average error is 13.0 km and the events again shift northeasterly. Hence, for this six-station network, the bias magnitude is 13 km, and the bias direction is unchanged. The results obtained by adding stations one at a time and without anomalies are shown in Figures 11b, 11c, and 11d, in each case the aperture remaining at 157°. The average location errors in Figures 9 and 11 can be summarized as follows:

Without Anomalies

Network	Error, km	Direction	No. of Events	Figure
5-station	22.9	Northeast	17	9
6-station	13.0	Northeast	15	11a
7-station	10.8	Northeast	15	11b
8-station	8.7	Northeast	12	11c
9-station	9.8	Northeast	11	11d

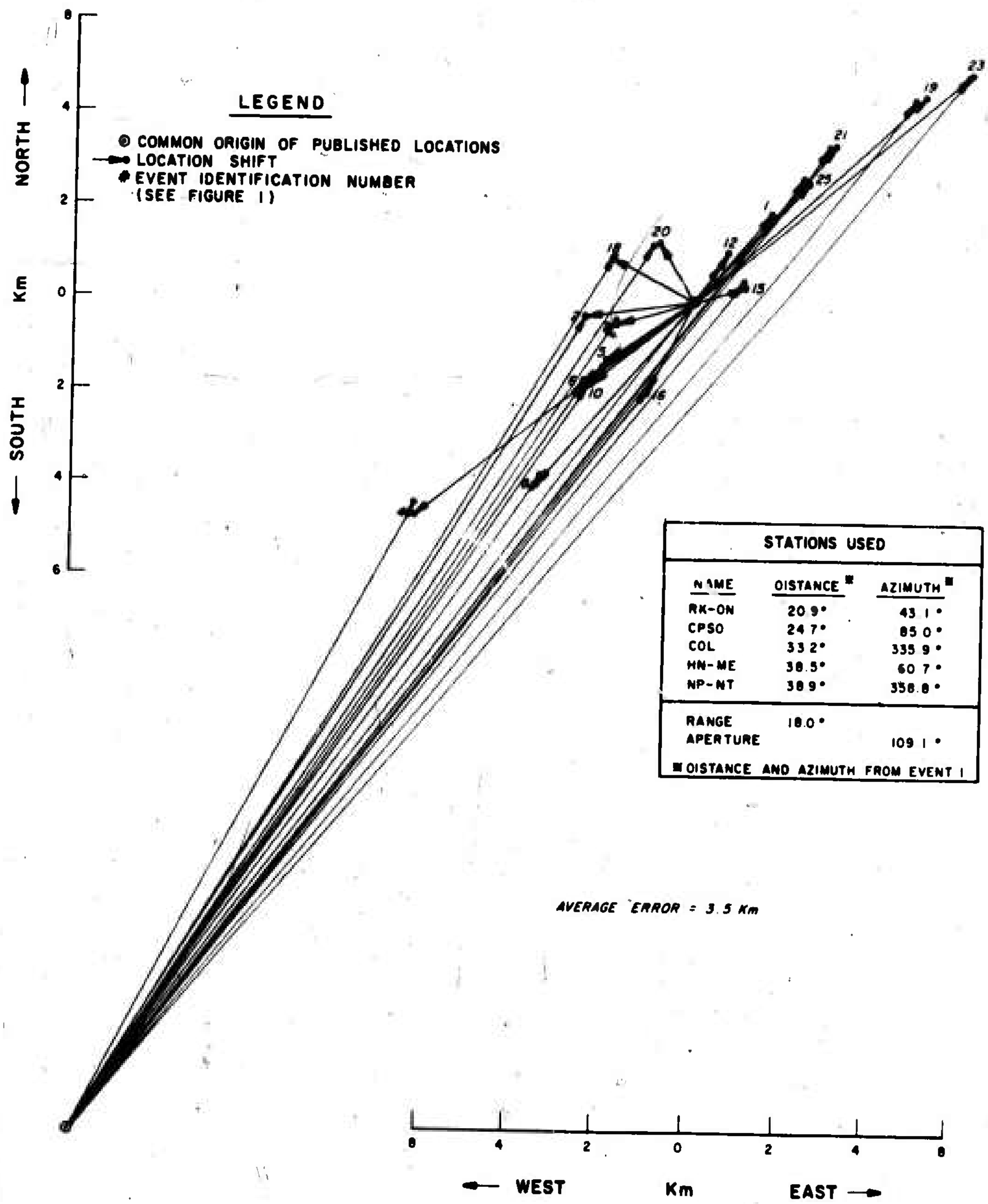


Figure 10. Restrained location shifts using a constant five-station network and anomalies plotted from a common origin.

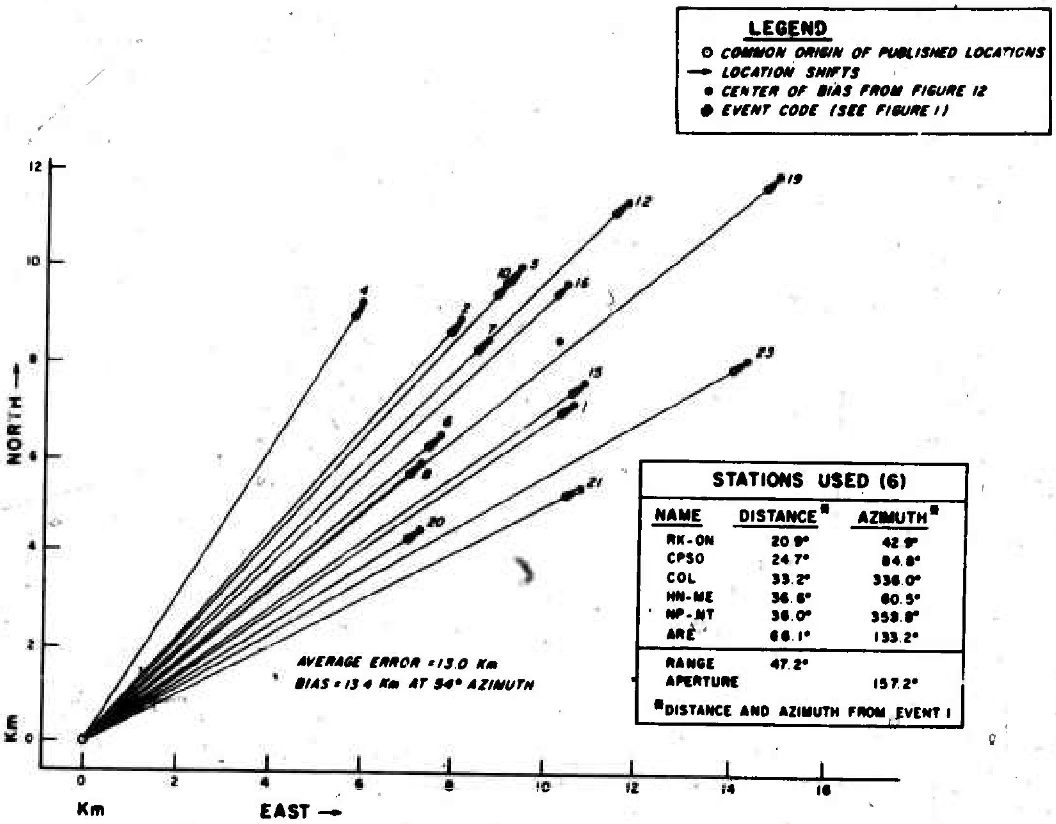


Figure 11a. Restrained location shifts using constant six-station networks and no anomalies plotted from common origins.

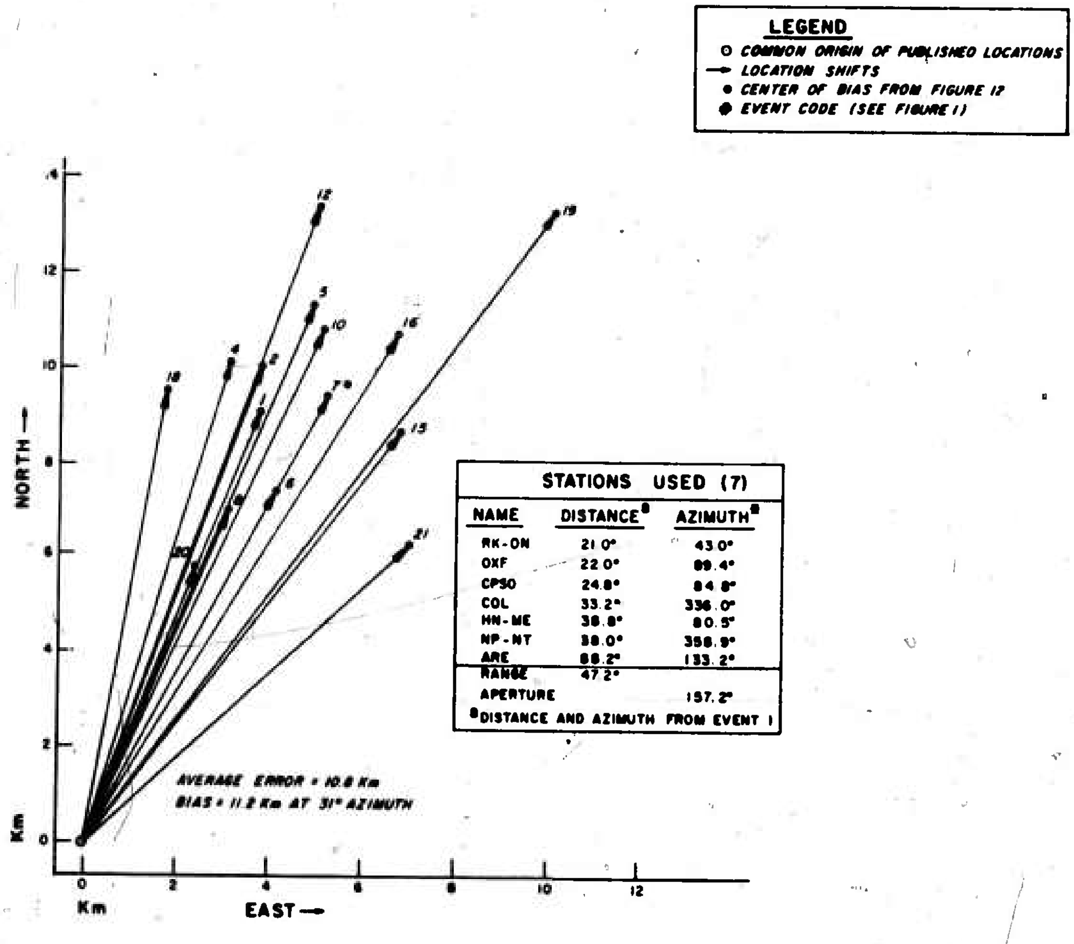
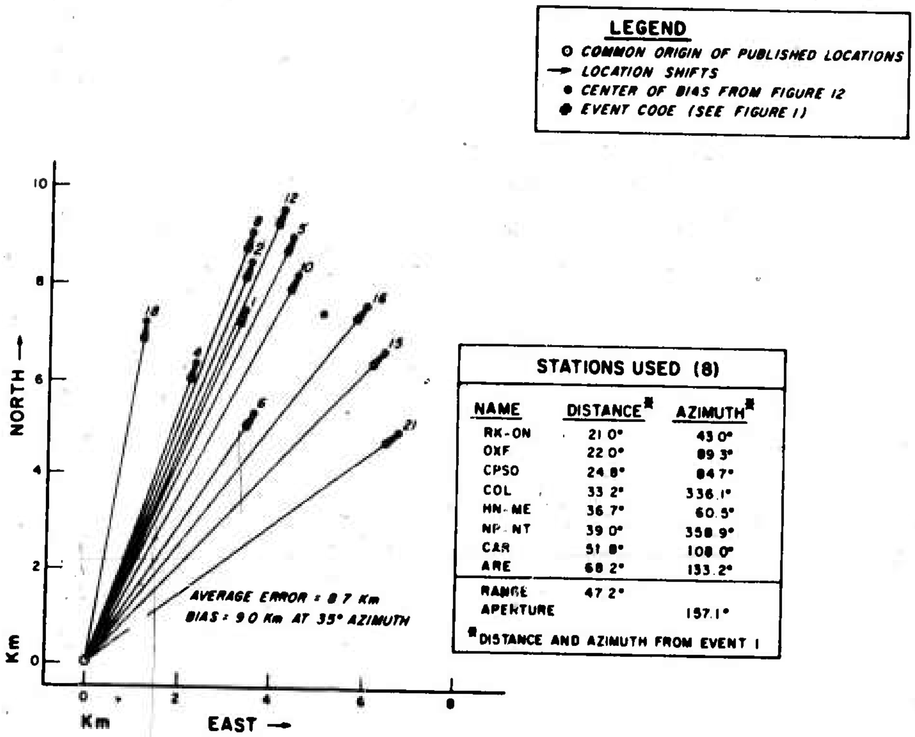


Figure 11b. Restrained location shifts using constant seven-station networks and no anomalies plotted from common origins.

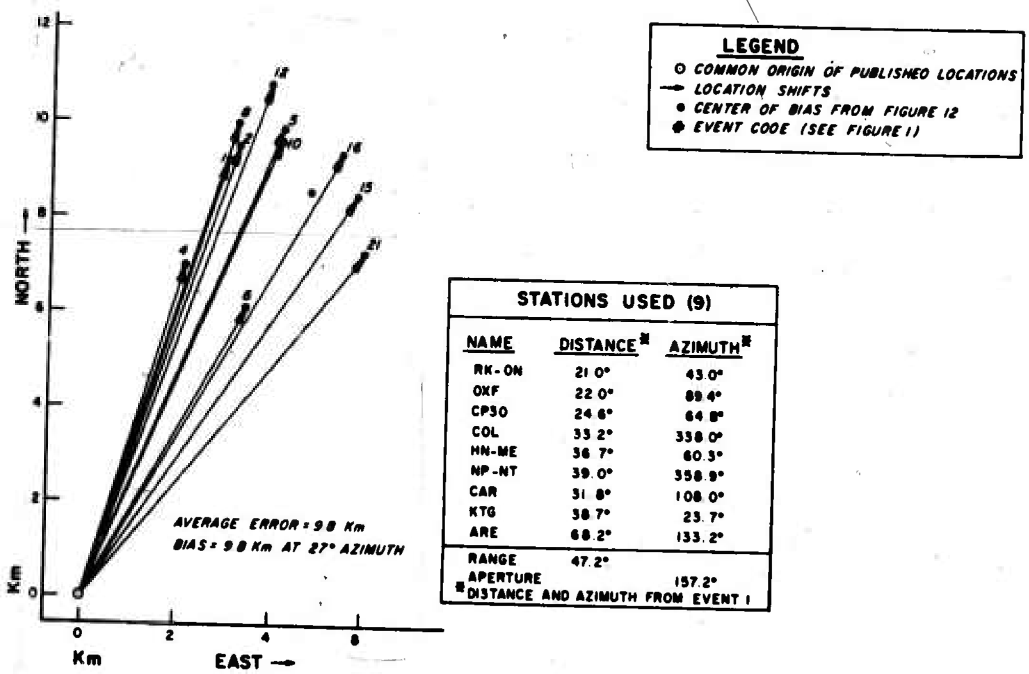


STATIONS USED (8)

NAME	DISTANCE*	AZIMUTH*
RK-ON	21.0°	43.0°
OXF	22.0°	89.3°
CPSO	24.8°	84.7°
COL	33.2°	336.1°
HN-ME	36.7°	60.5°
NP-NT	39.0°	358.9°
CAR	51.8°	108.0°
ARE	68.2°	133.2°
RANGE	47.2°	
APERTURE		157.1°

*DISTANCE AND AZIMUTH FROM EVENT 1

Figure 11c. Restrained location shifts using constant eight-station networks and no anomalies plotted from common origins.



STATIONS USED (9)

NAME	DISTANCE*	AZIMUTH*
RK-ON	21.0°	43.0°
OXF	22.0°	89.4°
CP50	24.6°	64.8°
COL	33.2°	338.0°
HN-ME	36.7°	60.3°
NP-NT	39.0°	358.9°
CAR	31.8°	108.0°
KTG	38.7°	23.7°
ARE	68.2°	133.2°
RANGE	47.2°	
APERTURE		157.2°

*DISTANCE AND AZIMUTH FROM EVENT 1

Figure 11d. Restrained location shifts using constant nine-station networks and no anomalies plotted from common origins.

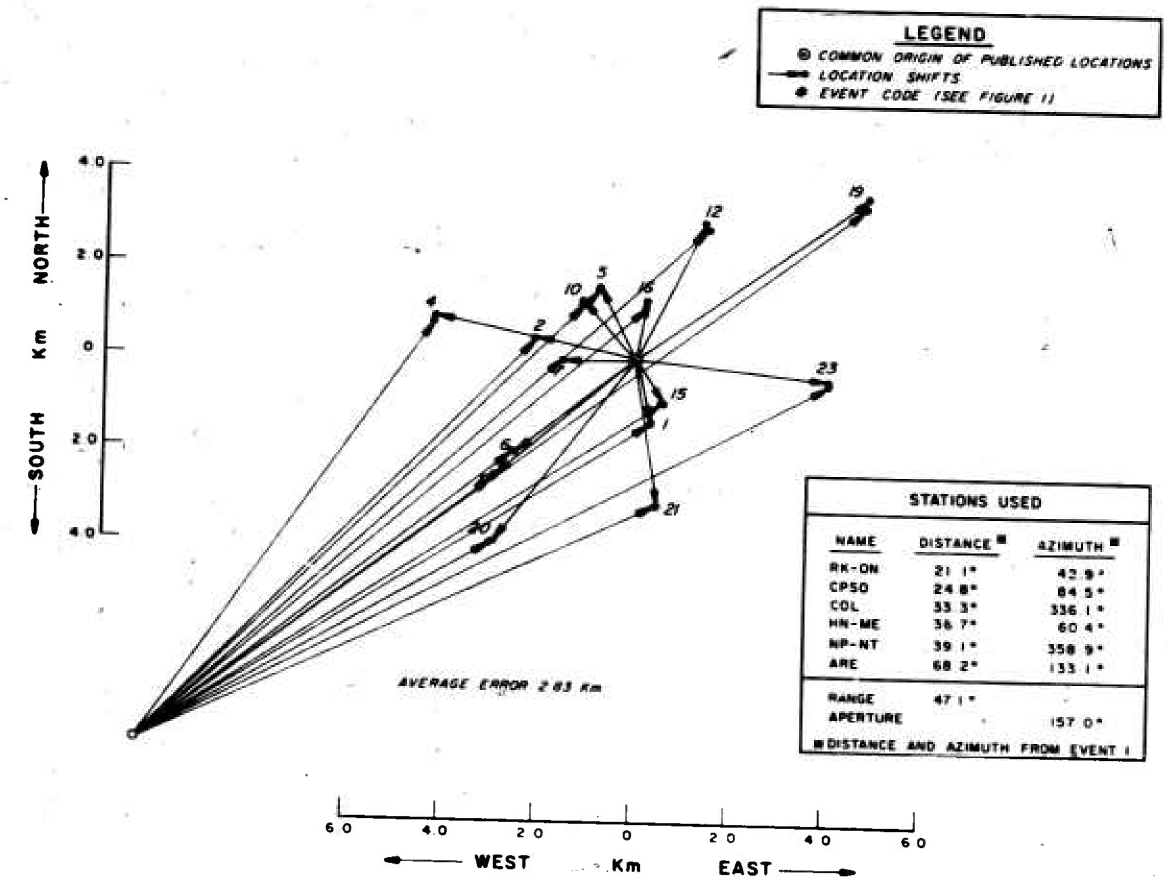
The location results obtained with these networks, but with anomalies applied, are shown in Figure 12 with the Figure 11 results included as blue lines, again demonstrating that the same precision is achieved if constant networks are used. The results of Figures 10 and 12 are:

With Anomalies

Network	Error, km	Direction	No. of Events	Figure
5-station	3.5	Random	17	10
6-station	2.8	Random	15	12a
7-station	2.8	Random	15	12b
8-station	2.2	Random	12	12c
9-station	1.9	Random	11	12d

Therefore, if a constant network is used to locate events from a particular region, anomalies need not be applied to achieve precise locations. However, the imposition of a constant-network requirement in routine operation is prohibitive; stations record events from a region in a highly variable way due to their detection thresholds, temporal microseismic noise fields, local seismic activity, and unpredictable malfunctions of instruments. It is much simpler in the long run to routinely apply anomalies such that the locations made with variable networks are consistent.

The northeast bias in Figures 9 and 11 is not to be construed as a function of the NTS region. Alternatively,

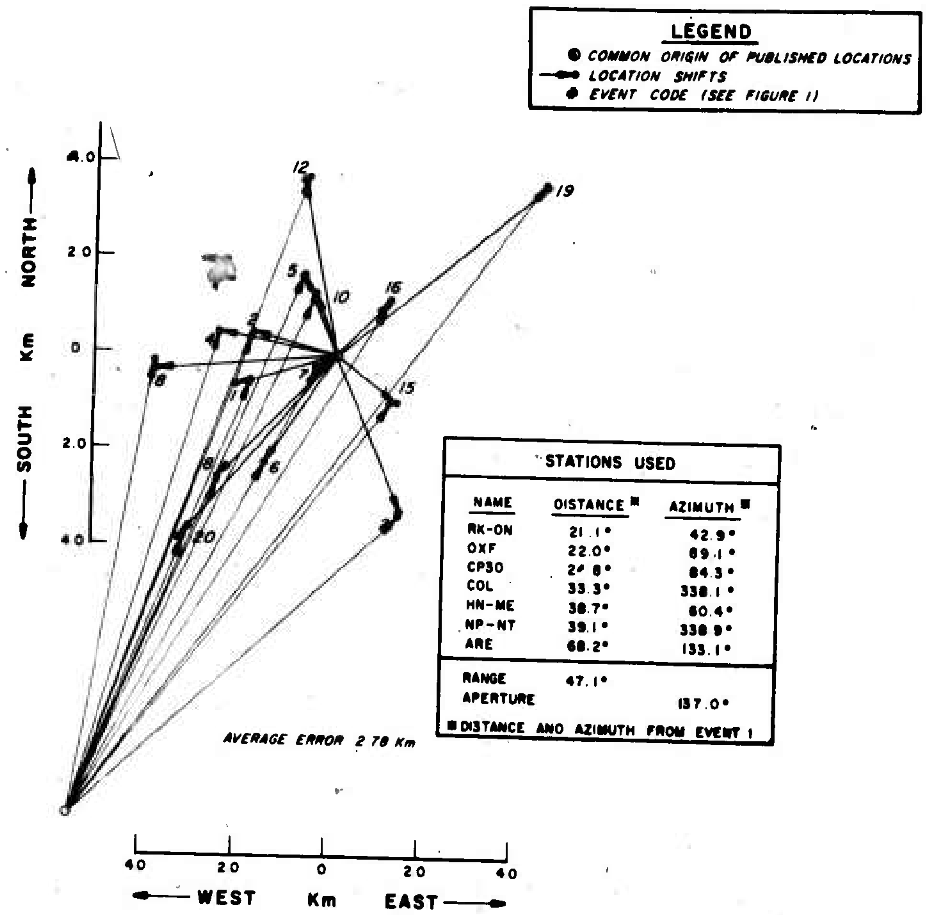


STATIONS USED

NAME	DISTANCE ■	AZIMUTH ■
RK-ON	21.1°	42.9°
CPSO	24.8°	84.5°
COL	33.3°	336.1°
HN-ME	36.7°	60.4°
NP-NT	39.1°	358.9°
ARE	68.2°	133.1°
RANGE	47.1°	
APERTURE		157.0°

■ DISTANCE AND AZIMUTH FROM EVENT 1

Figure 12a. Restrained location shifts using constant six-station networks and anomalies plotted from common origins.

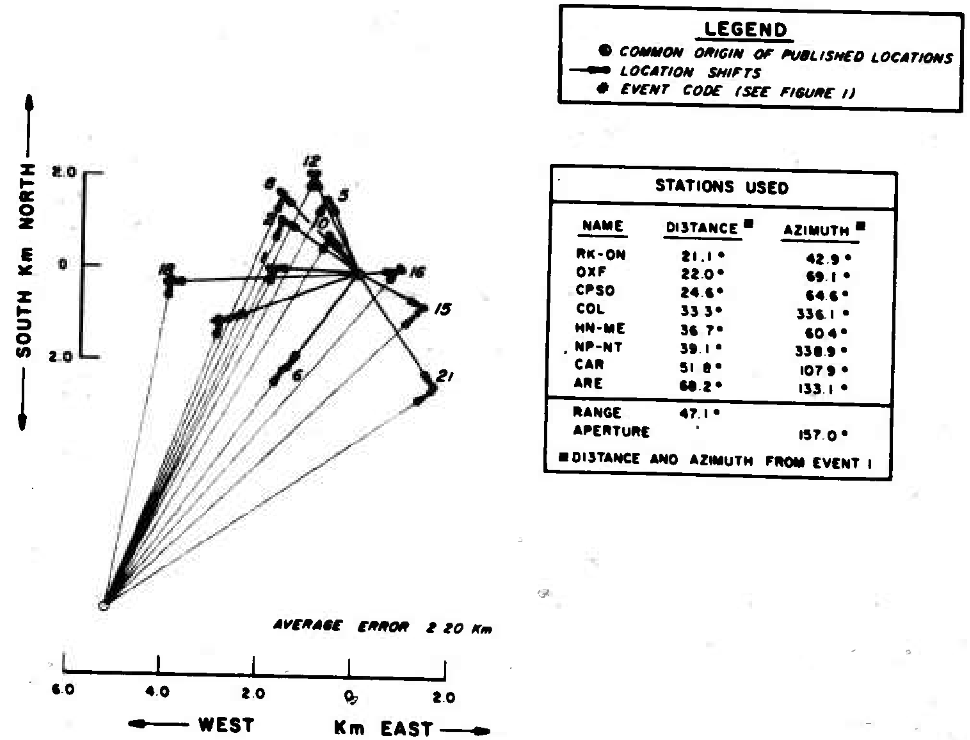


STATIONS USED

NAME	DISTANCE ■	AZIMUTH ■
RK-ON	21.1°	42.9°
OXF	22.0°	69.1°
CP30	24.8°	84.3°
COL	33.3°	338.1°
HN-ME	38.7°	60.4°
NP-NT	39.1°	338.9°
ARE	68.2°	133.1°
RANGE	47.1°	
APERTURE		137.0°

■ DISTANCE AND AZIMUTH FROM EVENT 1

Figure 12b. Restrained location shifts using constant seven-station networks and anomalies plotted from common origins.

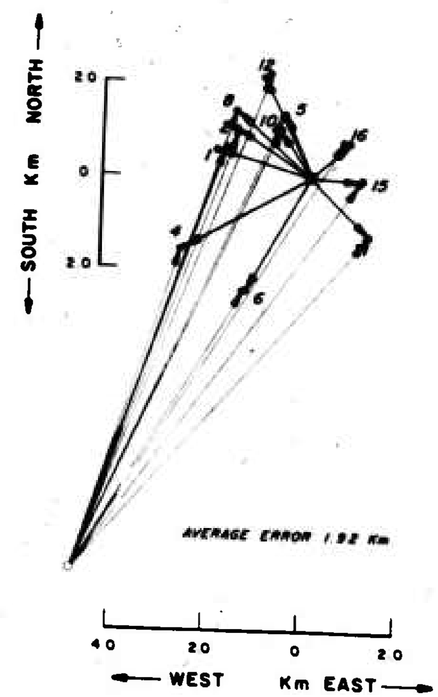


STATIONS USED

NAME	DISTANCE ■	AZIMUTH ■
RK-ON	21.1°	42.9°
OXF	22.0°	69.1°
CPSO	24.6°	64.6°
COL	33.3°	336.1°
HN-ME	36.7°	60.4°
NP-NT	39.1°	338.9°
CAR	51.8°	107.9°
ARE	68.2°	133.1°
RANGE	47.1°	
APERTURE		157.0°

■ DISTANCE AND AZIMUTH FROM EVENT 1

Figure 12c. Restrained location shifts using constant eight-station networks and anomalies plotted from common origins.



STATIONS USED

NAME	DISTANCE ■	AZIMUTH ■
RK-ON	21.1°	42.9°
OXF	22.0°	89.1°
CPSO	24.8°	84.6°
COL	33.3°	338.1°
HN-ME	38.7°	80.4°
CAR	51.8°	107.9°
KTG	58.8°	23.7°
ARE	88.2°	133.2°
RANGE	47.1°	
APERTURE		157.0°

■ DISTANCE AND AZIMUTH FROM EVENT 1

LEGEND

- ● COMMON ORIGIN OF PUBLISHED LOCATIONS
- ⟶ LOCATION SHIFTS
- ● EVENT CODE (SEE FIGURE 1)

Figure 12d. Restrained location shifts using constant nine-station networks and anomalies plotted from common origins.

another network could have been chosen, using stations FLO, OXF, COL, HN-ME, GDH, and TRN. The azimuth aperture of this network is 127°, and the stations are distributed azimuthally from north-northwest through east to southeast, as they were for the networks of Figures 9 through 12. The location results without anomalies are shown in Figure 13; the location bias for this network is nearly opposite to the others: 51 km to the southwest. When anomalies are applied, the location shifts are as shown in Figure 14 with the Figure 13 results included as blue lines. The complete results for this six-station network are:

	Error, km	Direction	No. of Events	Figure
Without Anomalies	51.2	Southwest	7	13
With Anomalies	5.57	Random	7	14

Similar networks could be selected to display virtually any bias magnitude and direction one desires. The lack of an apparent common bias among similarly-distributed networks definitely eliminates the source region as a principal factor in causing the bias.

Clearly, bias is a function of the particular network; more precisely, it is a function of the stations uniquely defining that network. But bias cannot be attributed only to "station effect", because the anomaly would then be a constant (late or early) or nearly so, for virtually all regions. Of course, some azimuthal dependence might be

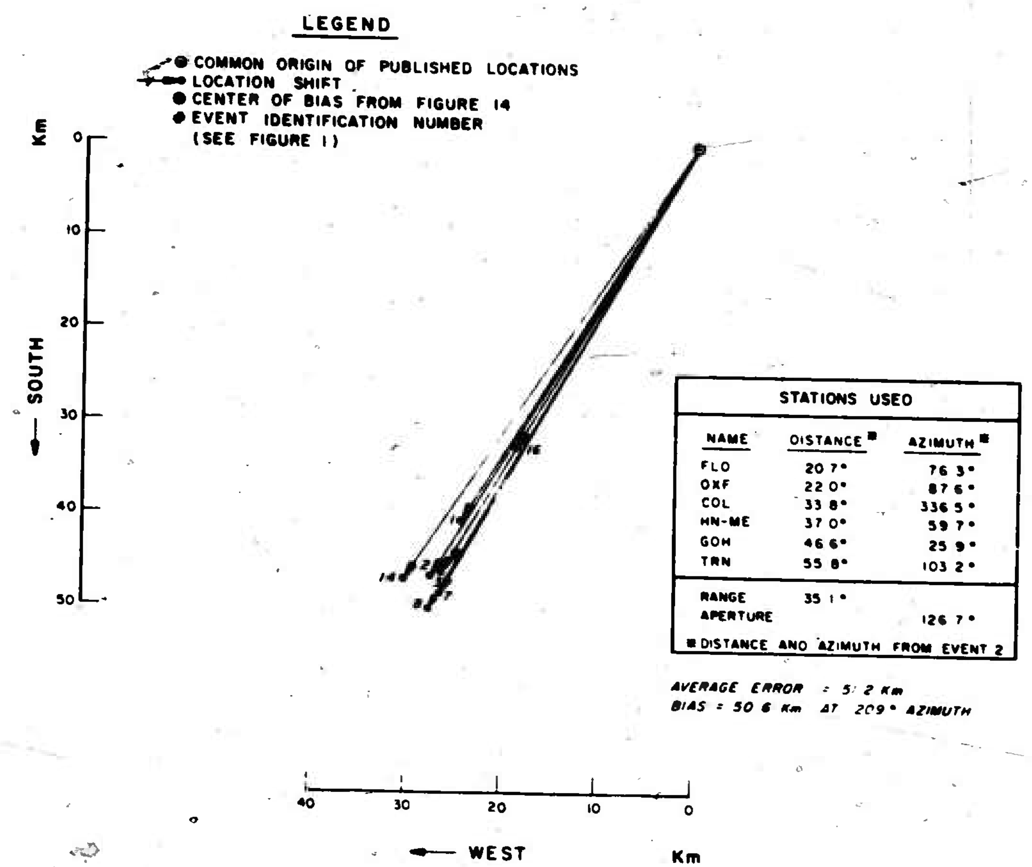
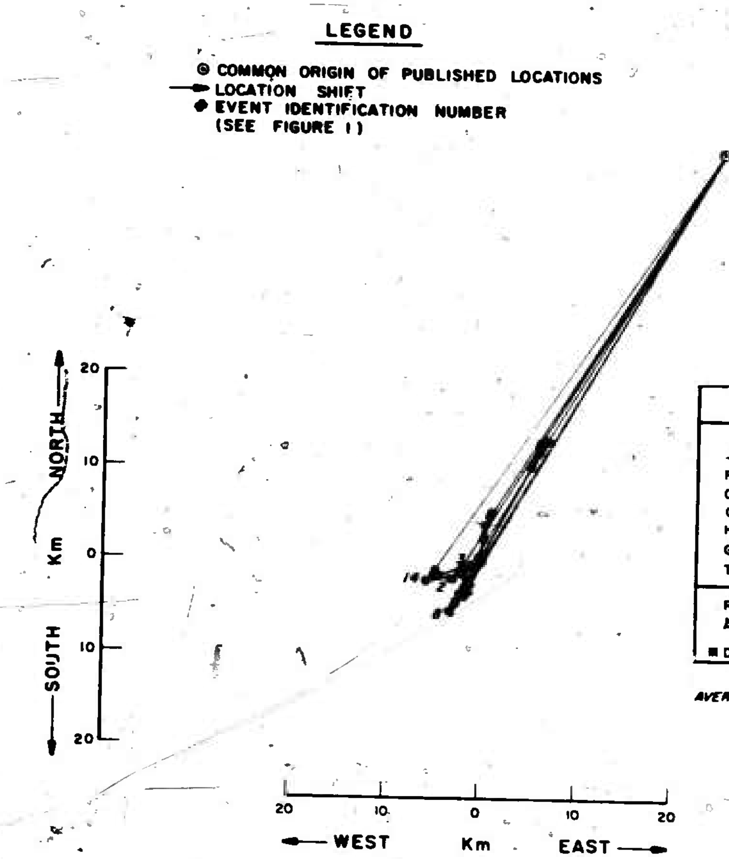


Figure 13. Restrained location shifts using another constant five-station network and no anomalies plotted from a common origin.



STATIONS USED		
NAME	DISTANCE*	AZIMUTH*
FLO	20.7°	76.3°
OXF	22.0°	87.6°
COL	33.8°	336.5°
HN-ME	37.0°	59.7°
GOH	46.6°	25.9°
TRN	55.8°	103.2°
RANGE	35.1°	
APERTURE		126.7°

* DISTANCE AND AZIMUTH FROM EVENT 2

AVERAGE ERROR = 5.57 Km

Figure 14. Restrained location shifts using another constant five-station network and anomalies plotted from a common origin.

observed if strong dips existed under the station, but a large proportion of the anomaly would be a simple DC shift. It is well-established, however, that the anomalies are not constant, are not simple functions of azimuth, and are highly variable with distance as well (Chiburis and Dean, 1965; Chiburis, 1966b, 1968a). The variations referred to are those occurring at a particular station for many event azimuths and distances and are not those occurring for a particular event at many station azimuths and distances (Cleary and Hales, 1966). The distinction is not subtle. In the latter case, a certain amount of residual averaging is done within specified windows in order to perceive any functional variations. Cleary and Hales (1966) have found a sinusoidal variation with distance, but in determining anomalies for location purposes (not the intent of Cleary and Hales), little is gained unless they are reproducible and known to within random reading error (about 0.25 sec) for each region. If many stations are contained within a window of either distance or azimuth, the range in anomalies will commonly be greater than 2 sec and is frequently as high as 5 sec, certainly too large for predicting station anomalies for accurate location, and too large to reasonably explain all bias as being due to a single phenomenon.

When it is desired to determine corrections for location purposes, the anomalies at a particular station should only be averaged within an anomaly region, because from one region to another the anomalies change substantially (although not erratically; see in particular, Chiburis, 1966a). The implication is that the major portion of an anomaly (especially the variation) is caused by slight lateral and vertical inhomogeneities within the mantle between the source and receiver, the effects of which are <u>integrated along the entire raypath</u>. Furthermore, any component in the anomaly due to a velocity distribution in the immediate vicinity of the station which does not conform to the travel-time model will be constant. However, the observed distance and azimuth <u>variations</u> in the station anomaly are so large (5-6 sec, in many instances) that they probably mask out the constant term entirely.

ANOMALIES FROM OTHER EXPLOSION REGIONS

The anomalies given in Table VI were determined from explosions in that portion of NTS shown in Figure 1. It is appropriate that a comparison be made between these anomalies and those determined from explosions in other regions. Figure 15 shows the positions of several explosions detonated in North America. Figure 16 and the first part of Table X give, for the stations used in this report, a comparison between the NTS average anomalies and the anomalies computed from the other explosions; the latter part of Table X includes the comparisons for an additional 122 stations whose anomalies were determined from published arrival times.

With these anomaly comparisons and with locations made using the NTS anomalies, several of the points made previously in this report will be further demonstrated and substantiated.

In Figure 16, the NTS average anomaly for each station is plotted against the anomaly determined from each of the other explosions. As in previous tables, the anomalies are with respect to station RK-ON. Of course, anomalies identical for both the NTS and the other explosions would generate straight lines on this type of plot with slopes equal to one. The lines shown, however, were determined from a least-squares regression of the data in each plot. The numerical values for the computed slopes, m, are shown in each sub-figure. The standard deviation about the least squares fitted line is also presented as $s_{y.x}$. A probable cause for the line not going through the point (0, 0) could be due to an anomalous reading at RK-ON.

The event JORUM is within the NTS area; hence, as expected, the slope of the fitted line for the JORUM/average NTS data, (Figure 16A), has a slope near 1.0 and a relatively small standard deviation of fit. At the other extreme are the results for the

Figure 15. Geographic map of selected explosions positions.

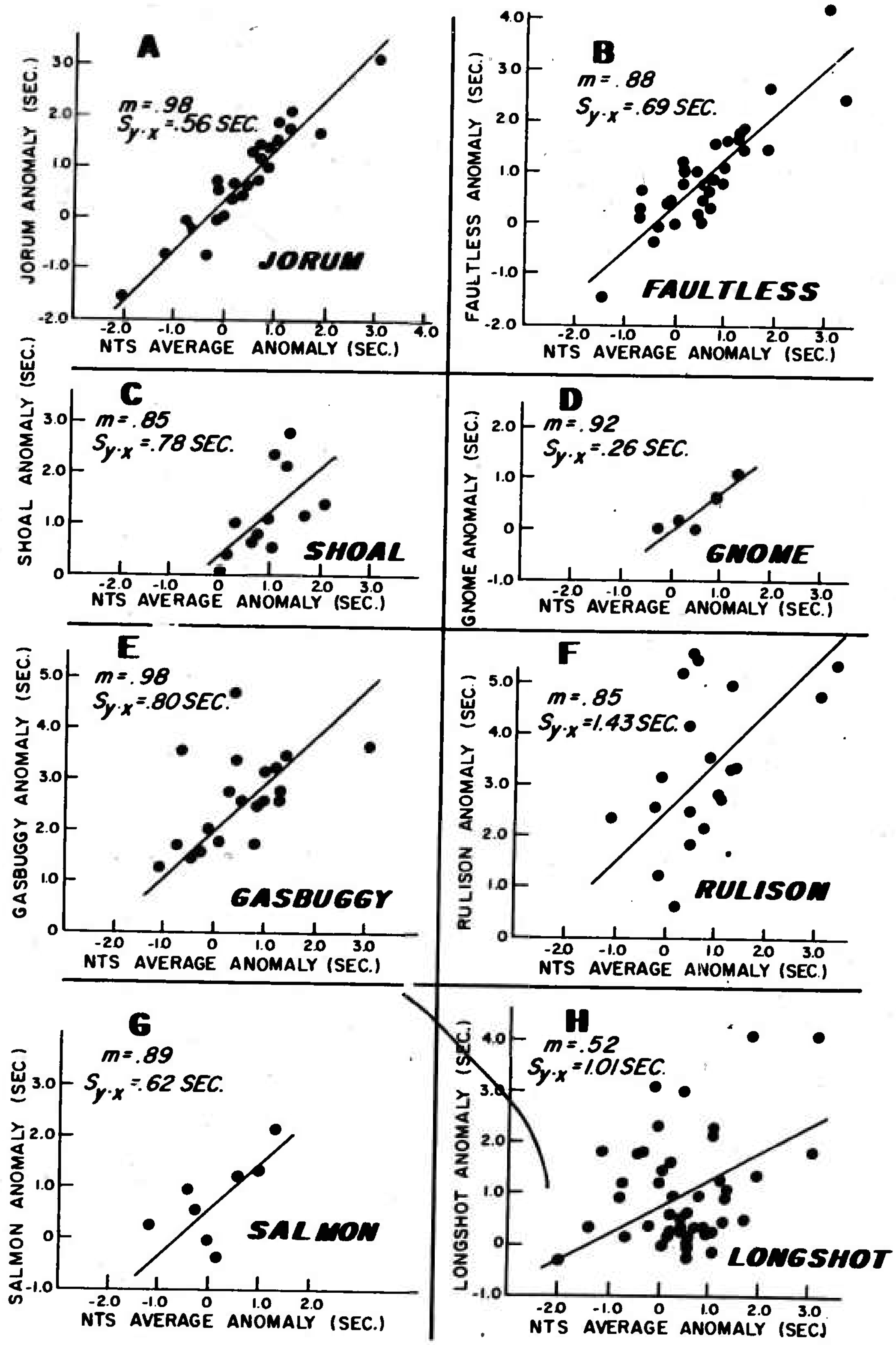


Figure 16. Comparison of anomalies between the Nevada Test Site and other regions.

TABLE X. COMPARISON OF ANOMALIES FOR SELECTED EXPLOSIONS

Event Name	AVG ATS	JORUM	FAULTLESS	SHOAL	GASBUGGY	GNOME	RULISON	SALMON	LONGSHOT	
Azimuth Aperture		266°	266°	156°	191°	85°	200°	261°	309°	
Number of Stations	66	76	105	22	46	12	68	22	111	
STATIONS										
VELA										
AD-IS	0.01								1.47	
AX2AL	1.85		1.46							
BE-FL	1.35		1.41						1.09	
BL-WV	0.75			0.82		0.61				
BR-PA	1.00			0.56						
CPSO	0.93	1.38	0.77	1.12	2.59		3.55		0.23	
DH-NY	0.17			0.39		0.17		-0.37	0.28	
EB-MT	0.26			0.98						
EN-MO	1.06								-0.13	
EU-AL	2.01			1.39						
EU2AL	2.01*			1.39*						* Anomaly For EU-AL
GG-GR	0.69									
HN-ME	0.64	0.71	0.28	0.64				1.17	-0.09	
LV-LA	1.96									
NP-NT	1.05	1.49	1.63	2.36	3.12		2.78	1.47	2.14	
OO-NW	-0.07								1.22	
PG-8C	3.06	3.[illegible]*	4.21		3.65		4.73*		1.88	* Anomaly For PG2BC
PG2BC	3.06*	3.10	4.21*		3.65*		4.73		1.88*	* Anomaly For PG-8C
PZ-PR	1.56									
RK-ON **	0.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	** All Anomalies Referenced To Station RK-ON
SI-BC	3.06								4.10	
SV20B	-0.45		-0.40*		1.42*			0.93	0.77*	* Anomaly For SV3Q8
SV3Q8	-0.47		-0.40		1.42			0.93*	0.77	* Anomaly For SV20B
WH2YK	1.25	1.70	1.66		3.19				1.35*	* Anomaly For WH-YK
C&GS										
AAM	0.51		0.40		2.59		5.55		0.68	
AKU	1.08	1.82							2.31	
ANT	1.12									
ARE	1.30	2.05	1.75	2.13	2.57		3.31			
ATL	1.00		1.06				2.84		0.25	
BEC	0.65		0.63						0.35	
BLA	1.28				2.74		4.99		0.44	
CAR	0.83	0.98			2.48				0.35	
COL	1.34		1.81	2.77	3.47	1.06	3.34	2.15	0.93	
COP	0.13		1.20							
CMC	0.24				2.72		5.16		1.55	
ESK	-0.77		0.10		1.67				0.83	
FLO	1.63			1.19					0.55	
GOH	0.72	1.41	1.53						1.09	
GEO	0.45						4.12		0.23	
GIE	2.00									
GUA	-1.43	-1.11	-1.46						0.36	
KEV	-1.13	-0.79			1.21		2.40	0.22	1.87	
KIP	1.89	1.64	2.65						4.11	
KON	0.12		0.79						0.60	
KTG	0.17	0.67	1.03		1.77				0.89	
LPB	0.23	0.65					0.66			
LPS	1.62									
MAL	0.55								0.11	
MAT	-0.18	0.69	0.39		2.07		1.28		3.11	
NOR	-0.70	-0.23	0.67		3.57				1.20	
NNA	0.37	0.40			4.71					

TABLE X (CONT'D.). COMPARISON OF ANOMALIES FOR SELECTED EXPLOSIONS

		256°	266°	156°	191°	85°	200°	261°	309°
	66	76	105	22	46	12	68	22	111
NUR	-0.28	0.03			1.63	-0.01	2.54	0.57	0.36
OGO	0.50		0.00				4.14		-0.23
OXF	1.99								0.36
PEL	-0.12	-0.02	0.45				3.14		
PTO	-0.74	-0.14	0.27						0.19
SCP	0.43	0.66	0.16		3.38	0.03	1.82		0.31
SEO	0.42								3.01
SHA	3.36		2.43				5.35		
SHK	-0.10	0.52	0.71						2.36
SJG	0.71	1.11	0.81		1.77		2.19		0.99
STU	0.46		1.03				2.46		0.45
TOL	0.17	0.34	0.98						0.18
TRN	-2.04	-1.59							-0.32
VAL	-0.38	-0.79	-0.11						1.81
WES	0.54	1.28	0.78				5.42		0.08
VELA									
AE-NC			-0.23						
AP-OK				3.78					
BMSO								4.37	1.44
FB-AK		1.60					3.11		
GL-TX			1.70						
HN-NO				4.16					
LS-NH			0.75						
NG-WS						-2.47			
SJ-TX			5.09						3.38
TFSO								3.45	2.74
WMSO				5.40					1.60
C&GS									
AOK		1.41	1.02				2.00		
AFI		0.94	0.80						3.41
ALE		-0.44					2.24		2.15
ATU			-0.56						
AVE		0.21					2.50		
AWI			-0.29						
BAE		0.50					2.24		
BAH			2.15						4.17
BCN								6.28	2.44
BOB			0.27						
BES			0.44						
BHP		0.24	1.03						1.07
BIG		1.12			3.38				
BLC		-0.64					2.41		0.74
BLO			2.60						0.54
BLR		2.21			4.45		4.18		
BOG							3.60		

TABLE X (CONT'D.). COMPARISON OF ANOMALIES FOR SELECTED EXPLOSIONS

		266°	266°	156°	191°	85°	200°	261°	309°
	66	76	105	22	46	12	68	22	111
BRW		1.08	1.52		3.08				2.17
BUF			3.96						
DUH		0.70	1.36						
CHC		1.35	0.41						
CLE		0.40					5.52		0.46
CLL		0.48	0.94		1.84		3.03		
DAL			2.18						1.71
DBQ		0.88	1.54						0.24
DUG								5.78	2.13
ECH			0.65						
EDM		1.64			3.22				0.44
FBC					2.32		4.50		0.29
FCC		0.80					3.40		
FEL			1.19						0.15
FLN		0.61	0.79		2.90		3.50		0.51
FSJ							5.88		1.57
GCA								4.43	
GIL		2.15			3.93		3.34		
GRF		1.10	1.52				3.41		1.23
GRR		0.74	0.89		3.21		4.30		0.40
GSC								3.26	1.74
GWC		0.24					4.65		0.18
IAS			-0.76						
IFR		0.25	0.65				2.43		2.76
INK							3.32		
IST		-0.88	0.46						-0.28
KEW			1.68						
KHC		0.49	0.89				3.53		0.79
KIR		-0.45		1.51		-0.13			-0.04
KJN		-0.35					2.25		-0.04
KLS				0.43					
KPH			2.02						4.19
KRK			0.88						
LAW		1.99	2.62						-0.41
LBF			0.40				2.99		0.68
LHN			0.57						0.11
LNS			1.65						1.14
LOR			1.04		2.38		3.15		0.63
LPF			0.97						
MBC				2.76	3.72	-0.44	3.56	1.94	2.19
MBO			1.36						
MLF			0.39				4.70		0.43
MNT		0.34			2.36		4.51		-0.63
MNY			1.14						
MOX		0.35	1.16				2.72		0.07
MRG		1.84	1.01	2.75	3.78				1.13
MSS			1.28						-0.92
NCS								4.69	
NEU			0.82						
OPA			2.41						
ORT		1.07			2.25		4.84		
OTT		0.57			3.87		4.15		-1.11
PAL						1.93	5.18		0.19

TABLE X (CONT'D.). COMPARISON OF ANOMALIES FOR SELECTED EXPLOSIONS

		266°	266°	156°	191°	85°	200°	261°	309°
	66	76	105	22	46	12	68	22	111
C&GS Contd.									
PBJ			2.91						2.79
PHC							5.33		3.80
PHI			3.14						
PJO		2.01			4.07		3.78		
PMR		2.07					5.43		
PMS							4.97		
PNS		0.49	0.19						
PRU		0.14	1.22				2.75		0.20
PVR									
QUI		2.71	3.22						
RAY			1.52						0.62
RES					1.60				1.54
RSL			1.23						0.21
RVR								2.97	
SCH							3.80		0.88
SCM		2.35					4.60		
SIT		2.24	2.48						
SKA						3.15			
SLM			1.45						
SOD		0.51				1.05	3.03	0.36	0.62
SSC		0.50	1.06		3.09		3.15		0.35
SSF			0.94		2.19		3.20		0.99
STR			1.20						1.02
SVW		1.81			3.37		3.66		
TAM					2.21				
TCF			0.65				2.68		1.16
TNN					4.23				
TNP								3.82	2.24
TNS			2.08						
TRI			0.37						0.01
TUB			1.63						0.68
TUC								3.02	2.32
TUL			2.39	3.20					
UNM			2.86						
UPP		0.30		0.32	1.08	0.43	4.34		0.47
VNM			2.91						2.58
VKA		0.58	1.14						
VRI			1.16						
WIT			1.92						
YKC		0.39					3.11	1.87	1.06
ZUR			1.73						

event LONG SHOT, located in the Aleutian Islands with a slope of 0.52 and a standard deviation of slightly greater than 1 sec, (Figure 16H). For the event FAULTLESS, which is approximately 100 km north of the NTS, the slope is 0.88 with a standard deviation 0.69 sec, which indicates a greater disagreement with the NTS anomalies than was evidenced in the JORUM anomalies. Each of the other explosions also show definite variations from the NTS values, either in the slope of the fitted line or in the standard deviation of the fit, or both. The standard deviation of fit for the GNOME explosion is only 0.26 sec but the slope is 0.72, which is far enough from 1.0 to cause a large error when the average NTS anomalies are used for locating GNOME. The comparison for the RULISON anomalies, with a slope of .96 indicates good agreement on the average with the NTS anomalies, but the standard deviation of fit is 1.43 sec, which is too large to expect good location results.

For many of these events, the epicenter-to-station azimuths are similar, but the anomalies are significantly different; the differences are so great that the cause of the anomalies cannot reasonably be attributed to local geology at the recording station. For example, NP-NT has an anomaly range of 1.73 seconds and KEV 3.53 seconds, changes which can hardly be due to station effect.

The largest anomaly variation for any one of the stations listed in the first part of Table X is 5.55 seconds at AAM; for any one of the stations in the entire table, 6.28 seconds at BCN. The largest range in the anomalies for a particular event is 6.65 seconds (-0.37 sec to +6.28 sec) for SALMON. The largest range for any station and any event is 9.43 seconds (-3.15 sec to +6.28 sec).

Locations of the events with depths restrained and using every available station in Table X, but without anomalies, are summarized in Table XI. If it is assumed that the NTS anomalies

TABLE XI

LOCATION RESULTS WITHOUT ANOMALIES FOR SELECTED EXPLOSIONS

Event Name	FAULTLESS	SHOAL	GASBUGGY	GNOME	RULISON	SALMON	LONG SHOT	JORUM
Number of Stations	103	20	44	12	66	21	111	74
Azimuth Aperture in Degrees	266.3	156.1	190.9	94.6	200.1	272.5	304.7	265.9
Distance Range in Degrees	79.4	60.8	76.1	60.2	67.7	58.0	77.5	79.8
Epicenter Shift in km	8.39	6.74	12.32	48.03	1.36	27.64	19.39	5.46
Direction of Shift in Degrees	7.9	332.2	52.6	4.0	263.4	54.0	356.1	109.0
Standard Deviation of Errors in Seconds	0.998	1.433	0.936	1.045	1.182	1.060	0.950	0.935
95% Confidence Ellipse in km²	141.8	1981.8	322.0	4481.6	325.1	531.3	175.0	172.2

are valid, locations made using them can be compared to the no-anomaly solution to note the improvement in location accuracy. Tables XII and XIII respectively give the no-anomaly and anomaly location results obtained using only those stations with a listed NTS average anomaly. Comparing the two tables, essentially no improvement is achieved by using NTS anomalies; for some events at large distances from NTS, the locations are worse. Excluding JORUM, which is in the NTS area, the average location error for the seven events obtained without anomalies is 20.2 km and with anomalies is 20.8 km. The ratio of the location error obtained without the NTS anomalies to that obtained with the NTS anomalies is presented in Table XIV. As expected, JORUM shows by far the greater improvement in location accuracy. Also presented are the ratios of the variances of time errors from the least-squares locations for each explosion. Again, the ratio for JORUM is significant, and so too is the ratio for FAULTLESS. The ratio for GNOME, 7.4, although very large is not statistically significant using the "F" test because there were only five stations used in the location scheme. The only other explosion with a reasonable improvement in variance was SALMON but again, too few stations were used for the ratio to be significant.

Therefore, it is known that the anomalies change significantly for most stations from one region to another nearby, and that for all stations they can change when the regions are far apart. Consequently, if for no other reason than that the labor expended in computing useless anomalies is saved and that the location results are less apt to be misinterpreted, it is better in routine location procedures to apply no anomalies at all than the wrong ones.

TABLE XII

LOCATION RESULTS WITHOUT ANOMALIES FOR SELECTED EXPLOSIONS USING STATIONS COMMON TO NTS

Event Name	FAULTLESS	SHOAL	GASBUGGY	GNOME	RULISON	SALMON	LONG SHOT	JORUM
Number of Stations	34	12	21	5	21	8	45	27
Azimuth Aperture in Degrees	246.2	156.5	190.9	91.5	196.9	71.7	242.0	244.6
Distance Range in Degrees	72.5	51.5	68.2	59.4	67.7	58.0	77.4	71.4
Epicenter Shift in km	5.11	23.09	12.35	64.01	4.80	20.89	11.12	5.51
Direction of Shift in Degrees	105.6	66.2	38.3	185.9	308.0	30.1	50.8	143.1
Standard Deviation of Errors in Seconds	0.971	0.401	1.000	0.255	1.460	0.626	0.874	1.017
95% Confidence Ellipse in km^2	407.3	288.8	612.0	2696.2	1250.9	2295.5	359.4	528.9

TABLE XIII

LOCATION RESULTS USING NTS AVERAGE ANOMALIES AND COMMON STATIONS FOR SELECTED EXPLOSIONS

Event Name	FAULTLESS	SHOAL	GASBUGGY	GNOME	RULISON	SALMON	LONG SHOT	JORUM
Number of Stations	34	12	21	5	21	8	45	27
Azimuth Aperture in Degrees	246.2	156.5	190.9	91.5	196.9	71.7	242.0	244.6
Distance Range in Degrees	72.5	51.5	68.2	59.4	67.7	58.0	77.4	71.4
Epicenter Shift in km	7.27	13.81	6.15	62.04	5.91	25.50	24.77	0.66
Azimuth of Shift in Degrees	123.4	98.9	25.1	10.0	251.8	7.2	90.2	199.0
Standard Deviation of Errors in Seconds	0.398	0.352	1.014	0.094	1.311	0.449	0.881	0.312
95% Confidence Ellipse in km^2	68.4	224.2	630.9	402.4	1010.3	1178.7	365.4	49.9

TABLE XIV

RESULTS OF ANOMALY AND LOCATION COMPARISONS BETWEEN THE NEVADA TEST SITE AND OTHER EXPLOSION REGIONS

Explosion	Fitted Line	Standard Deviation About Fitted Line (Seconds)	Ratio of No-Anomaly To Anomaly Results*: Location Error	Ratio of No-Anomaly To Anomaly Results*: Variance of Time Errors of Solution
JORUM	.98	0.56	8.3	10.6#
FAULTLESS	.88	0.69	0.7	6.0#
SHOAL	.85	0.78	1.7	1.3
GASBUGGY	.91	0.80	2.0	1.0
RULISON	.96	1.43	0.8	1.2
GNOME	.72	0.26	1.0	7.4
SALMON	.89	0.62	0.8	1.9
LONGSHOT	.52	1.01	0.4	1.0

*Ratio greater than one indicates improvement when using average NTS anomalies.

#Significant at the 95 per cent level.

CONCLUSIONS

A location study was made of 28 underground explosions detonated in the northern area of the Nevada Test Site (NTS). The events were large enough such that P-wave timing errors were within acceptable limits.

The networks used for locating the events were comprised of between 9 and 49 teleseismic stations having two- to three-quadrant distributions. Because all of the events have known positions, the results regarding the effectiveness of travel-time anomalies on location accuracy, location precision, depth error, etc., are more consistent and simpler to evaluate than if the events were earthquakes of unknown positions.

The conclusions inferred from this study are as follows:

1. Depth-restrained location errors, using all available stations without anomaly corrections, average about 7 km but are as large as 20 km. The lack of consistency among the locations suggests that the errors are not due solely to conditions in the vicinity of the source region (NTS). Also, if different travel-time tables are used, the average error is unchanged, but a significantly different pattern of locations is obtained.

2. Depth-restrained location errors, again using all available stations but with anomaly corrections determined from a few calibration events, are reduced to 2.5-3.0 km. Comparing

these results with those of a previous study (Chiburis, 1968), the same average error of 2.5-3.0 km is achievable regardless of the network used. In the present study, two- and three-quadrant networks are used, and the average error without anomalies is 7 km. In the previous study, many of the networks were single quadrant, and the average error without anomalies was about 25 km. However, when anomalies are applied the average error remains the same, and network stability is less a factor in producing location errors.

3. The size of the area at NTS across which the anomalies are valid is at least 25 km by 70 km as evidenced by the comparable location errors obtained at separated sub-regions within NTS. This implies that the task of calibrating other specific regions of interest would not be formidable.

4. If average anomalies are used, instead of those from a few calibration events, the location errors can be reduced to approximately 2 km. This represents the best possible teleseismic accuracy for NTS events.

5. Unrestrained-depth solutions, without applying anomalies, yield depth errors of about 70 km and epicenter errors of about 17 km. All of

the depth errors are positive (solutions too deep) for the networks involved.

A linear relationship is observed between the least-squares standard deviation σ of time errors of a <u>restrained</u> solution and the depth error dz of the corresponding <u>unrestrained</u> solution: dz(km) = 75σ (sec).

6. Unrestrained-depth solutions obtained with the application of anomalies yield depth errors of about 15 km and epicenter errors of 4 km, improvement factors of about five and four, respectively, over the no-anomaly solution.

A linear relationship is no longer observed between σ and dz, the relation now appearing random; hence, the anomalies effectively remove the NTS "depth bias".

7. Relative accuracy (precision) is unchanged, even if the calibration events are deliberately mislocated by 140 km; that is, if anomalies are determined from an event having an assumed-correct location, the location errors of subsequent events relative to the calibration event remains 2.5-3.0 km with the anomalies applied, regardless where the calibration event actually is.

8. When using a network composed of the same stations for an entire set of events, the

resultant "bias" (magnitude and direction of the location shifts) is a consistent and unique function of that network; when another constant network is used to locate the same events, an entirely different "bias" emerges. The apparent lack of a common bias eliminates the source region as the principal cause of the anomalies.

Location bias may then be considered in large measure as the result of slight lateral and vertical inhomogeneities within the mantle between the source and receiver, the effects of which are integrated along the entire path.

9. If a constant network is used, the relative locations obtained without anomalies are identical to those obtained with anomalies, except for a bias translation appropriate for that network. Therefore, anomalies need not be applied for precise location work, if the requirement of always using the same network is not too stringent.

10. Station anomalies determined from explosions occurring in regions other than NTS show large differences when compared to NTS, some exceeding 6 sec.

When using the NTS anomalies to locate these other events essentially no improvement is made in the solutions: the average error without anomalies for seven events not in the NTS area is 20.2 km and with anomalies 20.8 km. In general, it is better to apply no anomalies at all rather than the wrong ones.

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13 ABSTRACT

A location study is made of 28 large underground explosions detonated in the northern area of the Nevada Test Site (NTS). Recording networks were comprised of between 9 and 49 teleseismic stations having two- to three-quadrant distributions.

Errors of locations obtained without applying travel-time anomalies (relative residuals), and with depths restrained to the known values, average about 7 km but are as large as 20 km. With anomalies, the errors are consistently 2.5-3.0 km. The size of the area at NTS across which the anomalies are valid is at least 70 km by 25 km.

Depth errors average 70 km without anomalies and 15 km with anomalies. Without the anomalies, a linear relationship is observed between the least-squares standard deviation, σ, of time errors of the solution obtained when the depth is restrained to its true value and the depth errors, dz, of the corresponding unrestrained solution: $dz(km)=75\sigma$ (sec).

By deliberately mislocating a calibration event approximately 140 km, it is shown that relative accuracy (precision) remains at about 2.5-3.0 km.

If a constant network is used to locate a set of events, the "bias" is a consistent and unique function of that network. The lack of a common bias among networks with similar azimuthal distributions definitely eliminates the source region as the principal cause of the anomalies. Alternatively, the anomalies may be attributed to slight lateral and vertical inhomogeneities within the mantle between the source and receiver, the effects of which are integrated along the entire path.

Furthermore, when constant networks are used, the relative locations obtained without anomalies are identical to those obtained with anomalies, except for a bias translation appropriate for that network.

Finally, it is shown that station anomalies determined from explosions occurring in regions other than NTS do not agree with those at NTS. It is demonstrated that, in general, it is better to apply no anomalies at all rather than the wrong ones.

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