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A SEISMIC STUDY OF TRAVEL-TIME ANOMALIES, NETWORK EFFECTS AND LOCATION TECHNIQUES IN THE ALEUTIAN ISLANDS

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A study is made of a set of well-recorded Aleutian Islands earthquakes and the nuclear explosion LONG SHOT. Whereas past studies of travel-time anomalies and location errors have been based on seismic signals from explosions, the main object of the current study has been to extend our working principles to seismic data from earthquakes. Using a selected teleseismic station network, travel-time anomalies were computed and various techniques applied to achieve location consistency across the entire region. Basically, the techniques involve deriving space functions for the observed station anomalies and imposing the following criteria for success: tight clusters of locations for each event made with network subsets, acceptably low standard deviations from the least-squares solutions, and reasonable station anomaly functions.

Using LONG SHOT as a bias control point, a set of segmented constant anomalies were derived for the network of stations used. Neglecting depth, the relative location accuracy is believed to be about 5 km; standard deviations of solutions generally were reduced to less than [illegible] sec, a value accepted as being due to reading and timing error. Compared with published locations, the events in the Rat Islands and Near Islands as a result of applying the technique shift [illegible] km southerly, and those in the Fox Islands and Andreanof Islands shift 10-20 km southerly.

To demonstrate the difficulties of locating events in the Aleutian Islands, well-distributed sub-networks of a 329-station network were used to locate LONG SHOT. The locations obtained, all of which would have been accepted as not unusual because of network coverage, exhibit errors as large as 45 km with two-quadrant networks and 160 km with single-quadrant networks; travel-time anomalies computed from the various solutions have a range of more than [illegible] sec at station [illegible].

To verify the techniques used, a study is also made of a set of hypothetical events and station anomaly functions. It is shown that (1) even though a constant network is used and a constant anomaly is the only error, relative accuracy may suffer due to a network effect caused by the nonlinear travel-time/distance relationships; and (2) the techniques of functionalizing the station anomalies are valid and could be implemented as recommended for studies in selected regions.

14. KEY WORDS

Event Location
Location Bias
LONG SHOT

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ABSTRACT

A study is made of a set of well-recorded Aleutian Islands earthquakes and the nuclear explosion LONG SHOT. Whereas past studies of travel-time anomalies and location errors have been based on seismic signals from explosions, the main object of the current study has been to extend our working principles to seismic data from earthquakes. Using a selected teleseismic station network, travel-time anomalies were computed and various techniques applied to achieve location consistency across the entire region. Basically, the techniques involve deriving space functions for the observed station anomalies and imposing the following criteria for success: tight clusters of locations for each event made with network subsets, acceptably low standard deviations from the least-squares solutions, and reasonable station anomaly functions.

Using LONG SHOT as a bias control point, a set of segmented constant anomalies were derived for the network of stations used. Neglecting depth, the relative location accuracy is believed to be about 5 km; standard deviations of solutions generally were reduced to less than 0.25 sec, a value accepted as being due to reading and timing error. Compared with published locations, the events in the Rat Islands and Near Islands as a result of applying the technique shift 20-30 km southerly, and those in the Fox Islands and Andreanof Islands shift 10-20 km southerly.

To demonstrate the difficulties of locating events in the Aleutian Islands, well-distributed sub-networks of a 329-station network were used to locate LONG SHOT. The locations obtained, any of which would have been accepted as not unusual because of network coverage, exhibit errors as large as 45 km with two-quadrant networks and 160 km with single-quadrant networks; travel

time anomalies computed from the various solutions have a range of more than 11 sec at station NP-NT.

To verify the techniques used, a study is also made of a set of hypothetical events and station anomaly functions. It is shown that (1) even though a constant network is used and a constant anomaly is the only error, relative accuracy may suffer due to a network effect caused by the nonlinear travel-time/distance relationships; and (2) the techniques of functionalizing the station anomalies are valid and could be implemented as recommended for studies in selected regions.

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INTRODUCTION

The main purpose of the present study is to apply to earthquakes those techniques known to be valid for accurately locating underground explosions within a small region using travel-time anomalies and teleseismic networks. Additionally, we hope to demonstrate techniques for extending the region over which functional station anomalies can be derived so as to provide more accurate locations than those obtained from simple least-squares schemes.

Heretofore, most seismic studies dealing with travel-times, location accuracies, and "station corrections" have used explosions to provide the event data set, because only then can one be certain of the hypocenter and, hence, of actual travel times, origin times, station anomalies, and the effects of an inadequate earth model. Such studies could meaningfully investigate time deviations on the order of 0.2-0.3 sec. Should one include earthquakes in the data set, conclusions regarding location accuracy and travel-time anomaly stability from one region to another always remain in question. This stems from the fact that errors in the location of an event assumed correct can produce errors 10-20 times the size of the time anomaly or of the anomaly change one is trying to observe (Chiburis and Dean, 1965; Chiburis, 1966).

Earthquakes have been used generally to obtain first-order effects of inhomogeneity, principally in the vertical velocity distribution of the earth compared to a standard earth model. Two such models are presently in common use: the Herrin (1968) model and the classical Jeffreys-Bullen model. A number of other models have been proposed (e.g., Archambeau et al., 1969) to provide finer details in the velocity distribution usually emphasizing one or more low-velocity layers or transition zones not included in the Herrin and Jeffreys-Bullen models.

It is now clear that even these improved models are inadequate to give time-distance relations sufficiently accurate for locating large events much better than 20-25 km on the average. For small events, and correspondingly larger reading errors, the location errors can easily be 50 km or more.

Among others, Chiburis and Ahner (1970) pointed out, that the probable causes of the time anomalies are due to unknown lateral inhomogeneities in the mantle (all the way down to the core) and to complexities in the upper mantle and crust in the vicinity of the recording stations. It is doubtful that we will ever be able to devise a three-dimensional world model accurate enough to account for observed anomalies. However, in special cases one does not need a completely accurate model simply in order to locate events: anomalies can be determined from an explosion with known location and applied to subsequently recorded explosions in the same region. In this way, locations can be obtained with an absolute accuracy of 2-3 km (Chiburis, 1968). In fact, the exact location of the calibration event is immaterial; the accuracy of other events relative to it remains the same (Chiburis and Ahner, 1970). As a result of doing this for many regions, valuable information about the spatial patterns of event occurrence and the distribution of energy release could be provided. Most important, perhaps, is that location consistency among many events could be achieved, region by region, with the result that fewer events would have to be specially analyzed or would have to be excluded from bulletins simply because of poor time fits; furthermore, those events included would display significantly smaller station time errors. That such results are achievable when locating explosions has been demonstrated by (among others) Chiburis (1968) and Chiburis and Ahner (1969) and (1970).

However, if earthquakes are excluded from analysis of location techniques and of model inhomogeneities, the number of regions available for study is severely limited and the results are apt to be less general. Also, explosions are usually detonated in such widely separated regions that the large variations observed in the anomalies between regions sometimes cannot be assessed. Since anomalies at a given station are known to change significantly over epicentral distances of several hundred kilometers, it is almost certainly invalid to determine anomalies from two regions a thousand kilometers or more apart, linearly interpolate between them, and hence obtain anomalies having any significance for understanding mantle inhomogeneities.

The principal difficulty with using earthquakes is that the determination of a travel-time anomaly requires an event location in space: latitude, longitude, and depth. Knowledge of the origin time is unnecessary. Although several event lists are available which provide hypocenters from which anomalies can be calculated for any network, the location parameters have been determined with sets of stations differing in number, in kind, and in reliability and quality of recording; and with widely different earth models. Thus with such an event set, the station anomalies computed are usually not consistent, even for earthquakes occurring in a single region; for earthquakes occurring in adjacent regions, the anomalies agree hardly at all. For explosions, reproducibility has been verified many times in several different regions (e.g., Chiburis and Ahner, 1970). There is no known reason (other than mislocation) why earthquakes should yield inconsistent anomalies, but explosions consistent ones.

However, a study of earthquake anomalies need not be deterred if one is aware of the effects that mislocations can produce, and if the conclusions drawn are understood in that context. The objectives of the present study are: (1) to demonstrate that location and anomaly consistency can be achieved despite mislocation; and (2) to gain improvement in the relative locations of earthquakes throughout the Aleutian Islands region. Our criteria for success are location and anomaly consistency.

By <u>location consistency</u>, we mean that an event location obtained with a well-distributed network must agree within 5 km with the locations obtained with well-distributed subsets of the initial network. It must also be true that the least-squares time residuals of the several network solutions for the event reduce to levels generally accepted as being due to reading and timing error.

By <u>anomaly consistency</u>, we mean that the anomalies at a station must change across the Aleutian Islands in a physically plausible way, and that the set of anomaly functions derived for a network must produce location consistency.

The sequence of steps through which the report progresses to achieve the desired result is as follows. First, it is demonstrated that the location errors obtained by using different networks vary widely in magnitude and direction when locating the LONG SHOT explosion in the Aleutian Islands.

Therefore, a constant network is selected to locate a set of events across the Aleutians by (1) using no anomalies; (2) using the LONG SHOT anomalies; (3) using a linear anomaly function for each station (based on the reported locations); (4) using a linear anomaly function doubly constrained by an earthquake in the Fox Islands and the LONG SHOT explosion; (5) using a segmented linear anomaly function constrained by four events equally spaced across the Aleutians; and (6) repeating the last step but translating the function to remove the observed LONG SHOT bias. Finally, instead of allowing the anomalies to vary continuously between constants, the anomaly function is assigned either two or three constant values across the entire Aleutians. Each of the steps, increasingly more complex, provides for some improvement in location consistency and all are presented to illustrate the method of analysis for a region as large as the Aleutian Islands.

In order to verify the results obtained above, a set of synthetic data for a hypothetical earth model is analyzed; it is shown that the same order of consistency is achieved when the technique is applied to the synthetic data as it was to the real data.

DESCRIPTION OF THE DATA

A set of well-recorded earthquakes from the Aleutian Islands region, which includes the Fox Islands, Andreanof Islands, Rat Islands, and Near Islands, was selected to form our data base. The event set (Table I) is composed of 108 earthquakes and two explosions ranging in magnitude from 4.3 to 6.5. The earthquake parameters given under the "NOS" column are those reported on the National Ocean Survey (NOS) Preliminary Determination of Epicenters cards. The location parameters of LONG SHOT, an underground nuclear explosion on Amchitka Island in the Rat Islands, are those released by the Atomic Energy Commission. The location parameters of FLEXBAG, an underwater explosion detonated about 65 km southwest of Amchitka Island (Chiburis and Ahner, 1969, for a seismic analysis), are those reported by Kos and Kennedy (1969). A plot of the epicenters is shown in Figure 1.

A teleseismic network of 54 stations, well distributed in distance and azimuth, was selected (Table II); of these, 18 are World Wide Standard Seismic Stations (WWSS), 28 are Long Range Seismic Measurement (LRSM) stations, four are Geneva-type Observatories, and four are F-ring stations at the Large Aperture Seismic Array (LASA) in Montana. Arrival times were read for those events recorded at the LRSM stations and observatories; arrival times for the WWSS stations were taken from the Earthquake Data Reports (EDR) published by NOS.

TABLE I

Hypocenter Information of 110 Selected Aleutian Islands Events

pP Quality—(1) Depth Well Observed, (2) Probable pP, Poor, (3) No Observation.

*See Table I[illegible]
**See Table I[illegible]
***See page 1[illegible]

Event Number	Date	Region	[illegible] Latitude	[illegible] Longitude	[illegible] Depth km	[illegible] Number of Reporting Stations	mb	Adjusted Latitude	Adjusted Longitude	Adjusted Depth km	Adjusted Number of Reporting Stations	pP Quality	Shift from [illegible] Location to Adjusted Location: Distance km	Shift: Azimuth
[illegible]	[illegible] Jun [illegible]	Fox	[illegible]	[illegible]	[illegible]	85	[illegible]	[illegible]	[illegible]	52	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	Fox	[illegible]	[illegible]	33	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible] Mar [illegible]	Fox	[illegible]	[illegible]	[illegible]	[illegible]	4.8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible] Mar [illegible]	Fox	[illegible]	[illegible]	33	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	Fox	[illegible]	[illegible]	24	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	46	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	31	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4.4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4.9	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	45	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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[illegible]	[illegible]	And	51.960N	[illegible]	49	[illegible]	[illegible]	[illegible]	[illegible]	43	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	And	[illegible]	[illegible]	[illegible]	[illegible]	5.0	[illegible]	[illegible]	33	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	And	[illegible]	[illegible]	[illegible]	[illegible]	5.4	[illegible]	[illegible]	43	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	And	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	49	[illegible]	[illegible]	[illegible]	145.9
[illegible]	[illegible] Mar [illegible]	And	[illegible]	[illegible]	[illegible]	[illegible]	4.9	[illegible]	[illegible]	30	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	And	[illegible]	[illegible]	34	[illegible]	[illegible]	[illegible]	177.013E	[illegible]	[illegible]	[illegible]	[illegible]	36.3
[illegible]	[illegible]	And	[illegible]	[illegible]	[illegible]	33	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible] Mar [illegible]	And	[illegible]	178.340E	[illegible]	[illegible]	4.4	[illegible]	[illegible]	45	[illegible]	[illegible]	[illegible]	31.9
[illegible]	[illegible] Mar [illegible]	And	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	36	[illegible]	[illegible]	[illegible]	184.2
[illegible]	[illegible] Jun [illegible]	And	[illegible]	[illegible]	46	[illegible]	3.9	[illegible]	[illegible]	38	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible] Mar [illegible]	And	[illegible]	[illegible]	38	19	5.2	51.401N	[illegible]	32	19	[illegible]	3.41	[illegible]
[illegible]	[illegible] Jun [illegible]	And	[illegible]	[illegible]	34	24	5.1	51.452N	178.364E	30	24	[illegible]	1.34	143.4
[illegible]	[illegible] Dec [illegible]	And	[illegible]	178.930E	31	24	5.0	51.483N	178.883E	45	14	[illegible]	[illegible]	[illegible]
[illegible]	[illegible] Feb [illegible]	And	[illegible]	[illegible]	89	[illegible]	5.2	51.920N	178.924E	95	39	[illegible]	[illegible]	89.5
[illegible]	[illegible] Sep [illegible]	And	[illegible]	[illegible]	[illegible]	[illegible]	4.8	51.242N	179.044E	50	[illegible]	[illegible]	[illegible]	[illegible]
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[illegible]	[illegible]	And	[illegible]	179.380E	[illegible]	[illegible]	[illegible]	51.174N	[illegible]	35	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	And	51.430N	[illegible]	46	[illegible]	[illegible]	51.394N	[illegible]	45	[illegible]	[illegible]	4.33	[illegible]
[illegible]	[illegible]	And	[illegible]	179.030E	40	[illegible]	[illegible]	[illegible]	[illegible]	55	[illegible]	[illegible]	[illegible]	113.5
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[illegible]	15 Nov [illegible]	And	[illegible]	179.940E	43	33	[illegible]	51.362N	[illegible]	50	33	[illegible]	[illegible]	[illegible]
[illegible]	[illegible] Jun [illegible]	And	51.330N	179.990E	[illegible]	48	[illegible]	[illegible]	179.996E	[illegible]	[illegible]	[illegible]	[illegible]	103.2
[illegible]	[illegible] Oct [illegible]	Long Shot	[illegible]	[illegible]	[illegible]		5.8	Same Input Location As USC&GS						
[illegible]	14 Apr [illegible]	Rat	[illegible]	178.970E	36	[illegible]	[illegible]	[illegible]	179.093E	45	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible] Nov [illegible]	Rat	[illegible]	[illegible]	168	[illegible]	4.3	51.753N	[illegible]	188	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible] Sep [illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	Same Input Location as USC&GS						
[illegible]	[illegible]	Rat	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	51.321N	[illegible]	43	[illegible]	[illegible]	4.44	[illegible]
[illegible]	[illegible] Jan [illegible]	Rat	[illegible]	[illegible]	42	20	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	11.39	53.4
[illegible]	14 Nov [illegible]	Rat	[illegible]	[illegible]	123	38	[illegible]	[illegible]	[illegible]	[illegible]	38	[illegible]	[illegible]	[illegible]
[illegible]	[illegible] Mar [illegible]	Rat	51.410N	[illegible]	45	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	216.5
[illegible]	[illegible] Apr [illegible]	Rat	51.520N	[illegible]	33	[illegible]	[illegible]	51.516N	[illegible]	45	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	Rat	[illegible]	[illegible]	28	[illegible]	[illegible]	51.774N	[illegible]	65	[illegible]	[illegible]	[illegible]	161.5
[illegible]	[illegible] Dec [illegible]	Rat	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	80.9
[illegible]	[illegible] Mar [illegible]	Rat	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	93.2
[illegible]	[illegible] Dec [illegible]	Rat	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	33	[illegible]	[illegible]	0.49	[illegible]
[illegible]	[illegible] Dec [illegible]	Rat	[illegible]	[illegible]	33	[illegible]	5.4	[illegible]	[illegible]	33	[illegible]	3	1.56	[illegible]
[illegible]	[illegible] Dec [illegible]	Rat	51.479N	[illegible]	33	[illegible]	[illegible]	[illegible]	[illegible]	33	[illegible]	3	[illegible]	342.5
[illegible]	[illegible] Sep [illegible]	Rat	[illegible]	[illegible]	[illegible]	[illegible]	4.4	[illegible]	[illegible]	33	[illegible]	3	[illegible]	32.1
[illegible]	[illegible] Jan [illegible]	Rat	[illegible]	[illegible]	42	[illegible]	[illegible]	51.344N	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	194.0
[illegible]	[illegible] Mar [illegible]	Rat	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	329.4
[illegible]	[illegible] Mar [illegible]	Rat	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	55	[illegible]	3.53	199.4
[illegible]	[illegible] Feb [illegible]	Rat	[illegible]	[illegible]	[illegible]	43	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible] Jan [illegible]	Near	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	174.275E	[illegible]	[illegible]	[illegible]	[illegible]	356.9
[illegible]	[illegible]	Near	[illegible]	[illegible]	[illegible]	[illegible]	5.3	[illegible]	174.194E	[illegible]	[illegible]	[illegible]	[illegible]	333.9
100	[illegible]	Near	[illegible]	[illegible]	43	[illegible]	[illegible]	[illegible]	174.185E	[illegible]	[illegible]	[illegible]	[illegible]	354.0
[illegible]	[illegible]	Near	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	52.455N	173.544E	[illegible]	[illegible]	[illegible]	3.43	[illegible]
[illegible]	[illegible]	Near	[illegible]	[illegible]	36	33	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	Near	[illegible]	[illegible]	29	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible] Mar [illegible]	Near	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	10.84	[illegible]
[illegible]	[illegible]	Near	[illegible]	[illegible]	65	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	Near	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	Near	[illegible]	[illegible]	25	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	44	[illegible]	[illegible]	[illegible]
[illegible]	[illegible] Jan [illegible]	Near	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	44	[illegible]	[illegible]	320.1
[illegible]	[illegible]	Near	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	Near	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	20	[illegible]	[illegible]	3.93	[illegible]

TABLE 1b

• THE FOLLOWING EVENTS WERE OUTSIDE THE GEOGRAPHIC REGION USED IN THIS STUDY

Event Number	Date	Region	NOS Latitude	NOS Longitude	NOS Depth km	NOS Number of Reporting Stations	M	Adjusted Latitude	Adjusted Longitude	Adjusted Depth km	Adjusted Number of Reporting Stations	pP Quality	Shift from NOS Location to Adjusted Location: Distance km	Shift: Azimuth
7	18 May 68	Fox	53.784N	168.318W	131	36	4.5	53.696N	168.361W	120	36	2	9.76	196.2°
15	04 Dec 65	Fox	51.260N	170.610W	18	13	5.5	51.225N	170.706W	55	13	2	7.79	239.6
17	13 Jan 68	Fox	52.740N	171.230W	34	92	5.5	52.681N	171.294W	20	92	2	7.90	213.4
19	07 Aug 66	Fox	50.580N	171.330W	39	89	6.5	50.571N	171.338W	39	88	3	1.15	211.0
21	27 Oct 68	Fox	53.597N	171.410W	201	24	4.5	53.501N	171.452W	201	24	3	11.40	194.1
29	11 Nov 68	And	52.820N	175.017W	222	39	4.8	52.754N	175.053W	225	39	1	7.68	197.0
34	21 Feb 68	And	51.380N	176.000W	47	84	5.2	51.321N	176.087W	47	82	3	8.93	222.9
36	11 Dec 66	And	52.940N	176.130W	216	29	5.2	52.814N	176.233W	225	29	1	15.62	206.5
43	10 Mar 68	And	52.140N	177.260W	7	43	5.4	52.044N	177.233W	15	43	2	10.82	170.3
44	14 Dec 66	And	52.860N	177.620W	243	37	5.3	52.776N	177.624W	250	36	1	9.33	181.8
49	13 May 68	And	52.176N	178.543W	139	34	4.6	52.127N	178.493W	150	34	2	6.70	1[illegible]1.3
61	11 Aug 68	And	52.078N	179.949W	159	78	5.5	52.072N	179.947W	170	78	2	0.97	165.8
63	11 Dec 68	Rat	52.041N	179.501E	145	29	4.6	52.014N	179.556E	150	29	2	4.80	27.4
67	05 Aug 67	Rat	52.080N	178.430E	163	19	4.5	52.230N	178.742E	175	18	1	27.10	51.9
73	14 Oct 68	Rat	52.215N	178.348E	104	24	4.7	52.164N	178.402E	110	24	2	6.26	145.3
77	11 Mar 68	Rat	52.050N	178.170E	121	31	5.2	52.030N	178.265E	140	28	1	6.92	108.7
78	01 Oct 65	Rat	50.110N	178.250E	32	77	6.3	50.104N	178.229E	30	74	2	1.69	245.5
81	06 Dec 65	Rat	50.640N	177.390E	37	19	5.1	50.702N	177.491E	40	19	1	9.97	45.8
82	25 Oct 68	Rat	50.616N	177.389E	23	37	5.1	50.649N	177.456E	45	37	1	5.69	55.4
87	02 Jun 66	Rat	51.080N	175.970E	41	47	6.0	51.053N	175.955E	40	43	1	3.17	199.3
97	26 Feb 68	Near	51.080N	174.640E	33	33	4.7	51.197N	174.550E	45	33	1	14.50	334.2

TABLE 1c

•• THE FOLLOWING NINE EVENTS WERE SET ASIDE FOR A SPECIAL STUDY AT A LATER DATE

Event Number	Date	Region	NOS Latitude	NOS Longitude	NOS Depth km	NOS Number of Reporting Stations	M	Adjusted Latitude	Adjusted Longitude	Adjusted Depth km	Adjusted Number of Reporting Stations	pP Quality	Distance km	Azimuth
2	07 Nov 68	Fox	53.772N	165.717W	60	39	4.7	53.604N	165.766W	15	36	2	18.78	189.3
32	11 Sep 68	And	50.364N	175.958W	29	30	4.7	50.348N	176.034W	30	30	1	5.41	255.4
41	05 Nov 68	And	52.606N	176.711W	170	18	4.5	52.511N	176.916W	170	18	1	17.81	231.6
68	08 Nov 67	Rat	51.030N	178.700E	33	17	4.3	51.119N	178.690E	35	17	2	9.99	355.9
69	08 Nov 67	Rat	51.050N	178.570E	42	33	4.7	51.028N	178.555E	40	31	2	2.66	204.0
70	08 Nov 67	Rat	51.120N	178.520E	29	78	5.3	51.084N	178.509E	20	21	1	4.03	191.2
71	08 Nov 67	Rat	51.070N	178.420E	10	55	5.2	51.055N	178.415E	20	54	1	2.46	134.4
72	08 Nov 67	Rat	51.140N	178.420E	32	29	4.6	51.122N	178.436E	40	28	2	2.29	150.1
92	11 Nov 65	Rat	51.690N	176.220E	104	12	5.0	51.372N	175.568E	45	12	2	57.46	232.3

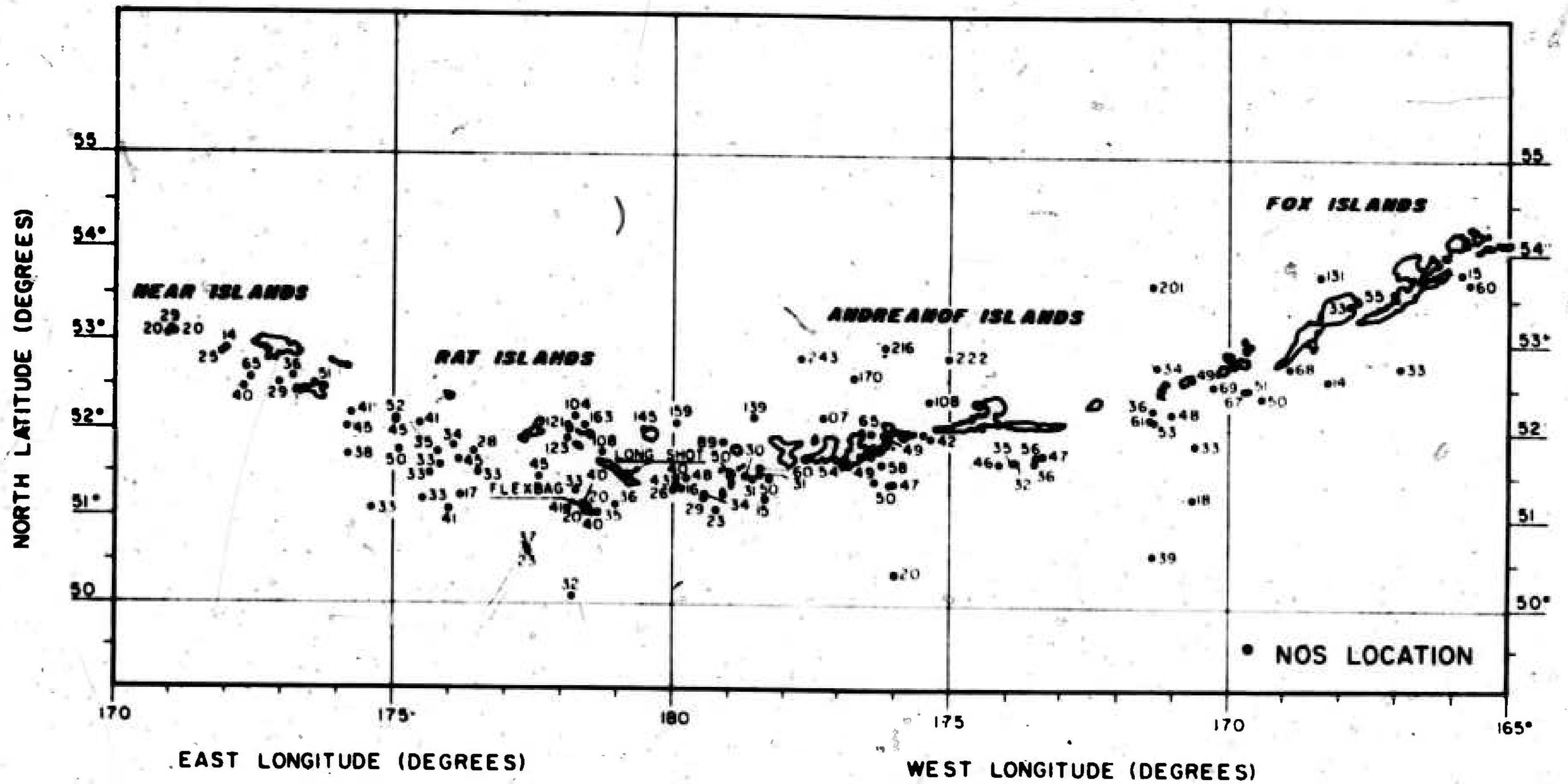

Figure 1. Geographic location map of selected Aleutian Island events. Numbers adjacent to locations are NOS reported depths.

DETERMINATION OF TRAVEL-TIME ANOMALY

As used in this report, the travel-time anomaly at station i relative to station j is defined as

$$A_{ij} = T_i - T_j - H_i + H_j$$

where T is observed arrival time and H is the travel time predicted from some established models. This definition has been used previously (e.g., Chiburis and Dean, 1965; Chiburis, 1966, 1968). In discussing travel time anomalies for a given network of stations, we refer travel times at all stations to that of a given station of the network. In other words, i varies and j remains constant.

Travel-time anomalies were computed using the Herrin (1968) tables for all the events in Table I and for those stations in Table II recording the events. Initially, the input latitudes, longitudes, and depths, necessary for calculating the predicted times, were those in Table I reported by NOS.

Plots of the anomalies for two selected stations relative to UBO are shown in Figures 2a and 2b as a function of longitude across the Aleutians. No implication is made as to the longitude parameter being of significance; it is mere convenience.

The variability observed in Figures 2a and 2b is far greater than expected: the anomalies are known to change as a function of event position, but not in the erratic manner shown. If the results in these two Figures were representative of actual anomaly profiles, the problem of calibrating seismic regions to the degree necessary for accurate location work would be almost impossible.

If it is assumed that the station anomalies are reasonably constant within a region, that they change only slowly if at all

TABLE II

INITIAL TELESEISMIC NETWORK. DISTANCES AND AZIMUTHS ARE FROM LONG SHOT.

LRSM	Distance (In Degrees)	Azimuth (In Degrees)
AD-IS	2.6	78.8
FB-AK	21.5	38.6
WH2YK	26.7	51.8
SI-BC	31.8	62.5
NP-NT	34.0	22.0
PG-BC	34.6	62.4
JP-AT	37.4	62.4
YR-CL	40.2	80.6
PH-WA	40.9	71.3
SW-MA	42.7	65.1
HL2ID	44.1	73.1
HV-MA	44.2	64.7
MN-NV	44.9	81.3
KN-UT	49.1	79.2
RG-SD	49.5	65.0
RK-ON	51.5	54.0
WN-SD	52.6	65.1
LC-NM	56.0	79.3
CR-NB	56.2	65.6
KC-MO	58.3	65.4
SV3QB	60.8	37.3
GV-TX	61.4	72.3
EN-MO	62.4	64.8
DH-NY	66.8	51.0
HN-ME	66.9	44.1
FN-WV	67.2	56.5
AX2AL	67.8	65.0
BE-FL	73.0	65.0

NOS	Distance (In Degrees)	Azimuth (In Degrees)
ADK	2.7	78.7
COL	21.7	39.0
NBC	34.0	22.1
EDM	39.9	60.0
JAS	43.8	83.5
NOR	46.9	3.2
PAS	47.6	85.9
TUC	53.4	82.3
SOD	59.7	348.1
NUR	66.5	346.6
UPP	68.1	350.1
SHL	68.8	284.6
NDI	75.0	297.2
CTA	76.8	211.6
PRU	78.1	349.9
KHC	79.1	350.4
QUE	79.3	305.4
STU	79.8	353.3

Observatories	Distance (In Degrees)	Azimuth (In Degrees)
LA010	47.2	64.9
F4	46.3	64.4
F3	47.1	66.1
F1	47.3	63.6
F2	48.0	65.3
UBO10	49.0	73.7
TFO60	51.8	80.8
WMO06	59.2	71.8

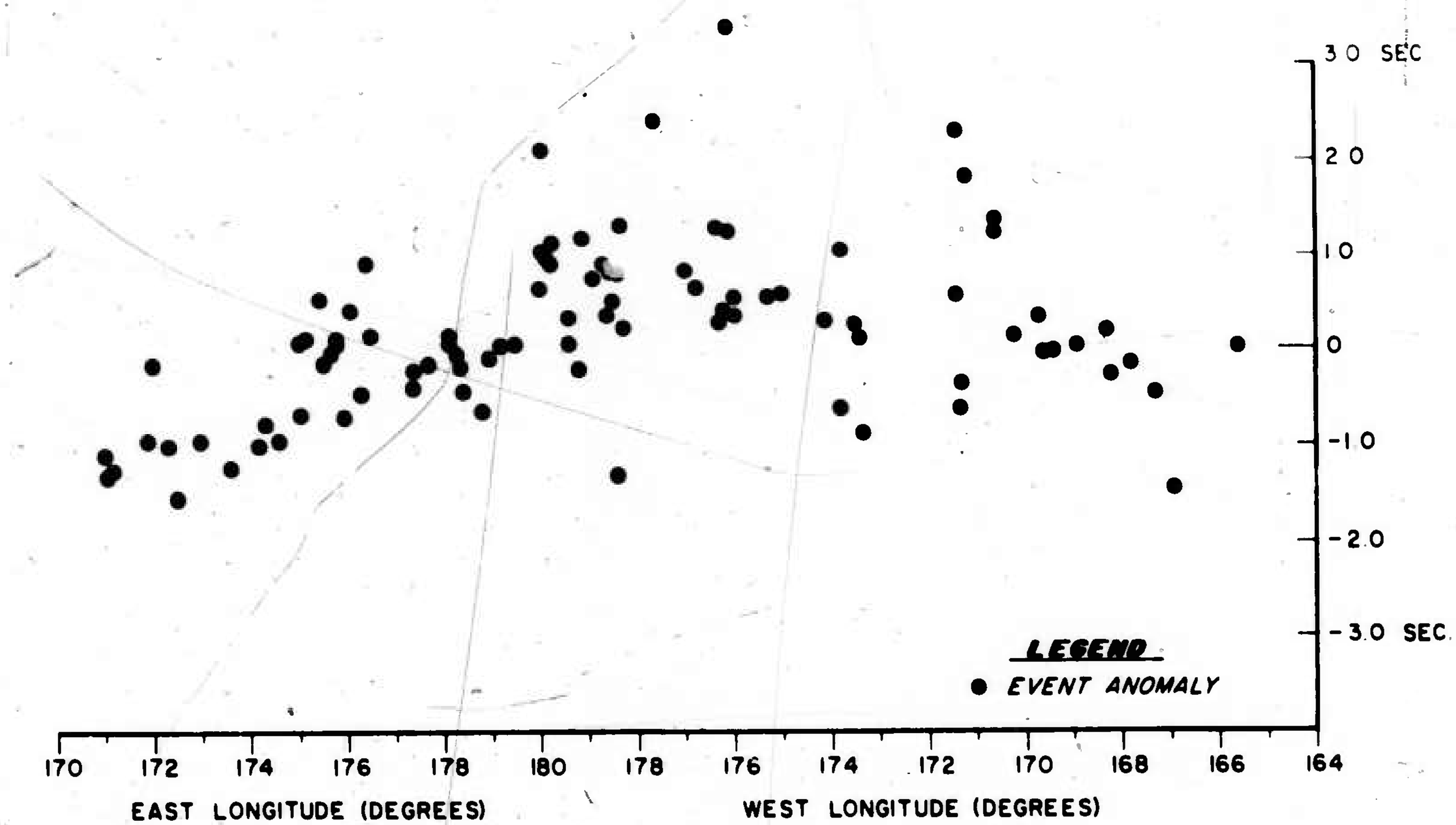

Figure 2a. Anomalies computed from NOS hypocenters for station NP-NT.

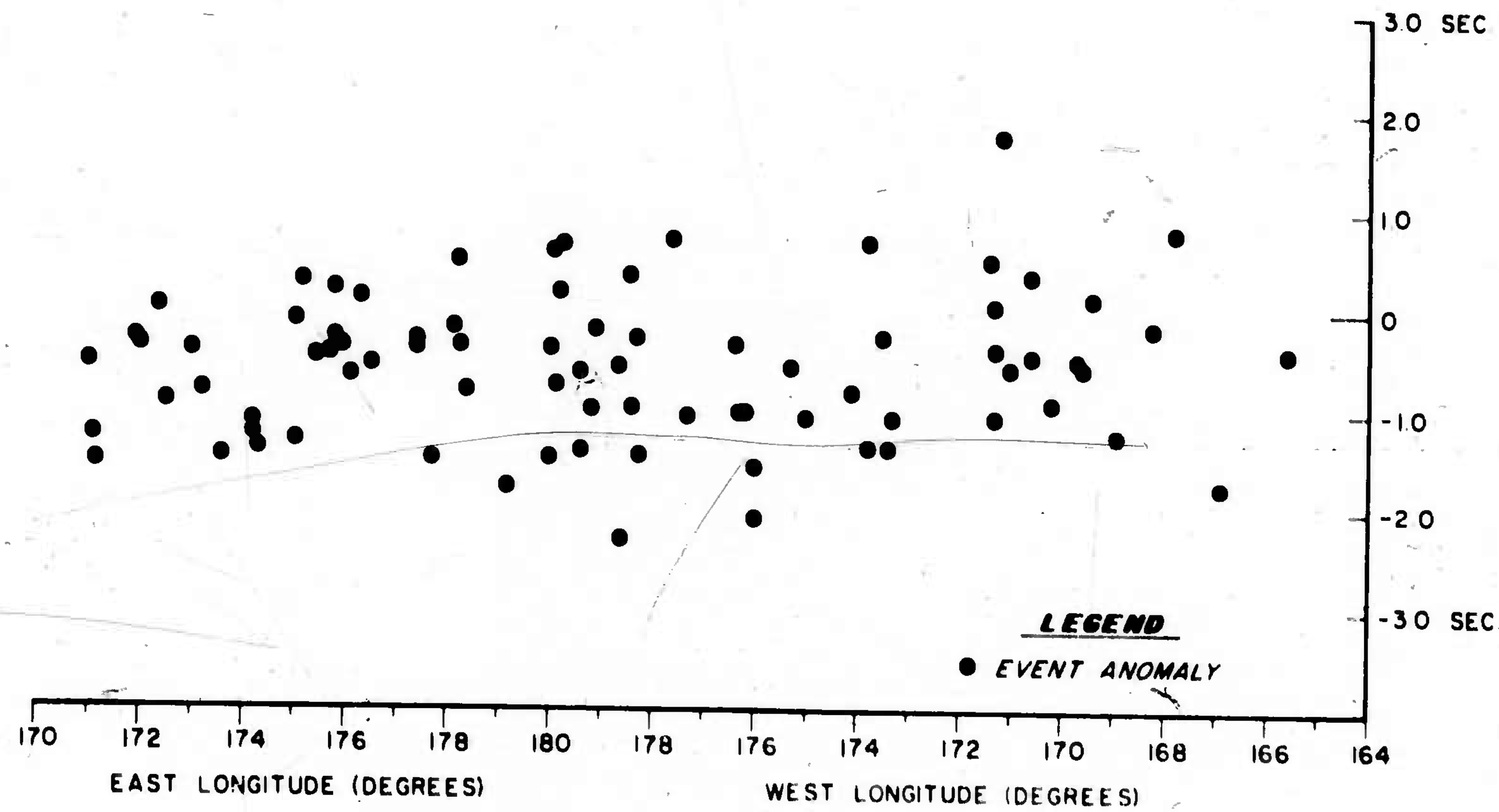

Figure 2b. Anomalies computed from NOS hypocenters for station NUR.

from one region to an adjacent one, and that the arrival times are read correctly to within 0.25 sec, the observed erratic behavior of the anomalies can be attributed only to mislocation of the hypocenter from which travel-times are computed.

It is well established that the anomalies for a station pair separated by a hundred kilometers or less computed from events in a particular region are constant, and that the anomalies vary slowly between adjacent regions (Chiburis and Dean, 1965; Chiburis 1966, 1968; Chiburis and Ahner, 1969, 1970). For example, in Figure 3 the anomalies at stations F4 and E2, relative to station AO at the Large Aperture Seismic Array (LASA) in Montana, are plotted as a function of epicentral distance for events arriving along a northwesterly azimuth. In this figure, the anomalies are virtually constant (within about 0.1 sec) for a particular distance window (anomaly region) and vary smoothly from one region to the next. The effect of any event mislocation in this example would be minimal for the stations used because of the small distances to the reference station AO (97 km for F4 and 69 km for E2) and this fact contributes to the consistency.

That the mislocation effect in computing the anomaly is a function of station pair separation has been discussed by Chiburis and Dean (1965) and by Chiburis 1966. In the latter study it was shown that the maximum anomaly error δA in seconds can be approximated by

$$\delta A \simeq \frac{a \cdot \delta r}{\Delta^2} T$$

where a is the distance in kilometers separating the station and its reference, δr is the event location error vector in km, T is

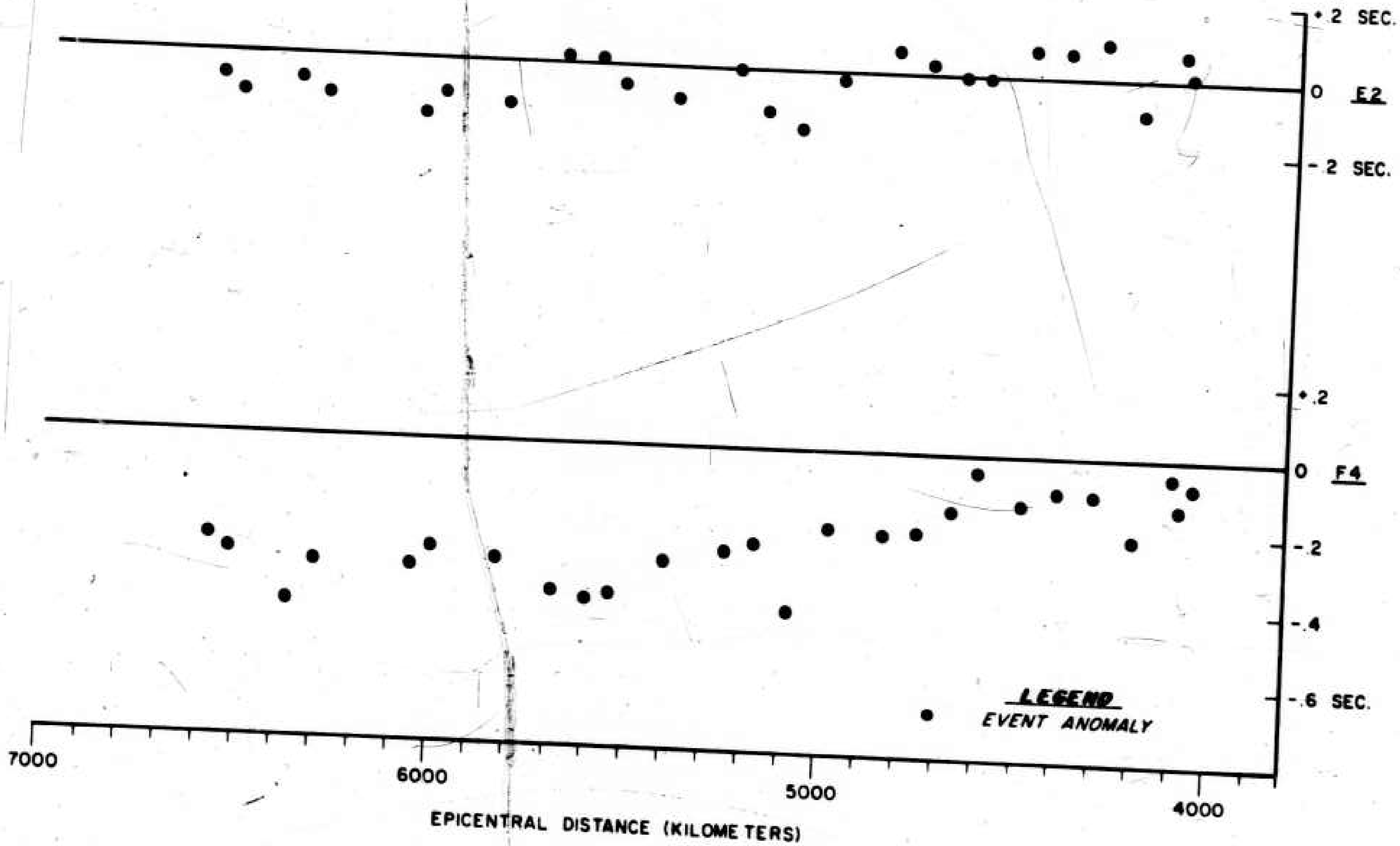

Figure 3. Anomalies vs distance for two LASA subarrays for northwesterly events.

the travel time in seconds, and Δ is the epicentral distance in km to the station pair. Therefore, if an event at a distance of 5,000 km is mislocated by 50 km, the errors in the computed anomalies for F4 and E2 would only be about 0.10 sec and 0.07 sec respectively. On the other hand, if the station-pair separation is 4,000 km, as is the case for NP-NT and UBO in Figure 2, the anomaly error would be about 4 sec. Clearly, even smaller location errors (on the order of 10-20 km) in the proper direction can explain quite large disagreements in the anomalies; such errors are the probable causes of the observed anomaly inconsistencies.

Before the anomaly errors due to epicenter mislocation can be properly assessed, the depths of the events must be known as well as possible. The depths resulting from an unrestrained least-squares solution of P arrival times, without corrections for travel-time anomalies, are known to have an average error of 75 km or more in some regions (Chiburis and Ahner, 1970). Such errors are far too large to permit a sensible determination of travel-time anomaly. The only known way to determine depth unambiguously is to identify the phase pP and restrain the least-squares solution. The selection of pP on an event seismogram recorded at a single station is highly subjective, principally because of signal-generated noise in the P coda and because of energy from a multitude of other phases. However, if a suite of seismograms recorded at different stations which are widely separated in distance and azimuth is aligned on the P wave, time-distance relationships of coherent energy can usually be correlated with distinct phases. Therefore, 110 events in Table I were analyzed in this way. The maximum disagreement with the NOS reported depths in the event set is about 50 km. Although depth errors by themselves do not produce large anomaly changes, the differences in epicenters, had the events been located with restrained depths, can be large and can produce significant anomaly changes. Therefore, all of the events in

Table I were relocated with depths restrained to our values based on pP, but <u>using the same stations</u> as were used by NOS and reported in the EDR. The number of stations varies between 12 and 126, excluding LONG SHOT. The resulting restrained epicenters are given under the "Adjusted" column in Table I. Also included are columns indicating the estimated reliability of the pP time pick and the shift vectors from the NOS locations to the Adjusted locations. The maximum shift is about 40 km, excluding the nine events appearing in Table Ic. (These nine events are unusual in their signal characteristics and in their anomalies; it is believed that they are multiple events, and they will be analyzed in a special study at a later date.) The reasons for the fact that there are slight differences between the number of stations used by SDL and by NOS are as follows: (1) no stations were included which reported PKP arrival times or two P wave arrivals close together; (2) where two stations are located at virtually the same site (e.g., MBC and NP-NT) only one was used.

Recomputing the anomalies from the Adjusted locations for stations NP-NT and NUR yields the anomaly plots shown in Figures 4a and 4b. A comparison of these results with those in Figures 2a and 2b shows essentially no improvement in the functional patterns. If it is assumed that some of the scatter is due to those events not lying within the Aleutian Islands region proper, these events can be separated and so noted by the circled values in Figures 4a and 4b. A total of 21 events was eliminated in this way; they are listed in Table Ib. However, the anomalies still do not show a consistent enough relation across the region to be used for location purposes.

The question of reading errors being the producer of anomaly errors can be only partly answered. Generally, for the LRSM and VELA stations listed in Table II and the examples in Figures 2 and 4,

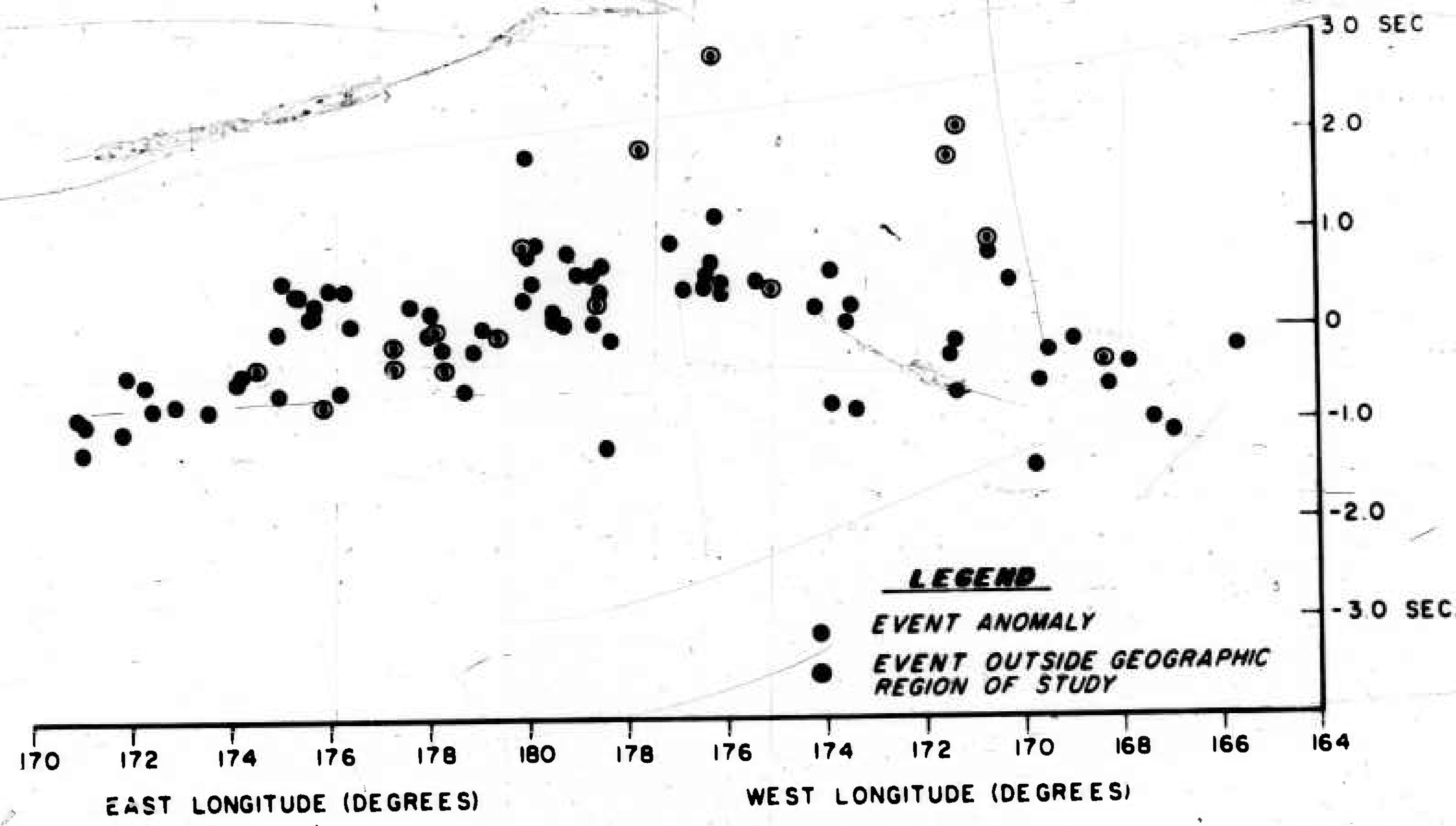

Figure 4a. Anomalies computed from adjusted hypocenters for station NP-NT.

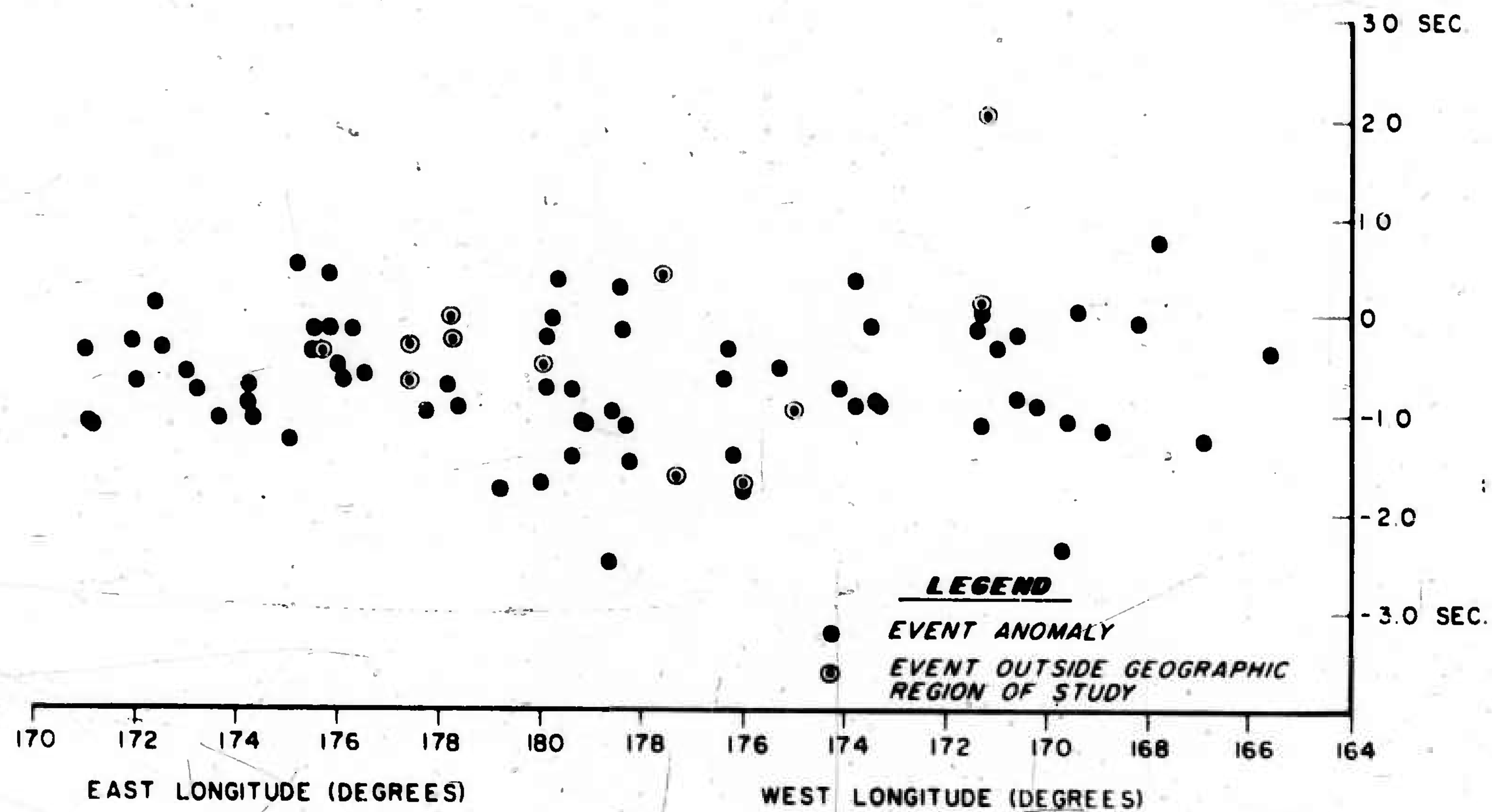

Figure 4b. Anomalies computed from adjusted hypocenters for station NUR.

all arrival times were read by SDL analysts, so reading errors are believed to be acceptably low. Arrival times for other stations were taken from the Earthquake Data Reports published by the NOS. Later in this report we show that these reported times are often in error by as much as one second.

Therefore, the event set in Table I, although largely composed of well-recorded earthquakes, most probably contains location errors of perhaps 30 km, or more and the anomaly inconsistency is not surprising. The possible errors one might encounter when locating events in the Aleutian Islands is demonstrated in the next section.

ERRORS IN LONG SHOT LOCATION USING DIFFERENT STATION NETWORKS

The underground nuclear explosion LONG SHOT was detonated 29 October 1965 on Amchitka Island in the Rat Islands with a yield of 80,000 tons TNT equivalent. P wave signals were well recorded at virtually all distances and azimuths. In their comprehensive report, Lambert et al., (1969) discuss the seismic location made with travel-time data from 329 stations available to them, although probably several hundred more stations recorded the event. The location obtained by restraining the focal depth to the known value and using either the Herrin (1968) or Jeffreys-Bullen tables was approximately 21 km in error to the northwest (Lambert et al., 1969). To now demonstrate the possible variations in location for the Rat Islands region, selected subsets of the 329-station network are taken in different ways and the resultant locations discussed.

First, a network can be defined on the basis of its azimuth aperture or quadrantal coverage. Requiring a minimum aperture of 180°, or two quadrants, and beginning with the sector 0°-180° (northeast and southeast quadrants), all stations within that azimuth range regardless of distance are used to locate. Incrementing the two-quadrant sector by 22.5°, a total of 16 separate locations can be made with networks all having 180° aperture. These results are shown in Figure 5, where the 329-station case is included for comparison, as well as the number of stations for each case, which varies from 57 to 272 stations. The resultant location errors are as small as 13 km and as large as 45 km. There appears to be a preferred shift toward the northwest, suggesting a bias independent of the network although five of the 16 locations shift otherwise.

From the results of this Figure, one can state with some assurance that the epicenters of events in the Rat Islands and

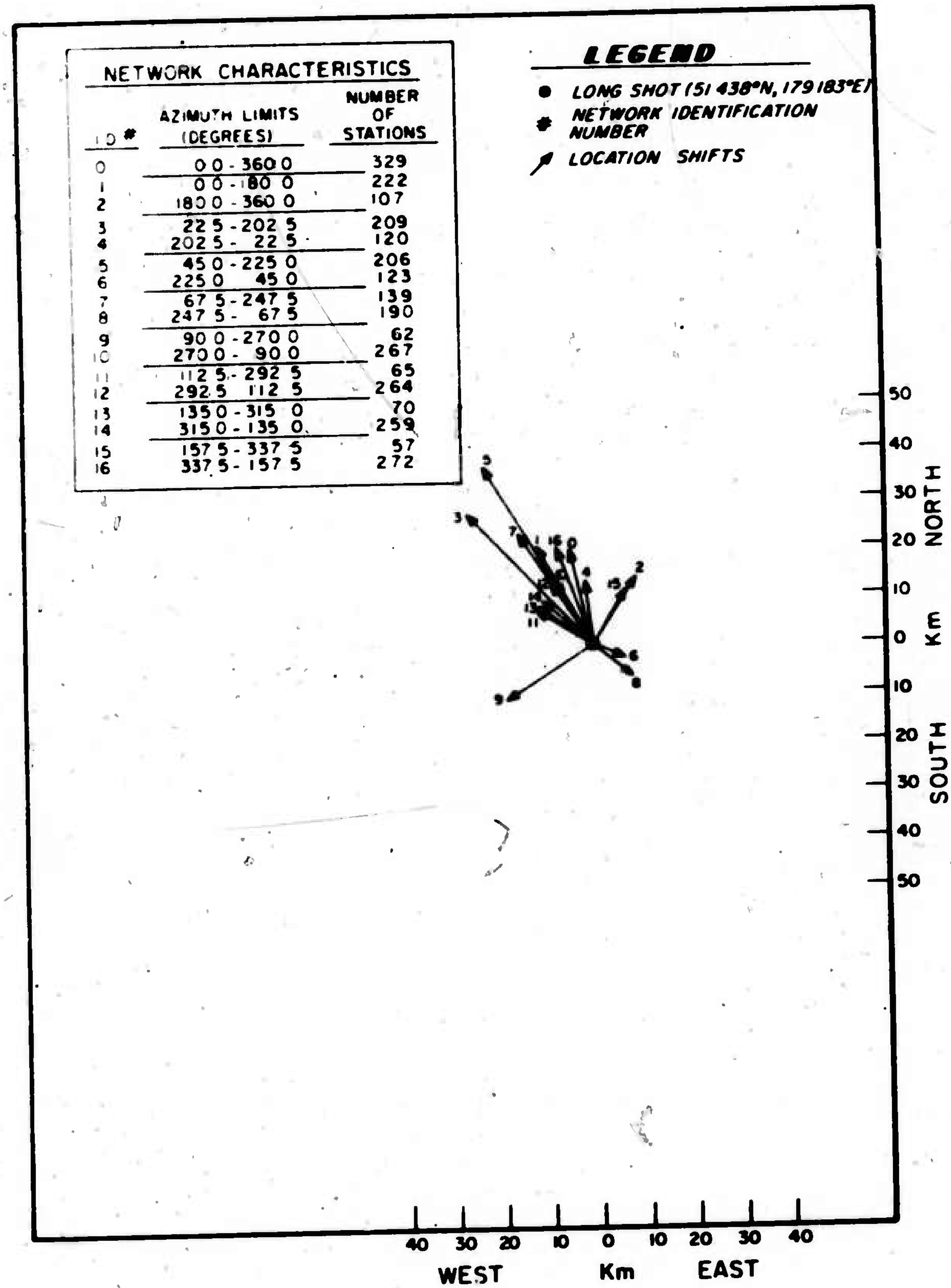

Figure 5. LONG SHOT location errors using two-quadrant networks.

Andreanof Islands (and probably throughout the entire Aleutian Islands) are not known to within 20 km of their true locations, regardless of the distribution or stability of the networks used to locate them. A reiteration of a conclusion previously drawn (Chiburis and Ahner, 1970) is in order: location errors are caused by the set of travel-time anomalies at those stations uniquely defining a particular network; several networks, similarly distributed but composed of different stations, can yield entirely different locations for the same event, even if a randomly selected network sometimes shows a bias due to the source.

If single-quadrant distribution (90° aperture) is accepted as a minimum, instead of two quadrants, and the quadrant is incremented by 22.5°, the resultant locations are shown in Figure 6. The errors now range between 2 km and 163 km, with an average of more than 50 km and no apparent preferred shift direction. The number of stations varies between 22 and 200 with no firm correlation with the size of the error.

If the entire network of 329 stations is now ordered on the basis of increasing azimuth (0° to 360°), and every tenth station of the ordered set is used for locating, a set of nine 32-station networks is obtained, each with approximately four-quadrant coverage. The location results are shown in Figure 7, where a distinct northwesterly error of about 17 km can be observed. This suggests that for the earth model used to compute travel times, those stations that "bear northerly" from LONG SHOT are early in time relative to those stations that "bear southerly". A plot of the zero-mean travel-time anomalies vs azimuth is shown in Figure 8, where the northerly stations, from 340° to 70° azimuth, are indeed seen to be generally early and the southerly stations from 70° to 340° generally late. However, the scatter of the anomalies, even within azimuth windows of 20°-30°, approaches

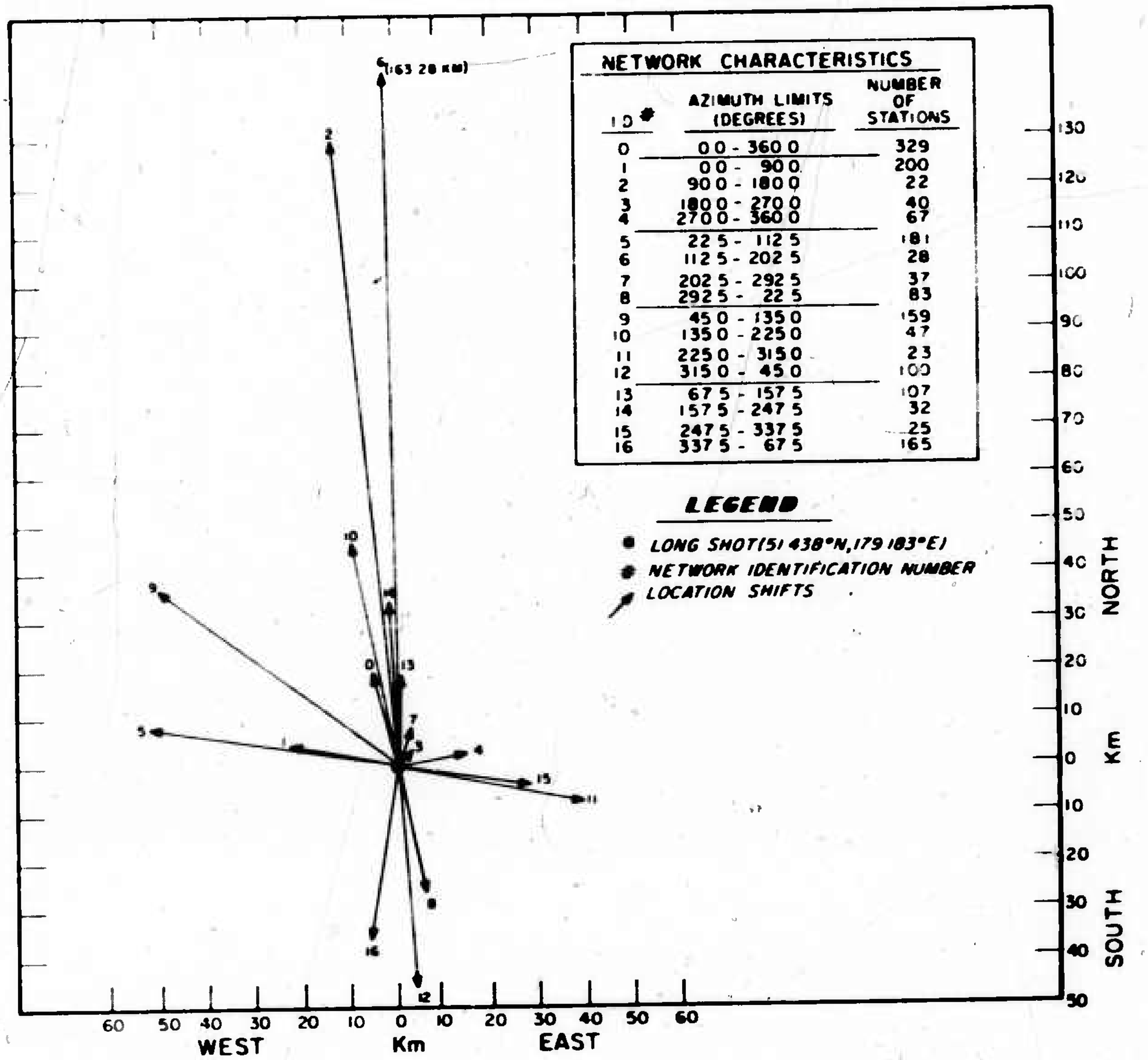

Figure 6. LONG SHOT location errors using single-quadrant networks.

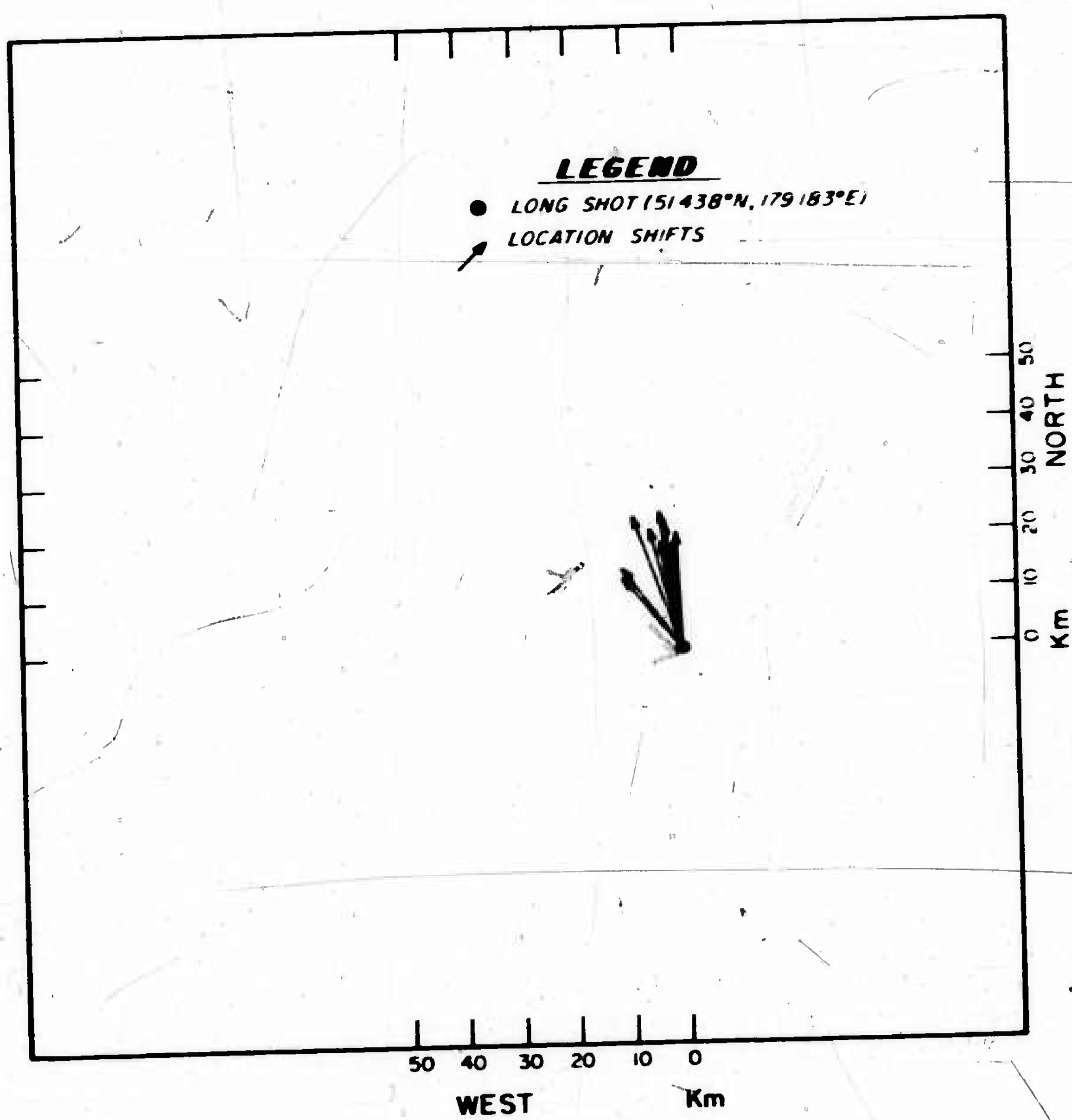

Figure 7. LONG SHOT location errors using four-quadrant, 32-station networks composed of every tenth station selected by increasing azimuth.

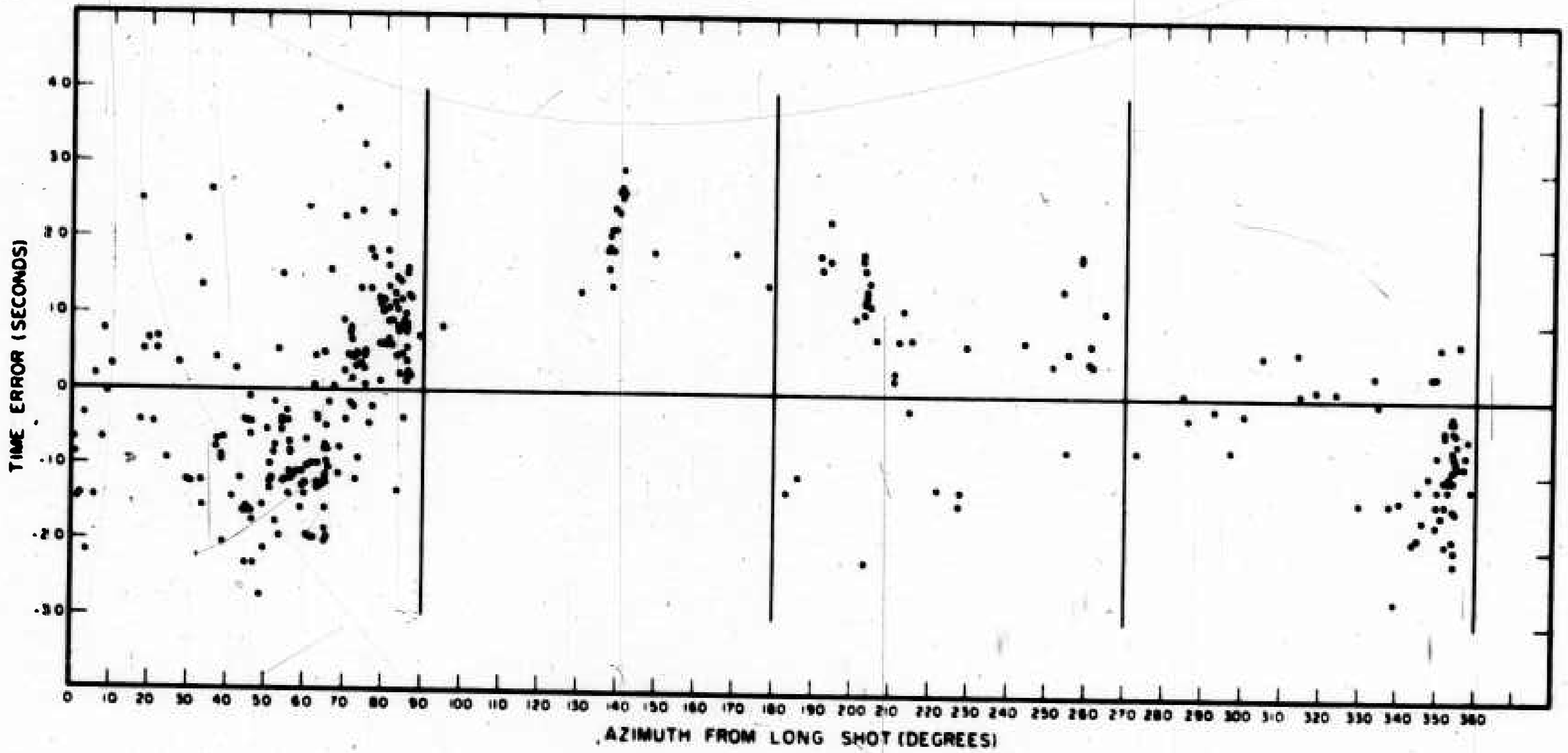

Figure 8. LONG SHOT anomalies as a function of azimuth.

3 sec, which in itself is enough to cause location errors of 50 km. Because of this fact, the practice of fitting a sinusoidal curve through these data in order to predict what the anomalies would be for events occurring in this region is hardly more than an exercise, although it may remove a portion of the bias. For precise location work, anomalies need to be known far better than 0.5 sec; but with a known scatter of 3 sec, any reduction in location errors obtained by applying sinusoidal azimuth-dependent corrections is entirely coincidental. If instead of ordering the station set by azimuth, ordering is on the basis of increasing epicentral distance and every 10th station selected, another set of nine 32-station networks is obtained, again each with approximately four-quadrant coverage. The results are shown in Figure 9, which show about the same northwesterly bias as in the azimuth-ordered results of Figure 7.

In any least-squares procedure of location, the distribution of the true (zero-mean) time errors regardless of distance or azimuth is critical to the result. In order to solve for the correction coefficients, the residual errors are assumed to have the normal distribution about an assumed travel-time distance relationship. But the actual errors for a particular event, may not, and indeed generally do not, have the normal distribution. A plot of the 329 time errors computed from the true location of LONG SHOT is shown in Figure 10a for a 1.0 sec error interval. There is seen to be a definite skewness toward negative errors or early arrival times relative to the earth model; the standard deviation for these data is 1.3 sec. This is another effect of the variation of travel time with azimuth. After least-squares adjusting the epicenter, resulting in a 21 km shift, the minimized zero-mean time errors are shown in Figure 10b. Now the nearly-normal distribution is clear, the standard deviation for these data being 1.0 sec. The assumption made by employing a least-squares scheme in the first place

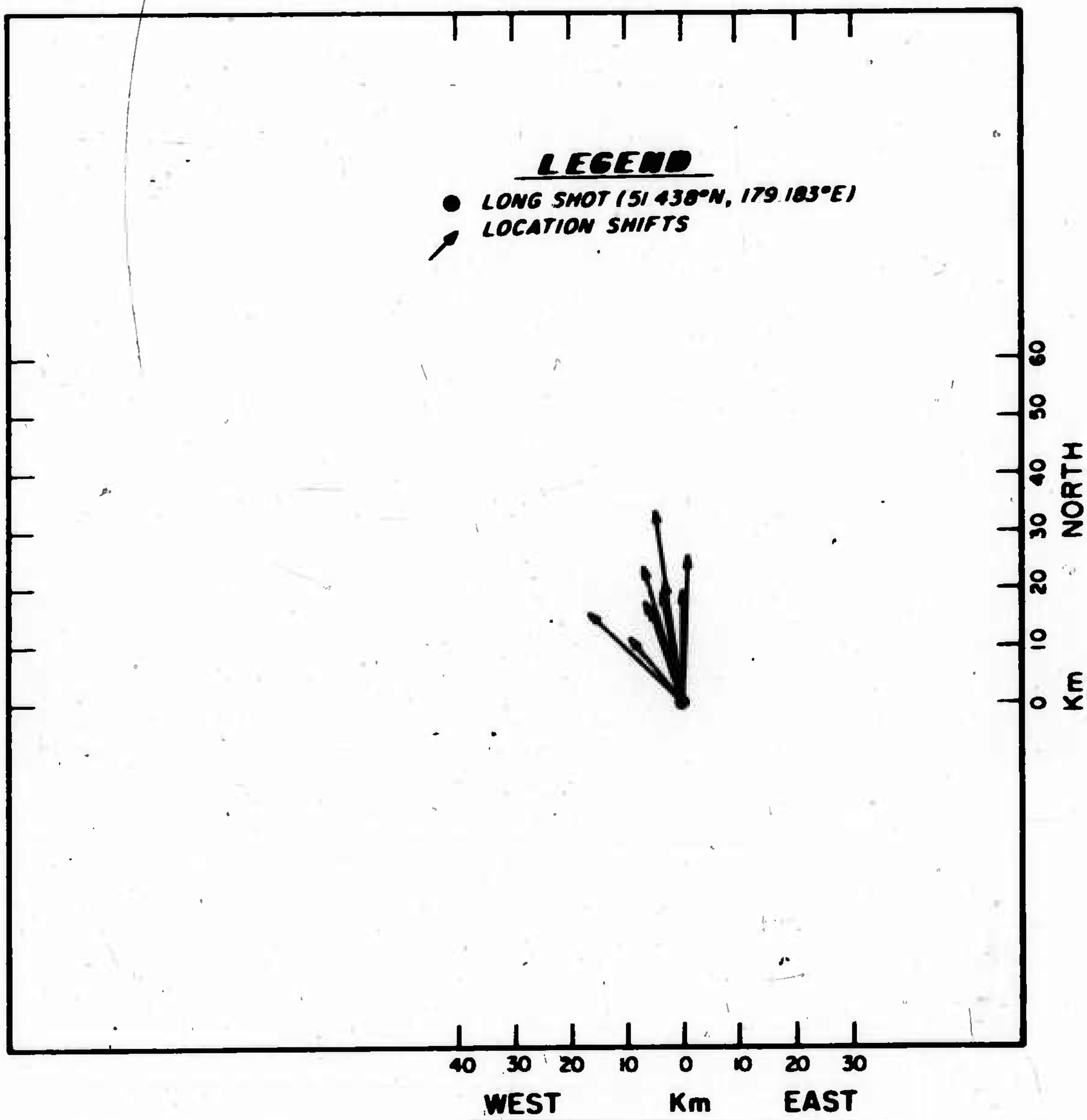

Figure 9. LONG SHOT location errors using four-quadrant, 32-station networks composed of every tenth station selected by increasing distance.

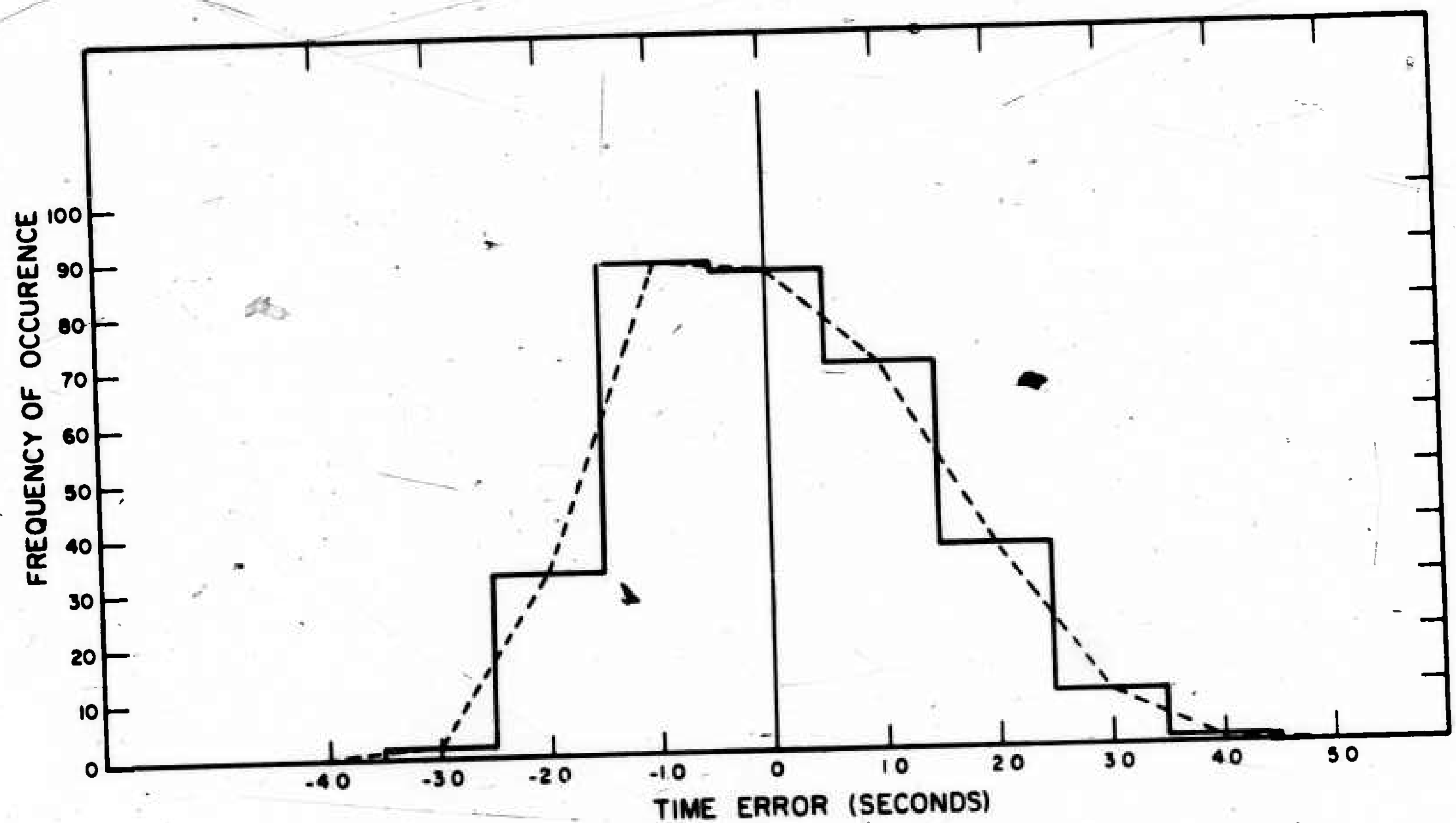

Figure 10a. LONG SHOT zero-mean error distribution computed from known location.

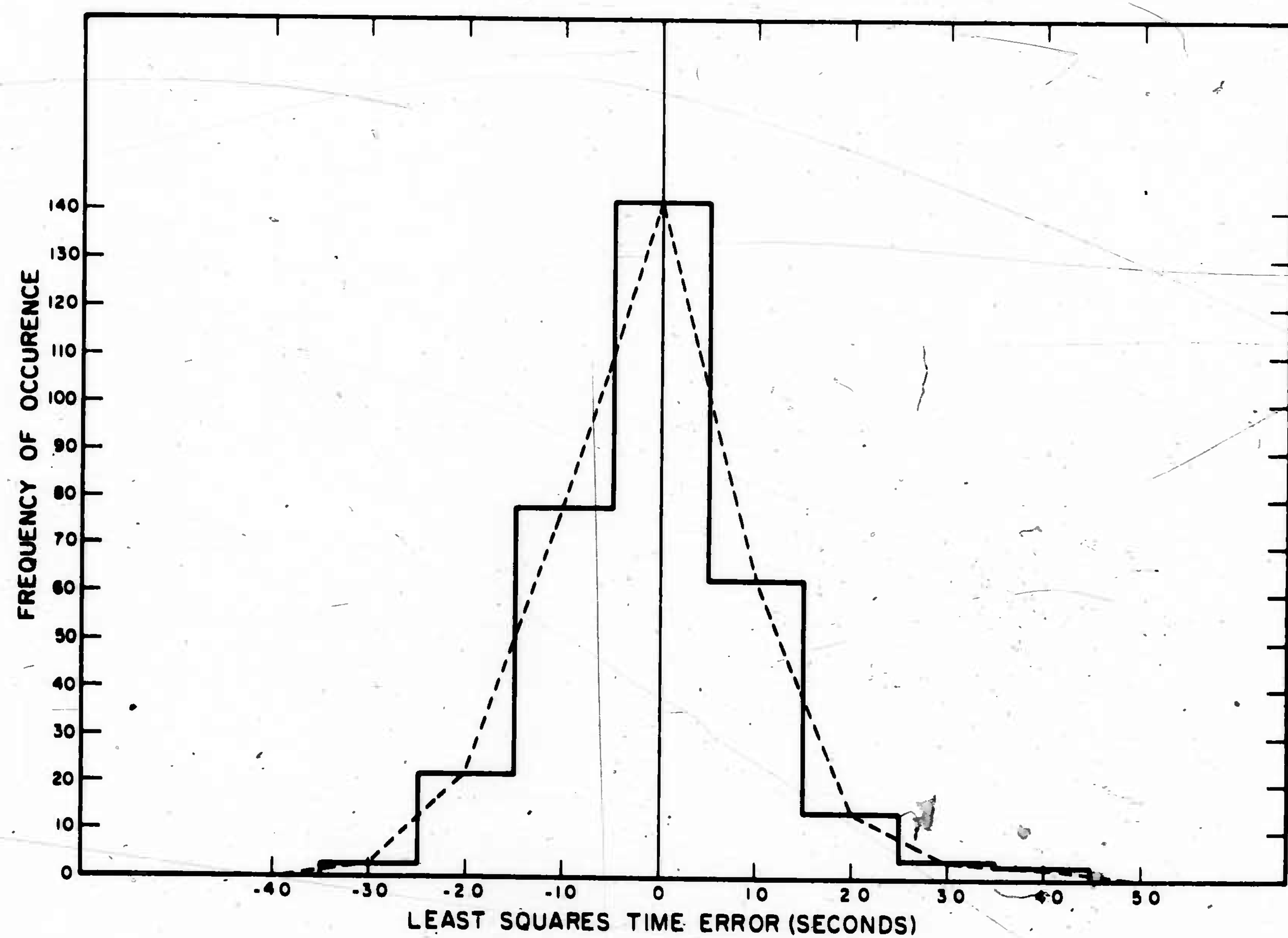

Figure 10b. LONG SHOT zero-mean least-squares error distribution computed from 329-station solution.

is that any subset of travel-time anomalies, even a large one (Figure 10a), has a normal distribution and must be minimized because of random imperfections not because of systematic early or late arrival times. The anomalies are due to lateral and vertical inhomogeneities which are not allowed for in the earth model; the actual effects of these inhomogeneities may be large and nothing dictates that a particular set of anomalies for the network locating the event should be as small as possible in a least-squares sense. The only errors which should ever be minimized are those due to reading precision; these are random and probably have a zero-mean normal distribution.

From the above results, an example can be given of the difficulty in working with a mislocated earthquake data set and of possible anomaly errors computed from the various LONG SHOT solutions for station NP-NT. The anomaly inconsistency for this station is shown in Table III, in which the range is 11.44 sec. If LONG SHOT had been an earthquake, any one of these epicenters might have been reported, depending on the particular network available at the time of occurrence, and hence, any one of these anomalies would have been computed and accepted. But if accurate locations are to be realized for a particular region, anomalies must be known to within 0.25 sec, including reading error; an 11 sec uncertainty is useless.

The principal conclusion to be drawn from the preceding exercise is that by studying anomalies across a region as large as the Aleutian Islands (approximately 1600 km in extent) and that by using earthquakes which are all differently mislocated, the anomalies must be expected to display variations and inconsistencies which are not real. However, even if event mislocation is the chief cause of the variations, an attempt can be made to achieve both anomaly and location consistency, no matter how

TABLE III

Travel-Time Anomalies at NP-NT Computed from Various LONG SHOT Seismic Solutions.

Long Shot Location	Method of Selecting the Network	Number of Stations	Azimuth Range (In Degrees)	Actual Aperture (In Degrees)	Distance Range (In Degrees)	NP-NT Anomaly Relative To UBO10 (In Seconds)
						+0.02
1	All Stations	329	0-360	359	20-99	+1.28
2	180° Sector	222	0-180	176	20-99	+1.53
3	180° Sector	107	180-0	177	32-98	+0.48
4	180° Sector	209	22.5-202.5	176	20-99	+2.42
5	180° Sector	120	202.5-22.5	179	20-98	+0.79
6	180° Sector	206	45-225	177	22-99	+2.79
7	180° Sector	123	225-45	178	20-96	-0.34
8	180° Sector	139	67.5-247.5	177	33-98	+1.85
9	180° Sector	190	247.5-67.5	[illegible]	20-99	-0.59
10	180° Sector	62	90-270	152	31-98	+0.06
11	180° Sector	267	270-90	163	20-99	+0.99
12	180° Sector	65	112.5-292.5	149	32-96	+0.83
13	180° Sector	264	292.5-112.5	154	20-99	+0.97
14	180° Sector	70	135-315	176	32-98	+0.89
15	180° Sector	259	315-135	132	20-99	+0.93
16	180° Sector	57	157.5-337.5	175	32-98	+0.38
17	180° Sector	272	337.5-157.5	171	20-99	+1.42
18	90° Sector	200	0-90	86	20-99	+1.12
19	90° Sector	22	90-180	38	36-76	+7.50
20	90° Sector	40	180-270	87	32-98	+0.09
21	90° Sector	67	270-360	75	57-91	-0.39
22	90° Sector	181	22.5-112.5	63	20-99	+2.42
23	90° Sector	28	112.5-202.5	62	36-97	+8.89
24	90° Sector	37	202.5-292.5	85	32-98	+0.39
25	90° Sector	83	292.5-22.5	49	20-96	-1.57
26	90° Sector	159	45-135	42	22-99	+3.76
27	90° Sector	47	135-225	84	35-98	+2.84
28	90° Sector	23	225-315	87	32-96	-1.79
29	90° Sector	100	315-45	90	21-96	-2.55
30	90° Sector	127	67.5-157.5	81	33-90	+1.14
31	90° Sector	32	157.5-247.5	84	47-98	+1.86
32	90° Sector	25	247.5-337.5	83	32-91	-1.25
33	90° Sector	165	337.5-67.5	89	20-99	-1.64
	Every Tenth Station:					
34	By Azimuth ↓	32	0-360	354	22-99	+1.26
35		32	0-360	354	22-89	+1.07
36		32	0-360	353	22-93	+1.42
37		32	0-360	352	20-95	+1.36
38		32	0-360	352	21-93	+1.14
39		32	0-360	351	20-96	+1.19
40		32	0-360	349	33-96	+1.47
41		32	0-360	349	22-96	+1.66
42		32	0-360	347	33-92	+1.89
43		32	0-360	347	23-98	+1.19
44	By Distance ↓	32	0-360	337	20-90	+1.06
45		32	0-360	339	20-98	+1.19
46		32	0-360	353	21-91	+1.22
47		32	0-360	352	22-91	+1.00
48		32	0-360	321	22-91	+1.40
49		32	0-360	316	22-92	+1.98
50		32	0-350	356	22-92	+1.55
51		32	0-360	354	22-92	+1.09
52		32	0-360	348	22-92	+1.12
53		32	0-360	345	23-93	+1.52

MAXIMUM ANOMALY	+8.89
MINIMUM ANOMALY	-2.55
ANOMALY RANGE	11.44

artificial the anomaly functions and the relative locations appear to be. With the LONG SHOT explosion providing a "bias" constraint in the vicinity of Amchitka Island, relative locations can be made using functional anomalies at increasing distances from LONG SHOT, always demanding least-squares consistency and reasonable functions.

DETERMINATION OF ANOMALY FUNCTIONS

Selection of a constant network

It was shown in a previous report (Chiburis and Ahner, 1970), as well as in the preceding section, that "location bias" is a function of the particular network used; also, if a constant network is used for locating a set of events in one region, relative accuracy within the event set is not affected, although all of the events may be translated by an unknown bias. However, if different networks are used to locate different events, the results of locating in a particular region display large unpredictable errors, unless anomalies are applied.

Therefore, in this report, in order to remove the network effect, a constant network is selected, all stations of which recorded a suitable number of the events in Table I. Subsets of this network can then be used to demonstrate location consistency.

Initially, the constant network was composed of seven LRSM and VELA stations and eight NOS and participating stations. The number of events was ten. Various techniques were initially employed to achieve consistency, none of which yielded satisfactory results. Eventually it was supsected that the reported arrival times at NOS stations were partly responsible for the poor results. An effort was made to obtain the seismograms from the NOS library in order to check the readings. Only those seismograms from the WWSS system were available; the seismograms from participating stations were not. Table IV is a list of only those reading discrepancies greater than 1.0 sec found at eleven selected WWSS stations for a set of 50 events.

A total of 279 readings was compared. Of these, 40 were different by more than 1.0 sec and 114 by more than 0.5 sec. Consequently,

TABLE IV

Selected Arrival-Time Discrepancies Greater than 1.0 Sec
(SDL - NOS)

-1.4	+1.8	-1.7	-1.1	-2.0	-1.0	-2.0	+1.4
+1.0	+1.4	+1.4	-1.5	-1.9	+1.7	+2.1	+1.4
+2.1	+1.0	-1.0	-1.2	-1.0	-1.0	-1.5	-1.8
-1.4	-1.7	-2.4	-1.1	-1.0	+1.1	-2.1	-1.7
-1.0	+1.0*	-1.0*	-1.1	-1.3	-19.9*	+1.2	-1.3

*Reading not used by NOS in location reported.

all readings used in the rest of this report are only those for which seismograms were obtained and analyzed at SDL.

The constant network finally selected, referred to as Network 1, is composed of fourteen stations. Three subsets of this network were devised (Table V). Also given in this table are seventeen events, each of which was recorded by all fourteen stations. The LONG SHOT explosion is included in this set, but not FLEXBAG, because it was not recorded by all fourteen stations. Therefore, only one event serves as bias control for the study. A geographic map of the seventeen events is shown in Figure 11. Although farther apart than desired, the number of events is the maximum obtainable for as many as fourteen stations. By decreasing the number of stations, one could obtain more events, but the network would be less effective in azimuth and distance distribution.

Initial locations

Using the Adjusted locations given in Table I as the input parameters, the seventeen events were located by the four networks with raw arrival times. Recall that the Adjusted locations are relocations of NOS hypocenters with depths restrained to pP readings. The shifts from the input location are shown in Figure 12 on a magnified scale. The four networks yield locations which disagree with the input location by over 60 km for some events, and the scatter within the clusters is as large as 35 km. The reason for this poor result is that the networks are composed of different sets of stations which have quite different distributions of anomalies. The clustering and standard deviations of the least-squares solutions for the seventeen events are listed in Table VI. Several standard deviations become quite small, showing that small residuals are a necessary but not sufficient indication of accuracy.

TABLE V

DEFINITION OF NETWORK SUBSETS AND EVENT SET

Network #1	Network #2	Network #3	Network #4	Azimuth From Long Shot (In Degrees)	Distance From Long Shot (In Degrees)
NDI	NDI			297	75
QUI		QUI		305	79
NUR	NUR			337	66
STU		STU		353	80
NOR	NOR			003	47
NP-NT	NP-NT		NP-NT	022	34
COL		COL	COL	039	22
HN-ME		HN-ME	HN-ME	044	67
RK-ON	RK-ON		RK-ON	054	51
LAO10		LAO10	LAO10	065	47
WMO06		WMO06	WMO06	072	59
OBO10	OBO10		OBO10	074	49
TFO60		TFO60	TFO60	081	52
TOL	TOL			082	53
Total Stations 14	[illegible]	[illegible]	8		
Aperture 115°	115°	136°	59°		

Events Recorded

Number From Table I	Date	Designator
1	01 Jun 67	Fox 1
3	19 Jun 67	Fox 2
6	06 Jul 67	Fox 3
18	23 Jan 68	Fox 4
22	15 Feb 68	Fox 5
23	19 Jul 66	AND 6
25	22 Jul 66	AND 7
31	21 Feb 68	AND 8
47	15 May 66	AND 9
48	11 Jun 66	AND 10
58	22 Nov 65	AND 11
63	29 Oct 65	Rat 12 (Long Shot)
84	04 Jul 66	Rat 13
86	2? May 67	Rat 14
102	26 Feb 66	Neat 15
106	13 Jan 66	Neat 16
108	08 Jun 66	Neat 17

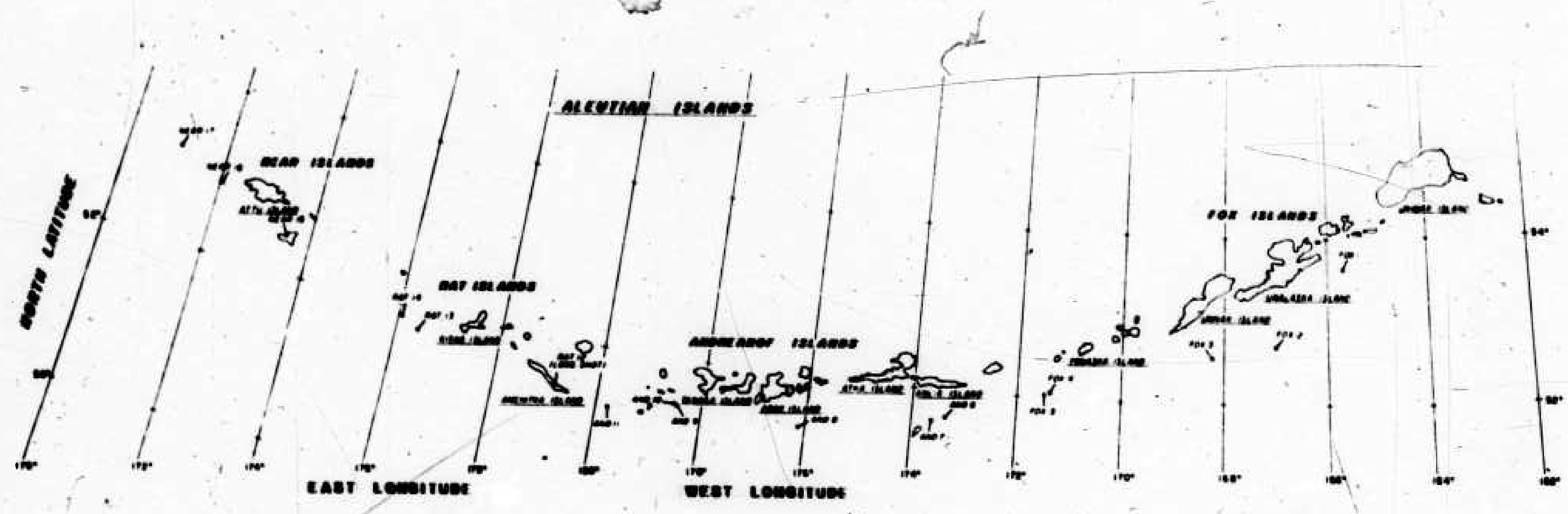

Figure 11. Geographic location map of 17 selected events.

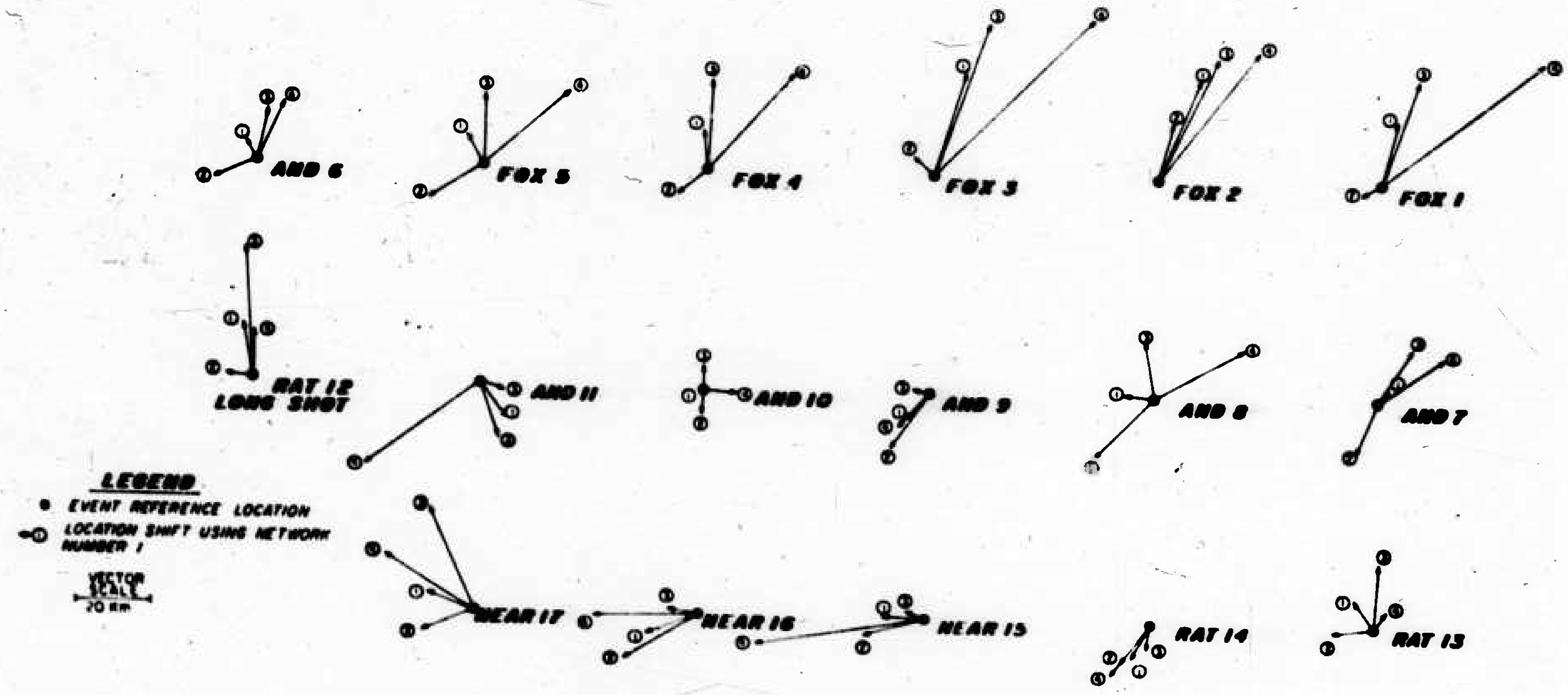

Figure 12. Location shifts for four networks obtained without anomaly corrections.

TABLE VI

Location Shifts, Standard Deviations (σ), and Clustering Effect (Shifts from the Mean) Obtained Without Anomaly Corrections

	Fus 1 Location Shifts			Fus 2 Location Shifts			Fus 3 Location Shifts			Fus 4 Location Shifts			Fus 5 Location Shifts		
Network	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)
1	1[illegible].0	.[illegible]59	4.8	20.4	.631	5.2	20.2	.020	7.6	11.1	.600	6.0	9.0	.533	5.8
2	6.3	.465	[illegible].6	16.6	.605	10.0	7.2	.530	32.0	10.7	.411	24.0	17.1	.640	24.8
3	30.0	.[illegible]10	1[illegible].4	36.5	.[illegible]35	5.0	44.2	.603	12.0	26.7	.175	11.2	19.3	.217	10.4
4	54.0	.655	35.2	41.2	.624	15.2	61.0	.725	31.2	34.7	.336	23.2	30.8	.420	25.6
Mean	[illegible].0	.655	20.9	31.[illegible]	.600	10.0	35.4	.604	21.1	20.3	.350	10.1	19.0	.404	16.6

	And 6 Location Shifts			And 7 Location Shifts			And 8 Location Shifts			And 9 Location Shifts		
Network	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)
1	6.9	.186	2.1	4.5	.547	4.4	8.2	.362	0.0	10.1	.660	0.0
2	12.1	.314	16.0	14.1	.300	22.0	23.8	.505	25.6	17.9	.012	0.0
3	13.9	.270	8.8	18.2	.418	10.9	15.9	.[illegible]4	12.0	5.1	.647	0.0
4	16.6	.351	12.0	26.2	.300	16.0	27.1	.517	[illegible]	12.5	.776	2.4
Mean	12.8	.351	10.0	15.2	.416	13.5	18.6	.452	10.4	11.8	.673	3.0

	And 10 Location Shifts			And 11 Location Shifts			Nat 12 Location Shifts			Nat 13 Location Shifts			Nat 14 Location Shifts		
Network	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)
1	0.0	.667	2.4	11.8	.764	10.4	15.6	.924	1.6	9.9	.406	2.4	10.0	.306	1.6
2	7.5	.000	7.2	16.6	.731	0.0	7.8	.795	16.8	12.0	.427	12.4	13.8	.306	2.4
3	7.0	.313	7.6	7.4	.020	14.4	36.9	.879	20.8	10.5	.342	12.0	7.2	.301	5.6
4	9.7	.657	0.0	38.8	.714	30.4	13.6	.996	4.0	6.4	.419	7.2	17.6	.305	6.3
Mean	6.2	.604	6.3	18.6	.767	16.0	18.5	.899	10.8	11.7	.418	8.5	12.2	.418	4.0

	Near 15 Location Shifts			Near 16 Location Shifts			Near 17 Location Shifts			Average of Shifts from Mean
Network	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	(km)
1	11.1	.525	8.0	16.0	.560	3.6	13.8	.507	5.6	4.9
2	16.7	.380	1.0	24.0	.376	8.8	10.1	.302	15.6	16.0
3	5.4	.604	15.2	9.0	.590	11.2	20.3	.431	10.0	11.7
4	16.0	.370	26.1	20.8	.341	11.6	20.3	.503	10.8	17.3
Mean	10.8	.441	13.6	10.4	.460	6.8	21.9	.465	12.6	12.6

LONG SHOT anomalies for corrections

The LONG SHOT anomalies, which are accurately known, are given in Table VII for the fourteen stations. If it is assumed that these anomalies are valid across the entire Aleutian region, they can be applied as corrections to all arrival times. The location results of doing this are shown in Figure 13. Several of the events, particularly in the Fox Islands, now tend to approach a tighter cluster of solutions for the four networks. But for the Andreanof 9, 10, 11, and the Rat Near events, no improved clustering is observed. In fact, when no anomalies were applied, far greater clustering was obtained for these events (Figure 12); regardless of the clustering, the standard deviations are generally now larger (Table VIII). This implies that a poorer travel-time fit is being obtained in the least-squares scheme when LONG SHOT anomalies are used as corrections.

Both network clustering and a reduction in the standard deviation (or an approach to an acceptable value -- say 0.25 - 0.50 sec) are necessary in order to achieve consistency and relative accuracy; but they are not, alone or together, sufficient to obtain absolute accuracy (complete removal of "bias"). The only known way to achieve absolute accuracy is to have seismic data available from a known explosion previously detonated in the vicinity. One might expect that LONG SHOT would approximately calibrate adjacent regions. In fact toward the east the standard deviations decrease for Andeanof -11, -10, and -9 when using the LONG SHOT anomalies. However, the clustering results for these same events are worse; thus the results are inconclusive.

As the LONG SHOT anomalies are not valid except in the immediate vicinity of Amchitka Island, and possibly eastward for

TABLE VII

LONG SHOT Anomalies for 14 Stations Relative to UBO

Station	Observed Long Shot Anomalies in Seconds
NDI	-1.23
QUE	-0.10
NUR	-1.46
STU	-2.74
NOR	-0.72
NP-NT	0.02
COL	-1.39
HN-ME	-2.21
RK-ON	-2.12
LAO10	-1.29
WMO06	-0.54
UBO10	0.00
TFO60	0.62
TUC	0.10

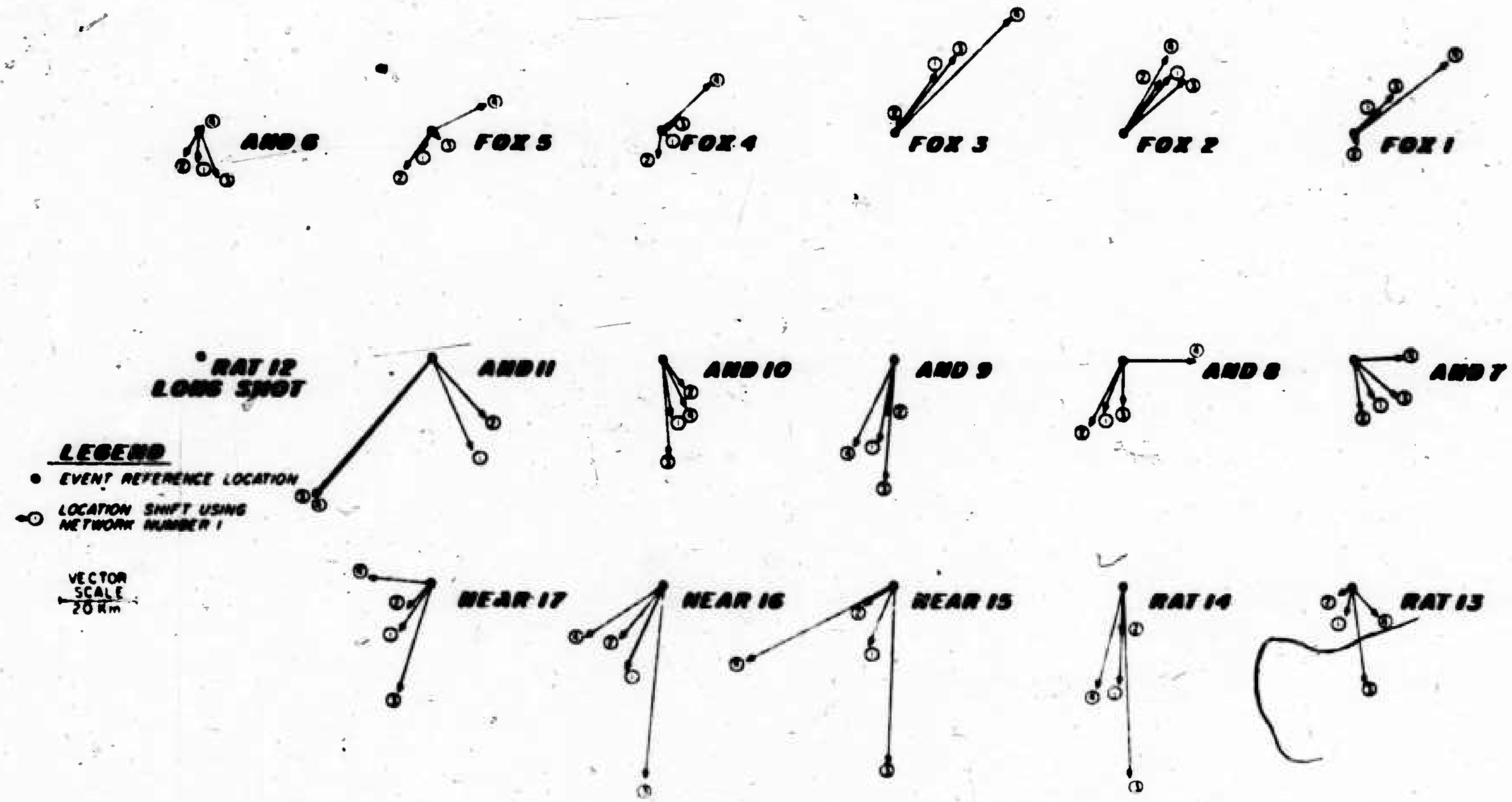

Figure 13. Location shifts for four networks obtained by applying LONG SHOT anomalies.

TABLE VIII

LOCATION SHIFTS, STANDARD DEVIATIONS (σ), AND CLUSTERING EFFECT (SHIFTS FROM THE MEAN) OBTAINED BY APPLYING LONG SHOT ANOMALIES

	Fox 1			Fox 2			Fox 3			Fox 4			Fox 5		
	Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts		
Network	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)
1	8.5	1.118	4.0	20.0	1.122	1.2	18.8	1.014	4.4	1.7	.854	4.8	5.8	.854	4.8
2	5.9	.595	15.2	17.9	.806	5.2	5.9	.525	19.6	7.5	.634	10.4	12.7	.636	12.0
3	14.6	1.556	3.2	22.3	1.505	4.8	27.4	1.315	3.2	3.4	1.113	1.2	4.5	1.015	0.8
4	31.0	.925	18.4	24.9	.926	4.8	42.2	.823	20.0	18.8	.803	16.0	15.8	.728	10.8
Mean	14.4	.998	10.2	21.3	1.039	5.5	23.1	.919	11.8	7.8	.861	7.9	9.7	.808	8.8

	And 6			And 7			And 8			And 9		
	Location Shifts			Location Shifts			Location Shifts			Location Shifts		
Network	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)
1	7.3	.849	2.4	11.5	.938	2.8	14.9	.825	6.8	22.2	.514	2.0
2	7.3	.732	4.8	14.0	.896	8.0	19.8	.653	12.0	15.7	.236	8.0
3	12.8	1.059	7.2	15.1	1.044	4.4	13.6	.919	2.4	32.4	.516	9.6
4	1.3	.974	8.0	12.5	1.018	10.8	18.7	.709	22.0	25.3	.467	6.0
Mean	7.2	.928	5.6	13.3	.924	6.5	16.7	[illegible]	10.8	23.9	.433	6.4

	And 10			And 11			Rat 12			Rat 13		
	Location Shifts			Location Shifts			Location Shifts			Location Shifts		
Network	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)
1	15.8	.645	1.6	26.8	.473	10.4	00	00	00	7.9	.767	4.0
2	10.5	.368	8.0	21.1	.375	18.4	00	00	00	4.4	.746	10.4
3	26.1	.720	10.4	59.4	.286	33.6	00	00	00	25.5	.535	15.2
4	15.0	.423	5.6	18.6	.396	33.6	00	00	00	10.0	.644	6.8
Mean	16.8	.538	5.9	34.0	.392	24.0	00	00	00	12.0	.673	9.1

	Rat 14			Near 15			Near 16			Near 17			Average of Shifts from Mean
	Location Shifts			Location Shifts			Location Shifts			Location Shifts			
Network	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	(km)
1	25.0	.747	3.0	17.6	.911	9.6	25.1	1.103	3.2	15.3	.931	2.4	4.2
2	12.0	.575	10.8	9.7	.602	18.1	18.7	.912	10.8	9.9	.775	6.0	11.4
3	51.0	.660	22.4	47.6	.758	28.0	52.1	1.039	27.2	29.9	.852	15.0	12.0
4	28.4	.576	5.6	43.6	.710	25.6	25.6	.770	14.4	16.0	.673	11.5	14.2
Mean	29.1	.640	12.1	29.6	.745	20.4	30.4	.956	15.9	17.9	.731	10.5	10.5

a short distance, a set of anomaly functions, one for each station, needs to be derived which will provide consistency, network clustering, and acceptable standard deviations across the entire Aleutian Islands. It would be trivial to draw functions exactly through the anomalies in Figures 4a and 4b, which are simply the anomalies from the Adjusted locations, for two reasons: first, it is hoped that the anomalies would not change as drastically as shown over such small distances, and second, that there should be at least a suggestion of the anomaly being monotonic or having a smooth rate of change over distances of 500 km or so. In other words, the functions that one derives should be geophysically realistic.

Simple functional anomalies

If it is assumed that the anomaly variations produced by the earth are greater than the errors due to mislocation or to measurement, the Adjusted locations can be used to compute anomalies at all of the stations and to estimate anomaly functions by fitting a linear relation through the anomalies for each station. Because the LONG SHOT anomalies are accurately known, bias constraints are available for each of the curves on the anomaly axes. These curves and their translations are shown in Figures 14a and 14b.

A linear function is the simplest possible and provides a starting point from which more complex functions can be devised.

If these values are now applied as a function of longitude, the event set can be located by the four networks, the results of which are plotted in Figure 15 and listed in Table IX. Except for Andreanof-11, it can be seen that both clustering and reduction in standard deviation are being accomplished about the same as in Figure 13. The four network solutions for an event are now

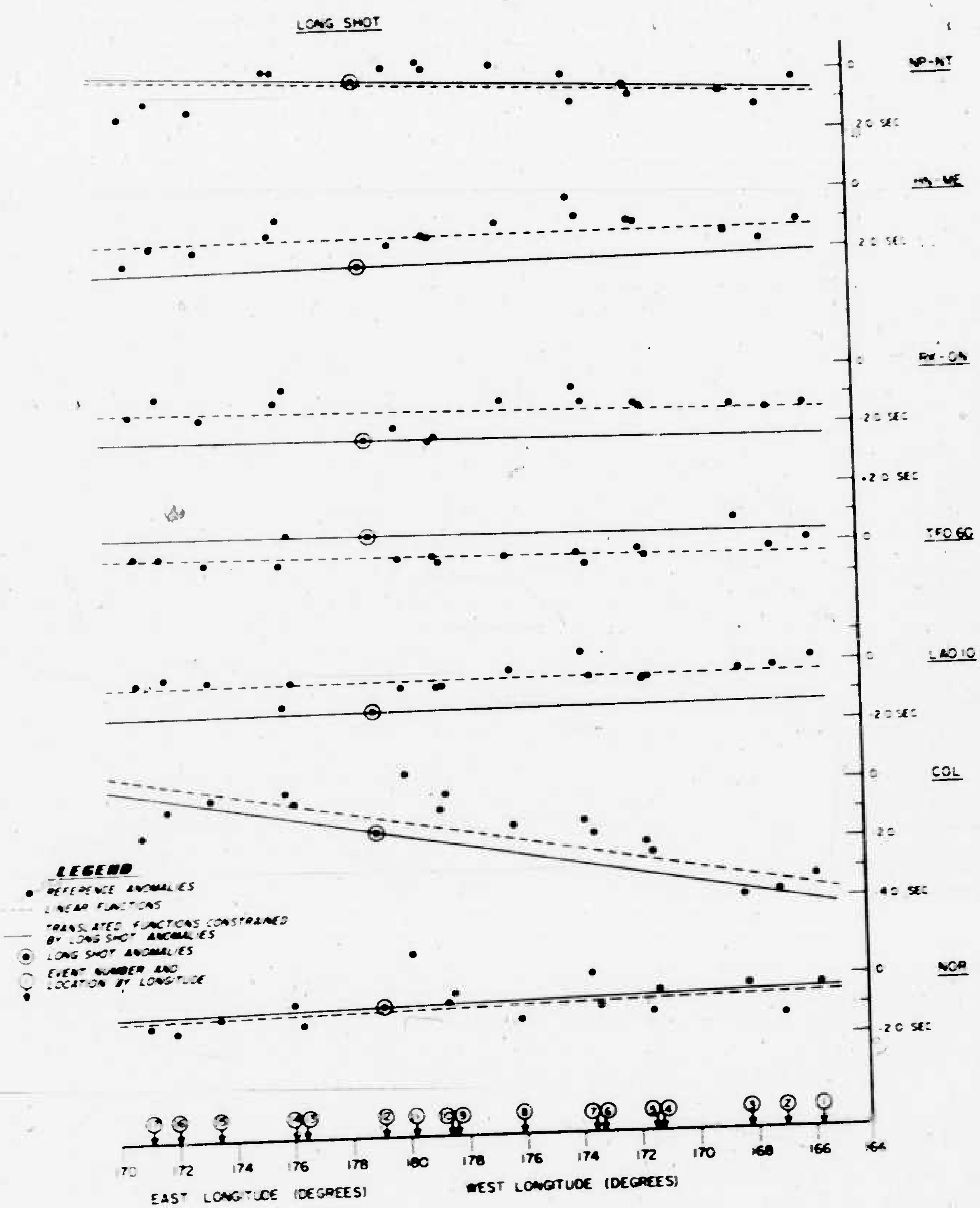

Figure 14a. Determination of simple functional anomalies.

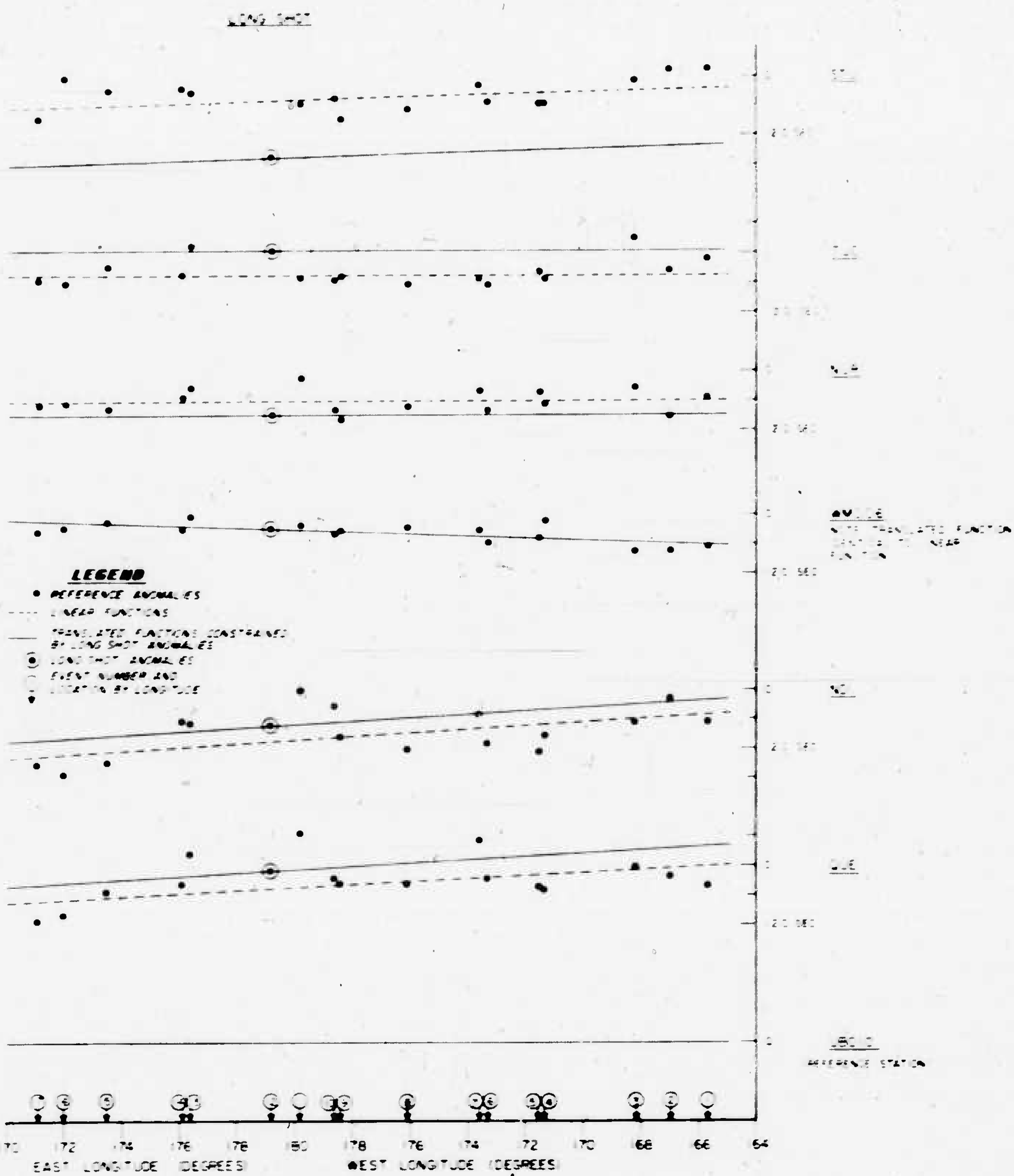

Figure 14b. Determination of simple functional anomalies.

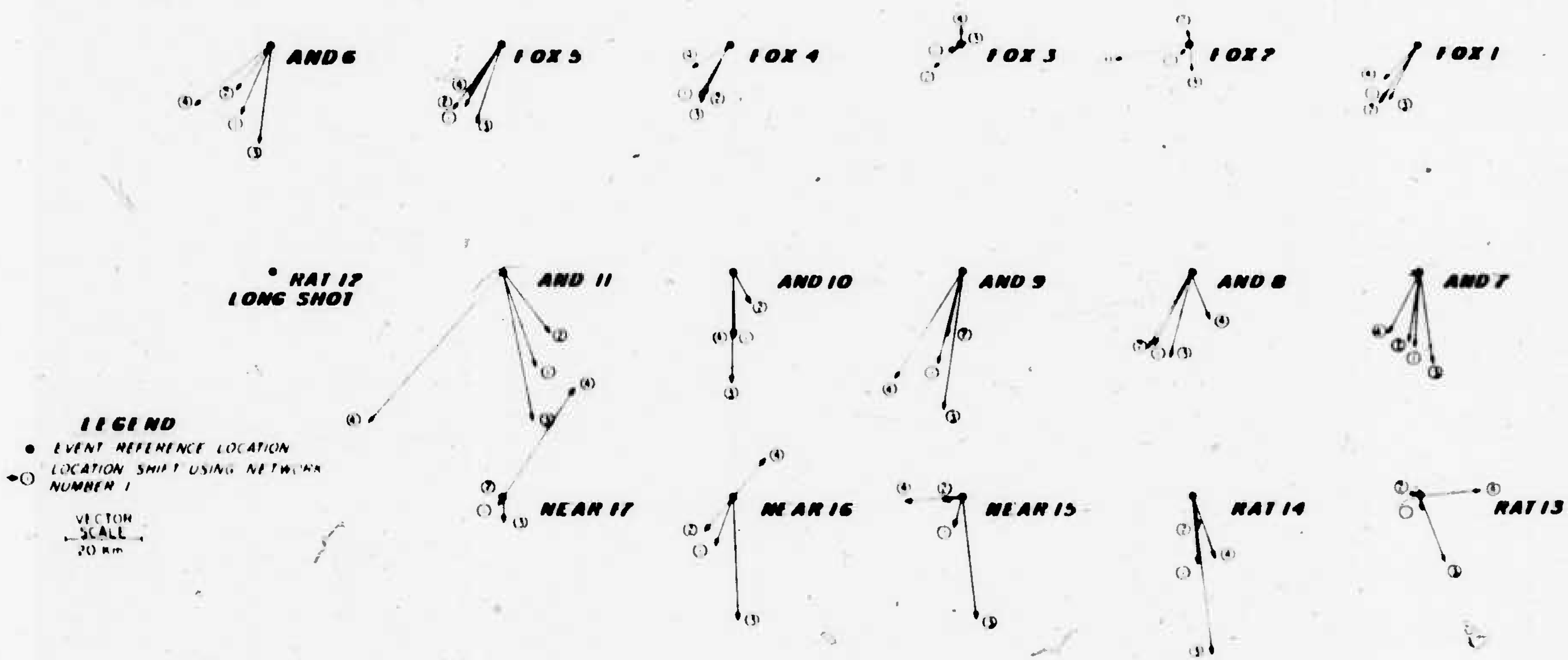

Figure 15. Location shifts for four networks obtained by applying simple functional anomalies.

clustered within approximately 9 km of the mean location, although the mean locations are as far as 20-30 km from the input epicenter. The standard deviations are generally improved, but not to low enough values. If the Near Islands events are excluded, the clustering error would reduce to about 6.5 km. The average clustering error of the Near events is more than 10 km. This poor result is expected, because the anomalies for these events show the largest departure from the linear functions in Figures 14a and 14b.

Summarizing the clustering and standard deviations for the cases considered thus far, the shifts from the input location are as large as 35 km, but the parameter of importance is the average shift from the mean location obtained using the four networks. When no anomalies are applied (Table VII), the shifts from the mean do not improve much over the shifts from the input location, the average being about 13 km but with some as large as 31 km. Therefore, no significant improvement in clustering is obtained without anomalies. The standard deviations are still too large (up to 1.0 sec) to claim consistency.

For the LONG SHOT anomaly case (Table VIII), a small improvement in clustering is obtained through the Fox Islands and into the Andreanof Islands, but not for Andreanof -8, -11, Rat -14, nor any of the Near Islands events. However, the standard deviations (up to 1.6 sec) are now larger for every event and each network, except Andreanof -9, -10, and -11. This may suggest that the LONG SHOT anomalies are approximately valid toward the east from Amchitka Island, but not at all toward the west.

The location results of applying simple linear functional anomalies (Table IX) are that the clustering in the Fox Islands and part-way into the Andreanof Islands is very good, but for Andreanof-11 and for the Rat and Near Islands, the clustering fails.

TABLE 1[illegible]

LOCATION SHIFTS, STANDARD DEVIATIONS (σ), AND CLUSTERING EFFECT [illegible] FROM THE MEANS OBTAINED BY APPLYING SIMPLE FUNCTIONAL ANOMALIES

	[illegible]			[illegible]			[illegible]			[illegible]			[illegible]			[illegible]			[illegible]			[illegible]			[illegible]		
	Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts		
Network	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)
1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Mean	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

	[illegible]			[illegible]			[illegible]			[illegible]			[illegible]			[illegible]			[illegible]			[illegible]			
	Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Average of Shifts from Mean
Network	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	(km)
1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	00	00	00	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	00	00	00	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	00	00	00	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	00	00	00	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Mean	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	00	00	00	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

The standard deviations do not improve to any degree over the no-anomaly case. It is believed that the reason for the poor results is that a simple linear anomaly function is not sufficient for locating across the Aleutians. However, as we progressed from the no-anomaly case, through the LONG SHOT anomaly and the linear functional anomaly cases, the average of shifts from the mean (Tables VI, VIII and IX) changes from 12.3 to 10.5 to 5.6 km, indicating steady improvement. We are now ready to introduce additional constraints to improve consistency.

Fox 1/LONG SHOT anomalies

If the anomaly functions dervied are constrained by two events, rather than just LONG SHOT, even though the second event is known to be mislocated, a set of functions (again linear) can be used to try to attain consistency, at least for events between the constraints.

In order to cover as large an area as possible, Fox-1 and LONG SHOT are used as the constraining events. The linear functional anomalies for the stations are shown in Figures 16a and 16b. The results obtained by applying these Fox-1/LONG SHOT anomalies as corrections are plotted in Figure 17 and are summarized in Table X. The clustering for the events from Fox-2 to Fox-8 is seen to converge slightly, but the other events are poor indeed. Andreanof-11, in particular, still appears to be unusual in that even though it is adjacent to LONG SHOT, the clustering is about the worst of any event. As expected, the clustering in the Fox Islands, except for Fox-2, is slightly improved over the previous case, but in the Near Islands, the clustering is noticably worse than in any other case heretofore. The reason for this is that the linear constraint provided by Fox-1 and LONG SHOT does not even grossly approximate the anomalies one should be using in the Near Islands. However,

TABLE X

LOCATION SHIFTS, STANDARD DEVIATIONS (σ), AND CLUSTERING EFFECT (SHIFTS FROM THE MEAN) OBTAINED BY APPLYING FOX-1/LONG SHOT FUNCTIONAL ANOMALIES

Network	Fox 1 Location Shifts From Input (km)	Fox 1 (σ)	Fox 1 From Mean (km)	Fox 2 Location Shifts From Input (km)	Fox 2 (σ)	Fox 2 From Mean (km)	Fox 3 Location Shifts From Input (km)	Fox 3 (σ)	Fox 3 From Mean (km)	Fox 4 Location Shifts From Input (km)	Fox 4 (σ)	Fox 4 From Mean (km)	Fox 5 Location Shifts From Input (km)	Fox 5 (σ)	Fox 5 From Mean (km)	And 6 Location Shifts From Input (km)	And 6 (σ)	And 6 From Mean (km)	And 7 Location Shifts From Input (km)	And 7 (σ)	And 7 From Mean (km)	And 8 Location Shifts From Input (km)	And 8 (σ)	And 8 From Mean (km)	And 9 Location Shifts From Input (km)	And 9 (σ)	And 9 From Mean (km)
1	00	00	00	12.5	.318	4.8	12.2	.288	0.2	5.8	.401	1.3	10.4	.372	0.4	10.1	.571	5.6	12.6	.520	1.0	16.6	.576	1.0	22.6	.425	1.2
2	00	00	00	20.5	.370	12.4	6.8	.202	6.0	5.5	.304	2.6	11.2	.448	2.0	6.3	.551	6.1	12.3	.571	0.2	16.8	.540	6.6	15.3	.234	10.4
3	00	00	00	8.2	.161	6.2	15.2	.270	3.5	5.8	.402	0.8	10.5	.225	2.6	16.5	.611	9.6	16.1	.408	2.6	16.5	[illegible]	2.4	33.2	.314	9.2
4	00	00	00	13.2	.151	17.0	14.0	.242	2.0	7.0	.450	3.6	9.8	.301	1.1	20.1	[illegible]	11.1	13.1	.645	[illegible]	11.3	.161	11.6	32.0	.400	10.4
Mean	00	00	00	13.7	.258	10.1	12.0	.260	2.0	6.0	.412	2.1	10.5	.336	1.5	13.3	.511	[illegible]	13.5	.541	3.4	15.8	[illegible]	6.1	25.8	.343	8.3

Network	And 10 Location Shifts From Input (km)	And 10 (σ)	And 10 From Mean (km)	And 11 Location Shifts From Input (km)	And 11 (σ)	And 11 From Mean (km)	Nat 12 Location Shifts From Input (km)	Nat 12 (σ)	Nat 12 From Mean (km)	Nat 13 Location Shifts From Input (km)	Nat 13 (σ)	Nat 13 From Mean (km)	Nat 14 Location Shifts From Input (km)	Nat 14 (σ)	Nat 14 From Mean (km)	Seat 15 Location Shifts From Input (km)	Seat 15 (σ)	Seat 15 From Mean (km)	Seat 16 Location Shifts From Input (km)	Seat 16 (σ)	Seat 16 From Mean (km)	Seat 17 Location Shifts From Input (km)	Seat 17 (σ)	Seat 17 From Mean (km)	Average of Shifts from Mean (km)
1	16.0	.530	1.0	20.7	.457	12.0	00	00	00	7.8	.902	5.6	25.0	.906	2.6	17.6	1.222	3.2	25.6	1.538	5.6	[illegible]	1.363	9.2	5.8
2	10.0	.379	20.1	21.0	.359	20.0	00	00	00	4.6	.787	10.4	13.0	.637	11.1	10.2	[illegible]	17.1	19.9	1.073	10.0	11.1	[illegible]	6.4	[illegible]
3	26.7	.487	10.4	39.2	.261	13.2	00	00	00	25.0	.830	15.6	50.3	.968	24.0	18.2	1.315	[illegible]	51.5	1.760	32.0	32.8	1.641	26.2	12.8
4	17.4	.351	1.3	51.4	.371	33.4	00	00	00	17.5	.753	15.6	20.4	.680	8.0	16.3	.916	16.8	9.0	1.112	[illegible]	[illegible]	[illegible]	33.4	13.6
Mean	17.5	.430	5.7	34.6	.362	19.9	00	00	00	13.7	.818	11.8	[illegible]	.796	17.3	23.1	1.056	[illegible]	[illegible]	1.371	[illegible]	21.9	[illegible]	19.1	9.7

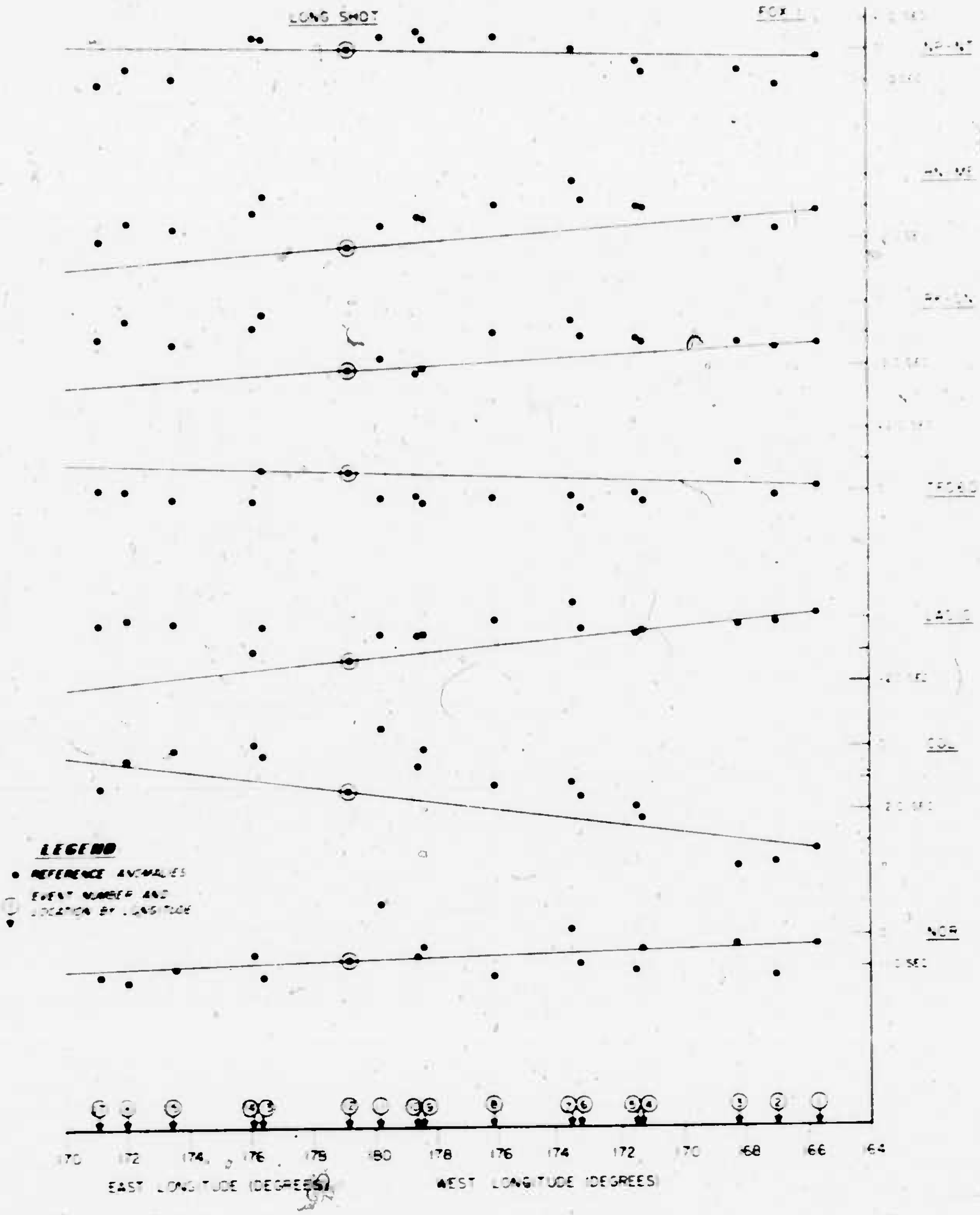

Figure 16a. Determination of FOX-1/LONG SHOT functional anomalies.

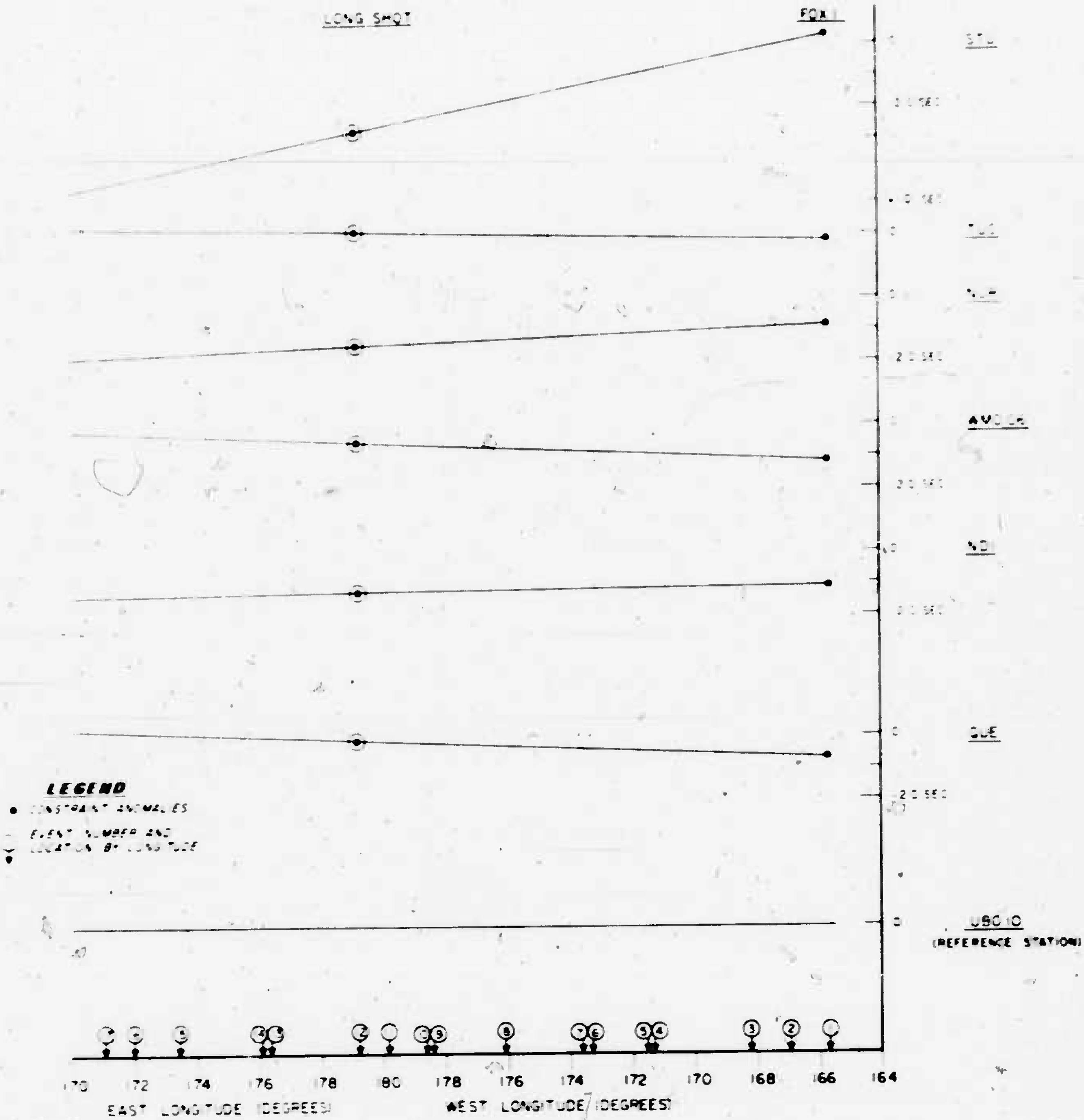

Figure 16b. Determination of FOX-1/LONG SHOT functional anomalies.

Figure 17. Location shifts for four networks obtained by applying FOX-1/LONG SHOT functional anomalies.

the standard deviations are remarkably improved through the Fox and Andreanof Islands, generally by a factor of about two. Therefore, using two widely separated events as constraints, the least-squares fits and the network clustering of events <u>between the two</u> are better than if no anomalies, constant anomalies, or single-constraint linear functional anomalies had been applied.

In order to gain location control in the Near Islands, and to improve the locations in the Andreanof Islands, two additional constraints can be imposed, one in each of the two regions.

<u>FARN anomalies</u>.

Because the anomalies are neither constant nor linear across the entire Aleutian region, a set of anomaly functions can be derived which are (1) constrained by the anomalies computed from four assumed-correct events (Fox-1, Andreanof-6, LONG SHOT, and Near-17) and (2) piecewise linear between the four constraints. A plot of the functions, referred to as "FARN" (for <u>F</u>ox-<u>A</u>ndreanof-<u>R</u>at-<u>N</u>ear), is shown in Figures 18a and 18b.

The location shifts obtained by applying the FARN anomalies are shown in Figure 19. The scatter of the clustered locations for each event is reduced and is now about the same across the entire Aleutian region, except for Near-15 and Andreanof-11. Even for these two events, if Network 4 is not included, the clustering approaches the average. It can be expected that Network 4 will be unstable due to its small aperture of about 59° where the effect of small reading errors is exaggerated. A summary of the results is given in Table ~~XI~~, where all of the standard deviations become less than 0.5 seconds, most being less than 0.35 seconds. The clustering error is about 8 km, and without Network 4 being considered for Andreanof-11 and Near-15, it is about 6 km.

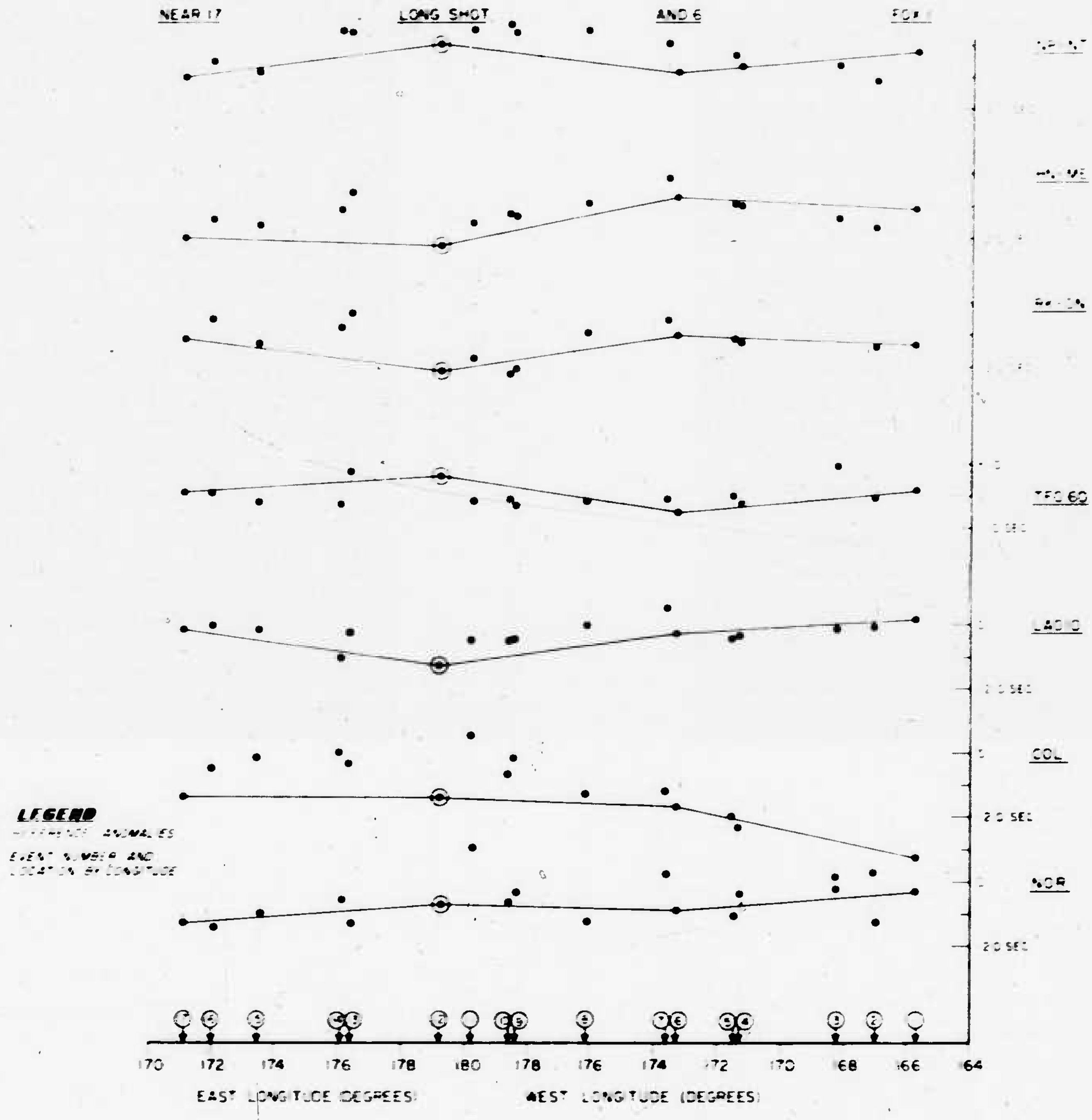

Figure 18a. Determination of anomalies using Fox, Andreanof, Rat, and Near (FARN) constraining events.

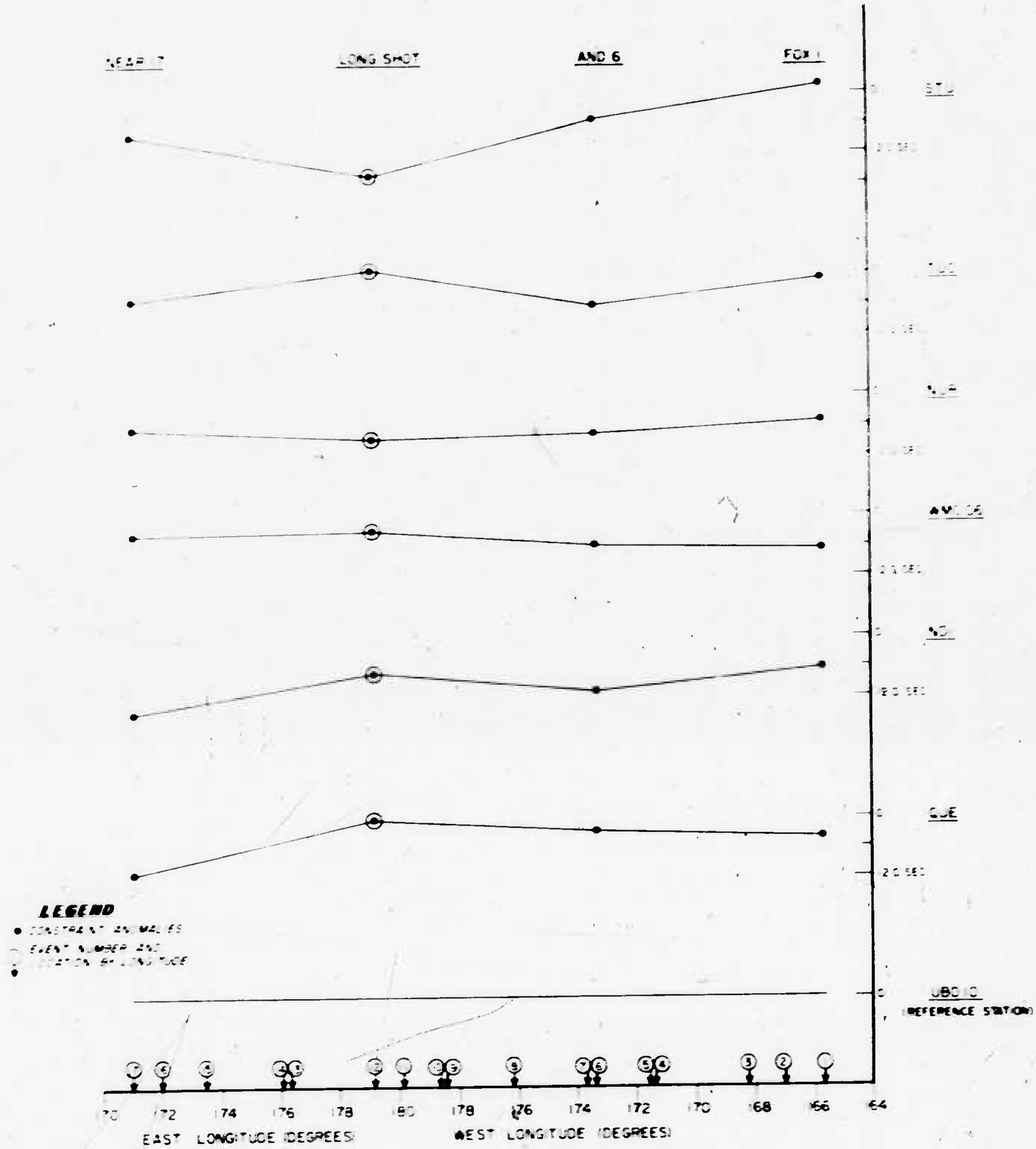

Figure 18b. Determination of anomalies using Fox, Andreanof, Rat, and Near (FARN) constraining events.

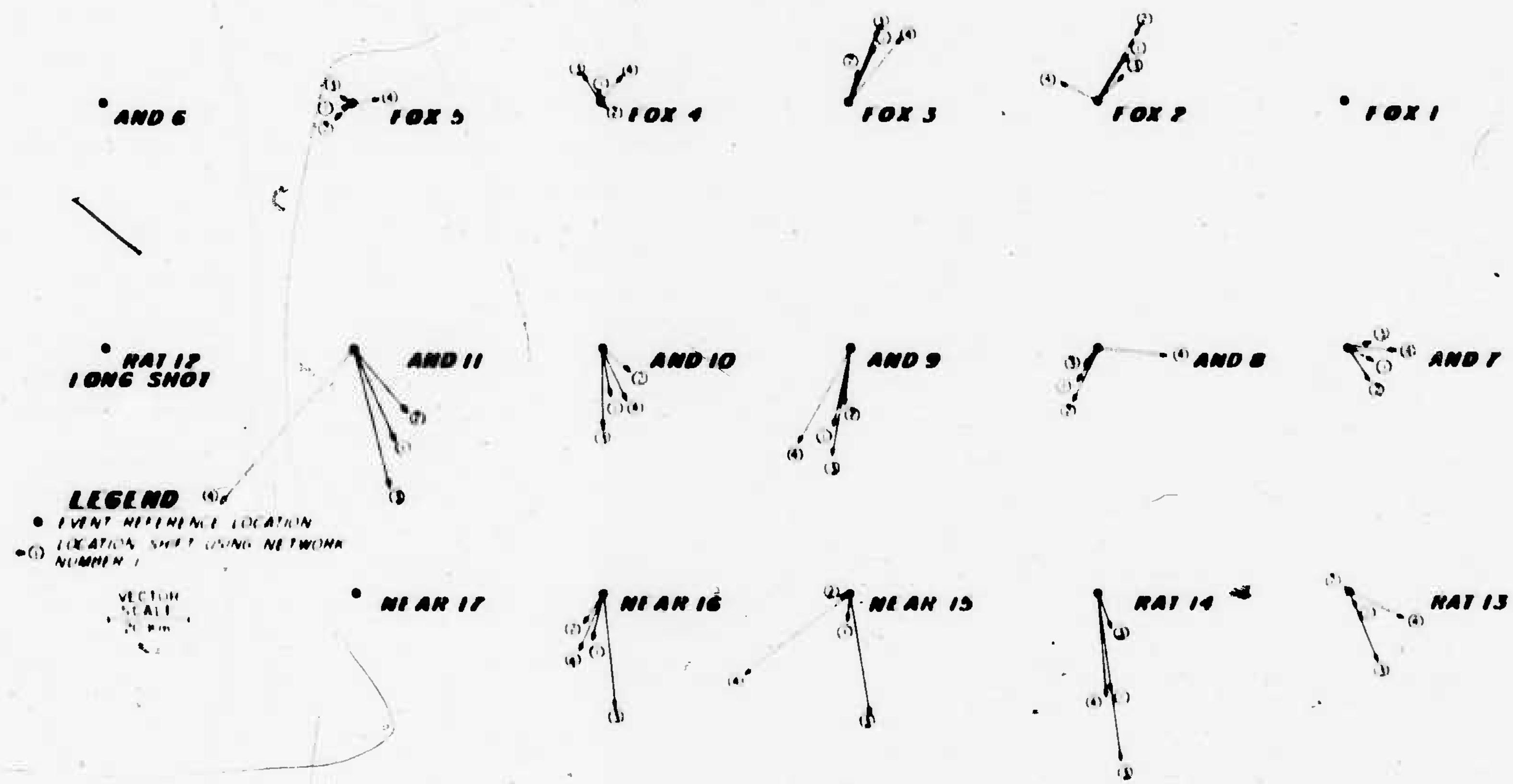

Figure 19. Location shifts for four networks obtained by applying FARN (see text) anomalies.

TABLE XI

LOCATION SHIFTS, STANDARD DEVIATIONS (σ), AND CLUSTERING EFFECT (SHIFTS FROM THE MEAN) OBTAINED BY APPLYING FARN FUNCTIONAL ANOMALIES

Network	Fox 1 Location Shifts From Input (km)	(σ)	From Mean (km)	Fox 2 Location Shifts From Input (km)	(σ)	From Mean (km)	Fox 3 Location Shifts From Input (km)	(σ)	From Mean (km)
1	00	00	00	13.9	.301	1.0	15.8	.375	1.0
2	00	00	00	21.5	.315	11.2	8.6	.336	8.0
3	00	00	00	10.1	.186	1.8	19.4	.312	4.0
4	00	00	00	10.8	.120	11.1	21.1	[illegible]	6.2
Mean	00	00	00	11.1	.231	8.6	16.2	.340	1.8

Network	Fox 4 Location Shifts From Input (km)	(σ)	From Mean (km)	Fox 5 Location Shifts From Input (km)	(σ)	From Mean (km)	Abd 6 Location Shifts From Input (km)	(σ)	From Mean (km)
1	2.3	.287	1.6	3.5	.283	2.1	00	00	00
2	2.0	.094	4.8	6.3	.330	5.6	00	00	00
3	8.0	.303	6.0	4.1	.197	3.6	00	00	00
4	8.6	.294	6.0	7.0	.221	8.8	00	00	00
Mean	5.2	.244	4.6	5.2	.258	5.1	00	00	00

Network	Abd 7 Location Shifts From Input (km)	(σ)	From Mean (km)	Abd 8 Location Shifts From Input (km)	(σ)	From Mean (km)	Abd 9 Location Shifts From Input (km)	(σ)	From Mean (km)
1	6.8	.215	1.2	10.1	.362	6.1	19.6	.329	2.4
2	9.3	[illegible]	5.5	13.3	.310	10.0	11.0	.257	8.0
3	6.2	.195	1.0	6.1	.381	8.0	27.1	[illegible]	1.4
4	11.9	.201	5.6	16.1	[illegible]	18.0	26.9	.306	8.0
Mean	[illegible]	.191	4.1	[illegible]	.321	10.6	21.9	.280	[illegible]

Network	Abd 10 Location Shifts From Input (km)	(σ)	From Mean (km)	Abd 11 Location Shifts From Input (km)	(σ)	From Mean (km)	Rat 12 Location Shifts From Input (km)	(σ)	From Mean (km)
1	13.1	.183	3.2	25.5	.401	10.4	00	00	00
2	10.0	.408	7.6	20.9	.312	17.6	00	00	00
3	20.6	.442	8.8	35.8	.261	10.8	00	00	00
4	15.1	.303	2.1	19.2	.293	31.4	00	00	00
Mean	14.8	.409	5.5	32.8	.318	18.3	00	00	00

Network	Rat 13 Location Shifts From Input (km)	(σ)	From Mean (km)	Rat 14 Location Shifts From Input (km)	(σ)	From Mean (km)	Sear 15 Location Shifts From Input (km)	(σ)	From Mean (km)
1	4.2	.581	[illegible]	20.8	.521	5.6	[illegible]	.196	5.6
2	1.3	.586	10.8	10.0	.375	15.6	[illegible]	.113	11.1
3	19.0	.293	8.8	42.6	.394	12.8	30.8	[illegible]	16.0
4	15.0	.459	8.8	27.0	.395	7.1	33.6	.301	[illegible]
Mean	9.0	.480	8.9	25.1	.421	9.1	[illegible]	.300	[illegible]

Network	Sear 16 Location Shifts From Input (km)	(σ)	From Mean (km)	Sear 17 Location Shifts From Input (km)	(σ)	From Mean (km)	Average of Shifts from Mean (km)
1	12.3	[illegible]	6.1	00	00	00	1.7
2	10.2	.303	8.1	00	00	00	9.8
3	28.1	.339	1.8	00	00	00	7.4
4	16.6	[illegible]	1.6	00	00	00	10.8
Mean	16.9	[illegible]	5.6	00	00	00	8.2

The principal drawback to using the FARM anomalies is that the location of LONG SHOT is accurately known but the locations of the other constraining events are not known at all. Mixing the two kinds of anomalies from which the functions are derived may achieve consistency, but there is no way of estimating the accuracy of the relative locations of the events. Furthermore, the earthquakes used as constraints may be grossly (30-50 km) mislocated and there is no way of knowing the effect of this on the technique. (It will be shown later in this report that the effect is not great for a theoretical case.) Therefore, our next step will be to determine the anomaly functions by neglecting the true LONG SHOT anomalies and using instead those computed from the reported seismic location.

Fiducial functional anomalies

Since it is known that the Aleutian Islands events have a large bias in their locations (as evidenced by locating LONG SHOT with a 329-station four-quadrant network and subsets thereof), it can be safely assumed that the true position of LONG SHOT is "mislocated" relative to any of the seismic locations of earthquakes thoughout the region from the Fox Islands to the Near Islands. Therefore, if the seismic location of LONG SHOT reported by Lambert et al., (1969) is taken to be the reported location of just another Rat Island event, the anomalies from this fiducial location (21 km in error) can be computed and compared to the anomalies from the Adjusted seismic locations of earthquakes. A set of fiducial functional anomalies can then be fitted, without constraints, to all of the observed anomalies. The only requirement on the functions is that they be piecewise linear; the number of linear segments derived for all of the stations varies from two to three. The anomaly plots and the fiducial functions for the stations are shown in Figures 20a and 20b. The observed true LONG SHOT anomalies are included for comparison. Significantly, for every station, the fiducial LONG SHOT anomaly agrees much better than the true anomaly with the earthquake anomalies, which supports the hypothesis that the Aleutian Islands earthquakes in the vicinity of LONG SHOT are mislocated in a similar way.

If the functions in Figure 20 are now applied as corrections, the locations obtained with the four networks are shown in Figure 21. and the results summarized in Table XII.

For nine of the events, Network 4 yields a result clearly at variance with the other networks; for Networks 2 and 3, there is one event at variance. Therefore, the results for these cases were not included in forming the average shift from the mean or in forming the "best estimate" of the epicenter. The excluded results are marked with an asterisk on Table XII.

The average shift from either the mean or "best estimate" is about 5.5 km, and for all networks the standard deviations are less than 0.5 sec (except for one result, the standard deviations are all less than 0.34 sec) with the average being less than 0.25 sec, an acceptable value to indicate reading precision. We should note, however that if the events with asterisks are included, then the deviation from the mean is 8.5 kilometers, about the same as for the FARX anomalies.

If anomalies are now computed from the mean epicenters derived above, the results as shown in Figures 22a and 22b indicate that the station anomalies display less scatter from a function than before the shifts.

It is now necessary to correct the anomaly functions for the known LONG SHOT bias and to attempt to smooth them (remove sharp changes) across the Aleutian.

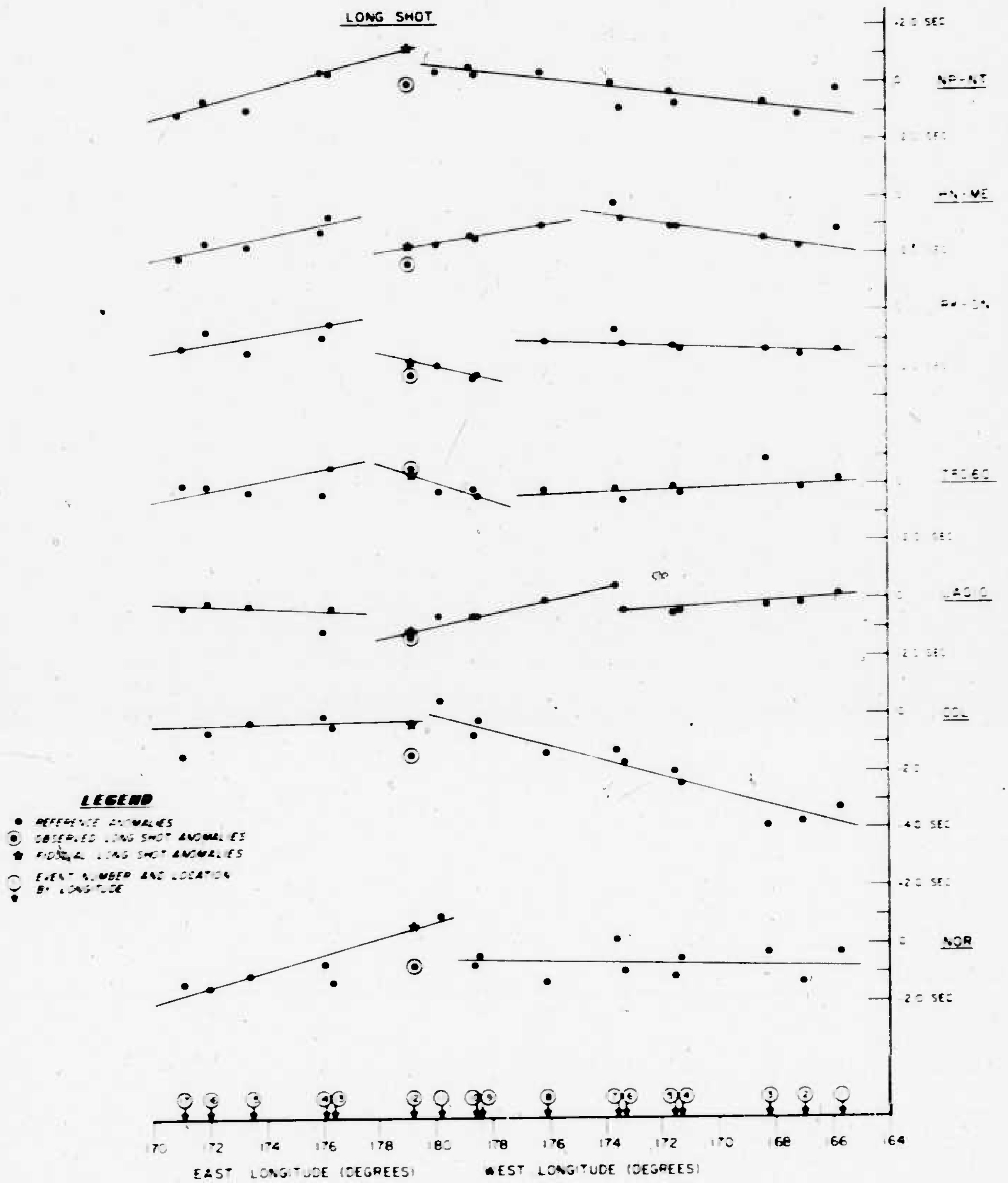

Figure 20a. Functional anomalies determined from fiducial LONG SHOT location.

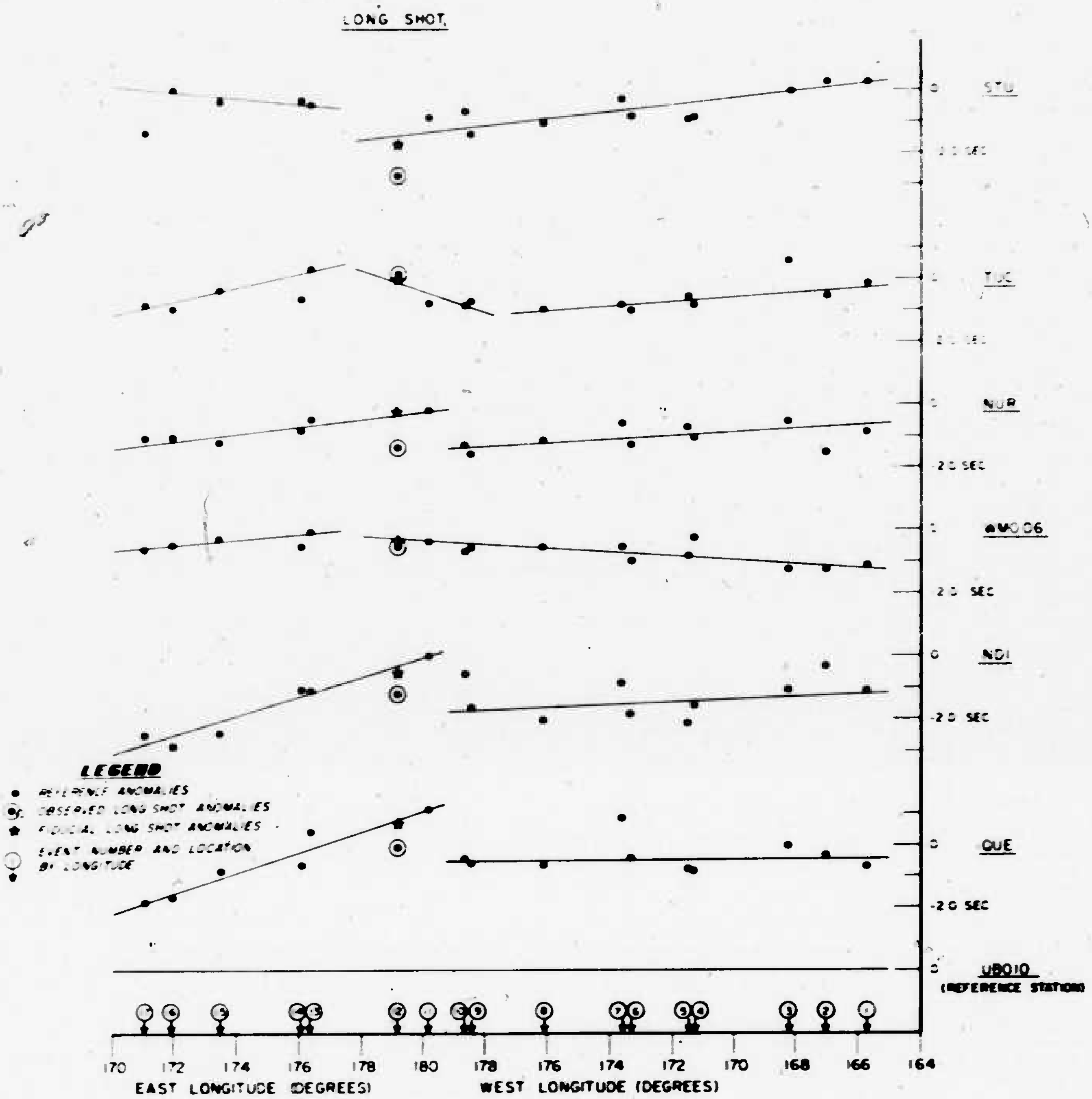

Figure 20b. Functional anomalies determined from fiducial LONG SHOT location.

TABLE XII

LOCATION SHIFTS, STANDARD DEVIATIONS (σ), AND CLUSTERING EFFECT (SHIFTS FROM THE MEAN) OBTAINED BY APPLYING FIDUCIAL FUNCTIONAL ANOMALIES

Network	Fox 1 Location Shifts From Input (km)	Fox 1 (σ)	Fox 1 From Mean (km)	Fox 2 Location Shifts From Input (km)	Fox 2 (σ)	Fox 2 From Mean (km)	Fox 3 Location Shifts From Input (km)	Fox 3 (σ)	Fox 3 From Mean (km)	Fox 4 Location Shifts From Input (km)	Fox 4 (σ)	Fox 4 From Mean (km)
1	[illegible]	[illegible]	.1	[illegible]	.333	[illegible]	10.1	.36[illegible]	[illegible]	[illegible]	.254	0.8
2	8.5	[illegible]	1.[illegible]	15.1*	.119	11.[illegible]	4.[illegible]	.34[illegible]	5.6	0.6	.1[illegible]3	1.0
3	[illegible]	.[illegible]20	[illegible].0	3.9	.058	[illegible].0	13.[illegible]	.31[illegible]	1.1	6.0	.268	3.[illegible]
4	16.1*	.126	20.0	[illegible]	[illegible]	[illegible].8	20.6*	.31[illegible]	13.6	4.8	.244	1.6
Mean	[illegible].9	.24[illegible]	1.[illegible]	1[illegible]	.150	[illegible].5	9.6	.310	3.5	3.1	.2[illegible]5	[illegible].4

Network	Fox 5 Location Shifts From Input (km)	Fox 5 (σ)	Fox 5 From Mean (km)	And 6 Location Shifts From Input (km)	And 6 (σ)	And 6 From Mean (km)	And 7 Location Shifts From Input (km)	And 7 (σ)	And 7 From Mean (km)	And 8 Location Shifts From Input (km)	And 8 (σ)	And 8 From Mean (km)	And 9 Location Shifts From Input (km)	And 9 (σ)	And 9 From Mean (km)
1	5.[illegible]	[illegible]	1.[illegible]	1.5	.[illegible]18	1.[illegible]	5.1	[illegible]	0.[illegible]	[illegible].1	.[illegible]13	0.4	1.0	.142	[illegible].0
2	6.1	.[illegible]70	1.[illegible]	5.[illegible]	[illegible]	[illegible]	5.8	.[illegible]05	[illegible]	[illegible]	.[illegible]89	3.[illegible]	[illegible].1	.141	4.8
3	5.5	.182	1.6	5.1	.1[illegible]	1.1	9.3	.[illegible]1	1.[illegible]	[illegible]	.011	[illegible]	3.0	.105	[illegible].0
4	5.3	.110	0.4	18.8*	.1[illegible]1	1[illegible]	1.4*	.180	[illegible]	1[illegible]*	.08[illegible]	11.8	4.[illegible]	.040	6.8
Mean	5.6	.196	1.1	[illegible]	.1[illegible]1	[illegible]	7.1	[illegible]	1.[illegible]	1[illegible]	.18[illegible]	[illegible]	3.9	.11[illegible]	3.9

Network	Vol 10 Location Shifts From (km)	Vol 10 (σ)	Vol 10 From (km)	Vol 11 Location Shifts From (km)	Vol 11 (σ)	Vol 11 From (km)	Bat 12 Location Shifts From (km)	Bat 12 (σ)	Bat 12 From (km)	Bat 13 Location Shifts From (km)	Bat 13 (σ)	Bat 13 From (km)	Bat 14 Location Shifts From (km)	Bat 14 (σ)	Bat 14 From (km)
1	8.[illegible]	.[illegible]56	0.8	6.0	.[illegible]21	0.8	1.4	.111	1.[illegible]	8.6	.[illegible]9	[illegible].4	8.9	.[illegible]83	[illegible]
2	15.3	.[illegible]24	3.6	[illegible].3	.150	1.9	2.4	.109	[illegible].1	9.[illegible]	.354	3.6	4.4	.269	10.4
3	5.0	.[illegible]30	[illegible]	1[illegible].3	.1[illegible]	6.1	1.5	.104	1.[illegible]	[illegible].6	.110	[illegible].0	19.6	.163	8.8
4	11.[illegible]	.150	[illegible].1	[illegible].4*	.144	[illegible].8	4.0	.070	4.0	[illegible]	.0[illegible]	3.2	14.[illegible]	.[illegible]76	6.4
Mean	[illegible].6	.[illegible]16	3.0	6.9	.18[illegible]	[illegible]	[illegible]	.099	[illegible]	[illegible].6	.208	[illegible].8	11.9	.[illegible]18	[illegible]

Network	Neat 15 Location Shifts From (km)	Neat 15 (σ)	Neat 15 From (km)	Neat 16 Location Shifts From Input (km)	Neat 16 (σ)	Neat 16 From Mean (km)	Neat 17 Location Shifts From Input (km)	Neat 17 (σ)	Neat 17 From Mean (km)	Average of Shifts from Mean (km)
1	[illegible].9	[illegible]	1.[illegible]	[illegible].1	.193	1.[illegible]	[illegible]	.1[illegible]	1.0	1.[illegible]
2	5.6	[illegible]	[illegible]	[illegible].3	[illegible]	[illegible]	[illegible]	[illegible]	1.0	1.[illegible]
3	[illegible].1	.1[illegible]	1.[illegible]	[illegible].8	.[illegible]1	1.[illegible]	[illegible]*	[illegible]	[illegible]	[illegible].1
4	15.6*	[illegible]	1[illegible]	11.8*	.151	10.1	[illegible]1*	.[illegible]09	[illegible]	11.[illegible]
Mean	[illegible]	[illegible]	[illegible]	1.8	[illegible]	[illegible]	[illegible].1	.106	[illegible]	[illegible]

*Not included in figuring mean

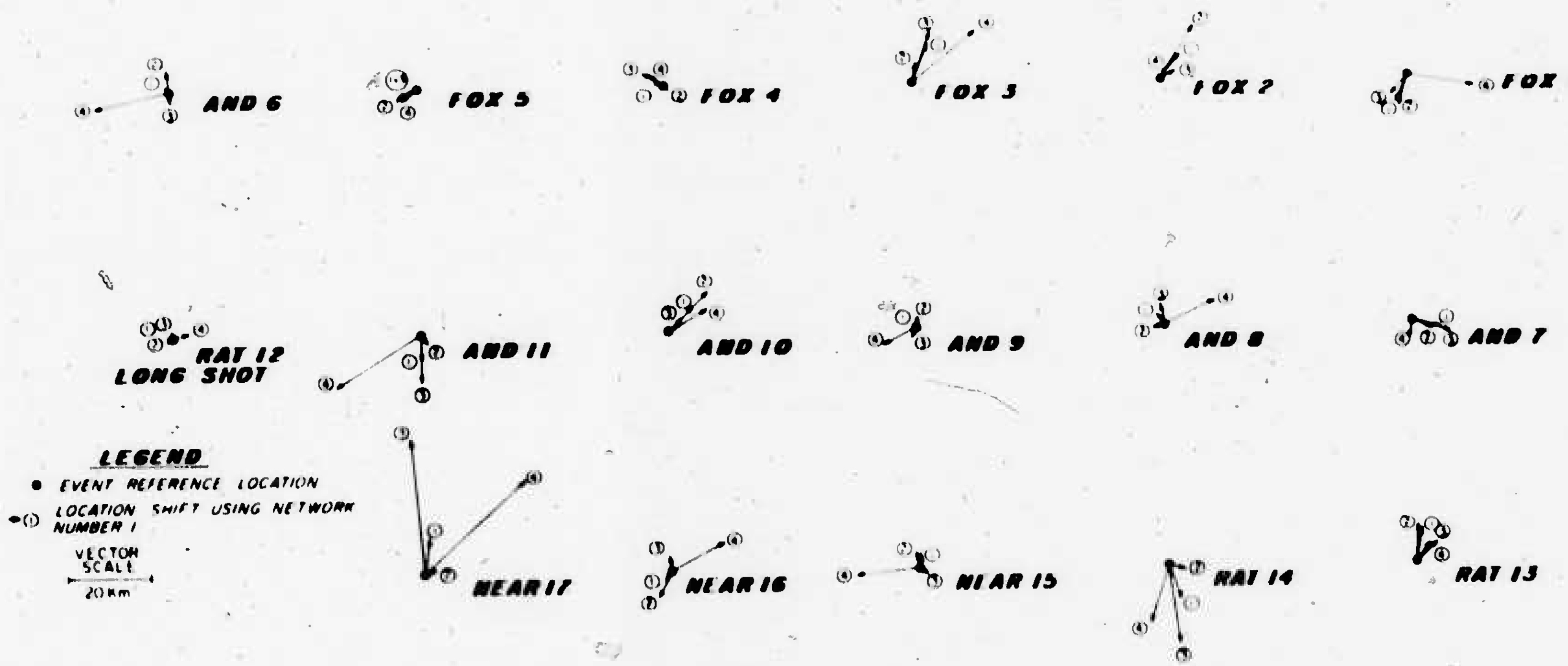

Figure 21. Location shifts for four networks obtained by applying fiducial LONG SHOT functional anomalies.

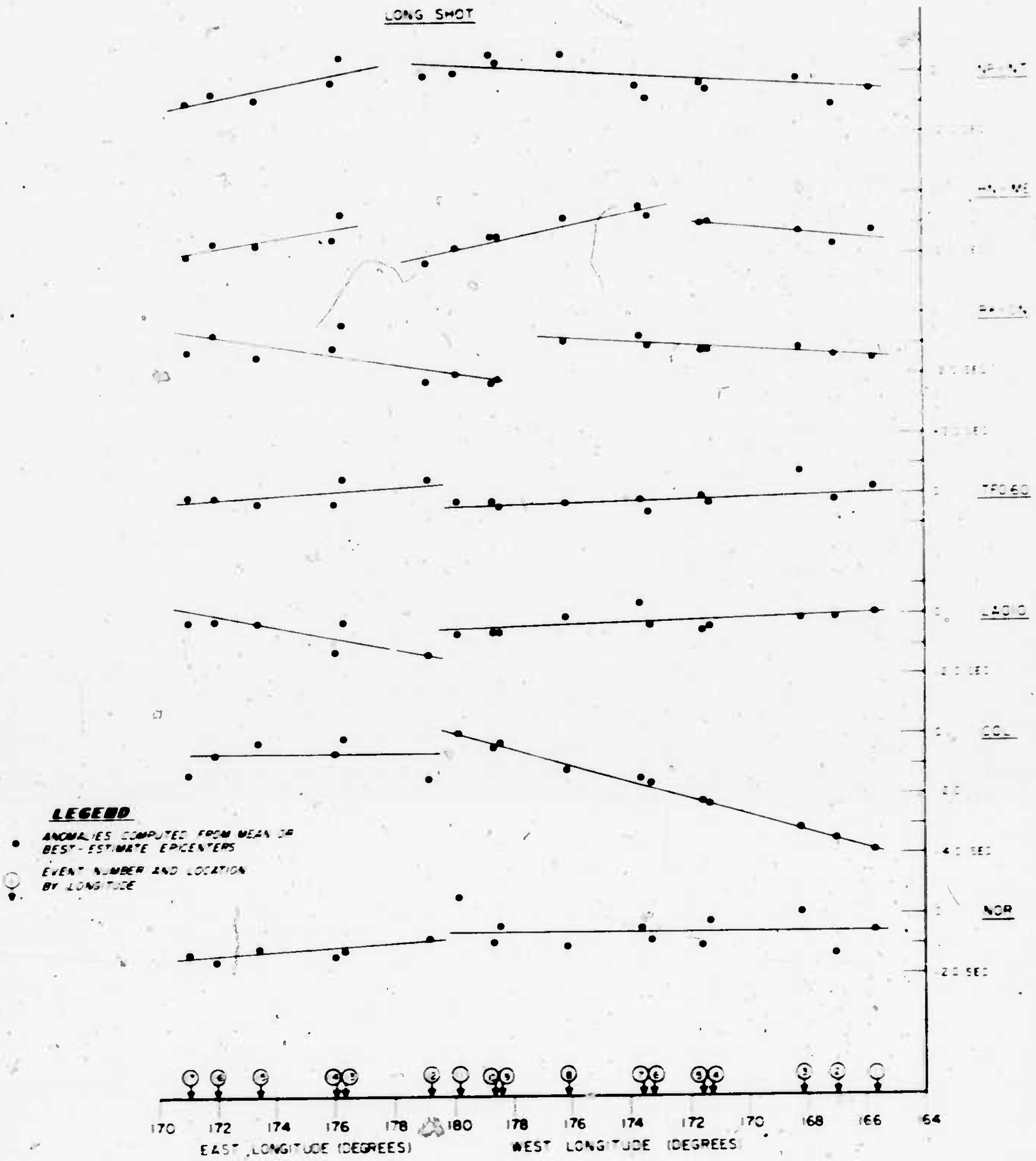

Figure 22a. Anomalies computed from "best estimate" epicenters as determined using fiducial functional anomalies.

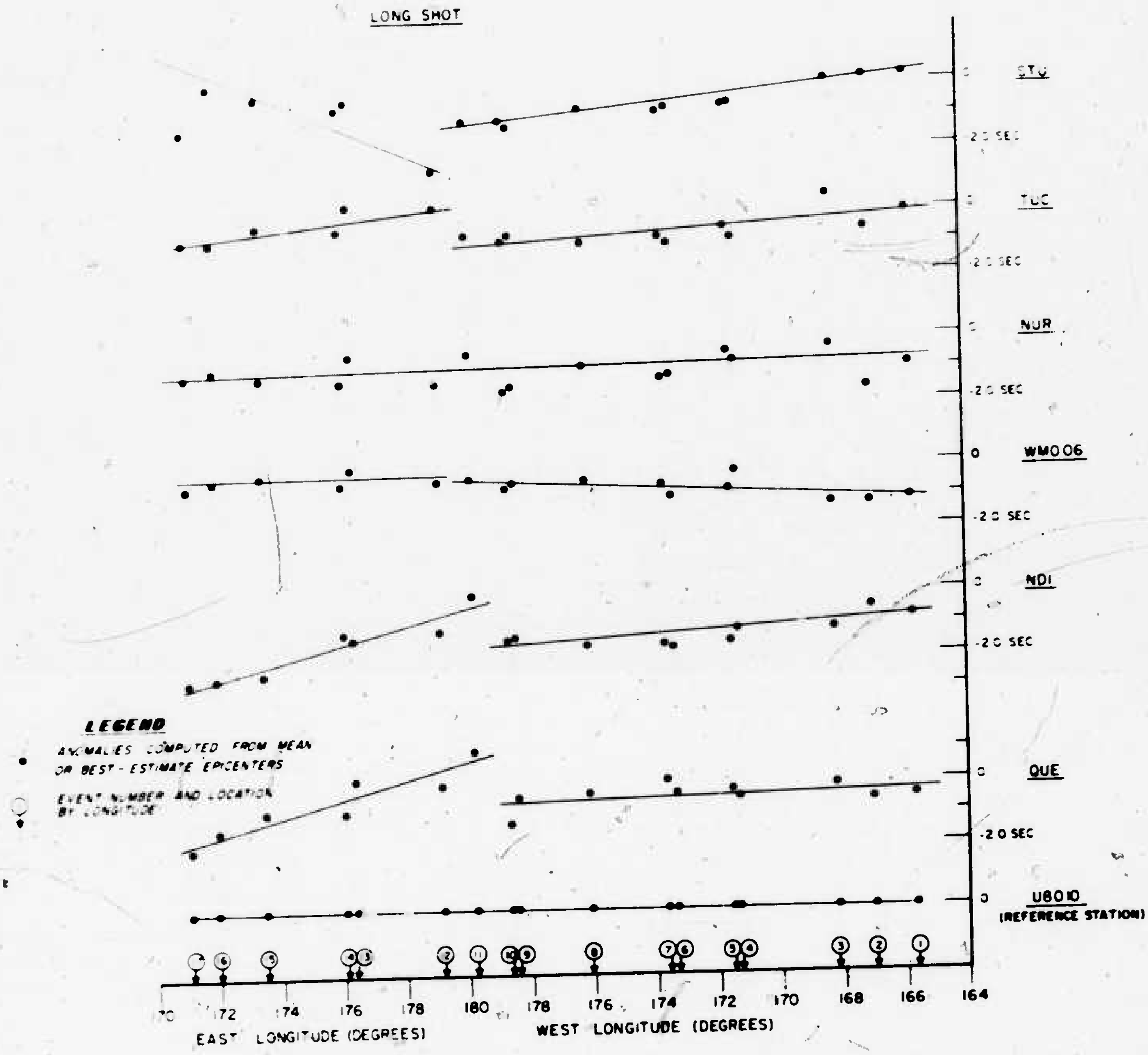

Figure 22b. Anomalies computed from "best estimate" epicenters as determined using fiducial functional anomalies.

Aleutian functional anomalies

Because it is known that LONG SHOT is actually mislocated by 21 km to the north-northwest, we see that to obtain anomalies which yield small absolute location errors LONG SHOT, and to some degree the other events, must be shifted toward the south-east. One would choose to shift them in such a way that the anomaly functions are further smoothed out. One of the guiding observations in determining which events to shift, and by how much, is the apparent "anomaly discontinuity" displayed by many of the stations (especially STU, NDI, QUE, and RK-ON) in the vicinity of 179°W (Andreanof-10 and -11). The reason for this discontinuity is traceable to the original mislocation effect in the Aleutians, but why it exists is presently not known. Another guiding observation is that the only quantitative bias information available is that provided from the LONG SHOT shift, which amounts to 21 km toward the north-northwest. With these guidelines, we choose to shift the positions of all of the events between Andreanof-11 and Near-17 21 km to the south-southeast from their respective "best estimates". All events between Andreanof-10 and Fox-1 were not shifted at all from their "best estimates". The plots of the anomalies computed from the variably shifted locations and the new anomaly functions which result are shown in Figures 23a and 23b. Although the discontinuity remains, it has been reduced, and the functions are slightly more continuous. We choose these "Aleutian functional" anomalies to be the best ones to apply when any combination of stations in Network 1 is used to locate events in the Aleutian Islands region.

The results obtained by applying the Aleutian functional anomalies are shown in Figure 24 for the four networks and are summarized in Table XIII. The corresponding final "best estimates" of the epicenters are given in Table XIV with the shifts from both the original NOS and the Adjusted locations in Table I.

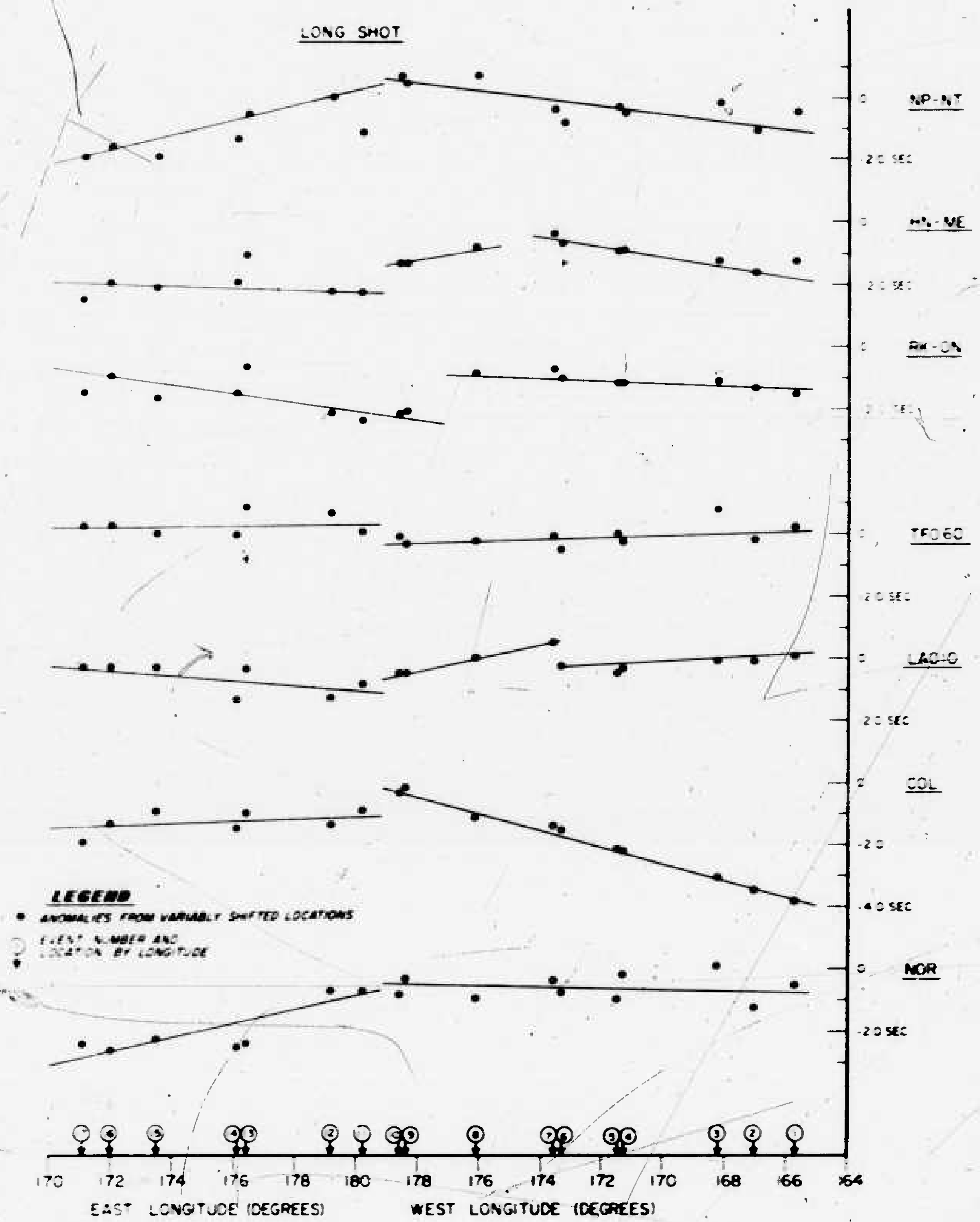

Figure 23a. Determination of Aleutian functional anomalies.

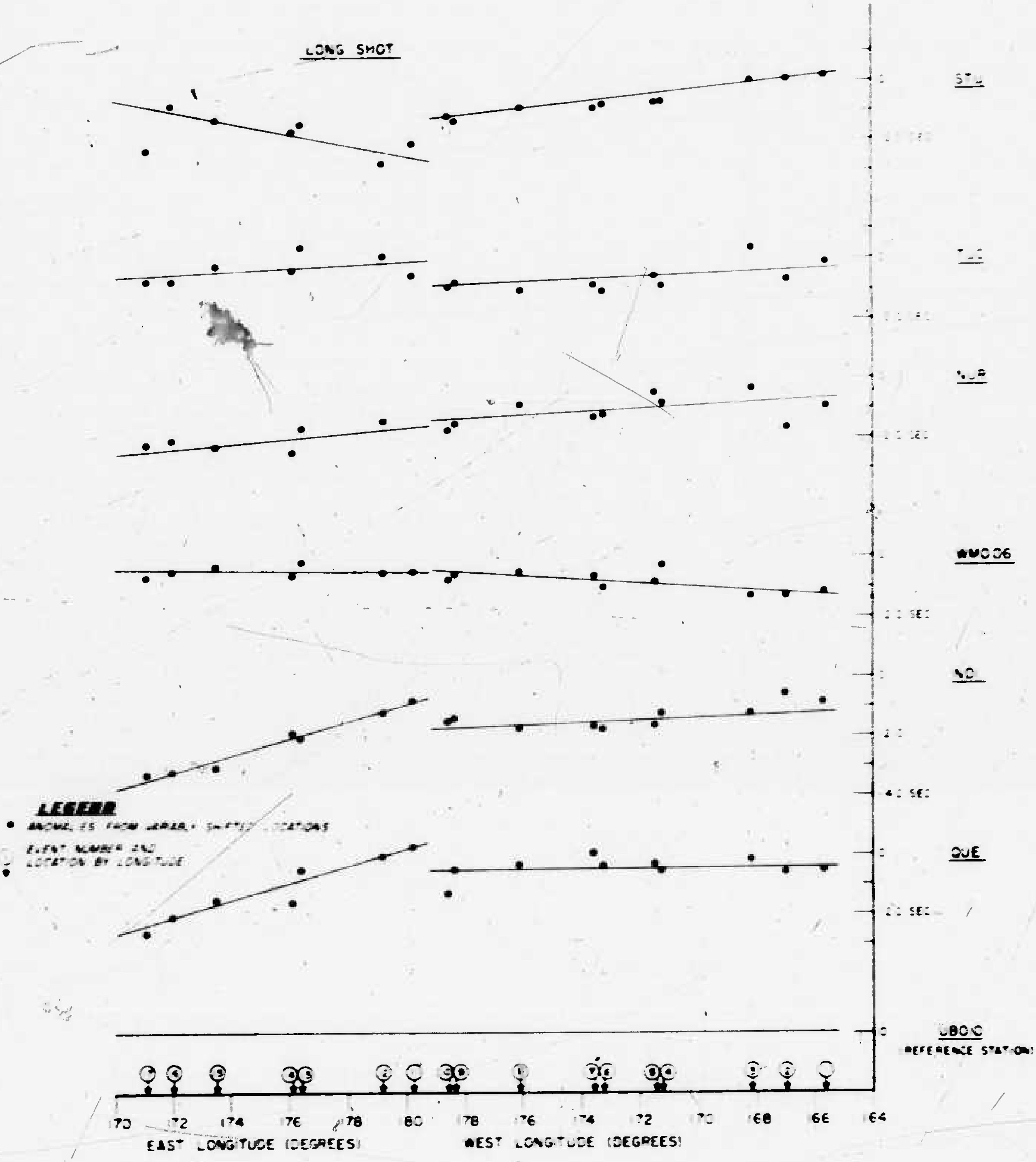

Figure 23b. Determination of Aleutian functional anomalies.

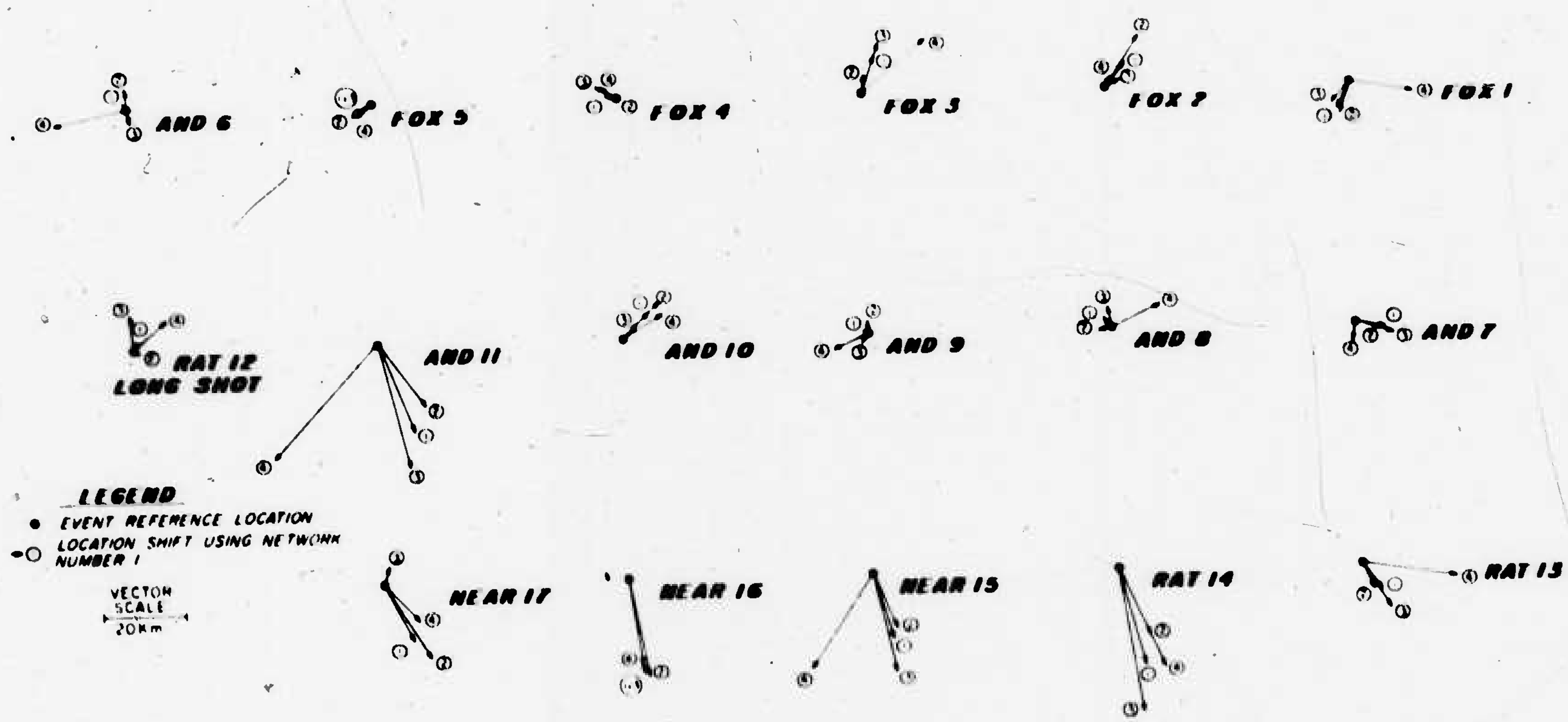

Figure 24. Location shifts for four networks using Aleutian functional anomalies.

TABLE XIII

LOCATION SHIFTS, STANDARD DEVIATIONS (σ), AND CLUSTERING EFFECT (SHIFTS FROM THE MEAN) OBTAINED BY APPLYING ALEUTIAN FUNCTIONAL ANOMALIES

Network	Fox 1 Location Shifts From Input (km)	Fox 1 (σ)	Fox 1 From Mean (km)	Fox 2 Location Shifts From Input (km)	Fox 2 (σ)	Fox 2 From Mean (km)	Fox 3 Location Shifts From Input (km)	Fox 3 (σ)	Fox 3 From Mean (km)	Fox 4 Location Shifts From Input (km)	Fox 4 (σ)	Fox 4 From Mean (km)	Fox 5 Location Shifts From Input (km)	Fox 5 (σ)	Fox 5 From Mean (km)	And 6 Location Shifts From Input (km)	And 6 (σ)	And 6 From Mean (km)	And 7 Location Shifts From Input (km)	And 7 (σ)	And 7 From Mean (km)	And 8 Location Shifts From Input (km)	And 8 (σ)	And 8 From Mean (km)	And 9 Location Shifts From Input (km)	And 9 (σ)	And 9 From Mean (km)
1	[illegible]	.248	0.4	[illegible]	.333	2.8	10.4	.362	0.4	2.3	.251	0.8	5.[illegible]	.222	1.2	1.[illegible]	.218	1.[illegible]	2.1	[illegible]	0.8	3.1	[illegible]	0.4	1.0	.142	2.0
2	8.5	[illegible]	1.2	15.4*	.319	11.2	4.[illegible]	.342	5.6	0.6	.173	4.0	6.1	.220	1.2	5.[illegible]	.208	1.[illegible]	5.8	.205	2.0	3.[illegible]	.289	3.2	2.4	.144	4.8
3	[illegible]	.210	2.0	5.9	.058	2.0	13.[illegible]	.315	4.4	6.0	.268	3.2	5.5	.182	1.6	5.1	.148	1.[illegible]	9.3	[illegible]	1.6	5.6	.044	3.2	3.0	.105	2.0
4	16.1*	.126	20.0	2.6	.058	2.8	20.6*	.313	13.6	4.8	.244	1.6	5.3	.110	0.4	18.8*	.191	10.[illegible]	1.4*	.150	8.8	13.5*	.087	14.8	9.2	.080	6.8
Mean	5.9	.24[illegible]		4.[illegible]	.150	2.5	9.6	.340	5.5	3.4	.235	2.4	5.6	.196	1.1	3.3	.191	[illegible]	5.4	[illegible]	1.5	4.2	.182	2.3	3.9	.117	3.9

Network	And 10 Location Shifts From Input (km)	And 10 (σ)	And 10 From Mean (km)	And 11 Location Shifts From Input (km)	And 11 (σ)	And 11 From Mean (km)	Rat 12 Location Shifts From Input (km)	Rat 12 (σ)	Rat 12 From Mean (km)	Rat 13 Location Shifts From Input (km)	Rat 13 (σ)	Rat 13 From Mean (km)	Rat 14 Location Shifts From Input (km)	Rat 14 (σ)	Rat 14 From Mean (km)	Semi 15 Location Shifts From Input (km)	Semi 15 (σ)	Semi 15 From Mean (km)	Semi 16 Location Shifts From Input (km)	Semi 16 (σ)	Semi 16 From Mean (km)	Semi 17 Location Shifts From Input (km)	Semi 17 (σ)	Semi 17 From Mean (km)	Average of Shifts from Mean (km)
1	8.[illegible]	.256	0.8	[illegible]	.133	1.2	2.0	.254	2.4	8.0	.400	1.2	25.0	.232	1.6	1[illegible]	[illegible]	1.5	[illegible]	[illegible]	0.1	16.0	.171	2.0	1.2
2	15.3	[illegible]	5.6	12.8	.465	8.0	1.5	.1[illegible]	5.6	6.[illegible]	.455	2.4	19.3	.19[illegible]	8.8	16.6	.261	1.8	[illegible]	[illegible]	1.6	21.5	.251	5.2	1.5
3	[illegible]	.250	[illegible]	[illegible]	.181	8.1	8.1	.188	5.6	12.9	.289	1.9	30.1	.303	13.2	[illegible]	.128	[illegible]	[illegible]	[illegible]	0.1	1.5	.314	20.8	5.1
4	11.[illegible]	.250	2.1	32.0*	.358	30.4	10.5	.167	[illegible]	33.8*	.365	19.2	[illegible]	[illegible]	1.[illegible]	5.1*	[illegible]	[illegible]	[illegible]	[illegible]	2.0	1[illegible]*	.269	4.8	10.0
Mean	[illegible]	.21[illegible]	3.0	23.1	.361	[illegible]	5.5	.192	[illegible]	[illegible]	.381	[illegible]	26.6	[illegible]	[illegible]	19.0	[illegible]	4.1	[illegible]	[illegible]	1.1	16.9	.330	4.0	5.4

*Not included in forming mean

TABLE XIV

Final Best-Estimates of Event Set Located with Aleutian Functional Anomalies

Event	Mean or Best-Estimate Locations Latitude (Degrees)	Longitude (Degrees)	Shift From NOS LOCATION km	Shift From Adjusted Location km
Fox 1	53.583 N	165.727 W	12	8
Fox 2	52.743 N	166.931 W	1	5
Fox 3	52.646 N	168.163 W	6	10
Fox 4	52.082 N	171.372 W	8	3
Fox 5	52.008 N	171.535 W	19	6
And 6	51.682 N	175.361 W	8	1
And 7	51.609 N	173.487 W	11	8
And 8	51.402 N	176.121 W	10	4
And 9	51.452 N	178.482 W	5	3
And 10	51.528 N	178.385 W	4	10
And 11	51.088 N	179.628 W	30	26
Long Shot	51.472 N	179.214 E	5	5
Rat 13	51.703 N	176.507 E	14	9
Rat 14	51.663 N	176.196 E	28	27
Near 15	52.292 N	173.621 E	17	19
Near 16	52.670 N	172.114 E	28	24
Near 17	53.004 N	171.217 E	12	17
		Average Shift	13	10

Several things have been accomplished with these Aleutian functional anomalies: (1) a tight location cluster (within about 5 km, 8 km if one includes the readings with asterisks) using three or four different networks; (2) acceptably low standard deviations (about 0.25 sec) for all networks and events; and (3) reasonable functional anomalies for each station.

The question persists, though, of the absolute and relative accuracy of location throughout the entire region. The anomaly functions were derived using assumed locations for the events. That these assumed locations are incorrect by an unknown amount is beyond reasonable doubt. However, as long as it is known which events were used to determine the functions, all subsequent events can be referenced to them, almost as if it did not matter what their actual location errors may have been. When and if an event occurs somewhere in the Aleutian Islands other than on Amchitka Island, under conditions such that its location is accurately known, the anomalies can be recomputed and the anomaly functions translated to accommodate the additional constraint. The position of this additional event may be accurately known due to it being another explosion (far away from Amchitka), due to its being recorded by a local high quality network, or due to clear surficial intensity effects (faulting, jointing, etc). The latter criterion can only serve to remove gross bias, because visible effects from earthquakes depend on many factors besides epicentral distance; this is further complicated by the Aleutian Islands region itself, being composed of small and sometimes uninhabited islands, thereby limiting the areal observation of intensity. But regardless of the availability of calibration events, as pointed out in an earlier section it is important that one first achieve consistency throughout a region, and then concentrate on removing bias by detailed empirical studies.

The nature of these studies can be briefly outlined. Select a network composed of more stations than were used in this report, perhaps 30, such that at least six or eight stable network subsets can be used. Unstable networks (as Network 4) should not be included. Increase the number of events to a far larger number than used here, perhaps 40. Critically read and re-read arrival times for all events at all stations. Using the constraints of network clustering, goodness-of-fit, anomalies from known explosions or "well located" earthquakes, reasonable functions (perhaps linear, but at least smoothly varying), and maximum permissible anomaly values, one could program and determine in a least-squares sense the best fit of all locations.

Aleutian regional anomalies

The derived anomaly functions shown in Figures 23a and 23b generally vary nearly continuously with longitude. This result may appear to be at variance with the conclusions drawn in previous reports (Chiburis 1968; Chiburis and Ahner, 1970), wherein station anomalies, determined from spatially separated explosions, were shown to be essentially constant, at least across an area approximately 70 km x 25 km. However, it must be pointed out that the functions derived in this report are made to change continuously for two reasons: (1) most of the events are farther apart than the distance over which the anomalies would normally be expected to be constant (probably about 100 km), such that a single anomaly could not be sensibly used as a correction; and (2) convenience. In spite of this, and also to provide a single value for a finite region, constant anomalies within regions of the Aleutian Islands can be determined from the values shown in Figures 23a and 23b by averaging several anomalies over areas somewhat larger than desirable. Because of the lack of events, the regions and the constant anomalies are arbitrary, as the results of determining the step functions indicate in Figures 25a and 25b. The location results obtained by using these regional anomalies are summarized in Table XV, in which it can be seen that good clustering and low standard deviations are being achieved to about the same degree as in the Aleutian functional anomaly case. Interestingly enough, the only event for which Network 4 was not included in the results is Andreanof-11. This suggests that perhaps constant anomalies over fairly broad regions may provide more stability to networks with geometries like Network 4.

In an operational sense, the regional anomalies thus determined (Figures 25a and 25b) are the ones to apply when locating events in the Aleutian Islands with any combination of the 14 stations in this report.

Incidentally, additional stations can be added to this 14-station network by first locating one or (better) several events with those stations having anomalies. With the resultant epicenters, an (average) anomaly can then be computed for the station to be added. For subsequent events in that region, the original network and the new station (or subsets of them) can now be used for locating. In this "bootstrapping" way, any number of new stations can be incorporated into an existing network such that eventually all stations of any importance would be able to contribute equally and consistently to any solution.

Summarizing the results of fitting functions to the observed anomalies in various ways, we conclude that the set of constant regional functions derived are plausible and estimate the station anomalies for events in the Aleutians. The anomalies, when applied as corrections, are believed capable of providing more accurate <u>relative</u> locations for events between the Fox Islands and the Near Islands.

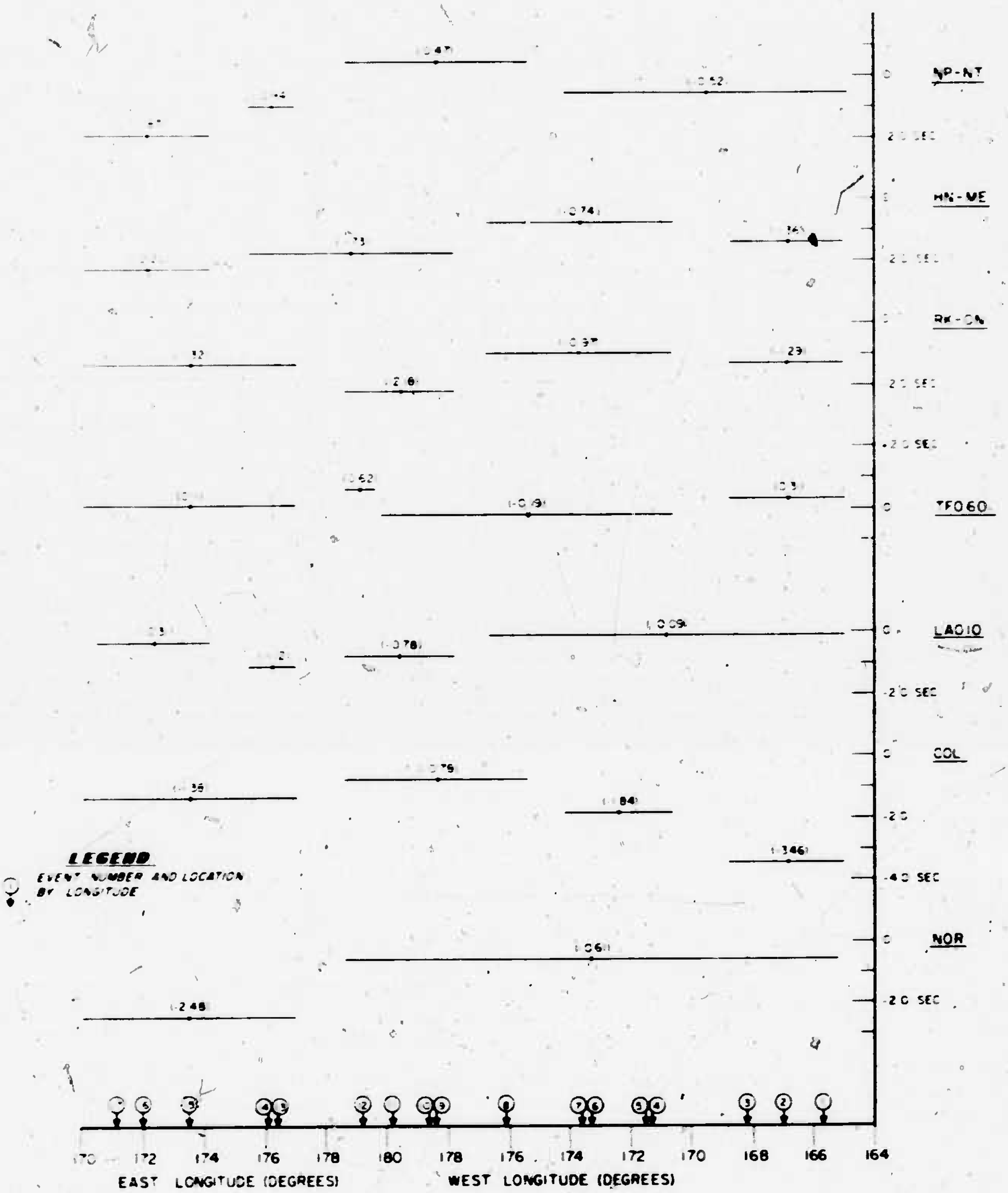

Figure 25a. Regional anomalies for Aleutian Islands events.

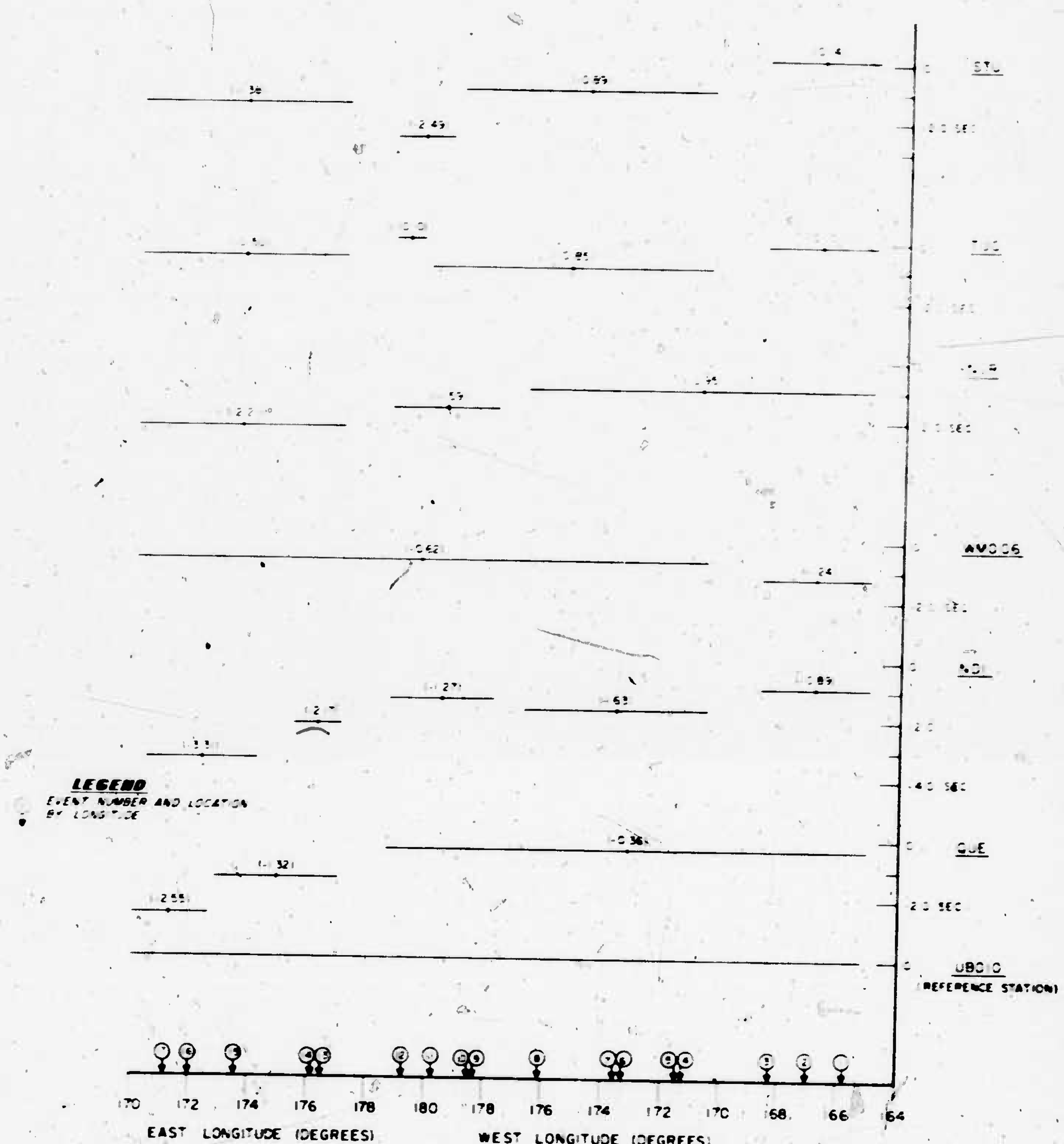

Figure 25b. Regional anomalies for Aleutian Islands events.

TABLE XV

LOCATION SHIFTS, STANDARD DEVIATIONS (σ), AND CLUSTERING EFFECT (SHIFTS FROM THE MEAN) OBTAINED BY APPLYING REGIONAL ANOMALIES

Network	Fox 1 Location Shifts From Input (km)	(σ)	From Mean (km)	Fox 2 Location Shifts From Input (km)	(σ)	From Mean (km)	Fox 3 Location Shifts From Input (km)	(σ)	From Mean (km)	Fox 4 Location Shifts From Input (km)	(σ)	From Mean (km)	Fox 5 Location Shifts From Input (km)	(σ)	From Mean (km)
1	5.6	.130	3.6	6.0	.301	3.2	5.4	.283	0.8	3.2	.221	1.6	2.5	.247	2.4
2	?.2	.0??	2.0	13.8	.312	10.4	1.9	.299	6.0	1.9	.136	3.2	4.7	.288	4.8
3	5.0	.144	3.2	2.8	.160	4.4	8.5	.211	3.2	6.0	.234	3.6	1.4	.179	1.6
4	4.2	.116	5.6	11.4	.139	13.2	8.5	.180	3.6	9.4	.171	4.8	6.5	.190	7.6
Mean	5.5	.116	3.6	8.5	.228	7.8	6.1	.243	3.4	5.1	.190	3.3	3.8	.226	4.1

Network	And 6 Location Shifts From Input (km)	(σ)	From Mean (km)	And 7 Location Shifts From Input (km)	(σ)	From Mean (km)	And 8 Location Shifts From Input (km)	(σ)	From Mean (km)	And 9 Location Shifts From Input (km)	(σ)	From Mean (km)
1	2.1	.170	[illegible]	7.1	.222	1.6	4.6	.169	3.2	8.1	.201	2.4
2	2.7	.093	[illegible]	6.9	.176	0.4	4.0	.193	6.4	5.0	.123	4.4
3	7.0	.070	5.6	8.6	.214	2.8	7.6	.085	3.2	10.8	.245	1.2
4	11.5	.158	8.0	7.2	.167	3.2	11.8	.117	8.8	14.1	.181	5.2
Mean	5.8	.123	5.5	7.4	.195	2.0	7.0	.141	5.4	9.5	.188	3.3

Network	And 10 Location Shifts From Input (km)	(σ)	From Mean (km)	And 11 Location Shifts From Input (km)	(σ)	From Mean (km)	Rat 12 Location Shifts From Input (km)	(σ)	From Mean (km)	Rat 13 Location Shifts From Input (km)	(σ)	From Mean (km)	Rat 14 Location Shifts From Input (km)	(σ)	From Mean (km)
1	2.1	.207	1.2	15.2	.381	0.8	8.4	.195	1.6	10.7	.292	1.6	27.2	.159	2.0
2	6.9	.112	4.0	13.4	.408	6.8	5.1	.149	2.8	13.4	.315	4.8	24.3	.121	8.0
3	2.8	.183	6.4	22.4	.252	7.2	12.4	.166	3.2	8.0	.255	4.4	30.5	.080	3.2
4	7.1	.160	4.0	38.0*	.196	44.4	9.8	.205	1.2	16.5	.249	6.4	29.5	.093	5.6
Mean	4.7	.166	3.9	17.0	.346	4.9	8.9	.179	2.2	12.2	.278	4.3	27.9	.113	4.5

Network	Near 15 Location Shifts From Input (km)	(σ)	From Mean (km)	Near 16 Location Shifts From Input (km)	(σ)	From Mean (km)	Near 17 Location Shifts From Input (km)	(σ)	From Mean (km)	Average of Shifts from Mean (km)
1	20.0	.214	[illegible]	22.8	.212	[illegible]	13.5	.273	4.8	2.2
2	16.7	.221	8.0	24.4	.221	4.8	18.?	.074	9.6	5.3
3	27.0	.127	5.6	23.2	.089	0.4	5.?	.1?3	11.6	4.2
4	24.5	.220	6.8	23.2	.093	[illegible]	10.5	.146	[illegible]	8.3
Mean	22.0	.190	5.8	23.4	.154	[illegible]	13.5	.166	9.3	5.0

*Best fit not used in forming mean

SYNTHETIC EARTH STUDIES

All the preceding results were obtained using real events and real arrival time data recorded by fourteen stations. These data necessarily contain time errors which are due to (1) reading precision because of less than perfect signal quality; (2) unaccountable travel-path effects (anomaly instability); and (3) station timing system errors. It would be desirable to completely eliminate the last two types of errors and to be able to concentrate on investigating particular aspects of the functional anomaly technique in order to verify or refute the general method. To achieve this, a data set was synthesized by assuming that the Herrin (1968) tables are perfect; from this ideal earth, theoretical arrival times were computed at the same fourteen stations for twelve hypothetical events equispaced across the Aleutians from the Fox to the Near Islands, but including the known LONG SHOT location in the Rat Islands. The latitudes and longitudes of the hypothetical events plus LONG SHOT are given in Table XVI. For simplicity, all events were assumed to have surface foci. The effect of ever-present reading error was incorporated in the following manner: a set of numbers was drawn randomly from a normal population (Huntsberger, 1961) by use of random number table. The set was then scaled to maintain a standard deviation of approximately 0.25 sec for each event, using all fourteen stations, by the relation

$$Y_i^j = (X_i^j - \overline{X}^j)\left[0.25(N-1)(S_x^j)^{-2}\right]$$

where Y_i^j is the random time error (attributable to reading) applied to the ith station for the jth event, X_i is the number drawn from the normal population, $\overline{X}^j$ is the mean of the X_i^j's

TABLE XVI

Event Parameters for 11 Hypothetical Epicenters Plus LONG SHOT

Event	Latitude (Degrees)	Longitude (Degrees)
Fox 1	53.50 N	166.00 W
Fox 2	53.00 N	168.00 W
Fox 3	52.40 N	170.00 W
And 4	52.00 N	172.00 W
And 5	51.60 N	174.00 W
And 6	51.50 N	176.00 W
And 7	51.50 N	178.00 W
Rat 8 (Long Shot)	51.44 N	179.18 E
Rat 9	51.40 N	178.00 E
Rat 10	51.60 N	176.00 E
Near 11	52.20 N	174.00 E
Near 12	52.80 N	172.00 E

for the jth event, N is the number of stations (14), and $(S_x^j)^2$ is the variance of the numbers drawn for the jth event. The entire set of random errors is given in Table XVII by station and by event. No random errors were applied to LONG SHOT, because when the anomalies (determined with real arrival times) are considered, random errors are already included.

The location errors produced solely by these reading errors are shown in Figure 26 for the same network subsets as defined in the previous sections of this report (Table V). The average location errors for each network are as follows:

Network	Average Error, km
1	4.1
2	5.7
3	5.4
4	7.2

These errors generally reflect a lower limit of accuracy expected for each network in locating events in the Aleutian Islands when reading errors are on the order of 0.25 sec.

Synthetic functional anomalies

Using the observed LONG SHOT anomalies as constraints, piecewise-linear synthetic functional anomalies were contrived for each station and are plotted in Figures 27a and 27b as functions of longitude. The only restrictions imposed on the synthetic functions were that they remain within reasonable anomaly ranges and that they contain no large discontinuities when viewed as a function of longitude.

If these anomalies, referred to as syn-1, are assumed to be caused by the synthetic earth, locations can be obtained using

TABLE XVII

Set of Random Errors Applied to Theoretical Arrival Times

Event	NP-NT	HN-ME	RK-ON	LAO10	WMO06	UBO10	TI060	TUC	COL	NOR	STU	NUR	QUI	NDI
Fox 1	.277	.089	.324	.168	.376	-.157	-.028	.081	-.320	-.241	-.439	.201	-.294	-.027
Fox 2	.046	-.004	.059	.064	.078	-.220	.173	-.211	-.542	.378	.182	-.300	-.110	.406
Fox 3	-.226	-.004	.000	.297	.125	.526	-.487	.057	-.330	.214	-.052	-.190	.093	-.022
AND 4	.172	-.164	-.422	.326	-.105	-.081	.258	-.313	-.088	.098	-.178	-.122	.529	.090
AND 5	.423	-.222	-.127	-.335	-.177	-.508	.353	.192	-.069	.088	.058	.059	.212	.053
AND 6	-.340	.342	.279	.125	-.013	-.048	-.022	.184	.247	.277	-.226	-.530	-.189	-.086
AND 7	.057	.264	-.220	.096	.450	-.130	.128	-.278	.275	.203	-.021	-.084	-.363	-.419
Long Shot	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
Rat 9	-.107	.140	-.085	.202	.058	.028	-.178	-.188	.275	.064	-.207	-.500	-.088	.587
Rat 10	-.334	.221	.002	.289	-.151	-.261	.447	.178	-.008	-.308	-.238	.084	-.231	.311
Near 11	-.527	.142	-.142	.169	-.212	.148	-.124	.403	-.343	-.033	.375	.132	-.051	.065
Near 12	-.127	-.189	-.417	.059	.298	.077	.292	.336	-.032	-.146	-.433	.277	.185	-.178

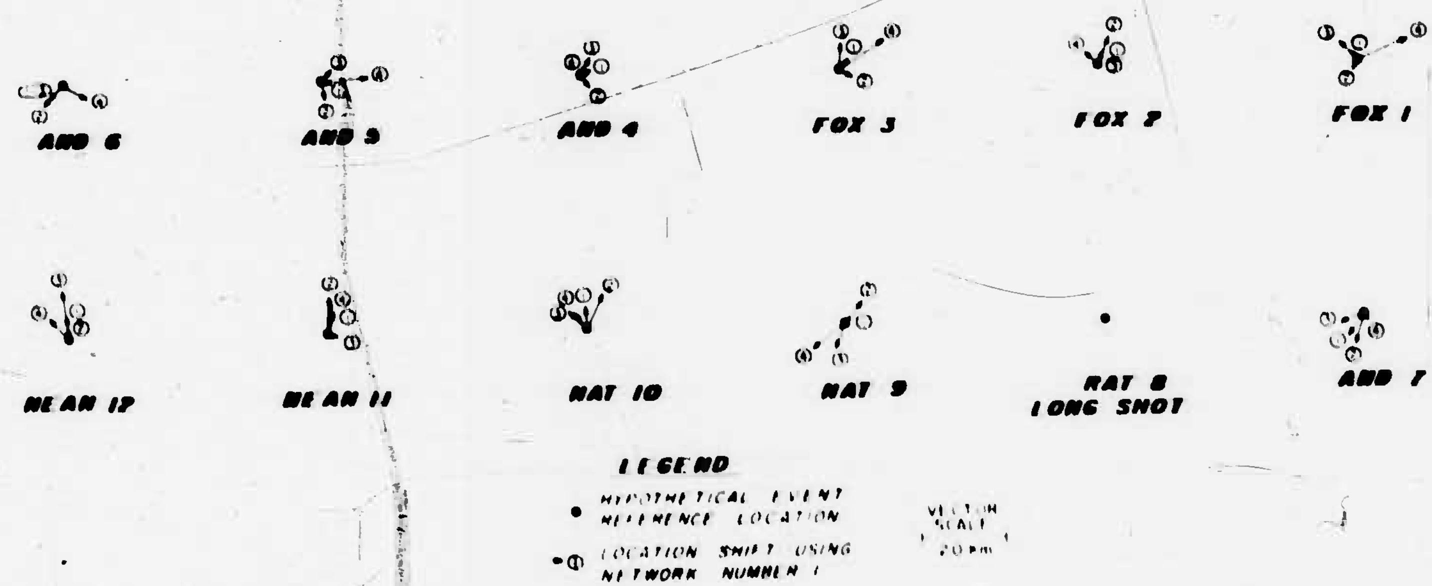

Figure 26. Location shifts of hypothetical events due to applied random errors (σ = 0.25 sec).

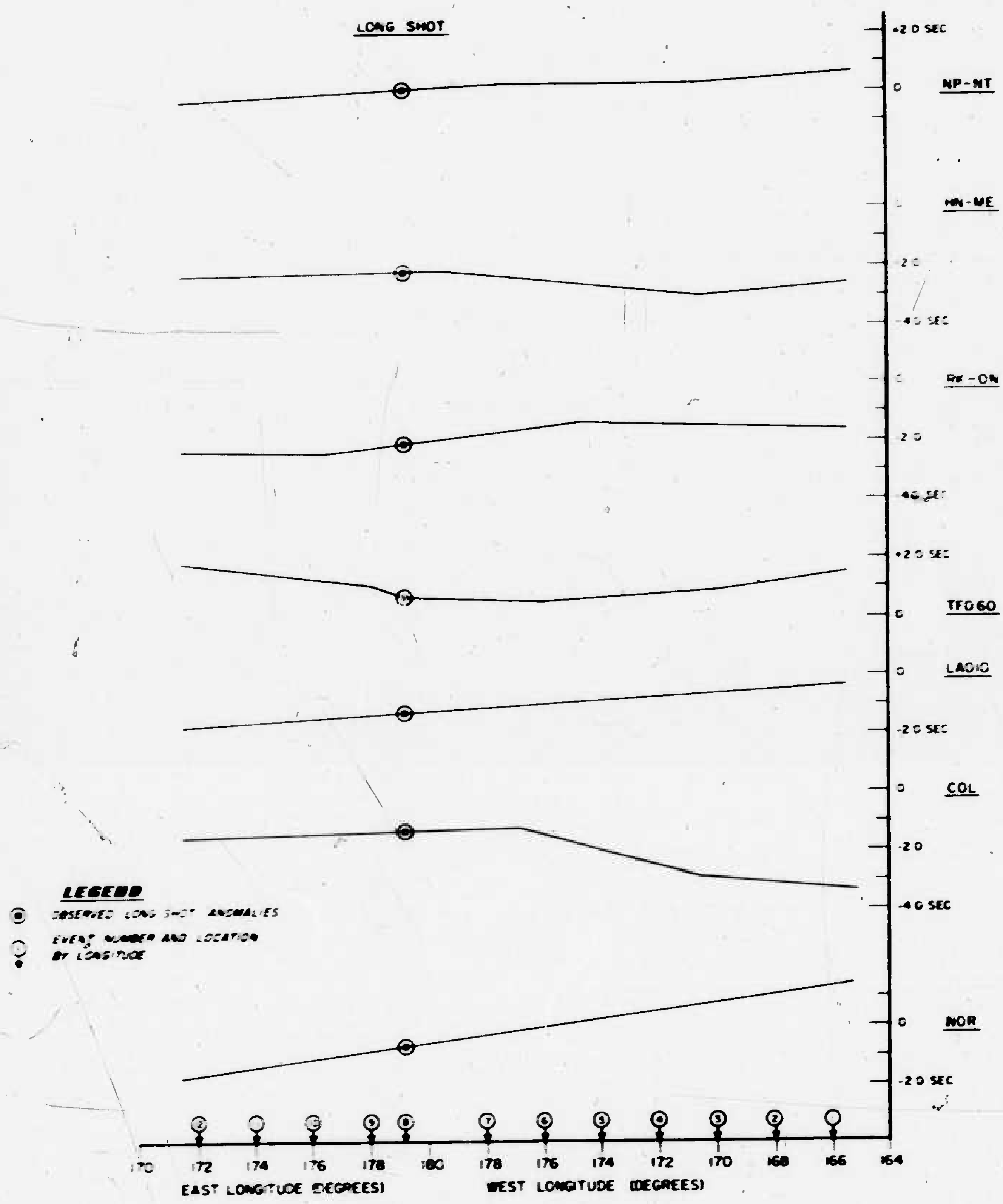

Figure 27a. Contrived functional anomalies (Syn-1) using synthetic data.

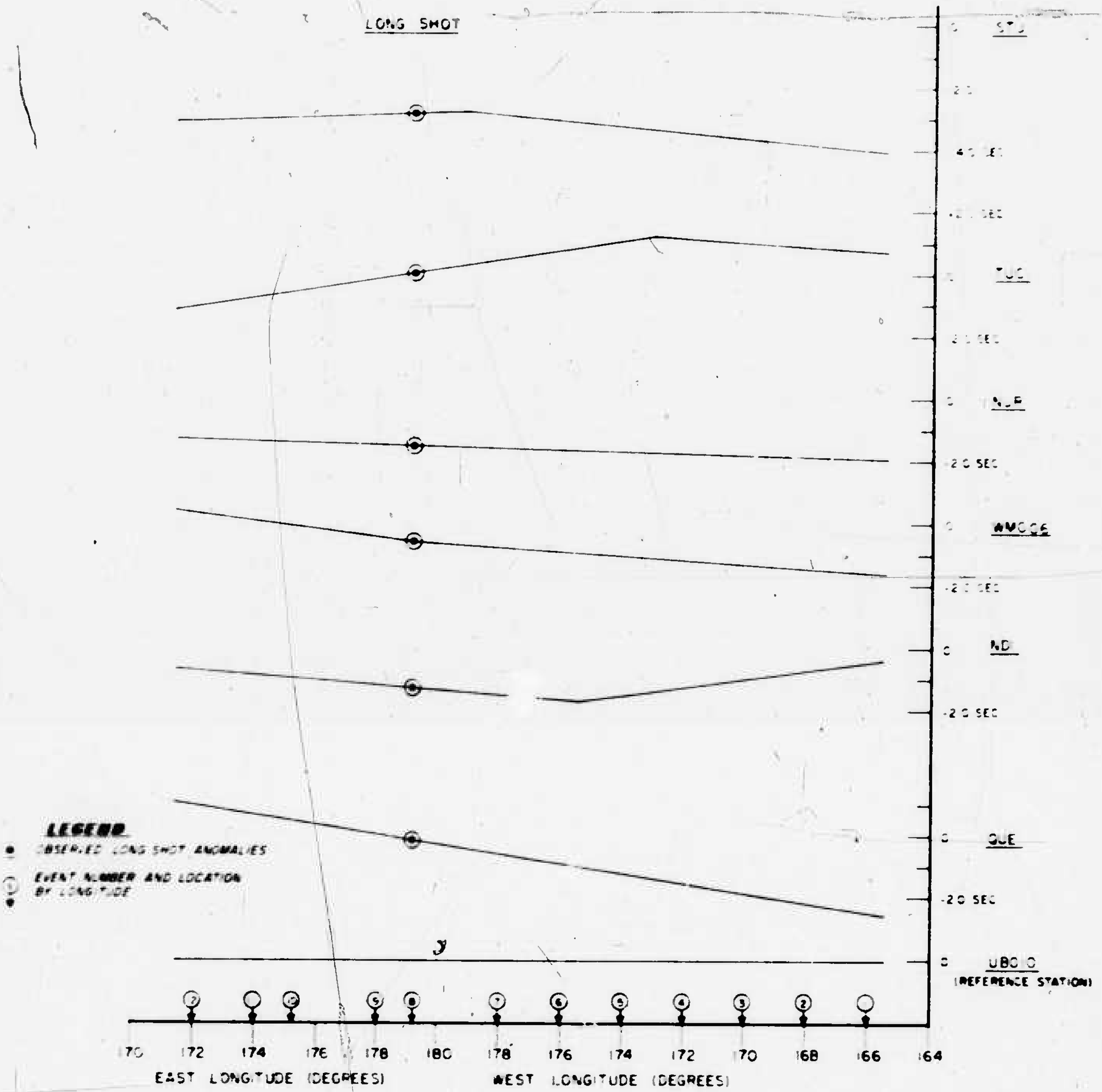

Figure 27b. Contrived functional anomalies (Syn-1) using synthetic data.

the four networks with no corrections applied. Symbolically, the arrival time T at station i for each event is made up of the following:

$$T_i = H_i + (A_i)_{syn-1} + E_i$$

where H is the theoretical time from the hypothetical epicenter, A_{syn-1} is the contrived anomaly applicable to that event, and E is the random error previously discussed ($\sigma(E_i) = 0.25$ sec for the set of fourteen stations). The location results are shown in Figure 28. The average and range of location errors for the four networks and for the twelve events are summarized in Table XVIII.

These errors are absolute because the true locations are known. The wide range of errors for a particular network clearly shows the difficulty one can have in attempting to understand the anomaly effect across a region as large as the Aleutian Islands, especially when real events are mislocated and are at different depths. Network 3 appears to exhibit the most instability, although it has a geometry similar to that of Network 2. The reason is that the stations in Network 3 have the most erratic and largest functional anomalies.

The contrived anomalies and the anomaly variations for the stations used are not considered too extreme or unrealistic. Similar and even larger variations have been observed in the station anomalies computed from the following explosion regions: the Nevada Test Site in southern and central Nevada, the SHOAL event in western Nevada, the RULISON event in northwestern Colorado, the GASBUGGY event in northwestern New Mexico, and the GNOME event in southeastern New Mexico (Chiburis and Ahner, 1970). The range of anomalies computed from these explosions at some stations exceeds 5 sec, with 2-3 sec being common. Significantly, the

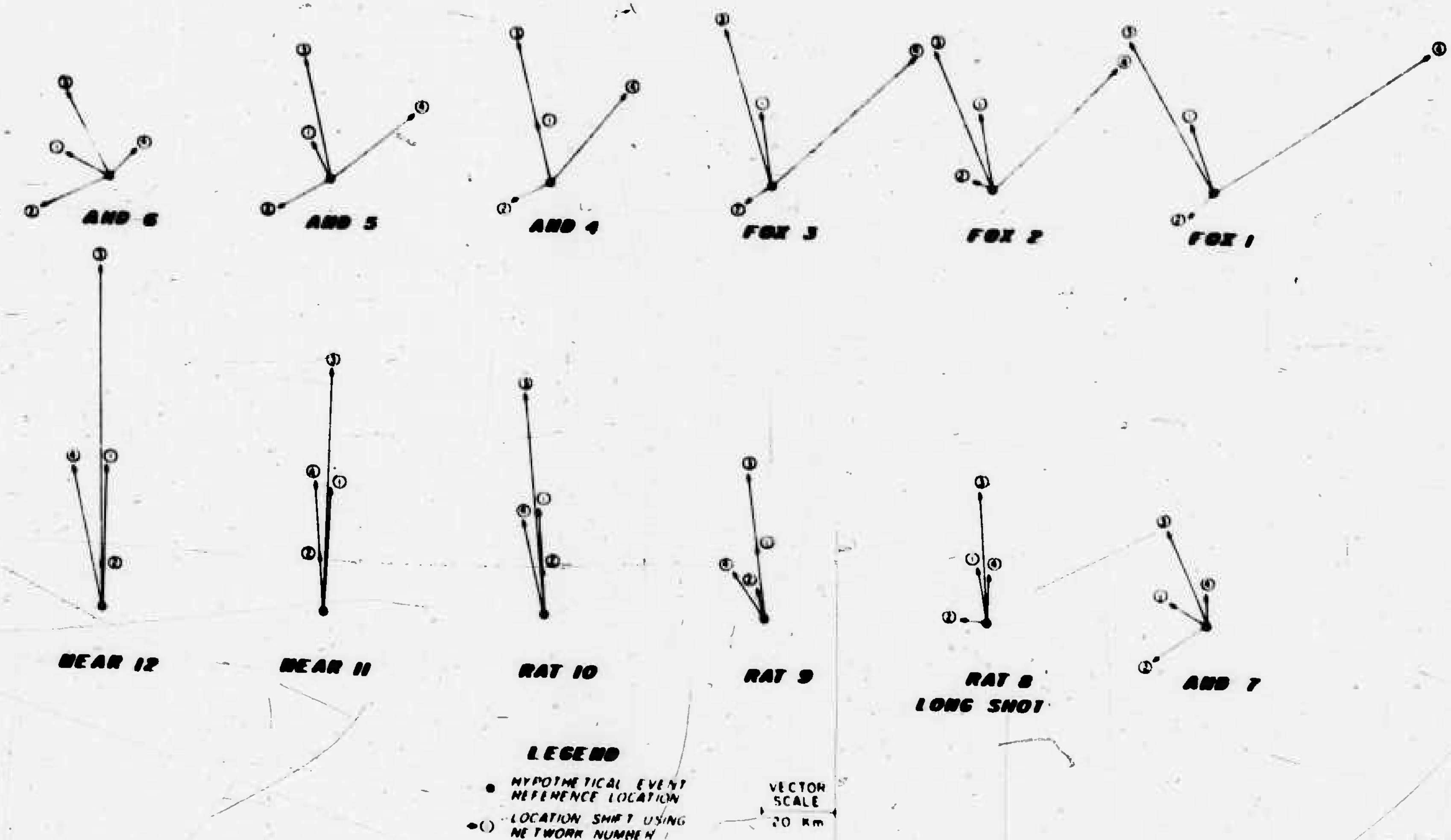

Figure 28. Location shifts using theoretical arrival times with random errors and Syn-1 anomalies as earth-model errors.

TABLE XVIII

Location Results with Synthetic Earth Model

Network	Average Error, km	Error Range, km
1	22.1	12.3 - 39.9
2	12.5	6.2 - 21.0
3	47.7	26.2 - 95.1
4	32.6	9.3 - 71.2

distance between SHOAL and GASBUGGY is about 1600 km, which is of the same order as the distance between the Fox Islands and Near Islands.

The results as shown in Figure 28 and Table XVIII were obtained with four subsets of a fourteen station network. If more stations were available and other more stable network subsets taken, the location of any particular event in the Aleutians would still be meaningless, except in a general way (see the earlier section of this report on LONG SHOT using subsets of a 329-station network). The point is that if no information is available on travel-time anomalies from a region of interest, then depending on the particular network selected for locating (even assuming the network is reasonably stable), the true location errors may be anywhere from zero to 50 km or more. It can be further pointed out that in some regions the anomalies may be distributed such that the resultant errors would be larger.

Referring again to Figure 28, the results using the four networks for each event are quite variable, but for any one network the shift vectors from event to event are considerably more consistent; although the errors are large, they vary slowly and regularly across the region. For example, using Network 1, Fox-1 shifts about 21 km north-northwest from the true location, and LONG SHOT shifts about 16 km, but also to the north-northwest. Therefore, Fox-1 relative to LONG SHOT is 6 km in error, etc. Table XIX gives the absolute and relative (to LONG SHOT) errors for all events located by Network 1. On the average, the relative errors are reduced by a factor of two over the absolute errors. For Network 3, which happens to have the poorest distribution of anomalies (as evidenced by the high average absolute error), the same comparison relative (to LONG SHOT) yields the results given in Table XX.

TABLE XIX

Absolute and Relative (to LONG SHOT) Location Errors for Hypothetical Events Using Network 1 and Synthetic Earth-Model

Event	Absolute Location Error, km	Relative Location Error, km
Fox-1	20.8	5.3
Fox-2	21.9	6.2
Fox-3	21.1	5.6
And-4	18.3	2.6
And-5	14.1	4.0
And-6	13.8	12.9
And-7	12.3	11.7
LONG SHOT	15.7	--
Rat-9	22.6	8.3
Rat-10	30.7	15.4
Near-11	33.6	18.6
Near-12	39.9	24.9
Average	22.1	10.5

TABLE XX

Absolute and Relative (to LONG SHOT) Location Errors for Hypothetical Events Using Network 3 and Synthetic Earth-Model

Event	Absolute Location Error, km	Relative Location Error, km
Fox-1	48.3	21.3
Fox-2	42.1	13.6
Fox-3	45.6	12.2
And-4	40.2	7.2
And-5	34.3	6.1
And-6	26.2	16.6
And-7	29.1	13.5
LONG SHOT	36.9	--
Rat-9	44.3	8.2
Rat-10	62.8	25.8
Near-11	67.4	30.5
Near-12	95.1	58.1
Average	47.7	19.4

Therefore although each network yields very different locations for an event (due to different distributions of the station anomalies within that network), the average location errors of the set of events relative to a calibration event are reduced by a factor of at least two when a constant network is used. This result further substantiates the conclusions drawn in a previous report (Chiburis and Ahner, 1970) in which the relative location accuracy of 2-3 km for a fairly small region was shown to be unaffected by travel-time anomalies if and only if a constant network was used for locating a set of events. However, for the synthetic data set used here, and for the real Aleutian Islands data set in general, it is known that the station anomalies across such a large region are not constant; thus the relative accuracy for any network is expected to be lower than that possible for the location of events within a small region across which the anomalies are constant.

Equally important as the criterion of constant anomalies, however, is that of "network effect". Any seismic network is uniquely defined by the stations in it and their geometrical relationships to the particular epicentral region of interest. These relationships are functions of epicentral distance Δ and azimuth θ, and of the travel-time table, $H(\Delta)$, neglecting depth of focus. Specifically, for the ith station,

$$\frac{\partial H_i(\Delta)}{\partial \Delta_i} \begin{pmatrix} \sin \theta_i \\ \cos \theta_i \end{pmatrix}$$

are the slopes of the travel-time/distance curve modified by the sine or cosine of the azimuth depending respectively on whether the rates of change with longitude or latitude are desired. If the region under investigation is large enough, these slopes of the travel-time curve change significantly at a station such that the advantages of constant network and constant anomalies are considerably undermined. This fact may be demonstrated with the synthetic data by allowing the known LONG SHOT anomalies to be the only time errors across the entire Aleutian Islands region. In this case, the arrival time data are constructed as

$$T_i = H_i + (A_i)_{LS}$$

where $(A)_{LS}$ is the LONG SHOT anomaly and the other terms being defined as before. This means that if the LONG SHOT anomalies are applied as corrections to the arrival time data, all location errors obtained with any network, constant or otherwise, would be zero. If, on the other hand, constant networks are used but no anomalies are applied, the results are as shown in Figure 29. Here it can be seen that Networks 1 and 2 have only slight network effects on relative location accuracy due to slope perturbations. Network 3, however, has a strong network effect in that the errors have similar directions, but the magnitudes differ by a factor of almost 3 between the Fox and Near Islands. The effect on Network 4 produces errors which change direction by about 60° and magnitude by a factor of 2/3 between the Fox and Near Island. These shift differences are due to network geometry, to the network relationship to the Aleutian Islands region, and to the non-linearity of the travel-time curves, because the network itself and the station anomalies are held constant; the only parameters which are variable are the station distances and azimuths to the twelve events. If constant anomalies were the only criterion necessary to maintain relative accuracy over a broad region, the location shifts for a constant network would all have had the same magnitude and direction. This is true over a small portion of the Aleutian

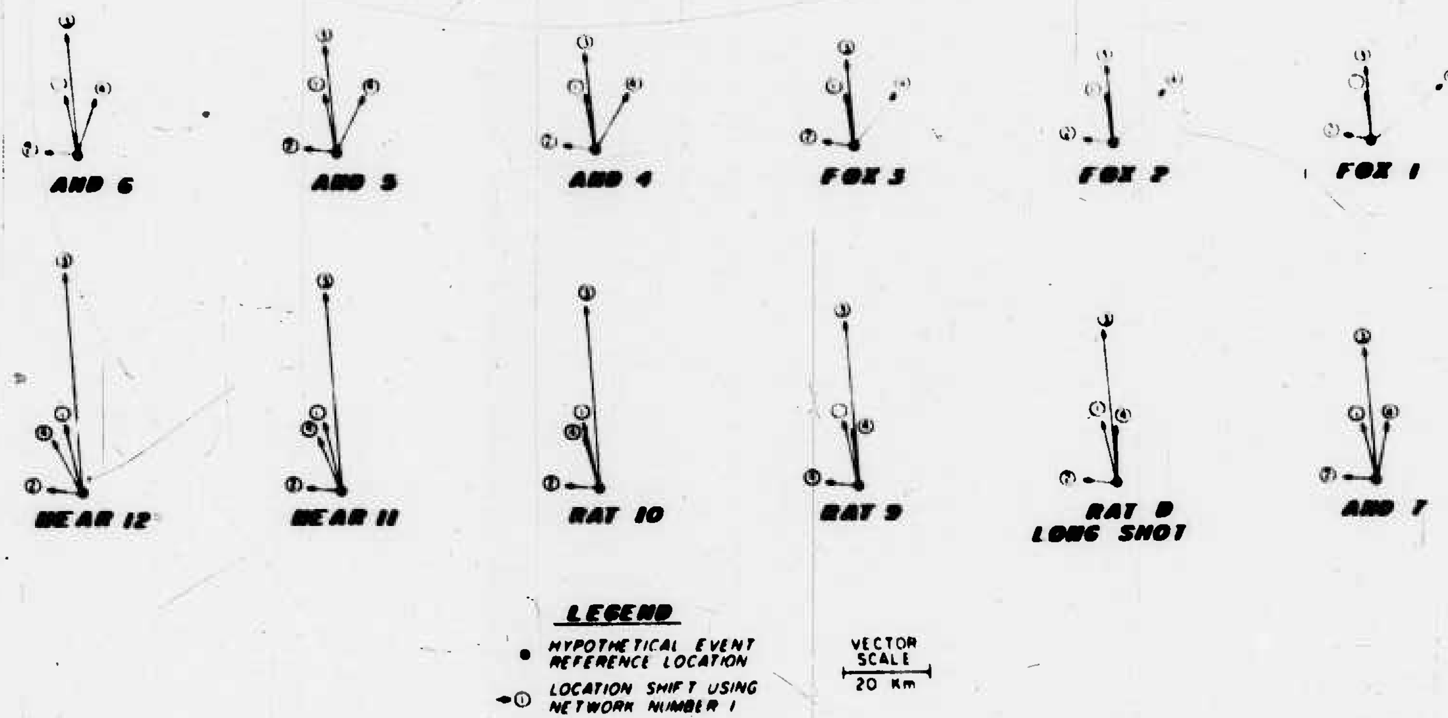

Figure 29. Location shifts using theoretical arrival times with LONG SHOT anomalies as earth-model errors.

region, in which the location shifts are nearly identical, but it is not true in general from one end to the other. For example, using Network 3, And-7 and Rat-9 relative to event 8, which is LONG SHOT, have errors of 4 km and 3 km respectively, whereas events Fox-1 and Near-12 relative to event 8 have errors of 20 and 16 km respectively. The latter errors are far larger than the 3-5 km errors expected if the region is small enough that the travel-time/distance slopes do not significantly change.

Therefore if a constant network is used, even if the anomalies are constant throughout a large region but are not applied, relative accuracy diminishes as a function of travel-time slopes with increasing distance between events due strictly to the network effect. Of course if the anomalies are applied as corrections, there would be no location errors except those due to reading precision. However, as was shown in Figure 28 and Table XIX and XX, using data which include the synthetic functional anomalies, one can achieve at least some improvement in relative accuracy. This is possible because the contrived anomalies are producing an effect greater than that produced by network geometry.

When the synthetic functional (syn-1) anomalies are included in the time data, if it is erroneously assumed that the LONG SHOT anomalies are valid across the entire Aleutians Islands region, they can be applied as corrections to the arrival times, and locations can be made with the four networks. The arrival time data now are

$$T_i = H_i + (A_i)_{syn-1} + E_i - (A_i)_{LS}$$

(the process of computing locations with this relation can also be graphically obtained by simply subtracting vectorially the shifts shown in Figure 29 (LONG SHOT anomalies) from the shifts in Figure 28 (syn-1 anomalies) for each event and for each network. For Fox-1 and for Network 4, this vector process is shown in Figure 30). The average location results for each network are given in Table XXI, which also includes for comparison the averages already given in Table XVIII obtained when no anomalies were applied.

For all networks, the average errors are reduced, and except for Network 2, which has a low average to begin with, the reductions are significant. These results suggest that, although the LONG SHOT anomalies are not completely valid across the entire region, they are at least partially effective in removing some of the gross bias errors. Stated differently, the effect of the LONG SHOT anomalies is greater than the effect of the synthetic anomaly <u>variations</u>; when the LONG SHOT anomalies are applied as corrections, first-order bias effects are eliminated but second-order bias effects remain. These second-order errors remain even for those events adjacent to LONG SHOT (And-6, And-7, Rat-9, and Rat-10), where the anomalies would be expected to be approximately valid, since the synthetic anomalies were made to change only slowly as a function of distance away from LONG SHOT. Figure 31 shows the results of applying the LONG SHOT anomalies to the synthetic data and locating with the four networks. Table XXII summarizes the complete results. The errors in the mean location (small circles on the Figure) are less than 10 km for events 4 through 9; for events 6 through 11 the clustering errors are reduced to less than 6 km and the standard deviations are acceptably low. The errors in the mean location indicate absolute accuracy, while clustering errors indicate relative accuracy. Therefore, as noted earlier, clustering and low standard deviation, alone or together, are necessary but not significant to guarantee improved absolute accuracy.

TABLE XXI

Average Location Errors Using LONG SHOT Anomalies
with Synthetic Earth-Model

Network	Average Error km, Using LS Anomalies	Error Range, km	Previous Average Error, km, Using no Anomalies
1	11.4	3.7 - 23.8	22.1
2	10.6	1.4 - 16.9	12.5
3	20.0	9.7 - 42.8	47.7
4	21.4	5.2 - 49.1	32.6

TABLE XXII

Average Location Shifts of Mean Epicenter, Standard Deviations (σ), and Clustering Effect Using LONG SHOT Anomalies with Synthetic Earth-Model

Event	Error in Mean Location	Average Shift From Mean	Mean σ
Fox 1	12.7	25.3	0.85
Fox 2	13.0	13.9	0.87
Fox 3	13.1	18.0	0.81
And 4	6.8	10.7	0.64
And 5	1.0	10.2	0.54
And 6	10.0	5.7	0.39
And 7	9.7	3.5	0.17
Long Shot	----	----	----
Rat 9	5.0	5.5	0.26
Rat 10	15.0	4.5	0.31
Near 11	19.3	3.6	0.26
Near 12	26.2	10.4	0.59
Average		10.1	

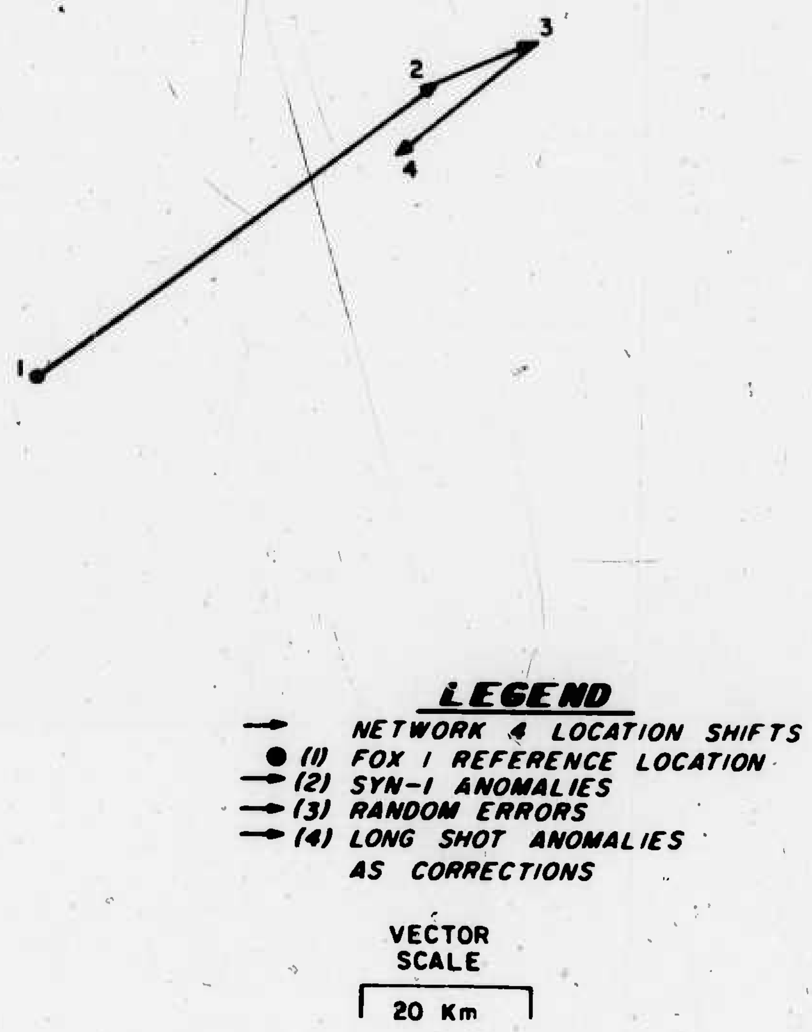

Figure 30. Vector addition for resultant location shift.

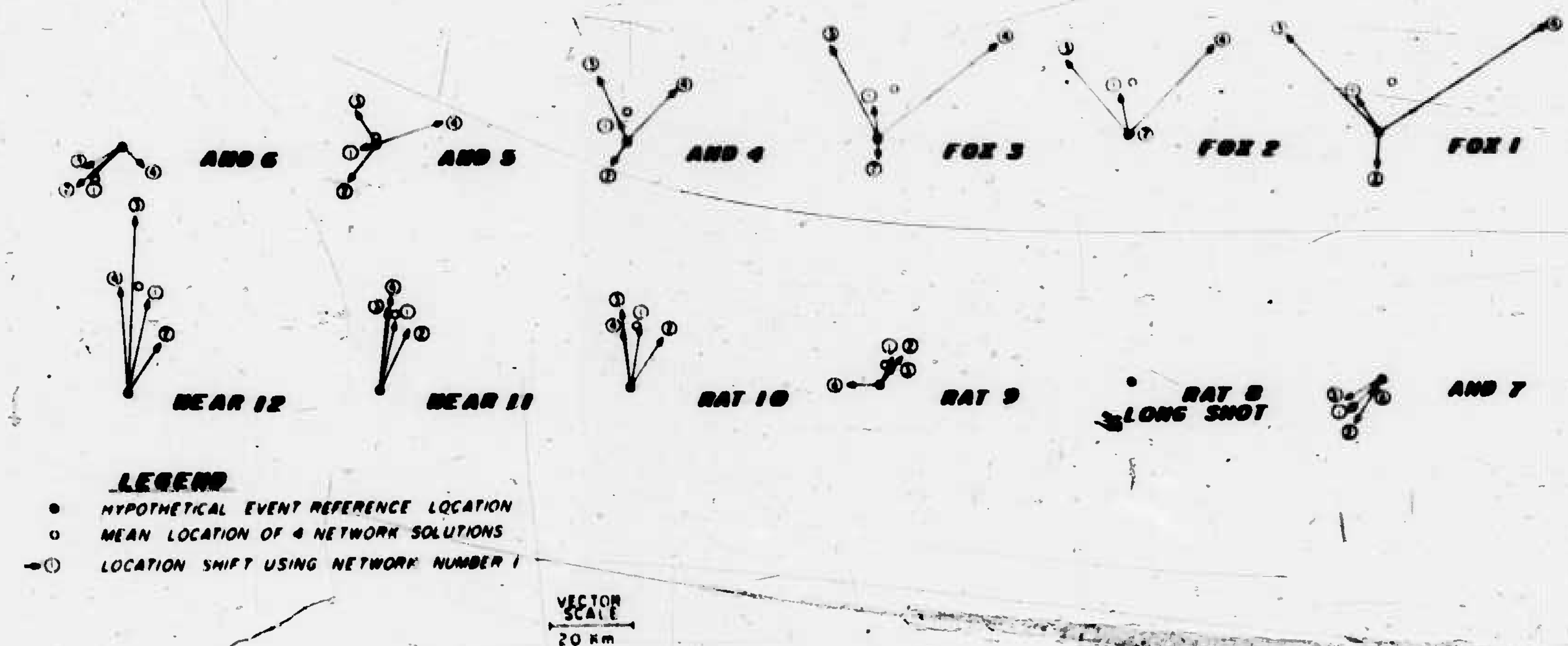

Figure 31. Location shifts using theoretical arrival times with random errors and Syn-1 anomalies as earth-model errors plus LONG SHOT anomalies as corrections.

Furthermore, the LONG SHOT anomalies appear to be valid only for the events immediately adjacent to it (events 7 and 9 at distances of about 180 km and 80 km respectively from LONG SHOT). The mean location error of event 7 is about 10 km; that of event 9 about 5 km. This result is in general agreement with previous conclusions concerning the size of an area across which a constant anomaly is good enough for accurate location (Chiburis and Ahner, 1970).

Anomaly interpolation using synthetic data

The location of LONG SHOT is known. If some location is assumed for event 1 (Fox Islands) and for event 12 (Near Islands), and if the anomalies are computed from the three locations with linear functions drawn between them, can improvement be gained in accuracy and in standard deviation over that obtainable if no anomalies are applied to the intervening events? Restated, can one combine the anomalies from a true location and from wrong locations and still expect to improve location capability? In the following discussion we will answer these questions in the affirmative.

Using the synthetic earth in which the anomalies are known, Fox-1 is deliberately mislocated by 0.2° north and Near-12 by 0.1° south. Computing the anomalies from these two fiducial locations and from the known LONG SHOT location, bilinear functions are fitted to the three constraints, as are shown in Figures 32a and 32b. Compare these functions with the synthetic functions originally contrived (Figure 27a and 27b).

Locating the twelve hypothetical events with the four network subsets and the bilinear functions (random reading errors are also included), gives the results shown in Figure 33. Because events 1 and 12 were deliberately given a location bias of 0.2°N

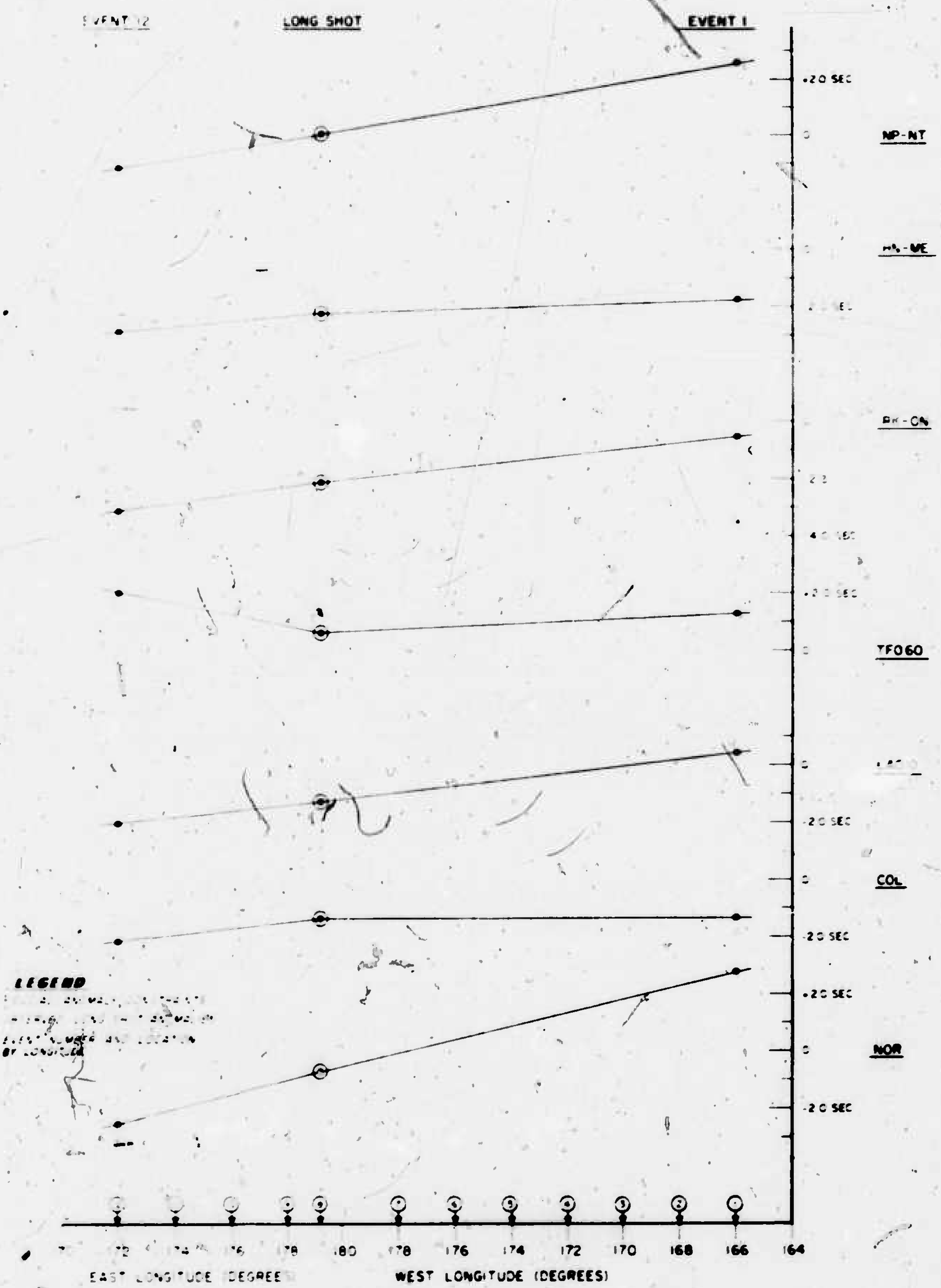

Figure 32a. Linear functional anomalies determined from two deliberately mislocated events plus LONG SHOT.

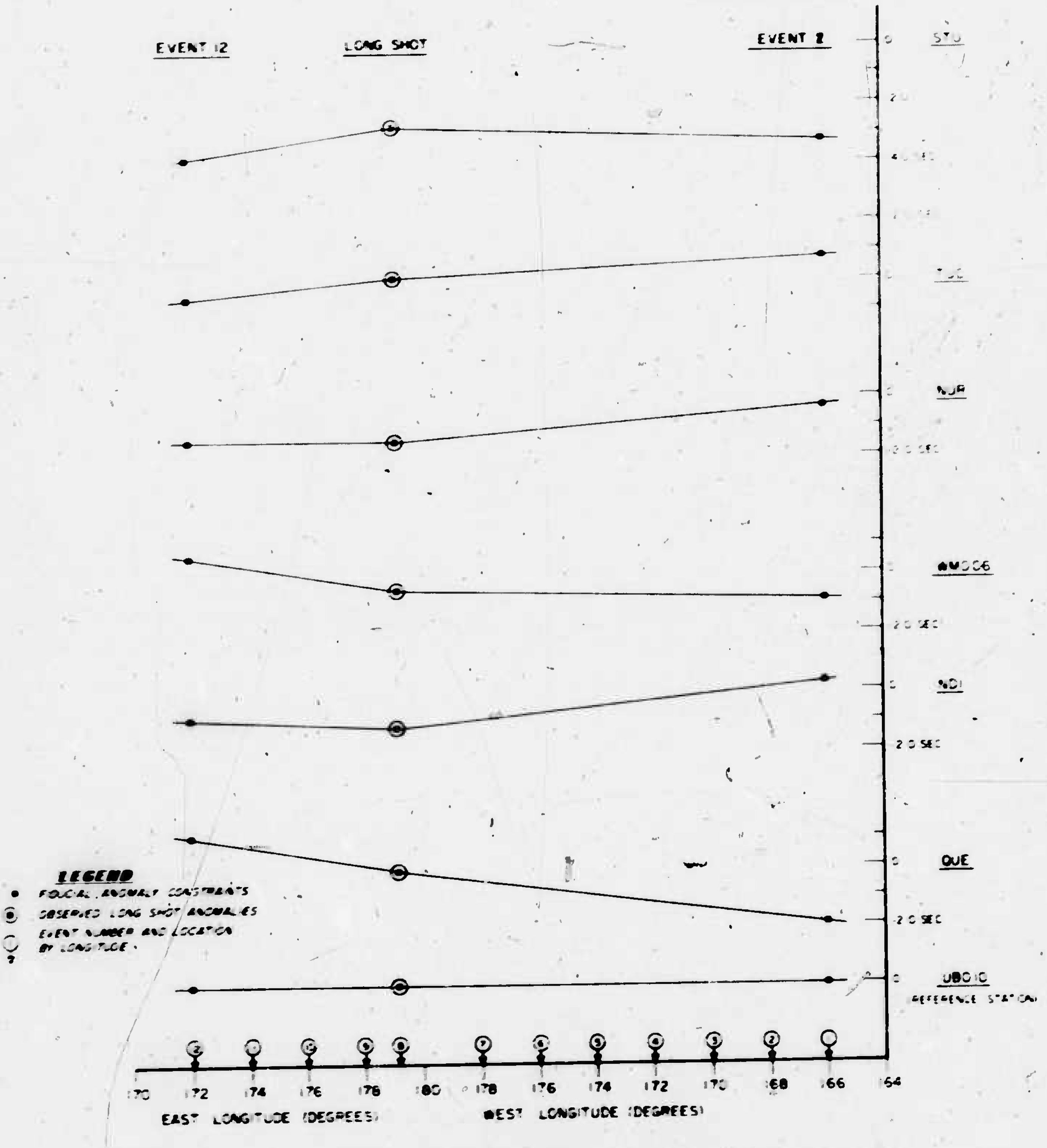

Figure 32b. Linear functional anomalies determined from two deliberately mislocated events plus LONG SHOT.

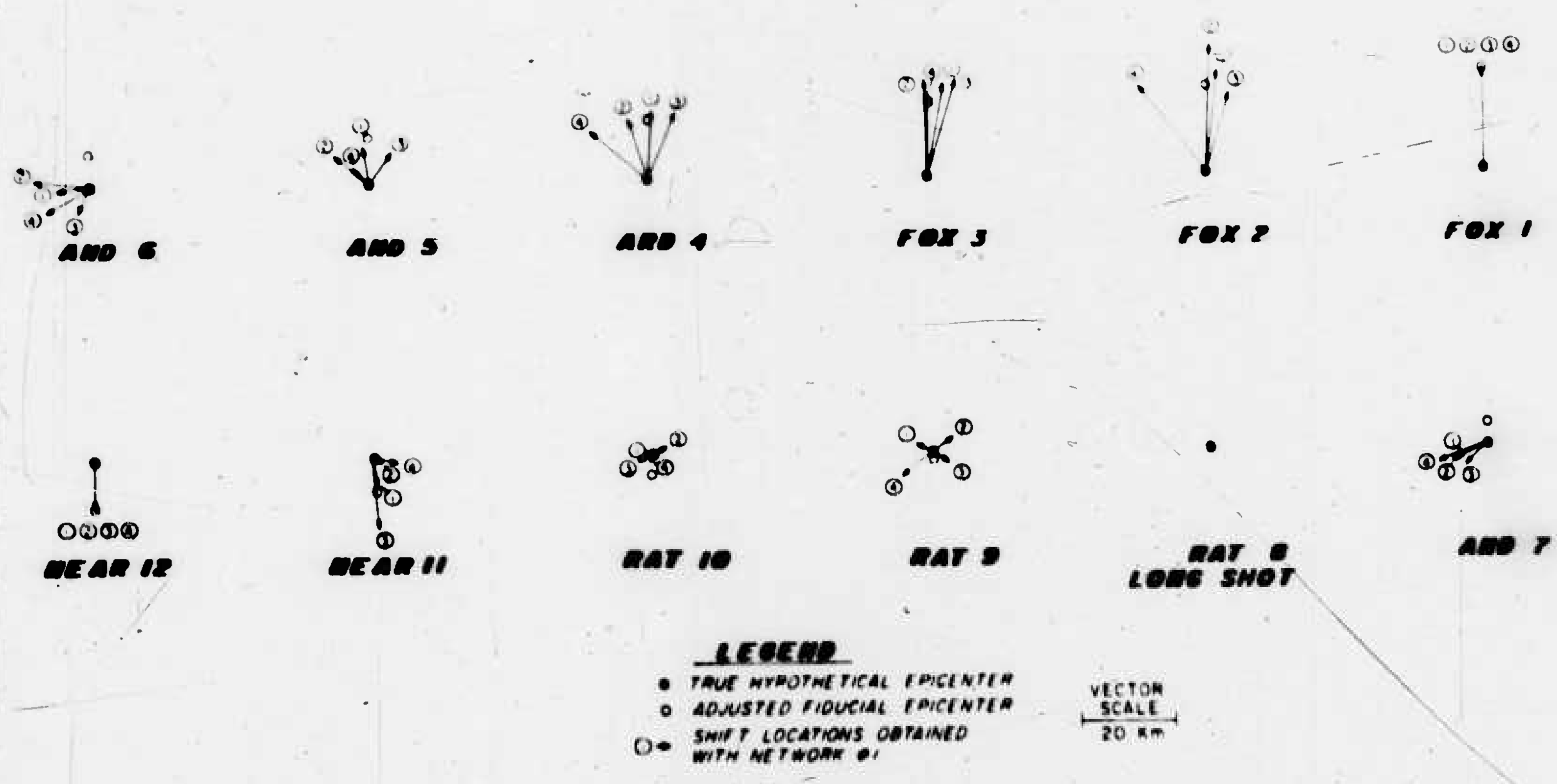

Figure 33. Comparison of least-squares solution errors with contrived functional anomalies at three stations.

and 0.1°S respectively, in order to discuss accuracies across the region, the other events need to be adjusted by an amount proportional to their locations relative to the calibration events. The adjustment relation is shown in Figure 34. The adjusted fiducial epicenters are shown as circles in the previous Figure 33.

The location errors relative to the adjusted epicenters and standard deviations are given in Table XXIII. Compared to the no-anomaly results with the same synthetic data (Table XVIII), significant improvement is obtained in relative accuracy by assuming the locations of "unknown" events and tying the anomalies to those of known explosions. The reason that the events And-6 and And-7 do not locate well is due to the nature of synthetic functions derived; many of the piecewise-linear functions were made to change sharply between events 5 and 8, which results in poor estimates of the anomaly when assuming strict linearity between the calibration events. Therefore, across a region the size of the Aleutian Islands, the technique of anomaly interpolation is valid and will yield improved relative locations. This conclusion bears directly on the interpolation results obtained with real data; viz, when several events are assumed to be located correctly and linear anomalies are fitted between them, the results are consistent both from clustering and standard deviation considerations (Figure 24 and Table XIII).

Step-off technique

A brief discussion is now given of a method, referred to as the "step-off" technique, that attempts to increase the area over which the known LONG SHOT anomalies remain valid. The observations which suggested the possible applicability of this technique were that the distribution of zero-mean time errors resulting

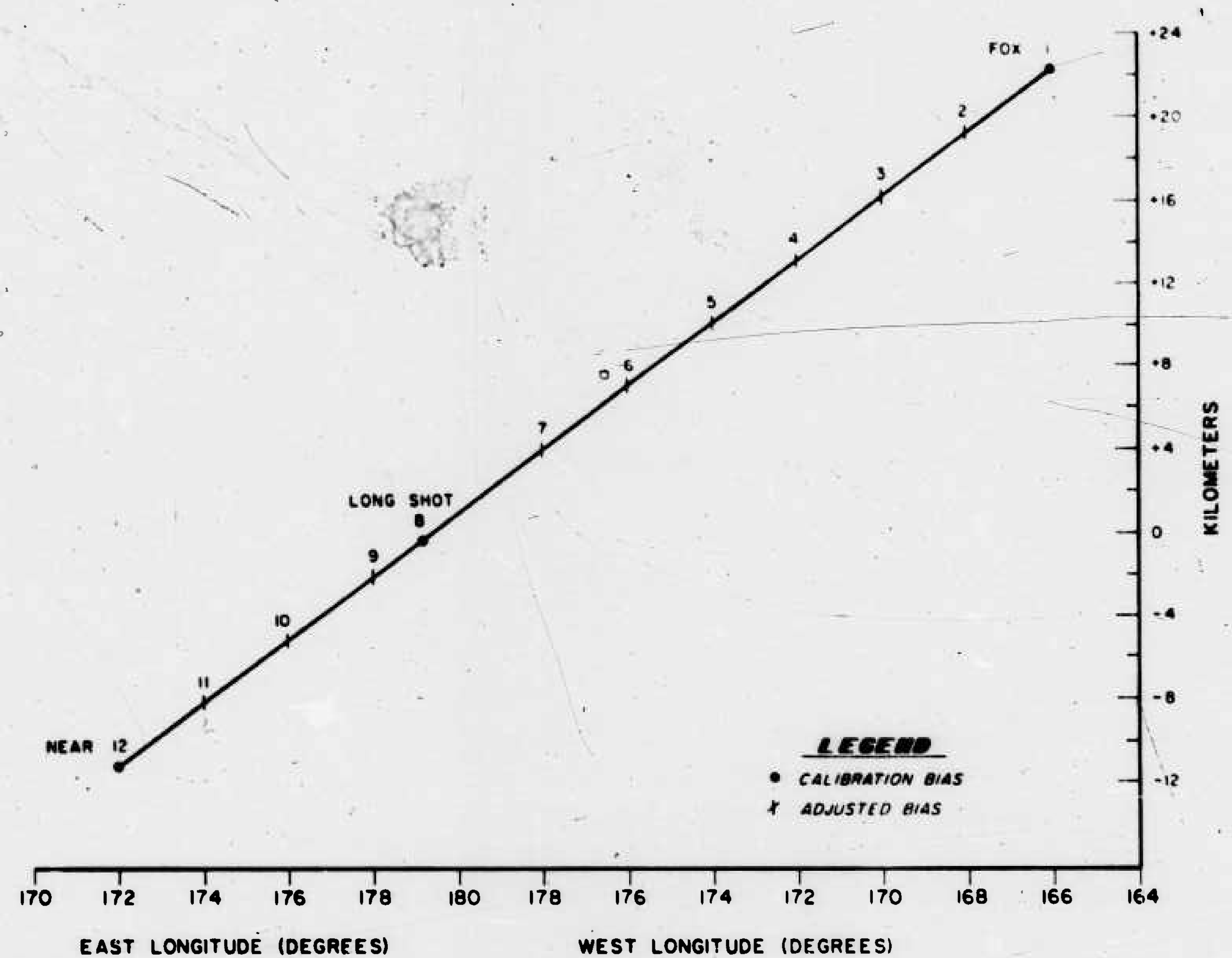

Figure 34. Location shifts obtained by applying functional anomalies shown in Figure 33.

TABLE XXIII

Adjusted Location Shifts Relative to Deliberately Mislocated Calibration Events

	Fox 1			Fox 2			Fox 3			And 4			And 5			And 6		
	Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts		
Network	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)
1	22.3	00	00	22.9	.372	4.4	20.9	.312	4.8	15.7	.339	2.4	8.5	.415	2.4	7.6	.318	11.2
2	22.2	00	00	28.4	.365	9.6	18.3	.325	2.4	14.2	.230	4.8	10.1	.398	8.4	12.4	.300	14.0
3	22.3	00	00	18.3	.262	4.8	22.1	.284	8.0	10.1	.333	6.4	8.7	.270	6.0	6.2	.076	13.6
4	22.3	00	00	24.0	.365	14.4	21.5	.181	5.0	10.7	.226	12.8	5.1	.274	7.2	11.2	.191	16.8
Mean	22.3	00	00	23.4	.341	8.3	20.7	.270	5.2	15.7	.282	6.6	8.1	.339	6.0	9.4	.221	13.9

	And 7			Rat 8			Rat 9			Rat 10			Near 11			Near 12			Average of Shifts From Mean to Adjusted Shifts
	Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			Location Shifts			
Network	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	From Input (km)	(σ)	From Mean (km)	(km)
1	7.5	.207	10.4	00	00	00	3.7	.291	4.8	0.4	.242	5.6	6.9	.352	0.8	11.1	00	00	5.2
2	8.0	.168	10.8	00	00	00	5.5	.294	7.2	4.4	.119	8.0	1.6	.144	6.8	11.1	00	00	8.0
3	7.2	.153	11.2	00	00	00	4.0	.237	3.6	3.1	.248	4.4	16.4	.445	8.8	11.1	00	00	7.4
4	11.2	.203	14.0	00	00	00	8.6	.122	8.0	0.7	.299	4.0	5.4	.288	8.0	11.1	00	00	10.1
Mean	8.5	.183	11.6	00	00	00	5.4	.236	5.9	2.2	.227	5.5	7.6	.307	6.1	11.1	00	00	7.7

from the least-squares solution followed fairly closely the distribution of functional anomalies contrived for the Aleutian Islands region. For example, using Network 1 and the synthetic data, the set of 12 hypothetical epicenters was located using only the LONG SHOT anomalies as corrections across the whole region; the residuals for stations HN-ME, STU, and TFO resulting from the least squares solutions, and the anomalies originally contrived for these stations are plotted as functions of longitude in Figure 35. As can be seen in the Figure, these residuals estimate quite well the anomalies actually incorporated into the arrival time data, especially in the vicinity of LONG SHOT. At larger distances, the residuals begin to diverge from the contrived anomalies as expected. Therefore, if one applies the LONG SHOT anomalies to an adjacent event (say event A) and then attributes the cause of the residuals resulting from the location of event A to a real change in the anomaly between the two events, these errors can be algebraically added to the LONG SHOT anomalies, and the sum applied as an anomaly correction to the next event (say event B). In this way, one can "step-off" away from LONG SHOT, event by event, and hopefully improve the bias normally observed between the Fox and Near Islands. The i'th station's anomaly to be applied to the first event in distance away from LONG SHOT is just the LONG SHOT anomaly:

$$A_i^{(A)} = (A_i)_{LS}$$

These anomalies yield a location of event A with a set of least-squares errors $E_i^{(A)}$. The step-off anomaly to be applied to the second event away from LONG SHOT is

$$A_i^{(B)} = (A_i)_{LS} + E_i^{(A)}$$

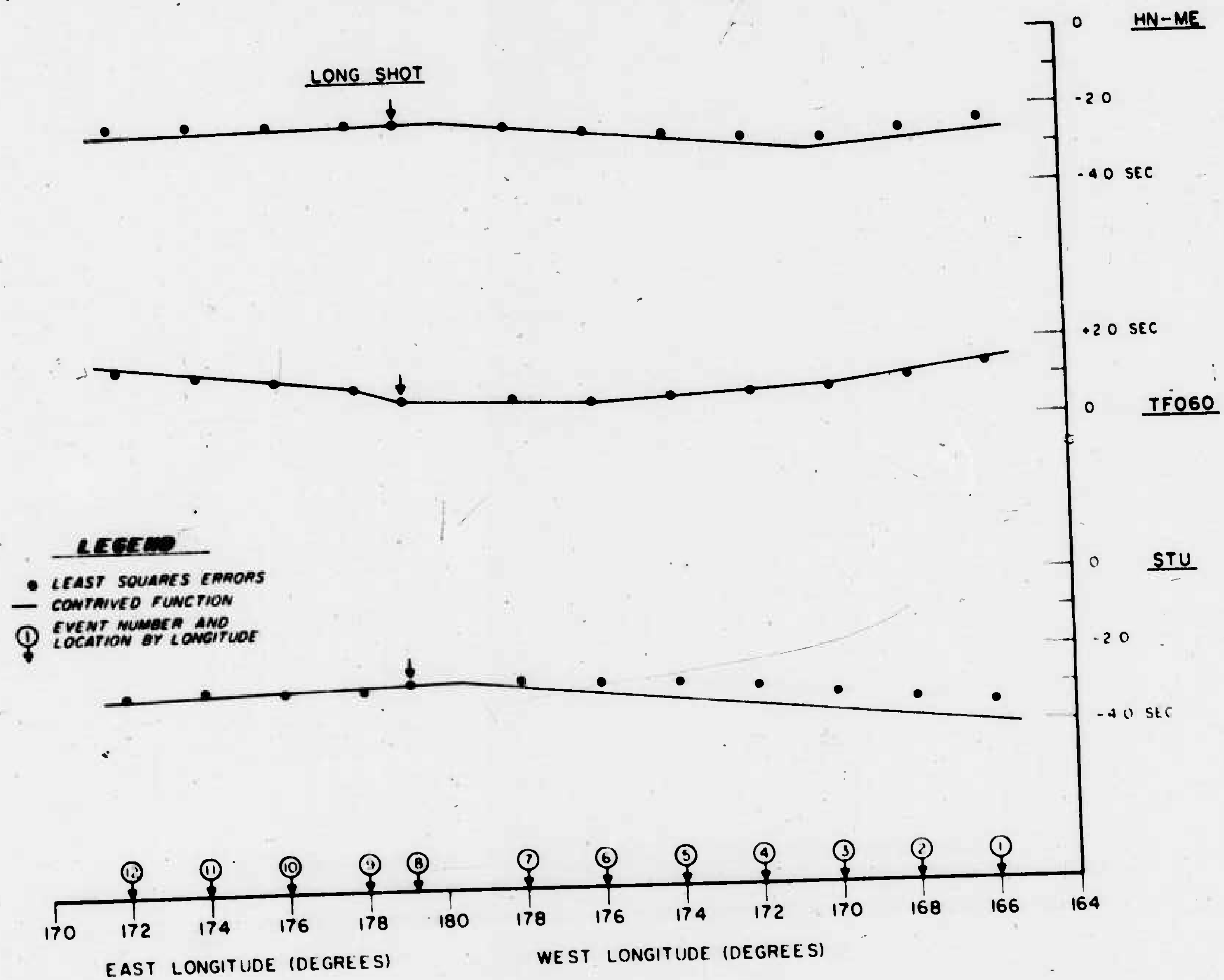

Figure 35. Bias adjustment relation for determining location errors shown in Figure 34.

yielding a new set of errors $E_i^{(B)}$. In general,

$$A_i^{(j)} = (A_i)_{LS} + E_i^{(j-1)}$$

Although the application of the step-off anomalies results in a considerably reduced standard deviation in the solutions, all of the final locations were found to be nearly identical (within 1/2 km) to those obtained by applying only the LONG SHOT anomalies. In other words, applying a set of residuals, which results from the location of one event, to the set of arrival times of an adjacent event has a negligible effect on the location, even though these applied errors are large. Table XXIV gives the least-squares errors from the final locations obtained by using the LONG SHOT anomalies; the three standard deviations, σ_o, σ_{LS}, σ_{LS+E}, are respectively those obtained with no anomaly corrections, those with the LONG SHOT anomalies, and those with the LONG SHOT anomalies plus the least-squares errors from the adjacent event. The least-squares errors in locating event 7 (Andreanof) with the LONG SHOT (event 8) anomalies are given in the first column of Table XXIV. This set has a standard deviation of 0.201 sec. (The standard deviation obtained by applying no anomalies is shown as σ_o.) Adding these errors to the LONG SHOT anomalies and locating event 6 results in a standard deviation of 0.408 sec instead of 0.478 sec as obtained with the LONG SHOT anomalies alone. When locating event 1 (Fox) using only the LONG SHOT anomalies, the standard deviation is 1.286 sec; if the least-squares errors from event 2 are stepped-off, the standard deviation is reduced to 0.414 sec. For the synthetic data set, the standard deviation when the LONG SHOT anomalies are applied, σ_{LS}, compared to the standard deviation without anomalies, σ_o, is

TABLE XXIV

Set of Least-Squares Errors Applied in Step-Off Technique and Resultant Standard Deviations. (See Text)

LEAST-SQUARES ERRORS (IN SECONDS)

Station	AND7	AND6	AND5	AND4	FOX3	FOX2	FOX1
COL	-.23	-.54	-.84	-1.01	-1.58	-1.51	-1.81
NP-NT	-.10	.22	.64	.63	.75	.64	1.25
NOR	.47	.90	1.12	1.61	2.31	2.46	2.33
LA010	.11	.18	.08	.89	.81	1.08	.98
UB010	-.27	-.28	-.61	-.23	-.38	.24	-.56
RK-ON	-.13	.54	.53	.25	.74	.55	.72
TF060	.02	-.32	.25	.17	.14	-.39	.30
TUC	.19	.76	1.11	.57	.45	.45	.28
WMO06	.17	-.50	-.71	-.82	-.78	-.99	-.93
NUR	-.02	-.46	.01	-.13	-.31	-.21	.23
HN-ME	-.01	-.15	-.77	-.84	-.70	-.58	-.37
NDI	-.01	.26	.08	.26	.75	1.09	1.16
QUE	-.25	-.30	-.60	-.69	-1.74	-1.96	-2.25
STU	.08	-.31	-.28	-.65	-.46	-.85	-1.34
σo	.941	1.074	1.284	1.366	1.470	1.536	1.666
σLS	.201	.478	.672	.766	1.072	1.168	1.286
$\sigma LS+E$	.201	.408	.357	.357	.444	.304	.414

reduced significantly in the vicinity of the LONG SHOT explosion, which indicates that the LONG SHOT anomalies are estimating well the contrived anomalies; the improved locations for these events (Table XXII) bear this out. But all of the standard deviations with the step-off errors applied (σ_{LS+E}) compared to the σ_{LS} are also reduced but the location errors are not. This would indicate only that the contrived anomaly changes are being estimated well by the step-off process, but since the location errors remain identical to those obtained with the LONG SHOT anomalies, nothing is being gained except artificially low standard deviations.

The preceding exercise was made merely to demonstrate the futility of using a set of computed errors (residuals) from a network solution in an attempt to improve the location of a subsequent and nearby event. The reason this cannot work is that since the set of errors has a minimum value in a least-squares sense, and since the network is uniquely defined by the stations within it, the set of errors applied to some event already located in the region by that network has a mathematically null effect as far as further perturbations are concerned. Stepping-off slowly in this way across a broad region keeps this effect negligible, and the resultant locations remain the same as if no corrections were applied.

CONCLUSIONS

This study deals with travel-time anomalies, networks, and location consistencies from two viewpoints -- real data and hypothetical data for Aleutian Islands events. The hypothethical data were used to validate some of the techniques employed on the real data. Physically, the technique of functionalizing and regionalizing the anomalies works well enough to justify further study and general applicability. No implication is made as to the ease with which it can be accomplished, but foremost among the criteria for using it is that the raw data set must be high quality; that is, the arrival times must read as unambiguously as possible. This usually involves a great deal of intrastation checking and interstation correlation. The earthquake signals from Aleutian Islands events are frequently subtly complicated: double events separated by 2-5 seconds, usually very different in magnitude; low amplitude first motions (which may be called precursors) not normally observed at noisier or low-magnification stations, etc. Since studies of anomalies and location techniques should not concern themselves with the ability of a seismic analyst to read seismograms correctly, the major effort of future studies must be to obtain as clean a data set as possible using all available techniques.

In using the real data for Aleutian Islands events, the complications introduced in the location stabilities are undoubtedly due in part to a depth effect. If the anomalies are caused by the integration of small imperfections in the earth model along a unique travel path (which is then related to a region/station description), there is good reason to expect the anomalies to be dissimilar when computed from two events in the same region but at significantly different depths. It is not presently known what size of depth differences are to be considered significant, but the significance would probably depend on the particular stations used. However, before sensible studies can be made relevant to this depth effect, all possible efforts must be made to eliminate (1) arrival-time errors; (2) epicenter errors; (3) depth errors; and (4) network instabilities. To eliminate the first of these requires labor and patience. To eliminate the second may be impossible, except in the case of explosions or of using well-distributed local networks (<100 km epicentral distance). To eliminate the third requires the success of the first two plus the clear observation of pP. The fourth may be eliminated, or certainly be made manageable, by selection of suitable networks.

Neglecting depth effects, the analysis of the real and hypothetical data using various interpolation and adjustment schemes permits an estimate of resultant relative location error to be placed at 5-10 km throughout the Aleutian Islands for the seventeen events studied. The absolute location error is probably about the same, because LONG SHOT provides bias control in the vicinity of the Rat Islands and because all functional and regional anomalies were tied to LONG SHOT.

The regional anomalies finally determined for the Aleutian Islands yield consistent location patterns and least-squares time fits using four subsets of a fourteen station network.

That epicenters may be mislocated in the Aleutian Islands regions was demonstrated by taking various stable subsets of a 329-station network and the LONG SHOT explosion. The variable locations obtained, any of which could have been reported had LONG SHOT been an earthquake, produce a computed anomaly range at the teleseismic station NP-NT of more than 11.4 sec. This result implicates epicenter mislocation as the chief cause of observed anomaly scatter.

Finally we have shown that arrival times in published bulletins are frequently in error by 1 second and more. The causes of these errors are probably: (1) missing first motion in complicated signals (such as double events), and (2) weak first motions (as at noisy stations). Any future studies of anomalies, networks, location accuracies, and earth models must begin with an analysis of raw seismograms in order to place any significance on the relation of anomalies or anomaly variations to physical processes.

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