Department of Natural Resources
MARYLAND GEOLOGICAL SURVEY
Kenneth N. Weaver, Director

REPORT OF INVESTIGATIONS NO. 47

LORAN-C Calibration in Chesapeake Bay

by Jeffrey P. Halka

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INTRODUCTION

LORAN-C has become, in recent years, the primary radionavigation system utilized in nearshore waters due to its wide geographic coverage, operational reliability and the continued reduction in cost of receivers for shipboard use. Vessels operated by the State of Maryland have come to rely more heavily on this system since operation of the State-owned Raydist radionavigation system was discontinued in 1984.

As with all navigation systems the intended purpose of LORAN-C is to enable a vessel at sea to determine its location. There are two important aspects of this determination: accuracy and repeatability. Accuracy is the ability to arrive at a predetermined location at sea or, conversely, to plot a location on a chart once a navigation fix has been obtained. Repeatability refers to the ability to return to a location at which a navigation fix has previously been obtained. The locational capability of LORAN-C signals or other radionavigation transmissions with respect to these two components is quite different. The work reported in this paper primarily concerns an improvement in the accuracy of position determination in the Chesapeake Bay through the development of regional correction factors; however, repeatability is generally discussed because of its dependence on LORAN-C signal propagation and its effect on user expectations for precise navigation. The results of this effort have been incorporated into a computer program, included in the appendix, which permits conversion between LORAN-C time differences for the X and Y lines of position and latitude and longitude coordinates referenced to the North American Datum of 1927 (NAD-27).

Accuracy

The accurate determination of location basically involves the calculation of the latitude and longitude of a point from the received LORAN signals. This is the case whether the vessel operator plots a location from the LORAN lines of position overprinted on a National Oceanic and Atmospheric Administration, National Ocean Service chart; utilizes the LORAN signal to latitude/longitude conversion incorporated in most LORAN receivers; or uses a separate computer program to calculate the conversion to geographic coordinates (as described herein).

The LORAN to latitude/longitude conversion has three basic parts:

1) determination of the distance between the receiver and the master and secondary transmitter stations;

2) determination of the radio wave travel times for the above calculated distances and from these the differences in arrival times of the transmitted signals at the receiver's position (referred to as a time difference - TD);

3) the actual mathematical conversion from a given TD pair to latitude and longitude, having solved for 1 and 2.

In the case of the LORAN lines of position (LOP) printed on a chart, the National Ocean Service (NOS) has performed the above calculations along each of the printed lines. However, the following caveat is included on these charts: "LORAN-C lines of position overprinted on this chart...are presently compensated only for theoretical propagation delays which have not yet been verified by observed data." That is, in item 2 above, the radio wave travel times have been only theoretically estimated without on site verification. In addition accurate locational positioning from the NOS charts of the Bay is difficult in practice because of the scales at which lines of position are overprinted (largest scale available is 1:80,000) and because of the hyperbolic and non-orthogonal nature of the lines. If the geographic coordinates of a position are needed, the operator must translate the plotted point into latitude and longitude from the scales along the edge of the chart. This process is error-prone and, if many plotted points are to be converted, time consuming.

The internal conversion routines incorporated into most LORAN receivers currently available would seem to circumvent these difficulties. The operator can instruct the unit to convert from a given TD pair to latitude and longitude, simplifying reporting and plotting of the determined location and allowing positioning at scales larger than 1:80,000. However, the internal conversion routines of LORAN receivers are not standardized industry-wide (Frank, 1983) and are, furthermore, proprietary information. Indeed, the same TDs produce different latitude and longitude readouts with different makes of receivers (Dwelle, 1986). Because of differences between sets it is difficult to justify using the internal geographic conversion routines for accurate locational work, particularly if an operator later changes receivers or reports locations to another operator with a different receiver.

The operator has little control over these conversion routines except that manual adjustment is available on some sets. In making a manual adjustment, the operator skews the geographic readout to correspond with the latitude/longitude at a known location when the receiver is at that location. The geographic output from the receiver can then be expected to be reasonably accurate while in the vicinity of the known location. However, for locations further away, a new adjustment will need to be made. The geographic coordinates for the stations utilized in this calibration procedure and reported in Table II may be used for this purpose, as may any of the coordinates included on the U.S. Coast Guard List of Lights.

The use of a separate computer program to convert from geographic coordinates to TDs and vice versa obviates many of the problems inherent in the above two locational methodologies. The user controls the conversion procedure and may incorporate correction factors where appropriate. A routine can be incorporated into the program to calculate automatically the correction factor to be applied at any geographic position in the region, provided appropriate calibration has been performed. Use of a program allows an operator to pre-determine LORAN-C TDs for specific geographic locations prior to leaving the dock and to head for those coordinates using the receiver on board. Changing receivers has little effect on the final destination because all appropriately installed receivers should obtain approximately the same TD values irrespective of their internal LORAN to geographic coordinate conversion routines. Additionally, for those operators having access to a computer-driven plotter and appropriate software, the locations can be plotted at any scale from the TDs themselves after conversion to geographic coordinates. The difficulty of plotting TDs directly on the NOS charts or at scales other than those generally available is overcome. The differences inherent in different receivers' conversion routines are also eliminated.

The basis of the computer model utilized herein is the Defense Mapping Agency SALT-Model program. This program is comprised of : 1) an earth curvature model to find the great ellipse distance between the LORAN transmitting towers and the receiver, and 2) a model to convert these distances to travel times for the signals. The times derived from the SALT-model approximate travel times through the atmosphere over open ocean water of average salinity and temperature, hence the name. This SALT-model accounts for approximately 99.98% of the actual, observed LORAN travel times in a computationally expedient fashion (McCullough et al., 1985).

As written the program utilizes the North American Datum of 1927 (NAD-27). This datum was selected because it is the one in use on the National Ocean Survey Charts, which are routinely used for plotting of locations by agencies of the State of Maryland. The locations of the master and secondary LORAN-C transmitting stations referenced to the NAD-27 coordinate system are shown in Table I. Also utilized in the Program is the Clark 1866 spheroid of the earth, having an equatorial radius of 6,378,206.4 meters and a polar radius of 6,356,583.8 meters.

This spheroid is used for locational calculations in the NAD-27 coordinate system.

TABLE I: Locations of the master and secondary LORAN-C transmitting stations referenced to the NAD-27 coordinate system.

Station		latitude	longitude
9960-M	Seneca, NY	42°42'50.465''N	76°49'34.470''W
9960-X	Nantucket, MA	41°15'11.728''N	69°58'40.449''W
9960-Y	Carolina Beach, NC	34°03'45.596''N	77°54'47.143''W

Use of the Program with another datum (e.g. WGS-72) will produce inaccurate results unless the spheroid and station coordinates are appropriately altered for that datum. The National Geodetic Survey is in the process of updating the geographic coordinate systems for the United States. The new system to be utilized on NOS charts, the North American Datum of 1983 (NAD-83), will be phased in over a period of time. If the program is utilized with the new series of charts, inaccurate locations will be generated. Changes in coordinate location from NAD-27 to NAD-83 in the Chesapeake Bay region will be significant. It is anticipated that latitude coordinates will change by approximately 8 meters and longitude coordinates by about 30 meters (NOAA, 1985).

Deviations between the theoretical LORAN-C TDs predicted by the SALT Model and the observed TDs at a known station are due to geographic, geologic, meteorologic, and hydrologic factors. A minor component of these factors includes changes in the temperature and salinity of sea water from the average, changes in the speed of propagation of electromagnetic radiation due to changes in atmospheric temperature and humidity and other seasonal, diurnal, weather and noise effects. By far the greatest cause of propagation delays is the presence of land, rather than open ocean, between the transmitting towers and the receiver, because LORAN-C signals travel more slowly over ground than over water. The geography and geology of the land, including terrain roughness, vegetation type, rock and soil type, stratification, temperature and moisture content, affect the signal propagation times. The signal propagation delay caused by passage over land rather than the open ocean is termed the Additional Secondary-phase Factor (ASF). The ASF can be theoretically estimated, as noted in the NOS charts, but must be verified by observational data.

Clearly, the ASF, which largely affects the accuracy of LORAN-C radionavigation, is relatively constant over time: land masses remain fixed for practical purposes, and geology and soil characteristics do not change in the time frame under consideration. Other of the factors such as moisture content of the soil, vegetation characteristics (whether or not there are leaves on the trees), temperature of the atmosphere and sea water, and humidity and salinity, vary seasonally or more frequently. The passage of weather fronts also affects propagation delays (McCullough et al., 1985). Because of their short duration, these factors cannot be modeled. However, the Coast Guard operated monitors, which actively steer the LORAN timing, partially compensate for them (Frank, 1983; McCullough et al., 1985). In the Chesapeake Bay region, one would expect the ASF to be large because of the long overland, versus sea-water, signal propagation paths from the master and secondary stations.

The land-sea geometry also has an effect upon signal propagation due to large relative surface conductivity changes across the boundary (Pressey et al., 1956; McCullough et al., 1985). Figure 1 illustrates the rapid changes in ASF across the land-sea interface in the vicinity of Weekapaug, RI with an offshore "recovery" extending seaward 100 km or more. In an area with a highly convoluted shoreline, such as the Chesapeake Bay, the recovery phases for the propagated signal are probably complex and highly irregular.

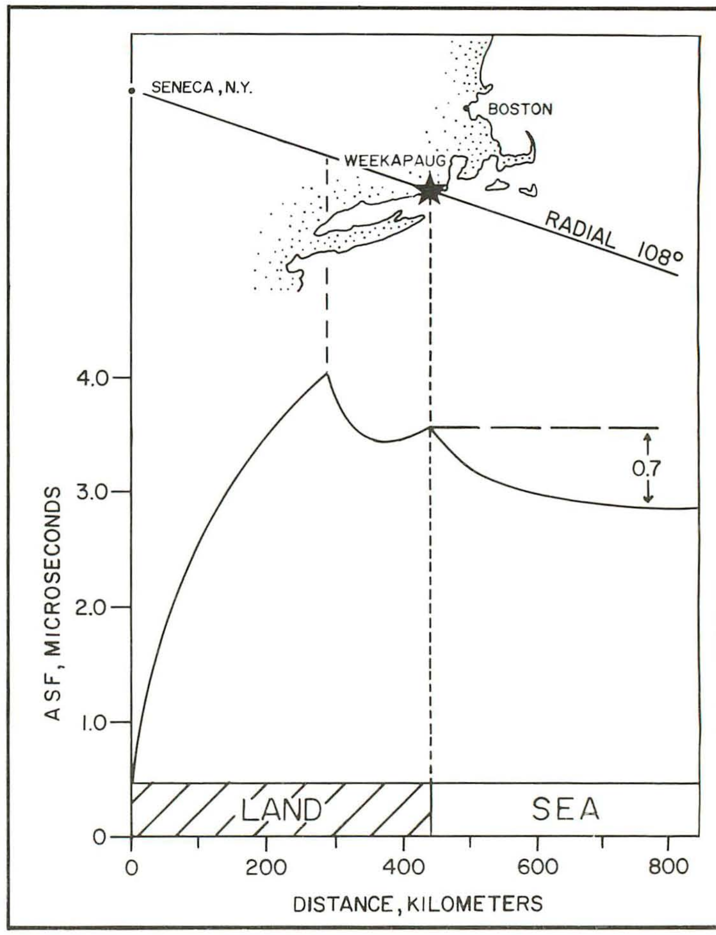

Figure 1: — ASF model prediction along 108° radial from the master station at Seneca, NY. Of particular significance is the rapid change which occurs across the land-sea boundary at Weekapaug, RI. Observational data support the model prediction (from McCullough et al., 1985).

Repeatability

Variations in propagation speed due to seasonal and weather related changes along the signal transmission path most directly affect the repeatability of LORAN-C navigation. Data from the U.S. Coast Guard Harbor Monitor at Yorktown, Virginia (Figure 2) provide an example of the repeatable error ranges which may occur (US Coast Guard, 1983). This figure presents deviations from the average X and Y TDs during 1982. Peak-to-peak variations at this station were 0.256 μsec for the X-lines and 0.521 μsec for the Y-lines, with standard deviations of 0.035 and 0.085, respectively. In the central Chesapeake Bay, a 1.0 μsec time difference equals approximately 285 meters for the X lines of position and 156 meters for the Y lines. Therefore, the variations shown on Figure 2 suggest that the locational repeatability that can be expected in the Chesapeake Bay region is on the order of 100 meters. The greatest deviation occurs during the winter, between days 7 and 35. Extreme weather events during this period coupled with ground freezing and thawing, which greatly affect conductivities, result in the worst repeatability for the year period. Signals are most stable during the late spring, summer, and early fall. This period, roughly between days 100 and 280,

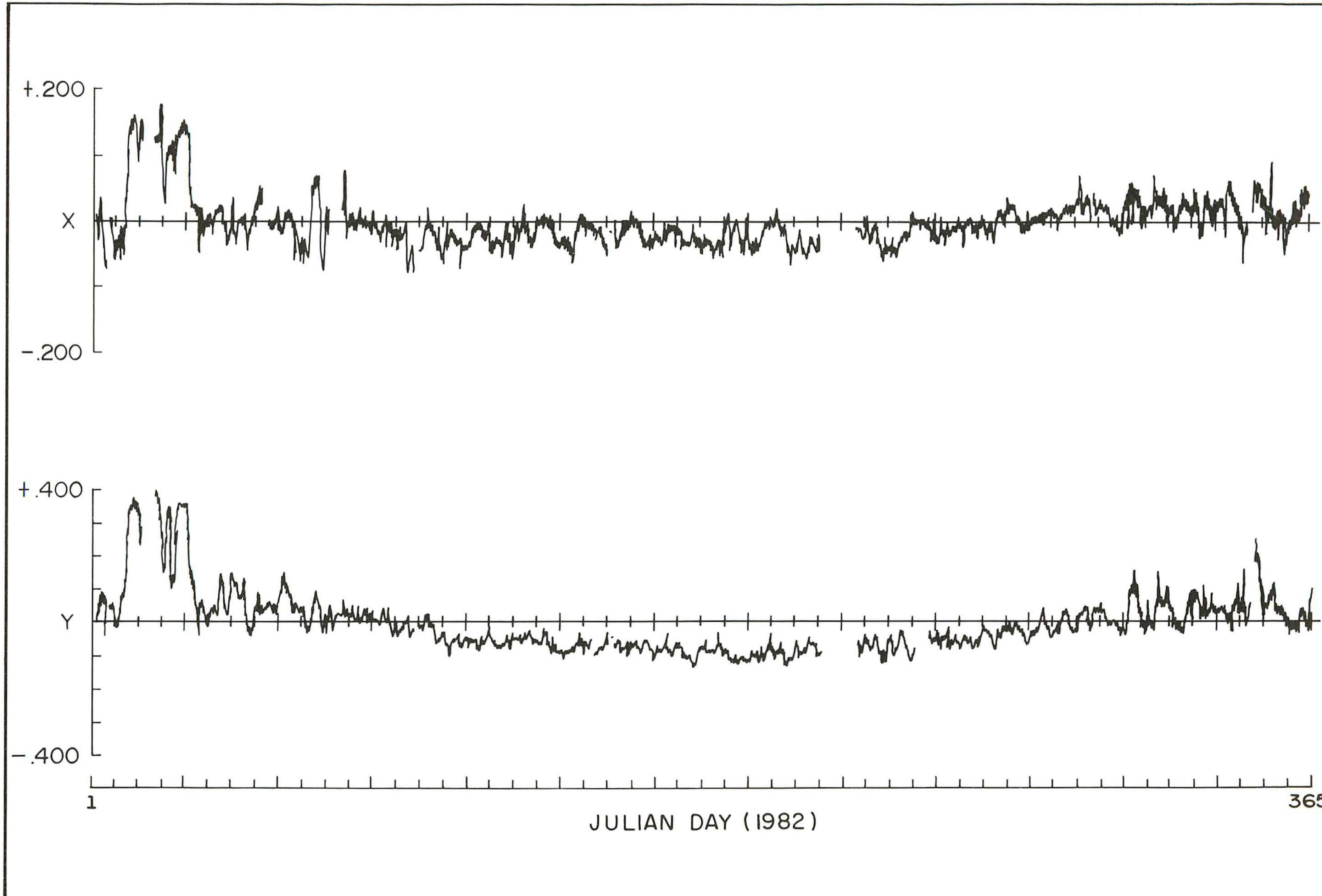

Figure 2: — Harbor monitor time delay variations (in microseconds) recorded at Yorktown, VA for 1982 (from U.S.C.G., 1983).

represents the time of best repeatability. Additionally, LORAN receiver instability and noise generated on board the vessel will affect repeatability.

Repeatability is also affected by the geometry of the transmitting towers and their distance from the receiver. The optimal crossing angle for any two lines utilized for a fix determination is ninety degrees. At shallow angles or when the lines are nearly parallel, the potential for repeatable errors increases significantly. In the Bay region, The LORAN 9960-X and 9960-Y lines of position cross almost at right angles. The transmitting towers for these lines are also the closest of those available. Because signal strength decreases rapidly with distance from the transmitters, the proximity results in the highest Signal to Noise Ratio (SNR) of the available transmitters. For these reasons the calibration effort reported in the remainder of this paper refers to the 9960-X and Y lines only.

CALIBRATION PROCEDURE

Calibrating the computer program for the Chesapeake Bay area involved determining the difference between the computer calculated TDs at a known location (the SALT-model) and the received TDs when the vessel was at that station. The computer program calculated the theoretical TDs based on distance from the transmitters over an all sea-water path. Thus, this calibration accounts for the major differences produced by overland propagation delays (the ASF) and the land-sea interface. Discrepancies attributable to short-term seasonal and weather related variations in signal propagation or to receiver instability are also included in these differences.

To minimize the effects of short term signal propagation variations, the calibration fixes were obtained on the 26th and 27th of August 1985 (Julian Days 238-239), during the time of year when signal propagation is most stable and close to the average (Figure 2). Because repeatable accuracy for the Bay region is on the order of 100 meters (from Figure 2), while absolute accuracy is approximately 500 meters (U.S. Coast Guard, 1980), the differences due to short term effects should account for at most 20 percent of the observed differences. This represents an upper bound for the significance of short term signal propagation effects because of the relative stability of propagation times during the summer.

A total of 44 stations in the Bay were occupied in the calibration procedure. Of these, 33 were sizable, permanently located fixed marks, the geographic coordinates of which are reported in the Coast Guard List of Lights. To complete coverage in areas where major fixed marks were absent, five smaller marks, which did not have reported geographic coordinates, were utilized. The geographic locations of the remaining six stations, all in Virginia waters, were determined from a land based tellurometer navigation system. This system has a reported precision of ± 1.0 meters (Dr. Robert Byrne, personal communication). In no case was a floating or non-fixed mark utilized for the calibration. Stations covered the main portion of Chesapeake Bay, from the vicinity of Pooles Island in the north to Hampton Roads in the south, and included stations in the major subestuaries of the Bay: Eastern Bay, the Choptank River, and Tangier Sound. The Potomac River was not included. No effort was made to obtain calibration points up all of the small subestuaries and tributary rivers because the complexity of the land-sea interfaces in these areas would probably not permit data from a specific calibration point to be extended any distance away from that point.

The latitude and longitude for each station was determined by one of the following three methods, depending on the availability of appropriate data: 1) measured from a NOAA-NOS chart of the largest scale available, 2) obtained from the Coast Guard List of Lights, or 3) derived from the tellurometer data. The geographic coordinates for each station were used as input to the SALT-model computer program to derive the theoretical LORAN-C TD coordinates for the X and Y lines of position.

On 26-27 August 1985, two vessels visited the fixed mark stations and recorded the LORAN-C TDs at each. The receivers utilized were Raynav 6000 units, manufactured by Raytheon Corporation. Neither receiver had been independently calibrated.

For each station there now existed (1) a pair of theoretical LORAN-C coordinates determined by the computer model and based on an idealized all-sea-water transmission path (the SALT-model), and (2) a pair of coordinates obtained with a receiver at that site. The difference between the theoretical and observed values represents the deviation from the model caused by the Additional Secondary-phase Factor (ASF) along with all other factors that alter the propagation speed of radio signals. As mentioned previously, these differences are largely produced by the presence of land between the transmitters and receivers and by the configuration of the land-sea interface, both of which remain relatively constant over time.

OBSERVATIONS

The differences between the theoretical and the observed X and Y time delays at the calibration stations are reported in Table II and shown in Figures 3 and 4. The differences were calculated by equation (1):

$$\text{difference}(\mu\text{sec}) = \text{observed time delay} - \text{theoretical time delay} \quad (1)$$

The mean of the differences for the X line TDs for the Bay region is -2.06 μsec with a standard deviation of 0.29 μsec and a range of 1.19 μsec (Table II). The value is negative because the expected values calculated by the program were larger than those observed at each of the stations visited. There is a general increase in the absolute value of the differences from the northern portion of the Bay, where they average under two microseconds, to the southern Bay where they exceed two microseconds (Figure 3).

For the Y-TDs, the mean difference is -0.47 μsec. The smaller absolute value of the mean indicates that the average ASF for the Y time delays is smaller than that for the X in the Bay region. The standard deviation and range values, at 0.29 and 1.21 μsec, are equal or nearly equal to those recorded for the X lines. This indicates that the ASF gradient in the Bay region, and/or those short term factors that affected signal propagation speeds during occupation of the calibration stations are nearly the same for the X and Y lines of position. As was true for the X differences, there is a tendency for the absolute value of the Y-TD differences to vary across the Bay, in this case increasing in an easterly direction (Figure 4).

During the study period a fixed station was established at Solomons, Maryland at 38°19'5.6"N; 76°27'9.9"W. Here, X and Y TDs were recorded every minute. Data from this approximately centrally located station permitted verification of signal stability at the times that the on-the-water stations were being visited. If a large TD anomaly had been recorded at the fixed site while a calibration station was being occupied, the observed TD at the station would have been suspect and, therefore, deleted from the data set. In fact, this situation did not occur. For the time during which a calibration station was occupied, five one-per-minute readings from the fixed station were averaged. For the X-lines the range in the signal TDs observed at the fixed station was 0.08 μsec, and for Y the range was 0.12 μsec. Considering that the observed minus the theoretical TDs at the calibration stations averaged -2.06 μsec and -0.47 μsec for the X and Y lines, respectively, the signal variation at the fixed station represented less than 4 percent of the observed X line differences and 26 percent of the Y line differences. In addition, the variability observed at this station was much lower than that observed by the Coast Guard at the Yorktown Harbor Monitor site (Figure 2). Variability at this fixed site represented a small fraction of the TD differences observed at the calibration stations: hence, the differences observed at the stations are real.

Table II.—Calibration stations utilized, their geographic coordinates in degrees, minutes and seconds (NAD-27), observed and theoretical Loran-C time delays for X and Y lanes, and the differences (observed minus theoretical values). Also shown are summary statistics for the differences.

STATION NO.	LOCATION	LATITUDE ° ' "	LONGITUDE ° ' "	OBSERVED TIME DELAYS X (μsec)	OBSERVED TIME DELAYS Y (μsec)	THEORETICAL TIME DELAYS X (μsec)	THEORETICAL TIME DELAYS Y (μsec)	DIFFERENCES X (μsec)	DIFFERENCES Y (μsec)
1	Pooles Island Lt.	39 15 43	76 16 42	27614.4	42919.3	27616.04	42919.54	-1.64	-0.24
2	Hart Miller #1	39 13 34	76 23 46	27640.9	42888.1	27642.74	42888.62	-1.84	-0.52
3	Seven Foot Knoll	39 09 20	76 24 34	27629.5	42836.1	27631.48	42836.59	-1.98	-0.49
4	Baltimore Light	39 03 33	76 23 57	27606.6	42766.6	27608.38	42766.80	-1.78	-0.20
5	Love Point Light	39 03 26	76 17 01	27573.1	42770.4	27574.77	42770.61	-1.67	-0.21
6	Sandy Point Light	39 00 56	76 23 05	27593.6	42735.5	27595.33	42735.70	-1.73	-0.20
7	Thomas Point	38 53 55	76 26 10	27584.4	42647.7	27586.25	42648.03	-1.85	-0.33
8	Bloody Point	38 50 01	76 23 31	27559.5	42602.7	27561.15	42602.92	-1.65	-0.22
9	Cox Creek Ent.	38 53 55	76 18 50	27550.3	42653.8	27551.81	42654.04	-1.51	-0.24
10	Claiborne Ent.	38 50 08	76 17 17	27530.7	42609.5	27532.24	42609.55	-1.54	-0.05
11	Holland Point Bar	38 44 26	76 30 51	27575.0	42528.3	27576.83	42528.75	-1.83	-0.45
12	Poplar Isl. (South)	38 44 02	76 21 21	27530.5	42531.8	27531.99	42532.30	-1.49	-0.50
13	Sharpes Island	38 38 20	76 22 33	27517.9	42462.3	27519.84	42462.23	-1.94	0.07
14	Tilghman I. #1 (East)	38 41 22	76 18 45	27509.8	42502.4	27511.61	42502.34	-1.81	0.06
15	Broad Crk. Ent.	38 41 39	76 14 59	27492.9	42508.6	27494.84	42509.09	-1.94	-0.49
16	Choptank River Lt.	38 39 20	76 11 06	27467.5	42484.3	27469.49	42484.63	-1.99	-0.33
17	Cook Point Cove #2	38 37 28	76 16 11	27485.9	42457.4	27487.76	42457.56	-1.86	-0.16
18	N. Pier Lng Term.	38 24 20	76 23 13	27479.2	42292.3	27481.19	42292.25	-1.99	0.05
19	Fishing Crk. Ent. #1	38 21 07	76 16 21	27439.1	42260.0	27441.04	42260.41	-1.94	-0.41
20	Patuxent River #1	38 19 01	76 24 04	27467.8	42227.0	27469.79	42227.13	-1.99	-0.13
21	Hooper Island Light	38 15 22	76 15 00	27417.0	42192.4	27419.06	42192.70	-2.06	-0.30
22	Point No Point	38 07 41	76 17 26	27407.2	42097.4	27409.36	42097.73	-2.16	-0.33
23	Hooper Straight	38 13 36	76 04 34	27364.5	42181.9	27366.78	42182.80	-2.28	-0.90
24	Holland Island Bar	38 04 07	76 05 46	27345.7	42067.6	27347.92	42068.42	-2.22	-0.82
25	Point Lookout	38 01 36	76 19 20	27399.6	42022.2	27401.82	42022.47	-2.22	-0.27
26	Smith Point	37 52 47	76 11 03	27341.3	41926.4	27343.44	41926.96	-2.14	-0.56
27	Roasting Ear Pt. #3	38 16 51	76 00 55	27356.3	42224.7	27358.39	42225.45	-2.09	-0.75
28	Sharkfin Shoal	38 12 07	75 59 16	27336.0	42170.1	27338.43	42170.96	-2.43	-0.86
29	Solomons Lump	38 02 52	76 00 55	27320.6	42058.6	27322.81	42059.27	-2.21	-0.67
30	Hazards Point #2	38 04 10	75 53 23	27289.00	42082.60	27291.38	42083.57	-2.38	-0.97
31	Janes Island	37 57 48	75 55 08	27282.00	42005.20	27284.23	42006.34	-2.23	-1.14
32	Wolf Trap	37 23 26	76 11 23	27275.75	41577.02	27278.08	41577.98	-2.33	-0.96
33	Stingray Point	37 33 40	76 16 13	27318.45	41691.82	27320.82	41692.31	-2.37	-0.49
34	Windmill Point	37 35 48	76 14 10	27314.77	41720.15	27317.00	41720.57	-2.23	-0.42
35	Great Wicomico	37 48 15	76 16 05	27352.05	41865.90	27354.35	41866.46	-2.30	-0.56
36	Tangier Sound	37 47 16	75 58 28	27272.39	41877.10	27274.86	41877.84	-2.47	-0.74
37	Thimble Shoals	37 00 52	76 14 26	27241.84	41306.32	27244.52	41307.13	-2.68	-0.81
38	Tellurometer	37 23 40	76 04 36	27247.81	41590.61	27250.08	41591.16	-2.27	-0.55
39	Tellurometer	37 41 04	76 09 02	27304.84	41789.58	27307.05	41790.22	-2.21	-0.64
40	Tellurometer	37 18 48	76 05 35	27241.89	41531.84	27244.16	41532.45	-2.27	-0.61
41	Tellurometer	37 45 39	76 09 38	27317.96	41843.30	27320.25	41843.86	-2.29	-0.56
42	Tellurometer	37 15 00	76 08 27	27245.95	41482.57	27248.33	41483.21	-2.38	-0.64
43	York Spit	37 12 33	76 15 16	27268.84	41442.81	27271.30	41443.30	-2.46	-0.49
44	Tellurometer	37 34 30	76 09 14	27290.94	41711.51	27293.09	41712.09	-2.15	-0.58

	X	Y
MEAN	-2.06	-0.47
STD. DEV.	0.29	0.29
MINIMUM	-2.68	-1.14
MAXIMUM	-1.49	0.07
RANGE	1.19	1.21

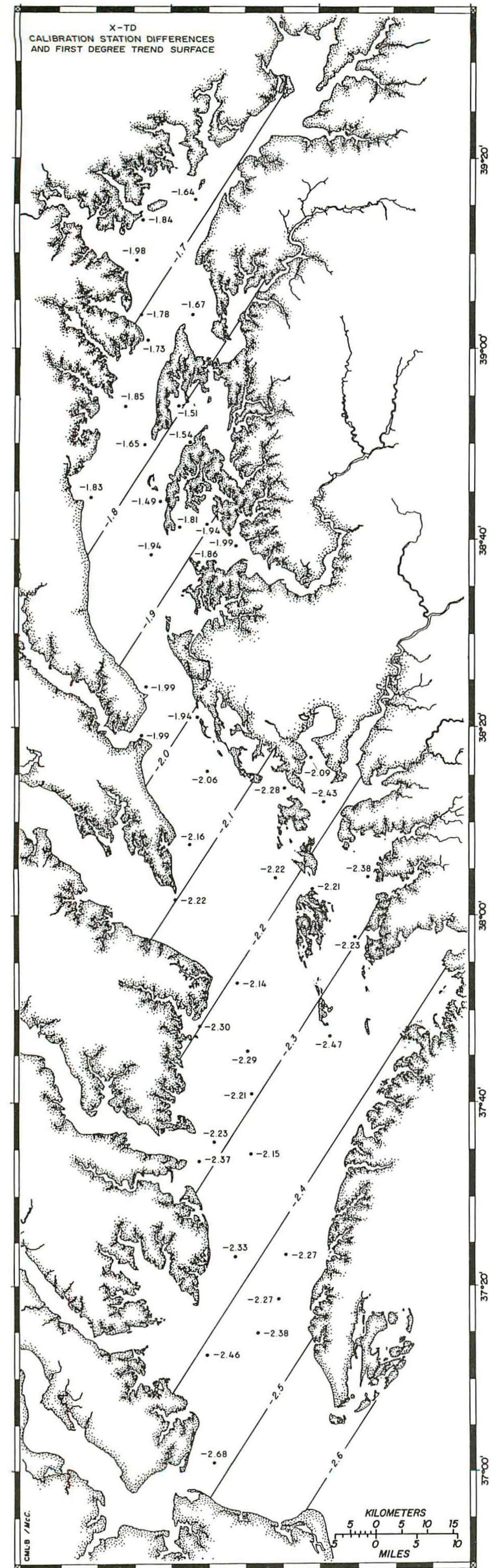

Figure 3: — Observed minus computer calculated differences for X-lane time delays at the 44 calibration stations (in microseconds), and contours of first-degree trend surface fit to these data.

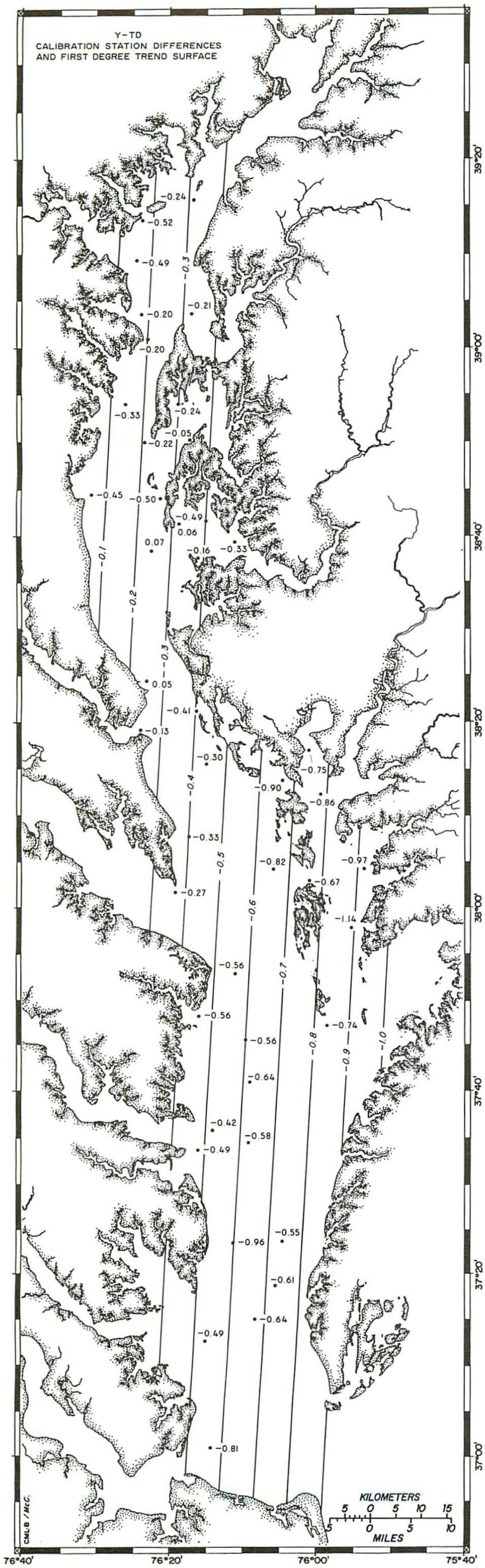

Figure 4: — Observed minus computer calculated differences for Y-lane time delays at the 44 calibration stations (in microseconds), and contours of the first-degree trend surface fit to these data.

A knowledge of the differences between the TDs observed at a station and those calculated by the SALT-model permits corrections to be applied to the TDs. In this way an operator can arrive at a location which has been pre-selected from known geographic coordinates using LORAN-C TDs. Conversely, knowing LORAN-C TDs from a field station and applying correction factors permit conversion to accurate latitude and longitude coordinates within the limits of repeatability. Without the application of correction factors, locational differences may exceed 2.5 μsec in the X-TD and 1.0 μsec in the Y-TD (Figures 3, 4). For the central portion of Chesapeake Bay, 1.0 μsec represents distances of approximately 285 meters and 156 meters for X and Y time differences, respectively. Without the application of correction factors, displacements exceeding 700 meters in the X direction and 150 meters in the Y direction may occur. Clearly if the program is to be utilized for converting between TDs and geographic position, the application of the correction factors becomes a necessity if an accurate location is desired. Repeatability, the ability to return to a location once LORAN-C TDs for that location have been obtained in the field, is not improved or affected by this methodology. Rather, repeatability is affected by the stability of the LORAN-C signal propagation and the receiver and is within 100 meters for the Bay region (Figure 2).

One method of utilizing the correction factors is to apply them manually for a given location when the computer program conversion routine is utilized. However, this method is unwieldy if more than a few station locations need to be calculated. To expedite the conversions, a polynomial trend surface analysis was performed on the calibration data. Equations for calculating the correction factors at a geographic location were derived from this analysis and have been incorporated into the computer program.

Polynomial trend surface analysis is a 2-dimensional extension of least squares analysis that minimizes the absolute values of the differences between the calculated trend and the observed values. In this way a trend representing a "best fit" to the original data is obtained. The trend surface analysis seeks to identify broad scale variations within the area of interest as opposed to localized variations. Once these regional trends in LORAN differences have been identified, values at locations other than the calibration stations but contained within the calibration area can be predicted.

The data input into the trend surface analysis consisted of the latitudes and longitudes of each of the occupied calibration stations along with the differences between the observed and theoretical LORAN-C TDs at the stations. A trend surface program (Davis, 1973) was run once with the calculated differences for X as the dependent variable and the geographic coordinates as the independent variables (as listed in Table II) and again with the calculated differences for Y as the dependent variable. First through sixth degree trend surfaces were generated. At each level, analysis of variance techniques were employed to test whether or not the surface represented a significant improvement in fit over the previous level of analysis. The results indicated that orders higher than the first did not significantly improve the fit. Therefore, the first order equations were selected to provide estimates of the differences at any geographic location in the central Bay.

The derived trend surface formulae used for estimating the X and Y differentials are given in equations 2) and 3), respectively:

$$\text{X-difference} = 0.3471\ (\text{latitude}) + 0.4284\ (\text{longitude}) - 47.9914 \quad (2)$$
$$\text{Y-difference} = 0.09\ (\text{latitude}) + 1.2778\ (\text{longitude}) - 101.3177 \quad (3)$$

where geographic latitude and longitude are entered as decimal degree values. Goodness-of-fit (R^2) values for these trend surfaces were 0.78 for X-TD differentials and 0.60 for the Y-TD. Table III shows the difference between the observed and theoretical LORAN-C value at each station; the value predicted by the trend surface equation; and the residual value or the difference between the observed difference and that predicted by the trend surface.

A first degree trend with the two independent variables (latitude and longitude) produces a planar surface with a regional dip. The surfaces developed from equations 2) and 3) are shown in Figures 3 and 4 respectively. The surfaces shown, representing broad scale estimates of the differences, can be viewed as predictions of the regional time difference ASF for LORAN X and Y lines of position. The X-ASF increases to the southeast in the Bay region while the Y-ASF increases in an easterly direction. Figures 3 and 4 also show the observed differences at each station which the trend surfaces are meant to predict. The residuals, or the differences between the trend surface prediction and the time difference at each station (listed in Table III), are plotted for each station in Figures 5 and 6. These residuals can be viewed as representing local factors that affect the propagation speed of the LORAN signals, plus variations in the original observational data due to receiver instability, changing signal to noise ratios, short term factors that affect signal propagation, such as weather and diurnal effects, and errors in the reported geographic locations of the calibration stations. In effect these factors, if they occur as random 'noise,' are removed by the 'best fit' process of the trend surface procedure.

For the X lines the derived trend surface equation provides a good prediction of the differences expected at each of the calibration stations. The goodness of fit value for the surface is fairly high at 0.78, and 27 of the residual values are less than 0.1 μsec (Table III). More importantly, there are no systematic trends apparent in the residual values (Figure 5). Were a systematic trend present, it would indicate that the trend surface is failing to model the ASF successfully on a regional basis or that the 'noise' factors are not random.

However, there are certain areas of the Bay in which the residuals at a number of stations are comparatively large. These are: near the mouth of Baltimore Harbor around 35°10'N; near the mouth of Eastern Bay between 38°45'N and 38°55'N; in certain portions of Tangier Sound between 38°05'N and 38°15'N; and in the southern part of the Bay south of 37°20'N. In these areas, localized factors may be altering the signal propagation speeds, reducing the ability of the trend surface equation to predict the X-ASF.

In the case of the Y lines, the derived trend surface is somewhat less efficient at predicting the differences observed at each of the calibration stations. The goodness of fit value is 0.6 versus 0.78 for the X lines, and residuals at 21 of the 44 calibration stations exceed 0.1 microsecond (Table III). As was the case for the X lines, there are no regional trends apparent in the residual values (Figure 6). High residual values are somewhat more scattered throughout the study area than was the case for the X lines. However, relatively high residual values are grouped in certain areas of the Bay on Figure 6. These are: in the vicinity of Baltimore Harbor; near 38°45'N; and in the southern portion of the Bay near 37°20'N.

The ability of the first degree trend surfaces to predict both the X and Y ASFs is evidenced by the fairly high goodness of fit values for the derived equations and the absence of regional trends in the residual data. Therefore equations 2) and 3) have been incorporated in the computer program which is described and listed in the Appendix. In the Chesapeake Bay proper these correction factors will significantly improve the accuracy of converting between LORAN-C and geographic coordinates. However, users should be aware that in those local areas where residual values are relatively high, accuracy may be diminished.

Table III.—The observed minus theoretical differences, the differences predicted by the first order trend surfaces and the residuals for each of the calibration stations (μsec).

STATION NO.	LOCATION	OBSERVED MINUS THEORETICAL TIME DELAYS (DIFFERENCES) X	Y	DIFFERENCES PREDICTED BY TREND SURFACE X	Y	TREND SURFACE RESIDUALS (DIFFERENCE MINUS PREDICTED DIFFERENCE) X	Y
1	Pooles Island Lt.	-1.64	-0.24	-1.69	-0.32	0.05	0.08
2	Hart Miller #1	-1.84	-0.52	-1.65	-0.17	-0.19	-0.35
3	Seven Foot Knoll	-1.98	-0.49	-1.67	-0.16	-0.31	-0.33
4	Baltimore Light	-1.78	-0.20	-1.71	-0.18	-0.07	-0.02
5	Love Point Light	-1.67	-0.21	-1.76	-0.33	0.09	0.12
6	Sandy Point Light	-1.73	-0.20	-1.73	-0.20	-0.00	0.00
7	Thomas Point	-1.85	-0.33	-1.75	-0.15	-0.10	-0.18
8	Bloody Point	-1.65	-0.22	-1.79	-0.21	0.14	-0.01
9	Cox Creek Ent.	-1.51	-0.24	-1.80	-0.30	0.29	0.06
10	Claiborne Ent.	-1.54	-0.05	-1.83	-0.34	0.29	0.29
11	Holland Point Bar	-1.83	-0.45	-1.77	-0.06	-0.06	-0.39
12	Poplar Isl. (South)	-1.49	-0.50	-1.84	-0.26	0.35	-0.24
13	Sharpes Island	-1.94	0.07	-1.86	-0.25	-0.08	0.32
14	Tilghman I. #1 (East)	-1.81	0.06	-1.87	-0.32	0.06	0.38
15	Broad Crk. Ent.	-1.94	-0.49	-1.90	-0.40	-0.04	-0.09
16	Choptank River Lt.	-1.99	-0.33	-1.94	-0.49	-0.05	0.16
17	Cook Point Cove #2	-1.86	-0.16	-1.91	-0.38	0.05	0.22
18	N. Pier Lng Term.	-1.99	0.05	-1.94	-0.25	-0.05	0.30
19	Fishing Crk. Ent. #1	-1.94	-0.41	-2.01	-0.41	0.07	-0.00
20	Patuxent River #1	-1.99	-0.13	-1.96	-0.24	-0.03	0.11
21	Hooper Island Light	-2.06	-0.30	-2.05	-0.44	-0.01	0.14
22	Point No Point	-2.16	-0.33	-2.08	-0.40	-0.08	0.07
23	Hooper Straight	-2.28	-0.90	-2.13	-0.67	-0.15	-0.23
24	Holland Island Bar	-2.22	-0.82	-2.18	-0.66	-0.04	-0.16
25	Point Lookout	-2.22	-0.27	-2.10	-0.37	-0.12	0.10
26	Smith Point	-2.14	-0.56	-2.21	-0.56	0.07	0.00
27	Roasting Ear Pt. #3	-2.09	-0.75	-2.14	-0.74	0.05	-0.01
28	Sharkfin Shoal	-2.43	-0.86	-2.18	-0.78	-0.25	-0.08
29	Solomons Lump	-2.21	-0.67	-2.22	-0.76	0.01	0.09
30	Hazards Point #2	-2.38	-0.97	-2.27	-0.92	-0.11	-0.05
31	Janes Island	-2.23	-1.14	-2.29	-0.89	0.06	-0.25
32	Wolf Trap	-2.33	-0.96	-2.38	-0.60	0.05	-0.36
33	Stingray Point	-2.37	-0.49	-2.28	-0.48	-0.09	-0.01
34	Windmill Point	-2.23	-0.42	-2.28	-0.52	0.05	0.10
35	Great Wicomico	-2.30	-0.56	-2.20	-0.46	-0.10	-0.10
36	Tangier Sound	-2.47	-0.74	-2.33	-0.84	-0.14	0.10
37	Thimble Shoals	-2.68	-0.81	-2.49	-0.57	-0.19	-0.24
38	Tellurometer	-2.27	-0.55	-2.42	-0.74	0.15	0.19
39	Tellurometer	-2.21	-0.64	-2.29	-0.62	0.08	-0.02
40	Tellurometer	-2.27	-0.61	-2.44	-0.73	0.17	0.12
41	Tellurometer	-2.29	-0.56	-2.26	-0.60	-0.03	0.04
42	Tellurometer	-2.38	-0.64	-2.45	-0.67	0.07	0.03
43	York Spit	-2.46	-0.49	-2.41	-0.53	-0.05	0.04
44	Tellurometer	-2.15	-0.58	-2.33	-0.63	0.18	0.05
					MEAN	-0.0002	-0.0002
					STD. DEV.	0.14	0.19
					MINIMUM	-0.31	-0.39
					MAXIMUM	0.35	0.38
					RANGE	0.66	0.77

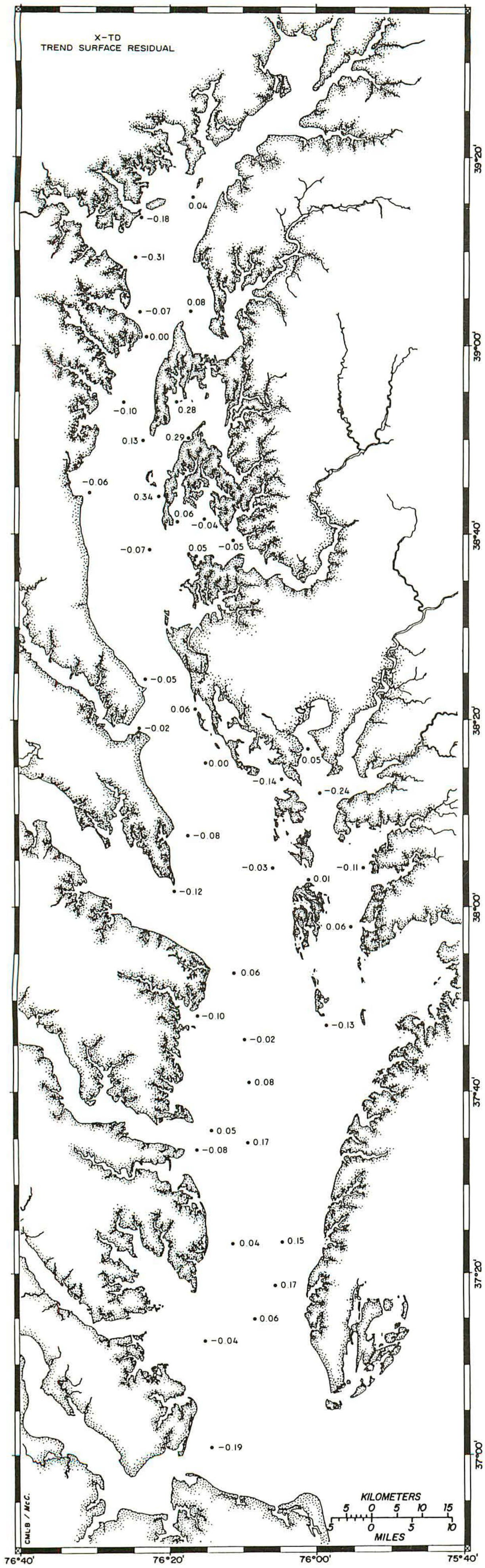

Figure 5: — Residuals for the X-lane trend-surface fit at the 44 calibration stations. High absolute values indicate where the calibration differentials are not well accounted for by the trend surface.

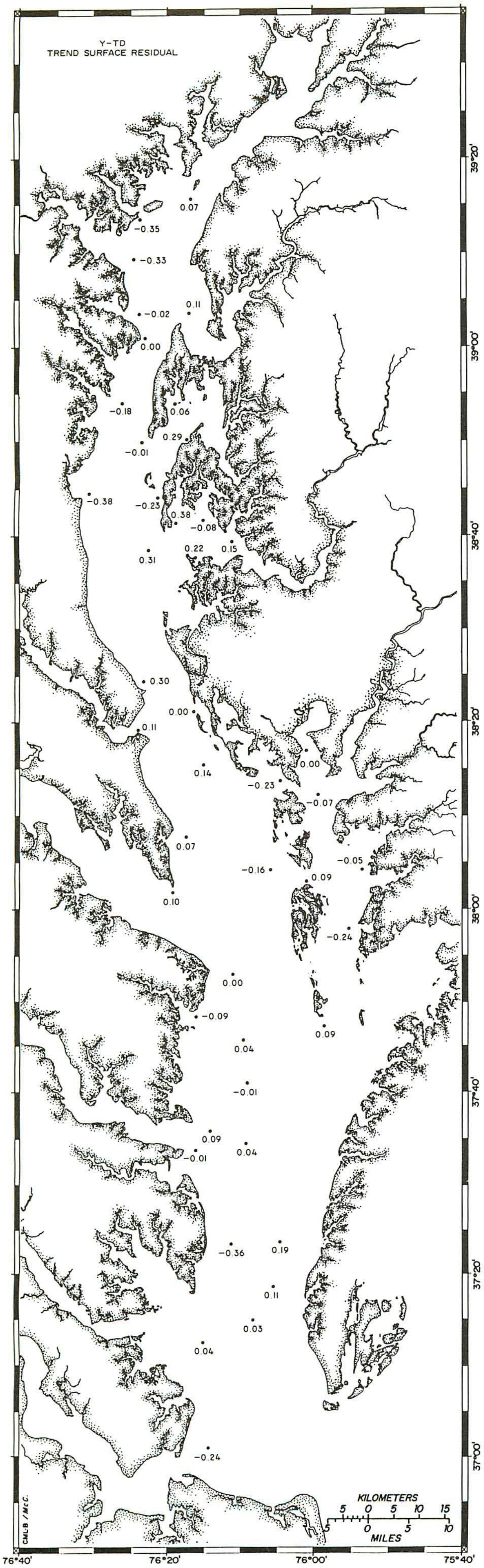

Figure 6: — Residuals for the Y-lane trend-surface fit at the 44 calibration stations. High absolute values indicate where the calibration differentials are not well accounted for by the trend surface.

SUMMARY AND CONCLUSIONS

1. Time Difference (TD) anomalies have been determined by observation at 44 stations located in the Chesapeake Bay. The anomalies represent differences between the observed TDs at each station and the theoretical TDs predicted from the SALT-Model program for the X and Y lines of position. For the X-TDs the anomalies averaged -2.06 μsec at the calibration stations, ranging from less than -2.0 μsec in the the northern part of the Bay to greater than -2.0 μsec in the south. The observed Y-TDs were closer to the theoretical, with an average anomaly of -0.47 μsec. The Y-TD anomaly was somewhat larger on the eastern shore of the Bay than on the western.
2. To derive correction factors within the Bay region a polynomial trend surface analysis was conducted on the anomaly data. For both the X and Y TDs a first degree surface provided the best fit to the data. This permitted the development of simple formulae (2 and 3) for determining the anomalies at any geographic position in the Bay region. The equations can be viewed as models of the regional X and Y ASFs.
3. Locational differences in the Chesapeake Bay can be significant. Figures 3 and 4 show the TD anomalies predicted by equations 2) and 3) in microseconds. Figure 7 exhibits the locational offsets anticipated at 10 minute squares represented by vectors. The base of each vector is the uncorrected SALT-Model location while the tip of the arrow shows the direction and magnitude of the offset. Displacement is to the WNW throughout the Bay with the greatest magnitude occurring in the south. Table IV summarizes the magnitude and direction of the offsets for half degree latitudinal sections of the Bay. These are calculated from the 10 minute grid points shown on Figure 7. While the direction of the offset changes from 287° in the south to 279° in the north, the distance offset is only about half as much (464 meters) in the north as in the south (823 meters).

Table IV: The average offsets anticipated within one half degree regions of the Bay, in meters and degrees from theoretical to corrected location.

Section of Bay	Offsets meters	Offsets degrees
37°00'N to 37°30'N	823	287
37°30'N to 38°00'N	710	287
38°00'N to 38°30'N	626	283
38°30'N to 39°00'N	539	280
39°00'N to 39°20'N	464	279

4. Equations 2 and 3 have been incorporated into the SALT- Model program included in the appendix. This program utilizes the North American Datum of 1927 (NAD-27), the same as that in use in NOAA-NOS charts of the Chesapeake Bay. Using this program an operator can quickly obtain an accurate geographic location for a given X and Y TD pair or, conversely, an accurate TD pair from a given geographic location. The program produces both corrected and uncorrected locations. If an operator has reason to doubt the applicability of the correction factors to a particular locale, the uncorrected SALT-Model values may be used or a locally derived correction factor may be applied. Interested parties may obtain a copy of the source code and compiled executable code for use on an IBM-PC or compatible system by sending a formatted DS/DD 5¼'' floppy disk to the author.

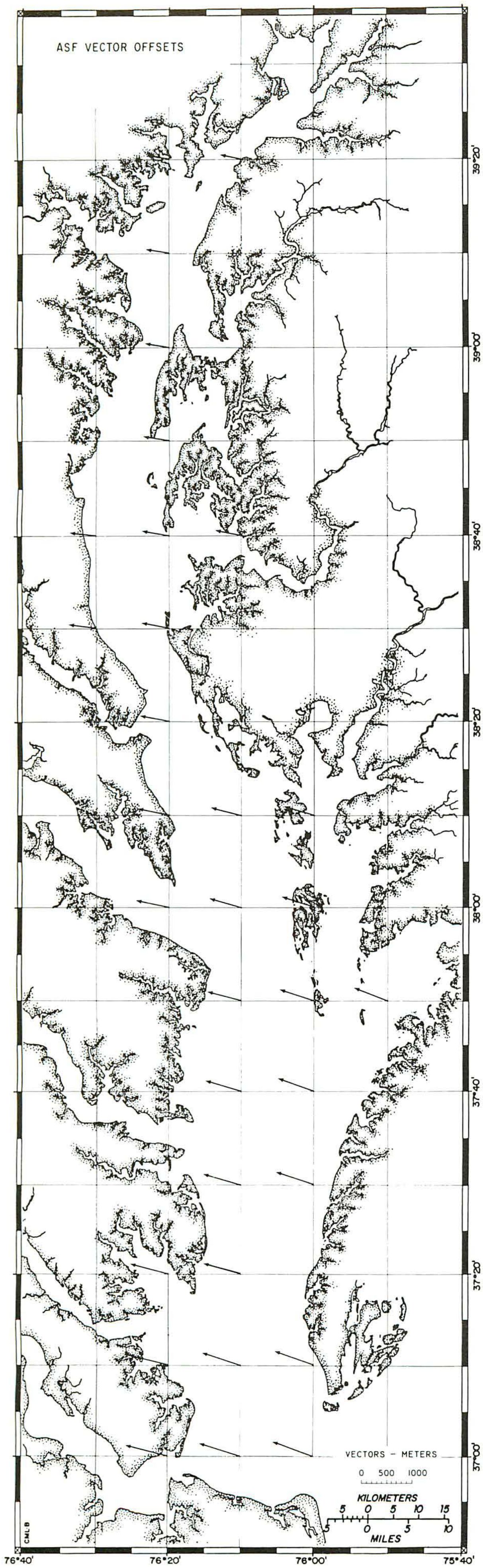

Figure 7: — Vectors showing calculated displacements for 10 minute squares on the Chesapeake Bay. Arrow tails represent theoretical SALT-model locations while tips represent corrected locations. Note that vector and chart scales are different.

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APPENDIX

Instructions for use of the LORAN-C conversion program, and FORTRAN source code for the main driver program and the three subroutines which it calls.

Use Of The Program

The source code for the computer program, written in FORTRAN, is listed below. The basic elements for the program were derived from one obtained from the Defense Mapping Agency, Hydrographic/Topographic Center.

As written the program utilizes the North American Datum of 1927 (NAD-27), the same system presently utilized on National Ocean Survey (NOS) Charts. Use of the program with other datums will produce inaccurate results. Once conversion to the NAD-83 standard is completed, locations will no longer plot accurately on NOS charts. Interested users may contact the author for an update to the program and the calibration data at such time as the new coordinate system is in general use.

The main driving program (LORAN) calls three FORTRAN subroutines whose source code follows the main program listing. The first subroutine, FIX, computes the geographic coordinates of a fix from the approximate location and the X and Y LORAN-C time differences. This computation utilizes an iterative mathematical process with a maximum of fifteen passes through the routine. To convert from geographic coordinates to LORAN-C X and Y TDs an inverse of the FIX subroutine is utilized. This subroutine is called INV. Both the main driver program, LORAN, and the FIX subroutine call another subroutine, ASFCMP, which computes the all sea-water path correction factor for the time difference calculations (the SALT-model).

Utilization of the program is straightforward. Prior to entering locational values, the operator enters a series of numeric values in response to prompts which appear on the screen. These responses concern the form of the data to be input/output, the type of calculations and the output form.

The first question to which the operator responds concerns the form in which the geographic coordinate data is to appear either on input or as output. One of three responses is possible. If value of '1' is entered, the geographic coordinate data occur in the form of degrees and decimal degrees. This form is particularly suitable if the coordinate data is to be utilized in plotting routines for boat path, sampling locations, etc. A value of '2' indicates that the data will be in the form of degrees, minutes and decimal minutes. Data of this form are useful when working with NOS charts because the latitude and longitude on the chart borders occur in this form. The more traditional degrees, minutes, and seconds is selected by entering a value of '3' in response to this question.

The operator is then prompted to choose the desired type of coordinate conversion. Entering a value of '0' indicates that LORAN-C to Geographic is to be calculated while Geographic to LORAN-C is chosen by entering a value of '1'. The results of the calculations are automatically output to the screen. If a printer is connected to the computer the operator can obtain a hard copy by entering a value of '1' in response to the next prompt.

In the case of LORAN-C time differences that are to be converted to geographic coordinates, the approximate geographic location must first be entered for each conversion for the iterative computing process to function properly. If the tolerance limit called for in the FIX subroutine is not exceeded within fifteen iterations, the display will indicate 'NO FIX' and request a new approximate location as a seed value. This approximate position must be input in the form of degrees and minutes of both latitude and longitude even if the data form selected previously was different. In response to the question 'APPROX DEGREES LATITUDE', the operator has the option of ending the program session by entering a value of '99', switching to converting from geographic coordinates to LORAN-C TDs for subsequent calculations by entering a value of '95', or using the same approximate location as a seed value by entering '5'. This latter entry is useful when most or all of the fix locations are in the same area and eliminates the need to enter a seed location for each calculation.

In the case of geographic coordinates to LORAN-C conversions a seed value is not required. The geographic location is entered in the previously selected form, and the time differences are calculated. As above the operator can end the session by entering a value of '99', or can switch to converting from LORAN-C to geographic coordinates by entering '95'.

The results of the calculations are output to the screen and the printer, if selected. The input value and both an uncorrected and a corrected result are produced. Uncorrected results are the straight product of the conversion program without having the correction factors for the Chesapeake Bay region applied. Operators can utilize uncorrected results if they are working outside of the region in which the calibration is valid, or if they have reason to suspect the validity of the calibration in their area of work. Calibration was performed within the main Bay proper and is probably subject to varying amounts of error as one proceeds up any tributary away from the main Bay. Therefore, within the tributary rivers the corrected results should be used with caution. No calibration was performed in the waters of the Atlantic Ocean or its direct tributaries and the uncorrected results can be utilized in these areas with caution. In those areas of the Bay where the trend surface residuals were relatively high (see analysis section above) the corrected results are less accurate than in the remainder of the Bay, but still represent a significant improvement over the uncorrected results.

The general usage of the program can be described as follows. If one inputs LORAN-C TDs obtained in the field from a properly installed and operating system, the corrected latitude and longitude produced by the program can be used to plot these locations on a chart or map, unless the calibration work is suspect or invalid for the work area. Similarly, if an operator inputs the geographic coordinates of a location the corrected LORAN-C time differences will permit arrival at that location in the field within the repeatable error range outlined above.

FORTRAN source code for the main driver program

```
C     THIS PROGRAM WILL CONVERT TO/FROM LORAN-C TD'S FROM/TO THE GEOGRAPHIC
C      POSITION IN LATITUDE AND LONGITUDE AND CALCULATE CORRECTION FACTORS
C      FOR THE CHESAPEAKE BAY REGION.  AS CURRENTLY SET UP IT WILL WORK FOR
C      THE X AND Y LANE TD'S.  ADAPTED FROM THE
C      DEFENSE MAPPING AGENCY PROGRAM FOR A UNIVAC SYSTEM
C      BY JEFF HALKA, MARYLAND GEOLOGICAL SURVEY.  MODIFIED TO RUN ON THE
C      IBM-PC; COMPILED AND LINKED USING MICROSOFT FORTRAN(C) VERSION 3.31.
      INTEGER C,D,E
      DIMENSION DEG(4,2),XMIN(4,2),SEC(4,2),RAD(4),ZLATM(2),
     1ZLATS(2),ZLONM(2),ZLONS(2),RRHO(2),DEL(2),BEDL(2),XK(2),
     1SYSTEM(3),PAIR(3),SM(2),SS(2)
      DATA RD,RM,RS,DR/0.1745329252E-1,0.2908882086E-3,0.4848136800E-5,
     157.29577951/
      OPEN(6,FILE='LPT1')
      A=6378206.4
      B=6356583.8
C    IMPLEMENT DATA FOR MASTER STATION
      DO 2 I=1,2
      DEG(1,I)=42.
      XMIN(1,I)=42.
      SEC(1,I)=50.465
      DEG(2,I)=76.
      XMIN(2,I)=49.
      SEC(2,I)=34.470
    2 CONTINUE
C    IMPLEMENT DATA FOR SLAVE STATION, X
      BEDL(1)=26969.93
      DEG(3,1)=41.
      XMIN(3,1)=15.
      SEC(3,1)=11.728
      DEG(4,1)=69.
      XMIN(4,1)=58.
      SEC(4,1)=40.449
C   IMPLEMENT DATA FOR SLAVE STATION, Y
      BEDL(2)=42221.64
      DEG(3,2)=34.
      XMIN(3,2)=3.
      SEC(3,2)=45.596
      DEG(4,2)=77.
      XMIN(4,2)=54.
      SEC(4,2)=47.143
C   CALCULATE CONSTANTS
      FLAG=0.0
      E2=1.-(B*B)/(A*A)
      DO 4 I=1,2
      DO 3 J=1,4
    3 RAD(J)=(ABS(DEG(J,I))*RD+XMIN(J,I)*RM+SEC(J,I)*RS)*SIGN(1.,DEG(J,I
     1))
```

```
      ZLATM(I)=RAD(1)
      ZLONM(I)=RAD(2)
      ZLATS(I)=RAD(3)
      ZLONS(I)=RAD(4)
      RRHO(I)=299.6911624
    4 CONTINUE
C     END DATA INPUT
C  SELECT DATA TYPE FOR GEOGRAPHIC COORDINATES
    6 WRITE(*,*)'SELECT DATA FORM FOR LAT/LONG COORDINATES'
      WRITE(*,*)'1=DD.dddd (DEGREES AND DECIMAL DEGREES)'
      WRITE(*,*)'2=DD MM.mmmm (DEGREES, MINUTES AND DECIMAL MINUTES)'
      WRITE(*,*)'3=DD MM SS.ss (DEGREES, MINUTES AND SECONDS)'
      READ(*,*)IDATA
      WRITE(*,*)'LORAN TO GEOGRAPHIC (0); OR GEOGRAPHIC TO LORAN (1)??'
      READ(*,*)IGO
      IF(IGO.EQ.1) GOTO 95
    5 WRITE(*,*) 'WRITE OUTPUT TO PRINTER?  (0=NO, 1=YES)'
      READ(*,*) IF
      IF(IF.EQ.0) GOTO 21
C  WRITE PRINTER HEADINGS IF CHOSEN
      WRITE(6,100)
      WRITE(6,101)
      IF(IDATA.NE.1) GOTO 104
      WRITE(6,103)
      GOTO 21
  104 IF(IDATA.NE.2) GOTO 106
      WRITE(6,105)
      GOTO 21
  106 IF(IDATA.NE.3) GOTO 6
      WRITE(6,107)
  100 FORMAT( 27X,'UNCORRECTED',18X,'CORRECTED')
  101 FORMAT( 22X,'LATITUDE',5X,'LONGITUDE',6X,'LATITUDE',5X,
     1'LONGITUDE')
  103 FORMAT( 3X,'TD-X',5X,'TD-Y',6X,'DEGREES',7X,'DEGREES',7X,
     1'DEGREES',7X,'DEGREES'/)
  105 FORMAT( 3X,'TD-X',5X,'TD-Y',4X,'DEG',1X,'MINUTES',3X,'DEG',
     11X,'MINUTES',3X,'DEG',1X,'MINUTES',3X,'DEG',1X,'MINUTES'/)
  107 FORMAT( 3X,'TD-X',5X,'TD-Y',4X,'DEG',1X,'MIN',1X,'SEC',3X,'DEG',1X,
     1'MIN',1X,'SEC',3X,'DEG',1X,'MIN',1X,'SEC',3X,'DEG',1X,'MIN',1X,
     1'SEC'/)
   21 WRITE(*,*)'  '
      I=1
      WRITE(*,*)'LORAN LANES TO GEOGRAPHIC POSITION'
      WRITE(*,*)' '
      WRITE(*,*)'APPROX DEGREES LATITUDE?'
      WRITE(*,*)'(99=END,'
      WRITE(*,*)' 95=GEOGRAPHIC POS. TO TDs, 5=SAME APPROX LOCATION)'
      WRITE(*,*)'  '
```

```
      READ(*,*) ADEG
      IADEG=INT(ADEG)
      IF(IADEG.EQ.5) GOTO 25
      IF(IADEG.GT.100) GOTO 21
      REPT=IADEG
      IF(IADEG.EQ.99) GOTO 99
      IF(IADEG.EQ.95) GOTO 95
      WRITE(*,*)'APPROX. MINUTES LATITUDE?'
      READ(*,*) IAMIN
      WRITE(*,*)'APPROX. DEGREES LONGITUDE?'
      READ(*,*) IODEG
      WRITE(*,*)'APPROX. MINUTES LONGITUDE?'
      READ(*,*) IOMIN
   25 IADEG=REPT
      WRITE(*,*)'TIME DELAY-X?'
      READ(*,*) XK(1)
      WRITE(*,*)'TIME DELAY-Y?'
      READ(*,*) XK(2)
   27 ISUM=IADEG+IAMIN+IODEG+IOMIN
      IF(ISUM.EQ.0) GOTO 30
      ADEG=IADEG
      AMIN=IAMIN
      ODEG=IODEG
      OMIN=IOMIN
      ZLAT=(ABS(ADEG)*RD+AMIN*RM)
      ZLON=(ODEG*RD+OMIN*RM)
C   COMPUTE FIX
   30 CALL FIX(A,B,ZLATM,ZLONM,ZLATS,ZLONS,BEDL,XK,RRHO,E2,FLAG,
     1ZLAT,ZLON)
C   TEST FOR 'NO FIX'
      IF(FLAG.LT.-98.) GOTO 37
C   WRITE FIX
      ZDEG=ABS(ZLAT)*DR
      DLAT=ZDEG
      IDEG=ZDEG
      ZZDEG=IDEG
      ZMIN=(ZDEG-ZZDEG)*60.
      DLATM=ZMIN
      MIN=ZMIN
      ZZMIN=MIN
      ZSEC=(ZMIN-ZZMIN)*60.
      ZDEG=ABS(ZLON)*DR
      DLON=ZDEG
      IIDEG=ZDEG
      ZZDEG=IIDEG
      ZMIN=(ZDEG-ZZDEG)*60.
      DLONM=ZMIN
      MMIN=ZMIN
```

```
      ZZMIN=MMIN
      YSEC=(ZMIN-ZZMIN)*60.
      IF (I.EQ.2) GOTO 35
C  SAVE UNCORRECTED LAT/LONG DATA
      DLAT1=DLAT
      DLON1=DLON
      IDEG1=IDEG
      DLATM1=DLATM
      IIDEG1=IIDEG
      DLONM1=DLONM
      MIN1=MIN
      ZSEC1=ZSEC
      MMIN1=MMIN
      YSEC1=YSEC
C   COMPUTE CHESBAY CORRECTION FACTORS
      CORRX=-47.9914+0.4284*DLON+0.3471*DLAT
      CORRY=-101.3177+1.2778*DLON+0.090*DLAT
C   WRITE UNCORRECTED VALUES TO SCREEN
      WRITE(*,*)'UNCORRECTED'
      IF(IDATA.NE.1) GOTO 303
      WRITE(*,300)DLAT,DLON
      GOTO 310
  303 IF(IDATA.NE.2) GOTO 307
      WRITE(*,304)IDEG,DLATM,IIDEG,DLONM
      GOTO 310
  307 WRITE(*,308)IDEG,MIN,ZSEC,IIDEG,MMIN,YSEC
C  CALCULATE CORRECTED TD'S AND RECOMPUTE LAT/LONG
  310 TD1=XK(1)
      TD2=XK(2)
      XK(1)=XK(1)-CORRX
      XK(2)=XK(2)-CORRY
      I=2
      GOTO 30
C  WRITE CORRECTED VALUES TO SCREEN
   35 WRITE(*,*)'CORRECTED'
      IF(IDATA.NE.1) GOTO 323
      WRITE(*,300)DLAT,DLON
      GOTO 330
  323 IF(IDATA.NE.2) GOTO 327
      WRITE(*,304)IDEG,DLATM,IIDEG,DLONM
      GOTO 330
  327 WRITE(*,308)IDEG,MIN,ZSEC,IIDEG,MMIN,YSEC
  330 IF(IF.EQ.0) GOTO 21
C  WRITE ALL DATA TO PRINTER IF SELECTED
      IF(IDATA.NE.1) GOTO 333
      WRITE(6,332)TD1,TD2,DLAT1,DLON1,DLAT,DLON
      GOTO 350
  333 IF(IDATA.NE.2) GOTO 337
```

```
      WRITE(6,334)TD1,TD2,IDEG1,DLATM1,IIDEG1,DLONM1,IDEG,DLATM,
     1IIDEG,DLONM
      GOTO 350
  337 IF(IDATA.NE.3) GOTO 6
      WRITE(6,338)TD1,TD2,IDEG1,MIN1,ZSEC1,IIDEG1,MMIN1,YSEC1
     1,IDEG,MIN,ZSEC,IIDEG,MMIN,YSEC
  350 GOTO 21
  300 FORMAT( 5X,'LATITUDE=',F8.4,5X,'LONGITUDE=',F8.4/)
  304 FORMAT( 5X,'LATITUDE=',2X,I2,1X,F8.4,3X,'LONGITUDE=',2X,I2,1X,
     1F8.4/)
  308 FORMAT( 5X,'LATITUDE=',I2,I3,F6.2,5X,'LONGITUDE=',I3,I3,F6.2/)
  332 FORMAT( 2(1X,F8.2),4X,F8.5,3(5X,F9.5)/)
  334 FORMAT( 2(1X,F8.2),2X,I2,2X,F7.4,3(3X,I2,2X,F7.4)/)
  338 FORMAT( 2(1X,F8.2),2(2X,I2),1X,F4.1,3(3X,I2,2X,I2,1X,F4.1)/)
C   WRITE 'NO FIX'
   37 WRITE(*,*)'*********NO FIX*********'
      FLAG=1.0
      GOTO 21
C      ----------------------------------------
C   READ DATA (GEOGRAPHIC TO LORAN)
   95 WRITE(*,*) 'WRITE OUTPUT TO PRINTER?  (0=NO, 1=YES)'
      READ(*,*) IF
      IF(IF.EQ.0) GOTO 98
C  WRITE PRINTER HEADINGS IF CHOSEN
      WRITE(6,500)
      IF(IDATA.NE.1) GOTO 504
      WRITE(6,503)
      GOTO 98
  504 IF(IDATA.NE.2) GOTO 506
      WRITE(6,505)
      GOTO 98
  506 IF(IDATA.NE.3) GOTO 6
      WRITE(6,507)
  500 FORMAT( 2X,'LATITUDE',5X,'LONGITUDE',6X,'UNCORRECTED',10X,
     1'CORRECTED')
  503 FORMAT( 2X,'DEGREES',7X,'DEGREES',6X,'TD-X',5X,'TD-Y',7X,
     1'TD-X',6X,'TD-Y'/)
  505 FORMAT( ' DEG',1X,'MINUTE',3X,'DEG',1X,'MINUTES',6X,'TD-X',5X,
     1'TD-Y',7X,'TD-X',6X,'TD-Y'/)
  507 FORMAT( ' DEG',1X,'MIN',1X,'SEC',3X,'DEG',
     11X,'MIN',1X,'SEC',4X,'TD-X',5X,'TD-Y',7X,
     1'TD-X',6X,'TD-Y'/)
   98 WRITE(*,*)'  '
      WRITE(*,*)'GEOGRAPHIC POSITION TO LORAN LANES'
      WRITE(*,*)'  '
      WRITE(*,*)'DEGREES LATITUDE?'
      WRITE(*,*)'(99=END,'
      WRITE(*,*)'(95=LORAN TDs TO GEOGRAPHIC POSITION)'
```

```
      READ(*,*) ADEG
      IADEG=INT(ADEG)
      IF(IADEG.GT.100) GOTO 98
      IF(IADEG.EQ.95) GOTO 5
      IF(IADEG.EQ.99) GOTO 99
      AMIN=0.0
      ASEC=0.0
      OMIN=0.0
      OSEC=0.0
      DLAT=ADEG
      IF(IDATA.EQ.1) GOTO 40
      WRITE(*,*)'MINUTES LATITUDE?'
      READ(*,*) AMIN
      DLAT=ADEG+AMIN/60
      IF(IDATA.EQ.2) GOTO 40
      WRITE(*,*)'SECONDS LATITUDE?'
      READ(*,*) ASEC
      DLAT=ADEG+AMIN/60+ASEC/3600
   40 WRITE(*,*)'DEGREES LONGITUDE?'
      READ(*,*) ODEG
      DLON=ODEG
      IF(IDATA.EQ.1) GOTO 50
      WRITE(*,*)'MINUTES LONGITUDE?'
      READ(*,*) OMIN
      DLON=ODEG+OMIN/60
      IF(IDATA.EQ.2) GOTO 50
      WRITE(*,*)'SECONDS LONGITUDE?'
      READ (*,*) OSEC
      DLON=ODEG+OMIN/60+OSEC/3600
   50 ZLAT=(ADEG*RD+AMIN*RM+ASEC*RS)
      ZLON=(ODEG*RD+OMIN*RM+OSEC*RS)
      DO 51 I=1,2
C    COMPUTE DISTANCE TO MASTER
      CALL INV(A,B,ZLATM(I),ZLONM(I),ZLAT,ZLON,FLAG,DIST,A40)
      DIST=DIST/RRHO(I)
C    COMPUTE ALL-SEAWATER PATH CORRECTION FOR LORAN-C
      CALL ASFCMP(DIST)
      SM(I)=DIST
C    COMPUTE DISTANCE TO SLAVE
      CALL INV(A,B,ZLATS(I),ZLONS(I),ZLAT,ZLON,FLAG,DIST,A40)
      DIST=DIST/RRHO(I)
C    COMPUTE ALL-SEAWATER PATH CORRECTION FOR LORAN-C
      CALL ASFCMP(DIST)
      SS(I)=DIST
C    COMPUTE DIAL READINGS
      XK(I)=BEDL(I)+SS(I)-SM(I)
   51 CONTINUE
C    COMPUTE CHESBAY CORRECTION FACTORS
```

```
      CORRX=-47.9914+0.4284*DLON+0.3471*DLAT
      CORRY=-101.3177+1.2778*DLON+0.090*DLAT
C    WRITE TD'S TO SCREEN
      WRITE(*,600) (XK(I),I=1,2)
      WRITE(*,601) XK(1)+CORRX,XK(2)+CORRY
      IF(IF.EQ.0)GOTO 98
C   WRITE DATA TO PRINTER IF SELECTED
      TD1=XK(1)+CORRX
      TD2=XK(2)+CORRY
      IF(IDATA.NE.1) GOTO 633
      WRITE(6,632) ADEG,ODEG,XK(1),XK(2),TD1,TD2
      GOTO 650
  633 IF(IDATA.NE.2) GOTO 637
      IODEG=ODEG
      WRITE(6,634) IADEG,AMIN,IODEG,OMIN,XK(1),XK(2),TD1,TD2
      GOTO 650
  637 IODEG=ODEG
      IAMIN=AMIN
      IOMIN=OMIN
      WRITE(6,638) IADEG,IAMIN,ASEC,IODEG,IOMIN,OSEC,XK(1),XK(2),
     1TD1,TD2
  600 FORMAT(' UNCORRECTED-TD(X)=',F8.2,5X,'UNCORRECTED-TD(Y)=',F8.2/)
  601 FORMAT(' CORRECTED-TD(X)=',F8.2,5X,'CORRECTED-TD(Y)=',F8.2)
  632 FORMAT( 1X,F9.5,5X,F9.5,4X,F8.2,1X,F8.2,5X,F8.2,1X,F8.2/)
  634 FORMAT( 1X,I2,2X,F7.4,3X,I2,2X,F7.4,2(3X,F8.2,2X,F8.2)/)
  638 FORMAT( 1X,I2,1X,I3,1X,F4.1,3X,I2,1X,I3,1X,F4.1,4(2X,F8.2)/)
  650 GOTO 98
   99 STOP
      END
```

FORTRAN source code for the INV Subroutine

```
C                      INVERSE SUBROUTINE
C
      SUBROUTINE INV(EQRAD,PORAD,RLAT1,RLON1,RLAT2,RLON2,CFLG,DIST,AZ)
      IF(CFLG)501,501,502
  501 FLAT=1.-PORAD/EQRAD
      FLAT2=FLAT*FLAT
      F1=FLAT2*1.25
      F2=FLAT2*.5
      F3=FLAT2*.25
      F4=FLAT2*.125
      F5=FLAT2*.0625
      F6=FLAT2+FLAT
      F7=F6+1.
      F8=F6*.5
      PI=3.1415926
      TWOPI=6.2831853
      CFLG=1.
  502 BETA1=ATAN((1.-FLAT)*SIN(RLAT1)/COS(RLAT1))
      SBETA1=SIN(BETA1)
      CBETA1=COS(BETA1)
      BETA2=ATAN((1.-FLAT)*SIN(RLAT2)/COS(RLAT2))
      SBETA2=SIN(BETA2)
      CBETA2=COS(BETA2)
      DELL=RLON1-RLON2
      ADELL=ABS(DELL)
      IF(ADELL-PI)506,505,505
  505 ADELL=TWOPI-ADELL
  506 SIDEL=SIN(ADELL)
      CODEL=COS(ADELL)
      A=SBETA1*SBETA2
      B=CBETA1*CBETA2
      COPHI=A+B*CODEL
      SIPHI=SQRT((SIDEL*CBETA2)**2+(SBETA2*CBETA1-SBETA1*CBETA2*CODEL)**
     12)
      C=B*SIDEL/SIPHI
      EM=1.-C*C
      PHI=ASIN(SIPHI)
      IF(COPHI)507,508,508
  507 PHI=PI-PHI
  508 PHISQ=PHI*PHI
      CSPHI=1./SIPHI
      CTPHI=COPHI/SIPHI
      PSYCO=SIPHI*COPHI
      TERM1=F7*PHI
      TERM2=A*(F6*SIPHI-F2*PHISQ*CSPHI)
      TERM3=EM*(F2*PHISQ*CTPHI-F8*(PHI+PSYCO))
      TERM4=A*A*F2*PSYCO
      TERM5=EM*EM*(F5*(PHI+PSYCO)-F2*PHISQ*CTPHI-F4*PSYCO*COPHI*COPHI)
```

```
      TERM6=A*EM*F2*(PHISQ*CSPHI+PSYCO*COPHI)
      DIST=PORAD*(TERM1+TERM2+TERM3-TERM4+TERM5+TERM6)
      TERM7=F6*PHI
      TERM8=A*(F2*SIPHI+FLAT2*PHISQ*CSPHI)
      TERM9=EM*(F3*PSYCO+FLAT2*PHISQ*CTPHI-F1*PHI)
      ZLAM=C*(TERM7-TERM8+TERM9)+ADELL
      IF(ZLAM)610,609,610
  609 ZLAM=0.00000005
  610 CTAZ=(SBETA2*CBETA1-COS(ZLAM)*SBETA1*CBETA2)/(SIN(ZLAM)*CBETA2)
      IF(CTAZ)510,509,510
  509 CTAZ=.00000005
  510 AZ=ATAN(1./CTAZ)
      IF(DELL)515,514,514
  514 IF(DELL-PI)511,512,512
  511 IF(CTAZ)520,521,521
  520 AZ=AZ+PI
      GO TO 521
  512 IF(CTAZ)517,518,518
  515 IF(DELL+PI)511,511,516
  516 IF(CTAZ)517,518,518
  517 AZ=PI-AZ
      GO TO 521
  518 AZ=TWOPI-AZ
  521 AZ=AZ+PI
      AZ=AZ-TWOPI
      IF(AZ)513,519,519
  513 AZ=AZ+TWOPI
  519 RETURN
      END
```

FORTRAN source code for the FIX Subroutine

```
      SUBROUTINE FIX (ASMALL,BSMALL,ZLATM,ZLONM,ZLATS,ZLONS,BEDL,TD,
     1RRHO,E2,FLAG,ZLAT,ZLON)
      DIMENSION ZLATM(2),ZLONM(2),ZLATS(2),ZLONS(2),BEDL(2),TD(2),SM(2),
     1AZM(2),SS(2),AZS(2),A(2),B(2),C(2),RRHO(2)
      DATA PI,TWOPI,TOL/3.14159265365,6.28318530720,2./
C    INITIALIZE M = NUMBER OF ITERATIONS
      M=0
    1 DO 2 I=1,2
C    COMPUTE DISTANCE AND AZIMUTH TO MASTER
      CALL INV(ASMALL,BSMALL,ZLAT,ZLON,ZLATM(I),ZLONM(I),FLAG,DIST,AZ)
      AZM(I)=AZ
      SM(I)=DIST/RRHO(I)
C    COMPUTE ALL-SEAWATER PATH CORRECTION FOR LORAN-C
      CALL ASFCMP(SM(I))
C    COMPUTE DISTANCE AND AZIMUTH TO SLAVE
      CALL INV(ASMALL,BSMALL,ZLAT,ZLON,ZLATS(I),ZLONS(I),FLAG,DIST,AZ)
      AZS(I)=AZ
      SS(I)=DIST/RRHO(I)
C    COMPUTE ALL-SEAWATER PATH CORRECTION FOR LORAN-C
      CALL ASFCMP(SS(I))
    2 CONTINUE
C    COMPUTE A, B, C FOR HYPERBOLIC SYSTEM
      DO 4 I=1,2
      A(I)=SIN(AZS(I))-SIN(AZM(I))
      B(I)=COS(AZS(I))-COS(AZM(I))
      C(I)=(SS(I)-SM(I)-TD(I)+BEDL(I))*RRHO(I)
    4 CONTINUE
C    SOLVE FOR X AND Y
      Y=(C(2)*A(1)-C(1)*A(2))/(B(1)*A(2)-B(2)*A(1))
      X=(C(2)*B(1)-C(1)*B(2))/(A(1)*B(2)-A(2)*B(1))
C    COMPUTE DELTA LATITUDE, DELTA LONGITUDE
      DELLAT=(Y*(1.-E2*SIN(ZLAT)**2)**1.5)/(ASMALL*(1.-E2))
      DELLON=(-X*(1.-E2*SIN(ZLAT)**2)**.5)/(ASMALL*COS(ZLAT))
C    COMPUTE FIX POSITION
      ZLAT=ZLAT+DELLAT
      ZLON=ZLON+DELLON
      IF(ZLON.GT.PI)  ZLON=ZLON-TWOPI
      IF(ZLON.LT.-PI)  ZLON=ZLON+TWOPI
C    TEST FOR MORE THAN 15 ITERATIONS
      M=M+1
      IF(M.GT.15) FLAG=-99
C    TEST FOR WITHIN TOLERANCE
      IF((ABS(X).GT.TOL.OR.ABS(Y).GT.TOL).AND.FLAG.GE.0.0) GO TO 1
      RETURN
      END
```

FORTRAN source code for the ASFCMP Subroutine

```
C          ALL SEAWATER PATH CORRECTION SUBROUTINE
      SUBROUTINE ASFCMP (DIST)
      DIMENSION ASF1(2),ASF2(2),ASF3(2)
      DATA ASF1/129.04398,2.7412979/,ASF2/-.011402,-.40758/,ASF3/
     1.00064576438,.00032774642/
      K=2
      IF(DIST.GT.537.) K=1
      DIST=ASF1(K)/DIST+ASF2(K)+ASF3(K)*DIST+DIST
      RETURN
      END
```

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