APPLICATION OF ADDITIONAL SECONDARY FACTORS TO LORAN-C POSITIONS FOR HYDROGRAPHIC OPERATIONS

by

Gerald E. Wheaton

October 1982

Thesis Advisor: Gerald B. Mills

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Monterey, California 93940

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(2) computing the time difference based on a Semi-Empirical TD Grid, and (3) applying ASF Correctors from the DMAHTC LORAN-C Correction Table. The final method applied multiple observed ASF Correctors at five minute latitude and longitude intervals. By applying multiple observed ASF Correctors, which was the most accurate method, a 38.3 meter 1 drms with a lane offset of 3 to 12 meters using the 9940 X-Y LORAN-C combination was obtained. Based upon the results presented, it may be possible to use LORAN-C for hydrographic surveys at scales of 1:80,000.
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ABSTRACT

The application of LORAN-C in the hyperbolic mode as a positioning system for hydrographic surveys was investigated. Observed LORAN-C time differences from a field test conducted in Monterey Bay, California were compared to calculated time differences determined from geographic positions based on a microwave positioning system. Four methods were used to determine the calculated time differences. The first three methods were (1) applying only the seawater Secondary Factor, (2) computing the time difference based on a Semi-Empirical TD Grid, and (3) applying ASF Correctors from the DMAHTC LORAN-C Correction Table. The final method applied multiple observed ASF Correctors at five minute latitude and longitude intervals. By applying multiple observed ASF Correctors, which was the most accurate method, a 38.3 meter 1 drms with a lane offset of 3 to 12 meters using the 9940 X-Y LORAN-C combination was obtained. Based upon the results presented, it may be possible to use LORAN-C for hydrographic surveys at scales of 1:80,000.
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I. INTRODUCTION

A. USE OF LORAN-C

In recent years there has been an increasing usage of a LORAN-C receiver and the LORAN-C network as the primary horizontal control for such scientific studies as deep ocean dumpsites, marine fisheries studies [Rulon, 1979], bathymetric surveys, and recently, a reconnaissance hydrographic survey. Examples of bathymetric surveys conducted by the National Oceanic and Atmospheric Administration (NOAA), which have used Loran-C for positioning are:

1) Su-100-1-79 Gulf of Alaska [NOAA H-9822, 1979],
2) SU-100-2-79 Gulf of Alaska [NOAA H-9823, 1979],

Recently an attempt was made to use LORAN-C as the sounding position control for a reconnaissance hydrographic survey S-K902-WH-82 [NOAA, 1982]. This was a special survey conducted by the NOAA Ship Whiting in May 1982. Special surveys are field examinations of very limited extent or scope and frequently require unique survey or data collection procedures [Umbach, 1976]. The purpose of this project was to verify the existence and extent of reported shoaling in three safety fairways in the Gulf of Mexico [NOAA, 1982].

The use of Loran-C as a positioning system for basic hydrographic surveys has been very limited due to the absolute accuracy of the long range system. A basic hydrographic survey is defined as a survey which is so complete that it need not be supplemented by other surveys. "It must be adequate to supersede for charting purposes all prior
surveys" [Umbach, 1976]. Variables which affect the accuracy of LORAN-C are signal propagation variations, weather, and sky waves. The effects of weather and sky waves on LORAN-C propagation are best described by Samaddar [1980] and the American Practical Navigator, [DMA, 1977] respectively.

Signal propagation variations are due to the phase retardation of the signal as it passes over an all seawater path, over land paths, or partial seawater-land paths as compared to free space. Table I summarizes phase retardation changes [Mortimer, 1978]. Errors due to an all seawater path are known as the Secondary Factor (SF) and errors due to a land path or mixed path are known as the Additional Secondary Factor (ASF) [Speight, 1982].

**TABLE I**

Phase Retardation or Lag of Radio Waves

<table>
<thead>
<tr>
<th>Propagation Path</th>
<th>Representation Propagation Velocity (km/sec)</th>
<th>Difference in Phase Lag at 500 km Compared with Wave in Line Above (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum</td>
<td>299792.5</td>
<td>-</td>
</tr>
<tr>
<td>Direct wave through earth's atmosphere</td>
<td>299691</td>
<td>170</td>
</tr>
<tr>
<td>Ground wave over sea water</td>
<td>299560</td>
<td>220</td>
</tr>
<tr>
<td>Ground wave over rugged mountains</td>
<td>298899</td>
<td>1,300</td>
</tr>
</tbody>
</table>
ASF Corrections in the LORAN-C system can be as large as plus or minus four microseconds, which is 600 meters on the baseline. In other areas with the same LORAN-C coverage, these corrections may be much larger due to the expansion of the distance between adjacent hyperbolic lines of position. For example, at 320° W and 80° W, using lattice pair 9960-X, a four microsecond (μsec) error will offset the 9960-X line of position approximately 2438 meters [Speight, 1982].

B. APPLICATION OF ASF CORRECTORS FOR NAVIGATION

To compensate for the Loran-C positional errors caused by the ASF Correctors, the Secretary of Transportation tasked the Defense Mapping Agency Hydrographic/Topographic Center (DMAHTC), the National Oceanic and Atmospheric Administration (NOAA), and the United States Coast Guard (USCG) with the job of determining and applying the Additional Secondary Correctors for each Loran-C chain. This task was published in the Department of Transportation (DOT) National Plan for Navigation in the July 19, 1974 Federal Register. These corrections should provide 95% assurance that a vessel could fix its position to a predicted accuracy of 1/4 nautical mile (NM) within the U.S. Coastal Confluence Zone (CCZ) and the Great Lakes. The CCZ is defined as:

"the seaward approaches to land, the inner boundary of which is the harbor entrance and the outer boundary of which is 50 nautical miles offshore or the edge of the Continental Shelf (100 fathom contour) whichever is greater."

The 1/4-NM accuracy requirement also affects the nautical chart. The National Ocean Survey (NOS), which publishes charts for the CCZ, engaged in a program with the USCG and DMAHTC to provide the coastal navigator with charts overprinted with lattices which meet 1/4-NM accuracy. The USCG, as operator of the LORAN-C radionavigation system,
conducts surveys to ensure that LORAN-C coverage exists within the CCZ and will be responsible for the verification of 1/4-MM accuracy for all coastal LORAN-C service. In conjunction with NOS, it assists in surveys of coastal waters of the United States to allow production of LORAN-C charts based on observed field data to meet the standards set forth above [Speight, 1982].

DMAHTC, for LORAN-C civil need, prepares grid predictions from its data base. Based on analysis and verification of the predicted grid from a USCG and/or NOS survey, it produces revisions to the initial grid predictions [Speight, 1982]. At present, DMAHTC has provided NOS with ASF Corrected LORAN-C Lattices which are overprinted on the NOS Charts. Each chart with ASF Correctors applied contains one of the following notes:

"The LORAN-C lines of position overprinted on this chart have been prepared for use with groundwave signals and are presently compensated only for theoretical propagation delays, which have not yet been verified by observed data. Mariners are cautioned not to rely entirely on the lattices in inshore waters. Skywave corrections are not provided".

or

"The LORAN-C lines of position overprinted on this chart have been prepared for use with groundwave signals and are compensated with propagation delays computed from observed data. Mariners are cautioned not to rely entirely on the lattices in inshore waters. Skywave corrections are not provided" [Speight, 1982].

Presently, all of the NOS Charts of 1:80,000 to 1:120,000 scale covering the east coast, Gulf coast, and Great Lakes show LORAN-C lattices that have been compensated for Additional Secondary Factors. Most of the lattices on these charts have been constructed from DMAHTC data tapes that provide adjusted LORAN-C readings for each rate at every five minutes of latitude and longitude. A few lattices were constructed using a single ASF Correction for the entire chart area. Five minute data tapes were not
furnished by DMAHTC for constructing lines of position for LORAN-C rates on the West Coast charts. On these charts a single average ASP Correction was used to adjust each lattice [NOAA, Marine Chart Division, 1982].

In addition to supplying corrected LORAN-C lattices for nautical charts, DMAHTC prepares, distributes, and periodically updates unclassified ASP LORAN-C Correction Tables [Speight, 1982]. The ASP Correction Tables are for precision navigation, utilizing digital computers to convert LORAN-C time differences to geographic coordinates [Speight, 1982]. Presently, the ASP correctors found in the LORAN-C Correction Tables were determined using theoretical propagation delays. ASP correctors listed in the tables are going to be updated with observed data and reprinted the first quarter of 1983 [Wallace, 1982].

C. APPLICATION OF ASF TO HYDROGRAPHIC POSITIONING

Schnebele [1979] investigated the possibility of using Loran-C as an electronic positioning system for hydrographic surveying. He concluded that in Monterey Bay, California a single Additional Secondary Factor (ASF) applied to offshore lines of position gave a root mean square error (drms) of 66 meters for the West Coast 9940 Y-W pair and a predicted 42 meter drms error for 9940 X-Y rates.

The 42 meter predicted drms is larger than Nelson’s [General Electric Co., 1979] findings in San Francisco Bay. He demonstrated, in a dynamic mode, that the precision of LORAN-C was 60.8 meters 2 drms (30.4 meter 1 drms) with a worst case of 71.2 meters 2 drms (35.6 meter 1 drms). A mean difference or offset between the measured time difference and the calculated time difference was 34 nanoseconds for the 9940-X rate and one nanosecond for the 9940-Y rate.
He also obtained a precision of 38.0 meters 2 drms (19.0 meters 1 drms) in the static mode. Nelson also states, that the above precision is only achievable if the user has a LORAN-C receiver which has the performance capabilities of those used in the experiment. The LORAN-C receiver must have "comparable signal averaging time, extra notch filters, and attenuation of the signal" [General Electric Co., 1979].

D. OBJECTIVES

The National Ocean Survey requires that hyperbolic control systems used for hydrographic surveying exhibit a 1 drms of less than 0.5 millimeter at the scale of the survey [Umbach, 1976]. Although this requirement is generally for 2 mHz phase comparison systems, it can be inferred that it also applies to other hyperbolic systems such as LORAN-C. The scale routinely used for coastal surveys is between 1:40,000 and 1:80,000 [Umbach, 1976] yielding an allowable error of 20 to 40 meters not including systematic errors. Schnebele [1979] concluded that hyperbolic LORAN-C, after applying a single ASF Corrector, is unsuitable for basic hydrographic surveying.

Whether or not applying multiple Additional Secondary Factors (ASF) to LORAN-C lines of position will reduce the drms sufficiently to meet the accuracy standards set by the National Ocean Survey Hydrographic Manual will be ascertained in this study. The term multiple ASF Correctors refers to the application of more than one corrector to LORAN-C lines of position over a given area. The variable ASF Correctors result from varying delays of the electromagnetic wave as it propagates over different land segments.

Three methods of applying multiple ASF Correctors were tested. The first method was the application of a
Semi-Empirical Time Difference Grid Calibration Model developed by The Analytic Science Corporation (1979). The sponsoring agency was the United States Coast Guard. The Semi-Empirical Model applies Secondary Factors and Additional Secondary Factors for each geodetic position based on the distance over land, the distance over water, and the total distance using mean sea water and land conductivities.

The second method which was investigated applies ASF Correctors found in the DMAHTC LORAN-C Correction Tables [DMAHTC, 1981] to LORAN-C lines of positions. These correctors were derived from the ground conductivities which have been determined in the field by a Coast Guard calibration team [U.S. Naval Oceanographic Office, 1982].

Finally, a third method was pursued. ASF Correctors, which were determined by field observations, were applied to the LORAN-C lines of position. These were determined by computing the difference between the observed LORAN-C rates and the expected time difference which was calculated using four lines of position from a very accurate microwave positioning system. These ASF Correctors were determined at five minute latitude and longitude intervals.
II. NATURE OF THE PROBLEM

A. THE PRINCIPLES OF LORAN-C

To understand the problems associated with LORAN-C when used during hydrographic operations, one must first understand its principles of operation. LORAN-C is a low frequency, pulsed signal, hyperbolic, radio navigation system, employing time difference measurements of signals received by the navigator from at least three ground transmitting stations [Speight, 1982]. The stations are comprised of a master transmitting station, two or more secondary transmitting stations which are strategically spaced several hundred miles apart and, if necessary, a System Area Monitor (SAM) Station [U.S. Coast Guard, 1974].

System Area Monitor (SAM) stations associated with each LORAN-C chain apply differential-type corrections to the rates in real-time. SAM stations continuously monitor the signals from all transmitters in the chain. If the observed time difference deviates by more than 0.05 μsec from the expected value, then the appropriate secondary adjusts its emission delay time in order to remove the error [Schnebele, 1979].

The master and at least two secondary stations are located such that the signals from the transmitting stations can be received throughout the desired coverage area. The master station is designated by the letter "M" and the secondary stations or slave stations are designated W, X, Y, or Z [.U.S. Coast Guard, 1974].

All stations transmit on the common frequency of 100 kHz. Interference between transmitters is avoided through the use of time separation [Poppe, 1982]. After the master
station transmits a pulse, each secondary station delays its own transmission for a fixed time, called the secondary coding delay. This coding delay is synchronized through the use of cesium frequency standards at each station. The high stability and accuracy of these standards permit each station to derive its own time of transmission without reference to another station [DNA, 1977]. Secondary coding delays are predetermined by system propagation times and equipment characteristics [Laurila, 1976].

The pulse from the master transmitter is distinguished from those of the secondaries through phase coding of the pulses. Phase coding refers to the inversion of the negative and positive peaks of the sine wave comprising the 100 kHz carrier portion of the pulse. The purpose of the phase coding is twofold:

"First, it permits automatic discrimination between the master and the various secondary stations, thereby permitting all stations to be identified by their relative timing with respect to the master"

"Second, the phase coding provides protection against excessively long skywave delays which would cause the late arrival of the preceding pulse to coincide with the leading edge or groundwave portion of a pulse being tracked" [Poppe, 1982].

The signals are received by a mobile receiver where the differences in time of arrival of the master signal and various secondary signals are measured and displayed on the indicator portion of the LORAN-C set. The accuracy of this time difference is increased by phase comparison "of the synchronized 100 kHz carrier within the master and secondary pulses" [Laurila, 1976]. This measured time difference (TD - in microseconds) represents a hyperbolic Line of Position (LOP) [U.S. Coast Guard, 1974]. The intersection of two or
Figure 2.1 Hyperbolic Fix (From Coast Guard LORAN-C User Handbook, 1974)

more LORAN-C LOP's defines the position of the observer (Figure 2.1). When plotted on a chart, the intersection of the resultant hyperbolic lines defines a geographical position [Speight, 1982].
B. PHASE LAG

In a vacuum, the velocity of radiated energy from an antenna for LORAN-C is 299792.458 km/sec. Since radiated energy cannot be shown pictorially, the phase of the transmitted radiations is used. The lines of constant phase of the transmitted radiation are shown in Figure 2.2 by the curved lines labeled aa', bb', and other similar designations. They define the wave front as it proceeds outward from the antenna in all directions. The distance between each line of constant phase is one wavelength (\( \lambda \)) [Admiralty Manual, 1965].

\[ \lambda \ (\text{meters}) = \frac{299792.458 \ \text{km/sec}}{\text{frequency in kHz}} \]

![Figure 2.2 Transmitted Radiation](image)

The velocity of the radiated energy in air depends on temperature, pressure, humidity, and the nature of the
surface over which the transmissions pass. The retardation of a transmitted wave is known as phase lag. When low frequencies are employed, such as LORAN-C at 100 kHz, the effects of change of temperature, pressure, and humidity are swamped by the effects caused by changes in the nature of the surface over which the transmissions are traveling [Admiralty Manual, 1965]. The General Electric Company, TEMPO division, conducted a LORAN-C Signal Analysis Experiment under the direction of the U.S. Coast Guard. This experiment was conducted along the U.S. West Coast. The General Electric Company recorded an overall change of 108 nsec and 116 nsec time of arrival from the master and X-secondary stations respectively after a storm [Samaddar, 1980]. If ASP Correctors are as large as two microseconds on the West Coast [DMAHTC, 1981] then the ASP Corrections are 20 times larger in magnitude than weather effects for the 9940 West Coast LORAN-C chain.

The change in transmission rates or phase lag are a result of the amount of energy transferred from the transmitted radiation. This energy transfer depends on the absorption qualities (inversely related to conductivity) of the surface over which they are passing and their wavelength (or frequency). The lower the conductivity and the longer the wavelength (or lower the frequency) the greater the transfer of energy, and vice versa. Seawater has a relatively high conductivity (5.0 mhos/meter). Land has a much lower conductivity, which varies from marsh (fairly high) to dry sand and rock (very low) [Admiralty Manual, 1965]. Two excellent papers that discuss the electrical properties of soil are those of Smith-Rose [1934] and Pressey, Ashwell, and Fowler [1956]. Smith-Rose [1934] found that the conductivities for soil ranged from 0.18 mhos/meter for a grey clay with salt to .00001 mhos/meter for granite.
Phase lag is illustrated in Figure 2.3. The lines of constant phase, aa', bb', and cc' become distorted as they progress along the sea surface. The dotted lines represent the position of the lines of constant phase in the absence of the sea surface. The wavelength ($\lambda$) in meters, measured at heights of several wavelengths above the sea, remains about the same as the direct wave through the earth's atmosphere at 299691 km/sec at frequency in kHz. Near sea level the absorption of energy retards the progress of the wavefront, and makes the sea level wavelength ($\lambda'$) less than $\lambda$. As the lines of constant phase progress away from the antenna the phase lag increases with distance. This is known as the Secondary Factor (SF) [Admiralty Manual, 1965].

The most intriguing feature of phase lag occurs at the coastal interface where there is an extreme change in the conductivities between land and sea. Visualizing the wavefront in three dimensions, the lower part of the wave, slowed by the drag of the ground, lags further and further behind the upper part as the wave crosses the land.
coastline it suddenly encounters the much lower impedance of the sea, and in a very short distance the bottom of the wave tries to catch up with the top, as though the whole wave front were an elastic balloon. This is known as "phase recovery" [Eaton, 1979]. Phase recovery was verified during tests on Decca transmissions across the south coast of England by Pressey, Ashwell, and Fowler [1956].

The determination of the Secondary Factor for seawater is fairly direct since the conductivity of seawater (5.0 mhos/meter) is fairly constant. But for land the conductivity can vary depending on the type of soil and its water content [Smith-Rose, 1934].

Phase lag for radiated energy over land can be determined two ways:

1) Assign an average land conductivity to the ASF Model. For example, the average conductivity for the soil on the west coast is 0.003 mhos/meter. The average land conductivity will determine the average phase retardation of the path [The Analytic Science Corporation, 1979].

2) Determine every conductivity for each portion of a line segment from the transmitter to the receiver. The total of these conductivity segments constituting a land-water profile will determine the total phase retardation of the path [Speight, 1982].

C. TD MODEL

Positional fix accuracy using LORAN-C is primarily dependent on a chart maker's ability to accurately compute the expected difference in time-of-arrival (TOA) of received groundwave signals from the transmitting stations. Time
differences (TD), are the differences between the TOAs of the secondary and master transmitters.

\[ TD_i = TOA_i - TOA_m \]  
\[ i = \text{Secondary Station} \]
\[ m = \text{Master Station} \]

TOA computations are dependent upon an accurate knowledge of the signal phase delay.

The phase delay of a groundwave signal is generally expressed as:

\[ \phi = T + SF \]

\[ = \frac{nR}{C} + SF \]

where \( n \) is the surface refractive index, \( C \) is the speed of light in a vacuum, \( R \) is the range between the receiver position and the transmitting station. The primary phase delay, \( T \), is the computed travel time of the LORAN-C pulse over a distance equal to the transmitter-to-receiver great circle path length, taking into account the velocity of electromagnetic waves and the index of refraction of the atmosphere. The secondary factor (SF) is a correction to the primary phase delay and accounts for the phase lag. The dominant term in (2.2) is the primary phase delay (T). The SF is usually an order of magnitude smaller [The Analytic Science Corporation, 1979].

Thus, time-of-arrivals can be expressed as:

\[ TOA_i = T_i + SF_i + CD_i \]  
\[ TOA_m = T_m + SF_m \]

where \( CD \) is the true emission delay or coding delay for the LORAN-C chain [The Analytic Science Corporation, 1979]. The coding delay is equal to a time delay plus a computed one
way baseline time (Bc) which includes the secondary phase correction for an all seawater path. The oneway baseline time (Bc) is equal to the distance between the master and secondary transmitters in meters divided by the propagation velocity of LORAN-C through the earth's atmosphere (299.691 meters per microsecond [Navigation Department DMA, 1982]).

See Table II for Coding Delay values for the 9940 chain

TABLE II

Coding Delay 9940 LORAN-C Chain

<table>
<thead>
<tr>
<th>Pair</th>
<th>CD + Bc</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>9940-W</td>
<td>11000 + 2796.90</td>
<td>13796.90 μsec</td>
</tr>
<tr>
<td>9940-X</td>
<td>27000 + 1094.49</td>
<td>28094.49 μsec</td>
</tr>
<tr>
<td>9940-Y</td>
<td>40000 + 1967.27</td>
<td>41967.27 μsec</td>
</tr>
</tbody>
</table>

[Riordan, 1979]. Combining equations 2.1, 2.3, and 2.4, the true TD is given by equation 2.5 [The Analytic Science Corporation, 1979].

\[
TD_i = (T_i - T_m) + (SF_i - SF_m) + CD_i \quad (2.5)
\]

D. SEMI-EMPIRICAL TD GRID CALIBRATION MODEL

The Semi-Empirical TD Model was developed by The Analytic Science Corporation [1979] in Reading, Massachusetts for the West Coast 9940 LORAN-C chain. Similar "time difference (TD) grid calibration techniques have been successfully employed to develop an accurate (approximately 100 nsec dras) calibrated grid for St. Marys River LORAN-C chain", [The Analytic Science Corporation, 1979].
1. **Technical Approach**

The Semi-Empirical Model is based on Millington's empirical approach for computing the secondary factor over a mixed (multiple-homogeneous segment) path which combines land and sea phase delays. The generalized semi-empirical polynomial functional form for the SF of the LORAN-C station is given by:

\[
SF = SF(T_j, \beta_j) = \sum_{k=-K_1}^{K_2} A_k T_j + \sum_{l=1}^{L} (C_l \sin \beta_j + D_l \cos \beta_j) \quad (2.6)
\]

where

- \( j \) = secondary (W, X, or Y) or master (M) station,
- \( T_j \) = \(-\frac{1}{c} \) = jth station-to-user primary phase delay,
- \( R_j \) = jth station-to-user great-circle path length,
- \( \beta_j \) = user path bearing angle at the jth station,
- \( K_1, K_2 \) and \( L \) are positive integers,
- \( C_l \) and \( D_l \) are the station-dependent coefficients of harmonic terms in the model,
- \( A_k \) is the range-dependent coefficient of the model which may in general be station-dependent.

Data from 27 coastal sites distributed along the West Coast and 122 land-sea sites distributed in the Southern California CCZ (between Point Arguello and San Diego - see Figure 2.4) were used in a Kalman estimation algorithm to compute the uncertain coefficients of the land and sea models of the TD grid calibration algorithm. (An explanation of Kalman filtering for the layman is presented by Roger M. du Plessis [1967].) The calibrated algorithm...
Figure 2.4 Location of West Coast LORAN-C Stations
was used to compute TDs at each data site and the TD residuals (difference between measured and calibrated TDs) were examined. Adjustments were then made to the TD model structure in an attempt to further reduce the residuals. This process of adjusting the model structure is repeated until the residuals agree with the expected theoretical covariance associated with the TD model. The model which exhibited the "best" performance was selected as the West Coast TD grid model.

2. Generalized Range/Bearing Model

The Generalized Range/Bearing (GRB) Model was selected as the "best" semi-empirical calibration model for the West Coast chain. The semi-empirical function is:

\[
SF = A_0 + A_1 T + \sum_{j=1}^{L} \left( C \sin \theta_j + D \cos \theta_j \right) \mu \text{sec} \tag{2.7}
\]

where \(A_0, A_1, C\) and \(D\) are the model coefficients, \(\theta\) is the path bearing angle measured positive clockwise from north at the \(j\)th \( (W,X,Y\) or \(Z) \) station and \(T\) is the path range to the \(j\)th station. The GRB model is relatively complex and is expected to exhibit superior performance. The extensive model is based on knowing the distance overland (\(T_L\)), the distance over water (\(T_S\)), the total distance (\(T\)), and the path bearing angle \(\theta\) (Figure 2.5).

It was noted that the calibrated model was expected to be accurate and applicable only over the extent of ranges and bearing angles embodied in the calibration data. Hence, outside the region covered by the calibration data the model may not be as accurate as within the data coverage region. Using the GRB model, a \(\text{drms} \) value of approximately 0.8 \(\mu\text{sec} \) was expected in areas where land data alone was used to calibrate the model. Inclusion of sea calibration data produced a \(\text{drms} \) value of 0.35 to 0.50 \(\mu\text{sec} \).
The time difference (TD) is expressed by the following equation:

\[
TD_i = (T_i - T_m) + (SF_i - SF_m) + CD_i + b_i \text{ } \mu\text{sec} \tag{2.9}
\]
where

\[ T_i = \frac{n R_i}{c} \mu \text{sec}, \]

\[ T_m = \frac{n R_m}{c} \mu \text{sec}, \]

\[ R_i = \text{ith secondary station-to-user great-circle path length,} \]

\[ c = \text{the speed of an electromagnetic wave in a vacuum} = 2.99792458 \times 10^8 \text{ m/sec}, \]

\[ n = \text{surface refractive index} = 1.000338, \]

\[ R = \text{master station-to-user great-circle path length,} \]

\[ \text{CD}_i = \text{coding delay found in Table II,} \]

\[ \text{b}_i = \text{TD bias associated with the ith secondary station (\mu sec) (Table III).} \]

**TABLE III**

<table>
<thead>
<tr>
<th>TD Bias (b) - ( \mu \text{sec} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDW</td>
</tr>
<tr>
<td>TDX</td>
</tr>
<tr>
<td>TDY</td>
</tr>
</tbody>
</table>

\[ \text{SF}_i = 0.5 (-S1 + S2 + S3 - S4 + S5 + S6) \quad (2.9) \]

The term \( S1 \) is the \( \text{SF} \) of a land path of length \( S_j \) (\( \mu \text{sec} \)) from the \( j \text{th station:} \)

\[ S1 = \frac{0.795}{T_j} + 0.439 + (0.00245) T_j \mu \text{sec.} \quad (2.10) \]

The terms \( S2, S3, \) and \( S4 \) combine to make up the secondary factor for the seawater path lengths.
S2 is the SF for the total path. S3 is the SF using the seawater coefficients for the portion with seawater, and S4 is the SF using the seawater coefficients for the land path distance. The seawater coefficients are found in Table IV.

TABLE IV

Seawater Coefficients

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>a1</td>
<td>128.8</td>
<td></td>
</tr>
<tr>
<td>a2</td>
<td>0.187</td>
<td></td>
</tr>
<tr>
<td>a3</td>
<td>0.000652</td>
<td></td>
</tr>
<tr>
<td>b1</td>
<td>3.188</td>
<td></td>
</tr>
<tr>
<td>b2</td>
<td>-0.594</td>
<td></td>
</tr>
<tr>
<td>b3</td>
<td>0.000329</td>
<td></td>
</tr>
</tbody>
</table>

\[
S_F(T) = \begin{cases} 
  b_1/T + b_2 + (b_3) T \mu\text{sec}, & \text{if } 10 \leq T \leq 540 \mu\text{sec}, \\
  a_1/T + a_2 + (a_3) T \mu\text{sec}, & \text{if } T \geq 540 \mu\text{sec},
\end{cases} (2.11a)
\]

Term S5 and S6 are the SFs of land paths of length \( T_j \) and \( T_{Lj} \). SF5 is the Secondary Factor for the total length using the land coefficients whereas SF6 is the Secondary Factor for the distance over land using the land coefficients. The land coefficients are found in Table V.

\[
S_5 = S_F(T_j, \beta_j),
\]

\[
S_6 = S_F(T_{Lj}, \beta_j),
\]

where:

\[
S_F(T_j, \beta_j) = A_0 + (A_1) T_j + \sum_{l=1}^{2} (C_{jl} \sin \beta_j + D_{jl} \cos \beta_j) (2.12)
\]
TABLE V

Land Coefficients

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A0</td>
<td>1.428</td>
<td>D</td>
<td>0.942</td>
</tr>
<tr>
<td>A1</td>
<td>0.00158</td>
<td>C</td>
<td>0.0</td>
</tr>
<tr>
<td>C</td>
<td>0.0</td>
<td>C1</td>
<td>0.588</td>
</tr>
<tr>
<td>w1</td>
<td>-0.711</td>
<td>D1</td>
<td>0.0</td>
</tr>
<tr>
<td>w2</td>
<td>0.323</td>
<td>D2</td>
<td>0.0</td>
</tr>
<tr>
<td>D1</td>
<td>0.0</td>
<td>C2</td>
<td>1.010</td>
</tr>
<tr>
<td>w2</td>
<td>0.0</td>
<td>C3</td>
<td>-0.196</td>
</tr>
<tr>
<td>x1</td>
<td>0.0</td>
<td>C1</td>
<td>-0.893</td>
</tr>
<tr>
<td>x2</td>
<td>0.0</td>
<td>C2</td>
<td>-0.355</td>
</tr>
<tr>
<td>D1</td>
<td>0.0</td>
<td>D1</td>
<td>-0.355</td>
</tr>
</tbody>
</table>

E. DMAHTC MODEL

1. Sea SF Model

The equations for the Sea SF Model is:

\[
SF = (B1/T) + B2 + (B3 T) \ \text{usec, if } 10 \leq T \leq 537 \ \mu\text{sec}, \quad (2.13a)
\]

\[
SF = (A1/T) + A2 + (A3 T) \ \text{usec, if } T > 537 \ \mu\text{sec}, \quad (2.13b)
\]

where \( T \) is the primary phase delay (or range) in microseconds (usec); \( A_k \) and \( B_k \) (\( k = 1, 2, \) and \( 3 \)) are the sea model coefficients used by DMAHTC in program TDGRID [Funakoshi, 1982]. The coefficients are found in Table VI.

2. Land SF Model

The solution used to resolve DMAHTC Tables ASF Corrections is called Millington's Method [DMAHTC, 1981].
TABLE VI
Sea SF Model Coefficients

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>129.04323</td>
<td></td>
</tr>
<tr>
<td>A2</td>
<td>-0.40758</td>
<td></td>
</tr>
<tr>
<td>A3</td>
<td>0.00064576813</td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>2.741282</td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>-0.011402</td>
<td></td>
</tr>
<tr>
<td>B3</td>
<td>0.00032774815</td>
<td></td>
</tr>
</tbody>
</table>

This method is based on the premise that the phase distortion due to a composite land-sea path is the arithmetic average of the phase distortion found in the forward and reverse paths of the propagated signal [DMAHTC, 1981]. For example, in Figure 2.6 two azimuths have been drawn on the map and are labeled as 210° and 235°. Also placed on the map are the proper ground conductivities which have been determined in the field by the Coast Guard calibration team. A great circle drawn on the appropriate chart or charts from the LORAN-C Station coordinates to the area under consideration spans various lengths of land and seawater. Each length or segment will have a specific conductivity and distance. The total of these conductivity segments, constituting a land-water profile, will determine the total phase retardation along that path [U.S. Naval Oceanographic Office, 1982]. All azimuths and distances are computed based on the World Geodetic System (WGS) datum [DMAHTC, 1981]. The values of phase retardation for a given ground conductivity are tabulated in the National Bureau of Standards (NBS) Circular 573 [Speight, 1982].

The formula used to derive the ASP Correction for the time difference for a master-slave transmitting station pair is:

\[
\text{ASP Correction} = (-\text{Slave Error}) - (-\text{Master Error})
\]
The mean values derived for one station from the forward and reverse solution of Millington's Method are subtracted from the Sea SF Model. The differences are
presented in an azimuth array. This array is a series of geodetic azimuths radiating from the transmitter with corrections computed at incremented distances along each azimuth. After the values are computed in the azimuthal array a computer program rearranges them into a matrix form. The matrix form is the arrangement of corrections into rows and columns covering a specified geographical area at a constant spacing. The purpose of the matrix is to enable the corrections from two LORAN-C transmitters to be added algebraically, combined into a single matrix, and arranged in the desired tabular form. This tabular form is the body of the table [DMAHTC, 1981].

3. Table Description

Each table contains a complete chain. Figures 2.5, 2.6, and 2.7 depict LORAN-C ASF Correctors for chains 9940-W, X, and Y for Monterey Bay, California. A table section is prepared for each station pair (master station and one slave station) in a LORAN-C chain. As a rule the limits of the table coverage are determined by the range of the groundwave transmissions for the LORAN-C chain. Each page of corrections in the table covers an area three degrees in latitude by one degree of longitude, with corrections printed in increments of five minutes of arc. Rate designation and page numbers are printed at the top of each correction page. Those pages where latitude and longitude limits contain both land and sea are included but corrections apply only for the area covered by the U.S. Coastal Confluence Zone (CCZ). Large land bodies and areas outside the CCZ are represented by blank spaces on the page. ASF correction values can be either positive or negative (positive values are shown without sign). Areas requiring no correction show a zero value which in some cases in preceded
by a negative sign indicating that the zero results from the rounding off of a value slightly less than zero (indicates the trend of the correction).
<table>
<thead>
<tr>
<th>LATITUDE</th>
<th>39° 0'</th>
<th>38° 0'</th>
<th>37° 0'</th>
<th>36° 0'</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>55</td>
<td>0.9</td>
<td>0.9</td>
<td>0.8</td>
<td>0.9</td>
</tr>
<tr>
<td>55</td>
<td>0.9</td>
<td>0.9</td>
<td>0.8</td>
<td>0.9</td>
</tr>
<tr>
<td>45</td>
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<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>45</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
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<tr>
<td>40</td>
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<td>1.1</td>
<td>1.1</td>
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<tr>
<td>35</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
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<tr>
<td>30</td>
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<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
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<tr>
<td>25</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
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<tr>
<td>20</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
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<tr>
<td>15</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>10</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>5</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**Figure 2.8  9940-X ASF Correction Table**

The table can be entered directly by using the ship's position determined to the nearest five minutes of arc in latitude and longitude either by dead reckoning or
some other means. To find the page with the appropriate correction, the Page Indexes of the table should be utilized. These indexes show the limits and page number of
all pages in the table. To locate the number of the page on which the desired correction is to be found, the Page Index is entered with the ship’s position. In some cases the ship’s position will fall on the page limit if either latitude or longitude or both. These positions are repeated on both pages and either page may be used.

The ASF Correction is added algebraically to the time difference for the LORAN-C pair. Interpolation of this data will not necessarily improve the accuracy due to the method used to determine ASF Correctors [DMAHTC, 1981]. Since the correctors are computed in the azimuthal array and are based on the conductivity and distance over which the LORAN-C electromagnetic wave travels, the ASF Corrector between the published ASF Correctors in the tables may not be the linear interpolated values. For example, the ASF Corrector for a distance of 500 m with an azimuth of 180° is equal to 1.5 μsec. The ASF corrector for a distance of 500 m with an azimuth of 181° is equal to 1.6 μsec. The interpolated value between 1.5 and 1.6 is 1.55. The true ASF Corrector for the 180° 30' azimuth is 1.4 since the land distance for the same azimuth is less than the land distance for the 180° and 181° azimuth. The LORAN-C signal passed over a harbor [Dansford, 1982].

P. ATTEMPTED DETERMINATION OF ASF CORRECTORS BY HYDRO FIELD PARTIES

One of the major problems encountered by hydrographic survey operating units when using LORAN-C for position control is the determination of the ASF Correctors for the survey area. The four surveys mentioned in the Introduction all made attempts to determine the correctors by comparing the LORAN-C rates to a second source.
Bathymetric Surveys H-9822 [NOAA H-9822, 1979] and H-9823 [NOAA H-9823, 1979] Gulf of Alaska, compared the rates from an Internav LC-204 LORAN receiver to computed rates from a position obtained from a JMR-1 Satellite Navigation Receiver when available. Shore ties using radar ranges, visual bearings, and sextant angles in comparison to LORAN-C rates were also made prior to and after each survey. The calibrations of LORAN-C rates were based on the satellite positions only since the positional computation of LORAN-C and JMR Doppler Satellite were made on the WGS 1972 datum whereas the land ties were based on the NAD 1927 datum.

Bathymetric survey SU-40-7-82 which extended along the Washington, Oregon, and California Coasts used LORAN-C as navigational control. LORAN-C time differences were compared with SATNAV positions. The report did not indicate whether any correctors were applied [NOAA Ship Surveyor, 1982].

Finally, Hydrographic Survey S-K902-Wh-82, Reconnaissance Survey of Safety Fairways, Gulf of Mexico used LORAN-C as a positioning control system. The positioning unit was an LC-204 receiver. LORAN-C rates were input via the HYDROPLOT Controller, a special purpose input-output interface which is the nucleus of the computer system hardware [Umbach, 1976]. Positions were computed and plotted by Program RK121, LORAN-C Real-Time HYDROPLOT [Backus, 1980].

ASF Correctors for LORAN-C were achieved by visual calibration using three point sextant fixes using charted oil rigs as control in the vicinity of the survey area. A three-point sextant fix is a convenient and accurate method for determining the position of a hydrographic survey vessel. Sextants are used to measure two angles between
three objects of known geographic position. The center object is common to both angles. The position of the observers taking the angles is fixed by the intersection of three circular lines of position [Umbach, 1976].

These sextant angles were recorded and later transferred onto their respective charts using a plastic three-arm protractor. A plastic three-arm protractor is transparent and made up of one fixed arm and two movable arms which contain an etched line that is radial with the center of the protractor [Umbach, 1976]. Sextant angles observed in pairs for a resection fix with a common center mark may be plotted directly by this instrument. When the three arms are placed at the angles observed and fitted so as to pass through the plotted positions of the observed stations on the field sheet, the hole at the center of the three-arm protractor is the fixed position of the vessel [Ingham, 1975].

Partial correctors for each area surveyed were defined by comparing the observed rates and the determined rates plotted on the nautical chart. The partial correctors were applied via the HYDROPLOT Controller. However, even after applying these correctors, the plotted position still disagreed with the ship's determined position with respect to the oil rigs. Ship's personnel attributed the discrepancies to one or more of the following:

1) Accuracy of the charted rigs,
2) Weather effect on LORAN-C,
3) Time of day,
4) Propagation of signal over land path,
5) Three-arm protractor accuracy, and
6) Error in the conversion by the software of the LORAN-C rates to latitude and longitude [NOAA, 1982].
There is an apparent need for a LORAN-C calibration routine aboard NOAA ships which provides the ASP Correctors for program RK121, LORAN-C Real-Time HYDROPLOT. The routine should use the same geodetic distance computation found in RK121 and use the same datum as that of the nautical chart of the survey area.

The above mentioned discrepancies illustrate the deficiencies in applying a single ASP Corrector to LORAN-C data. The accuracies for hydrography cannot be met using single correctors because the errors are non-linear and systematic. They cannot be distributed like residuals in a traverse. Schnebele (1979) has already proven that single ASP area correctors to LORAN-C positions do not meet the accuracy standards of the NOS Hydrographic Manual.

Based on visual inspection of the DMAHTC LORAN-C Correction Tables, ASP Correctors should be updated every five minutes of Latitude or Longitude change. In Monterey Bay, California, there is approximately 0.1 to 0.2 µsec difference for every five minutes of change, a potential error of 55 to 110 meters.
III. EXPERIMENTAL PROCEDURE

A. FIELD PROCEDURES

In order to compare the use of differential LORAN-C with ASF multiple correctors, typical survey operations were planned for the southern portion of Monterey Bay, California. This survey was conducted in conjunction with a comparative evaluation of multiple lines of position for selective positioning methods [Anderson, 1982]. Four microwave ranging systems were set on known geographic positions.

TABLE VII

Geographic Names and Positions

<table>
<thead>
<tr>
<th>Microwave System Stations</th>
<th>Geographic Position (NAD 1927)</th>
<th>Dates used.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seaside 4 (1964)</td>
<td>36° 36' 23.44596&quot; N 121° 51' 38.83281&quot; W</td>
<td>June 3-5, 1982</td>
</tr>
<tr>
<td>Use Mon Ecc.</td>
<td>36° 36' 04.73031&quot; N 121° 52' 35.98040&quot; W</td>
<td>June 3-5, 1982</td>
</tr>
<tr>
<td>Geociever Ecc.</td>
<td>36° 36' 32.49281&quot; N 121° 53' 25.21162&quot; W</td>
<td>June 3-5, 1982</td>
</tr>
<tr>
<td>Mussel Ecc.</td>
<td>36° 36' 18.25484&quot; N 121° 54' 11.49661&quot; W</td>
<td>June 3-5, 1982</td>
</tr>
<tr>
<td>Park (1931)</td>
<td>36° 53' 13.30600&quot; N 121° 49' 46.74300&quot; W</td>
<td>June 6-7, 1982</td>
</tr>
<tr>
<td>Mulligan RM1</td>
<td>36° 44' 56.49531&quot; N 121° 47' 52.31090&quot; W</td>
<td>June 6-7, 1982</td>
</tr>
<tr>
<td>Range 7 (1972)</td>
<td>36° 39' 02.47787&quot; N 121° 49' 08.58202&quot; W</td>
<td>June 6-7, 1982</td>
</tr>
<tr>
<td>Mussel (1932)</td>
<td>36° 37' 18.15100&quot; N 121° 54' 11.49661&quot; W</td>
<td>June 6-7, 1982</td>
</tr>
</tbody>
</table>
listed in Table VII. A series of tracklines were run in two separate areas as shown on Figure 3.1. To ensure that the microwave positioning system was working properly, the equipment was calibrated over known baselines of 1497.47 meters and 7877.31 meters at the beginning and end of the project. Trackline observations were only made during the daytime in fair weather conditions so as to eliminate sky waves and weather changes that influence LORAN-C signal propagation characteristics [Samaddar, 1982]. The vessel used was the 126 foot R/V Acania which is operated by the Naval Postgraduate School.

The positioning equipment consisted of a Micrologic ML-1000 LORAN-C receiver (0.01 usec resolution) and a Trisponder Microwave System provided by Racal-DECCA Survey, Inc. The Trisponder Microwave System consisted of four DNT1 Model 217C transponders, four DNT1 Model 21017 HP sector antennas with 87° by 5° beam widths, one DNT1 DDMU (Digital Distance Measuring Unit), two Omni DVTI Model 21019 HP antennas, a Houston Instruments Model DP3-M2D/RC3 plotter, and a Texas Instruments 743 terminal (Table VIII). The manufacturer's published accuracy for the positioning equipment is ±1 m for a single range [Racal-DECCA Survey, 1981]. Anderson [1982] discusses the accuracy of four lines of position. The four Decca Trisponder distances were recorded via a Texas Instruments 743 data terminal while the LORAN-C rates were manually logged. The data was acquired at one minute intervals while the ship maintained constant course and speed. The recorded LORAN-C rates were 9940-W, X, and Y of the West Coast chain.

To test the potential for calibrating the LORAN-C System using the Semi-Empirical Model, the correction tables, and multiple observed field correctors, the positions derived from the microwave system measurements were used to compute
Figure 3.1 Location of Test Areas in Monterey Bay
expected LORAN-C time differences at each point. The difference or offset between these expected time differences and the observed values were computed for the three methods. The mean offset, standard error, and drms values were also computed and compared.

B. MICROWAVE SYSTEM POSITIONING

The geographic position of the ship based on four lines of position was determined using a computer program called GPBYLQ (Geographic Position by Least Squares) written by the author (See Appendix A). GPBYLQ contains subroutine LSQR (Least Squares), which is a least squares adjustment written by Paul R. Wolf, Ph.D. [1974] and revised by LCDR D. Leath [1981]. Geographic positions were converted to X, Y (meters) which in turn were converted to geographic position via subroutines GPTOXY and XYTOGP, respectively [Wallace, 1974].

### TABLE VIII
Microwave Positioning Equipment

<table>
<thead>
<tr>
<th>Equipment</th>
<th>S/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNT1 Model 217C Transponders</td>
<td>3323</td>
</tr>
<tr>
<td>(Code 72R)</td>
<td></td>
</tr>
<tr>
<td>(Code 74R)</td>
<td>3320</td>
</tr>
<tr>
<td>(Code 76R)</td>
<td>3321</td>
</tr>
<tr>
<td>(Code 78R)</td>
<td>3322</td>
</tr>
<tr>
<td>DNT1 Model 2107 HP Sector Antenna</td>
<td>185</td>
</tr>
<tr>
<td>(87° by 50° Beam Widths)</td>
<td>186</td>
</tr>
<tr>
<td></td>
<td>187</td>
</tr>
<tr>
<td></td>
<td>191</td>
</tr>
<tr>
<td>DNT1 DDMV Model 540</td>
<td>426</td>
</tr>
<tr>
<td>Omni, DNT1 Antenna Model 21019 HP</td>
<td>194</td>
</tr>
<tr>
<td></td>
<td>200</td>
</tr>
<tr>
<td>Houston Instruments Plotter Model DP3-M2D/RC3</td>
<td>10722-10</td>
</tr>
<tr>
<td>Texas Instruments 743 Terminal</td>
<td>34418</td>
</tr>
</tbody>
</table>
Subroutine GPTOXY and XYTOGP are based on the Modified Transverse Mercator Grid which was centered in the survey area.

The Modified Transverse Mercator (MTM) projection is used by the National Ocean Survey and is similar to the projection used in the Universal Transverse Mercator (UTM) system. The main difference is that in the MTM a Central Meridian is picked that is near the survey area instead of being fixed at a particular meridian [Wallace, 1971]. Central Meridian (CME), False Easting (FEST), and Controlling Latitude (CLAT) are the three parameters which define the MTM projection. CME is the mean longitude computed using the maximum and minimum longitudes of the survey limits, FEST is the X-Coordinate that is assigned to the Central Meridian, and CLAT is the distance in meters from the equator to some reference latitude [Wallace, 1971].

The Central Meridian, False Easting, and Controlling Latitude used for Monterey Bay, California referenced to NOS Chart 18685 are:

\[ \text{CME} = 121^\circ 56' 00.0'', \]
\[ \text{FEST} = 20000.0, \]
\[ \text{CLAT} = 4050000.0, \]

To be consistent with the National Ocean Survey charts of the area, all computations were done relative to North American Datum (NAD) 1927 geographic positions. All programs were executed on an IBM 3033 computer located at W.R. Church Computer Center, Naval Postgraduate School, Monterey, California.

C. LORAN-C COMPUTATIONS

The differences or offset between the observed and computed LORAN-C rates using the Semi-Empirical TD Model, ASF LORAN-C Correction Tables, or the Multiple Observed
TABLE IX
LORAN-C 9940 Chain Data

<table>
<thead>
<tr>
<th>Station</th>
<th>Geographic Position (NAD 1927)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Master - Fallon, Nevada</td>
<td>39° 33' 07.03&quot;N 118° 49' 52.23&quot;W</td>
</tr>
<tr>
<td>Slave - George, Washington 9940-\text{W}</td>
<td>47° 03' 48.82&quot;N 119° 44' 34.76&quot;W</td>
</tr>
<tr>
<td>Slave - Middletown, California 9940-\text{X}</td>
<td>38° 46' 57.49&quot;N 122° 29' 40.04&quot;W</td>
</tr>
<tr>
<td>Slave - Searchlight, Nevada 9940-\text{Y}</td>
<td>35° 19' 18.32&quot;N 114° 48' 13.95&quot;W</td>
</tr>
</tbody>
</table>

Correctors were compared to the offsets between the observed TD rates and the computed rates for which only the seawater Secondary Factors (SF) were applied. The comparison of the offsets between the four methods illustrates the improvement in positional accuracy after applying ASF Correctors.

1. **Seawater Secondary Factors (SF)**

Time differences using only the seawater Secondary Factors for each of the geographic positions were computed using program LORAN written by the author (Appendix C). Seawater Secondary Factors (SF) were computed using formula 2.13 and the coefficients found in Table VI. All TOA distances in meters were determined using subroutine INVER1. INVER1 is a geodetic inverse routine using T. Vincenty's modified Rainsford's method with Helmert's elliptical terms, programed by LCDR L. Pfeifer, NOAA [1975]. Subroutine INVER1 is accurate to 0.0001 m halfway around the world [Pfeifer, 1982]. All distances were converted to microseconds using 299.792458 m/μsec. Time differences (TD) were
computed from equation 2.5. North American Datum 1927 geographic positions were used for all computations. See Table IX for the positions of LORAN-C 9940 transmitters [Riordan, 1979].

To ensure that subroutine INVERI was functioning properly the distances between the master and secondary stations were compared to the NOS published baseline distance [Riordan, 1979]. The published distances and the results from routine INVERI are listed below.

<table>
<thead>
<tr>
<th>Published Baseline</th>
<th>Computed Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance (m)</td>
<td>Distance - INVERI (m)</td>
</tr>
<tr>
<td>9940-W</td>
<td>837,777.0929</td>
</tr>
<tr>
<td>9940-X</td>
<td>327,886.3720</td>
</tr>
<tr>
<td>9940-Y</td>
<td>589,298.5712</td>
</tr>
</tbody>
</table>

The difference between the published and computed baselines ranged from 0.02 to 0.06 m.

Differences or offsets \((x_i)\) were obtained by subtracting the observed LORAN-C rates from the computed values from the various methods. The mean difference or offset \((\bar{x})\) and standard deviation \((s)\) in microseconds for each rate were determined using equations 3.1 and 3.2 [Wonnacott, 1935]:

\[
\text{Mean offset (\(\mu\)sec)}: \quad \bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i \tag{3.1}
\]

where: \(x_i\) = original observation in \(\mu\)sec,

\(n\) = number of observations;

\[
\text{Standard error:} \quad s = \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2. \tag{3.2}
\]

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The mean offset in microseconds can be converted to meters using equation 3.3 [Heinzen, 1977]:

\[
\text{Mean offset (meters): } 1 = \frac{\bar{X} \cdot w}{\sin \alpha} \tag{3.3}
\]

where \( w \) = distance corresponding to one microsecond on the baseline = 149.896229 meters [Bigelow, 1963].

\( \alpha \) = one-half the angle between the radius vectors from the position to the master and secondary stations.

Equation 3.4 was used to compute \( \text{drms} \) values in meters [Heinzen, 1977]:

\[
\text{drms} = \frac{1}{\sin(\frac{\pi}{2})} \sqrt{\frac{(s \cdot w)^2}{\sin^2 \alpha_1} + \frac{(s \cdot w)^2}{\sin^2 \alpha_2} + \frac{2 \cdot c \cdot \cos(\alpha_1 + \alpha_2)}{\sin \alpha_1 \left(\sin^2 \alpha_2\right)}} \tag{3.4}
\]

where: \( \rho \) = correlation coefficient = 0.33, \( s \) and \( \alpha \) are as above with the subscript denoting the appropriate secondary station.

The correlation coefficient (\( \rho \)) is a result of the secondary station having a common line of position with the master station. Although often ignored, various authors assign values ranging from 0.33 to 0.40. Bigelow [1963] chooses \( \rho = 0.33 \).

2. **Semi-Empirical TD Grid**

To determine if the Semi-Empirical TD Grid would reduce either the \( \text{drms} \) value or the offset between the observed and expected TD rates, program LOPLC (Line of Position - LORAN-C) was written by the author (Appendix B). Program LOPLC computes the distance over land, distance over water, the total distance, and the azimuth from north for the transmitting station using Subroutine INVER1. The
land-sea distances were computed by selecting a point which was located along the coast of Monterey Bay. Subroutine SHORPT (Shore Point) interpolated a geodetic position from 23 geodetic points which outlined Monterey Bay, California. The land/sea Secondary Factor was determined in Subroutine SECFAC which is found in program LOPLC using equations 2.8 through 2.12. All computations were based on NAD 1927 geodetic datum.

Tests were made on program LOPLC using data found in the Semi-Empirical TD Grid article [The Analytic Science Corporation, 1979] using the WGS 1972 datum. Station TASC 55 located at latitude 34° 34' 18.3" N and longitude 120° 39' 40.3" W, was selected from The Analytic Science Corporation article. It was one of the stations used to calibrate the coefficients for the Semi-Empirical TD equations discussed earlier. The only distances listed for TASC 55 were the individual distances over land and over water. The total distance between the transmitters and TASC 55 was computed by adding the land and sea distances. The following station-to-site path segment lengths are listed for TASC 55:

<table>
<thead>
<tr>
<th>Station</th>
<th>TASC 55 Land Distance (km)</th>
<th>TASC 55 Sea Distance (km)</th>
<th>TASC 55 Total Distance (km)</th>
<th>INVER1 Land Distance (km)</th>
<th>INVER1 Sea Distance (km)</th>
<th>INVER1 Total Distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Master</td>
<td>540.730</td>
<td>35.548</td>
<td>576.278</td>
<td>540.730</td>
<td>35.548</td>
<td>576.083</td>
</tr>
<tr>
<td>X-Secondary</td>
<td>369.248</td>
<td>126.096</td>
<td>495.344</td>
<td>369.248</td>
<td>126.096</td>
<td>495.178</td>
</tr>
<tr>
<td>Y-Secondary</td>
<td>525.659</td>
<td>15.832</td>
<td>541.491</td>
<td>525.659</td>
<td>15.832</td>
<td>541.308</td>
</tr>
</tbody>
</table>

Using the land distances, sea distance, and total distances to TASC 55, and the computed azimuth from subroutine INVER1, program LOPLC produced offsets of 0.86 µsec and 1.13 µsec for 9940-X and 9940-Y respectively when compared to the expected time differences at TASC 55.
An attempt was made to determine if this discrepancy was due to program LOPLC. A comparison of the total distances in the report between the transmitters and TASC 55 were compared to the total distances computed by INVER1. The difference in distance between Subroutine INVER1 and the total distances from the Semi-Empirical TD Grid article ranged from 160 - 200 m corresponding to 0.5 to 0.65 usec. This results in time difference errors of 0.04 usec for the 9940-X rate and a 0.10 µsec for the 9940-Y rate, implying that the offsets, 0.86 µsec and 1.13 µsec, are caused in part by the method in which the azimuth from north is determined. Unfortunately, azimuth data from TSC 55 was not presented in the article. The Analytic Science Corporation has been contacted on numerous occasions in an attempt to ascertain their method of determining distance and azimuth. As of this date there has been no response.

Nevertheless, the data from Monterey Bay was utilized in Program LOPLC to obtain results that could be compared to that obtained by the other methods. If this method is accurate enough, ASF Correctors could be determined via computer for each individual position without using tables or field determined correctors. The mean offset (\( \bar{x} \)) and standard error (\( s \)) in microseconds between the observed and calculated rates were computed using equations 3.1 and 3.2, respectively. The mean offset (\( l \)) and drms in meters were computed using equation 3.3 and 3.4, respectively.

3. Calculated Table ASF Correctors

The offset between the observed LORAN-C rates and the expected values with applied ASF Correctors from the LORAN-C Correction Tables and the seawater Secondary Factor (equation 2.13) were determined using program LORTAB which
was written by the author (Appendix D). The ASF Corrector for each position was selected using subroutine TABLE. Subroutine TABLE, which is found in program LORTAB determines an ASF Corrector for each data point based on its geodetic position. The ASF Correctors used in subroutine TABLE (see Figures 2.5, 2.6, and 2.7) are located between latitude 36° 35' N and 36° 55' N and longitude 121° 50' W and 122° 00' W. The difference in sign between the ASF Correctors in subroutine TABLE and those found in the LORAN-C Correction Table is due to the difference in their application. ASF Correctors from the tables are applied to observed rates while ASF Correctors from Subroutine TABLE are applied to the calculated LORAN-C rates. Negative ASF Correctors from the LORAN-C Correction Table were applied to the calculated time differences to be consistent with the application of Secondary Factors to the computed primary phase delay.

As before equations 3.1 through 3.4 were used to compute the mean offset, standard error, and drms. If this application of LORAN-C Correction Tables is accurate enough, it precludes the need to determine ASF Correctors in the field.

4. Observed ASF Correctors

Observed ASF Correctors were determined using Program ASFSEL (ASF Selection) which was written by the author (Appendix E), Schnebele's prior data (1979), and the June 1982 data. Program ASFSEL (ASF Selection) was written by the author. This program computes the ASF Correctors by subtracting the observed LORAN-C rates from the expected values. Only the seawater Secondary Factors from equation 2.13 have been applied to the calculated time differences.
The mean ASF Correctors for the LORAN-C rates were determined at every minute of latitude and longitude between 36° 50' N and 36° 35' N and 122° 04' W and 122° 49' W. See Appendix E for mean ASF Correctors at one minute intervals. The ASF Correctors were then selected and assigned to subroutine TABLE in Program LORTAB at five minute latitude and longitude intervals. All values were entered to the nearest hundredth of a microsecond. Equations 3.1 through 3.4 were used as before for computations. This determination of ASF Correctors in the field, if accurate enough, may allow the use of LORAN-C as a positioning system for hydrographic surveying in the future.
IV. RESULTS

A total of 620 time differences (TD) and geographic positions based on four lines of position were recorded in the southern portion of Monterey Bay in order to compare the use of differential LORAN-C with ASF Multiple Correctors. The data was divided into four sets. The first data set is Schnebele's [1979] prior data consisting of a total of 130 data points collected on two separate days, June 12 and July 25, 1979 between latitude 36° 38' N and 36° 47' N and longitude 121° 49' W and 122° 02' W. The recorded LORAN-C time difference rates were 9940-Y and 9940-W.

The second data set consists of 193 time differences collected on June 7, 1982. The recorded LORAN-C rates were also 9940-Y and 9940-W. Data set Number 2 is located between latitude 36° 40' N and 36° 45' N and longitude 121° 54' W and 122° 00' W. See Figure 3.1 for the location of test areas in Monterey Bay, California.

Data set Number 3 is located in the same area as data set Number 2, between latitude 36° 40' N and 36° 45' N and longitude 121° W 54' and 122° 00' W. This set, consisting of 128 points with recorded rates 9940-X and 9940-Y, was recorded on June 6, 1982.

The final set, data set Number 4 was recorded between June 3 and June 5, 1982. It contains 169 points located between latitude 36° 36' N and 36° 39' N and longitude 121° 53' W and 121° 58' W. The recorded rates were 9940-X and 9940-Y which are the same as data set three. The data for rates 9940-X and 9940-Y was kept separate so as to determine if there was a significant difference between the offshore (data set three) and inshore (data set four) drms values due to phase recovery (see Chapter Two).
Table X provides a convenient breakdown of the parameters for each of the data sets. The table consists of the data set number, the date the data was collected, the LORAN-C time difference rates, the number of data points, and the area limits in latitude and longitude. It defines the parameters for the four data sets of Tables XI (Seawater Secondary Factor Errors), XII (Semi-Empirical TD Grid Correction Errors), XIII (Multiple LORAN-C Correction Table Errors), and XIV (Multiple Observed Correction Errors). All basic data and computations are kept on file with the NOAA hydrography instructor at the Naval Postgraduate School, Monterey, California. (Individuals seeking this information should contact the Oceanography Department.)

A. SEAWATER SECONDARY FACTORS

LORAN-C rates were computed using only the seawater Secondary Factor (equation 2.13). The LORAN-C computed time differences are basically uncorrected rates since no Additional Secondary Factors were applied. Offsets between
TABLE XI
Seawater Secondary Factor Errors

<table>
<thead>
<tr>
<th>Rates</th>
<th>Mean Offset (X-μsec)</th>
<th>Mean Offset (Y-m)</th>
<th>Standard Error (s-μsec)</th>
<th>drms (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Set 1 (Schnebele's data, 130 data points)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>-0.508</td>
<td>-148.636</td>
<td>0.088</td>
<td>110.4</td>
</tr>
<tr>
<td>W</td>
<td>-1.241</td>
<td>-683.693</td>
<td>0.134</td>
<td></td>
</tr>
<tr>
<td>b) Set 2 (June 7, 1982, 193 data points)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>-0.526</td>
<td>-154.295</td>
<td>0.077</td>
<td>101.3</td>
</tr>
<tr>
<td>W</td>
<td>-1.283</td>
<td>-701.947</td>
<td>0.124</td>
<td></td>
</tr>
<tr>
<td>c) Set 3 (June 6, 1982, 128 data points)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>1.565</td>
<td>535.449</td>
<td>0.059</td>
<td>38.6</td>
</tr>
<tr>
<td>Y</td>
<td>-0.550</td>
<td>-161.404</td>
<td>0.083</td>
<td></td>
</tr>
<tr>
<td>d) Set 4 (June 3-5, 1982, 169 data points)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>1.582</td>
<td>550.089</td>
<td>0.055</td>
<td>68.1</td>
</tr>
<tr>
<td>Y</td>
<td>-0.817</td>
<td>-237.109</td>
<td>0.187</td>
<td></td>
</tr>
</tbody>
</table>

the observed and calculated rates using only the seawater Secondary Factor were computed to illustrate the improvement in position after applying the Semi-Empirical TD Model, ASF Loran-C Correction Tables, or the Multiple Observed ASF Correctors. The mean offset in microseconds and meters, standard error, and the drms are found in Table XI. Examples of offsets for several data points are listed in Appendix B after program LORAN.

It was stated earlier in Chapter One that Schnebele obtained a 66 m 1 drms using Y and W rates. The drms of 66 m was obtained using 48 data points which were located 10 km or more offshore. The 110.4 m 1 drms for the Y and W rates in Table XI is a result of combining the 130 inshore and offshore positions. The increase from 66.0 m 1 drms for the offshore positions to 110.4 m for combined offshore and inshore positions indicates that the application of a single
ASP Corrector is dependant on the size of the area. The 48 data points were located between latitude 36° 41' N and 36° 46' N and longitude 121° 55' W and 122° 02' W.

Schnebele also obtained the 66 m 1 drms by adjusting the LORAN-C observed time differences which were skewed due to the ship's motion and the five second averaging interval of the LORAN-C receiver. These caused the observed TDs to be several seconds old in comparison to the microwave system measurements [Schnebele, 1979]. Due to the large amounts of data from the June 1982 survey operations, no deskewing was done.

The offset, standard error, and drms for data set Number 2 (June 7, 1982) compares well to data set Number 1 (Schnebele's data - all). Also, the 38.6 m 1 drms for the X-Y rates is between Schnebele's 42.0 m 1 drms prediction [Schnebele, 1979] and Nelson's findings of 30 m 1 drms in San Francisco Bay [General Electric Co., 1979]. The large drms of 68.1 m for data set Number 4 (X-Y rates) is probably due to the phase recovery of the electromagnetic wave from the 9940-Y transmitter located in Searchlight, Nevada. Finally, if ASF Correctors are not applied, drms values ranged from 38.6 m for 9940 X-Y to 101.4 m for 9940 Y-W for data sets 2 and 3. The large offsets for all data sets indicate a systematic error, ranging from 150 m to 700 m, which precludes the use of this method for hydrographic surveying.

B. SEMI-EMPIRICAL TD GRID

To determine if the Semi-Empirical TD Grid would reduce the offset and drms for hydrographic surveying, program LOPLC (Appendix C) was applied to data sets 1 through 4. The Semi-Empirical TD Grid applies a Secondary Factor and an Additional Secondary Factor to the primary phase delay based
on the distance overland, the distance over water, and the
total distance using mean land and water conductivities.
The mean offset in meters and microseconds, standard error,
and drms are listed in Table XII. Examples of offsets for
several data points can be found in Appendix C after program

**TABLE XII**

Semi-Empirical TD Grid Correction Errors

<table>
<thead>
<tr>
<th>Rates</th>
<th>Mean Offset</th>
<th>Mean Offset</th>
<th>Standard Error</th>
<th>drms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(X-μsec)</td>
<td>(Y-μsec)</td>
<td>(μ-μsec)</td>
<td>(m)</td>
</tr>
<tr>
<td>a) Set 1 (Schnebele's data, 130 data points)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>1.131</td>
<td>330.672</td>
<td>0.086</td>
<td>113.5</td>
</tr>
<tr>
<td>W</td>
<td>1.145</td>
<td>630.278</td>
<td>0.139</td>
<td></td>
</tr>
<tr>
<td>b) Set 2 (June 7, 1982 data, 193 data points)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>1.108</td>
<td>324.975</td>
<td>0.077</td>
<td>112.7</td>
</tr>
<tr>
<td>W</td>
<td>1.105</td>
<td>603.926</td>
<td>0.126</td>
<td></td>
</tr>
<tr>
<td>c) Set 3 (June 6, 1982 data, 128 data points)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>1.131</td>
<td>386.940</td>
<td>0.061</td>
<td>39.4</td>
</tr>
<tr>
<td>Y</td>
<td>0.589</td>
<td>172.923</td>
<td>0.084</td>
<td></td>
</tr>
<tr>
<td>d) Set 4 (June 3-5, 1982 data, 169 data points)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>1.050</td>
<td>365.113</td>
<td>0.052</td>
<td>68.2</td>
</tr>
<tr>
<td>Y</td>
<td>0.341</td>
<td>99.084</td>
<td>0.189</td>
<td></td>
</tr>
</tbody>
</table>

LOPLC. Earlier, Program LOPLC had been tested with data
found in the article by The Analytic Science Corporation
[1979]. Program LOPLC produced offsets of 0.86 μsec and
1.13 μsec for the time differences from rates 9940-X and
9940-Y, respectively. As previously stated, the large
offsets may be due to the method by which the distance and
azimuth were computed. The drms, for the data from Monterey
Bay, obtained with the Semi-Empirical TD Grid was similar to
the drms errors for seawater Secondary Factor Model. This
might be an indication that Program LOPLC is correct but the
bias needs to be adjusted to reduce the large offset between the observed and calculated PD rates. The mean offset ranged from 99 to 630 m. Bias reduction could be achieved by applying land-sea data for the entire West Coast to the Semi-Empirical model. Again, the existence of large offset values precludes the use of this method for hydrographic surveying.

C. TABLE ASP CORRECTORS

To determine if the multiple ASP corrections from the LORAN-C Correction Table would reduce the offset and drms to meet the NOS accuracy standards, program LORTAB (Appendix D) was applied to data sets 1 through 4. ASP Correctors from

| TABLE XIII | Multiple LORAN-C Correction Table Errors |

<table>
<thead>
<tr>
<th>Rates</th>
<th>Mean Offset (X-μSEC)</th>
<th>Mean Offset (Y-μSEC)</th>
<th>Standard Error (m)</th>
<th>drms (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Set 1</td>
<td>Schnebele's data</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>-0.229</td>
<td>-67.968</td>
<td>0.104</td>
<td>123.6</td>
</tr>
<tr>
<td>W</td>
<td>0.169</td>
<td>92.540</td>
<td>0.160</td>
<td></td>
</tr>
<tr>
<td>b) Set 2</td>
<td>(June 7, 1982 data)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>-0.309</td>
<td>-90.614</td>
<td>0.085</td>
<td>116.9</td>
</tr>
<tr>
<td>W</td>
<td>0.123</td>
<td>67.189</td>
<td>0.144</td>
<td></td>
</tr>
<tr>
<td>c) Set 3</td>
<td>(June 6, 1982 data)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>-0.559</td>
<td>161.134</td>
<td>0.073</td>
<td>47.3</td>
</tr>
<tr>
<td>W</td>
<td>0.319</td>
<td>-93.486</td>
<td>0.101</td>
<td></td>
</tr>
<tr>
<td>d) Set 4</td>
<td>(June 3-5, 1982 data)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>No ASP Corrections listed in Table for the south- east end of Monterey Bay next to the shore line.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

the LORAN-C Correction Tables are determined from field observation of land conductivities by the U.S. Coast Guard
The results are listed in Table XIII.

When compared to the Seawater Secondary Factor Error in Table XI, the drms values using LORAN-C Correction Tables were increased slightly while the offsets were reduced substantially. The offsets ranged from 65 - 200 m. Since the drms ranged from 47.3 to 116.9 m for rates 9940 X-Y and 9940 Y-W respectively, the application of ASP Corrector from the tables does not meet the NOS accuracy standard. Again, large offsets and the increase in drms precludes the use of this method for hydrographic surveying.

D. MULTIPLE OBSERVED CORRECTORS

To determine if multiple observed correctors would diminish the offset and drms values, mean ASF Correctors were selected at one minute latitude and longitude intervals using Program ASPSEL. One minute ASF Correctors are shown at the end of Program ASPSEL in Appendix E. From the one minute grid, mean ASF Correctors were selected and entered into Subroutine TABLE at five minute latitude and longitude intervals in Program LORTAS. The following is an example of the 9940-X ASF Correctors at five minute latitude and longitude intervals for the program:

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>122/00/00.0</td>
<td>121/55/00.0</td>
<td>121/50/00.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>36/50/00.0</td>
<td>-1.52</td>
<td>-1.63</td>
<td></td>
<td></td>
</tr>
<tr>
<td>36/45/00.0</td>
<td>-1.52</td>
<td>-1.56</td>
<td>-1.61</td>
<td></td>
</tr>
<tr>
<td>36/40/00.0</td>
<td>-1.58</td>
<td>-1.60</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

This is the same format used in the LORAN-C Correction Tables. Program LORTAB was applied to the four data sets. The error results are listed in Table XIV.

The drms value obtained with multiple observed correctors were all reduced when compared to the drms for the
TABLE XIV
Multiple Observed Correction Errors

<table>
<thead>
<tr>
<th>Rates</th>
<th>Mean Offset (X-μsec)</th>
<th>Mean Offset (Y-μsec)</th>
<th>Standard Error (μsec)</th>
<th>drms (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Set 1 (Schnebele's data, 130 data points)</td>
<td></td>
<td></td>
<td></td>
<td>87.6</td>
</tr>
<tr>
<td>Y</td>
<td>0.033</td>
<td>9.585</td>
<td>0.076</td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>0.052</td>
<td>28.604</td>
<td>0.113</td>
<td></td>
</tr>
<tr>
<td>b) Set 2 (June 7, 1982, 193 data points)</td>
<td></td>
<td></td>
<td></td>
<td>89.3</td>
</tr>
<tr>
<td>Y</td>
<td>0.028</td>
<td>8.318</td>
<td>0.073</td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>-0.016</td>
<td>-8.944</td>
<td>0.116</td>
<td></td>
</tr>
<tr>
<td>c) Set 3 (June 6, 1982, 128 data points)</td>
<td></td>
<td></td>
<td></td>
<td>38.3</td>
</tr>
<tr>
<td>Y</td>
<td>-0.034</td>
<td>-11.490</td>
<td>0.055</td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>0.010</td>
<td>2.913</td>
<td>0.086</td>
<td></td>
</tr>
<tr>
<td>d) Set 4 (June 3.5, 1982, 169 data points)</td>
<td></td>
<td></td>
<td></td>
<td>67.5</td>
</tr>
<tr>
<td>X</td>
<td>0.001</td>
<td>0.383</td>
<td>0.052</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>-0.008</td>
<td>-2.225</td>
<td>0.187</td>
<td></td>
</tr>
</tbody>
</table>

Seawater Secondary Corrector. The most impressive reduction in drms was within Schnebele's data which covered an area of seven minutes of latitude and 12 minutes of longitude. The drms for seawater Secondary Correctors was 110.4 m whereas the drms for the same data using multiple observed correctors was 87.6 m. This is a smaller drms than that of the June 7, 1982 data (data set Number 2) which was obtained three years later. It appears that 87.6 m 1 drms is nearly the minimum error that can be obtained for the 9940 Y-W rates in Monterey Bay after applying multiple observed ASF Correctors at five minute latitude and longitude intervals. For the LORAN-C rates 9940 X-Y, a 38.3 m 1 drms was obtained for same five minute area covered by data set Number 2 (June 7, 1982). LORAN-C rates 9940 X-Y were not obtained for the same size area covered by data set Number 1 (seven minutes of latitude and twelve minutes of longitude - 9940 Y-W) due
to the restriction of ship time and the length of time the Racal-DECCA Trisponder electronic equipment had been loaned.

The drms for the June 3-5, 1982 inshore data was only reduced to 67.5 m from 68.1 m for seawater Secondary Correctors. The small change in error at the coast is probably a result of the erratic behavior of phase recovery discussed earlier in Chapter Two. The drms value could presumably be reduced if the correctors were applied at one minute intervals. This would be a very costly method of calibrating Loran-C for hydrographic surveying.
V. CONCLUSIONS

It was noted in Chapter One that the smallest scale routinely used for coastal surveys is 1:80,000. This yields an allowable error of 40 m 1 drms with no systematic errors. This paper determined whether or not applying multiple Additional Secondary Factors (ASF) Correctors to LORAN-C lines of position would reduce the drms sufficiently to meet the accuracy standards set by the National Ocean Survey.

Three methods of applying multiple ASF Correctors were tested. The first approach computes the time difference based on a Semi-Empirical TD Grid. The Semi-Empirical Model produced large offsets in the 9940-W, 9940-X, and 9940-Y time differences. The offsets ranged from 99 to 630 m. The drms for 9940 X-Y combination was 39.4 m and the drms for 9940 W-Y combination was 102.7 m.

The second method applies ASF Correctors found in the DMAHTC LORAN-C Correction Tables to LORAN-C lines of position. The application of the tables reduced the offset in the LORAN-C time differences. The offsets were between 67 and 191 m. The drms was increased to 47.3 m for the 9940 X-Y combination and 116.9 m for the 9940 W-Y pair.

The final and most accurate method applies multiple observed ASF Correctors at five minute latitude and longitude intervals to LORAN-C lines of position. This method again reduced the offset in the time difference. This offset was between 3 and 12 m for the 9940 X-Y combination. Part of the offset may have been a result of the microwave positioning system. Reference is made to Anderson's [1982] paper (in preparation) on the evaluation of multiple lines of position.
The $\text{drms}$ values were also reduced to 38.3 m for the 9940 X-Y rates and 89.3 m for the 9940 W-Y combination. The 38.3 m 1 drms can be decreased by improving the sampling time for LORAN-C receivers. Nelson obtained 30 m 1 drms for the 9940 X-Y rates with special LORAN-C equipment used in San Francisco Bay, California [General Electric Co., 1979]. Improving the sampling time for LORAN-C receivers used as positioning equipment for hydrographic surveys should be investigated.

With $\text{drms}$ values of 38.3 m with the possibility of obtaining 30.0 m 1 drms and offsets ranging from 3 to 12 m, it may be possible to use LORAN-C for hydrographic surveys at scales of 1:80,000 or less using multiple observed ASF Correctors. The use of DMAHTC LORAN-C Correction Tables should not be ignored. After updating these ASF Correctors with observed data, the LORAN-C Correction Tables may allow LORAN-C to be used as a positioning system for hydrographic surveys.
APPENDIX A

PROGRAM GPELYQ

PROGRAM GPELYQ

GENERAL PROGRAM FOR DETERMINING GP FROM KNOWN STATION
POSITIONS AND THE DISTANCES FROM THEM USING LEAST
SQUARES. GP TO XY AND XY TO GP ARE DETERMINED BY
SUBROUTINES GPTOKY AND XYTOGP WHICH ARE BASED ON THE
MODIFIED TRANSVERSE MERCATOR PROJECTION (MTM).

PROGRAMMED BY GERALD E. WHEATON, LT. NOAA

LEAST SQUARES ADJUSTMENT BY PAUL R. WOLF, PH.D. AND
REVISED BY D. LEATH, LCDR

PROGRAM INPUT VARIABLE NAMES
TITLE = ANY JOB IDENTIFICATION NAMES OR NUMBERS
M AND ' = THE NUMBER OF EQUATIONS (M) AND UNKNOWNS (N)
XO AND YO = BEST ESTIMATE OF THE POSITION
STA(I,1) = X COORDINATE OF KNOW STATION
STA(I,2) = Y COORDINATE OF KNOW STATION
STA(I,3) = DISTANCE FROM KNOW STATION
A(I,J) = THE COEFFICIENT MATRIX
EL(I,J) = THE CONSTANT MATRIX
QLL(I,J) = THE WEIGHT MATRIX (WEIGHTS ARE ENTERED AS
1'S IF THE SOLUTION IS EQUALLY WEIGHTED)

IMPLICIT REAL*8 (A-H,O-Z)
DIMENSION XCORD(30),YCORD(30),WT(30),ISNO(30)
COMMON /ISTAT/ STA(30,3),FXY(30)
COMMON /LSQX/ A(30,30),EL(30,1),QLL(30,30),AT(30,30),
READ AND WRITE OUTPUT TITLE

WRITE (6,509)
READ (5,710) TITLE
WRITE (6,710) TITLE

DEFINE NUMBER OF SIGNALS (NOT GREATER THAN 30) AND NUMBER OF DATA SETS.

READ (5,502) NSIG,ndata
502 FORMAT (I5, I10)

DEFINE THE CENTRAL MERIDIAN (CMER), FALSE EASTING (FEST), AND CENTRAL LATITUDE (CLAT).
CMER IS EXPRESSED IN DEGREES, MINUTES, AND SECONDS.
FEST IS THE X-COORDINATE THAT IS ASSIGNED TO THE CENTRAL MERIDIAN AND IS EXPRESSED IN METERS.
CLAT IS DEFINED AS THE CONTROLLING LATITUDE.
IT IS USED TO REFERENCE THE Y-COORDINATES AND IS EXPRESSED IN METERS.

READ (5,503) ILONC, ILMINC, RLSECC, FEST, CLAT
503 FORMAT (1X, I3, 1X, I2, 1X, F8.5, 1X, F7.1, F10.1)
CMER = (IABS(ILONC) * 60 + ILMINC) * 60 + RLSECC

DEFINE VARIABLE FOR:
NUMBER OF EQUATIONS (M)
NUMBER OF UNKNOWNS (N)
IPAGE = NUMBER OF LINES PER PAGE.

IPAGE = 1

66
M = 4
N = 2

C NULL WEIGHTS
C
DO 3 IM=1,30,1
DO 3 JM=1,30,1
3 QLL(IM,JM) = 0.0
C
READ STATION NUMBERS, POSITION, AND WEIGHTS.
C CONVERT POSITIONS (GP) TO SECONDS AND THEN TO XY.
C
DO 12 J=1,NSIG,1
READ (5,800) ISNO(J),ILAT,IMIN,RSEC,JLON,JMIN,SSEC,WT(J)
800 FORMAT(1X,I3,I4,I3,F9.5,I5,I3,F9.5,F5.1)
C
RMAST = ((IABS(ILAT) * 60 + IMIN) * 60) + RSEC
RMASTL = ((IABS(JLON) * 60 + JMIN) * 60) + SSEC
C
CALL GPTOXY(RMAST,RMASTL,XMETER,YMETER,FEST,CLAT,CMER)
XCORD(J) = XMETER
12 YCORD(J) = YMETER
C
C READ DATA (STATION NUMBERS AND THE DISTANCES)
C
15 DO 40 JCOUNT=1,NDATA,1
READ(5,805) IF,IS,IT,I4,NREC
805 FORMAT(5I5)
DO 16 ICOUNT=1,NSIG,1
IF (ISNO(ICOUNT) .EQ. IF) IF=ICOUNT
IF (ISNO(ICOUNT) .EQ. IS) IS=ICOUNT
IF (ISNO(ICOUNT) .EQ. IT) IT=ICOUNT
16 IF (ISNO(ICOUNT) .EQ. I4) I4=ICOUNT
C
\[
\begin{align*}
\text{STA}(1,1) &= \text{XCORD}(\text{IF}) \\
\text{STA}(1,2) &= \text{YCORD}(\text{IF}) \\
\text{QLL}(1,1) &= \text{WT}(\text{IF}) \\
\text{STA}(2,1) &= \text{XCORD}(\text{IS}) \\
\text{STA}(2,2) &= \text{YCORD}(\text{IS}) \\
\text{QLL}(2,2) &= \text{WT}(\text{IS}) \\
\text{STA}(3,1) &= \text{XCORD}(\text{IT}) \\
\text{STA}(3,2) &= \text{YCORD}(\text{IT}) \\
\text{QLL}(3,3) &= \text{WT}(\text{IT}) \\
\text{STA}(4,1) &= \text{XCORD}(\text{I4}) \\
\text{STA}(4,2) &= \text{YCORD}(\text{I4}) \\
\text{QLL}(4,4) &= \text{WT}(\text{I4}) \\
\end{align*}
\]

Read the distance record and Loran rate.

\[\text{DO } 38 \text{ KCOUNT}=1, \text{NREC}, 1\]
\[\text{READ (5,507) STA (1,3), STA(2,3), STA (3,3), STA (4,3), RATE1, RATE2}\]
\[\text{507 FORMAT}(6F10.1)\]

Determine best guess coordinates \(XO\) and \(YO\) with subroutine GUESS.

\[\text{CALL GUESS}(XO,YO)\]

\[\text{IJUMP} = 0\]

Compute \(FXY\), \(A\) and \(L\) matrix

\[\text{DO } 25 I=1, M\]
\[\text{FXY}(I) = \text{DSQRT(DABS((XO-STA(I,1)))**2}\]

68
1 \((YO-STA(I,2)^{**2})\)
\[ A(I, 1) = (XO-STA(I,1)) \div (FXY(I)) \]
\[ A(I, 2) = (YO-STA(I,2)) \div (FXY(I)) \]

\[ EL(I, 1) = STA(I,3) - FXY(I) \]

CALL SUBROUTINE LSQR
CALL LSQR(M,N)

COMPUTE THE NEW QUESITIMATE FOR XO AND YO

XO = XO + X(1,1)
YO = YO + X(2,1)

EXIT IF STANDARD ARE MET USING IJUMP OR
XO AND YO CUTF OFF

IF(DABS(X(1,1)).LE.1.00 .AND. DABS(X(2,1)).LE.1.00) GOTO 35
IF(IJUMP .EQ. 10) GOTO 35
GOTO 20

CALL ELIPSE(SU,SV)

CALL XYTOGP(XO,YO,SECLAT,SECLON,FEST,CLAT,CMER)
CALL TODMS(SECLAT,IDEGP,IMINP,RSECP)
CALL TODMS(SECLON,JDEGP,JMINP,SSECP)

PAGE AND CONTINUE WITH NEXT SET OF OBSERVATIONS
C
WRITE(6,505) IDEGP,IMINP, RSECP, JDEGP, JMINP, SSECPS
1 RATE1, RATE2
C WRITE(6,505) IDEGP, IMINP, RSECP, JDEGP, JMINP, SSECPS,
1 SU, SV
C IF(IPAGE .EQ. 50) WRITE(6, 509)
IF(IPAGE .EQ. 50) IPAGE = 0
38 IPAGE = IPAGE + 1
C
C FORMAT STATEMENTS
C
710 FORMAT(80A1)
509 FORMAT(1H1)
40 CONTINUE
STOP
END

SUBROUTINE LSQR (M, N)

IMPLICIT REAL*8 (A-H, O-Z)
COMMON /LSQX/ A(30, 30), EL(30, 1), QLL(30, 30), AT(30, 30),
1 AQ(30, 30), QXX(30, 30), AQL(30, 10), X(30, 1), V(30, 1),
2 VAR(30), TITLE(80)
C
C COMPUTE A TRANSPOSE BY TRANPOSING THE A MATRIX (AT)
C
DO 61 I = 1, M
DO 61 J = 1, N
61 AT(J, I) = A(I, J)
C
C USING STEPS (1), (2), AND (3) COMPUTE THE INVERSE
C OF THE TRANSPOSE (AT) * WEIGHTED MATRIX (QLL) *
C MATRIX A = QXX.
(1) COMPUTE AQ = AT * QLL

DO 71 I=1,N
DO 71 J=1,N
AQ(I,J) = 0.
DO 71 K=1,M
71 AQ(I,J) = AQ(I,J) + (AT(I,K) * QLL(K,J))

(2) COMPUTE QXX = AQ * A

DO 81 I=1,N
DO 81 J=1,N
QXX(I,J) = 0.
DO 81 K=1,M
81 QXX(I,J) = QXX(I,J) + AQ(I,K) * A(K,J)

(3) INVERT QXX MATRIX

DO 307 K=1,N
DO 302 J=1,N
IF (J-K) 304, 302, 304
304 QXX(K,J) = QXX(K,J) / QXX(K,K)
302 CONTINUE
QXX(K,K) = 1./QXX(K,K)
DO 307 I=1,N
IF (I-K) 305, 307, 305
305 DO 303 J=1,N
IF (J-K) 306, 303, 306
306 QXX(I,J) = QXX(I,J) - QXX(I,K) * QXX(K,J)
303 CONTINUE
QXX(I,K) = -QXX(I,K) * QXX(K,K)
307 CONTINUE
C USING STEPS (4) AND (5), COMPUTE THE UNKNOWNS X BY MUL THE INVERSE QXX AND AQL.

C

(4) COMPUTE AQL = AQ * EL

DO 101 I=1,N
AQL(I,1)=0.
DO 101 K=1,M
101 AQL(I,1)=AQL(I,1)+AQ(I,K)*EL(K,1)

C

(5) COMPUTE X = QXX * AQL

DO 201 I=1,N

X(I,1)=0.
DO 201 K=1,N
201 X(I,1)=X(I,1)+QXX(I,K)*AQL(K,1)

C

(6) COMPUTE THE RESIDUAL (V = A * X -EL)

DO 301 I=1,M
V(I,1)=0.
DO 301 K=1,N
301 V(I,1)=V(I,1)+A(I,K)*X(K,1)
DO 1 I=1,M
1 V(I,1)=V(I,1)-EL(I,1)

C

COMPUTE THE STANDARD DEVIATION OF UNIT WEIGHT SIGMA

DM - NUMBER OF OBSERVATIONS
DN - NUMBER OF KNOWNNS

SIGMA=0.
DM=M
DN=N
DO 382 I=1,M
SIGMA=SIGMA+V(I,1)**2*QLL(I,I)
SIGMA=DSQRT(SIGMA/(D*M-DN))

COMPUTE THE STANDARD DEVIATION OF THE ADJUSTED UNKNOWNS
QXX - ARE THE ELEMENTS OF THE COVARIANCE MATRIX.

DO 446 I=1,N
446 VAR(I)=DSQRT(QXX(I,I)*SIGMA**2)

CONTINUE
RETURN
END

----------------------------------------
SUBROUTINE ELIPSE(SU,SV)
----------------------------------------

SOLVE FOR THE SEMI MAJOR AND SEMI MINOR AXIS OF
THE ERROR ELLIPSE

IMPLICIT REAL*8 (A-H,O-Z)
COMMON /LSQX/ A(30,30),EL(30,1),QLL(30,30),AT(30,30),
AQ(30,30),QXX(30,30),AQL(30,10),X(30,1),V(30,1),
2VAR(30),TITLE(80)

SUS = .5*(QXX(1,1) + QXX(2,2) + DSQRT(DABS(QXX(1,1) -
1 QXX(2,2) + 4.0*QXX(1,2)*QXX(2,1))))
SVS = .5*(QXX(1,1) + QXX(2,2) - DSQRT(DABS(QXX(1,1) -
1 QXX(2,2) + 4.0*QXX(1,2)*QXX(2,1))))

SU = DSQRT(SUS)
SV = DSQRT(SVS)

RETURN
END
SUBROUTINE GUESS(XO,YO)

SUBROUTINE GUESS DETERMINES THE BEST GUESS COORDINATES TO BE USED IN SUBROUTINE LSQR. USE RIGHT SIDE RULE FOR STATION ORDER.

IMPLICIT REAL*8 (A-H,O-Z)
COMMON /ISTAT/ STA(30,3),FXY(30)

Determine distance between station 1 and station 2

D=DSQRT((STA(2,1)-STA(1,1))^2+(STA(2,2)-STA(1,2))^2)

Determine angle \( \alpha \) between \( X_0YO \) and \( STA2 \) and \( STA1 \)

\[ \alpha = \text{DARCOS} \left( \frac{(STA(2,3)^2-STA(1,3)^2+D^2)}{1 (2.0*STA(2,3)*D)} \right) \]

Determine angle brovo between x-axis and \( STA2 \) and \( STA1 \)

\[ \text{BROVO} = \text{DARSIN} \left( \frac{(STA(1,2)-STA(2,2))}{D} \right) \]

Determine x and y length

\[ X = STA(2,3)*\text{DCOS} (\alpha + \text{BROVO}) \]
\[ Y = STA(2,3)*\text{DSIN} (\alpha + \text{BROVO}) \]

Determine xo and yo

\[ \text{XO} = STA(2,1)+X \]
\[ \text{YO} = STA(2,2)+Y \]
SUBROUTINE GPTOXY(SECLAT, SECLON, XCO, YCO, PEST, CLAT, CHER)

C
IMPLICIT REAL*8 (A-H, O-Z)
DATA E2, RKO, A /0.00676 8658 D0, 99998 D0, 6378206.4 D0/
DATA RKGeo, W1, W2 /0.048481368 D0, 0.11422 D0, 21.73607 D0/
DATA W3, W4/5104.57338 D0, 6367399.689 D0/
DATA RADSEC /0.000048481368111 D0/

C

RADLAT = SECLAT * RADSEC
SINLAT = DSIN(RADLAT)
SIN2LA = SINLAT * SINLAT
COSLAT = DCOS(RADLAT)
COS2LA = COSLAT * COSLAT
P = (CHER - SECLON) / 10000.0 D0
V = A / DSQRT(1.0 D0 - E2*SIN2LA)
TANCON = 1.0 D0 - SIN2LA/COS2LA
S = W4 * (RADLAT - SINLAT*COSLAT/10.0 D0**6 *
*(W3 -COS2LA*(W2-W1*COS2LA)))
T1 = S * RKO - CLAT
T2 = RKGeo * COSLAT * RKO * V
T3 = T2 * RKGeo / 2.0 D0
T4 = T3 * SINLAT
T5 = T3 * RKGeo * COS2LA / 3.0 D0
T6 = T5 * TANCON
T7 = (4.0 D0 + TANCON) *T5 * RKGeo * SINLAT / 4.0 D0
XCO = (T2 + (T6*P**2)) *P + PEST
YCO = (T7*P**4) + (T4*P**2) + T1
RETURN
END
SUBROUTINE UYTOGP(XCO,YCO,SECLAT,SECLON,FST,CLAT,CMER)

C

IMPLICIT REAL*8 (A-H, O-Z)

C

DATA E2,A,SR /0.006768658D0,6378206.4D0,
1 0.0000048481368D0/
DATA W1,W2,W3 /0.24682D0,30.02335D0,5078.64977D0/

C

D = CLAT + YCO
WO = 0.157049981D0/10.0D0**6 * D
SINWO = DSIN(WO)
COSWO = DCOS(WO)
COS2WO = COSWO * COSWO
PHI1 = WO + SINWO*COSWO/10.0D0**6 *
* " W3+COS2WO*(W2++W1*COSWO) )
PHI2 = PHI1 / 0.99998D0
PHI3 = PHI2 / SR
Q = (XCO - FST) / 10.0D0**6
V = A / DSQRT(1.0D0 - E2*DSIN(PHI2)**2)
T = DCOS(PHI2) * SR
C = V * 0.99998D0
T1 = 10.0D0**6 / (T*C)
T2 = (T1*10.0D0**6) / (2.0D0*C)
T3 = (T2*10.0D0**6) / (3.0D0*C)
T4 = (T3*10.0D0**6) / (4.0D0*C)
DELLON = (T1-Q**2*T3* (2.0D0*DTAN(PHI2)**2+1.0D0))*Q
SECLAT = (((3.0D0*DTAN(PHI2)**2+5.0D0)*T4) *Q**2-T2)
1 *Q**2*DSIN(PHI2) + PHI3
SECLON = CMER - DELLON
RETURN
END

ENTRY
DATA SET EXAMPLE - PROGRAM GPBYLQ.

<table>
<thead>
<tr>
<th>LATITUDE (D-M-S)</th>
<th>LONGITUDE (D-M-S)</th>
<th>9940-X (μsec)</th>
<th>9940-Y (μsec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>36 36 40.20</td>
<td>121 52 48.62</td>
<td>27508.79</td>
<td>42742.71</td>
</tr>
<tr>
<td>36 36 42.41</td>
<td>121 52 48.16</td>
<td>27508.81</td>
<td>42742.93</td>
</tr>
<tr>
<td>36 36 44.56</td>
<td>121 52 47.52</td>
<td>27508.83</td>
<td>42743.15</td>
</tr>
<tr>
<td>36 36 46.84</td>
<td>121 52 46.98</td>
<td>27508.76</td>
<td>42743.26</td>
</tr>
<tr>
<td>36 36 49.09</td>
<td>121 52 46.59</td>
<td>27508.76</td>
<td>42743.48</td>
</tr>
</tbody>
</table>
APPENDIX B

PROGRAM LORAN

C PROGRAM LORAN
C
C PROGRAM COMPUTES LINE OF POSITIONS FOR LORAN-C USING
C THE SECONDARY FACTOR (SF) BASED ON SEAWATER EM MODEL.
C
IMPLICIT REAL*8 (A-H, O-Z)
DIMENSION AXIS(13),RF(13)
DIMENSION XSLAV(1000),XSLAV2(1000)
DATA RHOSEC,PI,UNCOV, RN/2.062648062471D05,
 1 3.141592653589799.792458D0,1.000338D0/
DATA XMEAN1,XMEAN2,VAR1,VAR2/0.00D0,0.00D0,
 1 0.00D0,0.00D0/
DATA XMEAN3,XMEAN4/0.00D0,0.00D0/
C
CCC******************************
DATA AXIS/6.3782064D06,6.378388D06,6.377397155D06,
 1 6.37816D06,6.37816D06,6.378249145D06,6.378165D06,
 2 6.378166D06,6.37815 D06,6.378145D06,6.3775634D06,
 3 6.378245D06,6.3781350D06/
DATA RF/6.3565838D06,2.97D02,2.9915281285D02,
 1 2.9825D02,2.98247167427D02,2.93465D02,2.9825D02,
 2 2.983 D02,2.983D02,2.9825 D02,6.3562569D06,
 3 2.983 D02,2.9826D02/
C********ELLIPOID OPTION NUMBER
C
 1. CLARKE 1866
 2. INTERNATIONAL (HAYFORD)
 3. BESSEL 1841
 4. AND (AUSTRALIAN)
 5. 1967 REFERENCE
 8. MERCURY
 9. MARSHALL ISLAND
10. NAVY 8D
11. AIRY
12. KRASSOWSKI 1940

78
6. CLARKE 1880 MOD 13. WGS 1972
7. SAO

CC1-2 = ELLIPSOID NUMBER (K)
CC3-5 = NUMBER OF POINTS ALONG COAST (IREC)

READ (5, 100) K, IREC
100 FORMAT (1X, I2, I4)

TWOPI = 2.*PI
A = AXIS (K)
F = 1./RF (K)
IF (F .LT. 3.D-3) F = (A - 1./F) / A

READ MASTER AND SLAVE STATIONS POSITIONS
THE FIRST RECORD IS THE NUMBER OF MASTER AND SLAVE STATIONS FOR THE PARTICULAR CHAIN.

WRITE (6, 202)
202 FORMAT (1H1)
WRITE (6, 201)
201 FORMAT (1H1 )
READ (5, 105) ILATM, IMINM, RSECM, ILONM, ILMINM, RLSECM
WRITE (6, 105) ILATM, IMINM, RSECM, ILONM, ILMINM, RLSECM
105 FORMAT (1X, I3, 1X, I2, 1X, F5.2, 1X, I4, 1X, I2, 1X, F5.2)
RMST = ((IABS(ILATM) * 60 + IMINM) * 60 + RSECM) / 1 RHOSEC
IF (ILATM .LT. 0) RMST = -RMST
RMSTL = ((IABS(ILONM) * 60 + ILMINM) * 60 + RLSECM) / 1 RHOSEC
IF (ILONM .GT. 0) RMSTL = TWOPI - RMSTL

READ THE FIRST SLAVE STATION AND CHANGE THE LATITUDE AND LONGITUDE INTO RADIANS.
READ (5, 101) ILATS, IMINS, RSECS, ILONS, ILMINS, RLSECS,
1 DELAY1
WRITE (6, 101) ILATS, IMINS, RSECS, ILONS, ILMINS, RLSECS,
1 DELAY1
101 FORMAT (1X, I3, 1X, 12, 1XF5.2, 1X, 12, 1F5.2, P9.2)
RSLAV1 = ((IABS (ILATS) * 60 + IMINS) * 60 + RSECS) /
1 RHOSEC
IF (ILATS .LT. 0) RSLAV1 = -RSLAV1
RSLAL1 = ((IABS (ILONS) * 60 + ILMINS) * 60 + RLSECS) /
1 RHOSEC
IF (ILONS .GT. 0) RSLAL1 = TWOPI - RSLAL1
READ THE SECOND SLAVE STATION AND CHANGE THE LATITUDE
AND LONGITUDE INTO RADIANS.
READ (5, 101) ILATS, IMINS, RSECS, ILONS, ILMINS, RLSECS,
1 DELAY2
WRITE (6, 101) ILATS, IMINS, RSECS, ILONS, ILMINS, RLSECS,
1 DELAY2
RSLAV2 = ((IABS (ILATS) * 60 + IMINS) * 60 + RSECS) /
1 RHOSEC
IF (ILATS .LT. 0) RSLAV2 = -RSLAV2
RSLAL2 = ((IABS (ILONS) * 60 + ILMINS) * 60 + RLSECS) /
1 RHOSEC
IF (ILONS .GT. 0) RSLAL2 = TWOPI - RSLAL2
WRITE (6, 201)
READ THE RECORDS POSITIONS AND OBSERVED RATES, THEN
COMPUTE THE TOTAL DISTANCE.
DO 550 I=1, IREC, 1
READ (5, 104) ILAT, IMIN, RSEC, ILON, ILMIN, RLSEC,
1 RATE1, RATE2
C
C CONVERT LAT AND LONG TO RADIANS.
C
RPOST = ((IABS(ILAT) * 60 + IMIN) * 60 + RSEC) / 
1 RHSEC
IF(ILAT .LT. 0) RPOST = -RPOST
RPOSTL = ((IABS(ILON) * 60 + ILMIN) * 60 + RLSEC) / 
1 RHSEC
IF(ILON .GT. 0) RPOSTL = TWOPI - RPOSTL
C
C COMPUTE DISTANCES AND AZIMUTHS FROM THE OBSERVED POINT
C
C MASTER
C
CALL INVER1(A,F,RPOST,RPOSTL,RMAST,RMASTL,FAZM,BAZM,
1 DISTM)
UDISTM = (RN * DISTM) / UNCOV
CALL SECFAC(UDISTM,SPM)
C
C SLAVE1
C
CALL INVER1(A,F,RPOST,RPOSTL,RSLAV1,RSLAL1,FAZ1,BAZ1,
1 DIST1)
UDIST1 = (RN * DIST1) / UNCOV
CALL SECFAC(UDIST1,SP1)
C
C SLAVE2
C
CALL INVER1(A,F,RPOST,RPOSTL,RSLAV2,RSLAL2,FAZ2,BAZ2,
1 DIST2)
UDIST2 = (RN * DIST2) / UNCOV
CALL SECFAC(UDIST2,SP2)
C COMPUTE THE RATES AND COMPARE TO THE OBSERVED RATES

TDM1 = UDIST1 - UDISTM + SF1 - SFM + DELAY1
DIFF1 = TDM1 - RATE1

TDM2 = UDIST2 - UDISTM + SF2 - SFM + DELAY2
DIFF2 = TDM2 - RATE2

C COMPUTE THE LANE WIDTH IN METERS BASED ON EQUATION 4.20 IN ELECTRONIC SURVEYING AND NAVIGATION - LAURILA, PAGE 94.

BR1 = DABS(FAZ1 - FAZM)
BR2 = DABS(FAZ2 - FAZM)
WIDTH1 = (DIFF1 * UNCOV * 0.5) / DSIN(BR1 * 0.5)
WIDTH2 = (DIFF2 * UNCOV * 0.5) / DSIN(BR2 * 0.5)

C WRITE THE POSITION OF VESSEL, COMPUTED RATE, OBSERVED RATE, AND THE DIFF BETWEEN THEM.

WRITE(6,200) ILAT,IMIN,RSEC,ILON,IFORM,RLSEC,RATE1,
DIFF1,RATE2,DIFFl,
1 F12.2,F8.2)
WRITE(6,201) XMEAN1

C XMEAN1 AND XMEAN2 ARE THE MEAN DIFPS BETWEEN THE COMPUTED RATE AND THE OBSERVED. XSLAV1 AND XSLAV2 ARE THE STORED DIFPS.

XMEAN1 = XMEAN1 + DIFF1
XMEAN2 = XMEAN2 + DIFF2
XMEAN3 = XMEAN3 + WIDTH1
XMEAN4 = XMEAN4 + WIDTH2
XSLAV1(I) = DIFF1
XSLAV2(I) = DIFF2

CONTINUE

C
C COMPUTE THE MEAN AND STANDARD DEVIATION
C
XMEAN1 = XMEAN1 / IREC
XMEAN2 = XMEAN2 / IREC
XMEAN3 = XMEAN3 / IREC
XMEAN4 = XMEAN4 / IREC

DO 600 I = 1,IREC,1
VAR1 = VAR1 + ((XSLAV1(I) - XMEAN1)**2)
600 VAR2 = VAR2 + ((XSLAV2(I) - XMEAN2)**2)

VAR1 = VAR1 / (IREC - 1.0)
VAR2 = VAR2 / (IREC - 1.0)

SD1 = DSQRT(VAR1)
SD2 = DSQRT(VAR2)

WRITE (6,201)
WRITE(6,210) XMEAN1,SD1,XMEAN3
WRITE (6,201)
WRITE(6,211) XMEAN2,SD2,XMEAN4
WRITE(6,202)

210 FORMAT(1X, 'SLAVE #1, MEAN = ', F10.3,
1 ' STANDARD DEVIATION = ',
2 F10.3, ' DISTANCE IN METERS = ',F10.3)
211 FORMAT(1X, 'SLAVE #2, MEAN = ', F10.3,
1 ' STANDARD DEVIATION = ',
2 F10.3, ' DISTANCE IN METERS = ',F10.3)
STOP
END
C==========================================

SUBROUTINE SECPAC(UTDIST, SF)
C
C THIS ROUTINE WILL COMPUTE THE SEA SECONDARY FACTOR
C   UTDIST = TOTAL DISTANCE
C   SF = SECONDARY FACTOR
C
IMPLICIT REAL*8 (A-H, O-Z)
C
C COEFFICIENTS
C
A0 = 129.04323
A1 = -0.40758
A2 = 0.00064576813
C
B0 = 2.741282
B1 = -0.011402
B2 = .00032774815
C
IF (UTDIST .GT. 537) GO TO 10
SF = (B0 / UTDIST) + B1 + (B2 * UTDIST)
GO TO 20
10 SF = (A0 / UTDIST) + A1 + (A2 * UTDIST)
C
20 CONTINUE
RETURN
END

C==========================================

SUBROUTINE INVER1(A, PINV, GLAT1, GLON1, GLAT2, GLON2, BAZ, S)
C
C
C *** SOLUTION OF THE GEODETIC INVERSE PROBLEM AFTER
C *** T. VINCENTY MODIFIED RAINSFORD'S METHOD WITH HELMERT'S
C *** ELLIPTICAL TERMS. EFFECTIVE IN ANY AZIMUTH AND AT
C *** ANY DISTANCE SHORT OF ANTIPODAL STANDPOINT/FOREPOINT
C *** MUST NOT BE THE GEOGRAPHIC POLE
C
C *** A IS THE SEMI-MAJOR AXIS OF THE REFERENCE ELLIPSOID
C *** FINV IS THE FLATTENING (NOT RECIPROCAL) OF THE
C *** REFERECE ELLIPSOID LATITUDES AND LONGITUDES IN
C *** RADIANS POSITIVE NORTH AND EAST FORWARD AZIMUTHS AT
C *** BOTH POINTS RETURNED IN RADIANS FROM NORTH GEODESIC
C *** DISTANCE S RETURNED IN UNITS OF SEMI-MAJOR AXIS A
C
C *** PROGRAMMED FOR CDC-6600 BY LCDR L. PFEIFER NGS
C *** ROCKVILLE MD 18 FEB 75. MODIFIED FOR IBM SYSTEM 360
C *** BY JOHN G. GERGEN NGS ROCKVILLE MD 7507.
C
IMPLICIT REAL*8 (A-H, O-Z)
DATA EPS/0.5D-13/, PI/3.1415926535898D0/
TWOPI=2.*PI
R=-FINV
TU1=R*DSIN(GLAT1)/DCOS(GLAT1)
TU2=R*DSIN(GLAT2)/DCOS(GLAT2)
CU1=1./DSQRT(TU1*TU1+1.)
SU1=CU1*TU1
CU2=1./DSQRT(TU2*TU2+1.)
S=CU1*CU2
BAZ=S*SU1
FAZ=BAZ*SU1
X=GLON2-GLON1
100 SX=DSIN(X)
CX=DCOS(X)
TU1=CU2*SX
TU2=BAZ-SU1*CU2*CX
SY=DSQRT(TU1*TU1+TU2*TU2)
CY=S*CX+FAZ
Y=DATAN2(SY, CY)
SA=S*SX/SY
C2A=-SA*SA+1.
CZ=FAZ+FAZ
IF (C2A.GT.0.) CZ=-CZ/C2A+CY
E=CZ*CZ*2.-1.
C=((-3.*C2A+4.)*PINV+4.)*C2A*PINV/16.
D=X
X=((E*CY*C+CY)*SY+C+Y)*SA
X=(1.-C)*X*FINV+GLON2-GLON1
IF (DABS (D-X).GT.EPS) GO TO 100
FAZ=DATAN2(TU1, TU2)
IF (FAZ.GE.TWOPI) FAZ=FAZ-TWOPI
IF (FAZ.LT.0.DO) FAZ=FAZ+TWOPI
BAZ=DATAN2(CU1*SX, BAZ*CX-SU1*CJ2)+PI
IF (BAZ.GE.TWOPI) BAZ=BAZ-TWOPI
IF (BAZ.LT.0.DO) BAZ=BAZ+TWOPI
X=DSQRT((1./R/R-1.)*C2A+1.)*1.
X=(X-2.)/X
C=1.-X
C=(X*X/4.+1.)/C
D=(0.375*X*X-1.)*X
X=E*CY
S=1.-E-E
S=((((SY*SY*4.-3.)*S*CZ*D/6.-X)*D/4.+CZ)*SY*D+Y)*C*A*R
RETURN
END
$ENTRY
### DATA SET EXAMPLE – PROGRAM LORAN

<table>
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<tr>
<th>LATITUDE (D-M-S)</th>
<th>LONGITUDE (D-M-S)</th>
<th>9940-Y (µsec)</th>
<th>9940-E (µsec)</th>
<th>9940-W (µsec)</th>
<th>9940-EW (µsec)</th>
</tr>
</thead>
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<td>121 55 27.160</td>
<td>42789.34</td>
<td>-0.49</td>
<td>16294.04</td>
<td>-1.06</td>
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<tr>
<td>36 44 3.400</td>
<td>121 55 32.340</td>
<td>42791.13</td>
<td>-0.38</td>
<td>16293.46</td>
<td>-1.10</td>
</tr>
<tr>
<td>36 44 21.180</td>
<td>121 55 37.390</td>
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<td>-0.38</td>
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<td>-1.06</td>
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<tr>
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<td>42796.93</td>
<td>-0.51</td>
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<td>-1.27</td>
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</tbody>
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APPENDIX C

PROGRAM LOPLC

PROGRAM Computes Line of Positions for Loran-C Using
The Secondary Factor (SF) and Additional Secondary
Factor (ASF) the SF and ASF are Based on
Semi-Empirical TD Grid.

IMPLICIT REAL*8 (A-H,O-Z)
DIMENSION PHI(100), ELON(100), DISTM(100), DIST1(100),
DIST2(100), AXIS(13), RF(13), AZ1(100), AZ2(100), AZM(100)
DATA RHOSEC, PI, UNCOV/2.062648062471D05,
1 3.1415926535898D0, 299.693D0/

C CCC**********

DATA AXIS/6.3782064D06, 6.378388 D06, 6.377397155D06,
1 6.37816 D06, 6.37816 D06, 6.378249145D06, 6.378165D06,
2 6.378166D06, 6.378165 D06, 6.378145D06, 6.3775634D06,
3 6.378245D06, 6.378135 D06/
DATA RF/6.3565838 D06, 2.97 D02, 2.9915281285D02,
1 2.9825D02, 2.98247167427D02, 2.93465D02, 2.9825D02,
2 2.983 D02, 2.983D02, 2.9825 D02, 6.3562569D06,
3 2.983 D02, 2.9826D02/

C CCC************ELLIPOSOID OPTION NUMBER
C 1. CLARKE 1866 8. MERCURY
C 2. INTERNATIONAL (HAYFORD) 9. MARSHALL ISLAND
C 3. BESSEL 1841 10. NAVY 8D
C 4. AND (AUSTRALIAN) 11. AIRY
C 5. 1967 REFERENCE 12. KRASSOWSKI 1940
C 6. CLARKE 1880 MOD 13. WGS 1972
7. SAO

CC1-2 = ELLIPSOID NUMBER (K)
CC3-5 = NUMBER OF POINTS ALONG COAST (IREC)

READ (5, 100) K, IREC, ISTA1, ISTA2
100 FORMAT (1X, I2, I4, 2I3)
TWOPI = 2. * PI
A = AXIS (K)
F = 1. / R (K)
IF (F .LT. 3. D-3) F = (A - 1. / F) / A

READ MASTER STATION POSITIONS.

READ (5, 105) ILATM, IMINM, RSECM, ILMOM, ILMINM, RLSECM
105 FORMAT (1X, I3, 1X, I2, 1X, F5.2, 1X, I4, 1X, I2, 1X, F5.2)
RHAST = ((IABS (ILATM) * 60 + IMINM) * 60 + RSECM) / RHOSEC
IF (ILATM .LT. 0) RHAST = - RHAST

RMASTL = ((IABS (ILONM) * 60 + ILMINM) * 60 + RLSECM) / RHOSEC
IF (ILONM .GT. 0) RMASTL = TWOPI - RMASTL

READ THE FIRST SLAVE STATION AND CHANGE THE LATITUDE
AND LONGITUDE INTO RADIANs. DELAY IS THE CODING DELAY
AND BIAS IS THE OFFSET IN MICROSECONDS.

READ (5, 101) ILATS, IMINS, RSECS, IIONS, ILMINS, RLSECS,
1 DELAY1, BIAS1
101 FORMAT (1X, I3, 1X, I2, 1X, F5.2, 1X, I4, 1X, I2, 1X, F5.2,
1 F9.2, F7.3)
RSLAV1 = ((IABS (ILATS) * 60 + IMINS) * 60 + RSECS) / RHOSEC

39
IF(ILATS .LT. 0) RSLAV1 = -RSLAV1
RSLAL1 = ((IABS(ILONS) * 60 + ILMINS) * 60 + RLSECS) / 1 RHOSEC
IF(ILONS .GT. 0) RSLAL1 = TWOPI - RSLAL1

C C READ THE SECOND SLAVE STATION AND CHANGE THE LATITUDE
C AND LONGITUDE INTO RADIANS.
C
READ (5, 101) ILATS, IMINS, RSECS, ILONS, ILMINS, RLSECS,
1 DELAY2, BIAS2
RSLAV2 = ((IABS(ILATS) * 60 + IMINS) * 60 + RSECS) / 1 RHOSEC
IF(ILATS .LT. 0) RSLAV2 = -RSLAV2
RSLAL2 = ((IABS(ILONS) * 60 + ILMINS) * 60 + RLSECS) / 1 RHOSEC
IF(ILONS .GT. 0) RSLAL2 = TWOPI - RSLAL2

C C READ COAST POINT LAT AND LONG AND CONVERT TO RADIANS.
C STORE LAT IN PHI AND LONG IN ELON.
C
DO 500 I = 1, IRZC, 1
READ (5, 102) INUM, ILAT, IMIN, RSEC, ILMON, ILMINS, RLSEC
102 FORMAT (1X, I4, I4, I3, F7.3, I5, I3, F7.3)
PHI(I) = ((IABS(ILAT) * 60 + IMIN) * 60 + RSEC) / 1 RHOSEC
IF(ILAT .LT. 0) PHI(I) = -PHI(I)
ELON(I) = ((IABS(ILON) * 60 + ILMINS) * 60 + RLSECS) / 1 RHOSEC
IF(ILON .GT. 0) ELON(I) = TWOPI - ELON(I)

C C COMPUTE DISTANCE FROM COAST POINT TO MASTER AND
C SLAVE STATIONS. SET UP COMPUTATION AND CALL INVER1
C
P1 = PHI(I)
E1 = ELOM(I)
CALL INVER1(A,F,P1,E1,RMST,RMST1,AZF,AZB,S)
DISTM(I) = S
AZM(I) = AZF
CALL INVER1(A,F,P1,E1,RSAS1,RSAS1,AZF,AZB,S)
DIST1(I) = S
AZ1(I) = AZF
CALL INVER1(A,F,P1,E1,RSAS2,RSAS2,AZF,AZB,S)
DIST2(I) = S
AZ2(I) = AZF
WRITE (6,210) I,INUM,ILAT,MIN,RSEC,ILON,ILMIN,RLSEC,
1 AZM(I),AZ1(I),AZ2(I)
210 FORMAT(1X,I4,I4,I4,I3,F7.3,I5,I3,F7.3,3F10.3)
500 CONTINUE
C
C READ THE NUMBER OF RECORDS AND THEIR POSITIONS.
C COMPUTE THE TOTAL DISTANCE OVER LAND AND SEA.
C TDISTM = TOTAL DISTANCE FROM MASTER TO DATA POINT.
C TDISTS = TOTAL DISTANCE FROM SLAVE TO DATA POINT.
C
C COMPUTE THE FORWARD AND BACK AZIMUTHS
C FAZM AND FAZS = FORWARD AZIMUTH TO THE MASTER AND
C SLAVE STATION.
C BAZM AND BAZS = BACK AZIMUTH TO THE MASTER AND
C SLAVE STATION.
C
READ (5,103) JREC
103 FORMAT(1X,I4)
C
DO 550 I=1,JREC,1
READ (5,104) ILAT,MIN,RSEC,ILON,ILMIN,RLSEC,RATE1,RATE2
C
C CONVERT LAT AND LONG TO RADIANS.

91
RPOST = ((IABS(ILAT) * 60 + IMIN) * 60 + RSEC) /
1 RHOSSEC
IF (ILAT .LT. 0) RPOST = -RPOST
RPOSTL = ((IABS(ILON) * 60 + ILMIN) * 60 + RLSEC) /
1 RHOSSEC
IF (ILON .GT. 0) RPOSTL = TWP91 - RPOSTL

COMPUTE DISTANCES AND AZIMUTHS FROM THE OBSERVED
POINT TO THE INTERPOLATED SHORE POINT AND WRITE.

ISTA = 1
CALL SHORPT(IREC,RPOST,RPOSTL,RMAST,RMASTL,UTDIS, 1 USDIST,ULDIST,PAZM,BAZM)
CALL SECFAC(UTDIS,USDIST,ULDIST,BAZM,ISTA,SM)

CALL SHORPT(IREC,RPOST,RPOSTL,RSLAV1,RSLAL1,UTDIS1, 1 USDIST,ULDIST,PAZ1,BAZ1)
CALL SECFAC(UTDIS1,USDIST,ULDIST,BAZ1,ISTA1,SM1)

CALL SHORPT(IREC,RPOST,RPOSTL,RSLAV2,RSLAL2,UTDIS2, 1 USDIST,ULDIST,PAZ2,BAZ2)
CALL SECFAC(UTDIS2,USDIST,ULDIST,BAZ2,ISTA2,SM2)

COMPUTE THE RATES AND COMPARE TO THE OBSERVED RATES

TDM1 = UTDIS1 + UTDISM + SM1 - SFM + DELAY1 + BIAS1
DIFF1 = TDM1 - RATE1

TDM2 = UTDIS2 + UTDISM + SM2 - SFM + DELAY2 + BIAS2
DIFF2 = TDM2 - RATE2

COMPUTE THE LANE WIDTH IN METERS BASED ON EQUATION
4.20 IN ELECTRONIC SURVEYING AND NAVIGATION - LAURILA,
BR1 = DABS(FAZ1 - FAZM)
IF(BR1 .GT. PI) BR1 = TWOPI - BR1
BR2 = DABS(FAZ2 - FAZM)
IF(BR2 .GT. PI) BR2 = TWOPI - BR2
WIDTH1 = (DIFF1 * UNCOV * 0.5) / DSIN(BR1 * 0.5)
WIDTH2 = (DIFF2 * UNCOV * 0.5) / DSIN(BR2 * 0.5)

WRITE THE POSITION OF VESSEL, OBSERVED RATES, AND THE DIFFERENCES BETWEEN THEM.

WRITE(6,200) ILATIMIN,RSEC,ILON,ILMIN,RLSEC,RATE1,1 DIFF1,RATE2,DIFF2

XMEAN1 AND XMEAN2 ARE THE MEAN DIFFS BETWEEN THE COMPUTED RATE AND THE OBSERVED. XSLAV1 AND XSLAV2 ARE THE STORED DIFFS.

XMEAN1 = XMEAN1 + DIFF1
XMEAN2 = XMEAN2 + DIFF2
XMEAN3 = XMEAN3 + WIDTH1
XMEAN4 = XMEAN4 + WIDTH2
XSLAV1(I) = DIFF1
XSLAV2(I) = DIFF2

CONTINUE

COMPUTE THE MEAN AND STANDARD DEVIATION

XMEAN1 = XMEAN1 / JREC
XMEAN2 = XMEAN2 / JREC
XMEAN3 = XMEAN3 / JREC
XMEAN4 = XMEAN4 / JREC
DO 600 I = 1, JREC, 1
VAR1 = VAR1 + ((XSLAV1(I) - XMEAN1)**2)
600 VAR2 = VAR2 + ((XSLAV2(I) - XMEAN2)**2)

VAR1 = VAR1 / (JREC - 1.0)
VAR2 = VAR2 / (JREC - 1.0)

SD1 = DSQRT(VAR1)
SD2 = DSQRT(VAR2)

WRITE (6, 201)
WRITE (6, 210) XMEAN1, SD1, XMEAN3
WRITE (6, 201)
WRITE (6, 211) XMEAN2, SD2, XMEAN4
WRITE (6, 202)
210 FORMAT (1X, 'SLAVE #1, MEAN = ', F10.3,
1 ' STANDARD DEVIATION = ',
2 F10.3, ' DISTANCE IN METERS = ', F10.3)
211 FORMAT (1X, 'SLAVE #2, MEAN = ', F10.3,
1 ' STANDARD DEVIATION = ',
2 F10.3, ' DISTANCE IN METERS = ', F10.3)
WRITE (6, 201)
201 FORMAT (1H )
202 FORMAT (1H1)
STOP
END

SUBROUTINE SHORPT(IREC,RPOST,RPOSTL,RCONT,RCONTL,UDIST,
1 USD, ULD, PA, BA)

SUBROUTINE SHORPT WILL SELECT A POINT ALONG THE SHORE
WHICH IS OUTLINED FROM NORTH BY SELECTED POINTS WITH

IMPLICIT REAL*8 (A-H,O-Z)
DIMENSION FAZM(100)
COMMON/SHORE/PHI(100),ELON(100),UNCOV,RN,A,F
DATA PI/3.141592653589798D0/

TWOPI = 2.0 * PI

CALL INVER1(A,F,RPOST,RPOSTL,RCONT,RCONTL,PA,BA,RDISTT)
UDIST = (RN * RDISTT) / UNCOV

RCOMP = 99999.99

DO 10 J=1,IREC,1
P1 = PHI(J)
E1 = ELON(J)
CALL INVER1(A,F,P1,E1,RCONT,RCONTL,AZF,AZB,RDISTL)
CALL INVER1(A,F,RPOST,RPOSTL,P1,E1,FAZ,BAZ,RDISTS)
USD = (RN * RDISTS) / UNCOV
ULD = (RN * RDISTL) / UNCOV
FAZM(J) = AZF


95
FDIFF = DABS(UDIST - (USD + ULD))
IF(FDIFF .GT. ECOMP) GO TO 10
RCOMP = FDIFF
JSTA = J
10 CONTINUE
C
C NOW DETERMINE THE INTERPOLATED LATITUDE AND LONGITUDE
C SHORE POINT USING AZIMUTH PERCENTAGE.
C
IUPPER = JSTA - 1
ILOWER = JSTA + 1
AZMU = FAZM(IUPPER)
AZML = FAZM(ILOWER)
IF(AZMU .GT. FA .AND. FA .GE. FAZM(JSTA)) ICH = IUPPER
IF(FAZM(JSTA) .GE. FA .AND. FA .GT. AZML) ICH = ILOWER
C
RADJ = 1.00 - DABS((FAZM(ICH) - FA) / (FAZM(ICH) - 1 FAZM(JSTA)))
C
RNWPHI = PHI(JSTA) + ((PHI(ICH) - PHI(JSTA)) * RADJ)
IF(ELON(JSTA) .LE. ELON(ICH)) RADJ = 1.0 - RADJ
RNWELN = ELON(JSTA) + ((ELON(ICH) - ELON(JSTA)) * RADJ)
C
CALL TODMS(RNWPHI,IDG,MIN,SEC)
RHOLD = TWOPI - RNWELN
CALL TODMS(RHOLD,IDGL,MINL,SECL)
C
CALL INVER1(A,F,RNWPHI,RNWELN,RCONT,RCONTL, AZ,BZ,RDISTL)
CALL INVER1(A,F,RPOST,RPOSTL,RNWPHI,RNWELN, AZ,BZ,RDISTL)
USD = (RN * RDISTS) / UNCOV
ULD = (RN * BDISTL) / UNCOV
RETURN
END
C==================================
SUBROUTINE SECFAC(UTDIST, USDIST, ULDIST, AZI, ISTA, SF)

C-----------------------------------------------
C
C THIS ROUTINE WILL COMPUTE THE LAND/SEA SECONDARY FACTOR
C
C UTDIST = TOTAL DISTANCE
C
C USDIST = DISTANCE OVER THE SEA WATER PATH
C
C ULDIST = DISTANCE OVER THE LAND PATH
C
C AZI = AZIMUTH FROM NORTH.
C
C
C MASTER = 1 (ISTA)
C
W = 2
C
X = 3
C
Y = 4
C

IMPLICIT REAL*8 (A-H, O-Z)
S1 = (.795 / USDIST) + 0.439 + (.00245 * USDIST)
C
C IF (UTDIST .GT. 540) GO TO 10
S2 = (3.188 / UTDIST) - 0.594 + (.000329 * UTDIST)
GO TO 20
10 S2 = (128.8 / UTDIST) + 0.187 + (.000652 * UTDIST)
C
20 IF (USDIST .GT. 540) GO TO 30
S3 = (3.188 / USDIST) - 0.594 + (.000329 * USDIST)
GO TO 40
30 S3 = (128.8 / USDIST) + 0.187 + (.000652 * USDIST)
C
40 IF (ULDIST .GT. 540) 30 TO 50
S4 = (3.188 / ULDIST) - 0.594 + (.000329 * ULDIST)
GO TO 60
50 S4 = (128.8 / ULDIST) + 0.187 + (.000652 * ULDIST)
C
60 S5 = 1.428 + (.00158 * UTDIST)
S6 = 1.428 + (.00158 * ULDIST)

97
TAZI = 2.0 * AZI
GO TO (70, 80, 90, 100), ISTA

70 RHOLD = (1.010*DSIN(AZI)) - (.196*DCOS(AZI)) - (.893*DSIN(TAZI)) - (.355*DCOS(TAZI))
GO TO 200

80 RHOLD = (.323*DCOS(AZI)) - (.711*DSIN(TAZI))
GO TO 200

90 RHOLD = (.942*DCOS(TAZI))
GO TO 200

100 RHOLD = (.588*DSIN(TAZI))

C

200 S5 = S5 + RHOLD
S6 = S6 + RHOLD
SF = 0.5 * (S5 + S6 - S1 + S2 + S3 - S4)
WRITE(6, 500) S1, S2, S3, S4, S5, S6, SF

500 FORMAT(1X, 7F15.5)
RETURN
END

C==========

SUBROUTINE INVER1(A, PINV, GLAT1, GLON1, GLAT2, GLON2, FAZ, BAZ, S)

C

See Appendix B for subroutine INVER1.
Short points around Monterey Bay, California. The points are used to interpolate geodetic point for computation of the distance over land and the distance over sea.

<table>
<thead>
<tr>
<th>NO.</th>
<th>LATITUDE</th>
<th>LONGITUDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>36 57 18.606</td>
<td>122 05 37.525</td>
</tr>
<tr>
<td>2</td>
<td>36 56 59.264</td>
<td>122 03 01.817</td>
</tr>
<tr>
<td>3</td>
<td>36 57 05.076</td>
<td>122 01 31.701</td>
</tr>
<tr>
<td>4</td>
<td>36 57 49.538</td>
<td>122 01 07.857</td>
</tr>
<tr>
<td>5</td>
<td>36 57 17.949</td>
<td>121 58 19.830</td>
</tr>
<tr>
<td>6</td>
<td>36 58 08.589</td>
<td>121 57 07.288</td>
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<tr>
<td>7</td>
<td>36 58 32.140</td>
<td>121 55 10.083</td>
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<td>36 58 01.498</td>
<td>121 53 57.390</td>
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<tr>
<td>9</td>
<td>36 56 46.115</td>
<td>121 52 22.313</td>
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<tr>
<td>10</td>
<td>36 55 38.140</td>
<td>121 51 24.399</td>
</tr>
<tr>
<td>11</td>
<td>36 53 13.806</td>
<td>121 49 46.743</td>
</tr>
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<td>12</td>
<td>36 49 38.384</td>
<td>121 47 48.895</td>
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<td>36 47 39.241</td>
<td>121 47 10.818</td>
</tr>
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<td>14</td>
<td>36 46 27.554</td>
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<td>15</td>
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<td>121 47 52.416</td>
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<td>36 41 14.439</td>
<td>121 48 32.642</td>
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<td>36 37 31.128</td>
<td>121 50 31.728</td>
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<td>19</td>
<td>36 36 23.446</td>
<td>121 51 34.833</td>
</tr>
<tr>
<td>20</td>
<td>36 36 03.628</td>
<td>121 52 50.879</td>
</tr>
<tr>
<td>21</td>
<td>36 36 24.782</td>
<td>121 53 48.453</td>
</tr>
<tr>
<td>22</td>
<td>36 37 18.151</td>
<td>121 54 11.628</td>
</tr>
<tr>
<td>23</td>
<td>36 38 00.300</td>
<td>121 55 57.538</td>
</tr>
<tr>
<td>Latitude (DEG-MIN-SEC)</td>
<td>Longitude (DEG-MIN-SEC)</td>
<td>Observed Loran Rates &amp; Errors (E)</td>
</tr>
<tr>
<td>------------------------</td>
<td>-------------------------</td>
<td>-----------------------------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9940-Y (μsec) 9940-W (μsec)</td>
</tr>
<tr>
<td>36 43 45.800</td>
<td>121 55 27.160</td>
<td>42789.34 1.14 16294.04 1.32</td>
</tr>
<tr>
<td>36 44 3.400</td>
<td>121 55 32.340</td>
<td>42791.13 1.25 16293.46 1.29</td>
</tr>
<tr>
<td>36 44 21.180</td>
<td>121 55 37.390</td>
<td>42793.04 1.25 16292.73 1.40</td>
</tr>
<tr>
<td>36 44 37.490</td>
<td>121 55 46.950</td>
<td>42795.13 1.05 16292.03 1.33</td>
</tr>
<tr>
<td>36 44 53.260</td>
<td>121 55 57.710</td>
<td>42796.93 1.12 16291.43 1.11</td>
</tr>
</tbody>
</table>
APPENDIX D

PROGRAM LORTAB

PROGRAM LORTAB

PROGRAM COMPUTES LINE OF POSITION FOR LORAN-C USING
SF SALT WATER CORRECTION FACTOR AND DMAHTC CALCULATED
OR FIELD OBSERVED ASF CORRECTIONS.

IMPLICIT REAL*8 (A-H,O-Z)

DIMENSION AXIS(13),RF(13)
DIMENSION XSLAV1(1000),XSLAV2(1000)

DATA RHOSFC,PI,UNCOV,RN/2.062648062471D05,
1 3.1415926535898D0,299.792458D0,1.000338D0/
DATA XMEAN1,XMEAN2,VAR1,VAR2/0.00D0,0.00D0,
1 0.00D0,0.00D0/
DATA XMEAN3,XMEAN4/0.00D0,0.00D0/

****ELLIPSOID OPTION NUMBER
C 1. CLARKE 1866
C 2. INTERNATIONAL (HAYFORD)
C 3. BESSEL 1841
10. NAVY 8D

101
C 4. AND (AUSTRALIAN) 11. AIRY
C 5. 1967 REFERENCE 12. KRASSOWSKI 1940
C 6. CLARKE 1880 MOD 13. WGS 1972
C 7. SAO
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
READ THE FIRST SLAVE STATION AND CHANGE THE LATITUDE
AND LONGITUDE INTO RADIANS.

READ(5,101) ILATS,IMINS,RSECS,ILONS,ILMINS,RLSECS,
1 DELAY1
WRITE(6,101) ILATS,IMINS,RSECS,ILONS,ILMINS,RLSECS,
1 DELAY1

FORMAT(1X,13,1X,12,1X,F5.2,1X,12,1X,F5.2,F9.2)
RSLAV1 = ((IABS(ILATS) * 60 + IMINS) * 60 + RSECS) /
1 RHOSEC
IF(ILATS .LT. 0) RSLAV1 = -RSLAV1
RSLAL1 = ((IABS(ILONS) * 60 + ILMINS) * 60 + RLSECS) /
1 RHOSEC
IF(ILONS .GT. 0) RSLAL1 = TWOPI - RSLAL1

READ THE SECOND SLAVE STATION AND CHANGE THE LATITUDE
AND LONGITUDE INTO RADIANS.

READ(5,101) ILATS,IMINS,RSECS,ILONS,ILMINS,RLSECS,
1 DELAY2
WRITE(6,101) ILATS,IMINS,RSECS,ILONS,ILMINS,RLSECS,
1 DELAY2
RSLAV2 = ((IABS(ILATS) * 60 + IMINS) * 60 + RSECS) /
1 RHOSEC
IF(ILATS .LT. 0) RSLAV2 = -RSLAV2
RSLAL2 = ((IABS(ILONS) * 60 + ILMINS) * 60 + RLSECS) /
1 RHOSEC
IF(ILONS .GT. 0) RSLAL2 = TWOPI - RSLAL2
WRITE(6,201)

READ THE RECORDS POSITIONS AND OBSERVED RATES, THEN
COMPUTE THE TOTAL DISTANCE.

DO 550 I=1,IREC,1
READ (5, 104) ILAT, IMIN, RSEC, ILOM, ILMN, RLSEC,
  1 RATE1, RATE2

C CONVERT LAT AND LONG TO RADIANS.

RPOST = ((IABS(ILAT) * 60 + IMIN) * 60 + RSEC) /
  1 RHOSEC
IF (ILAT .LT. 0) RPOST = -RPOST
RPOSTL = ((IABS(ILON) * 60 + ILMN) * 60 + RLSEC) /
  1 RHOSEC
IF (ILON .GT. 0) RPOSTL = TWOPI - RPOSTL

C COMPUTE DISTANCES AND AZIMUTHS FROM THE OBSERVED POINT

C MASTER

CALL INVER1 (A, F, RPOST, RPOSTL, RMAST, RMASTL, FAZM, BAZM,
  1 DISTM)
UDISTM = (RN * DISTM) / UNCOV
CALL SECFAC (UDISTM, SFM)

C SLAVE1

CALL INVER1 (A, F, RPOST, RPOSTL, RSLAV1, RSLAL1, FAZ1, BAZ1,
  1 DIST1)
UDIST1 = (RN * DIST1) / UNCOV
CALL SECFAC (UDIST1, SF1)

C SLAVE2

CALL INVER1 (A, F, RPOST, RPOSTL, RSLAV2, RSLAL2, FAZ2, BAZ2,
  1 DIST2)
UDIST2 = (RN * DIST2) / UNCOV
CALL SECFAC(UDIST2, SF2)

DETERMINE THE ADDITIONAL SECONDARY CORRECTORS FROM THE LORAN-C CORRECTION TABLE FOR THE WEST COAST CHAIN 9940

CALL TABLE(RPOST, RPOSTL, ID1, ASF1)
CALL TABLE(RPOST, RPOSTL, ID2, ASF2)

COMPUTE THE RATES AND COMPARE TO THE OBSERVED RATES

TDM1 = UDIST1 - UDISTM + SF1 - SFM + ASF1 + DELAY1
DIFF1 = TDM1 - RATE1

TDM2 = UDIST2 - UDISTM + SF2 - SFM + ASF2 + DELAY2
DIFF2 = TDM2 - RATE2

COMPUTE THE LANE WIDTH IN METERS BASED ON EQUATION 4.20 IN ELECTRONIC SURVEYING AND NAVIGATION - LAURILA, PAGE 94.

BR1 = DABS(FAZ1 - FAZM)
BR2 = DABS(FAZ2 - FAZM)
WIDTH1 = (DIFF1 * UNCOV * 0.5) / DSIN(BR1 * 0.5)
WIDTH2 = (DIFF2 * UNCOV * 0.5) / DSIN(BR2 * 0.5)

WRITE THE POSITION OF VESSEL, COMPUTED RATE, OBSERVED RATE, AND THE DIFF BETWEEN THEM.

WRITE(6, 200) ILAT, IMIN, RSEC, ILON, ILMIN, RLSEC, RATE1, DIFF1, RATE2, DIFF2
WRITE(6, 201)
XMEAN1 AND XMEAN2 ARE THE MEAN DIFFS BETWEEN THE
COMPUTED RATE AND THE OBSERVED. XSLAV1 AND XSLAV2
ARE THE STORED DIFFS.

XMEAN1 = XMEAN1 + DIFF1
XMEAN2 = XMEAN2 + DIFF2
XMEAN3 = XMEAN3 + WIDTH1
XMEAN4 = XMEAN4 + WIDTH2
XSLAV1(I) = DIFF1
XSLAV2(I) = DIFF2

550 CONTINUE

DO 600 I = 1,IREC,1
VAR1 = VAR1 + ((XSLAV1(I) - XMEAN1)**2)
600 VAR2 = VAR2 + ((XSLAV2(I) - XMEAN2)**2)

VAR1 = VAR1 / (IREC - 1.0)
VAR2 = VAR2 / (IREC - 1.0)

SD1 = DSQRT(VAR1)
SD2 = DSQRT(VAR2)

WRITE(6,201)
WRITE(6,210) XMEAN1,SD1,XMEAN3
WRITE(6,201)
WRITE(6,211) XMEAN2,SD2,XMEAN4
WRITE(6,202)
210 FORMAT(1X,' SLAVE #1, MEAN = ',F10.3,
1 ' STANDARD DEVIATION = ',
2 F10.3,' DISTANCE IN METERS = ',F10.3)
211 FORMAT(1X,' SLAVE #2, MEAN = ',F10.3,
1 ' STANDARD DEVIATION = ',
2 F10.3,' DISTANCE IN METERS = ',F10.3)
STOP
C=====================================================================

SUBROUTINE SECPAC(UDIST, SF)
C=====================================================================

C THIS ROUTINE WILL COMPUTE THE SEA SECONDARY FACTOR
C UTDIST = TOTAL DISTANCE
C SF = SECONDARY FACTOR
C
IMPLICIT REAL*8 (A-H,O-Z)
C
C COEFFICIENTS
C
A0 = 129.04323
A1 = -0.40758
A2 = 0.00064576813
C
B0 = 2.741282
B1 = -0.011402
B2 = 0.0032774815
C
IF(UDIST.GT. 537) GO TO 10
SF = ( B0 / UTDIST) * B1 + ( B2 * UTDIST)
GO TO 20
10 SF = ( A0 / UTDIST) * A1 + ( A2 * UTDIST)
C
SUBROUTINE TABLE(RLAT,RLON,ID,ASP)

C
C SUBROUTINE TABLE SELECTS THE PROPER ASF CORRECTOR FROM
C THE LORAN-C CORRECTION TABLE PUBLISHED BY THE DEFENSE
C MAPPING AGENCY.
C
C RLAT = POSITION LATITUDE IN SECONDS
C RLON = POSITION LONGITUDE IN SECONDS
C ID = LORAN-C CHAIN IDENTIFIER
C
C THE FOLLOWING TABLES OF ASF CORRECTORS ARE FOR
C MONTEREY BAY, CALIFORNIA - 9940 -W, -X, -Y.
C
C IMPLICIT REAL*8 (A-H, O-Z)
C DIMENSION TABLEW(3,5),TABLEX(3,5),TABLEY(3,5)
C
C DATA TABLEW/ 1.6D0,1.6D0,0.0D0,
1 1.6D0,1.5D0,1.4D0,
2 1.5D0,1.4D0,1.6D0,
3 1.4D0,1.3D0,1.5D0,
4 1.3D0,0.0D0,0.0D0/

C DATA TABLEX/ -0.9D0,-0.9D0,0.0D0,
1 -0.9D0,-0.9D0,-0.9D0,
2 -1.0D0,-1.0D0,-1.0D0,
3 -1.0D0,-1.2D0,-1.1D0,
4 

\[ -1.1D0, 0.0D0, 0.0D0 / \]

\[
\begin{align*}
\text{DATA TABLEY/} & \quad 0.2D0, 0.2D0, 0.0D0, \\
1 & \quad 0.3D0, 0.3D0, 0.3D0, \\
2 & \quad 0.3D0, 0.2D0, 0.4D0, \\
3 & \quad 0.4D0, 0.3D0, 0.6D0, \\
4 & \quad 0.5D0, 0.0D0, 0.0D0/ \\
\end{align*}
\]

\[
\text{DATA RHOSEC,PI/2.062648062471D05,3.1415926535898D0/}
\]

\[ \text{TWOPI} = \pi * 2.0 \]

\[
\begin{align*}
\text{CONVER BLAT AND RLON TO SECONDS} \\
\text{HLAT} &= \text{RLAT} * \text{RHOSEC} \\
\text{HLON} &= \text{TWOPI} - \text{RLON} \\
\text{HLON} &= \text{HLON} * \text{RHOSEC} \\
\end{align*}
\]

\[
\begin{align*}
\text{STARTING LAT AND LONG FOR SEARCH} \\
\text{LAT} &= 37/00/00.0 \quad \text{LONG} = 122/05/00.0 \\
\end{align*}
\]

\[
\begin{align*}
\text{DETERMINE THE ASF CORRECTOR FOR THE LORAN-C COMBINATION} \\
\text{LATITUDE} \\
\text{SLAT} &= 133200.0 \\
\text{SLON} &= 439500.0 \\
\text{RMID} &= 300.0 \\
\text{RDIFF} &= 150.0 \\
\end{align*}
\]

\[
\begin{align*}
\text{DO 10 J}=1,5,1 \\
\text{SLAT} &= \text{SLAT} - \text{RMID} \\
\text{ULAT} &= \text{SLAT} + \text{RDIFF} \\
\text{VLAT} &= \text{SLAT} - \text{RDIFF} \\
\end{align*}
\]

109
10 IF(hLAT .LT. ULAT .AND. hLAT .GE. VLAT) GO TO 15
15 CONTINUE
C
C LONGITUDE
C
DO 30 I=1,3,1
SLON = SLON - RMID
ULON = SLON + RDIFF
VLON = SLON - RDIFF
30 IF(hLON .LT. ULON .AND. hLON .GT. VLON) GO TO 35
35 CONTINUE
C
C DETERMINE ASP CORRECTOR
C
ASF = 0.0
IF(ID .EQ. 1) ASF = TABLEW(I,J)
IF(ID .EQ. 2) ASF = TABLEX(I,J)
IF(ID .EQ. 3) ASF = TABLEY(I,J)
RETURN
END
C=================================================================
SUBROUTINE INVER1(A,FINV,GLAT1,GLON1,GLAT2,GLON2,FAZ,
1 BAZ,S)
C=================================================================

See Appendix B for subroutine INVER1.
### DATA SET EXAMPLE - PROGRAM LORTAB

<table>
<thead>
<tr>
<th>SHIP'S POSITION</th>
<th>LATITUDE (D-M-S)</th>
<th>LONGITUDE (D-M-S)</th>
<th>9940-Y (µsec)</th>
<th>9940-X (µsec)</th>
<th>9940-W (µsec)</th>
<th>9940-E (µsec)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>36 43 45.800</td>
<td>121 55 27.160</td>
<td>42789.34</td>
<td>-0.29</td>
<td>16294.04</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>36 44 3.400</td>
<td>121 55 32.340</td>
<td>42791.13</td>
<td>-0.18</td>
<td>16293.46</td>
<td>0.30</td>
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<td>36 44 21.180</td>
<td>121 55 37.390</td>
<td>42793.04</td>
<td>-0.18</td>
<td>16292.73</td>
<td>0.41</td>
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<tr>
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<td>36 44 37.490</td>
<td>121 55 46.950</td>
<td>42795.13</td>
<td>-0.38</td>
<td>16292.03</td>
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<td>121 55 57.710</td>
<td>42796.93</td>
<td>-0.31</td>
<td>16291.43</td>
<td>0.13</td>
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APPENDIX E
PROGRAM ASPSEL

PROGRAM ASPSEL

PROGRAM DETERMINES OBSERVED ASP CORRECTORS BY SCANNING
DATA AT 1 DEGREE LATITUDE AND LONGITUDE INTERVALS. THE
ASP CORRECTORS ARE DETERMINED BY SUBTRACTING THE
CALCULATED TD USING THE SEAWATER SECONDARY FACTOR FROM
THE OBSERVED TD RATES.

IMPLICIT REAL*8 (A-H,O-Z)
DIMENSION AXIS(13),RF(13)
DIMENSION ASPCR1(16,26),ASPCR2(16,26),
INO1(16,26),INO2(16,26)
DATA RHSEC,PI,UNCOV,RN/2.062648062471D05,
1 3.1415926535898D0,299.792458D0,1.000338D0/
DATA XMEAN1,XMEAN2,VAR1,VAR2/0.00D0,0.00D0,
1 0.00D0,0.00D0/
DATA XMEAN3,XMEAN4/0.00D0,0.00D0/

CCCCCC***********CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

DATA AXIS/6.3782064D0,6.378388 D06,6.377397155D06,
1 6.37816 D06,6.37816D06,6.37816D06,6.37816D06,
2 6.37816D06,6.37816 D06,6.37816D06,6.3775634D06,
3 6.378245D06,6.378135 D06/
DATA RF/6.3565838 D06,2.97 D02,2.9915281285D02,
1 2.9825D02,2.98247167427D02,2.93465D02,2.9825D02,
2 2.983 D02,2.983D02,2.9825 D02,6.3562569D06,
3 2.983 D02,2.9826D02/

C****ELLIPSOID OPTION NUMBER
C 1. CLARKE 1866 8. MERCURY
2. INTERNATIONAL (HAYFORD)  9. MARSHALL ISLAND
3. BESSEL 1841  10. NAVY 8D
4. AND (AUSTRALIAN)  11. AIRY
5. 1967 REFERENCE  12. KRASSOWSKI 1940
6. CLARKE 1880 MOD  13. WGS 1972
7. SAO

CC1-2 = ELLIPSOID NUMBER (K)
CC3-5 = NUMBER OF POINTS ALONG COAST (IREC)

READ (5,100) K,IREC,ID1,ID2

100 FORMAT(1X,I2,I4,2I3)
TWOPI=2.*PI
A=AXIS(K)
F=1./RF(K)
IF(F.LT.3.D-3) F=(A-1./F)/A

READ MASTER AND SLAVE STATIONS POSITIONS
THE FIRST RECORD IS THE NUMBER OF MASTER AND SLAVE
STATIONS FOR THE PARTICULAR CHAIN.

WRITE (6,202)

202 FORMAT(1H1)
WRITE (6,201)

201 FORMAT(1H )
READ (5,105) ILATM,IMINM,RSECM,ILONM,ILMINM,RLSECM
WRITE (6,105) ILATM,IMINM,RSECM,ILONM,ILMINM,RLSECM

105 FORMAT(1X,I3,1X,I2,1X,F5.2,1X,I4,1X,I2,1X,F5.2)
RMAST = ((IABS(ILATM) * 60 + IMINM) * 60 + RSECM) / 1 RHOSEC
IF(ILATM.LT.0) RMAST = -RMAST
RMASTL = ((IABS(ILONM) * 60 + ILMINM) *60 +RLSECM) / 1 RHOSEC
IF(ILONM .GT. 0) RMASTL = TWOPI - RMASTL

READ THE FIRST SLAVE STATION AND CHANGE THE LATITUDE AND LONGITUDE INTO RADIANS.

READ(5,101) ILATS,IMINS,RSECS,ILONS,ILMINS,RLSECS,
1 DELAY1
WRITE(6,101) ILATS,IMINS,RSECS,ILONS,ILMINS,RLSECS,
1 DELAY1
101 FORMAT(1X,I3,1X,I2,1X,F5.2,1X,I4,1X,I2,1X,F5.2,F9.2)
RSLAV1 = ((IABS(ILATS) * 60 + IMINS) * 60 + RSECS) / RHOSEC
IF(ILATS .LT. 0) RSLAV1 = -RSLAV1
RSLAL1 = ((IABS(ILONS) * 60 + ILMINS) * 60 + RLSECS) / RHOSEC
IF(ILONS .GT. 0) RSLAL1 = TWOPI - RSLAL1

READ THE SECOND SLAVE STATION AND CHANGE THE LATITUDE AND LONGITUDE INTO RADIANS.

READ(5,101) ILATS,IMINS,RSECS,ILONS,ILMINS,RLSECS,
1 DELAY2
WRITE(6,101) ILATS,IMINS,RSECS,ILONS,ILMINS,RLSECS,
1 DELAY2
RSLAV2 = ((IABS(ILATS) * 60 + IMINS) * 60 + RSECS) / RHOSEC
IF(ILATS .LT. 0) RSLAV2 = -RSLAV2
RSLAL2 = ((IABS(ILONS) * 60 + ILMINS) * 60 + RLSECS) / RHOSEC
IF(ILONS .GT. 0) RSLAL2 = TWOPI - RSLAL2
WRITE(6,201)

READ THE RECORDS POSITIONS AND OBSERVED RATES, THEN

CCMPUTE THE TOTAL DISTANCE.
DO 550 I=1,IREC,1
READ(5,104) ILAT, IMIN, RSEC, ILOM, ILMN, RLSEC,
1 RATE1, RATE2

C CONVERT LAT AND LONG TO RADIANS.

RPOST = ((IABS(ILAT) * 60 + IMIN) * 60 + RSEC) / 1 RHSEC
IF(ILAT .LT. 0) RPOST = -RPOST
RPOSTL = ((IABS(ILON) * 60 + ILMN) * 60 + RLSEC) / 1 RHSEC
IF(ILON .GT. 0) RPOSTL = TWOPI - RPOSTL

C COMPUTE DISTANCES AND AZIMUTHS FROM THE OBSERVED POINT

MASTER

CALL INVER1(A,F,RPOST,RPOSTL,RMAST,RMASTL,FAZM,BAZM,
1 DISTM)
UDISTM = (RN * DISTM) / UNCOV
CALL SECFAC(UDISTM, SFM)

SLAVE1

CALL INVER1(A,F,RPOST,RPOSTL,RSLAV1,RSLAV1,FAZ1,BAZ1,
1 DIST1)
UDIST1 = (RN * DIST1) / UNCOV
CALL SECFAC(UDIST1, SF1)

SLAVE2

CALL INVER1(A,F,RPOST,RPOSTL,RSLAV2,RSLAV2,FAZ2,BAZ2,
### 1 DIST2

\[ \text{UDIST2} = (\text{RN} \times \text{DIST2}) / \text{UNCOV} \]

CALL SECPAC(UDIST2, SF2)

**C**

**Determine which LAT and LONG the ASF corrector is assigned to.**

CALL ASSIGN(RPOST, RPOSTL, JN1, JN2)

**C**

**Compute the rates and compare to the observed rates**

\[ \text{TDM1} = \text{UDIST1} - \text{UDISTM} + \text{SF1} - \text{SFNM} + \text{DELAY1} \]

\[ \text{DIFF1} = \text{TDM1} - \text{RATE1} \]

\[ \text{TDM2} = \text{UDIST2} - \text{UDISTM} + \text{SF2} - \text{SFNM} + \text{DELAY2} \]

\[ \text{DIFF2} = \text{TDM2} - \text{RATE2} \]

**C**

**Sum the differences to the matrix and count the number of ASF correctors for each block to latter determine the mean.**

\[ \text{ASFCR1(JN1,JN2)} = \text{ASFCR1(JN1,JN2)} + \text{DIFF1} \]

\[ \text{ASFCR2(JN1,JN2)} = \text{ASFCR2(JN1,JN2)} + \text{DIFF2} \]

\[ \text{INO1(JN1,JN2)} = \text{INO1(JN1,JN2)} + 1 \]

\[ \text{INO2(JN1,JN2)} = \text{INO2(JN1,JN2)} + 1 \]

**C**

**Determine the mean ASF corrector for each LAT and LONG**

DO 650 I=1,16,1
WRITE(6,201)
DO 600 J=1,26,1
IF(INO1(I,J) .EQ. 0) GO TO 580
ASFCR1(I,J) = ASFCR1(I,J) / INO1(I,J)

580 IF(INO2(I,J) .EQ. 0) GO TO 590

116
ASFCR2(I,J) = ASFCR2(I,J) / INO2(I,J)

590 IF (ASFCR1(I,J) .EQ. 0.0) ASFCR1(I,J) = 9.99

600 IF (ASFCR2(I,J) .EQ. 0.0) ASFCR2(I,J) = 9.99

650 CONTINUE

C
C WRITE THE CORRECTORS IN MATRIX FORMAT
C
C
C IF (ID1 .EQ. 1) WRITE(6,1000)
C IF (ID1 .EQ. 2) WRITE(6,1001)
C IF (ID1 .EQ. 3) WRITE(6,1002)

WRITE(6,201)

WRITE(6,300) ((ASFCR1(I,J), I=1,16), J=1,26)
DO 700 L=1,5,1
WRITE(6,201)
700 CONTINUE

C
C IF (ID2 .EQ. 1) WRITE(6,1000)
C IF (ID2 .EQ. 2) WRITE(6,1001)
C IF (ID2 .EQ. 3) WRITE(6,1002)

WRITE(6,201)
 WRITE(6,300) ((ASFCR2(I,J), I=1,16), J=1,26)
300 FORMAT(16F6.2)

1000 FORMAT(' TABLE FOR 9940-W ')
1001 FORMAT(' TABLE FOR 9940-X ')
1002 FORMAT(' TABLE FOR 9940-Y ')
STOP
END

C=============================================
SUBROUTINE SECFAC(UTDIST,SF)
C=============================================
C
117
THIS ROUTINE WILL COMPUTE THE SEA SECONDARY FACTOR

UTDIST = TOTAL DISTANCE
SF = SECONDARY FACTOR

IMPLICIT REAL*8 (A-H, O-Z)

COEFFICIENTS

A0 = 129.04323
A1 = -0.40758
A2 = 0.00064576813

B0 = 2.741282
B1 = -0.011402
B2 = .00032774815

IF (UTDIST .GT. 537) GO TO 10
SF = ( B0 / UTDIST) + B1 + ( B2 * UTDIST)
GO TO 20
10 SF = ( A0 / UTDIST) + A1 + ( A2 * UTDIST)

CONTINUE
RETURN
END

SUBROUTINE ASSIGN(RLAT,RLON,I6,J)

SUBROUTINE ASSIGN SELECTS THE COLUMN AND ROW FOR THE LATITUDE AND LONGITUDE OF THE RECORD.
RLAT = POSITION LATITUDE IN SECONDS
RLON = POSITION LONGITUDE IN SECONDS
I = COLUMN
C         J = ROW
C
IMPLICIT REAL*8 (A-H, O-Z)
DATA RHOSCE, PI/2.062648062471D05, 3.1415926535898D0/
C
TWOPI = PI * 2.0
C CONVER RLAT AND RLOW TO SECONDS
C
HLAT = RLAT * RHOSCE
HLON = TWOPI - RLOW
HLON = HLON * RHOSCE
C
STARTING LAT AND LONG FOR SEARCH
C
LAT = 37/05/00.0   LONG = 122/05/00.0
C
SLAT = 133200.0
SLON = 439500.0
C
LATITUDE
C
J = 0
DO 10 IC = 1, 26, 1
SLAT = SLAT - 60.0
RULAT = SLAT + 30.0
RLLAT = SLAT - 30.0
10 IF (HLAT .LT. RULAT .AND. HLAT .GE. RLLAT) GO TO 15
15 J = IC
C
LONGITUDE
C
I = 0
DO 20 IC = 1, 16, 1
SLON = SLON - 60.0
RLLON = SLON + 30.0
20
RRLON = SLON - 30.0
20 IF (RLON .LT. RRLON .AND. HLON .GE. RRLON) GO TO 25
25 I = IC
RETURN
END

SUBROUTINE INVER1 (A, FINV, GLAT1, GLON1, GLAT2, GLON2, PAZ, BAZ, S)

See Appendix B for subroutine INVER1.
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<td>-0.53</td>
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<td></td>
<td>-0.39 -0.54</td>
<td>-0.39 -0.55</td>
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<tr>
<td></td>
<td>-0.63 -0.57</td>
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<tr>
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