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Differential Loran-C
Using Three Secondary Stations

by

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Based on 496 sets of data taken at 5-second intervals at Range-7 in two groups, before and after 254 readings at Luces Point, the absolute accuracy of Luces Point data was improved from about 385 m to about 48 m compared to the known position of the point. Precision was improved from about 14.9 m to about 12.6 m circular error probable using the three-station correction. Further improvement would probably have resulted if two receivers were available for real time correction.

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Differential Loran-C
Using Three Secondary Stations

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ABSTRACT

Loran-C time difference (TD) readings were taken consecutively at several survey stations near Monterey, CA, over a period of three days. One station, Range-7, was designated the "known" point of a differential Loran-C system. Readings from the known point were used to correct readings from a second survey station, Luces Point. A method of improving the precision of Loran-C TD readings based on the redundancy and relative accuracy of three LOP's was developed and applied to the data. Since only one receiver was available, a linear regression of TD vs time was calculated and used in the differential correction.

Based on 496 sets of data taken at 5-second intervals at Range-7 in two groups, before and after about 250 readings at Luces Point, the absolute accuracy of Luces Point data was improved from about 385 m to about 48 m compared to the known position of the point. Precision was improved from about 14.9 m to about 12.6 m circular error (CEP) using the three-station correction. Further improvement would probably have resulted if two receivers were available for real time corrections.

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I. INTRODUCTION

A. Purpose

The purpose of this study was to investigate the potential accuracy of the Loran-C navigation system using a differential correction technique and a correction for the use of three secondary stations rather than the usual two.

Sources of error were first examined and their magnitudes estimated. Methods of expressing the accuracy of a determination of geographic position were also considered.

It was determined that position accuracy is composed of two factors: the absolute accuracy of the position (which can be considered the bias, or systematic error, in the system) and the precision of the individual readings.

Over longer periods of data collection it was considered possible to subtract out the system bias by means of a quasi-differential correction based on intermittent time difference readings at a fixed point, designated the "known" point of the differential system, and to improve the precision of TD readings by taking advantage of the redundancy of the reception of three master-secondary pairs.

For this purpose, a theory of corrections was developed and an experiment was designed to determine the effectiveness of the corrections. The experimental data was processed by computer, and the relative accuracies were calculated. Computer programs for processing and displaying data were written for this purpose.

B. Method

To collect data for processing, several known survey points with published positions were chosen as locations for collecting Loran-C data. Using known points provided a means of comparing results. One point in a relatively central location was chosen as the "known" point, where a larger amount of data was collected. Data from the other points was corrected based on the data from the "known" point.

During periods of about eight hours, the receiver was moved from one survey point to another. The antenna was set up over the points and time difference data was collected for periods of about 20 to 30 minutes at each point. The time required to move the receiver from one point to another varied from about 30 to 60 minutes.

Data was collected by a Racal Megapulse monitor receiver with internal clock accuracy of about 0.02 μsec. A Silent 700 data terminal was used to collect the data on cassette tapes. Data was recorded at intervals of 5 seconds. Later, the data was transferred to 5¼" disks for use on a computer.

Since there was no way to collect time difference data at two points simultaneously, a method of estimating the time differences at the known point was developed. This involved using the available data to establish linear regression lines of time difference versus time at the known point.

Using the known time of data collection at the other points, an estimate of the time differences at the known point could be used to calculate a correction for data at the other points at the times of data collection.

A number of computer programs were written to calculate the required information for differential corrections. A Correction For Three Secondary Stations was developed mathematically and used to process the data in an effort to reduce the random error of the time difference readings.

Based on reduction of standard deviations of the data and reduced circular error, the three station correction was effective to some degree, although absolute error turned out to be the limiting factor in the experiment. Reduction of absolute error by means of the differential correction was significant.

II. THE LORAN-C NAVIGATION SYSTEM

A. Basic Description

Loran-C is an electronic positioning system based on the reception of pulsed LF (90-110 kHz) signals from a master transmitting station and one or more secondary stations which comprise a Loran-C "chain". A brief description of the system will be provided here as a basis for later discussions of the accuracy considerations and differential methods used in the experiment.

In the hyperbolic mode, geographic position (GP) is determined from time difference (TD) readings provided by a Loran-C receiver. The difference in reception time of pulses received from the master station and pulses received from each secondary station give the receiver's position in terms of a hyperbolic lattice system. Geographic position can be calculated from the TD readings using Loran-C lattice tables published by the Defense Mapping Agency or computed directly using various computer techniques. Nautical charts overprinted with Loran-C TD lattices are also available for plotting geographic position directly without converting first to latitude and longitude.

The hyperbolic lattice system is a series of hyperbolas. A pulse (actually a group of pulses) is first transmitted by the master station. The wave travels to each secondary station of the Loran-C chain, and each secondary transmits its own pulse after a time delay (called the coding delay) which is unique to each secondary.

The master pulse is received first by the receiver. A short time later the pulses from the secondaries are received. The time difference between reception of the master and each secondary is measured in the receiver. Each TD identifies one line of position (LOP) in the set of LOP's for a master-secondary pair. Figure II-1 shows a typical Loran-C master-secondary pair with a set of hyperbolic LOP's. Each LOP in this set represents a line of equal time difference between reception of the master pulse and reception of the pulse from the secondary. Figure II-2 shows an example of a hyperbolic lattice system formed by two master-secondary pairs

As with latitude and longitude, two LOP's are required to define a geographic position. Unlike latitude and longitude, two TD readings from different secondaries do not uniquely define a GP, since the TD's may intersect at two points within the coverage area. This is normally not a problem, since even an approximate knowledge of the geographic position of the receiver will allow determination of the correct intersection point.

When more than two LOP's are available to define a GP (when signals from more than two secondary stations can be received), the intersection of the three LOP's define three geographic points (see Figure IV-2). The accuracy of the two best pairs of LOP's is sufficient for most navigation purposes, but it is possible to combine three or more LOP's to estimate the position of one point. A method using corrections from three LOP's is used in the experiment and will be discussed in Section IV.B.

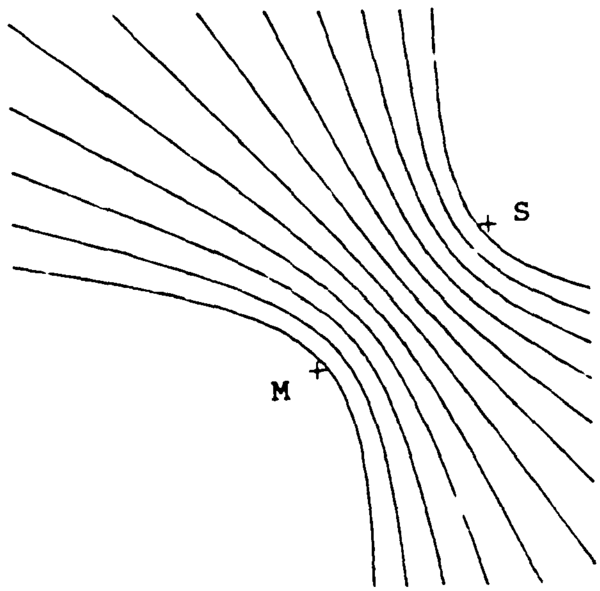

FIGURE II-1. Typical set of hyperbolic LOP's associated with a master-secondary pair.

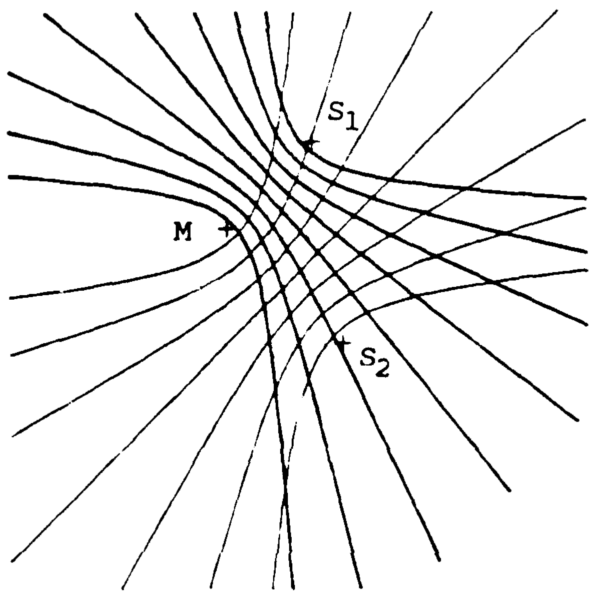

FIGURE II-2. Typical hyperbolic lattice formed by sets of LOP's associated with two master-secondary pairs with a common master station.

B. Time Difference Equations

The difference between arrival time of the signal from the master and arrival time of the signal from a secondary can be described by the following equations (Ref. 1):

The basic time difference equation for Loran-C is:

$$TD = t_s - t_m \qquad [II\text{-}1]$$

where:

TD = time difference at a given point P.

t_s = time of reception of secondary pulse.

t_m = time of reception of master pulse.

A more useful form of this equation takes into account the components which make up the travel time of the signals over each section of the paths from the stations to point P:

$$TD = (T_s + DT_s + ED) - (T_m + DT_m) + ASF \qquad [II\text{-}2]$$

where:

TD = Time Difference at a given point P.

T_s = Distance in time units between the secondary station and point P.

T_m = Distance in time units between the master station and point P.

DT_s = Secondary Phase Correction for all seawater path between secondary station and point P.

DT_m = Secondary Phase Correction for all seawater path between master station and point P.

ED = Emission Delay for the secondary station.

ASF = Additional Secondary Phase Correction for point P.

Equation II-2 contains two corrections which are applied to Loran-C TD readings. The velocity of electromagnetic waves in air under standard conditions is changed when the wave propagates over a surface. The Secondary Phase Correction Factor (DT_s and DT_m in equation II-2) is a time correction for the change in velocity caused by propagation of electromagnetic waves over seawater. This change in travel time can be calculated by the following empirically derived equations (Ref. 2):

For distances greater than 100 statute miles ($T > 537$ µsec):

$$DT = A_0/T + A_1 + A_2*T \qquad [II-3]$$

where:

DT = Secondary Phase Correction for all seawater path.

A_0 = 129.04398 µsec²

A_1 = -0.40758 µsec

A_2 = 0.00064576438

T = Travel time (T_s or T_m in equation II-1) in µsec.

For distances less than 100 statute miles ($T < 537$ µsec):

$$DT = B_0/T + B_1 + B_2*T \qquad [II-4]$$

where:

B_0 = 2.7412979 µsec²

B_1 = -0.011402 µsec

B_2 = 0.00032774624

T = Travel time in µsec.

In equation II-2 the Additional Secondary Phase Factor (ASF) corrects for propagation over land (actually any other non-seawater) surfaces, which have a wide variety of conductivities (see Section III-C-2 or Ref. 3 for further explanation of ASF Corrections). The ASF correction is in addition to the Secondary Phase Correction for all seawater path.

Secondary Phase Corrections for all seawater path are always added in before calculation of the geographic position from TD's. ASF corrections are much smaller, and are often determined from tables which require a dead reckoning position within 10' of latitude and longitude of the final position. If no DR position is available, the position calculated from TD's corrected only for all seawater path is used as a DR position to determine ASF corrections. When used in hyperbolic mode, the ASF correction in Equation II-2 is a net correction which applies to the particular master-secondary pair (the difference between the range-range corrections for each station).

Emission Delay (ED) in Equation II-2 includes a coding delay, which is the time between reception of the master pulse at the secondary station and transmission of the secondary's pulse, plus one way travel time from the master to the secondary, including the Secondary Phase Correction for all seawater path for the master-secondary baseline path (Ref. 4).

The result of application of these corrections to the basic time difference between reception of master and secondary signals is a reduction of the time difference to a path through air with an Index of Refraction of 1.000338 (Ref.4:p.4).

C. Differential Corrections

Differential techniques can be used to improve the absolute accuracy of Loran-C TD readings. Differential Loran-C uses monitor receivers located at fixed points in or near the area where improvement is needed. The most common method is to use TD readings of the monitor receivers to determine the magnitude of the variations in the TD's from the long term average of the TD's at the fixed points. These variations are then applied to receiver readings in the area of interest before geographic positions are calculated from them. Corrections are updated periodically as explained later in this section. (Ref.1:p.434)

The differential correction (including geographic correction) to Loran-C readings at an unknown point P_2 with a monitor receiver at a known point P_1 can be described by the following equation:

TD at P_2 = Received TD at P_2 + Differential Cor. + Geographic Cor.

or

$$TD_{2C} = TD_2 + (TD_1 - TD_{1C}) + TD_g \qquad [II-5]$$

where

TD_{2C} = Corrected TD reading at Point P_2 (the unknown point).

TD_{1C} = Long term average TD at P_1 (location of the monitor).

TD_1 = TD reading of receiver at the known point (P_1).

TD_2 = TD reading of the receiver at the unknown point (P_2).

TD_g = TD variation which is a function of location.

For practical purposes it is possible to use any correction from real time to a correction averaged over a period of up to several days. The method used in this experiment (described in Section IV-C) was to determine a regression line of monitor receiver TD readings at the known point. A computed correction was applied to the TD reading at the unknown point based on the time of the TD reading at the unknown point and the equation of the regression line. This method was used because only one monitor receiver was available and it was used as both a monitor at the known point and at the unknown points. In this experiment a correction based on reception of three secondary stations (rather than two) was applied to the TD readings from each secondary station before the regression line parameters were calculated, as explained later in Section IV-B.

The geographic correction - that part of the difference in TD readings at points P_1 and P_2 which is a due to the differences in ASF corrections at the two points - is a particular problem. For geographic points at sea, tables of ASF corrections within 10' of latitude and longitude are available, and may be accurate enough to provide corrections within the necessary accuracy. Tables of corrections for geographic points on land are not published, but were obtained for this experiment from the Defense Mapping Agency Hydrographic/Topographic Center.

Test results of differential Loran-C on the East Coast U.S. chain have shown accuracies of about 4.6 m CEP at distances up to 140 km from the monitor site (Ref.1:p.434).

III. GENERAL ANALYSIS OF ERRORS

To quantify the amount of error and compare the accuracy of different types of corrections made to Loran-C geographic position fixes, it is necessary to provide some basic definitions. The following sections give the definitions used in this study for the types of accuracy and measures of accuracy. One and two dimensional sources of error in Loran-C positioning are listed and approximate values for the error are given where possible. Error reduction based on differential correction is described.

A. Types of Accuracy

There are several ways to specify the accuracy of electronic navigation systems. The following definitions of three types of accuracy have been found useful in this study (from Ref. 5):

Absolute Accuracy: For purposes of this study, absolute accuracy is a measure of the ability to determine geographic position (in terms of latitude and longitude or other fixed coordinate system) from a given set of Loran-C coordinates (Ref.5:p.172). The error includes all types of systematic and random error associated with the system.

Absolute accuracy in this experiment refers to the accuracy of the calculation of the positions of the "unknown" points based on receiver TD readings, three station corrections, and differential corrections, compared to the known published positions of those points.

Repeatable Accuracy: The common navigation definition of repeatable accuracy is the ability to return to the same point using a given set of electronic coordinates (Ref.5:p.172). Error is measured in linear units. This differs from absolute accuracy in that the position itself need not be known in terms of some other coordinate system. Repeatable accuracy is normally better than absolute accuracy because the part of systematic error which is a function of position has been removed (the position remains the same), leaving only random error and time dependant systematic error. Repeatable accuracy in the context of this experiment is a measure of the precision of measurement of the TD's, which is most affected by the electronic circuitry of the transmitters and receivers involved (over short periods of time in which terrain and atmospheric factors do not change significantly).

Repeatable accuracy is similar to the accuracy expected from differential corrections. The difference between the two is that since repeatable accuracy refers to the ability to return to the same point using the same set of received TD readings, there is no difference in the ASF (terrain) correction but there may be some difference due to variability of TD's with time.

Differential corrections have different ASF corrections at different points. These must be calculated and applied to the TD readings. At a single point the ASF corrections will probably not change over the time period of interest, but over longer periods some error will be introduced. The uncertainty in ASF corrections could be a significant source of error.

Relational Accuracy: The accuracy with which it is possible to determine the position of one observer in relation to another observer using the same system (Ref.5:p.172). A form of relational accuracy enters into differential corrections when two different receivers are used. Even at the same point at the same time there will usually be a slight difference in the Loran-C readings of different receivers. This is caused by errors associated with the receiver circuitry and random errors over the slight differences in the time at which the readings are made by each receiver, since all other factors are the same. The same type of error exists with two different receivers separated by some distance (as with differential corrections), although this type of error is usually small compared to other sources of error.

B. Measures of Accuracy

In addition to the types of accuracy listed above, it is necessary to specify how accuracy is to be measured. This can be viewed as an estimate of the amount of error. The following are definitions of the basic methods used here of specifying the measures of accuracy of position. Their usefulness and limitations in this application are also described.

Root Mean Square (RMS) Error: This is the linear (one dimensional) error in the location of an LOP (Ref.5:p.172). It can be specified in linear units or time units (meters and microseconds are used here). The normal specification of RMS error is the number of meters or microseconds representing some whole number of standard deviations from the mean. In the application used here, the variation in TD readings from each master-secondary pair can be expressed as a standard deviation in microseconds, which corresponds to a displacement of the LOP by a corresponding number of meters measured normal to that line of position.

Circular Error Probable (CEP): This is the two dimensional error which specifies the radius of a circle within which there is a 50% probability of being located, based on positions calculated from the TD readings of the receiver. The estimated position of the point (based on latitude and longitude or other coordinate systems) and the radius of the circle are used to specify this measure of accuracy. Circles other than the standard 50% circle can be used (67% and 90% are common). (Ref.5:p.173) The main advantage of using CEP (rather than the error ellipse described below) is that direct comparison between accuracies of different systems, techniques, or at different points can be made. CEP in this experiment is used as a measure of the precision of the TD's indicated by the receiver at a fixed point and the precision of corrected TD's based on these uncorrected TD's. Corrections for the absolute position (the bias of the TD's from true readings) is of secondary importance in this application.

Circular error estimates in this experiment are based on the radius which 50% of the data are greater and 50% are less, as calculated by a sorting program.

Error Ellipses: Error ellipses are the preferred way of describing the accuracy of electronic navigation systems for many purposes. As with circular error, accuracy is specified in terms of the probability of an estimate of geographic position falling within a geometric figure centered on the actual geographic position (an ellipse rather than a circle is used) (Ref.6). Unlike the circle used in CEP, an ellipse provides additional information about the directional characteristics of the accuracy, which can be very important in some applications. The specifications for elliptical accuracy are usually the lengths of the major and minor axes and the orientation of the ellipse (such as the azimuth of the direction of the major axis). A disadvantage of using error ellipses in this experiment is the difficulty of directly comparing the accuracy of different ellipses with different orientations. For that reason most of the accuracy comparisons in this study have been specified in terms of circular error. Error ellipses have been used where appropriate.

Error ellipses are related to the orientation of two intersecting LOP's by the following equations (Ref.6:p.72-74):

$$\tan 2\theta = \frac{\sigma_1^2 \sin 2\phi}{\sigma_1^2(\cos 2\phi) + \sigma_2^2} \qquad \text{[III-1]}$$

$$\sigma_x^2 = \frac{\sigma_1^2 + \sigma_2^2 + ((\sigma_1^2 + \sigma_2^2)^2 - 4(\sin^2\phi)\sigma_1^2\sigma_2^2)^{\frac{1}{2}}}{2 \sin^2\phi} \qquad \text{[III-2]}$$

$$\sigma_y^2 = \frac{\sigma_1^2 + \sigma_2^2 - ((\sigma_1^2 + \sigma_2^2)^2 - 4(\sin^2\phi)\sigma_1^2\sigma_2^2)^{\frac{1}{2}}}{2 \sin^2\phi} \qquad [III-3]$$

where:

θ = the angle of the major axis of the ellipse from the direction of the LOP with smaller variance, toward the LOP with greater variance, in the direction of the smaller angle.

σ_1^2 = variance of the LOP with smaller variance.

σ_2^2 = variance of the LOP with the greater variance.

ϕ = the smaller angle between LOP's.

These equations were used to calculate the dimensions and orientation of the error ellipse for Range-7, the "known" point used for differential corrections (see Figure V-3).

C. Sources of Linear Error in Loran-C Time Differences

The position fixing accuracy of the LORAN-C system depends on a number of factors. These can be divided into two categories (Ref.7:p.18): temporal errors affecting the repeatability of the system (errors which vary with time), and systematic (time invariant) errors. Both of these types of error may also be functions of geographic position.

The effect of these errors is to produce TD readings at the receiver which differ from those which would be expected on a perfect hyperbolic lattice on the surface of a perfect ellipsoid, resulting in error in the calculation of the geographic position. A linear error of 1.0 μsec in time difference is approximately equivalent to 150 m on the baseline, with one dimensional error at other points being up to about ten times greater, depending on the location within the geometry of the system.

The main sources of error in the determination of TD's used to calculate geographic position can be classified as follows (Ref.8):

- Transmitter synchronization timing errors.
- Errors associated with propagation effects.
- Atmospheric noise.
- Receiver errors.

1. Transmitter Synchronization Timing Errors

Since time differences between reception of a master pulse and secondary pulses are used to calculate geographic position in hyperbolic Loran-C, it is essential that the synchronization of timing between transmissions from the master and secondaries be highly precise.

In order to accomplish this, each station is individually timed using cesium clocks which drive pulse and group repetition interval timing circuits. Independent monitor receivers are used to provide data to computers which adjust the relative timing between master and secondaries of the chain in small steps (usually 10 to 20 ns). Absolute timing of the master stations is adjusted to operate in coordination with Universal Time, Coordinated. (Ref.8:p.1129)

Estimates of timing error due to transmitter synchronization are on the order of 0.05 μsec (Ref.9:p.537). Actual data from an operational Loran-C chain showed time differences controlled within 0.024 μsec of the standard value, with a standard deviation (in absolute time) of 0.032 μsec (Ref.10:p.227). A transmitter synchronization error of 0.01 μsec is believed to be attainable if ground monitor data is used to remove the mean synchronization error (Ref.11:p.401).

2. Errors Associated with Propagation Effects

This includes most types of error external to the electronics of the system, and is the main source of error in the determination of geographic position.

Factors which influence groundwave propagation include the following (Ref.12:pp.39-53 and Ref.13:pp.173-187):

- Electrical Conductivity of the surface material
- Dielectric Constant of the surface
- Index of Refraction of the air
- Lapse Rate of the Index of Refraction with altitude

These factors are complex functions of several variables, the main ones being:

- type and composition of the surface over which the wave travels
- topography of the surface
- meteorological conditions

At any particular geographic position the effect of these variables may or may not be considered a function of time, depending on the time periods of interest.

Also of importance is the effect of these factors on TD as a function of geographic position. For each different geographic position, the electromagnetic waves from each transmitter must traverse a different route, with different types of surface, topography, and atmospheric conditions, to reach the receiver.

The effects of irregular terrain are practically time invariant, while ground conductivity and dielectric constant may vary seasonally (due to changes in moisture content of the soil, changes in vegetation, or other factors). Observed cyclic annual variations on the order of 0.5 μsec are probably due to seasonal variations in ground conductivity and dielectric constant and to seasonally varying atmospheric conditions.

Meteorological conditions sufficient to cause noticeable variations in TD readings may change in very short time periods (days or hours). Short term variations due to meteorological effects (cold front and warm front passage through the line of propagation) on the order of 0.025 μsec have been observed. These correlate with changes in the dry adiabatic lapse rate of the index of refraction. (Ref.14:p.1119).

For most differential Loran-C purposes it is necessary to consider only those temporal propagation effects which occur in short time periods (hours or days at most, for most applications). The variation of propagation effects with geographic position must also be considered for precise positioning. Many of these variations can be corrected by a computation of the Additional Secondary Phase Factor (ASF).

The Additional Secondary Phase Factor (ASF) is a measure of the systematic error resulting from differences in velocity of electromagnetic waves over ground with different conductivities and dielectric constants. The Defense Mapping agency uses a computerized system of maps with estimates of ground conductivity (effectively including dielectric constant) over large areas, and calculates ASF corrections in the Loran-C coverage areas. These corrections are published as tables of ASF corrections to be used in correcting Loran-C TD readings from receivers.

ASF corrections can be as large as 4 microseconds (Ref.3). The corrections provided in the Defense Mapping Agency tables require estimates of the geographic location of the receiver to the nearest 10' of latitude and longitude. ASF corrections based on the known positions of the survey points used in this experiment were provided by DMA using a computer program which calculates the corrections using the Millington Method (Ref.3:p.V).

3. Atmospheric Noise

The effects of atmospheric electrical noise are reduction of the range at which Loran-C signals can be effectively received and an increase the error in TD's computed by receivers in marginal reception areas. This is primarily dependent on the circuitry of the receiver.

In marginal areas the effect of atmospheric noise will be an increase in the standard deviation of the TD's and increased difficulty in locking on and maintaining reception of the weaker signals. Atmospheric noise varies with time and geographic location, with a significant diurnal variation (noise levels are higher at night). In this experiment, significant effects due to local sources of electrical noise were noticed in the Monterey harbor area.

4. Receiver Errors

Receiver errors are of two main types:

- timing error caused by limitations of the internal clock circuitry of the receiver
- errors caused by processing time of the receiver

For a receiver at a fixed geographic location, processing time is not a source of error. The receiver will be at the same location regardless of the time required to output the TD's or geographic coordinates. The main source of receiver error at a fixed location (other than the noise considerations discussed above) is the timing error in the internal clock circuitry. Loran-C receivers vary greatly in their timing errors. The Racal Megapulse Monitor receiver used in this experiment has a specified timing error of 0.02 μsec or better.

For mobile receivers the processing time of the receiver circuitry can be important. After the signal is received it must be processed and either stored in the form of electronic information or visually displayed. Error is introduced if the receiver moves during this time interval.

Obviously, the amount of error in the determination of geographic position from this source depends on the processing time and the speed of the receiver. Receivers which output data in the form of geographic coordinates must calculate latitude and longitude from the TD readings of the receiver, requiring more processing time and resulting in greater error from this source.

At the speeds normally used in hydrographic surveying (typically less than 20 kt) the processing time is insignificant for practically all receivers. For data which is stored in the form of receiver output TD's for later correction and conversion, as with the Racal Megapulse receiver used here, error should be insignificant even at much higher speeds.

D. Geometric Dilution of Precision

This source of error in geographic position results from the crossing angle of the Loran-C LOP's (lines of position). Figure IV-1 shows two hyperbolic LOP's with standard deviations σ_1 and σ_2 (in time difference) and crossing angle α. The optimum crossing angle of any two LOP's is 90°, resulting in minimum error in geographic position for a given set of standard deviations.

E. Summation of Errors

1. Absolute Accuracy vs. Precision

The absolute accuracy of an electronic positioning system can be viewed as a measure of its ability to give the geographic position of the receiver. Precision is a measure of the variation of individual time difference readings. If the receiver is set up at a point for a sufficient amount of time, many of the random errors can be averaged out; the average of a large number of readings can provide a basis for determining absolute accuracy.

In practice this is more difficult than it would seem, since some factors which do not vary significantly over short periods of time (hours or days) may vary significantly over longer periods (weeks or months). It is necessary to consider the time periods involved in order to determine which factors to consider random and which to consider "bias" in the system.

For this experiment, the sources of random error are considered to be transmitter timing errors, some meteorological conditions, atmospheric noise, and most receiver errors. Errors caused by long term "bias" of the system are due primarily to ground conductivity and type of surface, some meteorological effects, and any non-random bias in the timing of the transmitters.

Taking these factors into consideration, data taken at the "known" point (Range-7) of the differential system was processed to remove random error by averaging over a period of time, while long term error was removed by comparison of the TD's to their expected values derived from calculations provided by computer computations of the TD at that point.

Errors which may change within the time frame of the experiment were reduced by a linear regression of the trend of data taken at the known point and projected to the correction at the unknown point mathematically.

IV. THREE STATION AND DIFFERENTIAL CORRECTIONS

A. Basic Geometry of Loran-C Hyperbolas

This section provides a summary of the information necessary for the analysis of Loran-C corrections for three secondary stations and for differential Loran-C corrections presented in parts IV.B and IV.C, adapted from Laurilla (Ref.1) and others as noted.

1. Lanewidth

The baseline of a Loran-C master-secondary pair is the shortest path over which the transmitted signals may travel between the master station and the secondary station. On a spherical earth model it is the arc of the great circle through the positions of the master and secondary stations. On an ellipsoid it is the geodesic from the master to the secondary station. In the set of hyperbolas of time difference for the master-secondary pair, the separation between hyperbolas is a minimum constant value along the baseline.

A lane is the distance between two adjacent hyperbolas of unit time difference. The unit normally used is the μsec (10^{-6} sec). In a series of hyperbolas, as shown in Figure II-1, it is obvious that the lanewidth varies with location. At any point, lanewidth can be viewed as the inverse of the gradient of the ratio of the change in time difference to the change in distance (Ref.15), or:

$$L = \{ |(dTD/dl)| \}^{-1} \qquad [IV-1]$$

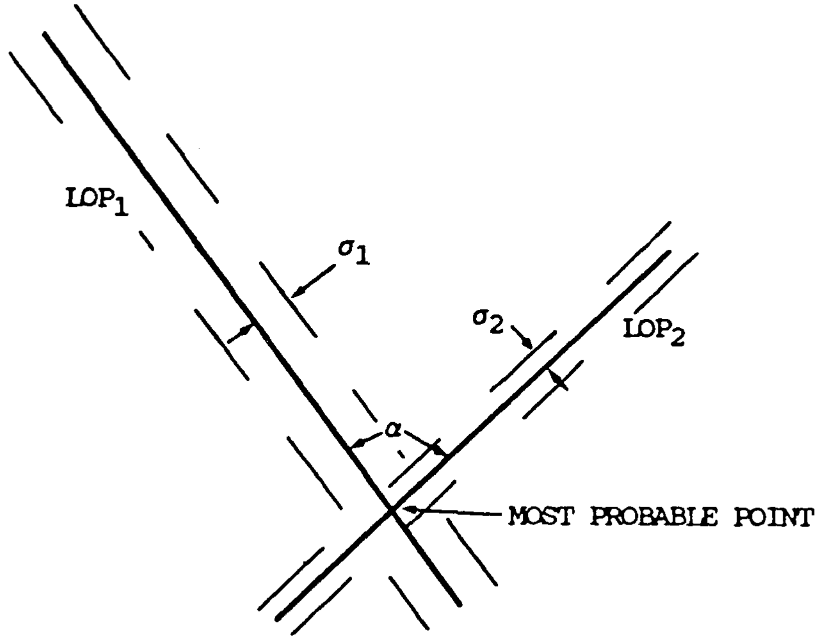

Figure IV-1. Typical intersection of two lines of position. Most probable point is at the intersection of the two LOP's.

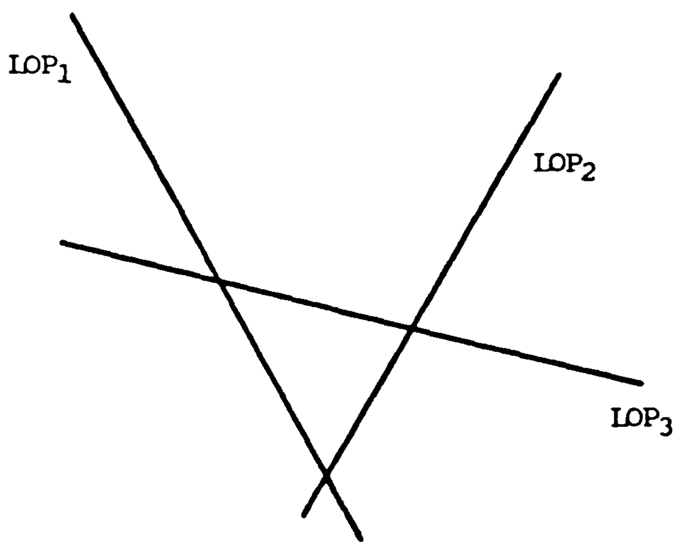

Figure IV-2. Typical intersection of three lines of position. When three or more secondary stations can be received at a geographic position, calculated position depends on the LOP's which are used to make the calculation.

The lanewidth at any point in the set of hyperbolas can be expressed in terms of the lane width on the baseline. Baseline lane width can be expressed by the following equation:

$$L_b = \frac{c}{2} \qquad [IV-2]$$

where:

L_b = Lanewidth on the baseline (meters/μsec)

c = Speed of electromagnetic waves on the baseline (m/μsec) (note that time units are in the unit lanewidth)

Lanewidth at any other point (not on the baseline) can be expressed by equation IV-3a, where β is the angle subtended by the baseline from the point. Note that this angle is the absolute difference between the azimuths from the point to the master and from the point to the secondary station.

$$L = L_b\{\sin(\beta/2)\}^{-1} \qquad [IV-3a]$$

or

$$L = L_b G$$

where:

L = Lanewidth at a point (per unit of time)

L_b = Lanewidth on the baseline (per unit of time)

β = Angle subtended by the baseline from the point

G = The Lane Expansion Factor, $G = \{\sin(\beta/2)\}^{-1}$

Note that the lane expansion factor depends only on the angular separation of the master and the secondary stations. This obviously depends on the distance of the point from the baseline center and the angular separation of the baseline and the vector from the baseline center to the point.

Equation IV-3a provides a means of calculating the normal distance between any two hyperbolas, provided they are near enough that their lanewidths are not significantly different:

$$d = Lt \qquad [IV\text{-}3b]$$

where:

d = distance in meters between the two hyperbolas.

L = lanewidth at the point of interest (in m/μsec).

t = time difference between the two hyperbolas in μsec.

2. Direction of Hyperbola

The direction of a hyperbola at any point on the hyperbola is along the tangent at that point, directed away from the baseline of the master and secondary stations used to define the hyperbola. For applications in this experiment, Laurilla (Ref 1) provides the following useful definition of the direction of a hyperbola: "... the direction of a hyperbola at any point coincides with the bisector of the angle formed by the lines joining the point to the pair of stations." (Ref.1:p.92)

For purposes of this experiment, it is convenient to express the direction of the hyperbola by its azimuth. This azimuth can be expressed in terms of the azimuths (from north) of the master and secondary stations by:

$$\alpha_h = (\alpha_m + \alpha_s)/2 \qquad (\text{where } |\alpha_m - \alpha_s| > 180^\circ) \qquad [IV-4a]$$

$$\alpha_h = 180^\circ + (\alpha_m + \alpha_m)/2 \qquad (\text{where } |\alpha_m - \alpha_s| < 180^\circ) \qquad [IV-4b]$$

where:

α_h = azimuth of the direction of the hyperbola.

α_m and α_s = azimuths of the master and secondary from the point.

3. Applications of Geometry of Hyperbolas to Error Analysis

The geometric description of Loran-C hyperbolas in parts IV.A.1 and IV.A.2 is particularly important in the analysis of error and the derivation of corrections used in this experiment. Some of the direct applications are outlined in the following paragraphs.

The error expressed as an error ellipse requires the directions of hyperbolas in order to determine the orientation of the ellipse. The dimensions of the ellipse require the conversion of variances of time differences of each hyperbola to variances of distance in the major and minor axis of the ellipse. Standard deviations of time differences can be converted to distances by the following equations:

$$\sigma_d = \sigma_t L \qquad [IV-5a]$$

$$\sigma_d^2 = \sigma_t^2 L^2 \qquad [IV-5b]$$

The correction for three secondary stations uses variances in time differences converted to distances as an input, using equation IV-5b. Converting time difference to distance in this way correctly weights the precision of the LOP's when determining the correction factor based on geometric considerations.

B. Correction for Three Secondary Stations

In situations where three secondary stations can be received, the result is three LOP's which do not, in general, intersect at one point (see Figure IV-2) when they are used to calculate the geographic position, although they must in fact intersect at the common point at which the readings were taken concurrently. Under usual navigation conditions the two best LOP's are used to determine a geographic fix. A drawback of this method is that it fails to consider all of the available information (i.e. one of the available lines of position is not used in the calculation of the geographic position). By utilizing all three LOP's it should be possible to improve the accuracy of the geographic fix.

Sections B.1 and B.2 will develop a mathematical adjustment which can be used to calculate the most probable corrected TD readings of a Loran-C receiver used as the fixed receiver in a differential Loran-C system utilizing three LOP's (i.e. receiving the master and three secondary stations). When the correction is applied, the three corrected TD's will intersect at the most probable point, based on long term average values of the TD's. The derivation of this adjustment could take any of several possible forms, but a primary consideration here is the need for a form which is easily applicable to computer processing. Section B.3 describes a method of applying the corrections for non-differential use, using only one receiver and with no known fixed point.

Section B.4 will develop regression equations for calculating the corrected TD's directly from time for use as a differential correction for a remote receiver. Note that the methods developed in these sections are primarily for use in the differential Loran-C computations necessary for this experiment.

1. Geometric Considerations Used to Develop a Correction Factor

The following assumptions are made for this derivation:

- Each LOP has a unique direction (described in Section IV.A.2)
- Long term average TD's (designated $TD1_{av}$, $TD2_{av}$, and $TD3_{av}$) for for the known point are available
- Variances of the TD values (designated σ_1^2, σ_2^2, and σ_3^2) are known or can be calculated
- Variations of TD's from their average values is in the form of a Gaussian distribution
- Over the relatively small area being considered, the surface can be considered a plane and LOP's for the same master-secondary pair can be considered parallel straight lines

Several things should be noted about these assumptions. Long term averaging times for this experiment will be on the order of a few hours during acquisition of data; for purposes of the derivation, standard deviations are converted between time units (μsec) and distance units (m) using Equation IV-5a; and, the assumptions of a

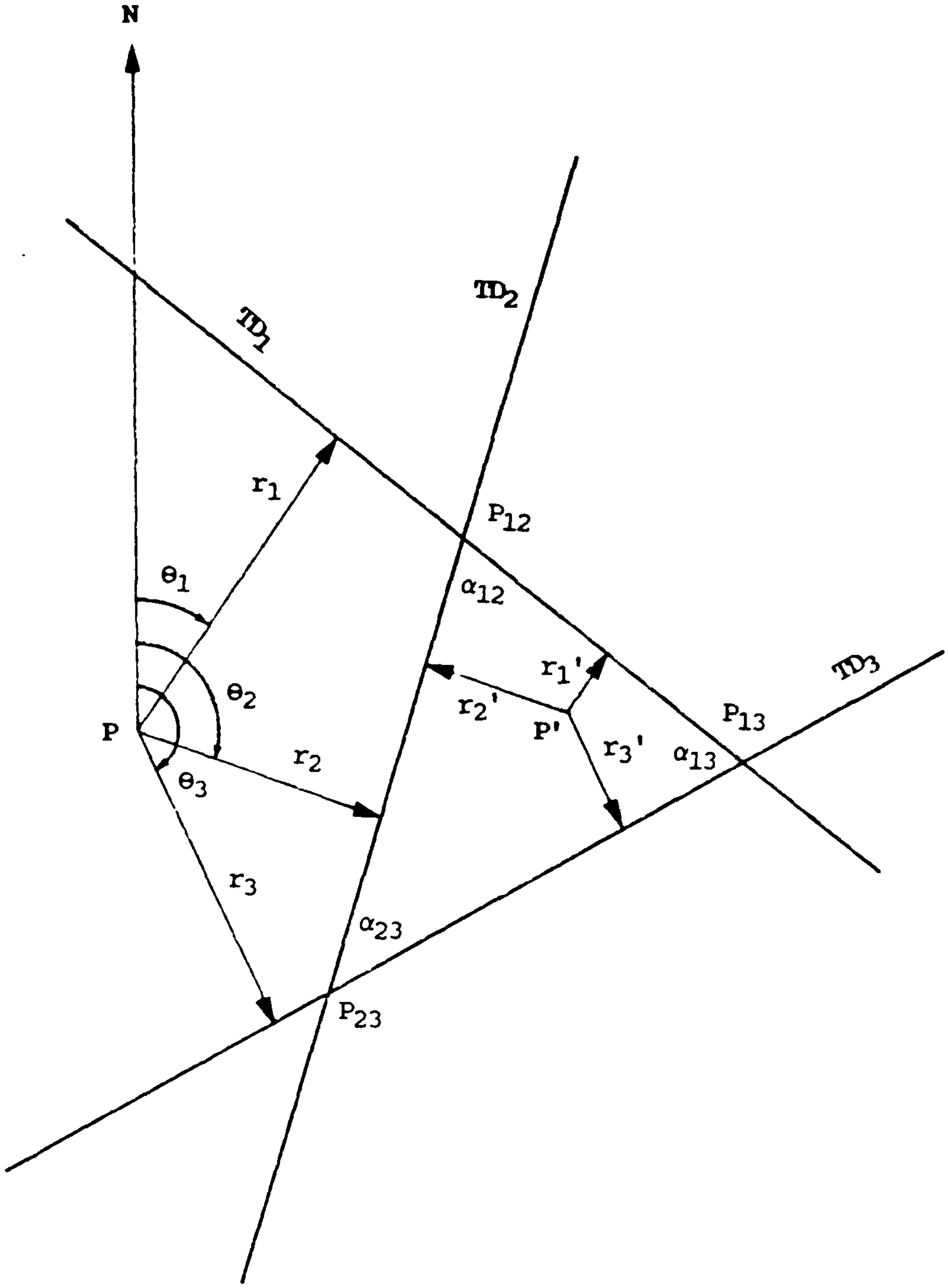

FIGURE IV-3. Geometry used in the derivation of a correction factor for three LOP's not intersecting at the same point.

Gaussian distribution, plane surface, and parallel LOP's are reasonable for this type of data (Ref.6:p.8). When two LOP's with different standard deviations intersect (see Figure IV-1), the point of intersection is the most probable geographic position (Ref.6:p.8-12). The probability of the location of the true position is best described using an error ellipse as described in Section III-B.

A typical situation is shown in Figure 3, a set of three concurrent LOP's intersecting at three different points. Point P is the location of the monitor receiver used to determine differential corrections, with $TD1_{av}$, $TD2_{av}$, and $TD3_{av}$ being the long term average TD values at that known point (note that in figure IV-3, the LOP's of $TD1_{av}$, $TD2_{av}$, and $TD3_{av}$ are not shown, but are parallel to TD_1, TD_2, and TD_3, respectively, and pass through point P, as shown in Figure IV-4). Although the long term average LOP values intersect at point P, triangle $P_{12}P_{13}P_{23}$ represents a triangle of fixes formed by the set of TD values which may occur from any concurrent set of TD's, which are unlikely to equal the long term average. Each set of TD readings (which occurs in the data every few seconds) will result in a new triangle of fixes.

The vectors r_1, r_2, and r_3 represent the difference between the individual TD values in a concurrent set of data and their respective long term TD values. The r vectors are at right angles to both the long term and current LOP's. For example, if the long term average of TD_1 ($TD1_{av}$) is 29939.200 and the value of TD_1 in a set of TD readings currently being considered is 29939.300, the value of r_1 for the current set of TD readings is 0.100 (all in μsec). When converted to meters using equation IV-3b, this is the distance between the average TD values ($LOPi_{av}$) and current TD values (TD_i). These LOP's can be considered as parallel straight lines over the relatively small distances considered for this correction. Note that there are three LOP's in each set of concurrent data representing TD values for three master-secondary pairs. The master station is common to each of these pairs.

Within the triangle of fixes $P_{12}P_{13}P_{23}$ formed by the three LOP's of a set of data, point P' represents the most probable point of the true geographic position indicated by that particular concurrent set of data compared to the long term average data. The distances of P' from each LOP (the lengths r_i') are related to the relative precision of each LOP, P' being closer to LOP's with higher precision (to be discussed in more detail in the next section).

The problem must be solved in general terms so that any set of TD's in the data can be corrected to a new set of TD's which intersect at the most probable point. Since the triangles formed by all sets of data are similar triangles, the lengths of r_1', r_2', and r_3', will have the same proportion for each set. The corresponding r_i' values between sets of data will be related by a common factor, which will be designated as the Correction Factor, k.

Other information which should be noted about Figure IV-3 include the following:

- The following sets of lines can be considered parallel over the area represented by the figure: $TD1_{av} \parallel TD_1$; $TD2_{av} \parallel TD_2$; $TD3_{av} \parallel TD_3$; $r_1 \parallel r_1'$; $r_2 \parallel r_2'$; and $r_3 \parallel r_3'$.

(continued on next page)

- The following sets of lines are perpendicular: r_1 and $r_1' \perp$ $TD1_{av}$ and TD_1 ; r_2 and $r_2' \perp TD2_{av}$ and TD_2 ; r_3 and $r_3' \perp$ $TD3_{av}$ and TD_3.

- The azimuths (from north) of the directions of the LOP's represented by $TD1_{av}$, $TD2_{av}$, and $TD3_{av}$ are α_1, α_2, and α_3, respectively. These are the same as the azimuths of TD_1, TD_2, and TD_3, respectively.

- The following angles of triangle $P_{12}P_{13}P_{23}$ are defined by: $\alpha_{12} = \alpha_2 - \alpha_1$; $\alpha_{13} = \pi/2 - (\alpha_3 - \alpha_1)$; and $\alpha_{23} = \alpha_3 - \alpha_1$. These angles will be the same in the similar triangles formed by any lengths of r_1, r_2, and r_3.

- LOP's 1 and 3 have the largest absolute angle (+ or -) between them, and LOP 2 is the intermediate angle.

The next section will provide a mathematical derivation of the expression for a correction factor to determine the lengths of r_1', r_2', and r_3' and the corresponding time adjustments to TD_1, TD_2, and TD_3, based on the geometry presented in this section.

2. Mathematical Derivation of the Correction Factor

An important question in this analysis is how to weight the relative precision of each LOP in such a way that it can be used in the calculation of a correction factor. Reference 16 shows that for this type of data the "weights are inversely proportional to variance" (Ref.16:p.60), meaning that the lengths of the r_i' corrections should be proportional to the variances (in units of length) of the corresponding TD values for each LOP. Using units of length, in the general solution for all sets of data, the following equation applies:

$$r_i'L_i = k\sigma_t^2 L_i^2 \qquad [IV-6]$$

where:

r_i' = corrections for TD's 1, 2, and 3 (in μsec).

σ_i^2 = variances of TD's 1, 2, and 3 (in μsec^2).

k = the Correction Factor (units are meters)

L_i = lanewidths of TD's 1, 2, and 3 (in $m/\mu sec$).

Note that $\sigma_i^2 L_i^2$ is a unitless weighting factor.

For any triangle there will be some unique value of k which relates the distances from point P' to each LOP to the variances of the LOP's according to equations IV-6. To obtain a general expression for k which can be easily calculated by computer, it will be helpful to use only the known values of the TD's, variances, azimuths, and lanewidths for each LOP. The r values are readily obtained from each set of TD data by subtracting the long term average values from current TD values. Values of σ_i^2 and L_i are constants for this small area.

If each LOP is considered a straight line and a cartesian coordinate system is assumed with north as the +y and east as the +x direction of the coordinate axes, then each LOP can be specified by the general equation for a straight line:

$$y = m_i x + b_i \qquad (i = 1, 2, \text{ or } 3) \qquad [IV\text{-}7]$$

Three such equations can be written (one for each LOP), giving three linear equations in two unknowns, x and y. These equations will not have a common solution when the three LOP's do not intersect at a common point.

For each master-secondary pair, all LOP's of the set will have the same slope (m_i) within the small area being considered (TD_i is parallel to TDi_{av} for any TD_i). The y-intercepts (the b_i's) will be zero for the average LOP's intersecting at point P. Y-intercepts for other LOP's with non-zero r values can be calculated from the relationships between azimuths (denoted α_i) and the r values of each LOP by the following equation:

$$b_i = \frac{r_i}{\cos(\alpha_i - \pi/2)} = \frac{r_i}{\sin \alpha_i} \qquad (i = 1, 2, \text{ or } 3) \qquad [IV\text{-}8]$$

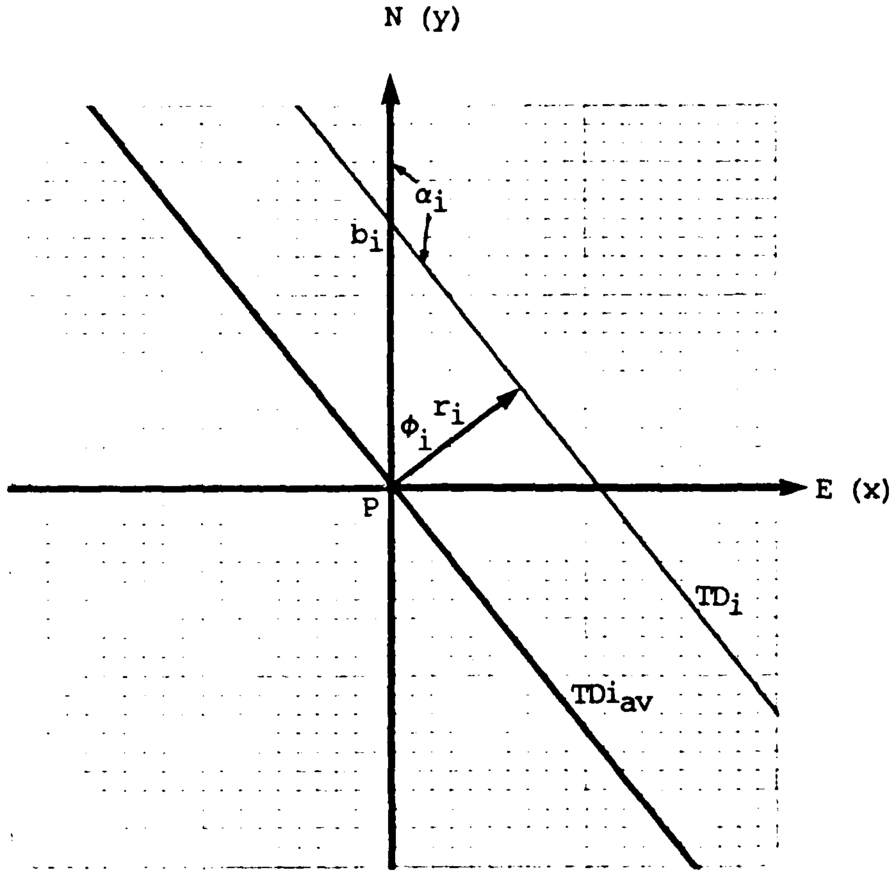

FIGURE IV-4. Typical average LOP through the origin of a cartesian coordinate system and corresponding parallel LOP of an individual TD reading. Slopes are the same for both. Y intercept is the b value in equation for the LOP (zero for the average LOP).

Slopes of the TD's can be expressed in terms of ϕ as:

$$m_i = -\tan \phi_i \qquad [IV-8b]$$

Figure IV-4 shows the assumed coordinate system along with the LOP's for which the slopes and intercepts are described. When corrections are applied, the corrected r values are as follows:

$$r_{iC}L_i = r_iL_i - k\sigma_i{}^2L_i{}^2 \qquad [IV-9]$$

Note that in the equation for corrections (IV-9) the units of $r_{iC}L_i$ are meters. If $\sigma_i{}^2L_i{}^2$ is considered a unitless weighting factor, then the units of k must be meters. This agrees with the units of Equation 13.

The value of r_i is calculated by:

$$r_i = TD_i - TDi_{av} \qquad [IV-10]$$

where:

r_i = deviation of an LOP from the long term average (μsec).

TD_i = time difference reading of a master-secondary pair at point P.

TDi_{av} = long term average of the TD for the same pair at point P.

Figure IV-3 shows that the r_i' corrections must be subtracted from r_1 and r_3, and added to r_2, for the configuration shown. It can be demonstrated that the r_i' corrections are always of the same sign (both + or both -) for the two most widely spaced LOP's and of the opposite sign for the intermediate LOP, where the direction vectors at point P are in the positive directions of increase of TD and the angle is in absolute terms (maximum being 180°). This is true for all positive and negative r values. Positive and negative k values will reverse the signs of all corrections in equations IV-9 so that they will be correct for all configurations.

The corrected r values of equations IV-9 can be substituted into equations IV-8, providing a set of y-intercepts (the b_i values in the set of general equations IV-7) for the corrected LOP's which intersect at point P'. These intercepts contain the unknown Correction Factor k. Note that the slopes of the corrected LOP's are equal to those of the corresponding uncorrected LOP's, meaning that the m_i values in equations IV-7 are unchanged.

Substituting the corrected y-intercept (b_i) values into equations IV-7 results in three linear equations in three unknowns: x, y, and k:

$$y = (-\tan \phi_1)x + \frac{r_1L_1 - k\sigma_1{}^2L_1{}^2}{\cos \phi_1} \qquad [IV\text{-}11a]$$

$$y = (-\tan \phi_2)x + \frac{r_2L_2 + k\sigma_2{}^2L_2{}^2}{\cos \phi_2} \qquad [IV\text{-}11b]$$

$$y = (-\tan \phi_3)x + \frac{r_3L^3 - k\sigma_3{}^2L_3{}^2}{\cos \phi_3} \qquad [IV\text{-}11c]$$

Equations IV-11 can be rewritten as the following set of linear equation in the unknowns x, y, and k:

$$(\tan \phi_1)x + y + \left(\frac{\sigma_1{}^2 L_1{}^2}{\cos \phi_1}\right)k = \frac{r_1 L_1}{\cos \phi_1} \qquad [IV-12a]$$

$$(\tan \phi_2)x + y - \left(\frac{\sigma_2{}^2 L_2{}^2}{\cos \phi_2}\right)k = \frac{r_2 L_2}{\cos \phi_2} \qquad [IV-12b]$$

$$(\tan \phi_3)x + y + \left(\frac{\sigma_3{}^2 L_3{}^2}{\cos \phi_3}\right)k = \frac{r_3 L_3}{\cos \phi_3} \qquad [IV-12c]$$

Solving equations IV-12 by Gaussian elimination gives the following general expression for the Correction Factor k:

$$k = \frac{L_1 r_1 \dfrac{\tan \phi_3 - \tan \phi_2}{\cos \phi_1} - L_2 r_2 \dfrac{\tan \phi_3 - \tan \alpha_1}{\cos \phi_2} + L_3 r_3 \dfrac{\tan \phi_2 - \tan \phi_1}{\cos \phi_3}}{L_1{}^2 \sigma_1{}^2 \dfrac{\tan \phi_3 - \tan \phi_2}{\cos \phi_1} + L_2{}^2 \sigma_2{}^2 \dfrac{\tan \phi_3 - \tan \phi_1}{\cos \phi_2} + L_3{}^2 \sigma_3{}^2 \dfrac{\tan \phi_2 - \tan \phi_1}{\cos \phi_3}}$$

[IV-13]

where:

r_i = differences from average TD's (μsec).

k = Correction Factor for three master secondary pairs (m).

ϕ_i = directions of increasing TD (azimuth from north).

$\sigma_i{}^2$ = variances of LOP's (part of unitless weighting factor).

L_i = lanewidths (in meters/μsec)

Note that $L_i{}^2 \sigma_i{}^2$ terms in denominator are unitless weighting factors.

Equation IV-13 may be simplified by the following substitutions:

$$A_1 = L_1(\tan\phi_3 - \tan\phi_2)/(\cos\phi_1) \qquad [IV-14a]$$

$$A_2 = L_2(\tan\phi_3 - \tan\phi_1)/(\cos\phi_2) \qquad [IV-14b]$$

$$A_3 = L_3(\tan\phi_2 - \tan\phi_1)/(\cos\phi_3) \qquad [IV-14c]$$

$$A_4 = L_1\sigma_1{}^2A_1 + L_2\sigma_2{}^2A_2 + L_3\sigma_3{}^2A3 \qquad [IV-14d]$$

Resulting in the following equation for k:

$$k = (A_1r_1 - A_2r_2 + A_3r_3)/A_4 \qquad [IV-15]$$

The x and y coordinates of point P' can be calculated by:

$$x = \frac{r_1\cos\phi_2 - r_2\cos\phi_1 - k\sigma_1{}^2\cos\phi_1 - k\sigma_2{}^2\cos\phi_2}{(\cos\phi_1)(\cos\phi_2)(\tan\phi_2 - \tan\phi_1)} \qquad [IV-16]$$

$$y = -(\tan\alpha_1)x + (r_1 - \sigma_1{}^2k)/(\cos\phi_1) \qquad [IV-17]$$

Two other useful parameters can be calculated from the values of x and y. These are the azimuth and range of the of point P' from point P. These are given by the following:

Azimuth (from north):

$$\alpha_{PP'} = \pi/2 - \tan^{-1}(y/x) \qquad (x > 0) \qquad [IV-18a]$$

$$\alpha_{PP'} = 3\pi/2 - \tan^{-1}(y/x) \qquad (x < 0) \qquad [IV-18b]$$

Note: when x=0 the azimuth is zero for positive y and π for negative y

Range(P to P'): $$R_{PP'} = (x^2 + y^2)^{\frac{1}{2}} \qquad [IV-19]$$

Using the computed value of k for a set of concurrent TD data, a correction can be made to the TD values using equations IV-9. Since IV-9 is in meters it must be converted to μsec using equation IV-3b. The resulting corrected TD's will intersect at the point P'.

Equations IV-15, IV-16, and IV-17 do meet the requirements stated at the beginning of this section. The inputs are limited to azimuths, variances, long term average TD values, and concurrent TD data, and the values of k, x, y, and the corrected TD values can be computed directly from these by equations which can be calculated easily by a computer.

3. Non-Differential Correction for Three Secondary Stations

When using the method of Section IV.B.2 with a single Loran-C receiver (i.e. not using differential methods) a correction can be calculated based on existing computer programs. While not used in this experiment, the method of correction will be outlined in this section.

Since variation from a known point cannot be used, the two best LOP's can be used as the basis for this calculation. While not as good as using a known fixed survey point, this will provide a correction based on three LOP's. The method is outlined below:

1. Using the two LOP's with the best fix accuracy (available from existing computer programs), calculate the geographic position of the point of intersection. This corresponds to point P.

2. From the geographic position of P, calculate the TD of the third master-secondary pair (the one not used in the previous step).

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3. Using point P calculate the azimuths (from north) of the LOP's. Number the TD's as described in the previous sections, with the intermediate TD as TD_2 and the TD's with the greatest angular separation as TD_1 and TD_3.

4. Use TD variances calculated over short time periods in the general area, or use the values of meters/microsecond calculated using equation IV-3 as the approximate weights of each LOP. Substitute these for the σ^2 values in equation IV-13.

5. Assume r values of zero for the LOP's with the best fix accuracy used in step one.

6. Calculate the difference between the observed third TD and the calculated value obtained in step 2. Use this for the third r value.

7. Calculate corrected r values as in the previous sections.

8. Using any two corrected TD's, calculate geographic position. This is the position corrected for three secondary stations.

Note that all of the above calculations are based on computer methods and programs already in use (Ref. 2) allowing corrected positions to be calculated readily using the method outlined.

C. Differential Corrections

One of the main objectives of this experiment is to apply differential corrections obtained at a known point to time difference data taken at unknown points. One problem encountered was the availability of only one Loran-C monitor receiver, making simultaneous data collection at two points impossible. Differential Loran-C does not require continuous updating of the differential correction for general navigation purposes (hourly or daily corrections are possible), but the need for the most accurate corrections possible for the experiment required a continuous update of the correction.

1. Mathematical Description of the Differential Correction

Data from the experiment consisted of a series of readings at each point. Data was recorded at intervals of 5.0 seconds for much of the experiment, although other time intervals were also used. Data consisted of time versus TD for up to four possible master-secondary pairs and the signal to noise ratios for each, in the following format:

Time (GMT) GRI TD_1 TD_2 TD_3 TD_4 S/N_1 S/N_2 S/N_3 S/N_4

Only three master-secondary pairs were receivable in the area of the experiment. One survey point (Range 7) was designated the "known" point, from which differential corrections were calculated for data taken at the other points. Over a period of several days, data was collected at the known point for periods of 20 to 30 minutes at irregular intervals spaced at about one to three hours (data was collected at the other points in the intervening periods as described in Section A.2).

To provide estimates of the continuous TD readings at the fixed point during all time periods (including the periods between data collection at that point), a least squares curve fitting process is used. The result is three equations: TD as a function of time, for each master-secondary pair.

These three equations can be used to provide an estimate of the TD values at the fixed point at any time. The difference between the calculated TD at a certain time and the long term average TD is the Differential Correction at that time. The ASF corrections at the fixed point and an estimate of the ASF correction at the unknown point (as described in Section II-B) also enter into the Differential Correction at the unknown point. An equation is written for each LOP:

$$C_d = TD_c - TD_{av} + (ASF_u - ASF_f) \qquad [IV-20]$$

where:

C_d = Differential Correction at the unknown point.

TD_c = TD (at known point) calculated from regression equation.

TD_{av} = Long term average TD at the known point.

ASF = ASF correction at the known and unknown points.

2. Least Squares Regression Equations for Time Difference

Linear regression equations for each TD can be written in the following form (Ref.17):

$$TD = b_0 + b_1 t \qquad [IV-21]$$

The b_i coefficients of the regression equation can be found by solving the following set of linear equations:

$$\begin{aligned} nb_0 + b_1\Sigma t_i &= \Sigma TD_i \\ b_0\Sigma t_i + b_1\Sigma t_i^2 &= \Sigma t_i TD_i \end{aligned} \qquad [IV-22a]$$

An alternate method of calculating the b_i values directly is:

$$\begin{aligned} b_1 &= \frac{n\Sigma t_i TD_i - (\Sigma t_i)(\Sigma TD_i)}{n\Sigma t_i^2 - (\Sigma t_i)^2} \\ b_0 &= \frac{\Sigma TD_i}{n} - b_1 \frac{\Sigma TD_i}{n} \end{aligned} \qquad [IV-22b]$$

In equations IV-22, Σt_i, $\Sigma t_i TD_i$, etc., refers to the sum of the time values, the sum of the products of time and time difference values, etc., for the whole set of data available at the fixed point. The total number of sets of TD vs t data is n.

V. RESULTS AND CONCLUSIONS

Part A of this chapter presents the results of calculations based on the theoretical principles previously discussed and data obtained from the experiment. Part B provides a summary of the results obtained, how these results differ from what would be expected based on the theory, possible reasons for any variations from expected outcome, and a general conclusion.

A. Calculations

1. Azimuths, Directions of Hyperbolas, and Directions of TD's

Azimuths of the Loran-C stations from the survey points are one of the basic requirements of several calculations used in this experiment. Station positions of Range-7 and Luces Point (the primary stations used in this experiment) and other points were obtained from Horizontal Control Data published by the U.S. Dept. of Commerce, Coast and Geodetic Survey (see Appendix A). Station positions of the Loran-C transmitters were obtained from Loran-C Data Sheets provided by the Defense Mapping Agency, Hydrographic/Topographic Center (see Appendix B). For convenience in avoiding datum conversion, the North American Datum 1927 (NAD 27) was used because published positions based on this datum were available for all of the station positions used in the experiment. Station positions are summarized in Table V-1.

Azimuths: Azimuths from Range-7 and Luces Point to Loran-C stations 9940-M, W, X, and Y were calculated using a Fortran 77 subroutine provided by DMAHTC (Appendix C). Operation of the program was checked using known data points and azimuths. Results of these computations are presented in tabular form in Table V-2. For convenience in visualizing the angular relation- ships, results are also presented in graphic form in Figures V-1a and V-2a.

Directions of Hyperbolas: The directions of hyperbolas for 9940-W, X, and Y were calculated using equations IV-4 and the azimuths obtained as described in the previous paragraph. A sample calculation follows:

Hyperbola Direction for 9940-X at Range-7:

$$HD_{R7} = \frac{(\text{Azimuth of 9940-X}) + (\text{Azimuth of 9940-M})}{2}$$

$$= \frac{343.071686 + 38.358551}{2} = 190.715118^\circ$$

(from North)

Decimal degrees are used in the calculations for convenience. Results of the calculations are again presented in Figures V-1b and 2b.

Direction of Increase of TD: Directions of increasing TD are at right angles to the hyperbola directions and increase in the direction of hyperbolas which approach the master station. This involves either adding or subtracting 90° from the direction of the hyperbolas. For checking purposes, a Loran-C chart of the area was used. Results are again presented in Figures V-1 and 2.

TABLE V-1. Station Positions (NAD 27).

Station	Latitude	Longitude
Range 7	36° 39' 02.47787" N	121° 49' 08.58202" W
Luces Point	36° 38' 10.524" N	121° 55' 38.399" W
9940-M	39° 33' 07.046" N	118° 49' 52.241" W
9940-W	47° 03' 48.594" N	119° 49' 52.241" W
9940-X	38° 46' 57.472" N	122° 29' 40.050" W
9940-Y	35° 19' 18.342" N	114° 48' 13.946" W

TABLE V-2. Azimuths From Range-7 and Luces Point.

Range-7 to	Degrees,min,sec.	Decimal Degrees
9940-M	38° 21' 30.784"	38.358551°
9940-W	7° 32' 22.823"	7.539673°
9940-X	343° 04' 18.070"	343.071686°
9940-Y	101° 47' 36.229"	101.793397°
Luces Point to		
9940-M	38° 51' 08.262"	38.852295°
9940-W	7° 45' 43.837"	7.762177°
9940-X	344° 23' 49.981"	344.397217°
9940-Y	101° 36' 16.319"	101.604533°

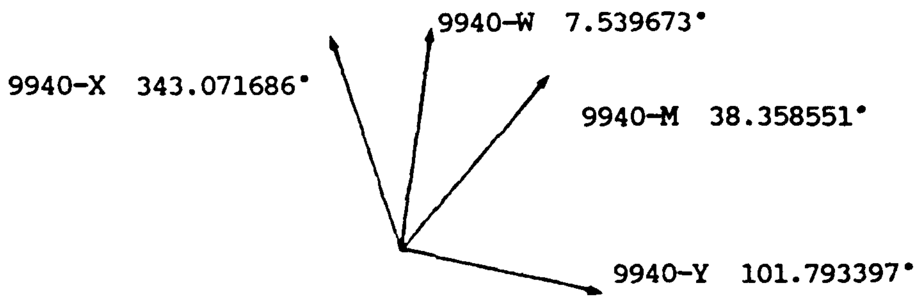

FIGURE V-1a. Azimuths From Range-7 to 9940-M,W.X,and Y.

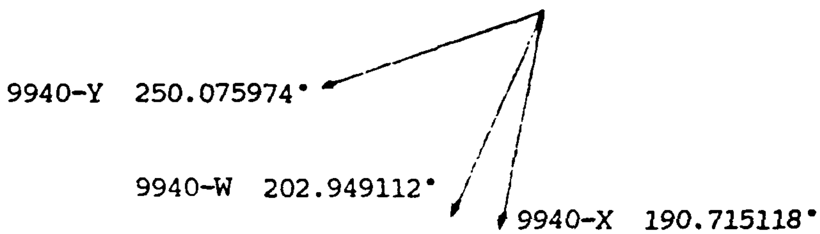

FIGURE V-1b. Directions of Hyperbolas at Range-7.

FIGURE V-1c. Directions of Maximum Increase (Gradient) of TD's at R-7.

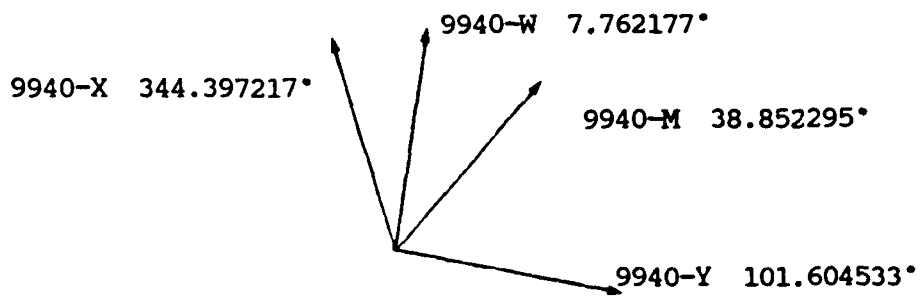

FIGURE V-2a. Azimuths From Luces Point to 9940-M,W.X,and Y.

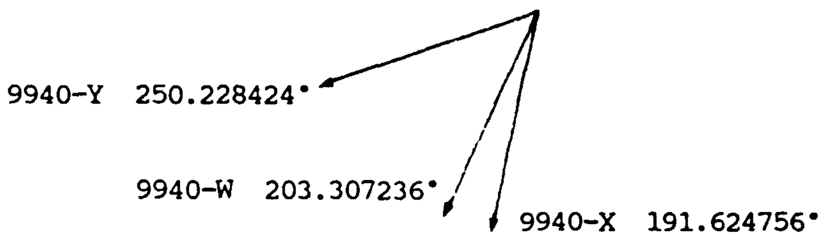

FIGURE V-2b. Directions of Hyperbolas at Luces Point.

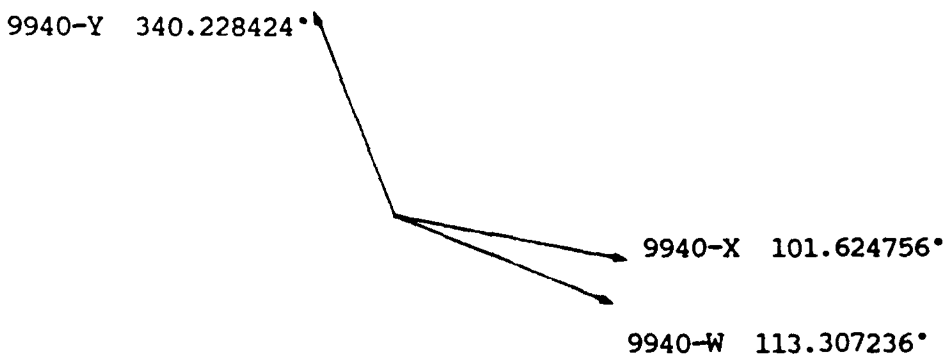

FIGURE V-2c. Directions of Maximum Increase (Gradient) of TD's at LP.

2. Lanewidths

Lanewidths were calculated from Equation IV-3a using the azimuths computed in Section V-A-1. Note that the units of lanewidth are m/μsec. With a standard lane of 1 μsec the width of a lane is the same number in meters. Velocity of transmission was calculated using c and the index of refraction specified in the table of Loran-C constants supplied by the Defense Mapping Agency (Ref. 4). Sample calculations of lanewidth follow:

$$\text{Velocity of Transmission} = \frac{c}{n} \qquad [V-1]$$

$$= \frac{2.99792453 \times 10^8 \text{ m/sec}}{1.000338}$$

$$= 2.996911624 \times 10^8 \text{ m/sec}$$

Lanewidth of 9940-Y at Range-7 for standard 1 μsec lane:

$$L_{R7} = \frac{(10^{-6}\text{sec})(2.996911624 \times 10^8 \text{ m/sec})}{2 \sin \dfrac{101.793397^\circ - 38.358551^\circ}{2}}$$

$$= 285.024 \text{ m}$$

Results of the calculation of lanewidths are given as the L values in Table V-3. In the table, L_1, L_2, and L_3 correspond to the lanewidths for 9940-W, X, and Y, respectively.

3. Average TD's, Standard Deviations, Variances

Because of the large amount of data involved, it was necessary to compute statistical information using a computer program. Since data was in the form of three TD's (one for each master-secondary pair) every five seconds, and readings were taken for periods of 20 to 40 minutes at each station, a Fortran 77 program with subroutines for statistical information was written (see Appendix C).

Station Range-7 was the "known" station of the differential system, at which more readings were taken than any other. For this reason, and because regression equations of TD vs Time were needed only at that station, statistical information was calculated only for station Range-7.

Mean of the TD's was computed by the following (Ref. 18):

$$\text{Mean TD} = \frac{\Sigma TD_i}{n} \qquad [V-2]$$

Variances of the TD's were calculated using the following (Ref. 18):

$$s^2 = \frac{\Sigma TD_i^2 - (\Sigma TD_i)^2/N}{N - 1} \qquad [V-3]$$

Standard deviations were calculated from variances by (Ref. 18):

formula (Ref.18):

$$s = (s^2)^{\frac{1}{2}} \qquad [V-4]$$

Equations V-2, V-3, and V-4 were incorporated into a Fortran 77 computer program which was used to calculate statistics of TD's for 9940-W, X, and Y.

It should be noted that these statistics were in terms of time differences, while in some cases it was necessary to know standard deviations and variances in terms of distances. Equations IV-5 were used for this conversion where necessary.

Corrected vs Uncorrected Data: One use of the statistics of the data was to compare the standard deviation of raw data to the standard deviation of data which was corrected for three secondary stations. It was considered unlikely that the three station correction could remove bias from the TD readings (error in terms of absolute position) because most of this is due to systematic error rather than random variations. It was believed that the three station correction would be most effective in reducing the effect of random variations in time differences. The statistics on uncorrected and corrected data show results consistent with this expectation (Table V-7).

4. Error Ellipse and Circular Error at Range-7

Range-7 was used as the known point of the differential system, and a larger amount of data was collected at that point. Using the crossing angles, standard deviations and variances of 9940-X and Y (the best pair at that point), dimensions and orientation of the standard error ellipse and CEP 50% and 90% circle radii were calculated for the point using the information outlined in section III-B.

The standard error ellipse and error circles for 50% and 90% were plotted over a scatter plot of data from Range-7. The result is shown in Figure V-3.

Calculations of the standard error ellipse dimensions were as follows:

Using 9940-X,Y:

$$\sigma_1 = \sigma_{9940-Y} = (0.072546)(285.024) = 20.677 \text{ m}$$

$$\sigma_2 = \sigma_{9940-X} = (0.068638)(322.024) = 22.103 \text{ m}$$

$$\phi = 250.075974° - 190.715118° = 59.360856°$$

Calculating the semi-major and semi-minor axes of the ellipse:

$$\sigma_x^2 = \frac{20.677^2+22.103^2+((20.677^2+22.103^2)^2-4(20.677^{22}2.103^2\sin^2\phi))^{\frac{1}{2}}}{2\sin^2\phi}$$

$$\sigma_x = 30.595 \text{ m}$$

$$\sigma_y^2 = \frac{20.677^2+22.103^2-((20.677^2+22.103^2)^2-4(20.677^{22}2.103^2\sin^2\phi))^{\frac{1}{2}}}{2\sin^2\phi}$$

$$\sigma_y = 17.362 \text{ m}$$

Orientation of the major axis of the ellipse:

$$\tan 2\theta = \frac{20.677^2\sin 2(59.360856°)}{20.677^2 \cos 2(59.360856°) + 22.103^2}$$

$$\theta = 26.474268°$$

Azimuth of major axis = 250.075974° - 26.474268 = 223.601716°

= 223.601716° - 180° = 43.601716° (from North)

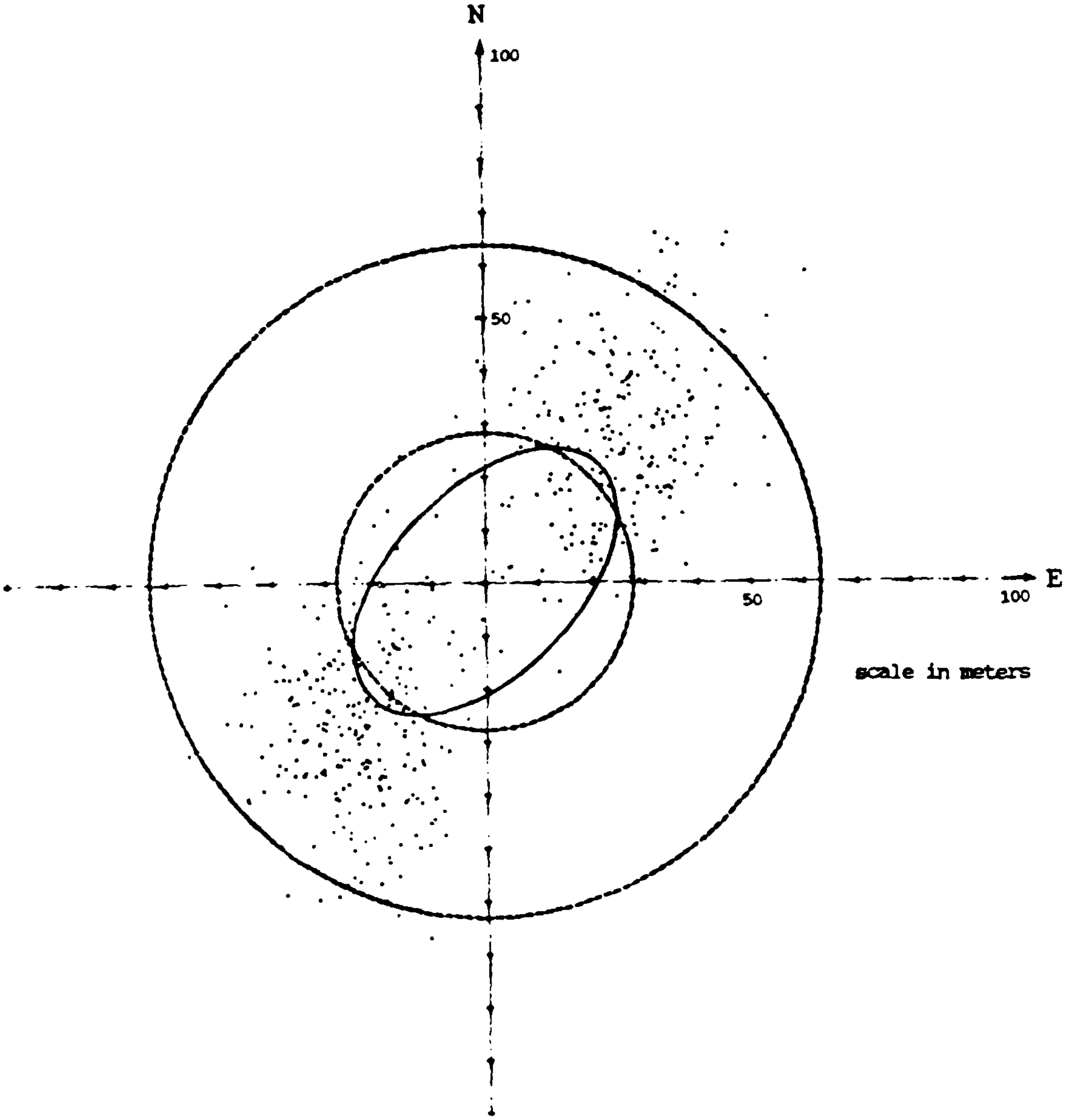

Figure V-3. Scatter Diagram, Standard Error Ellipse, and CEP_{50} and CEP_{90} Error Circles, for Range-7 Data (see text for details).

Using tables in Reference 6, pp.18-20, radii of the 50% and 90% error circles were calculated as:

$$CEP_{50} = 27.936 \text{ m} \qquad CEP_{90} = 63.226 \text{ m}$$

Because the data included in the plot of Figure V-3 includes two intervals of data collection, the points are not as evenly distributed as they would otherwise be. For this reason there are fewer points near the center of the plot than would normally be the case. The error circles and ellipse seem to be reasonably correct for the given data.

5. Correction Factor for Three Secondary Stations

The correction for three secondary stations was designed as a technique to reduce the random error associated with time difference data. It was expected to increase the precision of the position rather than the absolute position.

For a variety of reasons there will be some covariance between concurrent time difference readings from different master-secondary pairs. The correction for three secondary stations is not expected to reduce the error associated with this type of random error. The non-correlated random error in TD readings should be reduced by this correction to some extent.

In order to reduce the number of computations and the time required to process data, most constant factors associated with the correction factor can be computed in advance and used as constants in the computer program. This reduces the correction to only a few lines of relatively simple computation. Because of the large amount of data, this reduces significantly the time required to compute corrections.

In the calculations of adjustments to positions of Range-7 and Luces Point, the only factors which differ significantly are the long term time differences at the two points. In this case the same A_i factors can be used for correcting both positions for three secondary stations. In cases where some of the parameters may differ significantly, it would be necessary to calculate different A_i factors for each position. Table V-3 gives parameters for input to the Fortran 77 correction program for calculation of the A_i parameters and calculation of the corrections to data.

TABLE V-3. Parameters used in calculation of correction factor k.

Parameter	Value
ϕ_1	112.949112°
ϕ_2	100.715118°
ϕ_3	340.075974°
σ_1	0.150606 μsec
σ_2	0.068638 μsec
σ_3	0.072546 μsec
L_1	563.934 m/μsec
L_2	322.966 m/μsec
L_3	285.024 m/μsec

6. Regression Equations for Time Difference vs Time

Since only one Loran-C monitor receiver was available, it was necessary to develop a method of estimating TD's at the known point during times when differential corrections were required at the unknown points. Linear regression equations of TD vs time were used for this purpose.

Using equations IV-21 and IV-22, the data from Range-7 was processed to obtain the required summations of time and time difference necessary to calculate the b_0 and b_1 coefficients of the linear regression equation. Only Range-7 data from the nearest time periods before and after the differential correction period for Luces Point data were used.

The procedure for processing the data was first to apply the correction for three secondary stations to the Range-7 and Luces Point data during the time periods of interest. Range-7 data was then processed to obtain the necessary summations for the calculation of the b parameters of the regression equations. Using the regression equations for Range-7 data and long term TD averages at the two points, differential corrections for the Luces Point data were calculated as described (Section V-7). Fortran subroutines (Appendix C) were added added to the statistics program to obtain the summations and a separate program was used for the differential correction of Luces Point data. Results of the corrections were compared to calculated values of TD's provided by the Defense Mapping Agency, Hydrographic/Topographic Center. TD vs time is plotted in Figures V-4 along with the regression line for the data. Regression equations are in Table V-4.

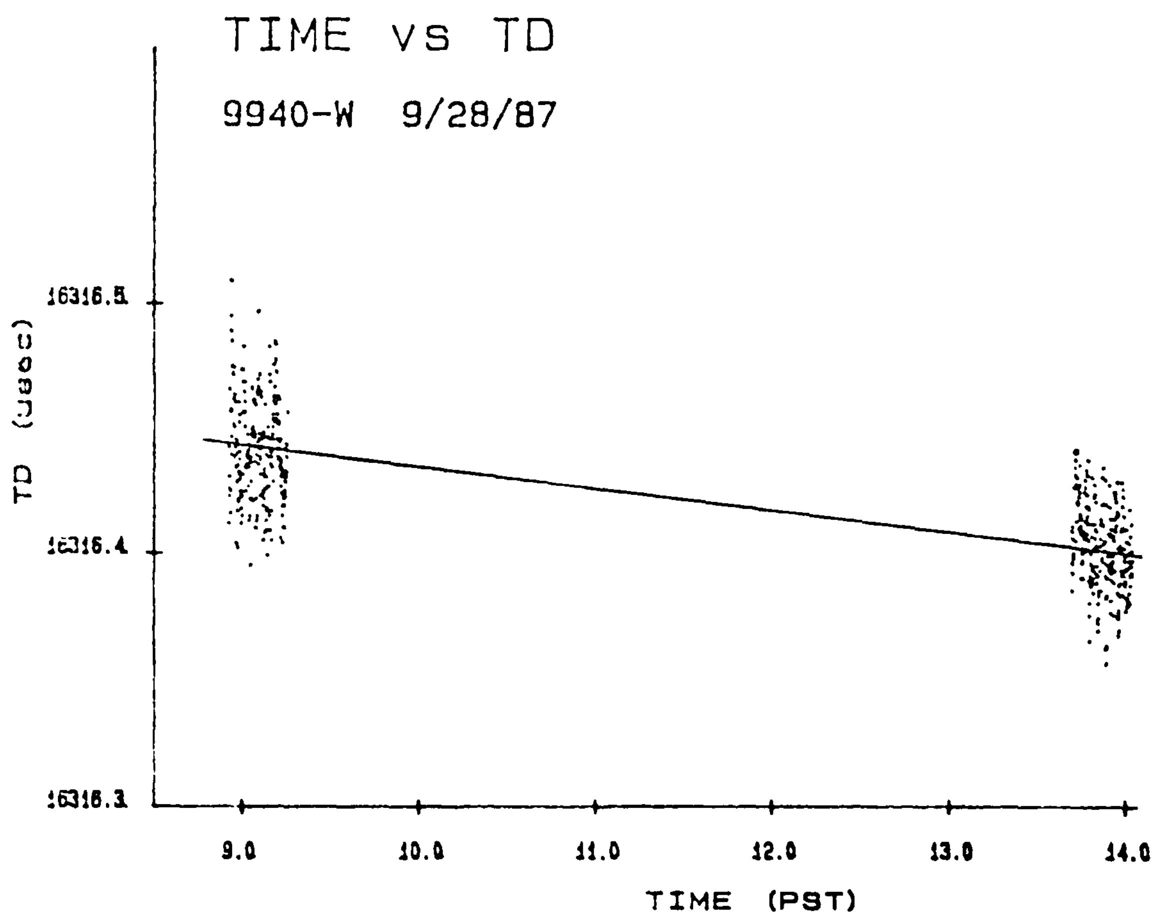

Figure V-4a. TD vs time and the regression line for 9940-W for Range-7 data corrected for three secondary stations.

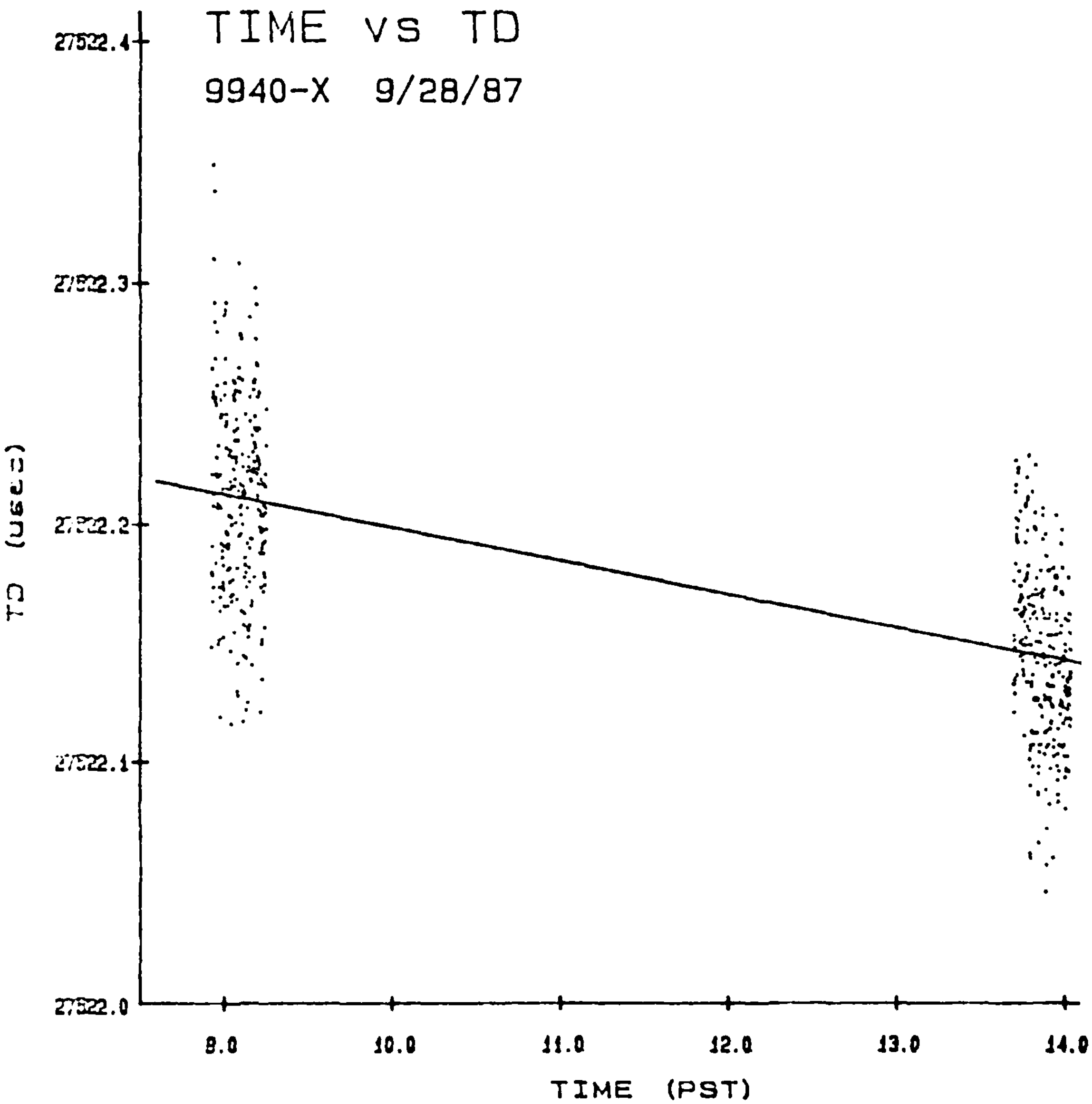

Figure V-4b. TD vs time and the regression line for 9940-X for Range-7 data corrected for three secondary stations.

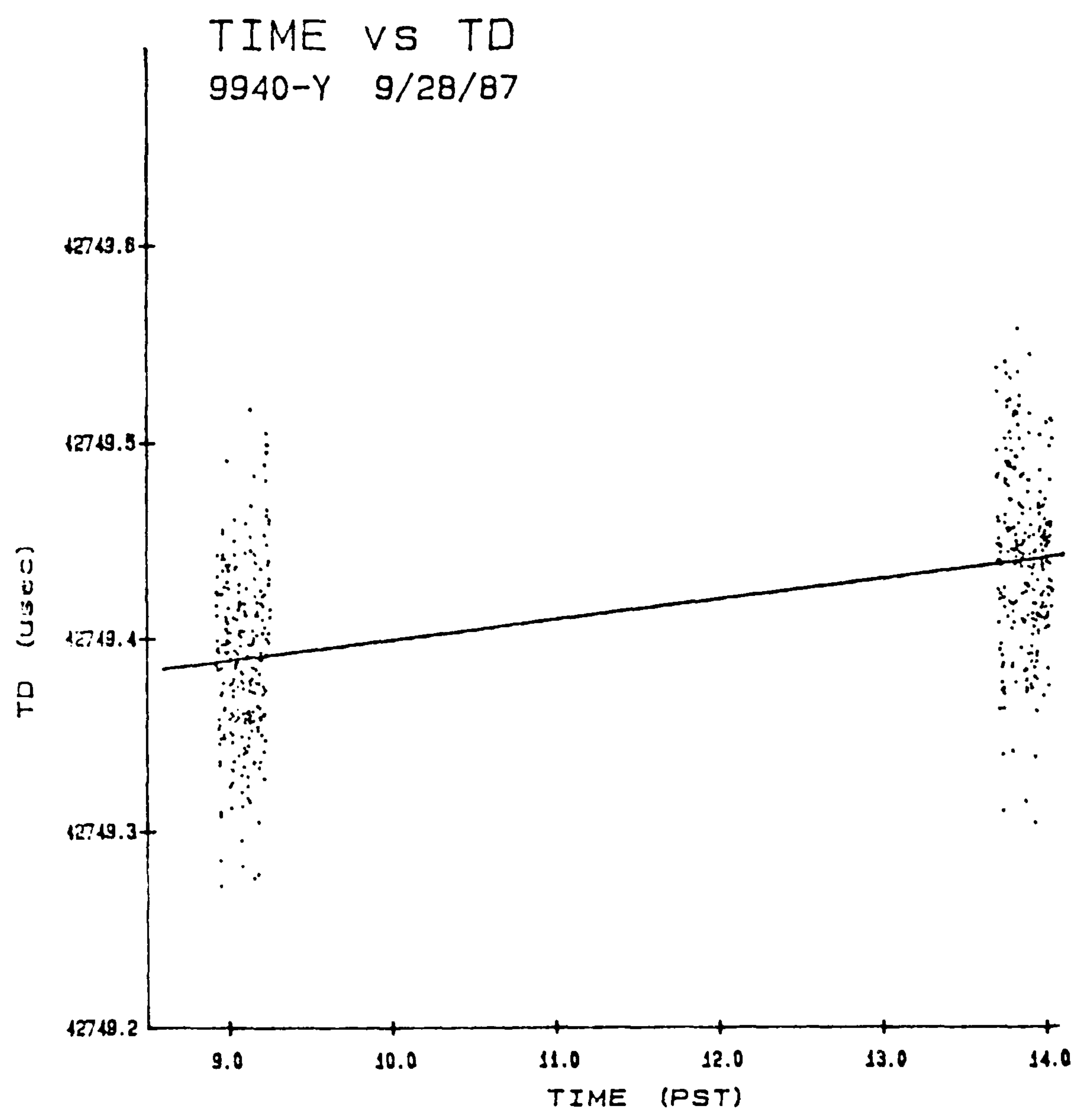

Figure V-4c. TD vs time and the regression line for 9940-Y for Range-7 data corrected for three secondary stations.

TABLE V-4. Regression Equations of TD vs Time at Range-7.

9940-W:	TD_W	=	16316.51564	-	0.00807243t
9940-X:	TD_X	=	27522.33725	-	0.01385199t
9940-Y:	TD_Y	=	42749.29371	+	0.01056707t

time units: hours with minutes and seconds in decimal hours.

7. Differential Corrections

Equation IV-20 describes the differential correction which is applied to TD readings at an unknown point based on TD's at a known point. In this experiment the positions of all points are known, based on their published positions from survey data (see appendices). One point, Range-7, was chosen as the known point for purposes of differential corrections. Data from one other point was chosen as the unknown point for purposes of comparison to its known position.

Three things must be known to calculate a differential correction based on equation IV-20. Rather than use long term averages in this equation, the expected TD's at both points were computed by a standard Loran-C program. Current TD's at Range-7 were calculated from the regression equations described in the last section. The ASF corrections in equation IV-20 were calculated for each point by the Defense Mapping Agency using a computer program which is used in the preparation of ASF correction tables, but which can be used for determining the correction at individual points. The difference in ASF corrections is used in equation IV-20. Table V-5 gives expected TD values (used as long term averages) at the two points of interest:

TABLE V-5. Calculated TD's used as long term averages (in μsec).

	Range-7	Luces Point
9940-W	16314.68	16300.09
9940-X	27523.13	27496.79
9940-Y	42749.49	42755.87

ASF corrections were approximately the same at both points due to the nearness of the points. Differences in ASF corrections used in equation IV-20 were very small: 0.005, 0.002, and 0.003 μsec for 9940-W, X, and Y, respectively. Corrections of this magnitude are probably less than the accuracy of the data used to calculate them, but at longer ranges these may be large enough to be significant.

The final equation for the differential corrections based on TD's at Range-7 are in Table V-6. Note that t is Pacific Standard Time in hours, with minutes and seconds expressed as a decimal.

TABLE V-6. Differential Corrections (C_d in μsec, t in hours PST)

$$C_{dw} = -1.83064 + 0.00807243t$$

$$C_{dx} = 0.79575 + 0.01385199t$$

$$C_{dy} = 0.19829 - 0.01056707t$$

8. Accuracy of Position Fix

Figure V-5a shows a plot of uncorrected Range-7 data based on expected TD's calculated from the known geographic position. The grid is in meters, oriented north-south and east-west, and with the center at the published geographic position of Range-7. When the Correction For Three Secondary Stations is applied and the average of the Range-7 data is placed at the origin, the result is as shown in Figure V-5b.

Note that the plot is now centered on the origin due to the fact that all absolute error (bias) has been removed from the data. The three station correction has also decreased the standard deviation and variance of the Range-7 data as shown in Table V-7.

Figure V-6a shows Luces Point data before application of any corrections. These points are plotted based on the expected TD's at the known coordinates of the point. The center of the uncorrected Luces Point data is at x = 375.820 m, y = 85.501 m, and at a range of 385.423 m and at an azimuth of 77.183° (from North) from the origin. Radii of the CEP_{50} and CEP_{90} error circles are 14.9 m and 28.4 m, respectively.

Figure V-6b shows Luces Point data after the application of both three station and differential corrections. Again, the origin is at the known position of the point. For visual comparison purposes, the same scale is used for both Figures V-6a and b. For the corrected data, the center of the data is at x = 47.213 m and y = -7.015 m, with a range of 47.731 m and at an azimuth of 98.451° (from North) from the origin. CEP_{50} and CEP_{90} radii were 12.6 m and 26.0 m, respectively.

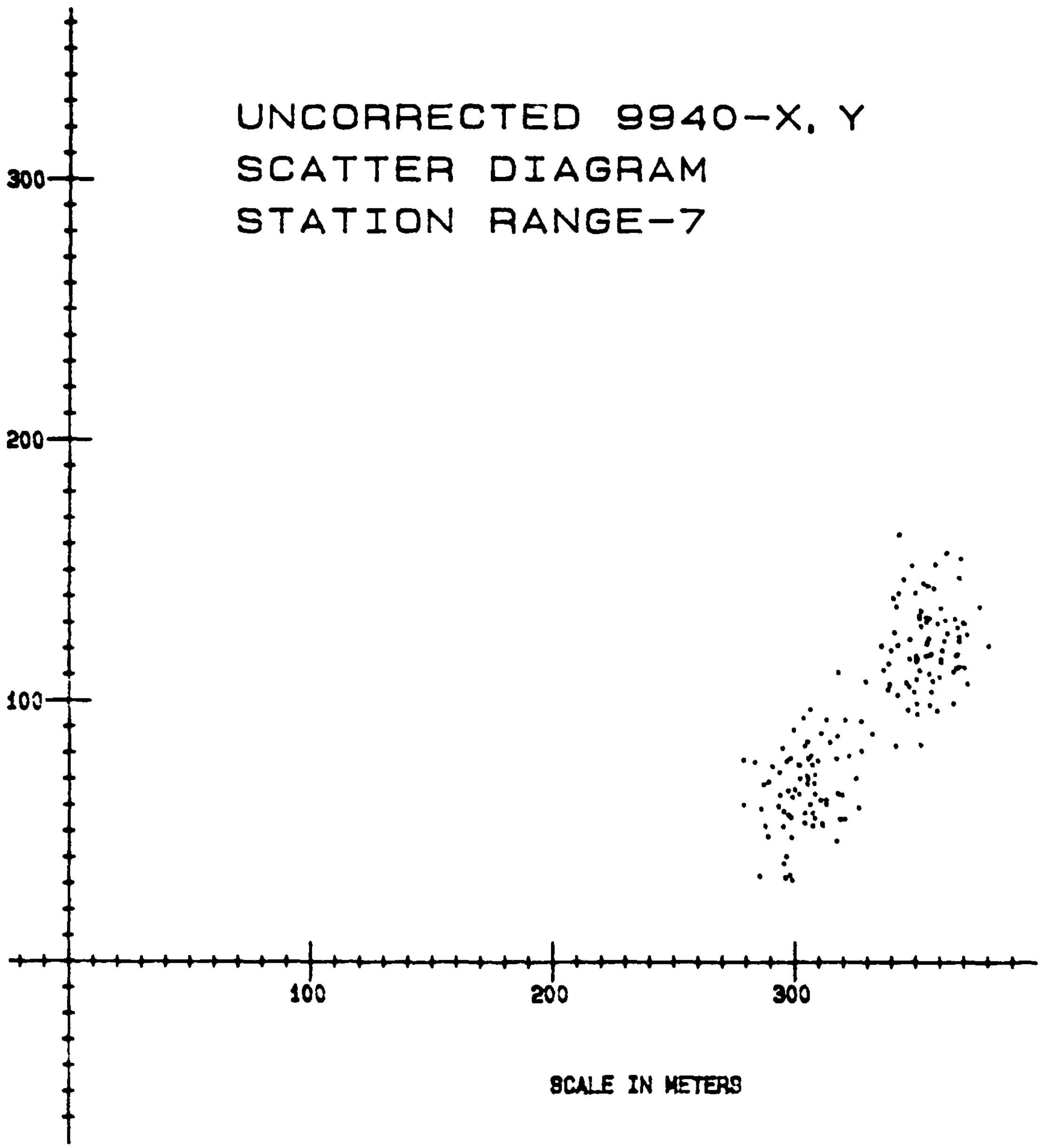

Figure V-5a. Scatter Diagram For Range-7 Uncorrected Data. Scale is in meters oriented N-S and E-W, centered on the time differences calculated from the published coordinates of the point.

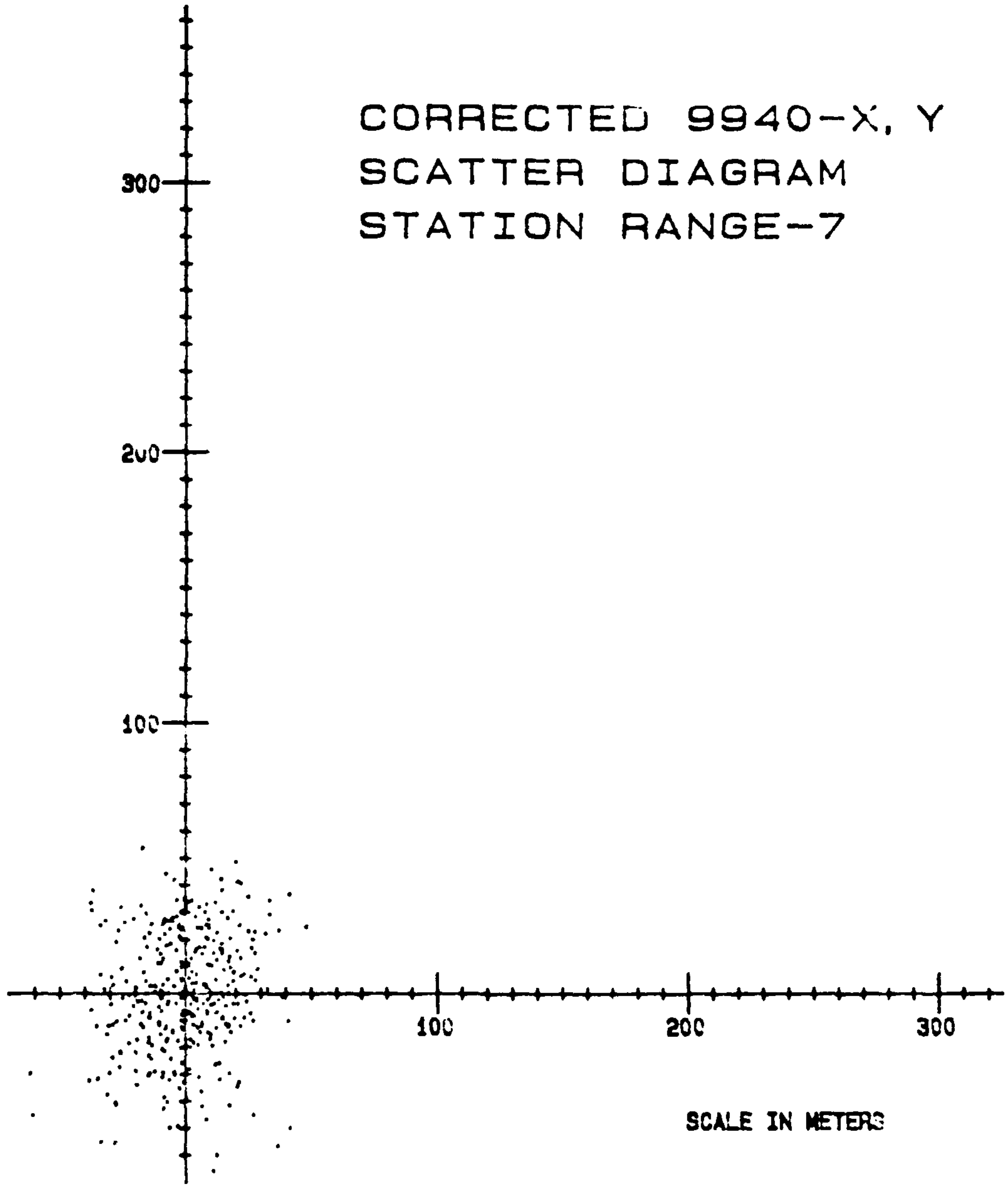

Figure V-5b. Scatter Diagram for Range-7 Data Corrected for Three Secondary Stations and Differential. Scale is in meters oriented N-S and E-W. Center of data is corrected to correspond with calculated time differences for the published coordinates of the point. See text for details.

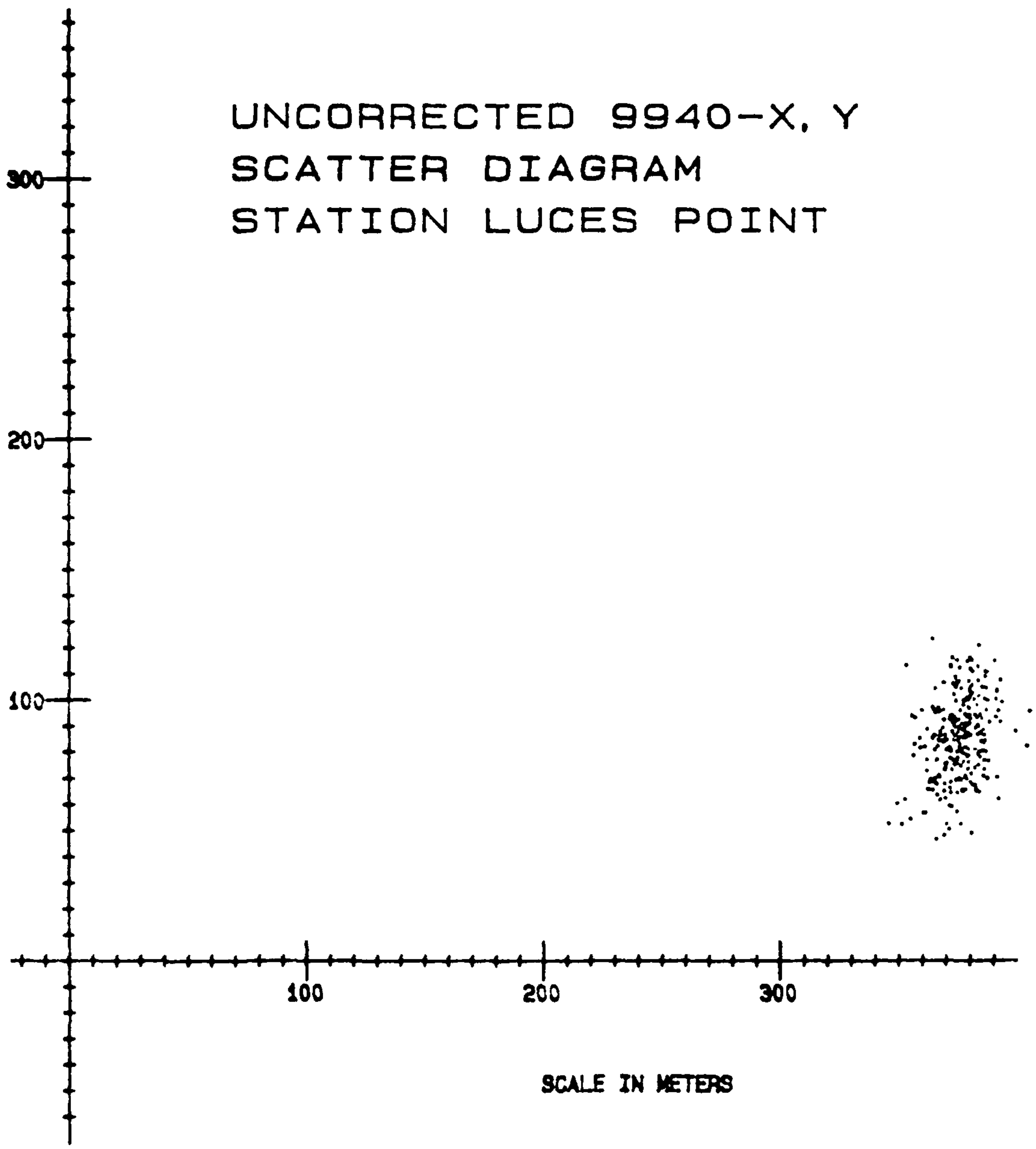

Figure V-6a. Scatter Diagram For Luces Point Uncorrected Data. Scale is meters oriented N-S and E-W, centered on the time differences calculated from the published coordinates of the point.

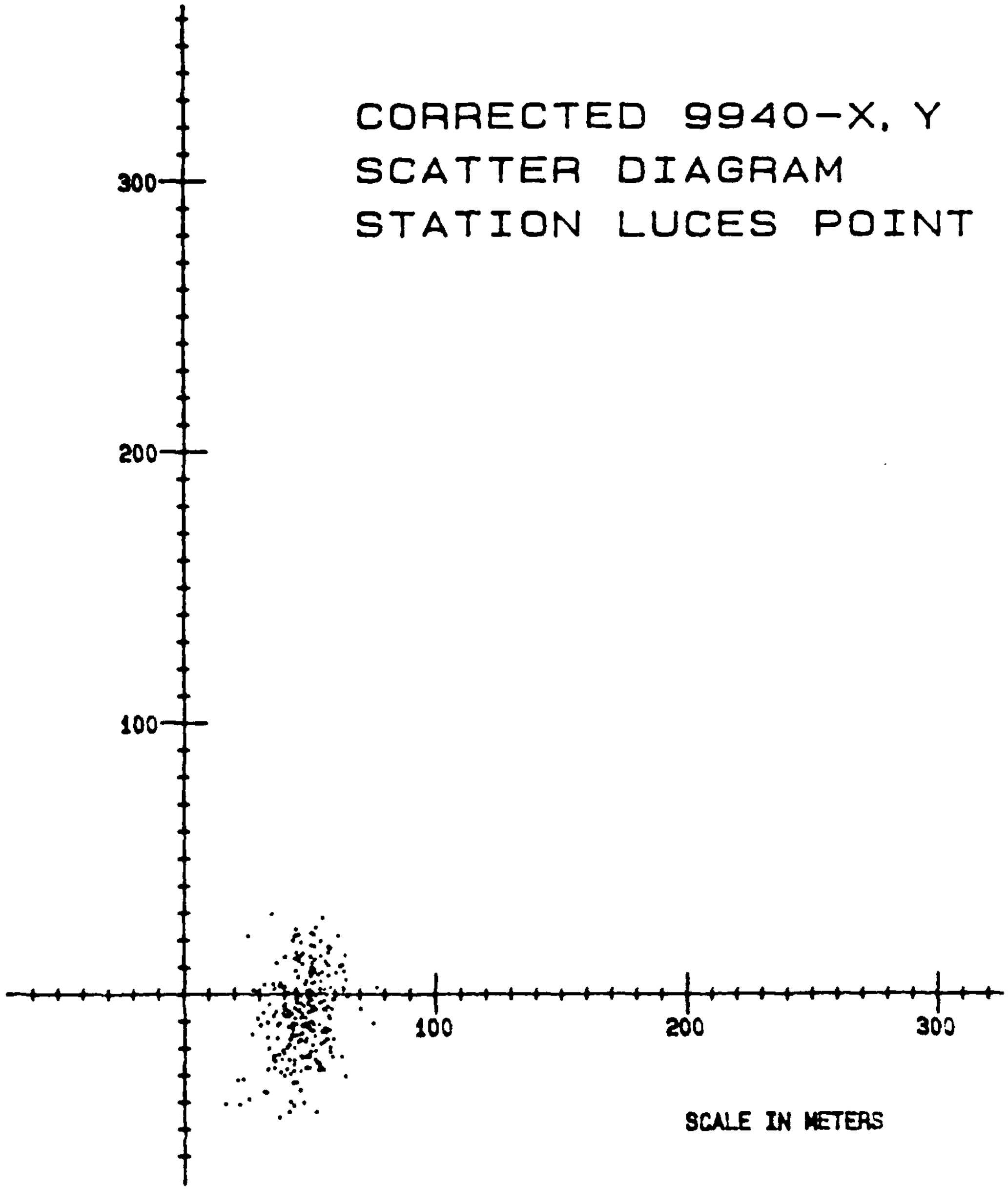

Figure V-6b. Scatter Diagram for Luces Point Data With Differential Corrections Based on Range-7 Data and With Correction For Three Secondary Stations. Origin of plot is at the time differences calculated from the published coordinates of the position.

TABLE V-7. Standard Deviation and Variance of Range-7 Data With and Without the Correction For Three Secondary Stations.

Pair		Without Correction	With Correction
9940-X	σ	0.068638	0.051161
	σ^2	0.004711	0.002617
9940-Y	σ	0.072546	0.052081
	σ^2	0.005263	0.002712

B. Conclusions

Based on the results given in part A, the absolute accuracy of the Luces Point Data was improved from an average error of 385.423 meters to an average error of 47.731 meters. Practically all of this improvement was a result of application of the differential correction.

Precision of the Luces Point data was improved from 14.9 m and 28.4 m for the 50% and 90% CEP radii, uncorrected, to 12.6 m and 26.0 m for the corresponding radii, corrected. Most of this improvement is a result of the correction for three secondary stations.

These figures are based on the processing of 486 sets of TD data from Range-7, the "known" point of the differential system, and 252 sets of TD data at Luces Point. Each set of data included time and three TD's, one for each master-secondary pair (9940-W, X, and Y).

Under ideal conditions a better absolute correction would be expected for these points. From an examination of the characteristics of the data, the weakest point is probably the lack of a continuous set of TD readings at Range-7. Error in the estimate of TD's based on the linear regression lines may be as much, or more than, the 48-meter average error in the corrected positions calculated for Luces Point.

Other sources of error may include the fact that some of the Loran-C signals traversed some seawater path near Luces Point, with unknown results on TD readings at that point. This type of error is known to result under similar conditions, but no means of estimating its magnitude is available at this time.

In summary, the absolute positions calculated from differential corrections of Loran-C data seem to be a significant improvement over the positions calculated from raw data. While the correction for three secondary stations does not add much to the estimate of positions in this experiment, the improvement of 50% CEP radii by about 15% does seem significant enough to warrant further consideration.

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APPENDIX A-1

SEP 1974
U.S. DEPARTMENT OF COMMERCE
ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION
COAST AND GEODETIC SURVEY

HORIZONTAL CONTROL DATA

by the
Coast and Geodetic Survey
NORTH AMERICAN 1927 DATUM

QUAD 361214 STATION 1143
CA. IF
LATITUDE 36°30' TO 37°00'
LONGITUDE 121°30' TO 122°00'
DIAGRAM NJ 10-12 SANTA CRUZ

DESCRIPTION OF TRIANGULATION STATION

Name of station: RANGE 7 (CGS)
State: California
County: Monterey
Nearest town: Marina
Diagram no.: 361214
Chief of party: L.D. Kinneavy
Year: 1972
Described by: L.D. Kinneavy

Height of telescope above station mark 1.40 meters. Height of light above station mark 1.46 meters.

Object	Bearing	Distance (feet)	Distance (meters)	Direction
Monterey Bay 4 (CGS)				0 00 00.0
R.M. 2	NW	32.614	9.941	115 42 10.2
R.M. 1	NE	31.371	9.563	205 28 55.4
R.M. 1 to R.M. 2		45.171	13.768	

This station is located approximately 5½ miles north of Monterey within the Fort Ord Military Reservation and between the ocean and Rte. 001. It is approximately 500 ft. N'ly of firing range 7 on a small hill.

To reach from the intersection of Rte. 001, Post Mile 83.89 and the Second Street Gate at Fort Ord, pass thru the gate on Second Street one block E'ly to First Avenue. Turn rt. on First Avenue and go one block S'ly to First Street. Bear right and take the underpass beneath Rte. 1 to Beach Range Road (about 600 ft). Turn lt. on Beach Range Road for 0.2 mile to the top of a small hill and the station which is located 30 feet W'ly of the centerline of the road.

Station marks are standard CGS brass discs stamped "RANGE 7 1972." The surface mark is set in the top of a 14-inch concrete cylinder that projects 6 inches and is marked with a 5-foot metal fence post. The underground mark is set in concrete 36 inches below ground.

Reference mark No. 1, a standard disc stamped "RANGE 7 No. 1 1972" is set in the top of a 12-inch concrete cylinder that projects 4 inches above the surface and is about 0.5 feet below the station.

Reference mark No. 2, a standard disc stamped "RANGE 7 NO. 2 1972" is set in the top of a 12-inch concrete cylinder that projects 4 inches above the surface and is about 0.5' above the station.

Permission to enter Port Ord to survey may be obtained from Mr. Joe Pintar, Directorate of Facilities Engineering, Fort Ord, California 93941. Phone No. 242-2806 or 242-4421

ADJUSTED HORIZONTAL CONTROL DATA

Name of station: RANGE 7 CGS — OBS BY CGS
State: CALIFORNIA — Year: 1972 — Order: SECOND
Locality: CALIF HWY SURVEY MONTEREY COUNTY-VICINITY OF MONTEREY AND SALINAS
Source: G-14052 — Field record: CALIF 576

Geodetic latitude	36 39 02.47787	Elevation	49.8 meters
Geodetic longitude	121 49 08.58202		163 feet

State coordinates (feet)

State & zone	Code	x	y	θ
CALIF. IV	0404	1,173,142.83	491,701.97	- 1 40 55

To station or object	Geodetic azimuth	Plane azimuth	Code
MONTEREY BAY 4 CGS	36 16 09.2	37 57 04	0404

42 118

[illegible] AND PRINTED BY
[illegible] DEPARTMENT OF COMMERCE
[illegible] AND GEODETIC SURVEY
[illegible]
OCT 1979

HORIZONTAL CONTROL DATA

by the
Coast and Geodetic Survey
NORTH AMERICAN 1927 DATUM

QUAD 361214 STATION 1051
CALIF
LATITUDE 36°30' TO 37°00'
LONGITUDE 121°30' TO 122°00'
DIAGRAM NJ 10-12 SANTA CRUZ

LUCES POINT (Monterey County, Calif., A.F.R., 1875; F.S., 1904)—On a point of rocks about 600 meters NE of Point Pinos Lighthouse and a quarter of a mile E of a small pond or lake near the beach at the northern part of the point. The station was marked by a hole drilled in the rock and filled with lead. The reference marks were two similar holes in the rock, each 6 feet from the station, to the N and S.

LUCES POINT (Monterey County, Calif., A.F.R., 1875; O.P., 1932)—Recovered as described by F. Swift in 1904, with the exception that the S reference mark was gone.

Station was re-marked by putting a standard disk in center, wedged in a drill hole in outcropping bedrock and surrounded by a triangle chiseled in the rock as described in note 2a.

Two reference marks, marked, as described in note 12a, by standard bronze disks in outcropping bedrock, were established.

Station reached from Monterey by following road to Point Pinos 1.3 miles. Station is about 50 yards NW of road.

OBJECT	DISTANCE meters	DISTANCE feet	DIRECTION
GIOLINO			0°00'00.0
R.M. No. 1	11.835	38.84	10 20 19.0
R.M. No. 2	5.395	17.71	250 27 39.0

LUCES POINT (Monterey County, Calif., A.F.R., 1875; F.L.P., 1932)—Original description not available. The station is NE of Pinos Point Lighthouse on the first small point E of the lighthouse reservation fence and about 50 yards NW of the road.

LUCES POINT (Monterey County, Calif., A.F.R., 1875; L.A.McA., 1937)—Station is in good condition. On Luces Point, about 1.5 miles NW of Pacific Grove, and 0.5 mile E of extreme NW point of Monterey Peninsula and about 800 feet E of fence surrounding Point Pinos Lighthouse reserve and close to shore line.

Station is marked by disk in large flat boulder. Two reference marks, disks in boulders, are lower than station. All disks are stamped "LUCES POINT 1904-1932" etc.

Reached from Pacific Grove by driving NW along Oceanview Boulevard about 1.5 miles. Station is on top of small flat rock knoll about 125 feet N of boulevard and just N of secondary road looping off boulevard, and about 10 feet above this road.

LUCES POINT (Monterey County, Calif., A.F.R., 1875; D.F. Carroll, [illegible] Lands Commission, 1962)

Station is located near the NW corner of Pacific Grove, on [illegible] first small point E of the Point Pinos Lighthouse Reservation, [illegible] 500 feet E of the NE gate to the reservation.

Station mark is about 50 yards N of Ocean View Boulevard, on [illegible] of a 10-foot-high flat rock knoll immediately N of a secondary [illegible] looping off the boulevard. It is a bronze station disk, [illegible] "LUCES POINT 1904-1932," and set in a drill hole in the [illegible].

Reference marks are similarly stamped and are set in drill holes [illegible] large boulders lower than the station.

Station and reference marks were recovered in good condition. [illegible] to reference marks were not checked.

OBJECT	DISTANCE feet	GEOD. AZIMUTH
GIOLINO		257°21'28"
R.M. 1	38.84	267 41 47
R.M. 2	17.71	147 40 07

(CONTINUED ON NEXT PAGE)

ADJUSTED HORIZONTAL CONTROL DATA

NAME OF STATION: LUCES POINT — YEAR: 1875-1932

STATE: Calif — LOCALITY: Monterey Bay and Vicinity

Third ORDER Triangulation — [illegible] 0-996 — [illegible] CALIF 23 [illegible]

[illegible] DATA	COORDINATES (FEET)	PLANE AZIMUTH [illegible] ANGLE	[illegible]
STATE: Calif ZONE: 3 CODE: 0403	x 1,581,152.55 y 52,807.22	- 0 57 26	
STATE: Calif. ZONE: 4 CODE: 0404	x 1,181,231.08 y 487,400.78	- 1 44 47	

GEODETIC DATA	POSITION					SECONDS IN METERS	ELEVATION
	LATITUDE	36°	38'	10".524	NORTH	324.4	METERS
	LONGITUDE	121	55	38.399	WEST	953.9	FEET

TO STATION	GEODETIC AZIMUTH (From south)	DISTANCE LOGARITHM (Meters)	DISTANCE METERS
GIOLINO	257°21'28".5		

APPENDIX B

LORAN-C CHAIN -- TRANSMITTING FACILITIES 6/17/85 LCP

RPT NAME NO.	GRI	LOCATION	EMISSION DELAY	ASSIGNED CODING DELAY	RADIATED POWER (KW)	NAD-27 COORDINATES	
7. SOUTHEAST U.S CHAIN							
	7980-M	MALONE			800	30°59'38.236"N	85°10'09.074"W
	7980-W	GRANGEVILLE	12809.54	11000	800	30°43'32.493"N	90°49'42.728"W
	7980-X	RAYMONDVILLE	27443.35	23000	400	26°31'53.976"N	97°49'58.583"W
	7980-Y	JUPITER	45201.68	43000	325	27°01'57.294"N	80°06'53.757"W
	7980-Z	CAROLINA BEACH	61542.71	59000	550	34°03'45.596"N	77°54'47.143"W
8. GREAT LAKES CHAIN							
	8970-M	DANA			400	39°51'07.514"N	87°29'11.543"W
	8970-W	MALONE	14355.06	11000	800	30°59'38.236"N	85°10'09.074"W
	8970-X	SENECA	31162.04	28000	800	42°42'50.465"N	76°49'[illegible]"W
	8970-Y	BAUDETTE	47753.72	44000	500	48°36'50.007"N	94°33'16.988"W
9. WEST COAST U.S. CHAIN							
	9940-M	FALLON			400	39°33'07.046"N	118°49'52.241"W
	9940-W	GEORGE	13796.89	11000	1600	47°03'48.594"N	119°44'34.793"W
	9940-X	MIDDLETOWN	28094.50	27000	400	38°46'57.472"N	122°29'40.050"W
	9940-Y	SEARCHLIGHT	41967.20	40000	540	35°19'18.342"N	114°48'13.946"W

APPENDIX C-1

```
C       THIS PROGRAM READS DATA FROM A FILE OF TIME, A, B, C
C       CONTINUES TO THE END OF THE FILE, CALCULATING THE MEAN,
C       VARIANCE, AND STANDARD DEVIATION OF THE A, B, AND C COLUMNS,
C       AND PRINTS OUT THE RESULTS INTO A FILE tdout.f
      double precision time,time1,time2,time3,a,b,c,na,na,nb,nc,
     +sum,suma,sumb,sumc,suma2,sumb2,sumc2,suma1,sumb1,sumc1,a1,b1,c1
      open (unit=1,file = 'out9.f', form = 'formatted',
     +access='sequential')
C      open (unit=2,file = 'out6.f', form = 'formatted',
C     +access='sequential')
      rewind 1
C      read(1,*) frstln
C      read(1,*) secln
   50 write (*,4) time1,time2,time3,a1,b1,c1,na,na,nb,nc
      time = time1 + time2/60. + time3/3600.
C      write (2,8) time,a1,b1,c1
      sum = sum + 1.
      suma = suma + a
      suma1 = suma1 + a1
      suma2 = suma2 + a*a
      sumb = sumb + b
      sumb1 = sumb1 + b1
      sumb2 = sumb2 + b*b
      sumc = sumc + c
      sumc1 = sumc1 + c1
      sumc2 = sumc2 + c*c
      read(1,2,err=10,iostat=ioerr) time1,time2,time3,a1,a,b1,b,
     +c1,c
      if (ioerr) 10,50,10
   10 sum = sum - 1.
      write(*,6) ioerr
      call s2(suma2,suma,sum,suma1)
      call s2(sumb2,sumb,sum,sumb1)
      call s2(sumc2,sumc,sum,sumc1)
    2 format(t1,d2.0,t4,d2.0,t7,d2.0,t18,d8.3,t21,d5.3,t27,
     +d8.3,t30,d5.3,t36,d8.3,t39,d5.3)
    4 format(f3.0,2x,f3.0,2x,f3.0,2x,f10.3,2x,f10.3,2x,f10.3,2x,
     +i4,i4,i4,i4)
    6 format('ioerr = ',i3)
    8 format(f12.8,2x,f10.3,2x,f10.3,2x,f10.3)
    9 format('data error')
   40 stop
      end
C
      subroutine s2(x2,x,d,s1)
      double precision x2,x,d,mean,varian,sd,s1
      mean = s1/d
      varian = (x2-x*x/d)/(d-1)
      sd = dsqrt(varian)
      write(*,12) mean,varian,sd
C      write(2,12) mean,varian,sd
      return
   12 format('mean = ',f12.3,2x,'variance = ',f12.8,2x,'sd = ',f12.8)
      end
```

APPENDIX C-2

```
10 rem -----------------------------------------------------------------
20 rem ---  PROGRAM FOR GAUSSIAN ELIMINATION WITH PIVOTAL CONDENSATION  ------
30 rem ----------  FOR SOLUTION OF SYSTEMS OF LINEAR EQUATIONS  -------------
40 rem -----------------   WITH UP TO 10 UNKNOWNS   ------------------------
50 rem -----------------------------------------------------------------
60 rem
70 open "i", #1, "ytest.f" : dim A#(10,11):dim B#(11):dim M#(11):dim x#(11)
80 input #1, rows!, cols!
90 r = rows! : c = cols! : rowl = 1 : coll = 1 : highrow = 1
95 rem
100 rem ------ input the matrix:
105 rem
110 for j = 1 to rows!
120 for k = 1 to cols!
130 input #1, A#(j,k)
140 if k <> cols! then 160
150 A#(j,k) = -1 * A#(j,k)
160 next k
170 next j
175 rem
180 rem ----- begin main program ------------------------------------------
185 rem
190 gosub 500 :            rem --- check if unique solution
200 gosub 890 :            rem --- prints out array
210 gosub 650 :            rem --- checks for row with highest first non-zero entry
215 rem
220 if highrow = rowl then 240
225 rem
230 gosub 700 :            rem --- exchange rows if necessary
240 gosub 760 :            rem --- sets first non zero entry in rowl to 1.0
250 gosub 820 :            rem --- sets first entry to zero in following rows
255 rem
260 rowl = rowl + 1 : coll = coll + 1 : highrow = rowl : rem --- increment counters
265 rem
270 if rowl <> rows then 200 :     rem --- checks if last row has been reached
280 gosub 760 :            rem --- sets first non zero entry in final row to 1.0
290 gosub 890 :            rem --- final printout of array
295 rem
300 rem ----- calculates the unknown x values:
305 rem
310 x#(cols!) = 1 : a = rows!
320 for i = a to 1 step -1
330 for j = i to cols! - 1
340 x#(i) = x#(i) - x#(j+1) * A#(i,j+1)
350 next j
360 next i
365 rem
370 rem ----- prints out the x values:
375 rem
380 for k = 1 to rows!
390 print "B" k-1 " = " x#(k)
400 next k
410 end
420 rem ----- end of main program ------------------------------------------
425 rem
430 rem ----- begin subroutines -------------------------------------------
435 rem
500 for i = 1 to rows!
510 for j = 1 to rows!
520 if i = j then 610
530 for k = 1 to cols!
540 if A#(i,k) = 0 then 560
550 M#(k)= A#(j,k)/A#(i,k)
560 next k
```

```
570 for m = 1 to cols! - 1
580 if M#(m) <> M#(m+1) then 610
590 next m
600 print "EQUATIONS NOT INDEPENDENT ... NO UNIQUE SOLUTION ... ONE SOLUTION FOLLOWS"
610 next j
620 next i
630 return
635 rem
640 rem ----- subroutine to check for row with highest first non-zero entry:
650 for i = row1 to rows! - 1
660 if abs(A#(i,col1)) > abs(A#(i+1,col1)) then 680
670 highrow = i + 1
680 next i
690 return
695 rem ----- sunroutine to exchange rows and put highest first entry first:
700 for i = col1 to cols!
710 B#(i) = A#(row1, i)
720 A#(row1,i) = A#(highrow,i)
730 A#(highrow, i) = B#(i)
740 next i
750 return
755 rem ----- subroutine to set first entry in first row to 1.0:
760 R# = A#(row1,col1)
770 for k = col1 to cols!
780 if A#(row1,col1) = 0 then 310
790 A#(row1,k) = A#(row1, k)/R#
791 print k
800 next k
810 return
815 rem ----- subroutine to set other first entries to zero:
820 for j = row1 + 1 to rows!
830 P# = A#(j,col1)/A#(row1,col1)
840 for k = col1 to cols!
850 A#(j,k) = A#(j,k) - A#(row1,k)*P#
860 next k
870 next j
880 return
885 rem ----- subroutine to print out the matrix A:
890 for j = 1 to rows!
900 for k = 1 to cols!
910 print A#(j,k),
920 next k
930 print
940 next j
950 print row1; "-----------------------------------------------------------------
960 return
970 print "NOT ENOUGH EQUATIONS ... MANY SOLUTIONS ARE POSSIBLE"
980 return
990 end
```

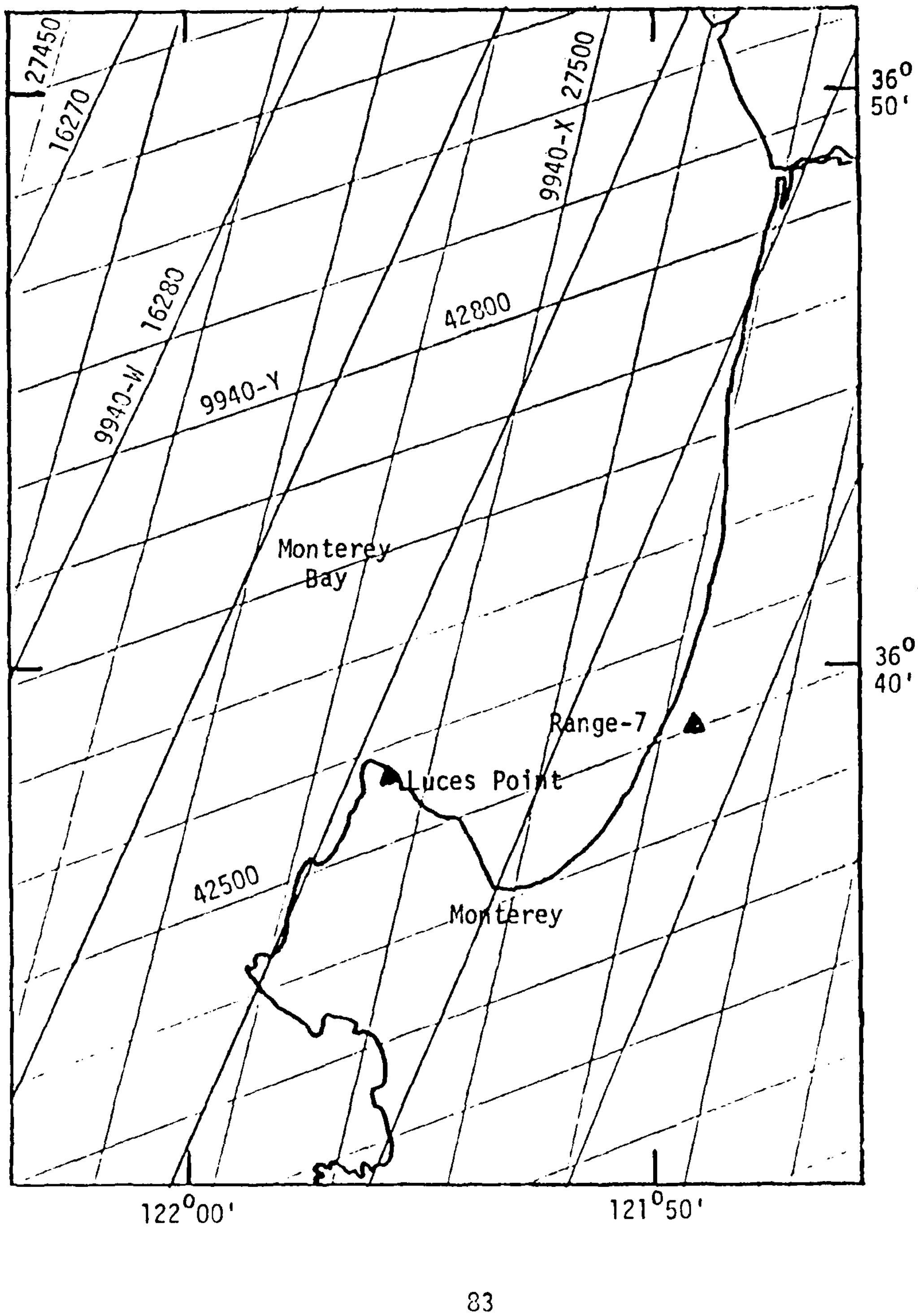
APPENDIX C-3

```
      PROGRAM AZM
      A = 6378206.4
      B = 6356583.8
      OPEN(UNIT=1,FILE='azin.f',FORM='FORMATTED',
     +ACCESS='SEQUENTIAL')
      REWIND 1
C       azimuth is from point 1 to point 2
      READ(1,2) ALAT2,ALON2
      READ(1,2) ALAT1,ALON1
      FLAG = 0.0
      CALL INV(A,B,ALAT1,ALON1,ALAT2,ALON2,FLAT,DIST,AZ)
      AZ = AZ + 3.141592654
      AZ = AZ/3.141592654*180.0
      IF (AZ-360.0) 10,10,20
   20 AZ = AZ - 360.0
   10 WRITE(*,3) DIST,AZ
      X = ALAT2/3.141592654*180.0
      Y = ALON2/3.141592654*180.0
      V = ALAT1/3.141592654*180.0
      W = ALON1/3.141592654*180.0
      WRITE(*,4) X,Y
      WRITE(*,5) V,W
    2 FORMAT(F9.8,T12,F9.8)
    3 FORMAT('DISTANCE = ',F12.3,1X,'METERS',3X,'AZIMUTH = ',F12.8,2X,
     +'(NORTH)')
    4 FORMAT('POINT2: ',2X,'LAT:',2X,F8.5,'N',3X,'LON:',2X,F9.5,'W')
    5 FORMAT('POINT1: ',2X,'LAT:',2X,F8.5,'N',3X,'LON:',2X,F9.5,'W')
      END
C
      SUBROUTINE INV(EORAD,PORAD,RLT1,RLN1,RLT2,RLN2,CFLG,DIST,AZ)
      IF (CFLG) 101,101,102
  101 FLAT = 1.0-PORAD/EORAD
      FALAT2 = FLAT*FLAT
      F1 = FALAT2*1.25
      F2 = FALAT2*0.5
      F3 = FALAT2*0.25
      F4 = FALAT2*0.125
      F5 = FALAT2*0.0625
      F6 = FALAT2+FLAT
      F7 = F6+1.0
      F8 = F6*0.5
      PI = 3.141592654
      TWOPI = 6.283185307
      CFLG = 1.0
  102 BETA1 = ATAN((1.0-FLAT)*SIN(RLT1)/COS(RLT1))
      SBETA1 = SIN(BETA1)
      CBETA1 = COS(BETA1)
      BETA2 = ATAN((1.0-FLAT)*SIN(RLT2)/COS(RLT2))
      SBETA2 = SIN(BETA2)
      CBETA2 = COS(BETA2)
      DELL = RLN1-RLN2
      ADELL = ABS(DELL)
      IF (ADELL-PI) 106,105,105
  105 ADELL = TWOPI-ADELL
  106 SIDEL = SIN(ADELL)
      CODEL = COS(ADELL)
      A = SBETA1*SBETA2
      B = CBETA1*CBETA2
      COPHI = A+B*CODEL
      SIPHI =
     &SQRT((SIDEL*CBETA2)**2+(SBETA2*CBETA1-SBETA1*CBETA2*CODEL)**2)
      C = B*SIDEL/SIPHI
      EM = 1.0-C*C
      PHI = ASIN(SIPHI)
```

APPENDIX C-3

```
      IF (COPHI) 207,208,208
207   PHI = PI-PHI
208   PHISQ = PHI*PHI
      CSPHI = 1.0/SIPHI
      CTPHI = COPHI/SIPHI
      PSYCO = SIPHI*COPHI
      TERM1 = F7*PHI
      TERM2 = A*(F6*SIPHI-F2*PHISQ*CSPHI)
      TERM3 = EM*(F2*PHISQ*CTPHI-F8*(PHI+PSYCO))
      TERM4 = A*A*F2*PSYCO
      TERM5 = EM*EM*(F5*(PHI+PSYCO)-F2*PHISQ*CTPHI-F4*PSYCO*COPHI*COPHI)
      TERM6 = A*EM*F2*(PHISQ*CSPHI+PSYCO*COPHI)
      DIST = PORAD*(TERM1+TERM2+TERM3-TERM4+TERM5+TERM6)
      TERM7 = F6*PHI
      TERM8 = A*(F2*SIPHI+FALAT2*PHISQ*CSPHI)
      TERM9 = EM*(F3*F3*PSYCO+FALAT2*PHISQ*CTPHI-F1*PHI)
      ZLAM = C*(TERM7-TERM8+TERM9)+ADELL
      CTAZ=(SBETA2*CBETA1-COS(ZLAMZ)*SBETA1*CBETA2)/(SIN(ZLAM)*CBETA2)
      IF (CTAZ) 210,209,210
209   CTAZ = 0.00000005
210   AZ = ATAN(1.0/CTAZ)
      IF (DELL) 215,214,214
214   IF (DELL-PI) 211,212,212
211   IF (CTAZ) 220,221,221
220   AZ = AZ+PI
      GOTO 221
212   IF (CTAZ) 217,218,218
215   IF (DELL+PI) 211,211,216
216   IF (CTAZ) 217,218,218
217   AZ = PI-AZ
      GOTO 221
218   AZ = TWOPI-AZ
221   AZ = AZ+PI
      AZ = AZ-TWOPI
      IF (AZ) 213,219,219
213   AZ = AZ+TWOPI
219   RETURN
      END
```

APPENDIX D



27450
16270
9940-X 27500
36° 50'
16280
42800
9940-W
9940-Y
Monterey Bay
36° 40'
Range-7
Luces Point
42500
Monterey
122°00'
121°50'

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12.	Chief of Naval Research 800 N. Quincy Street Arlington, VA 22217	1
13.	Director (Code PPH) Defense Mapping Agency Bldg. 56, U.S. Naval Observatory Washington, DC 20305	1
14.	Director (Code HO) Defense Mapping Agency Hydrographic Topographic Center 6500 Brookes Lane Washington, DC 20315	3
15.	Director (Code PSD-MC) Defense Mapping School Ft. Belvoir, VA 22060	1
16.	Director, Charting and Geodetic Services (N/CG) National Ocean and Atmospheric Administration Rockville, MD 20852	1
17.	Chief, Program Planning, Liaison and Training (NC2) National Oceanic and Atmospheric Administration Rockville, MD 20852	1
18.	Chief, Nautical Charting Division (N/CG2) National Oceanic and Atmospheric Administration Rockville, MD 20852	1
19.	Chief, Hydrographic Surveys Branch (N/CG24) National Oceanic and Atmospheric Administration Rockville, MD 20852	1
20.	Director, Pacific Marine Center (N/MOP) National Ocean Service, NOAA 1801 Fairview Avenue East Seattle, WA 98102	1

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24. Comandant 1
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6500 Brookes Lane
Washington, DC 20315

26. IHO/FIG International Advisory Board 1
International Hydrographic Bureau
Avenue President J.F. Kennedy
Monte Carlo, Monaco

27. Hydrographer of the Navy 1
Ministry of Defense
Hydrographic Department
Taunton, Somerset
TAI29N England

28. Hydrographer, Royal Australian Navy 1
Hydrographic Office
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North Sydney 2060
New South Wales, Australia

29. Dominion Hydrographer 1
Canadian Hydrographic Service
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Canada K1AOE6

30. Kapala Jawatan Hidro Oseanografi 1
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33. Civil Engineering Department 1
Ports and Lighthouses Administration
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37. Commanding Officer 1
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38. Library 1
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39. Library 2
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40. Library 1
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41. ARNAV Systems Inc. (attn: Mr. Walter Dean) 1
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42. Regional Director 1
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