AD-A122 499   POSITION DETERMINATION WITH LORAN-C TRIPLETS AND THE HEWLETT-PACKARD HP-41CV PROGRAMMABLE CALCULATOR(U) NAVAL POSTGRADUATE SCHOOL MONTEREY CA   R H SHUDDE   1/1

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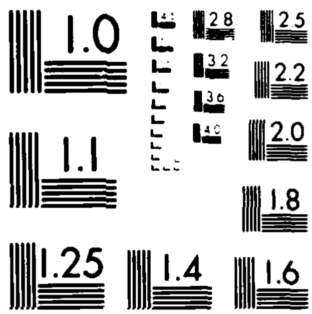

MICROCOPY RESOLUTION TEST CHART
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NAVAL POSTGRADUATE SCHOOL

Monterey, California

AD A122499

POSITION DETERMINATION WITH LORAN-C TRIPLETS AND THE HEWLETT-PACKARD HP-41CV PROGRAMMABLE CALCULATOR

by

Rex H. Shudde

September 1982

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CORRECTION

The coding delay for 7970W, given on page 61 of NPS55-82-022 should be 26000 microseconds.

ADDENDA

1. On 9 June 1982, the Defense Mapping Agency issued upgraded WGS-72 coordinates for the Loran-C stations. This update includes positions measured to the nearest 0.001", the *7930 Northwest Pacific Reconfiguation and the addition of the 5970 Commando Lion Chain. The upgraded coordinates are listed on the following page.

2. The HP-41CV program may be modified to display the station coordinates to the nearest 0.001" by changing line 953 to FIX7.

STATION COVERAGE

Station	No. of Pairs	Location
4990	2	Central Pacific
5930	2	Canadian East Coast
5970	3	Commando Lion
5990	3	Canadian West Coast
7930	3	North Atlantic
*7930	3	Northwest Pacific, Reconfigured
7960	2	Gulf of Alaska
7970	4	Norwegian Sea
7980	4	Southeast U.S.A.
7990	3	Mediterranean Sea
8970	3	Great Lakes
9940	3	West coast, U.S.A.
9960	4	Northeast U.S.A.
9970	4	Northwest Pacific
9990	3	North Pacific

22 November 1982

LORAN-C STATIONS

ID	CD	MS LAT	MS LON	SS LAT	SS LON
4990X	11000	16.4443950	169.3031200	20.1449160	155.5309700
4990Y	29000	16.4443950	169.3031200	28.2341770	178.1730200
5930X	11000	46.4827199	067.5537713	41.1511930	069.5839090
5930Y	25000	46.4827199	067.5537713	46.4632180	053.1028160
5970W	11000	36.1105797	-129.2027279	42.4437104	-143.4309245
5970X	31000	36.1105797	-129.2027279	35.0223871	-126.3226741
5970Z	42000	36.1105797	-129.2027279	26.3624975	-128.0856445
5990X	11000	51.5758780	122.2202240	55.2620851	131.1519648
5990Y	27000	51.5758780	122.2202240	47.0347990	119.4439530
5990Z	41000	51.5758780	122.2202240	50.3629731	127.2129043
7930W	11000	59.5917270	045.1027470	64.5426580	023.5521750
7930X	21000	59.5917270	045.1027470	62.1759640	007.0426538
7930Z	43000	59.5917270	045.1027470	46.4632180	053.1028160
*7930X	11000	24.1707888	-153.5853232	42.4437104	-143.4309245
*7930Y	30000	24.1707888	-153.5853232	26.3624975	-128.0856445
*7930Z	49000	24.1707888	-153.5853232	09.3245789	-138.0954970
7960X	11000	63.1942814	142.4831900	57.2620210	152.2211225
7960Y	26000	63.1942814	142.4831900	55.2620851	131.1519648
7970W	26000	62.1759640	+007.0426538	54.4829872	-008.1736312
7970X	11000	62.1759640	+007.0426538	68.3806150	-014.2747000
7970Y	46000	62.1759640	+007.0426538	64.5426580	+023.5521750
7970Z	60000	62.1759640	+007.0426538	70.5452610	+008.4358690
7980W	11000	30.5938740	085.1009305	30.4333018	090.4943600
7980X	23000	30.5938740	085.1009305	26.3155006	097.5000093
7980Y	43000	30.5938740	085.1009305	27.0158393	080.0653429
7980Z	59000	30.5938740	085.1009305	34.0346081	077.5446654
7990X	11000	38.5220587	-016.4306159	35.3120787	-012.3130245
7990Y	29000	38.5220587	-016.4306159	40.5820950	-027.5201520
7990Z	47000	38.5220587	-016.4306159	42.0336515	-003.1215512
8970W	11000	39.5107540	087.2912140	30.5938740	085.1009305
8970X	28000	39.5107540	087.2912140	42.4250603	076.4933862
8970Y	44000	39.5107540	087.2912140	48.3649844	094.3318469
9940W	11000	39.3306621	118.4956370	47.0347990	119.4439530
9940X	27000	39.3306621	118.4956370	38.4656990	122.2944529
9940Y	40000	39.3306621	118.4956370	35.1918180	114.4817435
9960W	11000	42.4250603	076.4933862	46.4827199	067.5537713
9960X	25000	42.4250603	076.4933862	41.1511930	069.5839090
9960Y	39000	42.4250603	076.4933862	34.0346081	077.5446654
9960Z	54000	42.4250603	076.4933862	39.5107540	087.2912140
9970W	11000	24.4803597	-141.1930303	24.1707888	-153.5853232
9970X	30000	24.4803597	-141.1930303	42.4437104	-143.4309245
9970Y	55000	24.4803597	-141.1930303	26.3624975	-128.0856445
9970Z	75000	24.4803597	-141.1930303	09.3245789	-138.0954970
9990X	11000	57.0912265	+170.1506789	52.4944040	-173.1048974
9990Y	29000	57.0912265	+170.1506789	65.1440306	+166.5312550
9990Z	43000	57.0912265	+170.1506789	57.2620210	+152.2211225

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents an algorithm and HP-41CV programs for position determination with Loran-C chains. Additional computational routines include the ability to calibrate Loran station triplet data to a known benchmark and ITD's (Indicated Time Delay's), predict ITD's at given positions, compute the geodesic (similar to great circle) bearing and distance from a fix to the destination and to compute the geodesic bearing and distance from any one location to another. Utility routines allow the user to transfer station pair data between the HP-41CV and magnetic cards, magnetic tape and an extended

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AND THE HEWLETT-PACKARD HP-41CV PROGRAMMABLE CALCULATOR

by

R. H. Shudde

Naval Postgraduate School
Monterey, California

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September 1982

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CONTENTS

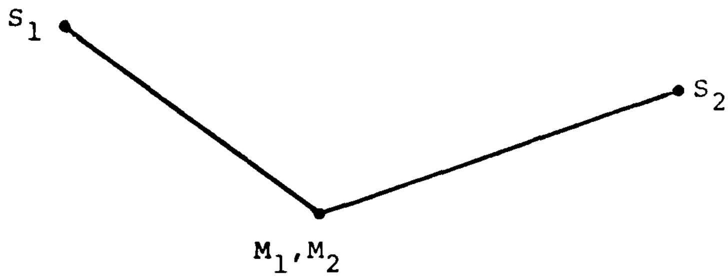
ABSTRACT

This report presents an algorithm and HP-41CV programs for position determination with Loran-C chains. Additional computational routines include the ability to calibrate Loran station triplet data to a known benchmark and ITD's (Indicated Time Delay's), predict ITD's at given positions, compute the geodesic (similiar to great circle) bearing and distance from a fix to the destination and to compute the geodesic bearing and distance from any one location to another. Utility routines allow the user to transfer station pair data between the HP-41CV and magnetic cards, magnetic tape and an extended function/ memory module.

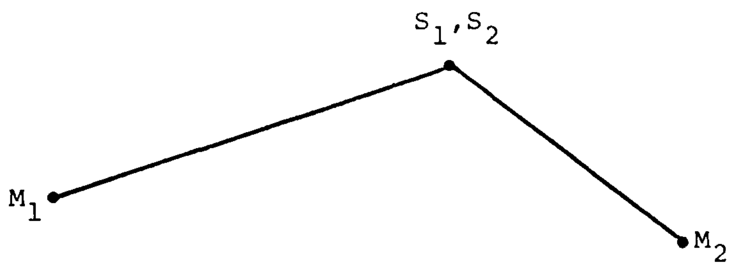
A. Introduction

The Loran system is a radio aid to navigation which utilizes the principle of hyperbolic fixing. The locus of points for which the difference in arrival time of synchronized signals from a pair of transmitters is constant determines a hyperbolic line of positions. The intersection of two hyperbolic lines of position from two pairs of stations determines position or a hyperbolic fix. That two pairs of stations are required for a fix does not necessarily mean that there are four separate stations, for one station of one pair may be colocated with one station of the other pair forming a Loran triplet (Figure 1). Triplets may be joined "end-to-end" by station colocation to form a Loran chain (Figure 2). Loran chains are common on both the East and West coasts of the North American continent.

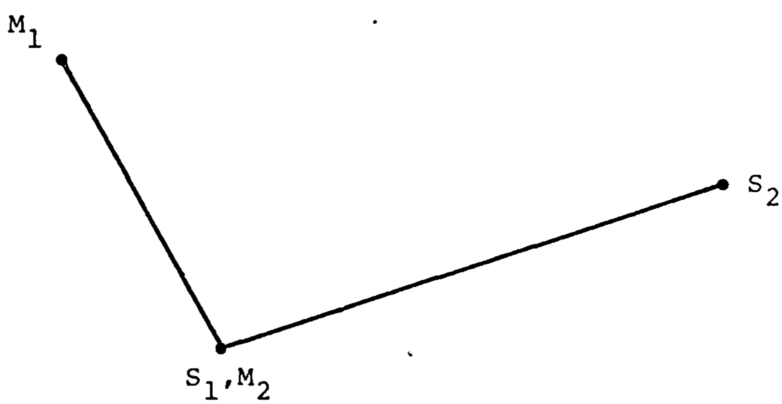
The present day Loran-C operates at 100-kHz and is in use in the Atlantic, Pacific and Mediterranean areas. The computational algorithm and programs described herein can be used for position determination with Loran-C triplets. Further information on the history, development and operation of the Loran systems may be found in References 1 and 2.



(a) Colocated Master Stations



(b) Colocated Slave Stations



(c) Colocated Master and Slave

Figure 1. Loran Triplets.

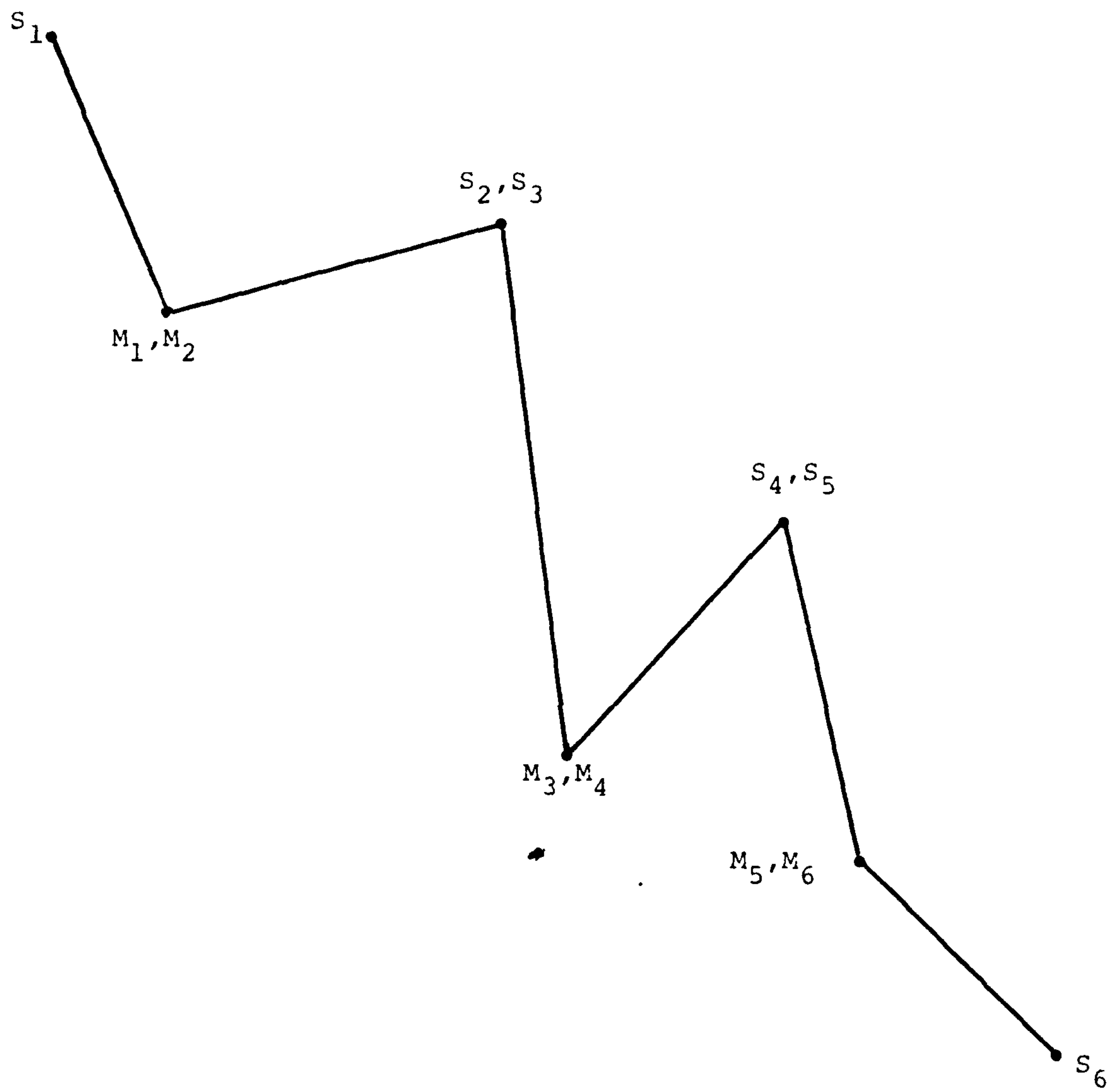


Figure 2. Loran Chain of Five Loran Triplets.

B. <u>User Routines</u>

1. Computational Routines:

   <u>FI</u> - The <u>FI</u>xing routine is the main program for calculating a Loran-C fix from indicated time delays.

   <u>AS</u> - The <u>A</u>lternate <u>S</u>olution routine will allow the second Loran fix solution to be computed. This routine toggles Flag 3 so that on subsequent fixes the FI routine will calculate the alternate solution.

   <u>DN</u> - The <u>D</u>esti<u>N</u>ation routine stores the latitude and longitude of a fixed destination.

   <u>HD</u> - Computes the <u>H</u>eading and <u>D</u>istance from the current fix to the destination stored by the DN routine.

2. Manual Mode Routines:

   <u>MI</u> - <u>M</u>anual <u>I</u>nput allows station data to be input and stored via the calculator keyboard.

   <u>ED</u> - <u>E</u>cho <u>D</u>ata is a utility routine for validating station triplet information stored in the calculator.

3. Card Reader Routines:

   <u>CS</u> - <u>C</u>ard <u>S</u>tore records station data onto magnetic cards.

   <u>CR</u> - <u>C</u>ard <u>R</u>ead inputs station data from magnetic cards.

   <u>CE</u> - <u>C</u>ard <u>E</u>cho is a utility routine for validating station information stored on data cards.

4. Extended Memory Routines:

   <u>XS</u> - <u>X</u>MEM <u>S</u>tore records station data onto the extended memory module.

   <u>XR</u> - <u>X</u>MEM <u>R</u>ecall inputs station data from the extended memory module.

XD - XMEM Delete erases station data from the extended memory module.

5. Tape Cassette Routines:

   TS - Tape Store records station data onto the tape cassette.

   TR - Tape Recall inputs station data from the tape cassette.

   TD - Tape Delete erases station data from the tape cassette.

6. Utility Routines:

   DH - This routine is similiar to the HD option except that it computes the heading and distance from any origin to any destination.

   PR - PR is used to PRedict the station ITD's that will be received at a given latitude and longitude.

   CA - CA is the CAlibration option. Given the latitude and longitude of a known position and the indicated time delays from a Loran-C triplet, the stored station data are modified so that the FI routine (or AS) will compute the known position from the same time delays.

   SW - SWitch data swaps the data of the two Loran stations stored in memory.

Note: There are no specific routines that relate to HP-41CV printer operations. However, all input and output will be recorded on a printer if one is attached.

C. <u>Recommended Key Assignments</u>

It is recommended that the following HP-41CV <u>user key</u> assignments be made and recorded onto the program cards if the program is first prepared manually:

			CA	ED
		CS	CR	CE
		TD	MI	SW
		TS	TR	DN
		XD	PR	DH
		XS	XR	HD
AS				
FI				

The <u>FI</u> function is placed on the ENTER key as a reminder that ENTER should <u>not</u> be used for data entry. To make the user key assignments on the HP-41CV, refer to the ASN function in the HP-41CV <u>Owner's Handbook and Programming Guide</u>.

D. User Instructions with Examples

1. Manual Input Routine - MI

This routine can be used to enter station data (Appendix C) to prepare data to be transferred to cards, extended memory, or tape cassette. It can also be used to enter station data manually if alternate data storage media are not available.

Example using 9940W and 9940Y. (Note: The notation <9>, for example, means that you must press the gold shift key and then the 9 key.)

See	Key in	Press
1.	XEQ"MI"	
2. ID?	<9><9><4><0>W	R/S
3. CODE DELAY?	11000	R/S
4. MS LAT?	39.330662	R/S
5. MS LON?	118.495637	R/S
6. SS LAT?	47.034799	R/S
7. SS LON?	119.443953	R/S

If desired, these station parameters can now be transferred to card, extended memory or tape using the CS, XS, or TS routines, respectively. Otherwise, repeat the steps above with the 9940Y station data. These two stations will be used in the remaining examples.

See	Key in	Press
1.		XEQ"MI"
2. ID?	<9><9><4><0>Y	R/S
3. CODE DELAY?	40000	R/S
4. MS LAT?	39.330662	R/S

5. MS LON? 118.495637 R/S

6. SS LAT? 35.191818 R/S

7. SS LON? 114.481743 R/S

8. NEXT OPTION?

At this point the station data for 9940W and 9940Y are stored in the calculator. The 9940Y data can be transferred to card, extended memory or tape cassette using the CS, XS or TS routines, respectively.

[Advanced User Note: The first action taken in the MI routine is to XEQ"SW". SW is the data swap routine which exchanges to content of R16 - R25 with R26 - R35. The incoming data are then stored in the R16 - R25 registers. The CS, XS and TS routines transfer the content of R16 - R25 to card, extended memory or tape cassette, respectively. If desired, the content of these registers can be swapped once more by using the SW utility routine.]

2. <u>Echo Data Routine - ED</u>

This routine allows the user to review the station data resident in the calculator.

Example: Load the station pairs 9940W and 9940Y using either the MI, CR, XR or TR routines.

See	Key in	Press
1.	XEQ"ED"	
2. ID: 9940W		R/S
3. CD: 11000		R/S
4. MLT: 39.330662		R/S
5. MLN: 118.495637		R/S
6. SLT: 47.034799		R/S
7. SLN: 119.443953		R/S
8. BL: 2796.903		R/S
9. ID: 9940Y		R/S
10. CD: 40000		R/S
11. MLT: 39.330662		R/S
12. MLN: 118.495637		R/S
13. SLT: 35.191818		R/S
14. SLN: 114.481743		R/S
15. BL: 1967.302		R/S
16. NEXT OPTION?		

Notation: CD = coding delay, M = master, S = slave, LT = latitude, LN = longitude and BL is the station pair baseline plus the secondary phase correction in microseconds.

/

3a. Card Store Routine - CS

With the card reader attached, station data (in R16 - R25), which has been input using the MI, XR or TR routine, can be transferred to magnetic card using the XEQ"CS" command or by pressing the appropriate user defined key.

Example using 9940W.

	See	Key in	Press
1.		XEQ"PD"	
2.	WRITE: 9940W	(Pass a blank card through the card reader. Label the card track "9940W")	
3.	NEXT OPTION?		

To proceed with the remaining examples it is recommended that you also prepare a card for the 9940Y station pair.

3b. Card Read Routine - CR

With the card reader attached, XEQ"CR" or press the appropriate user defined key. This routine can be used to input the data for two station pairs, which must form a triplet.

Example using 9940W and 9940Y.

	See	Key in	Press
1.		XEQ"CR"	
2.	1ST CARD	(Pass the data card for 9940W through the card reader.)	
3.	2ND CARD	(Pass the data card for 99440Y through the card reader.)	
4.	NEXT OPTION?		

3c. Card Echo Routine - CE

With the card reader attached, XEQ"CE" or press the appropriate user defined key. This routine is used to validate the content of data cards against the table in Appendix C.

Example using 9940W.

	See	Key in	Press
1.		XEQ"CE"	
2.	STA. CARD	(Pass one side of a data card [9940W] through the card reader).	
3.	ID: 9940W		R/S
4.	CD: 11000		R/S
5.	MLT: 39.330662		R/S
6.	MLN: 118.495637		R/S
7.	SLT: 47.034799		R/S
8.	SLN: 119.443953		R/S
9.	BL: 2796.903		R/S
10.	NEXT OPTION?		

Notation: CD = coding delay, M = master, S = slave, LT = latitude, LN = longitude and BL is the station pair baseline plus the secondary phase correction in microseconds.

/

4a. Store Data in Extended Memory - XS

With the extended memory module in the HP-41CV, station data (in R16 - R25), which has been input using the MI, CR, XR or TR routine, can be transferred to the module using the XEQ"XS" command or by pressing the appropriate user defined key. Example using 9940W.

	See	Key in	Press
1.		XEQ"XS"	
2.	NEXT OPTION?		

Should the station pair already be in extended memory, the message DUP FL (duplicate file) will be displayed. If needed, the duplicate file may be erased using the XD routine.

To proceed with the remaining examples it is recommended that you also store the 9940Y station pair.

4b. Recall Data from Extended Memory - XR

With the extended memory module installed, XEQ"XR" or press the appropriate user defined key to input the data for a station pair.

Example using 9940W. (Note: The notation <9>, for example, means that you must press the gold shift key and then the 9 key.)

	See	Key in	Press
1.		XEQ"XR"	
2.	ID?	<9><9><4><0>W	R/S
3.	NEXT OPTION?		

4c. Delete Data from Extended Memory - XD

XEQ"XD" or press the appropriate user defined key to delete the specific station pair data from the extended memory module.

Example using 9940W.

	See	Key in	Press
1.		XEQ"XD"	
2.	ID?	<9><9><4><0>W	R/S
3.	NEXT OPTION?		

The message FL NOT FOUND will be displayed if the file you wish to delete in not in the extended memory.

Note: The extended functions/ memory module will accommodate the data for 11 station pairs. The extended memory module will accommodate the data for an additional 22 station pairs.

5a. Store Data in the Tape Cassette - TS

With the tape cassette attached to the HP-41CV, station data (in R16 - R25), which has been input using the MI, CR, XR or TR routine, can be transferred to the tape using the XEQ"TS" command or by pressing the appropriate user defined key.

Example using 9940W.

	See	Key in	Press
1.		*XEQ"TS"*	
2.	NEXT OPTION?		

Should the station pair already be in extended memory, the message DUP FL NAME (duplicate file name) will be displayed. If needed, the duplicate file may be erased using the TD routine.

To proceed with the remaining examples it is recommended that you also store the 9940Y station pair.

5b. Recall Data from the Tape Cassette -TR

With the tape cassette attached, XEQ"TR" or press the appropriate user defined key to input the data for a station pair.

Example using 9940W. (Note: The notation <9>, for example, means that you must press the gold shift key and then the 9 key.)

	See	Key in	Press
1.		XEQ"TR"	
2.	ID?	<9><9><4><0>W	*R/S*
3.	NEXT OPTION?		

5c. <u>Delete Data from the Tape Cassette - TD</u>

XEQ"TD" or press the appropriate user defined key to delete the specific station pair data from the tape cassette.

Example using 9940W.

	See	Key in	Press
1.		XEQ"TD"	
2.	ID?	<9><9><4><0>W	R/S
3.	NEXT OPTION?		

The message FL NOT FOUND will be displayed if the file to be deleted is not on the tape.

6. Loran-C Fixing Routines FI and AS

Given the indicated time delay (ITD) from two station pairs which form a triplet, a Loran-C fix is obtained.

Example: Load 9940W and 9940Y into the calculator using the MI, CR, XR or TR routine. The ITD on 9940W is 16019 microseconds and the ITD of 9940Y is 42585 microseconds. Where are you?

See	Key in	Press
1.	XEQ"FI"	
2. ITD: 9940W	16019	R/S
3. ITD: 9940Y	42585	R/S
4. LAT: 39.1419		R/S
5. LON: 115.5052		R/S
6. NEXT OPTION?		

Since you are on a boat, you know that you cannot be in central Nevada at 39d14'19" North and 115d50'52" West. Every Loran-C fix has two solutions, so in this case you must use the alternate solution.

See	Key in	Press
7.	XEQ"AS"	
8. LAT: 35.0001		R/S
9. LON: 125.0009		R/S
10. NEXT OPTION?		

This is the proper solution at almost exactly 35 degrees North and 125 degrees West. Note that annunciator 3 (Flag 3) shows in the display indicating the alternate solution. If you should now repeat from Step 1, you will obtain the proper solution immediately.

The message "E: NO TRIPLET" will appear following Step 1 if the data do not comprise a valid triplet. The latitudes and longitudes of each station pair at the vertex must agree exactly. Should this error occur, use the ED routine to review the resident station data.

The message "E: ITD ERROR" will appear following Step 2 or 3 indicating that the ITD you keyed in is inconsistent with the station parameters. Press R/S to be requeried for the ITD.

7a. <u>Distance and Heading Routines DN and HD</u>

If you know the latitude and longitude of your destination, you may key these in and then see how far your fix is from your destination and what the geodesic heading (similiar to great circle heading) is to your destination.

Example: Your destination is Moss Landing at about 36d48'N and 121d47'W. Your current fix is 35dN and 125dW (see the FI-SA example). First, key in your destination.

See	Key in	Press
1.	XEQ"DN"	
2. DEST LAT?	36.48	R/S
3. DEST LON?	121.47	R/S
4. NEXT OPTION?		R/S

The destination is now stored in the calculator and will remain unchanged until you use either the DN or DH options. Also, the latest fix is stored and will remain unchanged until you use either the FI, AS or DH options. Now, find the distance and bearing from the latest fix (see the FI-AS example) to Moss Landing.

See	Key in	Press
1.	XEQ"HD"	
2. N.MI: 190.38		R/S
3. BRG: 54.3411		R/S
4. NEXT OPTION?		R/S

So the distance to Moss Landing is 190.38 nautical miles at a heading of 54d34'11".

7b. Distance and Heading Routine - DH

Given the latitude and longitude of an origin and destination, this routine will find the distance and heading from one to the other.

Example: How far, and in what direction, is Corvallis, Oregon (44d34'N, 123d16'W) from Cupertino, California (37d19N, 122d02'W)?

	See	Key in	Press
1.		XEQ"DH"	
2.	ORIG LAT?	37.19	R/S
3.	ORIG LON?	122.02	R/S
4.	DEST LAT?	44.34	R/S
5.	DEST LON?	123.16	R/S
6.	N.MI: 438.32		R/S
7.	BRG: 353.0259		R/S
8.	NEXT OPTION?		

Thus the distance is 438.32 nautical miles and the direction of Corvallis from Cupertino is 353d02'59".

8. ITD Prediction Routine - PR

As an aid to identification, this routine will allow the user to determine what ITD's should be received at a given location.

Example: Suppose that you know you are somewhere near latitude 35 North and longitude 125 West but are not sure what ITD's you should be receiving from 9940W and 9940Y. To determine these ITD's, proceed as follows:

	See	Key in	Press
1.		XEQ"PR"	
2.	LAT?	35	R/S
3.	LON?	125	R/S
4.	9940W: 16019.35		R/S
5.	9940Y: 42584.71		R/S
6.	NEXT OPTION?		

You should expect to receive an ITD of 16019.35 from 9940W and an ITD of 42584.71 from 9940Y.

9. <u>Calibration Routine - CA</u>

This routine will allow the user to calibrate the Loran data in the calculator to a known position when the indicated time delay (ITD) is known for each station pair.

Example: Suppose you are receiving an ITD of 16308 from 9940W and 42800 from 9940Y. These ITD's would tell you that your location is 36d47'55"N and 121d47'11"W. However, you <u>know</u> that your position is bench marked to be at 36d47'36"N and 121d46'58"W, and you wish to calibrate your calculator so that the ITD's of 16308 and 42800 will give you the latter fix instead of the former. Proceed as follows:

	<u>See</u>	<u>Key in</u>	<u>Press</u>
1.		XEQ"CA"	
2.	LAT?	36.4736	R/S
3.	LON?	121.4658	R/S
4.	ITD 9940W:	16308	R/S
5.	ITD 9940Y:	42800	R/S
6.	NEXT OPTION?		

Entering 16308 and 42800 into the FI routine will now give you a fix at 36d47'35"N and 121d46'59"W. The small discrepancy between this fix and the bench mark is due to assumptions made in the fixing algorithm.

Calibration is achieved by modifying the Master/Slave baseline (BL in the CE and ED routines). See Section F.

10. Switch Data Registers Routine - SW

The SW utility allows the user to swap the station data stored in R16 - R25 with the data stored in R26 - R35. Whenever the MI, XR or TR routine is used, the SW routine is invoked prior to the loading of the data; the incoming data are then placed in R16 - R25. The consequence is that the first station pair data reside in R26 - R35 and the second station pair data reside in R16 - R25.

One user application of SW would be to change the order of the station ID query in the FI routine (this also affects the order of determination of the solution and alternate solution). Another user application would be to output both resident station pairs to card, extended memory or tape cassette using the CS, XS or TS routines, respectively. To accomplish this, first use the CS, XS, or TS routine; then XEQ"SW" (note that the ID of the station data in R16 - R25 appears in the display instead of the NEXT OPTION? prompt); and finally use the CS, XS or TS routine once more.

11a. Recording the Loran-C Program onto Magnetic Cards

(1) Attach the card reader to the HP-41CV.

(2) Place the calculator in the USER mode.

(3) Press the PRGM key to place the calculator in the program mode.

(4) Pass one side of a blank magnetic card through the card reader. Then follow the display prompts until nine program cards (17 tracks) have been recorded.

(5) Press the PRGM key once more to leave the program mode.

(6) To record a status card, XEQ"WSTS". Then pass a blank card through the card reader following the display prompts.

11b. Recording the Loran-C Program onto Magnetic Tape

(1) Attach the tape cassette to the HP-41CV.

(2) Place the calculator in the USER mode.

(3) Press the alpha key, key in the word LORANC, press the alpha key once more, and then XEQ"WRTP".

(4) To record the program status, press the alpha key, key in the word STATUS, press the alpha key once more, and then XEQ"WRTS".

12a. <u>Loading the Loran-C Program from Magnetic Cards</u>

(1) Attach the card reader to the HP-41CV.

(2) Clear program memory: Turn the calculator off, then, while pressing the left arrow (erase) key down, turn the calculator on.

(3) Place the calculator in the USER mode.

(4) Read in the STATUS card. The status card will set the calculator to SIZE 42.

(5) Read in the nine program cards (17 tracks).

12b. <u>Loading the Loran-C program from Tape Cassette</u>

(1) Attach the tape cassette to the HP-41CV.

(2) Clear program memory. (See Step 2 above).

(3) Place the calculator in the USER mode.

(4) Press the alpha key, key in the word STATUS, press the alpha key once more, and then XEQ"READS". The status file will set the calculator to SIZE 42.

(5) Press the alpha key, key in the word LORANC, press the alpha key once more, and then XEQ"READP".

E. The Loran-C Fixing Algorithm

The principles of Loran lines of position (LOP's) and fixing are adequately covered in Reference 1 and will not be repeated here.

The basic Loran-C equation [Ref. 4] can be written as

$$ITD = [T_S + p(T_S)] - [T_M + p(T_M)] + [T_B + p(T_B)] + \delta \tag{1}$$

where

ITD is the "indicated time difference" in microseconds,

T_M is the distance, in microseconds, from the master to the receiver,

T_S is the distance, in microseconds, from the slave to the receiver,

T_B is the distance, in microseconds, between the master and the slave,

δ is the assigned station pair coding delay, in microseconds, and

p(T) is the secondary phase correction, in microseconds, for a surface seawater path of length T .

The quantity

$$\Delta t = T_B + p(T_B) + \delta$$

is a constant for each master/slave pair. The quantity T_B is computed from the positions of the master and slave using the reverse solution algorithm (Section H) at the time of manual data input (Routine MI).

The following World Geodetic System 1972 (WGS 72) values have been adopted for Loran-C navigation [Ref. 4]:

v_0 = 299792458 meters/second is the velocity of light in free space,

η = 1.000338 is the index of refraction of the surface of the earth for standard atmosphere and 100 kHz electromagnetic waves,

a_e = 6378135.000 meters is the equatorial radius of the earth

and f = 1/298.26 is the flattening factor ($1-b/a_e$, where b is the polar radius) of the earth.

Accurate formulas for computing the secondary phase correction p(T) are contained in Reference 4, but for use in the HP-41CV, the form

$$p(T) = a_0/T + a_1 + a_2 T \tag{2}$$

is used, where T is in microseconds and

1. For $T \geq 537$ µsec:

   a_0 = 129,

   a_1 = -0.408, and

   a_2 = 0.0006458.

2. For $T < 537$ µsec:

   a_0 = 2.74,

   a_1 = -0.011, and

   a_2 = 0.00033.

On the surface of a sphere, a hyperbolic line of position (LOP) can be represented by the equation [Ref. 1, page 175]

$$\tan r = \frac{\cos 2a - \cos 2c}{\sin 2c \cos \omega + \zeta \sin 2a} \tag{3}$$

where the origin of the coordinate system is at the prime focus of the spherical hyperbola, 2c is the spherical arc joining the foci, 2a is a constant for any one hyperbola, and r and ω are the spherical coordinates of a point on the hyperbola. If the base line of the coordinate system is the arc joining the foci the ω is the spherical polar angle from the baseline to a point P on the spherical hyperbola and r is spherical polar distance (or arc) from the prime focus to P. Using the Loran system we take $\zeta = +1$ if the prime focus is at a master station and $\zeta = -1$ if the prime focus is at a slave station.

If we let $v = v_0/\eta$ be the velocity of 100kHz electromagnetic radiation at the earth's surface then, for a spherical earth, we can relate the parameters in Equations 1 and 3 as follows:

$$2c = vT_B/a_e ,$$

and

$$2a = v(T_S - T_M)/a_e .$$

Using the spherical approximation for now, we see that 2c is known for any Loran pair. The "indicated time delay" ITD is measured by the receiver at point P, and to determine a hyperbolic line of position we must determine 2a, but $T_S - T_M$ cannot be computed from Equations 1 and 2. If a_0 were zero in Equation 2, then it would be possible to determine $T_S - T_M$ uniquely. As an approximation we use the following parameters in Equation 2:

$$a_0 = 0 ,$$

$$a_1 = -0.321 ,$$

and

$$a_2 = 0.000635 .$$

These values have been obtained by setting $a_0 = 0$ and determining a_1 and a_2 by linear regression of the $T > 537$ values over the interval of $1000 < T < 8000$. This approximation is quite good (within 0.03 μs) for distances up to 10,000 microseconds where small changes in the LOP's can cause large position errors. At short distances the error increases from 0.05 μs at 1000 μs to 0.58 μs at 10 μs; although these errors are large for small distances, the LOP's are not as sensitive to these changes as they would be at large distances. When this approximation is substituted into Equation 1, we obtain

$$[T_S + a_1 + a_2T_S] - [T_M + a_1 + a_2T_M] = ITD - \Delta t ,$$

or

$$T_S - T_M = (ITD - \Delta t)/(1 + a_2) \tag{4}$$

and hence $2a = v(T_S-T_M)/a_e$ is determined for use in the spherical approximation.

Consider a Loran-C triplet with the master stations co-located. Let ξ_1 and ξ_2 denote the azimuth angles of slave 1 (S_1) and slave 2 (S_2), respectively, measured from North toward the East from the master stations (M) (see Figure 3).

Further, let α and r be the azimuth and spherical polar arc (distance) of the receiver (R) from M. For this geometry, Equation 3 can be written in the form

$$\tan r_i = \frac{B_i}{C_i \cos(\alpha - \xi_i) + A_i} , \tag{5}$$

where

$$A_i = \zeta_i \sin 2a_i ,$$

$$B_i = \cos 2a_i - \cos 2c_i ,$$

and

$$C_i = \sin 2c_i$$

for the i^{th} Loran pair, $i = 1,2$. Since $r_1 = r_2 = r$, we can eliminate $\tan r$ between the two equations. The resulting equation can be rewritten as

$$C \cos \alpha + S \sin \alpha = K , \tag{6}$$

where

$$C = B_1C_2 \cos \xi_2 - B_2C_1 \cos \xi_1 ,$$

$$S = B_1C_2 \sin \xi_2 - B_2C_1 \sin \xi_1 ,$$

and

$$K = B_2A_1 - B_1A_2 .$$

If we define $\rho > 0$ and γ by the equations

$$\rho \cos \gamma = C , \tag{7}$$

and

$$\rho \sin \gamma = S ,$$

then

$$\rho = \sqrt{C^2 + S^2} ,$$

and

$$\gamma = \text{qatn } (S,C) .$$

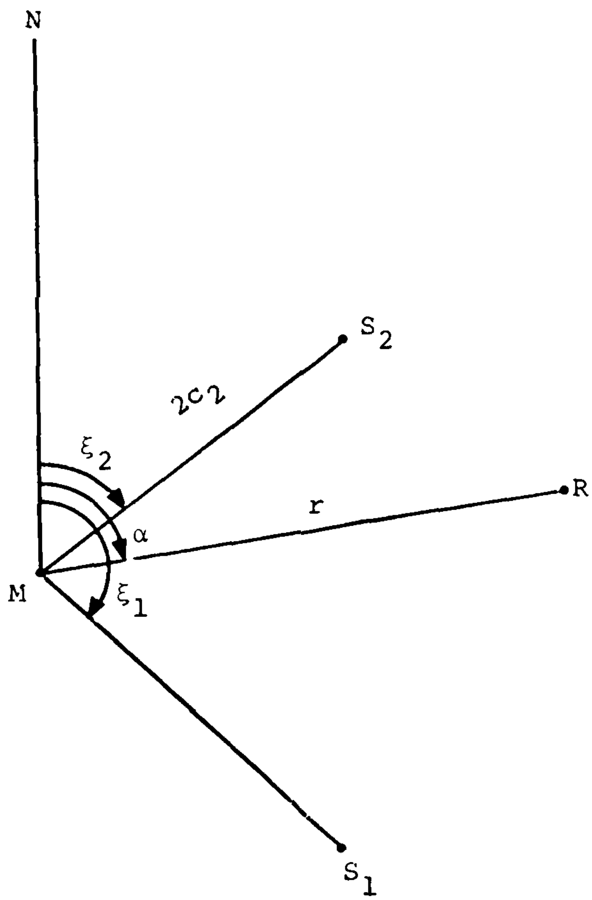


Figure 3. Geometry of a Loran Triplet and a Receiver.

Here the function qatn(y,x) is the arctangent of y/x adjusted for the proper quadrant according to the signs of x and y. A compact form of this function is

$$\text{qatn}(y,x) = \tan^{-1} \frac{y}{x + 10^{-9}\, t(x = 0?)} + \pi t(x < 0?)$$

where $t(z) = 1$ when z is true

and $t(z) = 0$ when z is false.

When convenient we will use the notation qatn(y/x) interchangeably with qatn(y,x). Now we can substitute Eq. (7) into Eq. (6) and solve for

$$\alpha = \gamma \pm \cos^{-1}(K/\rho) \tag{8}$$

to obtain the azimuth angle α of the two points of intersection of the spherical hyperbolic LOP's. Finally we can obtain a value for r by substituting each α into Eq. (5) for either i = 1 or i = 2. We find that

$$r = \text{qatn}\left[\frac{B_i}{C_i \cos(\alpha - \xi_i) + A_i}\right] \text{ for } i = 1 \text{ or } 2. \tag{9}$$

The distance and azimuth from M or the triplet vertex can be converted into the latitude and longitude of the two possible positions of r.

The fixing algorithm then uses α and r in the direct solution algorithm of spheroidal geodesy (Section G).

I. The Calibration and ITD Prediction Algorithms

Calibration can be achieved when an ITD is measured at a known bench marked position. From the bench marked position and the known master and slave positions, the quantities $T_M + p(T_M)$ and $T_S + p(T_S)$ can be computed using the reverse solution algorithm (Section H) and the accurate secondary phase correction formula (Eq. 2). Equation 1 can then be solved for $T_B + p(T_B)$ to obtain a modified baseline. This modified baseline is stored and then used instead of the true baseline in subsequent computations. The affect on the accuracy of fixes using this modified baseline with positions far removed from the bench mark has not studied.

The ITD prediction algorithm is a direct application of Equation 1. A known position, together with the known master and slave positions, is used to compute the quantities $T_M + p(T_M)$ and $T_S + p(T_S)$. When these values, along with a computed or calibrated baseline, $T_B + p(T_B)$, are substituted into Equation 1, a predicted ITD is obtained.

G. The Direct Solution Algorithm

This direct solution algorithm is a modification of the second order in flattening (f) algorithm given by Thomas [Ref. 5, pp. 7-8]. Thomas' notation has been followed as closely as possible for ease of comparison of the algorithms. The qatn function is defined in a previous section. East longitudes and South latitudes are negative. We are given the point $P_1(\phi_1, \lambda_1)$ on the spheroid, where ϕ_1, λ_1 are the geodetic latitude and longitude (geographic coordinates); the forward azimuth α_{12} and distance S to a second point $P_2(\phi_2, \lambda_2)$; and from these we are to find the geographic coordinates ϕ_2, λ_2 and the back azimuth α_{21}. The given quantities are ϕ_1, λ_1, α_{12} and S. No assumptions about the relative location of P_1 and P_2 are required. The modified direct solution algorithm is:

$$\theta_1 = \tan^{-1}[(1-f)\tan\theta_1],\ M = -\sin\alpha_{12}\cos\theta_1\ ,$$

$$C_1 = fM,\ C_2 = f(1-M^2)/4\ ,$$

$$D = (1-C_2)(1-C_2 - C_1M),\ P = C_2[1 + (1/2)C_1M]/D\ ,$$

$$N = \cos\theta_1\cos\alpha_{12}\ ,\ \sigma_1 = \mathrm{qatn}(N, \sin\theta_1)\ ,$$

$$d = S/(a_eD)\ ,\ u = 2(\sigma_1 - d)\ ,\ W = 1-2P\cos u\ ,$$

$$V = \cos(u+d)\ ,\ X = C_2^2\sin d\cos d(2V^2-1)\ ,$$

$$Y = 2PVW\sin d\ ,\ \Delta\sigma = d + X - Y\ ,$$

$$K = [M^2 + (N\cos{-\Delta\sigma}\sin\theta_1\sin\Delta\sigma)^2]^{1/2}\ ,$$

$$\theta_2 = \tan^{-1}[(\sin\theta_1\cos\Delta\sigma + N\sin\Delta\sigma)/K]\ ,$$

$$\Delta\eta = \mathrm{qatn}(-\sin\Delta\sigma\sin\alpha_{12}\ ,\ \cos\theta_1\cos\Delta\sigma - \sin\theta_1\sin\Delta\sigma\cos\alpha_{12})\ ,$$

$$H = C_1(1-C_2)\Delta\sigma - C_1C_2\sin\Delta\sigma\cos(2\sigma_1 - \Delta\sigma)\ ,$$

$$\lambda_2 = \lambda_1 + \Delta\eta - H\ ,$$

$$\alpha_{21} = \text{qatn}[-M, -(N \cos \Delta\sigma - \sin \theta_1 \sin \Delta\sigma)] ,$$

$$\phi_2 = \tan^{-1}[\tan \theta_2/(1-f)]$$

Details of the modifications made to Thomas' algorithm are contained in Reference 3. The algorithm above has been further modified so that Eastern longitudes, rather than Western longitudes, are negative.

H. The Reverse Solution Algorithm

This reverse solution algorithm is a modification of the second order in flattening (f) algorithm given by Thomas [Ref. 5, pp. 8-10]. Thomas' notation has been followed as closely as possible for ease of comparison of the algorithms. The qatn function is defined in a previous section. East longitudes (λ) and South latitudes (ϕ) are negative. We are given the points $P_1(\phi_1,\lambda_1)$, $P_2(\phi_2,\lambda_2)$ on the spheroid and are to find the distance S between the points and the forward and back azimuths, α_{12} and α_{21}. Given quantities are ϕ_1, λ_1, ϕ_2 and λ_2. No assumptions about the relative location of P_1 and P_2 are required. The modified reverse solution algorithm is:

$$\theta_i = \tan^{-1}[(1-f)\tan\phi_i] \;,\; i = 1,2 \;,$$

$$\Delta\lambda = \lambda_2 - \lambda_1 \;,\; \Delta\theta_m = (\theta_2 - \theta_1)/2 \;,\; \theta_m = (\theta_1 + \theta_2)/2 \;,$$

$$H = \cos^2 \Delta\theta_m - \sin^2 \theta_m \;,\; L = \sin^2 \Delta\theta_m + H \sin^2(\Delta\lambda/2) \;,$$

$$d = 2 \sin^{-1}\sqrt{L} \;,\; U = 2 \sin^2 \theta_m \cos^2 \Delta\theta_m/(1-L) \;,$$

$$V = 2 \sin^2 \Delta\theta_m \cos^2 \theta_m/L \;,\; X = U + V \;,\; Y = U - V \;,$$

$$T = d/\sin d \;,\; D = 4T^2 \;,\; E = 2 \cos d \;,\; A = DE \;,$$

$$C = T - (A-E)/2, \; n_1 = X(A+CX) \;,$$

$$B = 2D, \; n_2 = Y(B+EY) \;,\; n_3 = DXY \;,$$

$$\delta_2 d = f^2(n_1 - n_2 + n_3)/64 \;,\; \delta_1 d = f(TX-Y)/4 \;,$$

$$S/a_e = (T - \delta_1 d + \delta_2 d) \sin d \;,\; M = 32T - (20T-A)X - (B+4)Y \;,$$

$$F = 2Y - E(4-X) \;,\; G = fT/2 + f^2M/64 \;,\; Q = -(FG \tan \Delta\lambda)/4 \;,$$

$$\Delta\lambda_m' = (\Delta\lambda + Q)/2 \;,$$

$$t_1 = \mathrm{qatn}(\sin \Delta\theta_m \cos \Delta\lambda_m' , \cos \theta_m \sin \Delta\lambda_m') ,$$
$$t_2 = \mathrm{qatn}(- \cos \Delta\theta_m \cos \Delta\lambda_m' , \sin \theta_m \sin \Delta\lambda_m') ,$$
$$\alpha_{12} = t_1 + t_2 , \alpha_{21} = t_1 - t_2$$

Details of the modifications made to Thomas' algorithm are contained in Reference 3. The algorithm above has been further modified so that Eastern longitudes, rather than Western longitudes, are negative.

I. Program Accuracy

The direct and reverse solution algorithms are equivalent to the second order flattening algorithms given by Thomas (Ref. 5); the parameters of the WGS 1972 spheroid are used. The reverse solution algorithm reproduces the baselines provided by the Defense Mapping Agency for all 40 Loran-C stations to within 0.15 meters (the average deviation is -0.031 meters, DMA minus HP-41CV, with a standard deviation of 0.037 meters) and to within 0.01 microseconds, including the secondary phase correction for an all seawater path. The reverse solution algorithm is also used to generate predicted ITD's; these are presumed to be within 0.01 microseconds, also.

The fixing algorithm uses the direct solution algorithm with the azimuth and distance of the fix from the vertex of the Loran-C triplet computed from Equations 8 and 9 as inputs. Equations 8 and 9 are based upon spherical geometry and include an approximation to the secondary phase correction for an all seawater path. The largest source of error is the assumption that the azimuth and distance to the fix are accurately represented by this spherical approximation. This approximation has not been rigorously tested, however it is possible to use the reverse solution algorithm to predict the ITD's that will be received at a given position and then to enter these ITD's into the fixing algorithm to determine how accurately the fixing algorithm reproduces the original position. The distance between the fix and the original position can be determined using the HD algorithm. Tables 1, 2 and 3 were producted in this manner. Similiar tables with different station pairs are given in References 3, 6 and 7. It is felt that the results are accurate enough to not warrant the inclusion of an iterative improvement routine. Of the samples in Tables 1, 2 and 3, the largest error, 0.22 n.mi., is the first entry in Table 1. From the chart LCNC-2, it estimated that the angle of intersection of the two hyperbolic lines of position is about 5 degrees and so an error of 0.22 n.mi. should not be unexpected.

Table 1. Colocated Master Stations

Position		Predicted ITD's		HP-41CV Fix		
Lat	Long	9940W	9940X	Lat(N)	Long(W)	Error n.mi
31°	123°	16413.28	27570.93	30°59'47"	123°00'03"	0.22
37°	126°	15610.11	27020.50	36°59'53"	126°00'09"	0.17
42°	129°	13881.78	27285.58	42°00'00"	129°00'00"	0
44°	132°	13180.89	27371.19	44°00'00"	132°00'01"	0.01
48°	135°	12301.25	27552.06	48°00'01"	135°00'03"	0.03
50°	138°	12068.67	27584.22	50°00'01"	138°00'04"	0.05

Table 2. Colocated Slave Stations

Position		Predicted ITD's		HP-41CV Fix		
Lat	Long	9940W	5990Y	Lat(N)	Long(W)	Error n.mi
31°	123°	16413.28	27177.18	31°00'03"	122°59'58"	0.06
37°	126°	15610.11	27403.20	37°00'01"	125°59'59"	0.01
42°	129°	13881.78	27955.45	42°00'00"	129°00'00"	0
44°	132°	13180.89	28512.90	44°00'00"	132°00'00"	0
48°	135°	12301.25	29413.61	48°00'00"	134°59'59"	0.01
50°	138°	12068.67	29816.84	50°00'00"	137°59'59"	0.02

Table 3. Colocated Master and Slave Stations

Position		Predicted ITD's		HP-41CV Fix		
Lat	Long	5930Y	9960W	Lat(N)	Long(W)	Error n.mi
44°	63°	29864.46	11685.15	44°00'00"	63°00'00"	0
41°	66°	30585.61	12946.91	41°00'00"	66°00'00"	0
39°	69°	31020.46	14111.31	39°00'00"	69°00'00"	0
35°	72°	31064.57	15139.48	35°00'00"	72°00'00"	0
30°	75°	31040.82	15610.46	29°59'59"	75°00'01"	0.02
26°	78°	31106.20	15858.46	25°59'57"	78°00'02"	0.05

J. References

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2. G. Hefley, The Development of Loran-C Navigation and Timing, National Bureau of Standards Monograph 129, U.S. Department of Commerce, U.S. Government Printing Office, Washington, D.C. 20402, October 1972.

3. R. H. Shudde, "An Algorithm for Position Determination Using Loran-C Triplets with a BASIC Program for the Commodore 2001 Microcomputer", Technical Report NPS55-80-009, March 1980, Naval Postgraduate School, Monterey, CA 93940.

4. General Specifications for Loran-C (20 June 1977) and Loran-C Constants were obtained from the Chief, Navigation Department, Defense Mapping Agency, Hydrographic/Topographic Center, Washington, D.C. 20315.

5. Paul D. Thomas, "Spheroidal Geodesics, Reference Systems, and Local Geometry", PS-138, U.S. Naval Oceanographic Office, Washington, D.C., January 1970.

6. R. H. Shudde, "Position Determination with LORAN-C Triplets and the Hewlett-Packard HP-67/97 Programmable Calculators", Technical Report NPS55-80-010, March 1980, Naval Postgraduate School, Monterey, CA 93940.

7. R. H. Shudde, "Position Determination with LORAN-C Triplets and the Texas Instruments TI-59 Programmable Calculator", Technical Report NPS55-80-020, May 1980, Naval Postgraduate School, Monterey, CA 93940.

Appendix A: Program Storage Allocations, Flag Usage and Program Listing

Program Size: 42

Registers:

R00 - R13: Scratch storage

R14: Flattening

2nd Sta. Pair	Variable	1st Sta. Pair
R15:	2a	
R16:	ID	:R26
R17:	$T_B + p(T_B)$	:R27
R18:	2c	:R28
R19:	CD	:R29
R20:	θ master	:R30
R21:	λ master	:R31
R22:	α master-slave	:R32
R23:	θ slave	:R33
R24:	λ slave	:R34
R25:	α slave-master	:R35
	2a	:P36
R37:	θ fix	
R38:	λ fix	
R39:	α fix-dest	
R40:	θ dest	
R41:	λ dest	

Flag Usage:

F00: 1. Requery erroneous ITD at LBL06

2. Echo two data sets at LBL ED

F01: PR and CA interlock

F03: Set for 2nd solution

F05: Set if slave at vertex of 2nd station pair

F06: Set if slave at vertex of 1st station pair

F07: Set for XMEM functions, clear for tape functions

F08: DN and DH interlock

F09: Set if DMS conversion required

F10: 1. SW and AS interlock

2. Input interlock in FI vertex check

F14: PR and CA loop control

01◆LBL "LOR ANE"	DIRECT SOLUTION	38 ENTER↑	
02◆LBL 90	θ_1, λ_1, α_{12} and S/a_e are in the T, Z, Y and X registers	39 ENTER↑	
03 STO 00		40 RCL 07	
04 CLX		41 RCL 06	
05 .		42 *	
06 P-R		43 -	
07 STO 01	cos α_{12}	44 *	
08 RDN		45 STO 09	D
09 CHS		46 1/X	
10 STO 02	- sin α_{12}	47 RCL 08	
11 RDN		48 *	
12 STO 03	λ_1	49 1	
13 CLX		50 RCL 07	
14 1		51 RCL 06	
15 P-R		52 *	
16 STO 04	cos θ_1	53 2	
17 RCL 02		54 /	
18 *		55 +	
19 STO 06	M	56 *	
20 X<>Y		57 STO 10	P
21 STO 05	sin θ_1	58 RCL 04	
22 X<>Y		59 RCL 01	
23 RCL 14	f	60 *	
24 *		61 STO 11	N
25 STO 07	c_1	62 RCL 05	
26 1		63 RAD	
27 RCL 06		64 R-P	
28 X↑2		65 X<>Y	
29 -		66 STO 12	σ_1
30 4		67 RCL 00	
31 /		68 RCL 09	
32 RCL 14		69 /	
33 *		70 STO 09	
34 STO 08	c_2	71 RCL 12	
35 1		72 -	
36 -		73 CHS	
37 CHS		74 ENTER↑	
		75 +	

Program Listing

01◆LBL "LOR ANC"	DIRECT SOLUTION	38 ENTER↑	
		39 ENTER↑	
02◆LBL 90	θ_1, λ_1, α_{12} and S/a_e are in the T, Z, Y and X registers	40 RCL 07	
03 STO 00		41 RCL 06	
04 CLX		42 *	
05 1		43 -	
06 P-R		44 *	
07 STO 01	$\cos \alpha_{12}$	45 STO 09	D
08 RDN		46 1/X	
09 CHS		47 RCL 08	
10 STO 02	$- \sin \alpha_{12}$	48 *	
11 RDN		49 1	
12 STO 03	λ_1	50 RCL 07	
13 CLX		51 RCL 06	
14 1		52 *	
15 P-R		53 2	
16 STO 04	$\cos \theta_1$	54 /	
17 RCL 02		55 +	
18 *		56 *	
19 STO 06	M	57 STO 10	P
20 X<>Y		58 RCL 04	
21 STO 05	$\sin \theta_1$	59 RCL 01	
22 X<>Y		60 *	
23 RCL 14	f	61 STO 11	N
24 *		62 RCL 05	
25 STO 07	c_1	63 RAD	
26 1		64 R-P	
27 RCL 06		65 X<>Y	
28 X↑2		66 STO 12	σ_1
29 -		67 RCL 00	
30 4		68 RCL 09	
31 /		69 /	
32 RCL 14		70 STO 09	
33 *		71 RCL 12	
34 STO 08	c_2	72 -	
35 1		73 CHS	
36 -		74 ENTER↑	
37 CHS		75 +	

Program Listing

76 STO 13	u	114 RCL 09	
77 COS		115 +	
78 RCL 10		116 STO 13	
79 *		117 1	
80 ENTER↑		118 P-R	
81 +		119 RCL 11	
82 1		120 *	N cos $\Delta\sigma$
83 -		121 X<>Y	
84 CHS	w	122 RCL 05	
85 RCL 13		123 *	
86 RCL 09		124 -	
87 +		125 STO 10	N cos $\Delta\sigma$ - sin θ_1 sin $\Delta\sigma$
88 COS		126 X↑2	
89 STO 13	V	127 RCL 06	
90 X↑2		128 X↑2	M^2
91 ENTER↑		129 +	
92 +		130 SQRT	K
93 1		131 1/X	
94 -		132 RCL 13	
95 RCL 09	d	133 1	
96 1		134 P-R	
97 P-R		135 RCL 05	
98 *		136 *	
99 *		137 X<>Y	
100 RCL 08		138 RCL 11	
101 X↑2		139 *	
102 *	X	140 +	
103 X<>Y		141 *	
104 RCL 13	V	142 ATAN	
105 *		143 R-D	
106 RCL 10	P	144 STO 09	θ_2
107 *		145 RCL 13	
108 RCL 09	d	146 SIN	
109 SIN		147 RCL 02	
110 *		148 *	
111 ENTER↑		149 RCL 13	
112 +	Y	150 1	
113 -		151 P-R	

152 RCL 04		190 R-P	
153 *		191 CLX	
154 X<>Y		192 RCL 06	
155 RCL 05		193 CHS	
156 *		194 RCL 10	
157 RCL 01		195 CHS	
158 *		196 R-P	
159 -		197 RDN	
160 R-P	$\Delta\eta$	198 X<>Y	α_{21}, λ_2 and θ_2 are in the
161 CLX		199 RCL 09	Z, Y and X registers
162 1		200 RTN	
163 RCL 08		201♦LBL 80	REVERSE SOLUTION
164 -		202 X<>Y	
165 RCL 07		203 RDN	Stack contains θ_1, λ_1, θ_2
166 *		204 -	and λ_2 in the T,Z,Y and
167 RCL 13		205 CHS	
168 *		206 STO 00	$\Delta\lambda$ X registers
169 RCL 12		207 RDN	
170 ENTER↑		208 -	
171 +		209 LASTX	
172 RCL 13		210 X<>Y	
173 -		211 2	
174 COS		212 /	$\Delta\theta_m$
175 RCL 13		213 ENTER↑	
176 SIN		214 ENTER↑	
177 *		215 1	
178 RCL 07		216 P-R	
179 *		217 STO 01	cos $\Delta\theta_m$
180 RCL 08		218 X↑2	
181 *		219 RDN	
182 -	H	220 STO 02	sin $\Delta\theta_m$
183 -		221 RDN	
184 R-D		222 +	
185 RCL 03		223 1	
186 +		224 P-R	
187 DEG	λ_2	225 STO 03	cos θ_m
188 1		226 RDN	
189 P-R		227 STO 04	sin θ_m

228 X↑2		266 -	
229 -	H	267 STO 08	Y
230 RCL 00		268 RCL 06	
231 2		269 ENTER↑	
232 /		270 SIN	
233 SIN		271 /	
234 X↑2		272 STO 05	T
235 *		273 ENTER↑	
236 RCL 02		274 +	
237 X↑2		275 X↑2	
238 +		276 STO 09	D
239 STO 05	L	277 RCL 06	
240 SQRT		278 COS	
241 RAD		279 ENTER↑	
242 ASIN		280 +	
243 ENTER↑		281 STO 10	E
244 +		282 *	
245 STO 06	d	283 STO 11	A
246 RCL 04		284 RCL 10	
247 RCL 01		285 -	
248 *		286 2	
249 X↑2		287 /	
250 ENTER↑		288 RCL 05	
251 +		289 -	
252 1		290 CHS	C
253 RCL 05		291 RCL 07	
254 -		292 *	
255 /		293 RCL 11	
256 STO 07	U	294 +	
257 RCL 02		295 RCL 07	
258 RCL 03		296 *	n_1
259 *		297 RCL 09	
260 X↑2		298 ENTER↑	
261 ENTER↑		299 +	
262 +		300 STO 12	B
263 RCL 05		301 RCL 10	
264 /	V	302 RCL 08	
265 ST+ 07	X	303 *	

304 +		342 RCL 07	
305 RCL 08		343 *	
306 *	n_2	344 -	
307 -		345 RCL 12	
308 RCL 09		346 4	
309 RCL 07		347 +	
310 *		348 RCL 08	
311 RCL 08		349 *	M
312 *	n_3	350 -	
313 +		351 64	
314 64		352 /	
315 /		353 RCL 14	
316 RCL 14		354 *	fM/64
317 *	$\delta_2 d/f$	355 RCL 05	
318 RCL 05		356 2	
319 RCL 07		357 /	
320 *		358 +	
321 RCL 08		359 RCL 14	
322 -		360 *	G
323 4		361 RCL 08	
324 /		362 ENTER↑	
325 -	$\delta_2 d/f - \delta_1 d/f$	363 +	
326 RCL 14		364 4	
327 *		365 RCL 07	
328 RCL 05		366 -	
329 +	$T - \delta_1 d + \delta_2 d$	367 RCL 10	
330 RCL 06		368 *	
331 SIN		369 -	
332 *		370 *	F_{FG}
333 STO 13	S/a_e	371 RCL 00	
334 RCL 05		372 DEG	
335 32		373 TAN	
336 *		374 *	
337 RCL 05		375 4	
338 20		376 /	
339 *		377 CHS	Q
340 RCL 11		378 R-D	
341 -		379 RCL 00	

380 +	
381 2	
382 /	
383 STO 09	$\Delta\lambda'_m$
384 1	
385 P-R	
386 RCL 02	
387 *	
388 X<>Y	
389 RCL 03	
390 *	
391 R-P	
392 RDN	
393 STO 12	t_1
394 RCL 09	
395 1	
396 P-R	
397 RCL 01	
398 *	
399 CHS	
400 X<>Y	
401 RCL 04	
402 *	
403 R-P	
404 RDN	t_2
405 ST+ 12	α_{12}
406 -	
407 1	
408 P-R	
409 R-P	α_{21}
410 RCL 12	
411 X<>Y	
412 P-R	
413 R-P	
414 CLX	
415 RCL 13	Stack contains α_{21}, α_{12} and S/a_e in the Z,Y and X registers
416 RTN	

417♦LBL "MI"	MANUAL INPUT ROUTINE
418 XEQ "SW"	Swap registers, then input data
419 XEQ 15	
420 GTO 50	
421♦LBL "CR"	CARD INPUT ROUTINE
422 CF 21	Clear AVIEW flag
423 26.035	
424 "1ST CARD"	
425 AVIEW	
426 XROM 30,03	RDTAX - wait for data card
427 16.025	
428 "2ND CARD"	
429 AVIEW	
430 XROM 30,03	RDTAX - wait for data card
431 SF 10	Set input interlock
432 GTO 50	
433♦LBL 35	FIND TRIPLET VERTEX
434 SF 21	Set AVIEW flag
435 RCL 16	
436 RCL 26	
437 X≠Y?	ID2 = ID1 ?
438 GTO 11	
439 TONE 1	Error if "yes".
440 "E: ID1 = ID2"	
441 AVIEW	
442 GTO 50	- - - - - - - - - - - - - -
443♦LBL 11	
444 CF 05	
445 CF 06	
446 RCL 20	
447 RCL 30	Master 2 and Master 1 colocated?
448 -	
449 RCL 21	

450 RCL 31	
451 -	
452 +	
453 X=0?	
454 RTN	
455 SF 05	
456 RCL 23	Slave 2
457 RCL 30	and
458 -	Master 1 Colocated?
459 RCL 24	
460 RCL 31	
461 -	
462 +	
463 X=0?	
464 RTN	
465 SF 06	
466 RCL 23	Slave 2
467 RCL 33	and
468 -	Slave 1 Colocated?
469 RCL 24	
470 RCL 34	
471 -	
472 +	
473 X=0?	
474 RTN	
475 CF 05	
476 RCL 20	Master 2
477 RCL 33	and
478 -	Slave 1 Colocated?
479 RCL 21	
480 RCL 34	
481 -	
482 +	
483 X=0?	
484 RTN	
485 TONE 1	
486 "E: NO TRIPLET"	No triplet found

487 AVIEW	
488 GTO 50	
489♦LBL "PR"	PREDICT ITD ROUTINE
490 SF 01	
491 GTO 02	
492♦LBL "CA"	CALIBRATE ROUTINE
493 CF 01	
494♦LBL 02	CA and PR input routine
495 FIX 4	
496 XEQ 51	Flattening Factor
497 SF 21	Set AVIEW flag
498 SF 14	Set loop control
499 ADV	
500 "LAT? "	
501 XEQ 99	Input
502 XEQ 14	latitude
503 STO 37	
504 "LON? "	Input
505 XEQ 99	longitude
506 STO 38	
507♦LBL 66	Begin loop
508 FS? 01	*Transfer if PR input*
509 GTO 02	
510 ": "	
511 ASTO 00	
512 BEEP	Input benchmark
513 "ITD "	
514 ARCL 26	ITD.
515 ARCL 00	
516 XEQ 99	
517 STO 39	Initialize CA calculation
518 CLX	
519 GTO 08	Transfer
520♦LBL 02	
521 CLX	Initialize PR calculation
522 STO 39	
523♦LBL 08	CA and PR computations
524 RCL 37	

525 RCL 38	
526 RCL 33	Load stack.
527 RCL 34	
528 XEQ 80	Reverse solution from Slave.
529 XEQ 03	Secondary phase corr.
530 ST- 39	
531 RCL 37	
532 RCL 38	
533 RCL 30	Load stack.
534 RCL 31	
535 XEQ 80	Reverse solution from Master
536 XEQ 03	Secondary phase correction.
537 RCL 39	
538 +	
539 FS? 01	
540 GTO 02	Branch for PR
541 RCL 29	
542 -	Correct baseline to benchmark
543 STO 27	
544 GTO 08	
545♦LBL 02	Compute predicted ITD.
546 CHS	
547 RCL 27	
548 +	
549 RCL 29	
550 +	
551 ": "	
552 ASTO 00	Display
553 CLA	
554 ARCL 26	predicted
555 ARCL 00	ITD
556 FIX 2	
557 ARCL X	
558 BEEP	
559 AVIEW	
560♦LBL 08	
561 XEQ "SW"	Swap station data
562 FS?C 14	

563 GTO 66	Loop for second station
564 CF 01	
565 GTO 50	Done
566♦LBL "CS"	CARD STORE ROUTINE
567 16.025	
568 CF 21	
569 "WRITE: "	
570 ARCL 16	Prompt with station ITD
571 AVIEW	
572 XROM 30,08	WDATX
573♦LBL 50	"NEXT OPTION?"
574 CF 21	
575 TONE 6	Query
576 "NEXT OPTION?"	
577 AVIEW	
578 STOP	
579 GTO 50	
580♦LBL 51	STORE FLATTENING FACTOR
581 DEG	
582 298.26	
583 1/X	
584 STO 14	
585 RTN	
586♦LBL 44	CONVERT
587♦LBL 14	GEOGRAPHIC LATITUDE
588 TAN	TO
589 1	
590 RCL 14	PARAMETRIC LATITUDE
591 -	
592 *	
593 ATAN	
594 RTN	
595♦LBL 15	STATION DATA
596 ADV	INPUT PROMPTS
597 FIX 0	

598 SF 21	
599 CF 23	Clear alpha entry flag
600 "ID? "	
601 AON	
602 PROMPT	
603 ASTO X	Input station ID
604 CLA	
605 AOFF	
606 FC? 23	
607 RTN	
608 SF 09	
609 XEQ 01	Input
610 STO 16	Coding
611 "CODE DE LAY? "	delay
612 XEQ 00	
613 STO 19	
614 FIX 6	Input master
615 "MS LAT? "	station latitude.
616 XEQ 00	
617 XEQ 14	Convert to Parametric.
618 STO 20	
619 "MS LON? "	Input master station longitude.
620 XEQ 00	
621 STO 21	
622 "SS LAT? "	Input Slave station latitude.
623 XEQ 00	
624 XEQ 14	Convert to parametric.
625 STO 23	
626 "SS LON? "	Input Slave station longitude.
627 XEQ 00	
628 STO 24	
629 RCL 20	
630 RDN	

631 XEQ 80	Compute reverse solution to determine baseline and master-slave forward and reverse azimuths.
632 STO 18	
633 RDN	
634 STO 22	
635 RDN	
636 STO 25	
637 RCL 18	
638 XEQ 03	Add secondary phase correction to baseline.
639 STO 17	
640 RTN	
641♦LBL 99	DATA INPUT PROMPT AND PRINT
642♦LBL 00	
643 PROMPT	
644♦LBL 01	
645 ARCL X	
646 SF 25	Set error ignore flag
647 FS? 55	Print
648 PRA	
649 CF 25	Clear error ignore flag
650 FC?C 09	Convert DMS to DEG if FØ9 clear.
651 HR	
652 RTN	
653♦LBL 03	SECONDARY PHASE CORRECTION
654 21282.36	$a_e \eta / V_o$
655 *	
656 ENTER↑	
657 ENTER↑	
658 537	
659 X>Y?	
660 GTO 04	- - - - - - - - - - - - -
661 CLX	
662 129	
663 X<>Y	$T \geq 537$ µS
664 /	
665 LASTX	
666 6458 E-7	
667 *	
668 +	

669 .408 670 - 671 + 672 RTN	
673◆LBL 04 674 CLX 675 2.74 676 X<>Y 677 / 678 LASTX 679 33 E-5 680 * 681 + 682 .011 683 - 684 + 685 RTN	$T < 537\ \mu S$
686◆LBL 05 687 CF 00 688 LASTX 689 X<=Y? 690 GTO 06 691 CHS 692 X>Y? 693 GTO 06 694 CLX 695 21295.87 696 / 697 RTN	TIME DELAY VALIDITY CHECK Okay if $\lvert TD \rvert < T_B + p(T_B)$ a_p 2a in X-register
698◆LBL 06 699 SF 21 700 SF 00 701 TONE 1 702 "E: ITD ERROR" 703 AVIEW 704 RTN	ITD input error Set FØØ to requery.

705◆LBL "FI" 706 FS?C 10 707 XEQ 35 708 SF 21 709 ADV	FIXING ALGORITHM Find vertex if interloc flag 1Ø is set.
710◆LBL 10 711 XEQ 51 712 SF 09 713 FIX 2	Generate flattening No DMS conversion
714 " " 715 ASTO 01 716 "ITD: " 717 ASTO 00 718 ARCL 26 719 ARCL 01 720 XEQ 00	Input ITD of 1st pair
721 RCL 29 722 - 723 RCL 27 724 -	Compute TD
725 XEQ 05	TD validity check
726 FS?C 00 727 GTO 10 728 STO 36	Requery ITD Store $2a_1$
729◆LBL 07 730 SF 09	No DMS conversion
731 CLA 732 ARCL 00 733 ARCL 16 734 ARCL 01 735 XEQ 00	Input ITD of 2nd pair
736 RCL 19 737 - 738 RCL 17 739 -	Compute TD
740 XEQ 05	TD validity check
741 FS?C 00 742 GTO 07	Requery ITD

743 STO 15	Store $2a_2$	781 RCL 01	
744◆LBL 18	ALTERNATE SOLUTION entry.	782 *	
745 FS? 10	Input ITD's if vertex	783 RCL 02	
746 GTO "FI"	interlock set.	784 RCL 04	K
747 XEQ 51	Regenerate flattening	785 *	
748 RAD		786 -	
749 RCL 15		787 STO 07	
750 1		788 DEG	
751 P-R		789 RCL 22	
752 X<>Y		790 FS? 05	Station 2 vertex flag
753 FS? 05	Station 2 vertex flag	791 RCL 25	
754 CHS		792 STO 11	
755 STO 01	A_2	793 RCL 05	
756 CLX		794 RCL 03	
757 RCL 18		795 *	
758 1		796 P-R	
759 P-R		797 STO 08	$B_1C_2 \cos \xi_2$
760 X<>Y		798 RDN	
761 STO 03	C_2	799 STO 09	$B_1C_2 \sin \xi_2$
762 RDN		800 RCL 32	
763 -		801 FS? 06	Station 1 vertex flag
764 STO 02	B_2	802 RCL 35	
765 RCL 36		803 RCL 02	
766 1		804 RCL 06	
767 P-R		805 *	
768 X<>Y		806 P-R	
769 FS? 06	Station 1 vertex flag	807 RCL 08	
770 CHS		808 -	C
771 STO 04	A_1	809 X<>Y	
772 CLX		810 RCL 09	
773 RCL 28		811 -	S
774 1		812 X<>Y	
775 P-R		813 R-P	ρ and γ
776 X<>Y		814 RCL 07	
777 STO 06	C_1	815 X<>Y	
778 RDN		816 /	
779 -		817 ACOS	$\cos^{-1}(K/\rho)$
780 STO 05	B_1	818 FS? 03	Alternate solution?

819 CHS	
820 +	
821 STO 10	$\alpha = \gamma \pm \cos^{-1}(K/\rho)$
822 RCL 11	
823 -	
824 COS	
825 RCL 03	
826 *	
827 RCL 01	
828 +	$C_2 \cos(\alpha-\xi_2) + A_2$
829 RCL 02	
830 X<>Y	
831 R-P	
832 RDN	
833 D-R	
334 STO 12	r
835 RCL 20	
836 RCL 21	
837 FC? 05	Station 2 vertex flag
838 GTO 09	
839 RCL 23	
840 RCL 24	- - - - - - - - - - - - - -
841♦LBL 09	
842 RCL 10	
843 RCL 12	
844 XEQ 90	Compute direct solution
845 STO 37	θ_{fix}
846 FIX 4	
847 XEQ 19	θ_{fix}
848 SF 21	
849 "LAT: "	
850 ARCL X	Display latitude
851 BEEP	
852 AVIEW	
853 RDN	
854 STO 38	λ_{fix}
855 XEQ 20	
856 "LON: "	

857 ARCL X	
858 AVIEW	Display longitude
859 GTO 50	
860♦LBL 19	CONVERT PARAMETRIC LATITUDE TO GEOGRAPHIC LATITUDE
861 TAN	
862 1	
863 RCL 14	
864 -	
865 /	
866 ATAN	
867♦LBL 20	DMS ROUNDING ROUTINE
868 HMS	
869 RND	
870 0	
871 HMS+	
872 RTN	
873♦LBL "DH"	DISTANCE AND HEADING Any origin to any destination
874 SF 21	
875 ADV	
876 XEQ 51	
877 "ORIG LAT? "	Input origin latitude
878 XEQ 99	
879 XEQ 44	Convert to parametric
880 STO 37	
881 "ORIG LON? "	Input origin longitude
882 XEQ 99	
883 STO 38	
884 SF 08	Set FØ8 to compute
885♦LBL "DN"	STORE DESTINATION
886 SF 21	
887 FC? 08	
888 ADV	
889 XEQ 51	
890 "DEST LAT? "	Input destination latitude
891 XEQ 99	

892 XEQ 44	Convert to parametric
893 STO 40 894 "DEST LO N? "	Input destination longitude
895 XEQ 99 896 STO 41	
897 FC?C 08 898 GTO 50	Return if FØ8 not set to compute.
899♦LBL "HD" 900 RCL 37 901 RCL 38 902 RCL 40 903 RCL 41	COMPUTE DISTANCE AND HEADING
904 XEQ 80	Compute reverse solution
905 3443.917 906 *	Convert distance to n. mi.
907 BEEP 908 SF 21 909 "N.MI: " 910 FIX 2 911 ARCL X 912 AVIEW	Display distance
913 RDN 914 FIX 4 915 360 916 MOD	0° ≤ bearing < 360°
917 STO 39 918 XEQ 20	Round DMS
919 "BRG: " 920 ARCL X 921 AVIEW 922 GTO 50	Display bearing
923♦LBL "AS"	COMPUTE ALTERNATE SOLUTION
924 FS?C 03 925 GTO 18 926 SF 03 927 GTO 18	Toggle FØ3

928♦LBL "ED" 929 SF 00 930 XEQ "SW" 931 XEQ 13 932 XEQ "SW" 933 XEQ 13	ECHO DATA ROUTINE
934♦LBL "CE" 935 CF 21 936 16.025 937 "STA. CA RD" 938 AVIEW	CARD ECHO ROUTINE
939 XROM 30, 03	RDTAX
940♦LBL 13	Data review of R16-R25
941 FIX 0 942 XEQ 51	Regenerate flattening
943 SF 21 944 ADV 945 "ID: " 946 ARCL 16 947 AVIEW	Display station ID
948 "CD: " 949 ARCL 19 950 AVIEW	Display coding delay
951 "MLT: " 952 RCL 20 953 FIX 6 954 XEQ 19 955 ARCL X 956 AVIEW	Display master station latitude
957 "MLN: " 958 RCL 21 959 XEQ 20 960 ARCL X 961 AVIEW 962 "SLT: " 963 RCL 23	Display master station longitude

964 XEQ 19	Display slave station latitude
965 ARCL X	
966 AVIEW	
967 "SLN: "	
968 RCL 24	Display slave station longitude
969 XEQ 20	
970 ARCL X	
971 AVIEW	
972 FIX 3	Display base line in microseconds
973 "BL: "	
974 ARCL 17	
975 AVIEW	
976 FS?C 00	
977 RTN	
978 GTO 50	
979♦LBL "SW"	SWAP STATION DATA Swaps R16-R25 with R26-R35
980 SF 10	
981 35.025	
982 STO 01	
983 25	
984 STO 02	
985♦LBL 12	Begin loop
986 RCL IND 02	
987 X<> IND 01	
988 STO IND 02	
989 DSE 02	
990 " "	
991 DSE 01	
992 GTO 12	Loop to LBL 12
993 RTN	
994♦LBL "XR"	XMEM RECALL
995 SF 07	
996 GTO 02	
997♦LBL "TR"	TAPE RECALL
998 CF 07	

999♦LBL 02	
1000 XEQ "SW"	Swap data
1001 XEQ 60	ID Prompt
1002 ASTO 16	Store ID
1003 XEQ 08	Set pointer
1004 FS? 07	
1005 XROM 25,21	GETRX - Input from XMEM
1006 FC? 07	
1007 XROM 28,09	READRX - Input from tape
1008 GTO 50	
1009♦LBL "XS"	XMEM STORE
1010 SF 07	
1011 GTO 02	
1012♦LBL "TS"	TAPE STORE
1013 CF 07	
1014♦LBL 02	
1015 CLA	
1016 ARCL 16	Recall ID
1017 9	
1018 FS? 07	
1019 XROM 25,11	CRFLD - XMEM create
1020 FC? 07	
1021 XROM 28,01	CREATE - Tape create
1022 XEQ 08	Set pointer & register range
1023 FS? 07	
1024 XROM 25,40	SAVERX-Save in XMEM
1025 FC? 07	
1026 XROM 28,22	WRTRX - Save on tape
1027 GTO 50	

1028◆LBL "XD" 1029 SF 07 1030 GTO 02	XMEM DELETE
1031◆LBL "TD" 1032 CF 07	TAPE DELETE
1033◆LBL 02 1034 XEQ 60 1035 FS? 07 1036 XROM 25,31 1037 FC? 07 1038 XROM 28,04 1039 GTO 50	- - - - - - - - - - - - - - - PURFL - Purge from XMEM PURGE - Purge from tape
1040◆LBL 60 1041 CF 21 1042 "ID?" 1043 AON 1044 PROMPT 1045 AOFF 1046 RTN	ID INPUT PROMPT
1047◆LBL 08 1048 0 1049 FS? 07 1050 XROM 25,43 1051 FC? 07 1052 XROM 28,14 1053 17.025 1054 .END.	SET POINTER SEEKPT - Set XMEM pointer to zero SEEKR - Set tape pointer to zero R17-R25 to be transmitted.

Appendix B: STATION COVERAGE

Station	No. of Pairs	Location
4990	2	Central Pacific
5930	2	East Coast, Canada
5990	3	West Coast, Canada
7930	3	North Atlantic
7960	2	Gulf of Alaska
7970	4	Norwegian Sea
7980	4	Southeast U.S.A.
7990	3	Mediterranean Sea
8970	3	Great Lakes
9940	3	West coast, U.S.A.
9960	4	Northeast U.S.A.
9970	4	Northwest Pacific
9990	3	North Pacific

Appendix C: LORAN-C STATION DATA

The following list contains the pertinent parameters for each Loran-C station pair. This list was compiled from the data in Reference 4. Each column contains the following information:

1. The Loran-C station pair designator.
2. The coding delay.
3. The master station latitude.
4. The master station longitude.
5. The slave station latitude.
6. The slave station longitude.

In this list, positive longitudes are West, negative longitudes are East, positive latitudes are North and negative latitudes are South. In columns 3 through 6 the latitudes and longitudes appear to be in decimal form, but the actual format is DDD.MMSSFF (which is compatible with the HP-41CV D.MS or H.MS input mode) where

DDD designates degrees,
MM designates minutes,
SS designates seconds, and
FF designates hundredths of seconds.

ID	CD	MS [illegible]	[illegible]	SS LAT	SS LON
4990X	11000	[illegible]	[illegible]	20.144916	155.530970
4990Y	29000	[illegible]	[illegible]	28.234177	178.173020
5930X	11000	[illegible]	[illegible]	41.151193	069.583909
5930Y	25000	[illegible]	067.553771	46.463218	053.102816
5990X	11000	[illegible]	122.220224	55.262085	131.151965
5990Y	27000	[illegible]	[illegible]	47.034799	119.443953
5990Z	41000	[illegible]	122.220224	50.362972	127.212935
7930W	11000	[illegible]	[illegible]	64.542658	023.552175
7930X	21000	[illegible]	[illegible]	62.175968	007.042671
7930Z	43000	[illegible]	[illegible]	46.463218	053.102816
7960X	11000	[illegible]	[illegible]	57.262021	152.221122
7960Y	26000	[illegible]	[illegible]	55.262085	131.151965
7970W	36000	[illegible]	[illegible]	54.462980	-008.173633
7970X	11000	[illegible]	[illegible]	68.380615	-014.274700
7970Y	46000	[illegible]	[illegible]	64.542658	+023.552175
7970Z	60000	[illegible]	[illegible]	70.545261	+008.435869
7980W	11000	[illegible]	085.100930	30.433302	090.494360
7980X	23000	[illegible]	[illegible]	26.315501	097.500009
7980Y	43000	[illegible]	085.100930	27.015849	080.065352
7980Z	59000	[illegible]	085.100930	34.034604	077.544676
7990X	11000	[illegible]	-016.430596	35.312088	-012.312996
7990Y	29000	[illegible]	-016.430596	40.582095	-027.520152
7990Z	47000	[illegible]	-016.430596	42.033649	-003.121590
8970W	11000	[illegible]	087.291214	30.593874	085.100930
8970X	28000	[illegible]	087.291214	42.425060	076.493386
8970Y	44000	[illegible]	087.291214	48.364984	094.331847
9940W	11000	[illegible]	118.495637	47.034799	119.443953
9940X	27000	[illegible]	118.495637	38.465699	122.294453
9940Y	40000	[illegible]	118.495637	35.191818	114.481743
9960W	11000	[illegible]	076.493386	46.482720	067.553771
9960X	25000	[illegible]	076.493386	41.151193	069.583909
9960Y	39000	[illegible]	076.493386	34.034604	077.544676
9960Z	54000	[illegible]	[illegible]	39.510754	087.291214
9970W	11000	[illegible]	-141.19290	[illegible]	-153.58515
9970X	30000	[illegible]	[illegible]	[illegible]	-143.430906
9970Y	55000	[illegible]	-141.19290	26.362499	-128.085621
9970Z	75000	[illegible]	-141.19290	09.324566	-138.095523
9990X	11000	57.090988	+170.145981	52.494505	-173.105231
9990Y	29000	[illegible]	[illegible]	65.141012	+166.531447
9990Z	43000	57.090988	+170.145981	57.262021	+152.221122

EAST AND SOUTH ARE MINUS '-'

Appendix D: COLOCATED STATIONS

5930 MASTER	-	9960W
5930X	-	9960X
5930Y	-	7930Z
5990X	-	7960Y
5990Y	-	9940W
7930W	-	7970Y
7930X	-	7970 MASTER
7960X	-	9990Z
7980Z	-	9960Y
7980 MASTER	-	8970W
8970X	-	9960 MASTER
8970 MASTER	-	9960Z

Slave stations are denoted with a letter suffix. Master stations are so designated.

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