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13. ABSTRACT

The Omega navigation system is a vlf radio navigation system which will provide worldwide coverage with an accuracy of 1 to 2 mi or better using eight transmitting stations. This absolute accuracy is limited by the stability of the phase velocity and the ability to predict it. The relative accuracy of the Omega system, the determination of the distance between two receivers, is much better than the geographic accuracy of 1 or 2 mi because the propagation variations over a comparatively small area are correlated.

This report gives the results of the relative accuracy of the Omega system, based on a study which was made in the Washington area. Relative accuracies of 350 yd or better were obtained. The maximum receiver separation was 40 mi.

Two type AN/WRN-2(XN-1) Omega monitor receivers were modified to obtain the greatest accuracy possible with this equipment. The data obtained with these equipments on relative Omega in the Washington area showed that a significant portion of the error was instrumental, and if further studies are conducted, improved equipment should be obtained.

DD FORM 1 NOV 65 1473 (PAGE 1)

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CONTENTS

Abstract	ii
Problem Status	ii
Authorization	ii
INTRODUCTION	1
PROCEDURES	1
CALCULATIONS AND RESULTS	3
SUMMARY	34
CONCLUSIONS	34
RECOMMENDATIONS	35
ACKNOWLEDGMENTS	35
REFERENCES	35

ABSTRACT

The Omega navigation system is a vlf radio navigation system which will provide world-wide coverage with an accuracy of 1 to 2 mi or better using eight transmitting stations. This absolute accuracy is limited by the stability of the phase velocity and the ability to predict it. The relative accuracy of the Omega system, the determination of the distance between two receivers, is much better than the geographic accuracy of 1 or 2 mi because the propagation variations over a comparatively small area are correlated.

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Two type AN/WRN-2(XN-1) Omega monitor receivers were modified to obtain the greatest accuracy possible with this equipment. The data obtained with these equipments on relative Omega in the Washington area showed that a significant portion of the error was instrumental, and if further studies are conducted, improved equipment should be obtained.

PROBLEM STATUS

This is an interim report on one phase of this problem; work is continuing on this and other phases.

AUTHORIZATION

NRL Problem R04-11
Project SS 161-001-6154

Manuscript submitted March 23, 1970.

ACCURACY STUDIES OF THE DIFFERENTIAL OMEGA TECHNIQUE

INTRODUCTION

Omega is a vlf radio navigation system which will provide worldwide coverage with eight transmitting stations. Each station transmits in sequence for short periods of approximately 1 sec each. The navigator's receiver measures the phase difference between a pair of stations to get a line-of-position (LOP). A fix is made by obtaining a second LOP. The basic Omega frequency is 10.2 kHz, so lines of equal phase difference will be repeated at approximately 8-mi intervals on the base line. A lane resolution system is provided by the transmission of 13.6-kHz and 11-1/3-kHz signals. The difference frequencies between these and the 10.2-kHz transmissions provide a lane resolution system that is approximately 72 mi in width.

The accuracy of the system is 1 to 2 mi when it is used as a general navigational aid. This accuracy is limited in part by the stability of the phase velocity and the ability to predict it. The phase velocity has spatial, diurnal, and annual variations. Correction tables are prepared in advance for use by the navigator for application to the receiver reading so that the proper charted values can be obtained. Fully automatic receivers, such as the AN/ARN-99 aircraft receiver, contain a computer which makes this phase velocity correction in real time; however, the normal shipboard receiver does not have this capability.

The relative accuracy of the Omega system, the determination of the distance between two or more receivers, is much better than the geographic accuracy of 1 to 2 mi because the propagation variations over a comparatively small area are correlated. The relative positions can be determined from simultaneous measurements at each site. The relative accuracy of Omega may also be related to geographic position if the location of one of the receivers is accurately known. The difference between the receiver reading and the charted value of the known location can then be broadcast as a correction factor. Such an operational technique is known as differential Omega.

An example of the use of relative Omega would be the determination of the positions of the ships of a task force with respect to that of a command ship. This could be done in real time without the use of correction factors. If the command ship had a satellite navigation system or other precise means of determining position, the Omega correction factors could be broadcast to the other ships and each ship could be provided a fix only slightly less accurate than that of the command ship.

This is a report on the results of a study of the relative accuracy of Omega. Receiver separations up to 40 mi were used. A preliminary study of differential Omega was made by the Naval Research Laboratory (NRL) in 1966 (1). Both studies show that a major factor in the accuracy of the results was the insufficient accuracy of the receivers that were available for the studies, and that the inherent accuracy of differential Omega could yield much better results.

PROCEDURES

Sites that are controlled by the Navy around the Washington area were chosen for the study of the relative accuracy of the Omega system. The relationship of these sites to

each other is shown in Fig. 1. The coordinates and charted Omega readings for these sites are given in Tables 1 and 2. These coordinates were taken from the best information available, and the data show that the relative accuracy obtained by Omega is of the same order of accuracy as the survey. However, the accuracy of the results was not affected by the survey accuracy, as only the variation in the distance as obtained by the Omega system was used to determine the relative accuracy. If additional investigations are made, and a direct-distance error as obtained by relative Omega is desired, more accurate surveys will be required. In each case, the antenna was located in a position to minimize the effects of power lines, nearby structures, and local noise.

Table 1
Coordinates of Monitor Sites*

Site	Latitude	Longitude	Distance from Waldorf (ft)†
Waldorf	38°38'35.22"N	77°01' 0.17"W	—
Pomonkey	38°33'37.69"N	77°03'36.79"W	32,720
Brandywine	38°40'59.2"N	76°51'08.8"W	49,145
Webster Field	38°09'21.15"N	76°25'46.25"W	244,963

*Yards per centilane (CEL) in area—AC, 190 yd; BC, 170 yd.
†±200 ft.

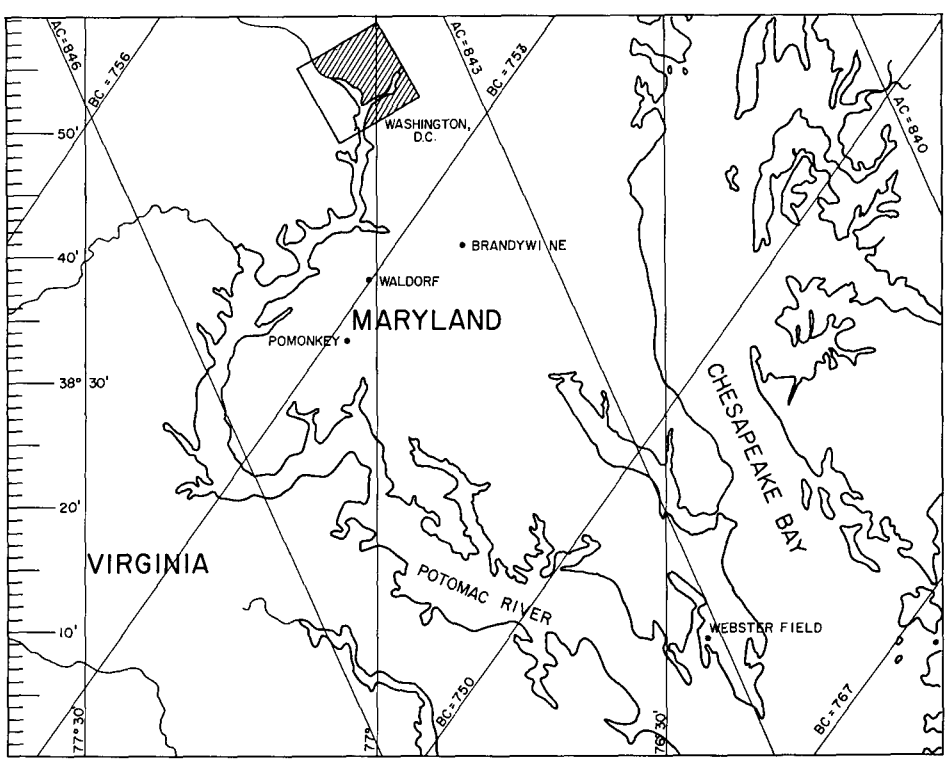

Fig. 1 - Map of monitor locations

Table 2
Charted Omega Readings

LOP	Waldorf	Pomonkey	Difference (CEL)
AC	844.518	844.914	39.6
BC	753.061	752.919	14.2
Brandywine			
AC	844.518	843.706	81.2
BC	753.061	752.503	55.8
Webster Field			
AC	844.518	843.184	133.4
BC	753.061	748.513	454.8

Since there were no equipments available of sufficient accuracy to conduct this investigation, two type AN/WRN-2(XN-1) receivers were modified (2). Briefly, this modification consisted of using a digital readout as a substitute for the analog readout. The data were recorded by a printer, the timing of which was controlled by a precision clock to assure that the data at the two locations would be recorded simultaneously. This modification resulted in instrumental errors of less than 0.6 centicycle (CEC) peak-to-peak at signal-to-noise ratios of 10:1 or better, which was the ultimate practical limit of this equipment.

One set of equipment was permanently installed at Waldorf and is referred to as the fixed monitor. The other equipment was installed in a van and taken alternately to the Pomonkey, Brandywine, and Webster Field sites, as well as Waldorf where it was operated next to the fixed monitor. It is referred to as the mobile monitor in this report; however, it was not operated in motion but with fixed antenna at the surveyed point at each site.

CALCULATIONS AND RESULTS

The terms *differential Omega* and *relative Omega* are sometimes used interchangeably. In this report differential Omega refers to the operational technique of obtaining correction factors by comparing the phase difference of a pair of stations with the charted value of one receiver location which must be accurately known. Relative Omega refers to the determination of the distance between two receivers without regard to geographical position.

Within the general framework of the differential or relative Omega concept, there are some differences in procedure which can affect the accuracy of the system to the user. For example, the most elementary usage of the differential Omega concept would be to broadcast one differential Omega correction from the area monitor each hour. This correction would be applied to the user's readings. Improvement in accuracy could be obtained by the broadcasting of differential Omega corrections as often as every 5 to 10 min, or further, for convenience, there could be instantaneous readings available for automatic data processing. In addition to the possibilities of various time intervals,

various procedural differences can be utilized in the preparation of correction information itself. This broadcasted correction could be an instantaneous monitor reading, an average reading over any number of various time intervals, or yet a third possibility would be that of projecting a slope which would consist of the least-squares trend of the readings throughout a given period. In the latter case, the broadcast correction of the least-squares trend of the data has produced an effect similar to increasing the time constant of the receiver and has reduced the noise excursions of the signal. Toward these procedural differences, then, this section is directed.

Figures 2 through 17 show the effect of using 5-min averages of the instantaneous data points as the differential correction to a user which is similarly averaging instantaneous data points for 5 min. The top portion of these figures shows the 5-min averages of raw data for both the mobile monitor and the fixed monitor site referenced to their respective LOPs as shown by the horizontal line. The solid curve running through this chart is the predicted reading as indicated by the skywave correction data for the Waldorf site. The skywave correction curves for the other sites were very close to this, so only one was plotted. The vertical distance between the actual data points and the line of skywave correction is the error of position for the user correcting his position with skywave correction data only. The vertical distance between the 5-min averages for the mobile monitor vs the fixed monitor, then, is the error of the relative position using this form of the differential Omega concept. The 5-min averages of both the mobile monitor and the fixed monitor are plotted as equilateral triangles which are rotated 180 degrees to each other, so that when the two 5-min averages coincide, a six-pointed star is formed by the two triangles (✡).

It should be noted that there is good agreement between the observed readings and the skywave correction data except for the periods of April 14-15 and April 15-16, 1969. The observed data show an offset of approximately 50 centilanes (CEL) from the correction factors. A polar cap absorption (PCA) was observed for this period (3). This offset was also observed at NRL (Fig. 18). Data are also shown for April 29 that are typical of data at this location for an undisturbed day. It should also be noted that the PCA did not adversely affect the relative accuracy.

In order to show this relative error of position more clearly, a larger vertical scale is used in the bottom portion of Figs. 2 through 17. In this large-scale graph, the mobile monitor is plotted with reference to the fixed monitor showing to a larger scale the error of relative position. This then is a plot of the differences obtained from the graph at the top of each figure.

The second series of figures (Figs. 19 through 26) shows the effect of using both the instantaneous differences as well as the effect of using the line of least squares as the correction to a user operating with similar procedures. These figures show the fine detail of the points which made up the 5-min averages for our set of Figs. 2 through 17; however, only 3 hours of typical curves are shown. The top graphs in each set show the 5-min series of points from the fixed Waldorf site. Below these are graphs of data from the mobile monitor site, and at the bottom are graphs of the differences on a point-by-point basis of the fixed and mobile monitor readings. These point-by-point readings form the jagged line of these graphs. The straight line through these graphs is the line of the least squares of the data. This line is given in equation form as

$$y = \bar{y} + m(t - \bar{t}) ,$$

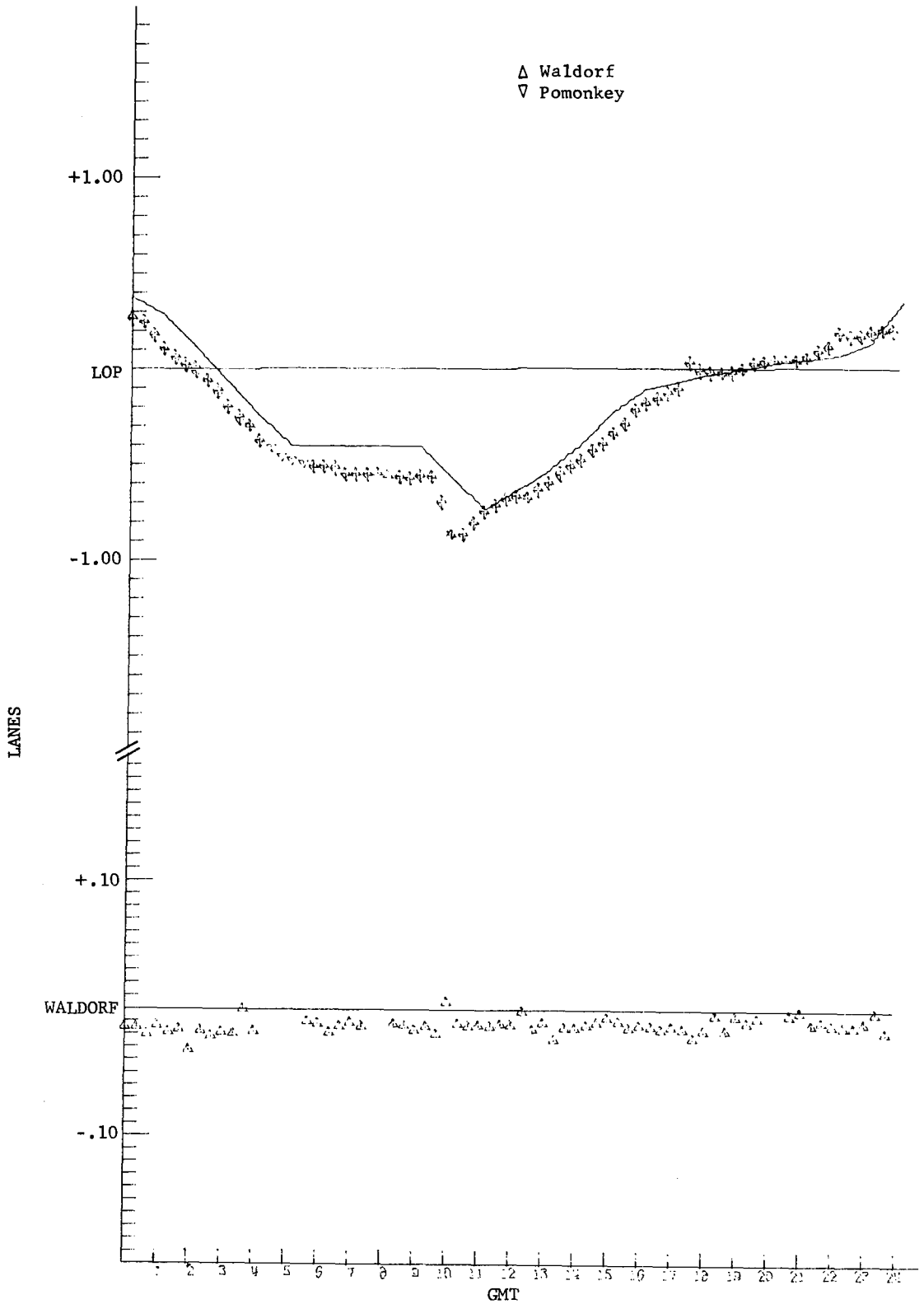

Fig. 2 - Wideband operation for April 14-15, 1969, Trinidad vs Hawaii

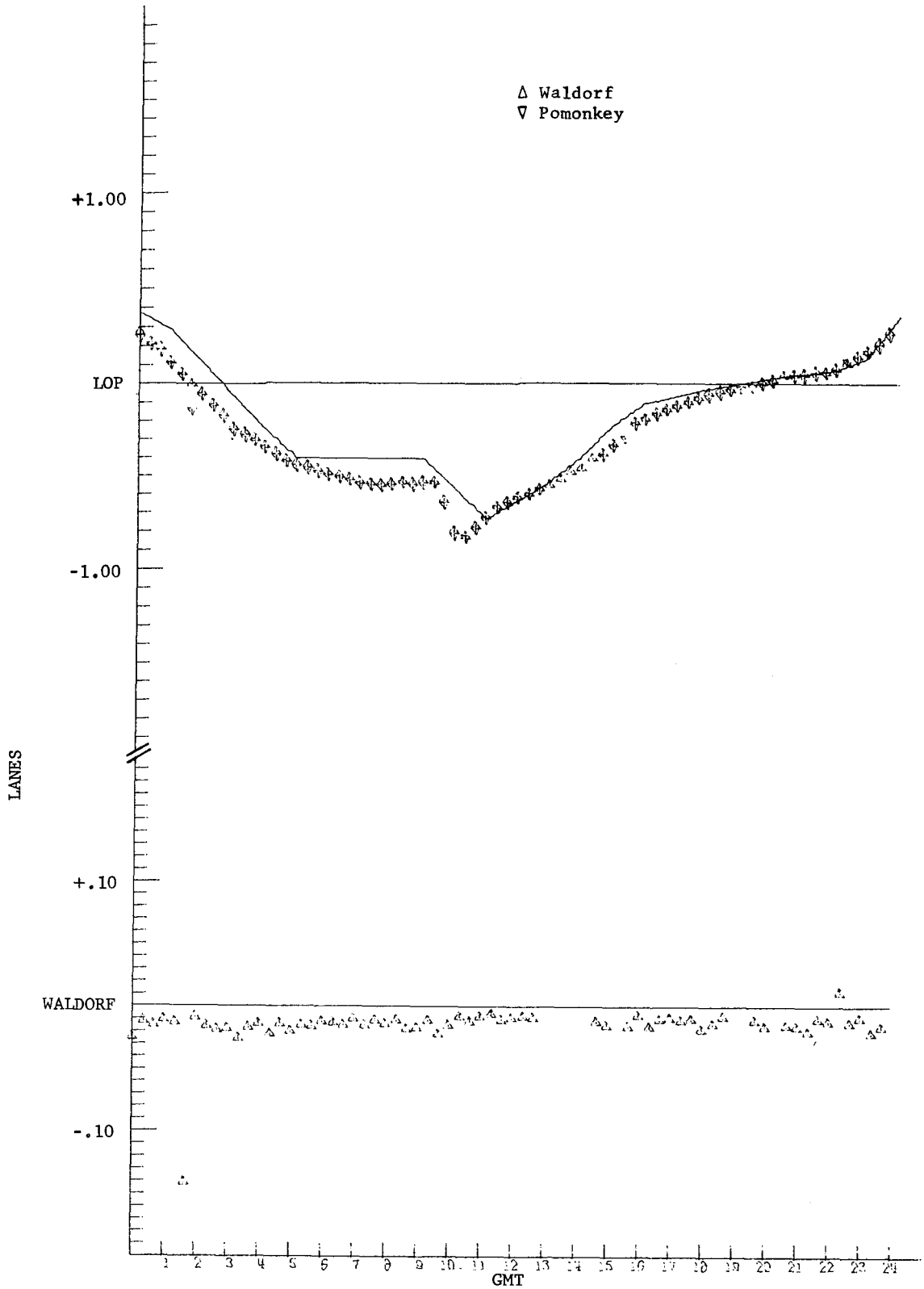

Fig. 3 - Narrowband operation for April 15-16, 1969, Trinidad vs Hawaii

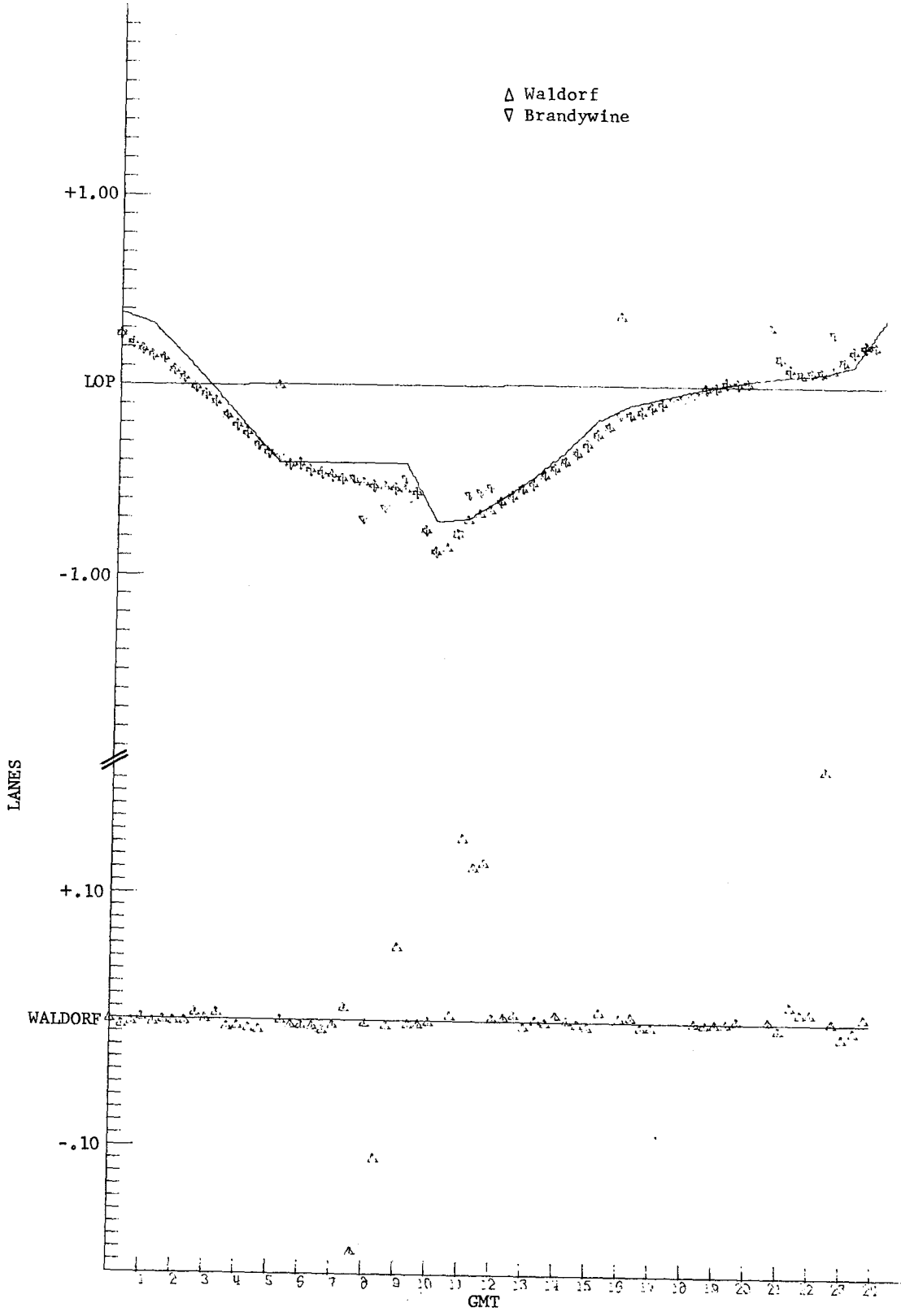

Fig. 4 - Wideband operation for April 21-22, 1969, Trinidad vs Hawaii

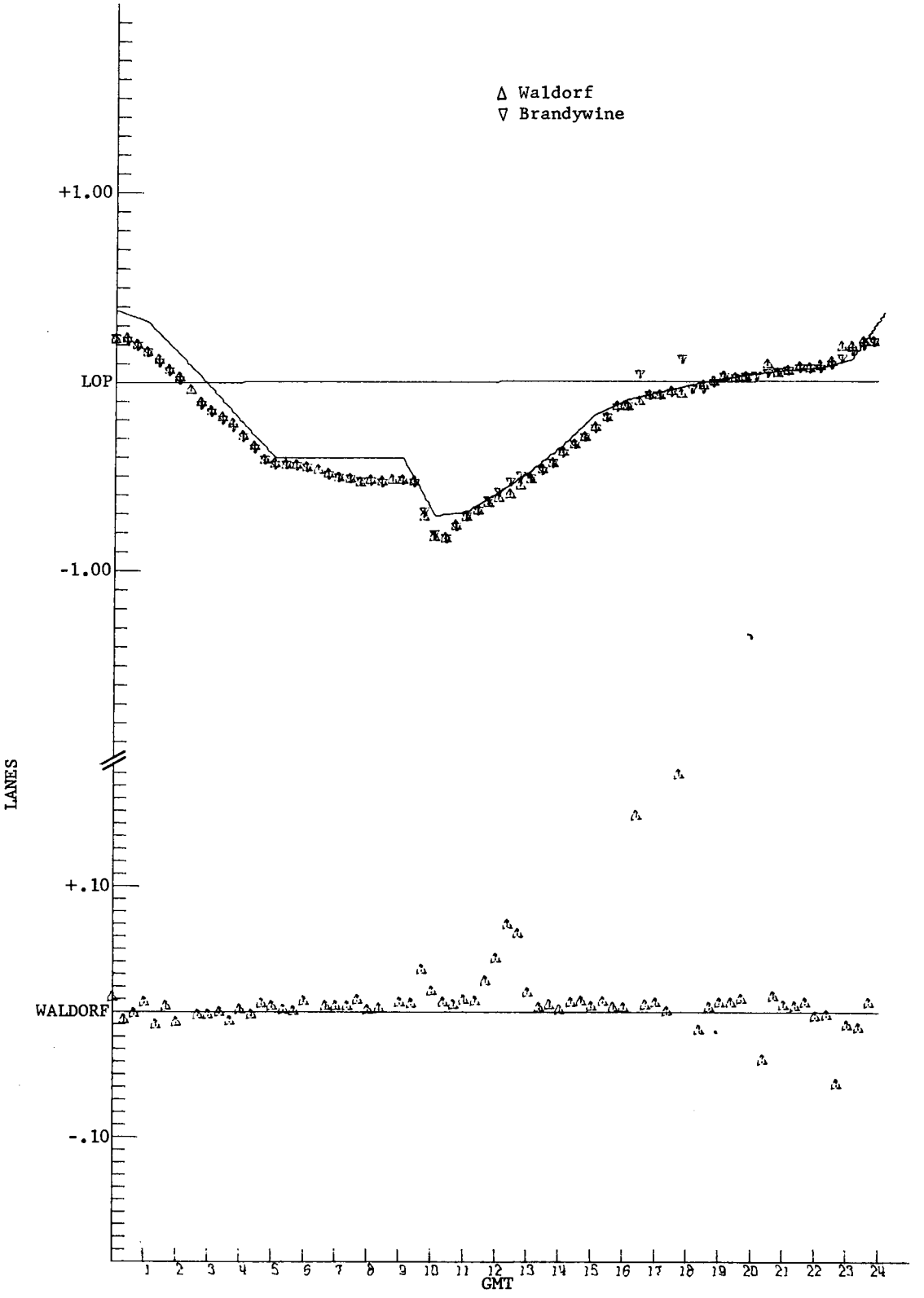

Fig. 5 - Narrowband operation for April 22-23, 1969, Trinidad vs Hawaii

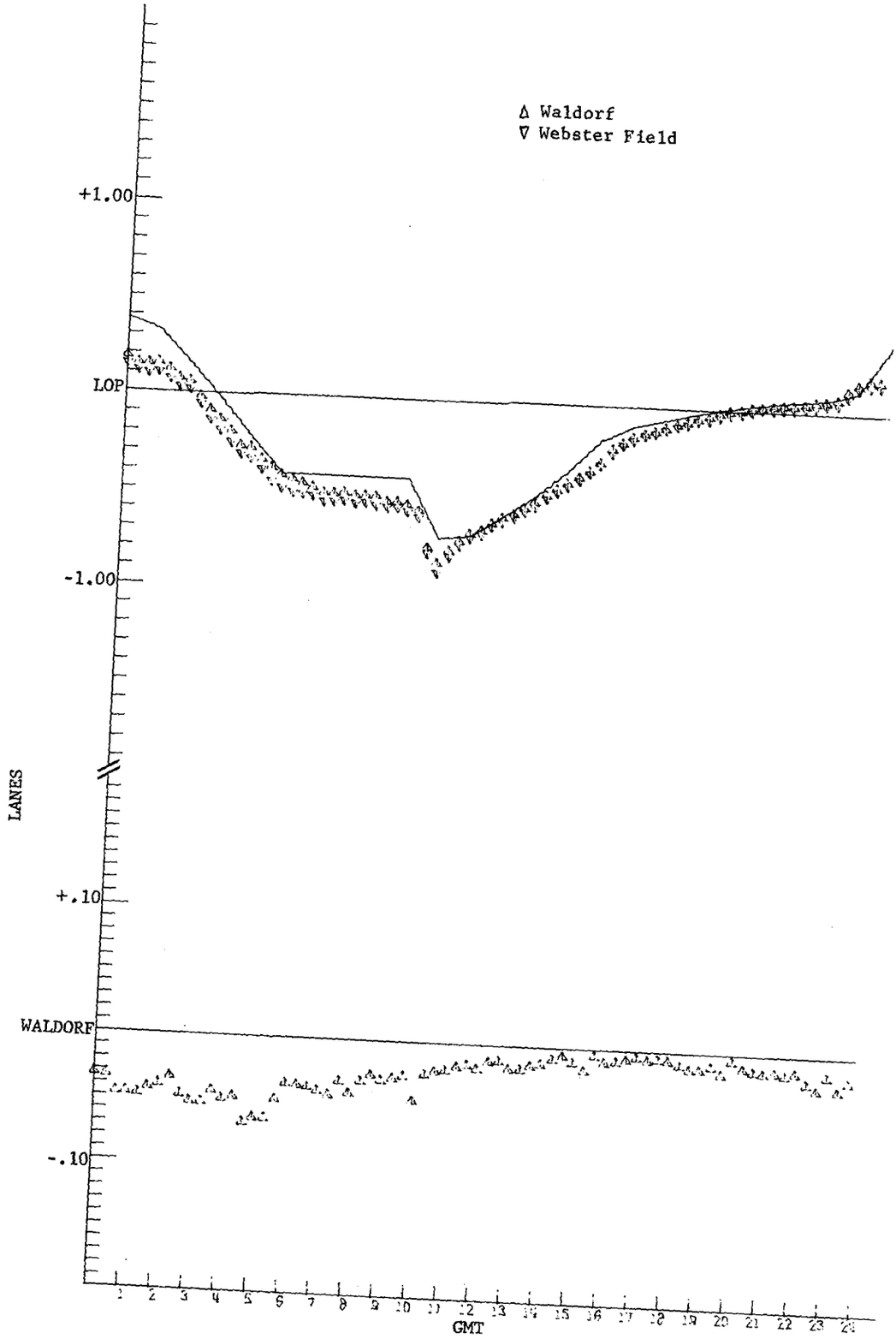

Fig. 6 - Wideband operation for April 28-29, 1969, Trinidad vs Hawaii

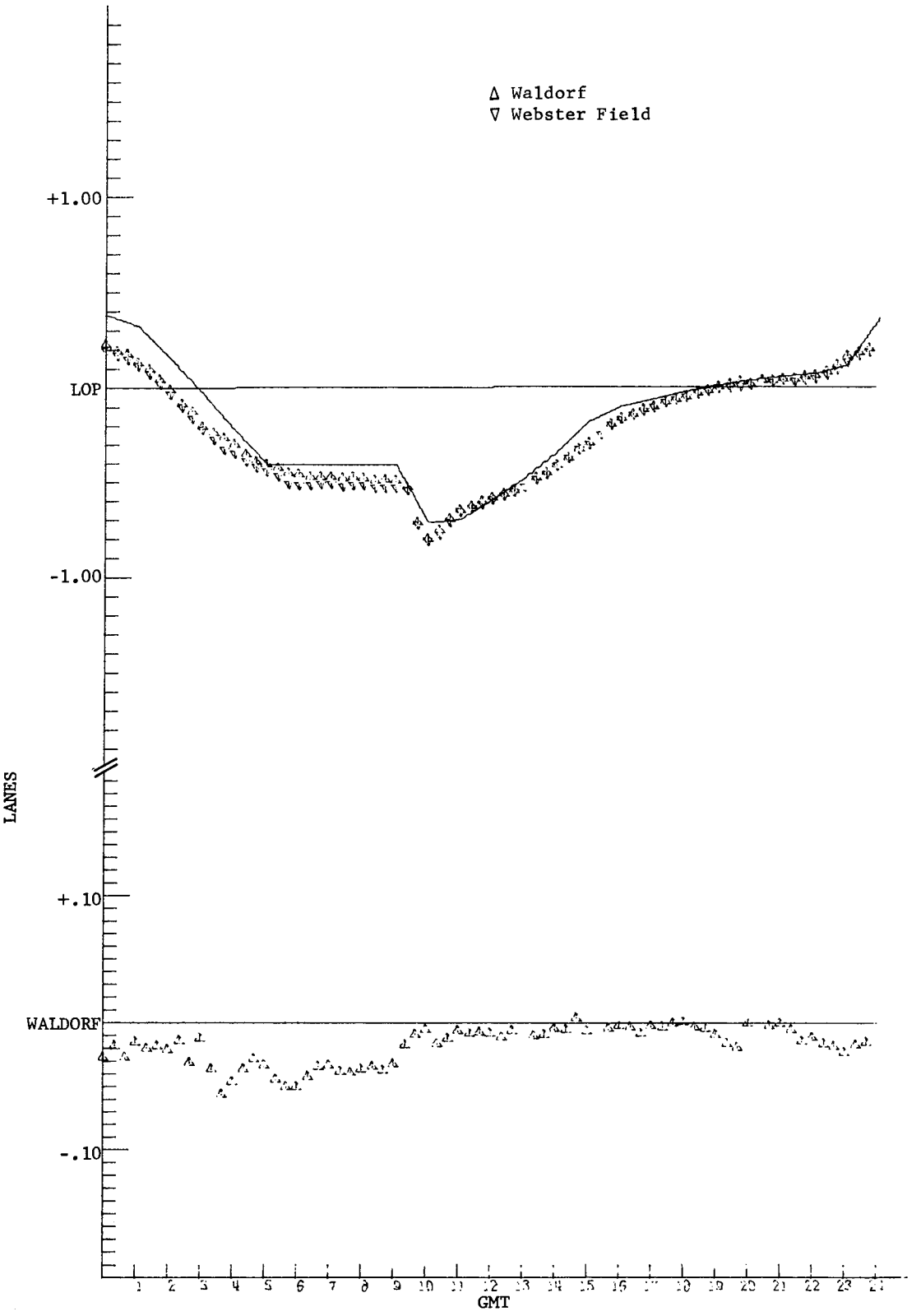

Fig. 7 - Narrowband operation for April 29-30, 1969, Trinidad vs Hawaii

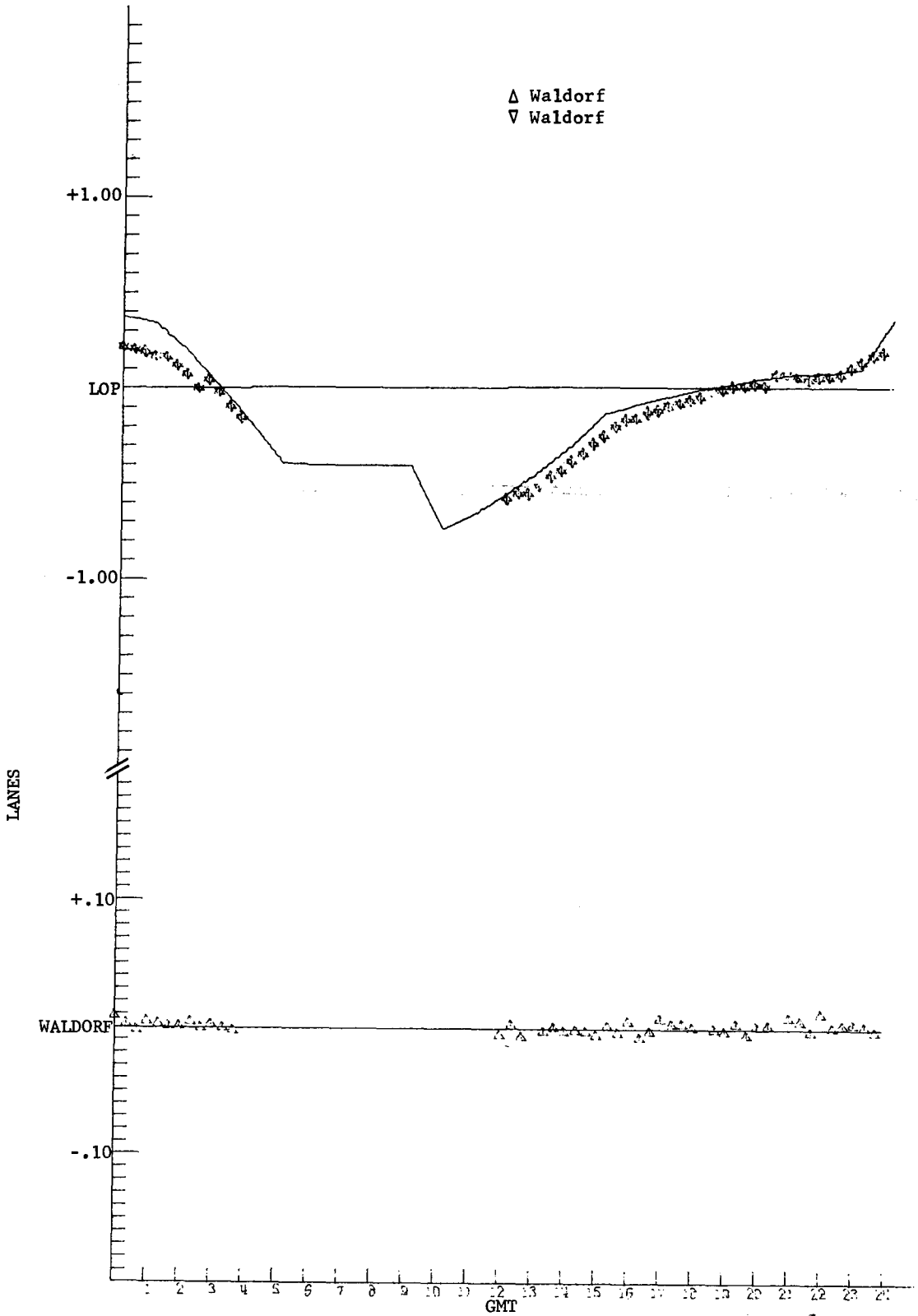

Fig. 8 - Wideband operation for May 5-6, 1969, Trinidad vs Hawaii

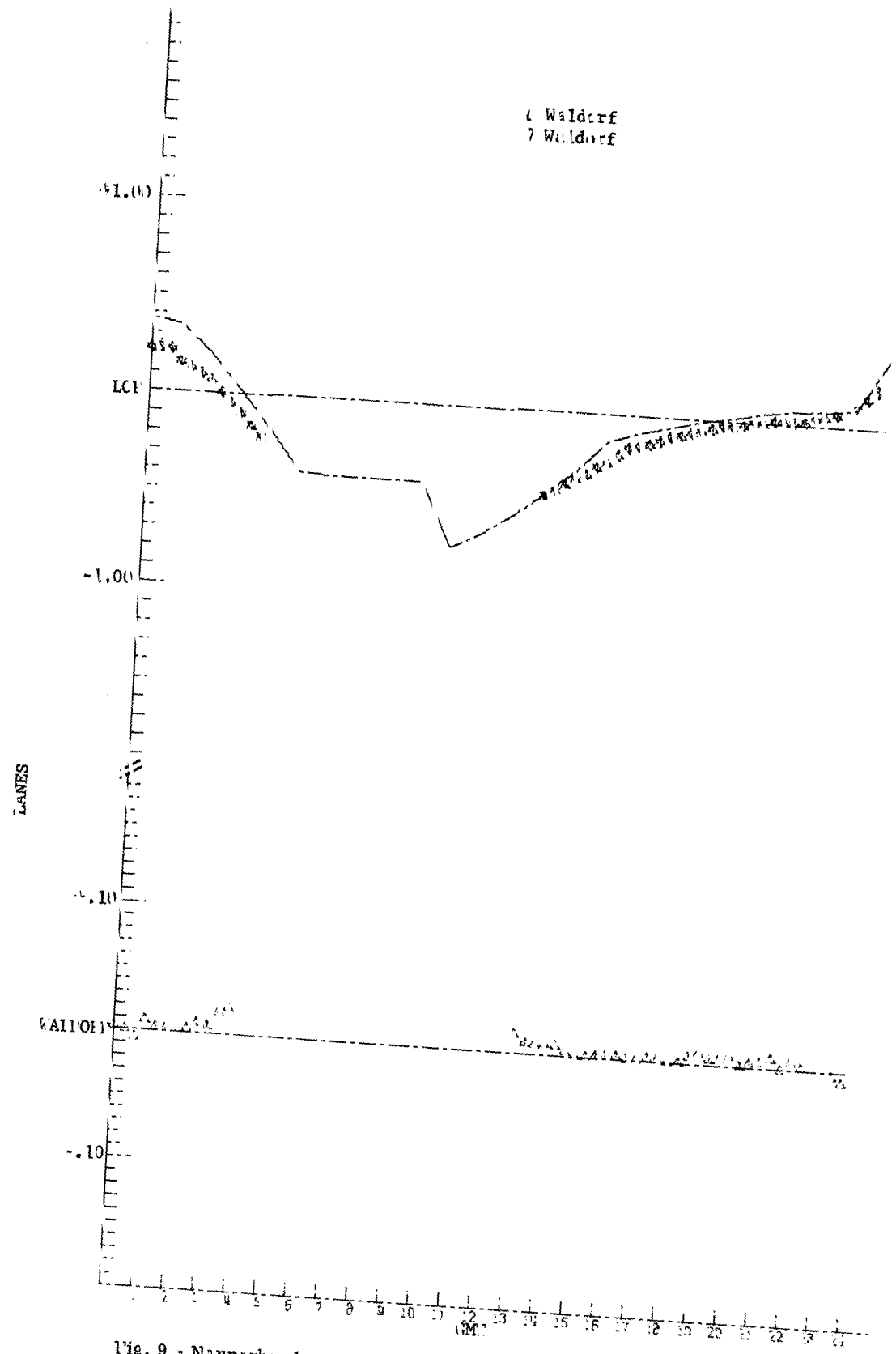

Fig. 9 - Narrowband operation for May 6-7, 1969, Trinidad vs Hawaii

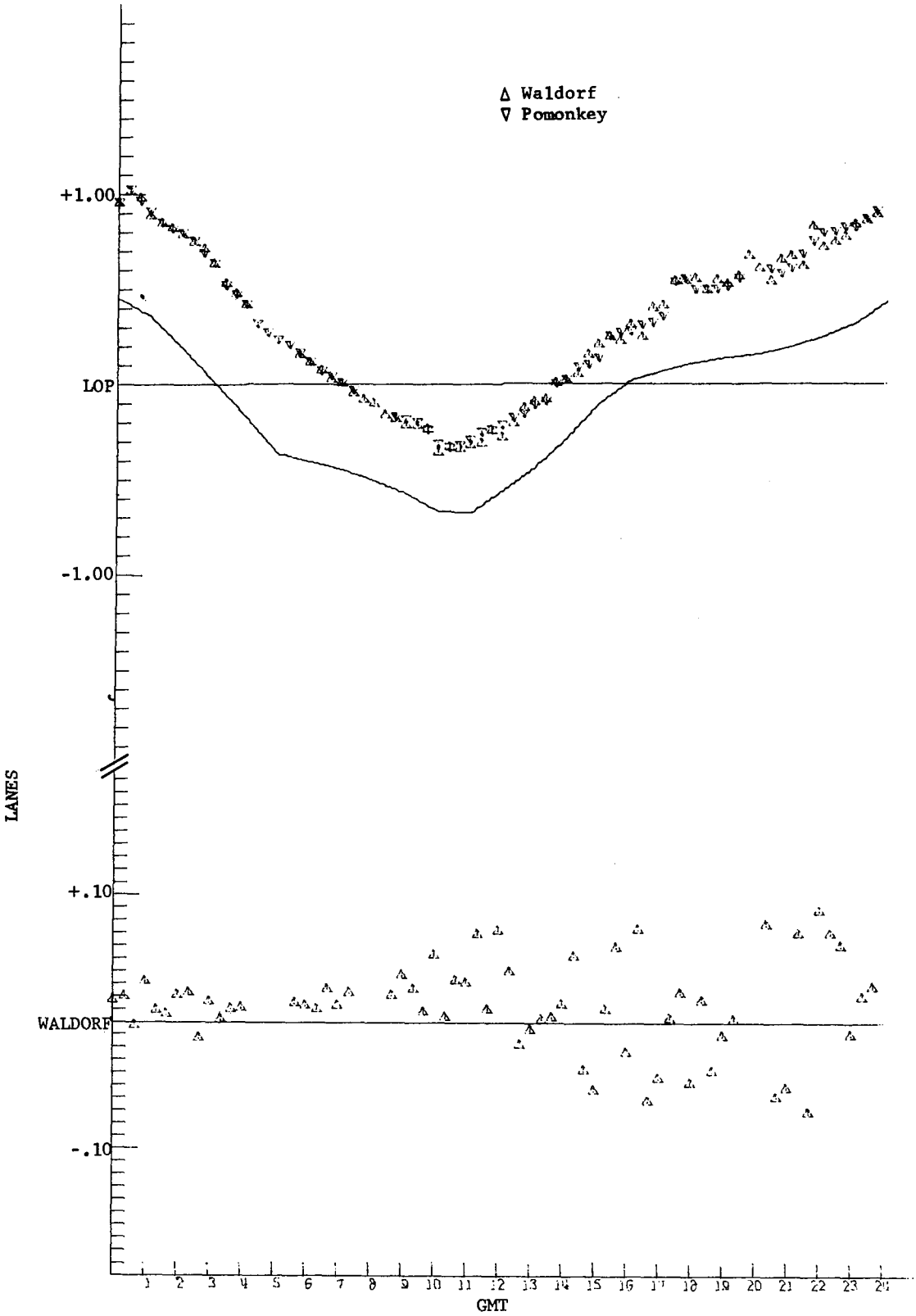

Fig. 10 - Wideband operation for April 14-15, 1969, Norway vs Hawaii

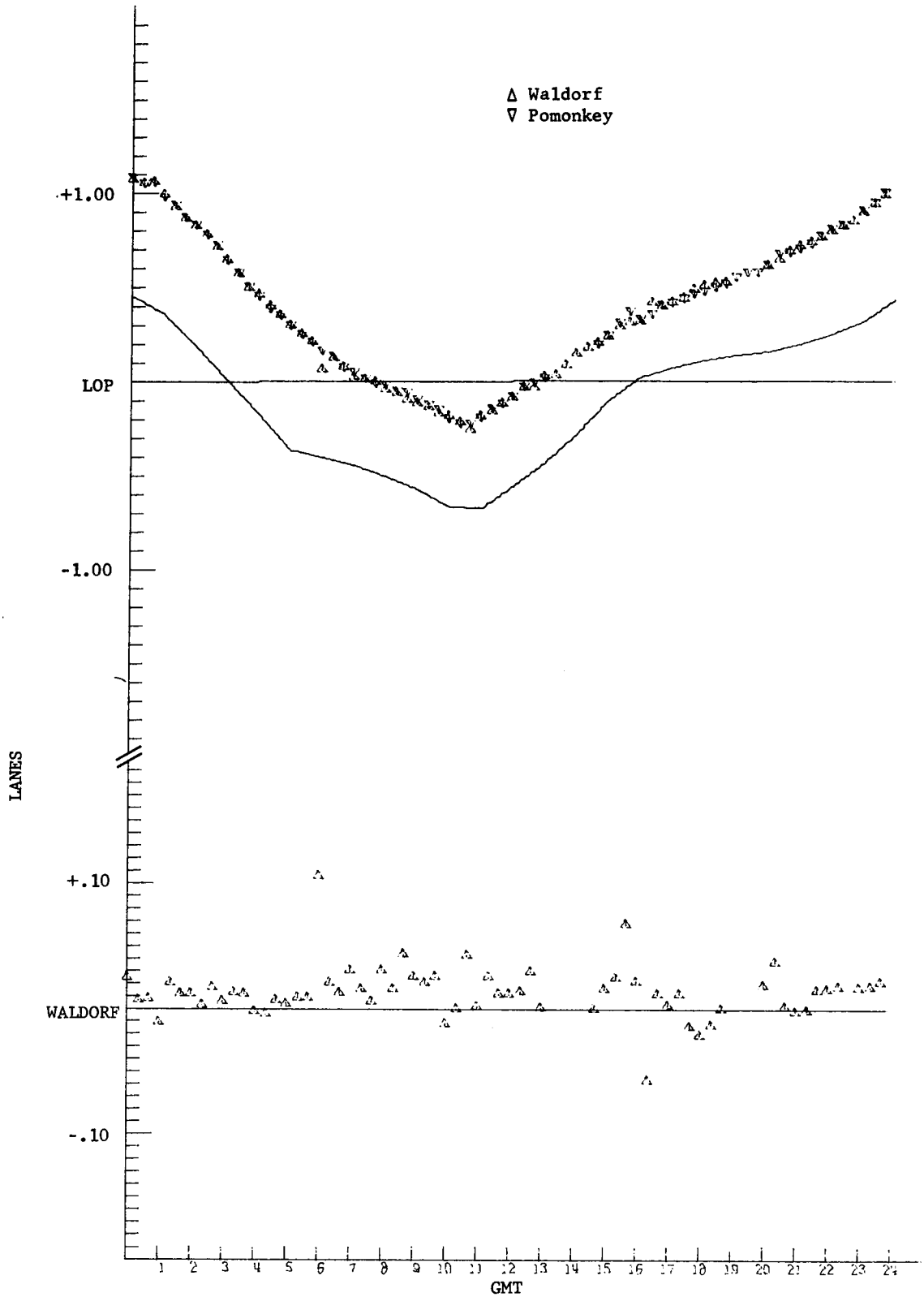

Fig. 11 - Narrowband operation for April 15-16, 1969, Norway vs Hawaii

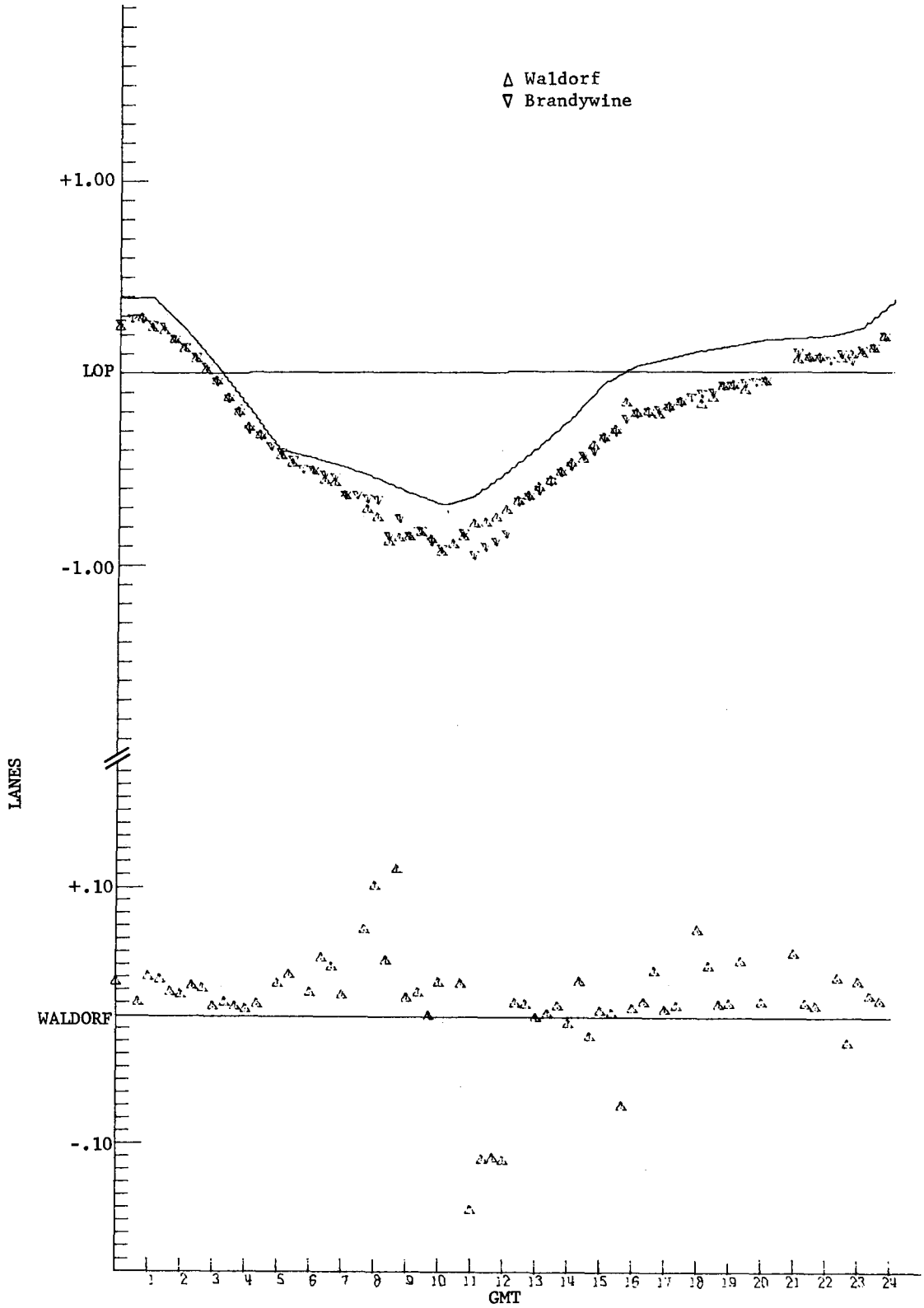

Fig. 12 - Wideband operation for April 21-22, 1969, Norway vs Hawaii

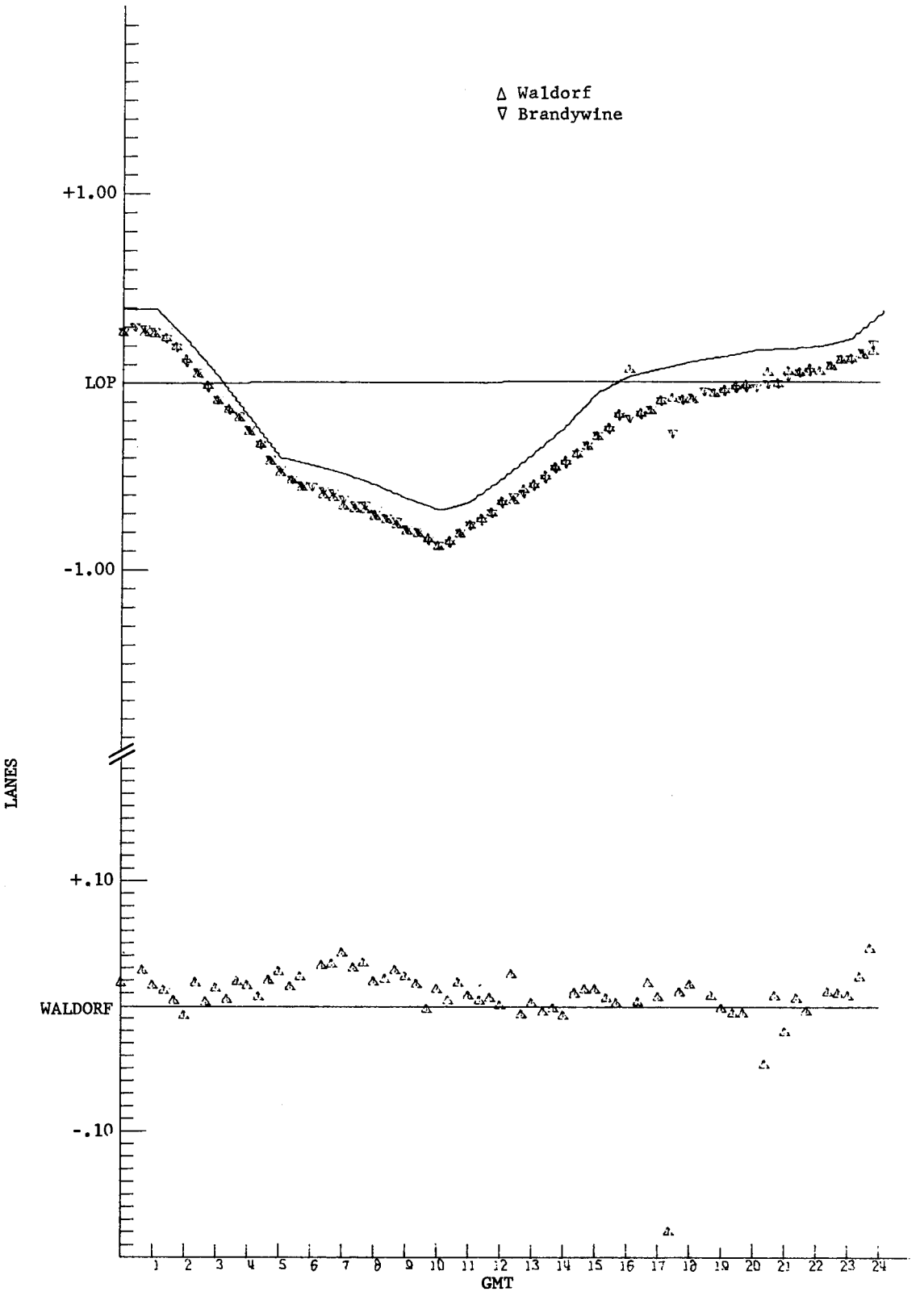

Fig. 13 - Narrowband operation for April 22-23, 1969, Norway vs Hawaii

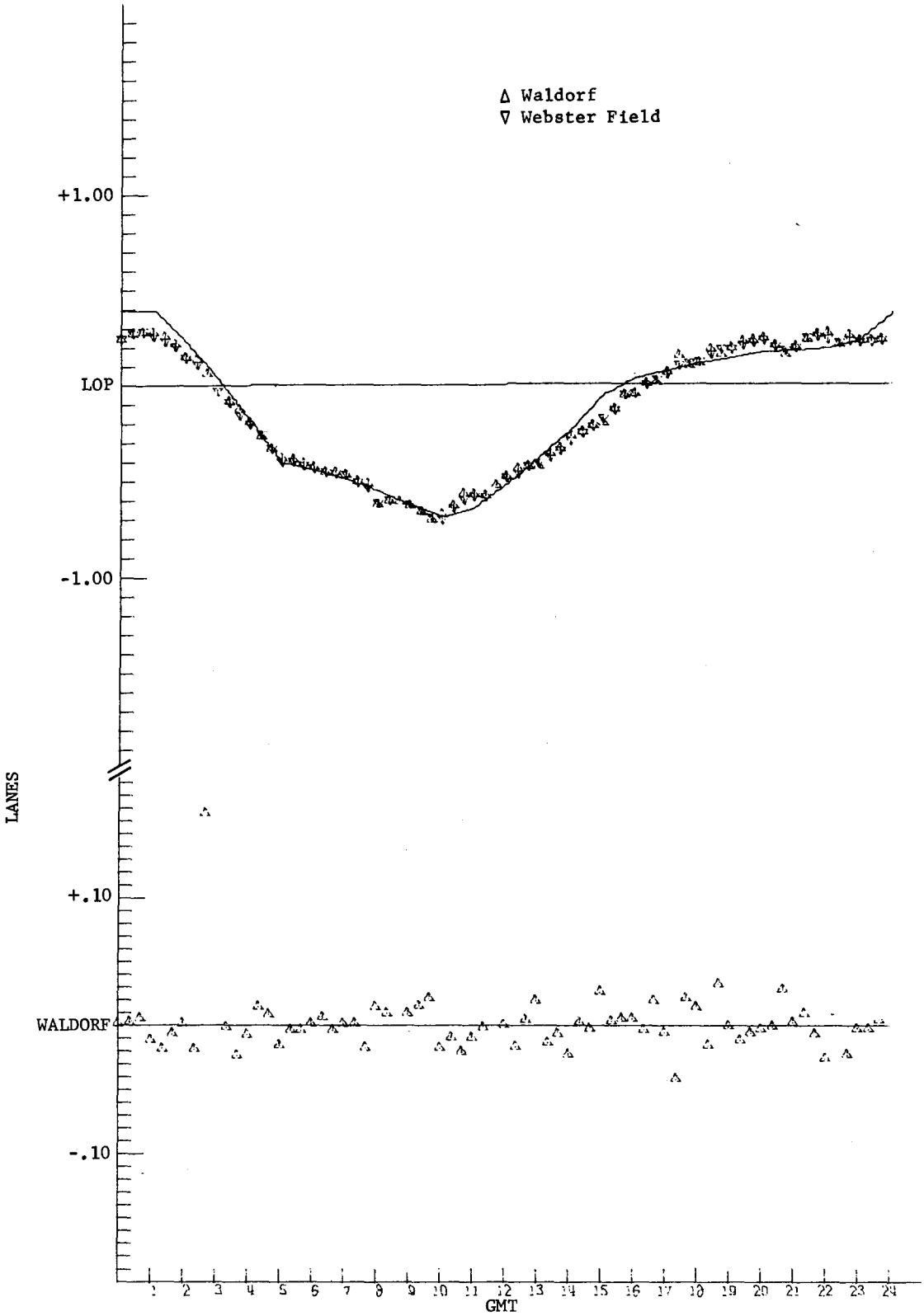

Fig. 14 - Wideband operation for April 28-29, 1969, Norway vs Hawaii

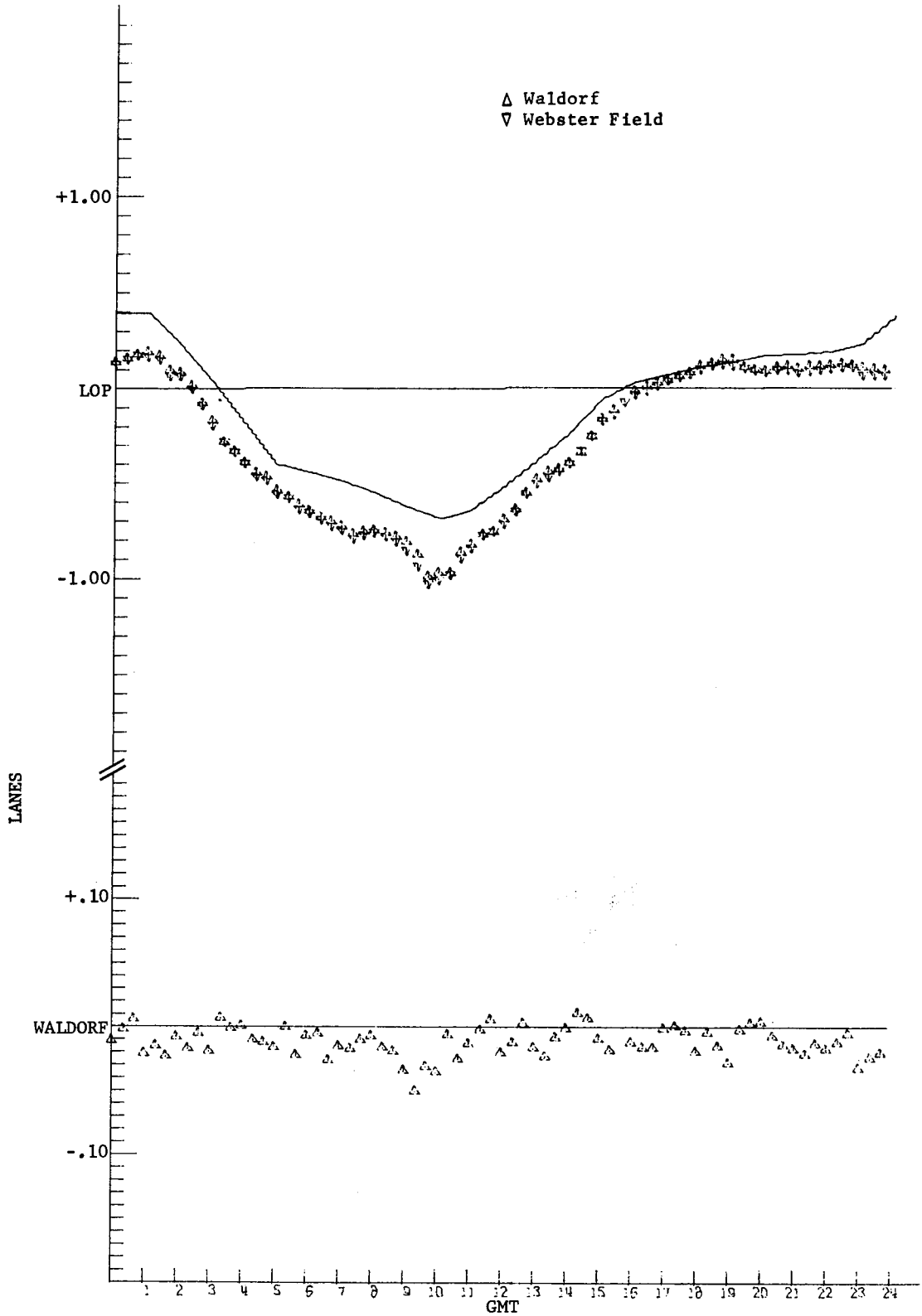

Fig. 15 - Narrowband operation for April 29-30, 1969, Norway vs Hawaii

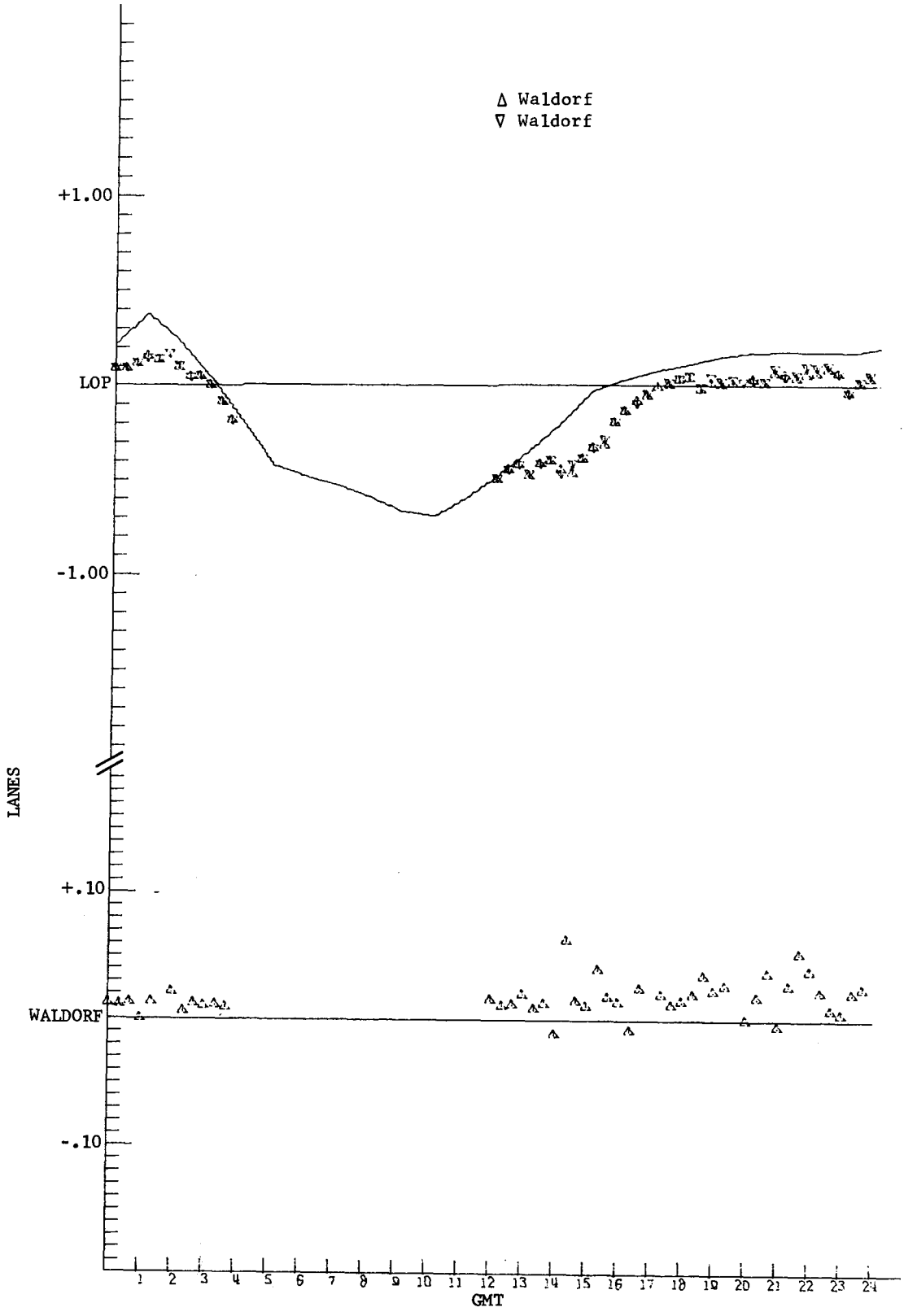

Fig. 16 - Wideband operation for May 5-6, 1969, Norway vs Hawaii

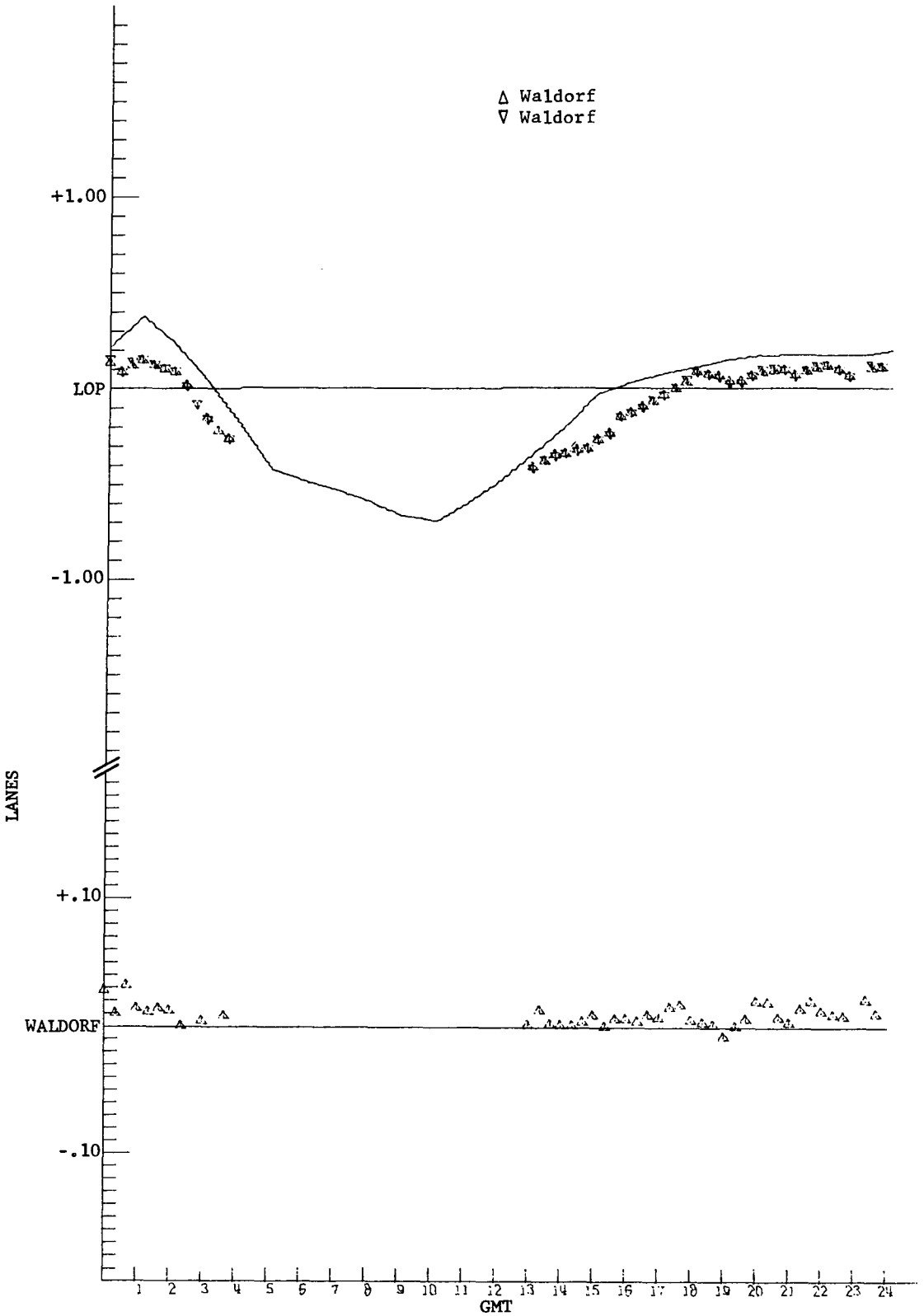

Fig. 17 - Narrowband operation for May 6-7, 1969, Norway vs Hawaii

where

$\bar{y}$ is the average value of the points of data,

t is the time that the reading was taken,

$\bar{t}$ is the average time or the center of the sequence,

m is the slope of y given by (4)

$$m = \frac{\Sigma ty - \bar{t}\Sigma y}{\Sigma t^2 - 2\bar{t}\Sigma t + \Sigma \bar{t}^2} = \frac{\Sigma xt - n\overline{yt}}{\Sigma t^2 - n\bar{t}^2},$$

n being the number of points which comprise the data sample.

The scale of Figs. 19 through 26 is marked off by short tick marks at CEL intervals on the left edge of each graph. Also, each of the bottom graphs of these figures has a longer tick mark which is a reference point from which the error of position can be shown. It can be demonstrated that the center point on the line of the least squares is actually the average of the instantaneous points. The error of position then, using the 5-min averaging method of differential Omega operation, would be represented graphically as the vertical distance from the large tick marks to the center of the line of the least squares. The error of position of each instantaneous reading would be the vertical distance from this large tick mark to the instantaneous readings, which as described earlier is the jagged line of these bottom graphs.

The error of position using the least squares method would be the vertical distance from the large tick mark to any point along the straight line. As an approximation, there are 190 yd per CEL for AC and 170 yd per CEL for BC.

The 5-min average errors of position, as shown in Figs. 2 through 17, are also shown in Tables 3 through 10, which also show the standard deviations of the points which comprise these 5-min averages.

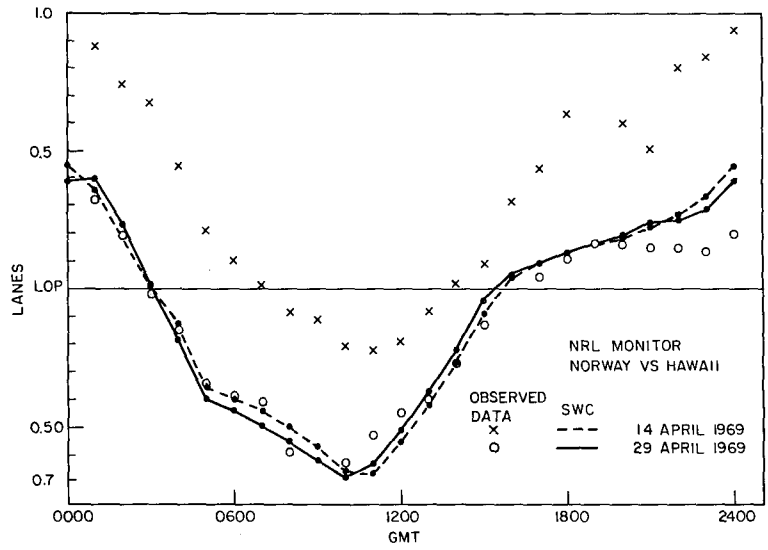

Fig. 18 - Effect of polar cap absorption (PCA) on NRL monitor location

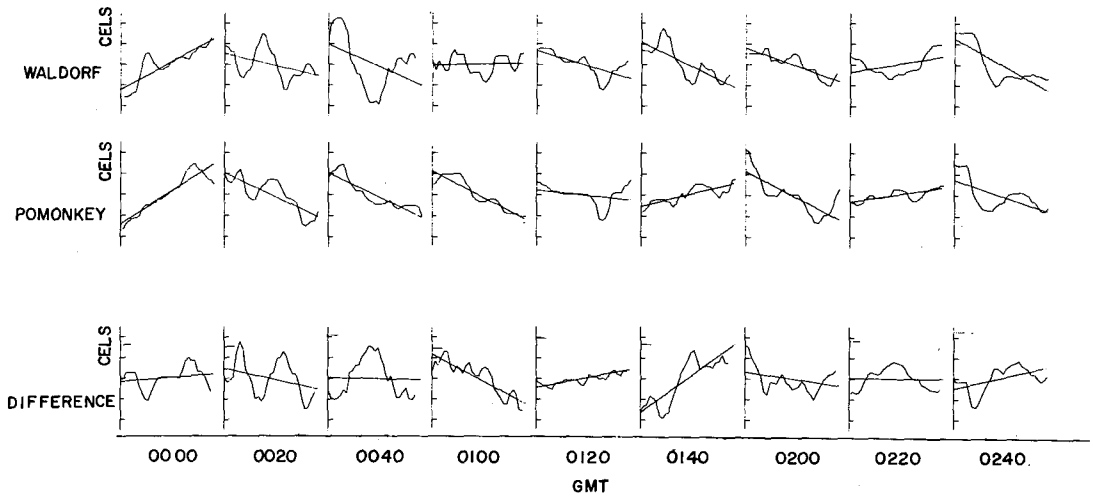

Fig. 19 - Waldorf and Pomonkey data for the Trinidad minus Hawaii transmitter pair taken on April 15-16, 1969, wideband operation

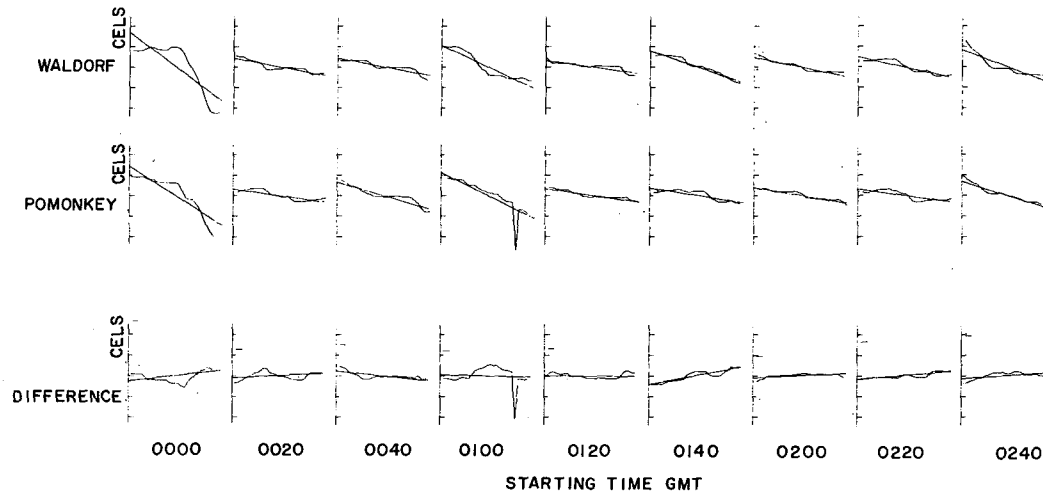

Fig. 20 - Waldorf and Pomonkey data for the Trinidad minus Hawaii transmitter pair taken on April 16-17, 1969, narrowband operation

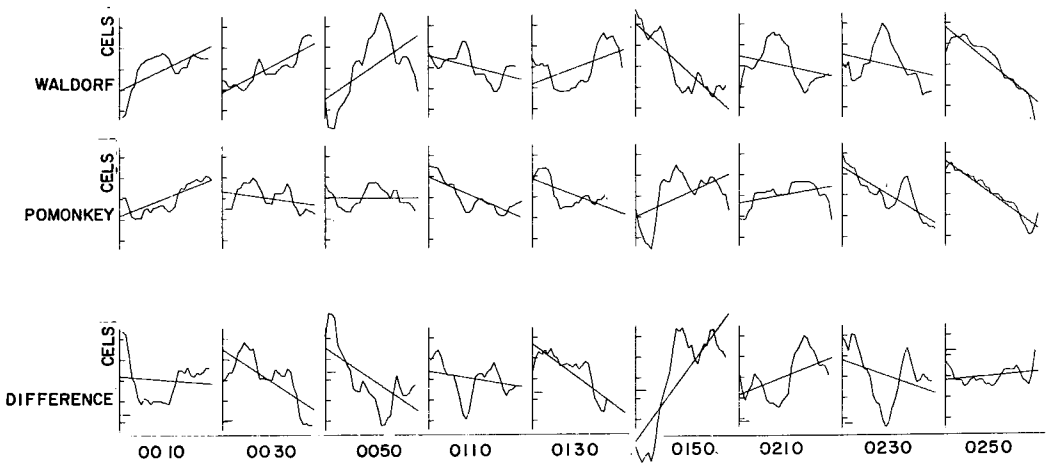

Fig. 21 - Waldorf and Pomonkey data for the Norway minus Hawaii transmitter pair taken on April 15-16, 1969, wideband operation

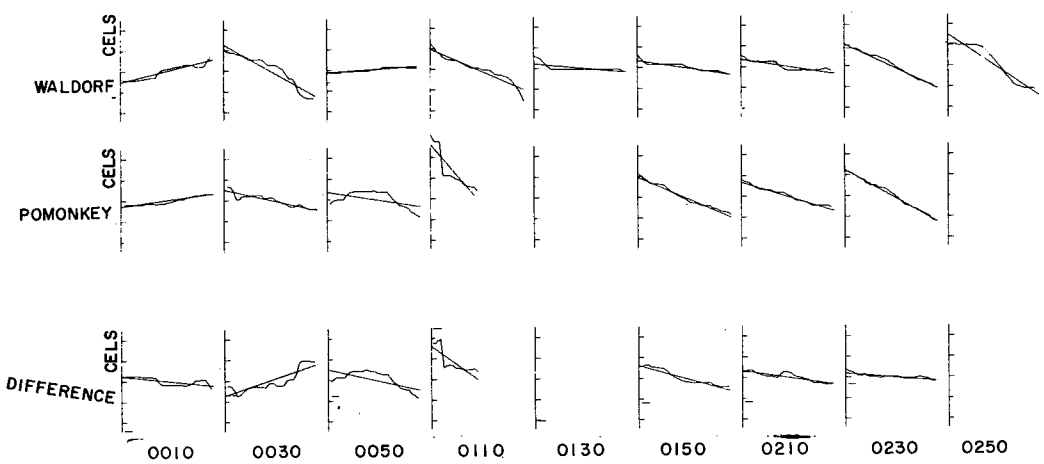

Fig. 22 - Waldorf and Pomonkey data for the Norway minus Hawaii transmitter pair taken on April 16-17, 1969, narrowband operation

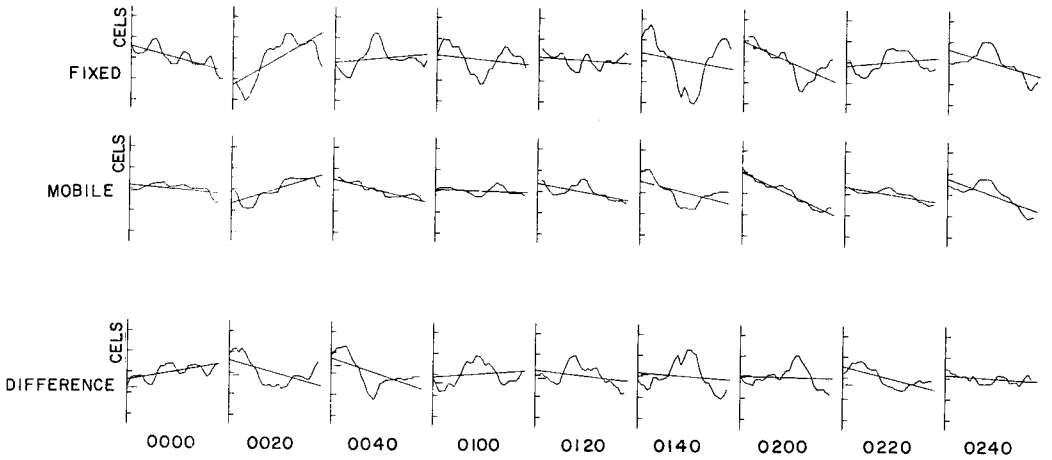

Fig. 23 - Waldorf fixed and Waldorf mobile data taken on May 5-6, 1969, for the Trinidad minus Hawaii transmitter pair, wideband operation

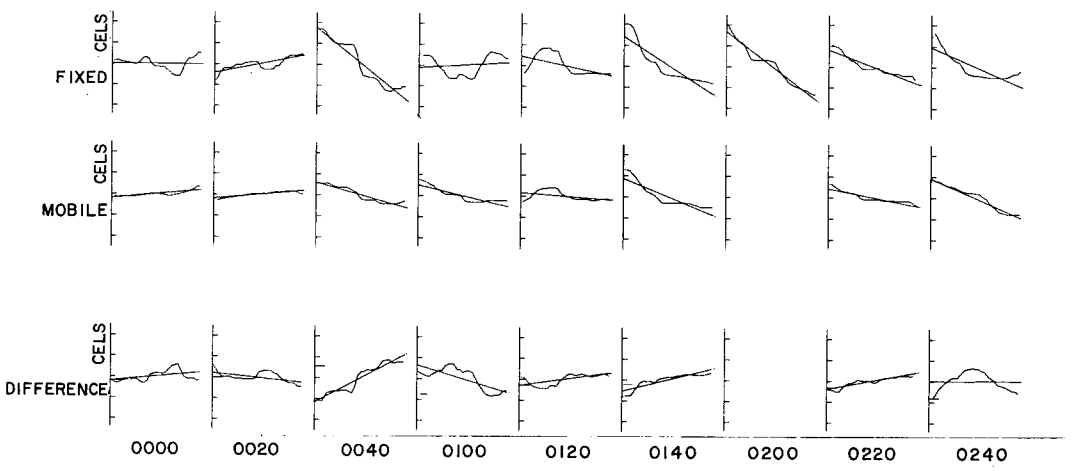

Fig. 24 - Waldorf fixed and mobile data taken on May 6-7, 1969, for the Trinidad minus Hawaii transmitter pair, narrowband operation

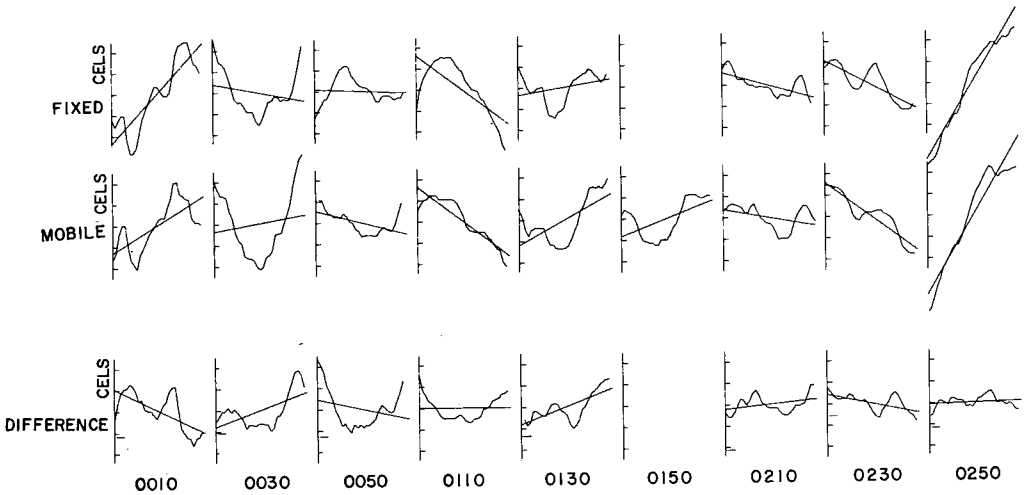

Fig. 25 - Waldorf fixed and mobile data taken on May 5-6, 1969, for the Norway minus Hawaii transmitter pair, wideband operation

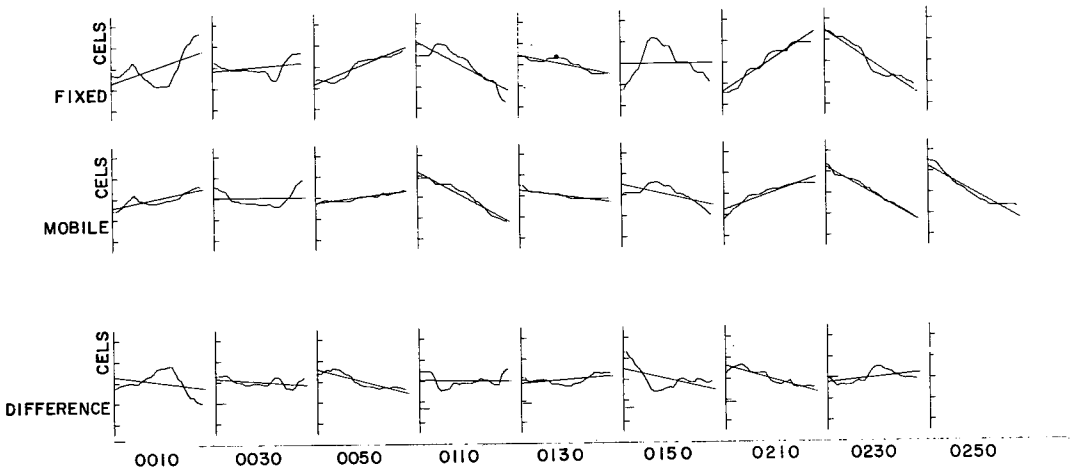

Fig. 26 - Waldorf fixed and mobile data taken on May 6-7, 1969, for the Norway minus Hawaii transmitter pair, narrowband operation

Table 3
Differences of Waldorf and Pomonkey Data of Trinidad—Hawaii Transmitter Pair

Time Started	Average (Lanes)	Standard Deviation (Lanes)	Time Started	Average (Lanes)	Standard Deviation (Lanes)	Time Started	Average (Lanes)	Standard Deviation (Lanes)
Wideband, April 15-16, 1969								
1600	0.026	0.043	1620	-0.073	0.039	1640	0.064	0.023
1700	0.045	0.022	1720	-0.003	0.018	1740	-0.022	0.021
1800	0.049	0.023	1820	-0.016	0.031	1840	0.040	0.047
1900	0.010	0.030	1920	-0.002	0.014	1940		
2000			2020	-0.077	0.060	2040	0.060	0.044
2100	0.053	0.048	2120	-0.069	0.038	2140	0.072	0.035
2200	-0.086	0.040	2220	-0.070	0.057	2240	-0.060	0.030
2300	0.010	0.024	2320	-0.020	0.015	2340	-0.027	0.016
0	-0.017	0.010	20	-0.020	0.011	40	0.004	0.015
100	-0.032	0.008	120	-0.011	0.009	140	-0.006	0.023
200	-0.022	0.011	220	-0.023	0.013	240	0.013	0.004
300	-0.015	0.008	320	-0.001	0.010	340	-0.010	0.005
400	-0.011	0.005	420			440		
500			520			540	-0.015	0.011
600	-0.014	0.006	620	-0.010	0.010	640	-0.026	0.013
700	-0.013	0.004	720	-0.023	0.011	740		
800			820			840	-0.021	0.011
900	-0.037	0.010	920	-0.026	0.018	940	-0.007	0.033
1000	-0.053	0.014	1020	-0.004	0.042	1040	-0.033	0.045
1100	-0.031	0.031	1120	-0.067	0.028	1140	-0.009	0.009
1200	-0.069	0.032	1220	-0.040	0.019	1240	0.020	0.037
1300	0.007	0.024	1320	-0.000	0.019	1340	-0.003	0.075
1400	-0.013	0.013	1420	-0.053	0.036	1440	0.037	0.074
1500	0.056	0.044	1520	-0.004	0.008	1540	-0.058	0.058
Narrowband, April 16-17, 1969								
1600	-0.021	0.004	1620	0.057	0.114	1640	-0.011	0.004
1700	-0.003	0.003	1720	-0.012	0.008	1740	0.014	0.001
1800	0.020	0.010	1820	0.014	0.004	1840	0.000	0.002
1900			1920			1940		
2000	-0.019	0.002	2020	-0.038	0.003	2040	-0.001	0.003
2100	0.003	0.003	2120	0.001	0.032	2140	-0.015	0.003
2200	-0.016	0.001	2220	-0.018	0.001	2240		
2300	-0.017	0.004	2320	-0.017	0.005	2340	-0.021	0.004
0	-0.024	0.002	20	-0.007	0.005	40	-0.008	0.004
100	0.016	0.006	120	-0.020	0.007	140	-0.012	0.004
200	-0.012	0.002	220	-0.003	0.001	240	-0.019	0.059
300	-0.005	0.001	320	-0.013	0.001	340	-0.012	0.002
400	0.001	0.023	420	0.004	0.011	440	-0.007	0.002
500	-0.004	0.001	520	-0.008	0.001	540	-0.009	0.003
600	-0.106	0.006	620	-0.021	0.002	640	-0.013	0.003
700	-0.031	0.058	720	-0.016	0.003	740	-0.006	0.002
800	-0.031	0.002	820	-0.015	0.030	840	-0.044	0.004
900	-0.026	0.003	920	-0.020	0.002	940	-0.026	0.003
1000	0.012	0.010	1020	0.000	0.004	1040	-0.043	0.010
1100	-0.001	0.004	1120	-0.025	0.004	1140	-0.012	0.002
1200	-0.012	0.002	1220	-0.013	0.003	1240	-0.029	0.003
1300	-0.000	0.004	1320			1340		
1400			1420			1440	0.000	0.003
1500	-0.016	0.001	1520	-0.025	0.003	1540	-0.068	0.004

Table 4
Differences of Waldorf and Brandywine Data of Trinidad—Hawaii Transmitter Pair

Time Started	Average (Lanes)	Standard Deviation (Lanes)	Time Started	Average (Lanes)	Standard Deviation (Lanes)	Time Started	Average (Lanes)	Standard Deviation (Lanes)
Wideband, April 21-22, 1969								
1600	-0.006	0.007	1620	-0.010	0.004	1640	-0.035	0.013
1700	-0.005	0.013	1720	-0.008	0.016	1740		
1800	-0.067	0.032	1820	-0.038	0.012	1840	-0.008	0.028
1900	-0.009	0.013	1920	-0.044	0.008	1940		
2000	-0.011	0.030	2020			2040		
2100	-0.049	0.015	2120	-0.010	0.029	2140	-0.008	0.021
2200			2220	-0.030	0.016	2240	0.020	0.017
2300	-0.027	0.018	2320	-0.016	0.014	2340	-0.012	0.031
0	-0.026	0.008	20			40	-0.010	0.009
100	-0.030	0.007	120	-0.028	0.009	140	-0.018	0.005
200	-0.016	0.004	220	-0.023	0.010	240	-0.021	0.007
300	-0.007	0.004	320	-0.010	0.007	340	-0.007	0.005
400	-0.005	0.005	420	-0.010	0.003	440		
500	-0.025	0.013	520	-0.032	0.010	540		
600	-0.018	0.005	620	-0.045	0.009	640	-0.038	0.006
700	-0.016	0.025	720			740	-0.064	0.019
800	-0.102	0.071	820	-0.040	0.035	840	-0.114	0.164
900	-0.011	0.019	920	-0.018	0.012	940	-0.000	0.036
1000	-0.025	0.007	1020			1040	-0.025	0.019
1100	0.153	0.018	1120	0.113	0.018	1140	0.111	0.006
1200	0.113	0.017	1220	-0.010	0.012	1240	-0.008	0.012
1300	0.001	0.010	1320	-0.001	0.010	1340	-0.007	0.016
1400	0.007	0.010	1420	-0.027	0.008	1440	0.017	0.010
1500	-0.003	0.013	1520	-0.002	0.009	1540	0.071	0.029
Narrowband, April 22-23, 1969								
1600	0.254	0.100	1620	-0.002	0.003	1640	-0.018	0.004
1700	-0.006	0.003	1720	0.180	0.004	1740	-0.011	0.005
1800	-0.017	0.092	1820			1840	-0.008	0.002
1900	0.002	0.002	1920	0.006	0.003	1940	0.006	0.002
2000			2020	0.047	0.041	2040	-0.008	0.006
2100	0.021	0.004	2120	-0.006	0.002	2140	0.004	0.001
2200			2220	-0.011	0.010	2240	-0.010	0.005
2300	-0.008	0.006	2320	-0.022	0.001	2340	-0.046	0.005
0	-0.018	0.005	20			40	-0.027	0.005
100	-0.015	0.005	120	-0.011	0.005	140	-0.003	0.007
200	0.008	0.007	220	-0.017	0.002	240	-0.002	0.005
300	-0.014	0.003	320	-0.005	0.005	340	-0.019	0.001
400	-0.016	0.003	420	-0.007	0.002	440	-0.021	0.001
500	-0.027	0.001	520	-0.015	0.002	540	-0.022	0.001
600			620	-0.032	0.001	640	-0.033	0.002
700	-0.042	0.001	720	-0.030	0.003	740	-0.034	0.001
800	-0.019	0.001	820	-0.021	0.001	840	-0.028	0.001
900	-0.023	0.001	920	-0.017	0.001	940	0.004	0.003
1000	-0.012	0.006	1020	-0.003	0.002	1040	-0.018	0.002
1100	-0.007	0.001	1120	-0.003	0.002	1140	-0.005	0.003
1200	0.000	0.001	1220	-0.025	0.003	1240	0.008	0.001
1300	-0.002	0.001	1320	0.006	0.001	1340	0.002	0.002
1400	0.008	0.003	1420	-0.010	0.002	1440	-0.012	0.001
1500	-0.013	0.002	1520	-0.006	0.001	1540	-0.002	0.003

Table 5
Differences of Waldorf and Webster Field Data of Trinidad—Hawaii Transmitter Pair

Time Started	Average (Lanes)	Standard Deviation (Lanes)	Time Started	Average (Lanes)	Standard Deviation (Lanes)	Time Started	Average (Lanes)	Standard Deviation (Lanes)
Wideband, April 28-29, 1969								
1500	-0.026	0.023	1520	-0.004	0.007	1540	-0.006	0.012
1600	-0.005	0.010	1620	0.003	0.033	1640	-0.020	0.019
1700	0.005	0.015	1720	0.042	0.012	1740	-0.022	0.019
1800	-0.015	0.022	1820	0.015	0.051	1840	-0.033	0.023
1900	-0.000	0.032	1920	0.011	0.018	1940	0.005	0.014
2000	0.002	0.009	2020	0.001	0.027	2040	-0.029	0.026
2100	-0.003	0.021	2120	-0.010	0.004	2140	0.006	0.007
2200	0.025	0.009	2220	-0.011	0.013	2240	0.023	0.008
2300	0.003	0.010	2320	0.002	0.015	2340	-0.004	0.021
0	-0.002	0.011	20	-0.003	0.009	40	-0.006	0.009
100	0.011	0.006	120	0.018	0.006	140	0.006	0.004
200	-0.002	0.006	220	0.018	0.006	240	-0.166	0.007
300			320	0.001	0.006	340	0.024	0.008
400	0.007	0.010	420	-0.015	0.008	440	-0.009	0.009
500	0.014	0.008	520	0.004	0.008	540	0.003	0.004
600	-0.002	0.004	620	-0.007	0.005	640	0.004	0.003
700	-0.002	0.002	720	-0.001	0.004	740	0.017	0.004
800	-0.015	0.009	820	-0.009	0.013	840	-0.376	0.007
900	-0.010	0.014	920	-0.016	0.033	940	-0.022	0.017
1000	0.017	0.041	1020	0.010	0.008	1040	0.021	0.004
1100	0.009	0.003	1120	0.001	0.005	1140		
1200	-0.001	0.004	1220	0.016	0.010	1240	-0.005	0.012
1300	-0.020	0.012	1320	0.014	0.009	1340	0.006	0.006
1400	0.023	0.011	1420	-0.003	0.008	1440	0.001	0.012
Narrowband, April 29-30, 1969								
1500	0.009	0.005	1520	0.018	0.001	1540		
1600	0.012	0.002	1620	0.017	0.003	1640	0.016	0.002
1700	0.001	0.005	1720	-0.001	0.003	1740	0.004	0.003
1800	0.019	0.001	1820	0.004	0.003	1840	0.015	0.004
1900	0.028	0.007	1920	0.002	0.003	1940	-0.003	0.010
2000	-0.003	0.003	2020	0.007	0.002	2040	0.014	0.002
2100	0.018	0.008	2120	0.022	0.004	2140	0.014	0.006
2200	0.017	0.006	2220	0.013	0.002	2240	0.006	0.006
2300	0.032	0.006	2320	0.024	0.003	2340	0.020	0.003
0	0.011	0.005	20	0.003	0.004	40	-0.006	0.004
100	0.021	0.002	120	0.015	0.004	140	0.023	0.003
200	0.008	0.004	220	0.018	0.005	240	0.005	0.001
300	0.018	0.001	320	-0.007	0.002	340	0.001	0.003
400	-0.001	0.003	420	0.010	0.003	440	0.012	0.003
500	0.016	0.002	520	-0.000	0.001	540	0.022	0.002
600	0.007	0.001	620	0.005	0.002	640	0.026	0.003
700	0.015	0.002	720	0.017	0.002	740	0.010	0.001
800	0.007	0.002	820	0.016	0.002	840	0.019	0.001
900	0.034	0.005	920	0.050	0.005	940	0.031	0.006
1000	0.035	0.001	1020	0.007	0.006	1040	0.025	0.004
1100	0.014	0.003	1120	0.002	0.004	1140	-0.005	0.002
1200	0.020	0.001	1220	0.012	0.004	1240	-0.002	0.001
1300	0.017	0.001	1320	0.023	0.002	1340	0.008	0.004
1400	0.001	0.002	1420	-0.011	0.004	1440	-0.007	0.002

Table 6
Differences of Waldorf Fixed and Mobile Data of Trinidad—Hawaii Transmitter Pair

Time Started	Average (Lanes)	Standard Deviation (Lanes)	Time Started	Average (Lanes)	Standard Deviation (Lanes)	Time Started	Average (Lanes)	Standard Deviation (Lanes)
Wideband, May 5-6, 1969								
1200	-0.016	0.008	1220	-0.011	0.006	1240	-0.012	0.010
1300	-0.019	0.007	1320	-0.010	0.011	1340	-0.012	0.011
1400	0.012	0.012	1420	-0.063	0.023	1440	-0.014	0.015
1500	-0.011	0.016	1520	-0.040	0.026	1540	-0.018	0.019
1600	-0.014	0.011	1620	0.009	0.018	1640	-0.025	0.011
1700			1720	-0.019	0.011	1740	-0.012	0.022
1800	-0.014	0.011	1820	-0.020	0.010	1840	-0.035	0.035
1900	-0.023	0.015	1920	-0.026	0.010	1940		
2000	-0.001	0.012	2020	-0.018	0.018	2040	-0.037	0.007
2100	0.006	0.012	2120	-0.027	0.010	2140	-0.052	0.014
2200	-0.039	0.014	2220	-0.022	0.025	2240	-0.007	0.015
2300	-0.005	0.009	2320	-0.021	0.016	2340	-0.025	0.009
0	-0.012	0.009	20	-0.010	0.008	40	-0.013	0.009
100	0.000	0.006	120	-0.013	0.007	140		
200	-0.021	0.004	220	-0.006	0.004	240	-0.012	0.003
300	-0.010	0.003	320	-0.011	0.009	340	-0.009	0.007
400			420			440		
500			520			540		
600			620			640		
700			720			740		
800			820			840		
900			920			940		
1000			1020			1040		
1100			1120			1140		
Narrowband, May 6-7, 1969								
1300	-0.001	0.001	1320	-0.013	0.002	1340	-0.001	0.001
1400	-0.001	0.001	1420	-0.000	0.001	1440	-0.003	0.002
1500	-0.009	0.001	1520	0.001	0.001	1540	-0.006	0.009
1600	-0.006	0.003	1620	-0.004	0.002	1640	-0.009	0.003
1700	-0.006	0.001	1720	-0.015	0.005	1740	-0.017	0.001
1800	-0.005	0.002	1820	-0.002	0.004	1840	-0.001	0.001
1900	0.008	0.005	1920	-0.000	0.002	1940	-0.005	0.005
2000	-0.020	0.002	2020	-0.018	0.003	2040	-0.007	0.002
2100	-0.002	0.002	2120	-0.013	0.003	2140	-0.020	0.004
2200	-0.012	0.006	2220	-0.008	0.003	2240	-0.008	0.005
2300			2320	-0.021	0.003	2340	-0.010	0.002
0	-0.028	0.005	20	-0.010	0.002	40	-0.032	0.004
100	-0.013	0.003	120	-0.011	0.002	140	-0.014	0.005
200	-0.012	0.004	220	0.000	0.003	240		
300	-0.004	0.004	320			340	-0.008	0.002
400			420			440		
500			520			540		
600			620			640		
700			720			740		
800			820			840		
900			920			940		
1000			1020			1040		
1100			1120			1140		
1200			1220			1240		

Table 7
Differences of Waldorf and Pomonkey Data of Norway—Hawaii Transmitter Pair

Time Started	Average (Lanes)	Standard Deviation (Lanes)	Time Started	Average (Lanes)	Standard Deviation (Lanes)	Time Started	Average (Lanes)	Standard Deviation (Lanes)
Wideband, April 15-16, 1969								
1610	0.014	0.008	1630	0.015	0.010	1650	0.016	0.007
1710	0.017	0.009	1730	0.015	0.008	1750	0.024	0.011
1810	0.017	0.011	1830	0.005	0.008	1850	0.018	0.009
1910	0.005	0.011	1930	0.012	0.006	1950	0.007	0.006
2010			2030			2050	0.005	0.006
2110	0.002	0.006	2130	0.012	0.009	2150	0.011	0.011
2210	0.014	0.012	2230	0.015	0.010	2250	0.014	0.014
2310	0.011	0.010	2330	0.004	0.005	2350	0.018	0.009
10	0.016	0.005	30	0.015	0.009	50	0.021	0.009
110	0.014	0.008	130	0.020	0.002	150	0.018	0.011
210	0.033	0.006	230	0.018	0.005	250	0.023	0.006
310	0.019	0.007	330	0.020	0.005	350	0.001	0.083
410	0.018	0.005	430			450		
510			530			550	0.011	0.006
610	0.012	0.003	630	0.019	0.007	650	0.014	0.003
710	0.011	0.003	730	0.014	0.003	750		
810			830	0.013	0.002	850	0.014	0.004
910	0.017	0.004	930	0.014	0.005	950	0.019	0.005
1010	-0.005	0.036	1030	0.013	0.012	1050	0.014	0.004
1110	0.013	0.006	1130	0.015	0.004	1150	0.012	0.004
1210	0.013	0.008	1230	0.002	0.022	1250	0.017	0.007
1310	0.011	0.011	1330	0.024	0.006	1350	0.015	0.005
1410	0.015	0.013	1430	0.013	0.004	1450	0.012	0.006
1510	0.008	0.005	1530	0.011	0.011	1550	0.015	0.010
Narrowband, April 16-17, 1969								
1610	0.008	0.003	1630	0.017	0.005	1650	0.010	0.004
1710	0.009	0.003	1730	0.011	0.002	1750	0.010	0.007
1810	0.018	0.003	1830	0.014	0.002	1850	0.008	0.001
1910			1930			1950	0.011	0.003
2010	0.016	0.002	2030			2050	0.015	0.003
2110	0.016	0.004	2130	0.020	0.002	2150	0.010	0.003
2210	0.012	0.003	2230	-0.003	0.073	2250	0.013	0.001
2310	0.009	0.002	2330	0.022	0.005	2350	0.016	0.002
10	0.027	0.003	30	0.013	0.002	50	0.015	0.002
110	0.012	0.005	130	0.013	0.001	150	0.142	0.003
210	0.009	0.001	230	0.016	0.001	250	0.019	0.002
310	0.018	0.002	330	0.026	0.001	350	0.017	0.002
410	0.014	0.001	430	0.022	0.001	450	0.014	0.001
510	0.020	0.001	530	0.015	0.001	550	0.017	0.001
610	0.012	0.003	630	0.013	0.002	650	0.016	0.001
710	0.010	0.001	730	0.015	0.002	750	0.011	0.001
810	0.014	0.001	830	0.011	0.001	850	0.018	0.001
910	0.017	0.001	930	0.011	0.001	950	0.021	0.002
1010	0.015	0.001	1030	0.008	0.004	1050	0.012	0.001
1110	0.008	0.001	1130	0.007	0.001	1150	0.011	0.001
1210	0.009	0.001	1230	0.009	0.001	1250	0.010	0.002
1310			1330			1350		
1410			1430			1450	0.011	0.011
1510	0.015	0.003	1530			1550	0.016	0.003

Table 8
Differences of Waldorf and Brandywine Data of Norway—Hawaii Transmitter Pair

Time Started	Average (Lanes)	Standard Deviation (Lanes)	Time Started	Average (Lanes)	Standard Deviation (Lanes)	Time Started	Average (Lanes)	Standard Deviation (Lanes)
Wideband, April 21-22, 1969								
1610	-0.003	0.005	1630	-0.004	0.002	1650	0.004	0.003
1710	0.004	0.004	1730			1750		
1810			1830	0.000	0.003	1850	0.001	0.008
1910	0.001	0.006	1930	0.000	0.010	1950	-0.002	0.006
2010			2030			2050	-0.002	0.010
2110	0.005	0.012	2130	-0.013	0.006	2150	-0.008	0.010
2210	-0.008	0.009	2230	-0.199	0.011	2250	-0.001	0.011
2310	0.011	0.009	2330	0.006	0.008	2350	-0.005	0.005
10	0.001	0.008	30	0.005	0.004	50	0.003	0.003
110	-0.001	0.006	130	0.004	0.008	150	0.002	0.006
210	0.003	0.006	230	0.002	0.005	250	-0.005	0.005
310	0.003	0.003	330	-0.005	0.002	350	0.006	0.004
410	0.005	0.004	430	0.007	0.006	450	0.008	0.003
510	0.375	0.003	530	-0.000	0.005	550	0.005	0.002
610	0.004	0.009	630	0.005	0.003	650	0.008	0.004
710	0.004	0.007	730	-0.010	0.027	750	0.176	0.101
810	0.002	0.002	830	0.109	0.118	850	0.005	0.012
910	-0.060	0.036	930	0.003	0.002	950	0.003	0.004
1010	0.001	0.003	1030			1050	-0.004	0.003
1110	-0.143	0.006	1130	-0.121	0.003	1150	-0.124	0.010
1210	-0.002	0.003	1230	-0.002	0.002	1250	-0.005	0.004
1310	0.004	0.003	1330	-0.001	0.006	1350	0.002	0.007
1410	-0.004	0.004	1430	-0.001	0.005	1450	0.003	0.003
1510	0.005	0.003	1530	-0.008	0.008	1550	0.513	0.090
Narrowband, April 22-23, 1969								
1610	-0.003	0.004	1630	-0.155	0.006	1650	-0.005	0.004
1710	-0.007	0.004	1730	0.000	0.002	1750	-0.189	0.027
1810			1830	0.015	0.024	1850	-0.003	0.003
1910	-0.007	0.001	1930	-0.007	0.005	1950	-0.010	0.010
2010			2030	0.039	0.014	2050	-0.012	0.003
2110	-0.005	0.006	2130	-0.003	0.002	2150	-0.007	0.002
2210	0.004	0.002	2230	0.003	0.006	2250	0.059	0.048
2310	0.011	0.003	2330	0.013	0.002	2350	-0.007	0.006
10	-0.011	0.006	30	0.007	0.007	50	0.002	0.006
110	-0.007	0.003	130	0.011	0.003	150	-0.004	0.007
210	0.009	0.004	230			250	0.003	0.002
310	0.003	0.001	330	0.002	0.005	350	0.008	0.002
410	-0.001	0.001	430	0.003	0.001	450	-0.006	0.001
510	-0.003	0.002	530	-0.001	0.001	550	-0.000	0.003
610	-0.007	0.002	630			650	-0.004	0.001
710	-0.004	0.003	730	-0.004	0.003	750	-0.009	0.001
810	-0.001	0.001	830	-0.002	0.001	850		
910	-0.007	0.001	930	-0.006	0.002	950	-0.034	0.003
1010	-0.016	0.003	1030	-0.007	0.001	1050	-0.005	0.001
1110	-0.009	0.002	1130	-0.007	0.002	1150	-0.024	0.001
1210	-0.042	0.002	1230	-0.069	0.001	1250	-0.062	0.003
1310	-0.014	0.003	1330	-0.003	0.001	1350	-0.005	0.001
1410	-0.001	0.001	1430	-0.007	0.002	1450	-0.008	0.002
1510	-0.003	0.001	1530	-0.007	0.001	1550	-0.003	0.002

Table 9
Differences of Waldorf and Webster Field Data of Norway—Hawaii Transmitter Pair

Time Started	Average (Lanes)	Standard Deviation (Lanes)	Time Started	Average (Lanes)	Standard Deviation (Lanes)	Time Started	Average (Lanes)	Standard Deviation (Lanes)
Wideband, April 28-29, 1969								
1510	0.011	0.003	1530	0.017	0.008	1550	0.006	0.014
1610	0.010	0.005	1630	0.010	0.005	1650	0.007	0.010
1710	0.005	0.007	1730	0.007	0.010	1750	0.006	0.006
1810	0.007	0.012	1830	0.010	0.007	1850	0.013	0.007
1910	0.013	0.005	1930	0.011	0.006	1950	0.016	0.007
2010	0.005	0.009	2030	0.011	0.008	2050	0.013	0.008
2110	0.014	0.013	2130	0.014	0.006	2150	0.015	0.006
2210	0.013	0.003	2230	0.021	0.009	2250	0.026	0.003
2310	0.016	0.007	2330	0.026	0.011	2350	0.019	0.012
10	0.033	0.008	30	0.034	0.009	50	0.047	0.008
110	0.047	0.009	130	0.049	0.007	150	0.043	0.005
210	0.040	0.004	230	0.034	0.004	250	0.048	0.005
310	0.053	0.007	330	0.053	0.005	350	0.044	0.004
410	0.051	0.007	430	0.048	0.002	450	0.068	0.003
510	0.065	0.002	530	0.064	0.005	550	0.050	0.002
610	0.036	0.003	630	0.037	0.004	650	0.038	0.002
710	0.041	0.002	730	0.044	0.002	750	0.033	0.001
810	0.043	0.002	830	0.032	0.002	850	0.027	0.004
910	0.031	0.003	930	0.029	0.001	950	0.026	0.004
1010	0.047	0.047	1030	0.025	0.007	1050	0.022	0.001
1110	0.021	0.004	1130	0.019	0.002	1150	0.016	0.005
1210	0.019	0.001	1230	0.014	0.003	1250	0.013	0.005
1310	0.018	0.005	1330	0.018	0.005	1350	0.015	0.006
1410	0.014	0.006	1430	0.010	0.009	1450	0.006	0.013
Narrowband, April 29-30, 1969								
1510	0.007	0.002	1530			1550	0.004	0.002
1610	0.002	0.002	1630	0.003	0.002	1650	0.008	0.003
1710	0.002	0.003	1730	0.004	0.002	1750	0.000	0.002
1810	-0,001	0.004	1830	0.003	0.003	1850	0.004	0.002
1910	0.009	0.006	1930	0.016	0.006	1950	0.020	0.004
2010	-0,000	0.002	2030			2050	0.003	0.003
2110	0.001	0.004	2130	0.005	0.004	2150	0.015	0.006
2210	0.011	0.004	2230	0.016	0.006	2250	0.018	0.004
2310	0.024	0.002	2330	0.018	0.004	2350	0.015	0.004
10	0.028	0.005	30	0.018	0.001	50	0.027	0.007
110	0.015	0.003	130	0.021	0.004	150	0.019	0.001
210	0.022	0.005	230	0.015	0.004	250	0.031	0.002
310	0.012	0.005	330	0.036	0.005	350	0.056	0.002
410	0.046	0.003	430	0.036	0.003	450	0.028	0.005
510	0.033	0.001	530	0.044	0.002	550	0.051	0.001
610	0.050	0.002	630	0.042	0.001	650	0.034	0.002
710	0.034	0.002	730	0.038	0.001	750	0.039	0.003
810	0.036	0.001	830	0.034	0.003	850	0.037	0.001
910	0.032	0.001	930	0.016	0.003	950	0.009	0.002
1010	0.005	0.002	1030	0.016	0.002	1050	0.012	0.002
1110	0.007	0.002	1130	0.008	0.001	1150	0.008	0.002
1210	0.008	0.002	1230	0.011	0.001	1250	0.006	0.001
1310			1330	0.011	0.003	1350	0.009	0.002
1410	0.005	0.002	1430	0.005	0.003	1450	-0.003	0.003

Table 10
Differences of Waldorf Fixed and Mobile Data of Norway—Hawaii Transmitter Pair

Time Started	Average (Lanes)	Standard Deviation (Lanes)	Time Started	Average (Lanes)	Standard Deviation (Lanes)	Time Started	Average (Lanes)	Standard Deviation (Lanes)
Wideband, May 5-6, 1969								
1210	0.006	0.004	1230	-0.002	0.003	1250	0.007	0.002
1310			1330	0.003	0.005	1350	0.000	0.008
1410	0.004	0.009	1430	0.002	0.007	1450	0.003	0.012
1510	0.007	0.007	1530	-0.000	0.011	1550	0.004	0.008
1610	-0.005	0.004	1630	0.008	0.010	1650	0.003	0.004
1710	-0.006	0.008	1730	-0.003	0.004	1750	-0.003	0.004
1810	0.000	0.008	1830			1850	0.001	0.005
1910	0.003	0.007	1930	-0.003	0.007	1950	0.006	0.006
2010	-0.000	0.017	2030	-0.002	0.005	2050		
2110	-0.008	0.009	2130	-0.005	0.007	2150	0.003	0.005
2210	-0.010	0.005	2230	0.000	0.008	2250	-0.002	0.009
2310	-0.003	0.005	2330	-0.001	0.004	2350	0.003	0.005
10	-0.007	0.003	30	-0.002	0.006	50	0.004	0.007
110	-0.004	0.005	130	-0.002	0.005	150	0.001	0.007
210	0.001	0.005	230	-0.004	0.004	250	0.001	0.002
310	-0.002	0.004	330	0.001	0.002	350	0.003	0.006
410			430			450		
510			530			550		
610			630			650		
710			730			750		
810			830			850		
910			930			950		
1010			1030			1050		
1110			1130			1150		
Narrowband, May 6-7, 1969								
1310	-0.015	0.001	1330	-0.008	0.001	1350	-0.008	0.001
1410	-0.009	0.001	1430	-0.008	0.001	1450	-0.004	0.002
1510	-0.001	0.001	1530	-0.001	0.002	1550	-0.002	0.001
1610	-0.003	0.002	1630	-0.003	0.002	1650	-0.001	0.002
1710	-0.000	0.001	1730	-0.003	0.003	1750	-0.002	0.001
1810	-0.001	0.002	1830	-0.000	0.004	1850	-0.005	0.003
1910	-0.008	0.002	1930	-0.005	0.004	1950	-0.005	0.002
2010	-0.008	0.003	2030	-0.000	0.002	2050	-0.004	0.003
2110	-0.005	0.008	2130	-0.008	0.005	2150	0.001	0.002
2210	-0.006	0.006	2230	-0.001	0.003	2250		
2310			2330	0.003	0.002	2350	0.008	0.005
10	-0.002	0.003	30	-0.000	0.002	50	0.006	0.007
110	-0.008	0.005	130	-0.003	0.003	150	-0.002	0.004
210			230	-0.003	0.002	250	-0.008	0.004
310	-0.006	0.004	330	-0.017	0.003	350	-0.021	0.003
410			430			450		
510			530			550		
610			630			650		
710			730			750		
810			830			850		
910			930			950		
1010			1030			1050		
1110			1130			1150		
1210			1230			1250		

Table 11 shows the daily average of the 5-min relative position errors and the standard deviation of these 5-min errors. It should again be noted that the wide and narrow band measurements were made on different days so a direct comparison of the difference cannot be made.

Table 11
Daily Averages of Relative Position Between the Mobile Monitor and the Fixed Monitor at Waldorf

Mobile Monitor Location with Stationary Monitor at Waldorf	Band	Trinidad vs Hawaii		Norway vs Hawaii	
		Average Lanes	Standard Deviation Lanes	Average Lanes	Standard Deviation Lanes
Pomonkey	Wide	-0.012	0.036	0.014	0.006
Pomonkey	Narrow	-0.013	0.021	0.016	0.017
Brandywine	Wide	-0.010	0.043	0.009	0.090
Brandywine	Narrow	-0.004	0.042	-0.009	0.033
Webster Field	Wide	-0.007	0.051	0.026	0.017
Webster Field	Narrow	0.012	0.011	0.018	0.015
Waldorf	Wide	-0.017	0.014	0.000	0.004
Waldorf	Narrow	-0.009	0.008	-0.004	0.005

SUMMARY

Figures 2 through 17 show how closely the readings of the two locations follow one another. It is the variation of the difference between the reading at a pair of sites that is important. This variation is shown in the lower graph of the figures. Each unit of the ordinate is equal to 10 CEL's (0.1 lane) or approximately 1900 yd for AC and 1700 yd for BC. It should be noted that it is the variation of this plot which is significant rather than any offset this variation may have. The offset is partially due to the inaccuracy of the geographic position, and further refinement of the experiment will require more precise position location.

The effect of noise is shown more clearly in a second set of curves from Figs. 19 through 26. However, the variation is again of the same order as the instrumentation. Of interest here was the hope that a stable difference could be achieved by taking the difference between the lines of the least squares of Waldorf and the mobile monitor. This would be indicated in Figs. 19 through 26 by the bottom graph showing a perfectly horizontal line of least squares. Inacmuch as this line shows a slope, the noise element of the signal has not been completely filtered out and the signals are not perfectly correlated. This is partially due to instrumentation and is indicated in Figs. 23 through 26. The data for these figures were taken with the mobile monitor located next to the stationary monitor at Waldorf. The differences here indicate a difference in each receiver's response to noise and phase variations.

CONCLUSIONS

The accuracy that can be obtained with Omega when it is used in a relative sense cannot be defined with one number. The accuracy is a variable and will depend on the

time of day, noise level, and other effects. However, the data show that standard deviations of the variations in distance can be as low as 100 yd or less. However, this is not a typical value. A conservative estimate of the overall accuracy would be of the order of 350 yd, even though better results were obtained much of the time.

The investigations show that the accuracy of this relative Omega study was, in part, limited by the instrumental accuracy of the equipment available. The use of receivers especially designed for Omega studies will reduce the error in determining the distance between two points. When the transmitters in the operational system are radiating the recommended power (10 kW), improvement can be expected during periods of high atmospheric noise.

RECOMMENDATIONS

The results of this study show the potentials of relative and differential Omega. The effects of terrain, direction, and local anomalies were not investigated because of time and equipment limitations. It is therefore recommended that improved equipment be obtained and further investigations conducted, which should include monitor receiver separations of at least 200 mi. Such equipment should have an instrument accuracy of 0.05 CEC or better and be equipped with an automatic digital data recording system.

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