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EQUATORIAL SCINTILLATIONS EXPERIENCED DURING APOLLO 11 SUPPORT JULY 12 TO JULY 24

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SEPTEMBER 1969

GSFC
GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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PREFACE

The information contained in this report was originally prepared under Contract NAS 5-11-513 for inclusion in one of the regular "updates" distributed to holders of the ATS Technical Data Report (TDR). However, it was recognized that many TDR holders would have no requirement for this extensive and detailed material. As a matter of economy, therefore, it was decided to present the information as a separate document with a smaller printing and simply call attention to it in the TDR.

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SUMMARY

The ATS-1 VHF transponder was used as a communication link between ships of the Apollo 11 task force and the U.S. mainland from July 12 to 24. During 13 days of testing, several fading and changes in apparent angle of arrival of signals were experienced. The fading is attributed to equatorial scintillations, but the changes in the apparent angle of arrival are difficult to account for. Some changes can be attributed to the effects of the ship's structure on the antenna radiation patterns, but it does not account for all the changes. It is recommended that a formal experiment be performed to obtain a larger, more controlled sample and from these data calculate statistically reliable results.

INTRODUCTION

The VHF transponder on the ATS-1 satellite was used as a backup communications link from the Apollo 11 recovery ship U.S.S. Hornet, and the tracking ships Huntsville, Mercury and Redstone to the U.S. mainland. A basic block diagram of the system used is depicted in Figure 1. The shipboard stations all use identical equipment capable of transmitting 250 watts and using 12-db gain, circularly polarized antennas. The Mojave ATS ground station has a transmitter capable of 1 KW; it has a 21-db gain circularly polarized receive antenna and a 14-db gain circular polarized transmit antenna.

The spacecraft VHF transponder is a saturated amplifier that is power limited and proportions its output power, with some compression, between the two carrier signals according to the ratio of the input signal powers. Therefore, the 49.1-dbm EIRP of the spacecraft is proportioned to 48.4 dbm and 36.8 dbm. The derivation of these values is indicated in Appendix I. Because of this proportionment, the fading of one signal reflects its effect on the other signal. For instance, if the power ratio of the two input signals varies, the output ratio will also vary with the same proportion. (Assuming both signals are above the threshold of the transponder). This effect is mentioned because it could be interpreted on the recordings as fading of a channel that is not fading.

SYSTEM CALCULATIONS

The predicted performance of the two carrier channels is indicted in Appendix I, System Calculations. A comparison of sections A and B of Appendix I indicates that there is an 8-db difference in the power level of the two signals impinging upon the spacecraft. Previous tests of ATS-1 indicate that an 8-db ratio is converted to a 12-db output ratio because of the compression of the transponder. This 12 db is reflected in section D where it can be seen that the shipboard signal (S_2) is retransmitted by the spacecraft at 36.8 dbm compared to 48.8 dbm for S_1 signal.

Sections E and F indicate the received levels of these signals from the output of a terrestrial isotropic radiator. Sections H through K indicate the predicted received levels of the two signals at the ground station and the shipboard station. The expected level of the signal emanating from the ground station and received by the ship is -111.8 dbm. The signal level measured by the ships varied from -105 dbm to -125 dbm with a mode of -110 dbm. The difference between the predicted level of -111.6 dbm and the measured -110 dbm is probably due to values of feeder loss used in the calculations.

The signal level received by Mojave of its own signal is approximately -103 dbm, which compares favorably with the -102.8 dbm predicted. The received level at Mojave of the signal transmitted by the ships is approximately -111 dbm. The predicted value of -114.8 dbm is approximately 4 dbm less than the measured and could be accounted for by possible feeder loss error, transmitter power error, or compression ratio error.

RESULTS

Received signal level tests were made at Mojave at various times between July 12 and July 24, inclusive. Signal level was determined by recording the AGC level on four receivers at Mojave. Two receivers were receixing the ground station signal and the other two recorded the signal being transmitted from the shipboard station. The bandwidth used was 10 kHz with an AGC time constant of 0.3 second.

A review of Table 1 indicates that a great deal of signal fading was encountered during the tests. A close look at the time of occurrence of fades indicates that all the fading occurred at local night time. Because of the small amount of data, it is impossible to indicate with any high degree of certainty the time zone of fading. The small amount of data indicated, however, that the fading started at approximately 1900 hours (local) and stopped on one occasion at approximately 0500 hours and on another occasion at approximately midnight.

Previous VHF tests among a ground station, ATS spacecraft, and airplanes or Coast Guard cutters have indicated fading, but not of the duration and depth witnessed during these tests. Tests made by others [1,2] however, indicate that stations located near the geomagnetic equator experience severe fading. These equatorial scintillations appear to vary as a function of the time of day, season, sunspot cycle, and geomagnetic latitude of the earth station. According to the literature, equatorial scintillations are most serious during local night time starting at approximately 1700 hours and ending at approximately 0800 hours. It has also been shown that the scintillations reach a maximum during the equinox and minimum during the solstice. Since this experiment was performed nearer a solstice than an equinox, it can be assumed that the scintillations would have been worse for a different season of the year.

Figure 2 is a strip chart recording made at Mojave of two signals from the spacecraft. One signal (the upper trace) originated from Mojave; the other signal (the lower two traces) originated at the shipboard station on the U.S.S Hornet. The recordings were made from four identical receivers connected to the same antenna. (Only three are shown.)

The bandwidth used was 10 kHz with an AGC time constant of 0.3 second. The recording was taken on July 24 between the time of 0924 GMT to 0944 GMT. At this time, the Hornet was positioned at 11° 10.5' north latitude and 172° 09' west longitude. From Figures 5 and 6 it can be seen that this position corresponds to a north geomagnetic latutude of approximately 22° N.

Figure 2 is a typical recording of a station going through a short fading sequence. The entire fade sequence extends from 0925Z to 0940Z (15 minutes). This corresponds to local time of 2025 to 2040. The chart indicates that the average signal level at Mojave of its own signal is approximately -102 dbm and of the U.S.S. Hornet's signal -111 dbm. These compare very favorably with the calculated values of -102.8 dbm and -111.8 dbm. The fading starts with very shallow depths of approximately ± 2 db and duration of approximately 5 seconds between adjacent zero crossings. After approximately 5 minutes, the fade depths reach magnitude of + 7 db to -15 db. The 15 db is not necessarily the depth of the fade but could be a limitation caused by the equipment capability. Although it took approximately 5 minutes to enter into full fading, it can be seen that the fade ends in approximately 1 minute (0939-40 to 0940-40).

The slight scintillation of Mojave's signal between 0928-25 and 0932-20 is due to the power sharing effect of the spacecraft and not to fading. The decrease in the Mojave signal can be correlated with an increase in signal level of the Hornet signal. Specifically at 0930, the Mojave signal level has a deep spike, but the Hornet signal has a sharp increase at the same time. Since the spacecraft is a constant power device, the output power on the two signals is a function of their input power ratios and the compression ratio of the S/C.

Figure 3 indicates the signal level of two ships, the Huntsville and the Hornet on July 19 at approximately 0830. From figure 6 it can be seen that on July 19 the Huntsville was at a geomagnetic north latitude of approximately 28° and the Hornet was at a geomagnetic north latitude of approximately 10°. Because of the relative distance of the two ships with respect to the geomagnetic equator, it could be surmised that the Hornet would undergo more severe fading than the Huntsville. Figure 3 does substantiate this hypothesis.

Figure 4 indicates the signal level of ship Redstone received at Mojave at approximately the same time of 0815 GMT. From figure 6 it can be seen that the Redstone is positioned at approximately 8° south geomagnetic latitude. Because of its nearness to the geomagnetic equator it would be surmised that its scintillations would be as severe as the Hornet located at 10° N geomagnetic latitude. The strip chart does not indicate this; however this short sample does not provide sufficient information on which to draw a conclusion. It appears that the signal is going into deep fading towards the end of the sample and the fading being witnessed on the Hornet does not start until some time between 0820 and 0832 GMT. Therefore, it could be possible that the experiment is time varient, and the two events are independent.

Another phenomenon witnessed by the experimenters on the U.S.S. Hornet was a change in the apparent angle of arrival of the signal emanating from an impinging upon the S/C. Most of the time the signal appeared to be coming from a source not positioned along the line-of-sight path to the satellite. The difference was in the azimuth angle, no difference was noted in the true elevation angle. Table 3 gives some indication of the changes in the apparent angle of arrival that were experienced by the experimenters aboard the U.S.S Hornet July 22 and 23rd. The azimuth angle to the LOS of the spacecraft is 117°, but it can be seen from the table that maximum receive signal is obtained for angles from 70° to 180° and maximum signal is received at Mojave for azimuth angles from 30° to 180°. In addition to the change in angle of arrival of the signal, the transmit and receive angles differ at a given time.

A plot of the frequency of occurrence of the different angles of arrival is shown on Figure 7. This is a crude attempt to show the distribution of the apparent angle of arrival. It is crude because the experiment results contain biased samples and the criteria used for determining the angle of arrival could be erroneous. It is a well known fact that the ship's strucure has an effect on the radiation pattern of antennas and since the effect is not known, the true angle of arrival of the signal may not be as measured. Because of these effects and biases there is little confidence that the results are repeatable, and are therefore not statistically stable.

Figures 8, 9, and 10 are graphs of the scintillation index as a function of local time. The scintillation index was determined from the strip charts recorded at Mojave. It was concluded to be scintillations in the link from the shipboard station to the spacecraft because the link from the spacecraft to the Mojave ground station did not experience scintillations. The method of determining scintillation index is the method adopted by AFCRL (Air Force Cambridge Research Labs) and the JSSG (Joint Satellite Studies Group) which is:

$$\text{Scintillation Index} = \frac{P_{MAX} - P_{MIN}}{P_{MAX} + P_{MIN}}$$

Where:

P_{MAX} is the power amplitude of the third peak down from the maximum excursion in a 5-minute interval.

P_{MIN} is the power amplitude of the third level up from the minimum excursion in the same 5-minute interval.

Figures 8 and 9 indicate the scintillation index at predominately the local night time hours. It can be seen that they are relatively high during this time period. Figure 10 indicates the scintillation index as a function of time for the days of July 22, 23, and 24. It is the most complete record of all the data taken and indicates the diurnal variation of the scintillation index. Since the task force was located near the geomagnetic equator during these tests and since the scintillation index diurnal variation indicates high values at night and low values during the day; it is hypothesized that the VHF problems experienced during the Apollo 11 splashdown were due to "Equatorial Scintillations". Except for the large variations at 1600, the distribution of the scintillation index follows the typical pattern of equatorial scintillations (high at night-low during the day).

The cumulative distribution of Scintillation index is plotted in Figure 11. Most of the data prior to July 23 was local night time. If it were used, the distribution would be biased to the large scintillation indicics. In order to depict evenly weighted measurements over one day, the 24 hours of data of July 23 were used for the graph of Figure 11. Since this is only one day of data, it should not be construed to be an average or mean distribution. It is just one data point of the set. The indicated mean is 50% scintillation index. The calculated mean is 47.93 and the standard deviation is 39.88.

CONCLUSIONS

The fading of the VHF channel experienced by the recovery ship and tracking ships during the Apollo 11 mission is caused by the propagation mechanism "equatorial scintillations". Experiments by others indicate that it occurs within $\pm 20°$ of the geomagnetic equator and is most severe during local night time hours. The literature also indicates that it is seasonal and is expected to reach a maximum during the equinox and a minimum during the solstice. Since the experiments were performed in the middle of July and solstice occurs on June 21st, it can be assumed that the situation could have been worse.

The change in the apparent angle of arrival of the signal is a function of time and the different angle of arrival of transmit and receive signals at a given time are characteristics which appear to be peculiar to this experiment. Other experimenters have not reported this phenomenon, possibly because they were not aware of it or it did not occur. The statistics of this phenomenon can not be determined from this experiment because of insufficient data, biased samples, erroneous measurements, and uncalibrated shipboard antenna radiation patterns. The experiment results do, however, imply the existence of the phenomena despite the fact that the measurement procedure is not constant through the experiment.

RECOMMENDATIONS

Because of the small amount of data available for analysis, the inconsistent measurement procedure used, and the importance of VHF communication from synchronous satellites, it is recommended that a formal VHF experiment be performed. It would be desirable to have as many stations as possible, spread over the surface of the earth, to participate in the experiment. By spreading the stations over the earth, the hypothesis of equatorial scintillations as a function of distance from the geomagnetic equator can be investigated. The diurnal effects at different latitudes could also be investigated with an attempt to statistically describe the fading characteristics and the time availability of each station.

The change in the apparent angle of arrival of the signal can be ascertained. If it exists, it implies that possible space, angle, or frequency diversity may be methods of counteracting the fading. These techniques, along with different methods of combining, should be investigated to determine if reliable VHF communication can be provided in the future.

In conclusion, it is recommended that the ATS Project Office seriously consider performing formal VHF scintillation and angle of arrival experiments. The results of these experiments could determine with statistical reliability the diurnal and seasonal fading characteristics of the "equatorial scintillation" propagation mechanism. The experiments will also determine if the apparent angle of arrival changes, its distribution, and the effects of diversity and combining.

REFERENCES

1. "A Survey of Scintillation Data and its Relationship to Satellite Communications" prepared by: Radio Astronomy Branch Ionospheric Physics Laboratory, August 1969, Air Force Cambridge Research Laboratories.

2. Golden, T. "Ionospheric Distortion of Minitrack Signals in South America" Feb. 1968, NASA Document X-525-68-56.

ACKNOWLEDGMENTS

The names of many of those who contributed to this experiment will never be known. To these anonymous people I wish to express my gratitude. I am also grateful to Mr. T. Golden of Goddard Space Flight Center and Mr. R. Boldridge of Westinghouse Electric Corporation for their many discussions and suggestions. I am particularly grateful to Messrs. L. Harman and B. Watts, also of Westinghouse for the many hours they spent reducing the data of this experiment. I am also most grateful to Mr. E. Metzger, the Operations Manager of ATS, for the spacecraft and ground station time, and additionally for providing me the opportunity to perform this analysis.

TABLE 1. SUMMARY OF ACTIVITY REPORT FROM U.S.S. HORNET

DATE (LOCAL)1969	OPERATING TIME (LOCAL)	NOTES ON FADING
July 11	2100 to 2200	No interference reported
July 12	2100 to 2200	Some intermittent interference
July 13	2100 to 0155 (July 14)	Sporadic interference
July 14	2100 to 2200	Severe fading (-112dbm to -123dbm)
July 15	2100 to 2320	Prolonged and deep fades (-110dbm to -123dbm)
July 16	2040 to 2300	Signal fading (-110 to -125dbm)
July 17	2100 to 0007 (July 18)	Occasional fades increasing to frequent
July 18	2100 to 2330	Deep fading (-110dbm to -125dbm)
July 19	0500 to 0857	No fading (-113dbm)
July 19	2100 to 2300	Deep occasional fades (-105dbm to -120dbm)
July 20	0700 to 0903	No fading
July 21	0400 to 0805	No fading
July 21	1530 to 1845	No fading
July 22	0645 to 2400	No fading until 1930Z (Fading until 2400)
July 23	0000 to 2400	Fading at 0000 until 0432. No fading between 0500 and 1845. Fading between 1845 and 2400.
July 24	0000 to 1015	Fades diminish at 0400.

TABLE 2. SHIP LOCATIONS

DATE	REDSTONE		HORNET		HUNTSVILLE		MERCURY	
	LAT.	LONG.	LAT.	LONG.	LAT.	LONG.	LAT.	LONG.
7-11-69	8°45'N	167°42E	-------	--------	-------	--------	0°15'N	180°W
7-12-69	8°45'N	167°42E	-------	--------	-------	--------	8°44'N	175°54'W
7-13-69	5°20'N	167°11E	19°4'N	165°34'W	-------	--------	9°56'N	175°10'W
7-14-69	0°30'N	166°49'E	13°32'N	165°00'W	-------	--------		
7-15-69	2°34'S	166°35'E	6°46'N	175°3'W	-------	--------	9°49'N	175°14'W
7-16-69	2°17'S	166°43'E	-------	--------	-------	--------	9°55'N	175°9'W
7-17-69	0°32'S	177°50'E	2°1.5'N	165°28'W	21°22'N	157°58'N	-------	--------
7-18-69	2°48'N	167°00'E	1°52'N	166°31'W	17°14'N	162°32'W	13°0'N	169°20'W
7-19-69	1°8'N	166°31'E	4°59'N	168°2'W	14°16'N	166°54'W	16°37'N	176°13'W
7-20-69	3°13'S	176°38'E	7°53'N	168°21'W	10°52'N	171°23'W	-------	--------
7-21-69	3°12'S	165°29'E	9°19'N	170°45'W	7°35'N	175°47'W	-------	--------
7-22-69	3°39'S	164°15'E	11°11'N	172°7'W	5°28'N	178°9'W	21°22'N	157°58'W
7-23-69	8°02'S	163°02'E	11°10'N	172°9'W	5°28'N	178°00'W	21°21'N	157°14'W
7-24-69	7°50'S	163°51'E	12°3'N	171°51'W	5°25'N	177°50'W		

TABLE 3. APPARENT ANGLE OF ARRIVAL

TIME (Z)	SHIP'S POSITION LAT.	LONG.	AZ. ANGLE OF ARRIVAL REC.	TX	SHIP'S HEADING	TIME(Z)	SHIP'S POSITION LAT.	LONG.	AZ. ANGLE OF ARRIVAL REC.	TX	SHIP'S HEADING
JULY 22						JULY 23					
0230	11°4.3'N	172°16.2'W	85°	85°	270°	1224			70°	70°	0°
1850	11°11'N	172°07'W	115°	40°	270°	1255			70°	70°	0°
1953			100°	95°	270°	1410			70°	70°	75°
2006			180°	--	270°	1532	11°30'N	172°55'W	80°	120°	75°
2009			85°	30°	270°	1705			130°	130°	74°
2035			70°	--	60°	1725			70°	130°	
JULY 23						1825			90°	90°	40°
0006			95°	--		1855			90°	90°	60°
0040			110°	--	75°	1940			130°	130°	40°
0115			120°	100°	265°	1945			130°	130°	40°
0257			70°		175°	1959			150°	150°	40°
0400			140°	90°	165°				100°	100°	40°
0520			90°	90°	0°	2010			50°	120°	40°
0602			90°	90°	235°	2105			90°	120°	40°
0615			110°	120°	235°	2225			90°	90°	50°
0630			90°	180°	235°						
0715			145°	100°	230°						
0725	11°56'N	172°41W	---	---	240°						
0845			90°	90°	240°						
----			175°	LOST	240°						
1000			90°	90°	0°						
1045			150°	150°	0°						
1055			70°	150°	0°						
1105			150°	[illegible]	0°						
1142			70°	70°	0°						

Azimuth L.O.S. angle is 117°

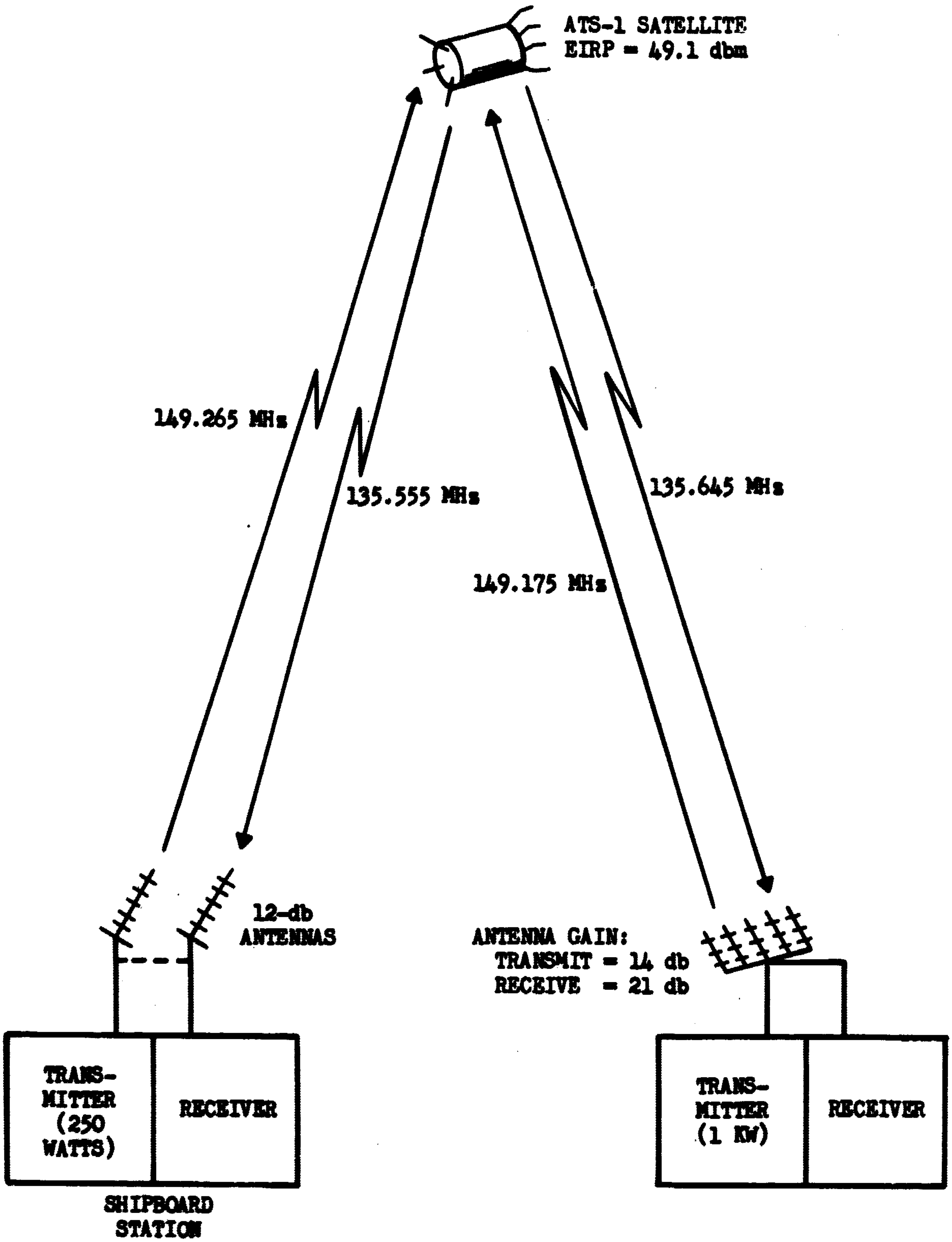


Figure 1. System Configuration

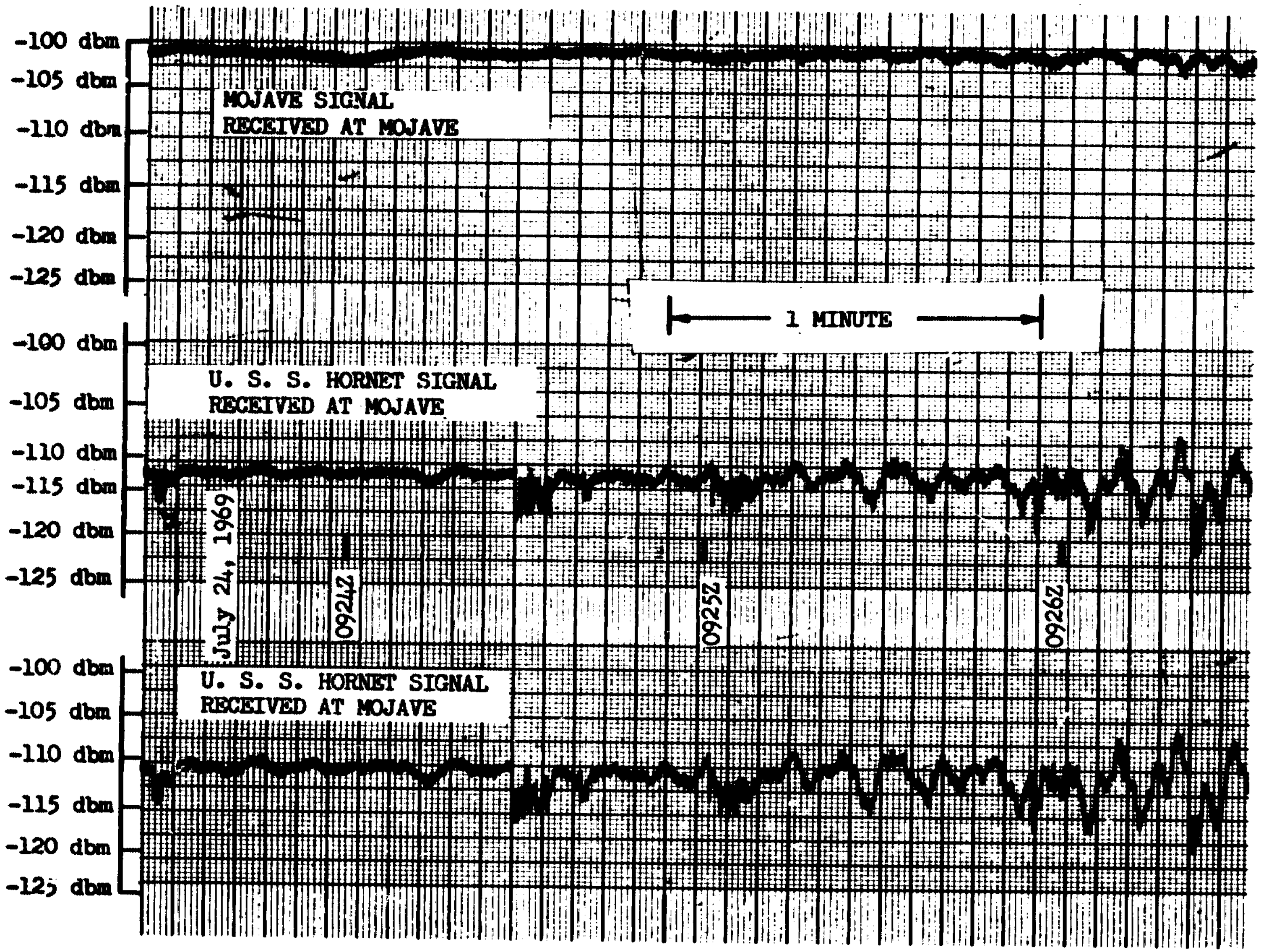


Figure 2. Signal Level of Mojave and U.S.S. Hornet (Sheet 1 of 6)

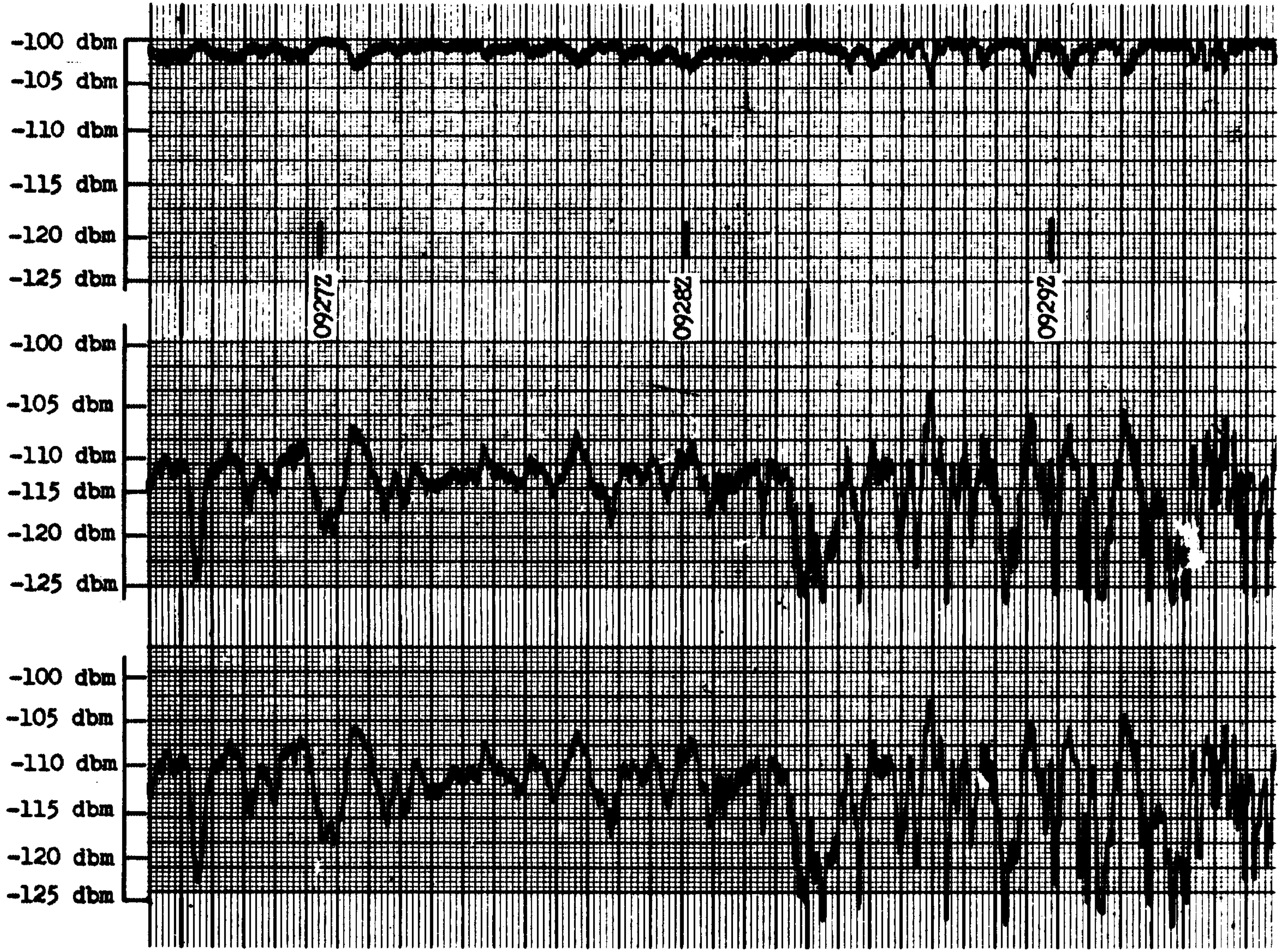


Figure 2. Signal Level of Mojave and U.S.S. Hornet (Sheet 2 of 6)

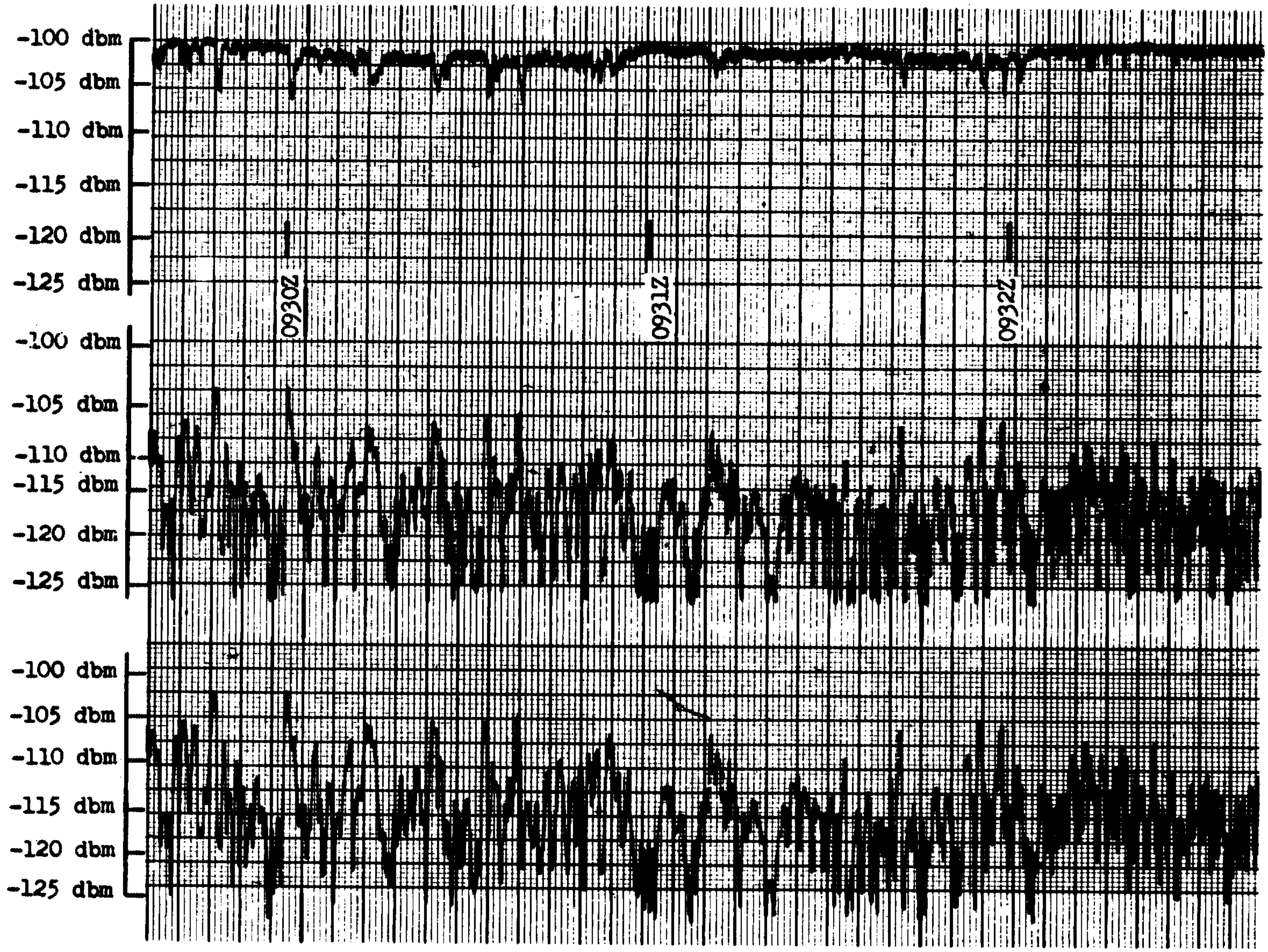


Figure 2. Signal Level of Mojave and U.S.S. Hornet (Sheet 3 of 6)

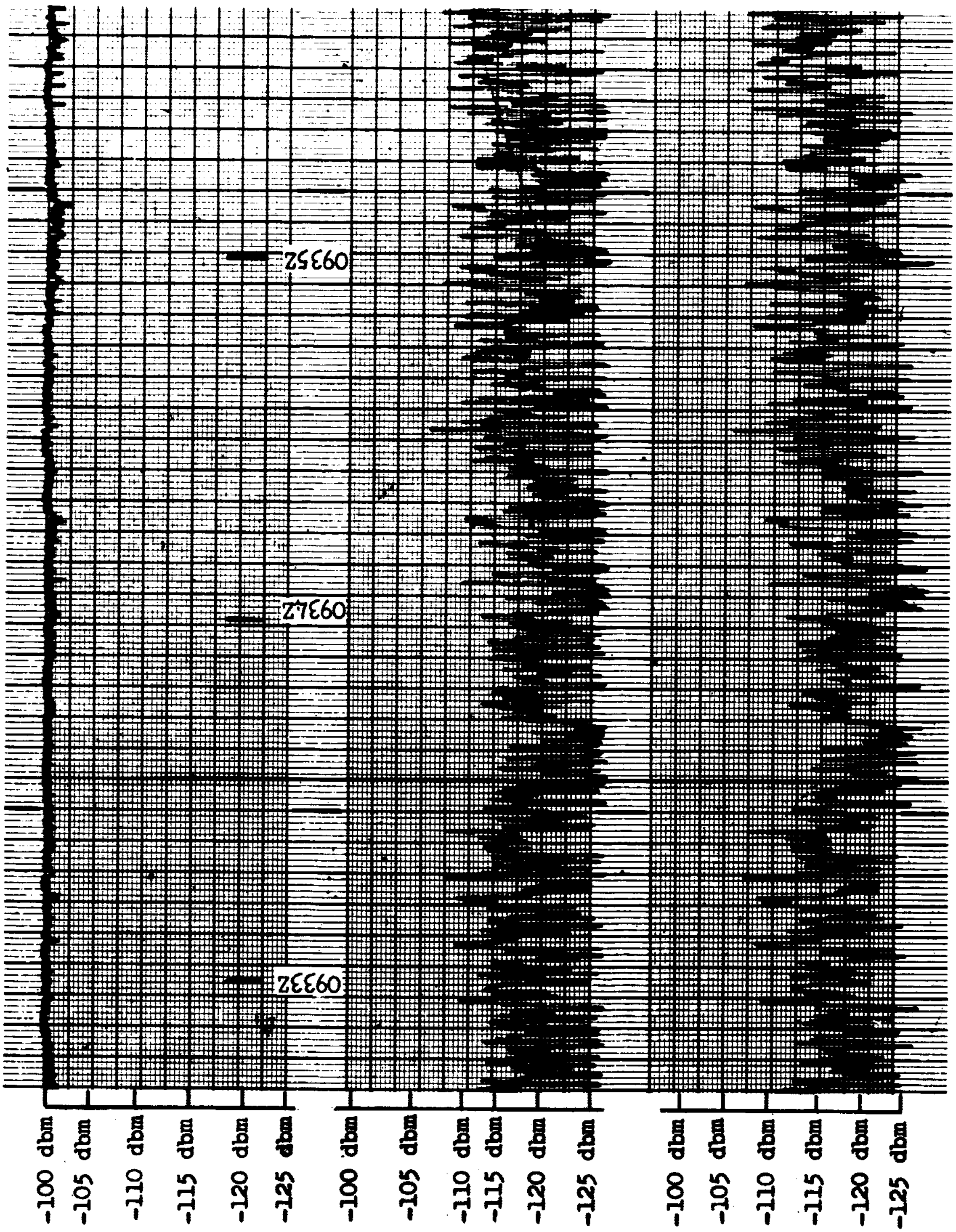


Figure 2. Signal Level of Mojave and U.S.S. Hornet (Sheet 4 of 6)

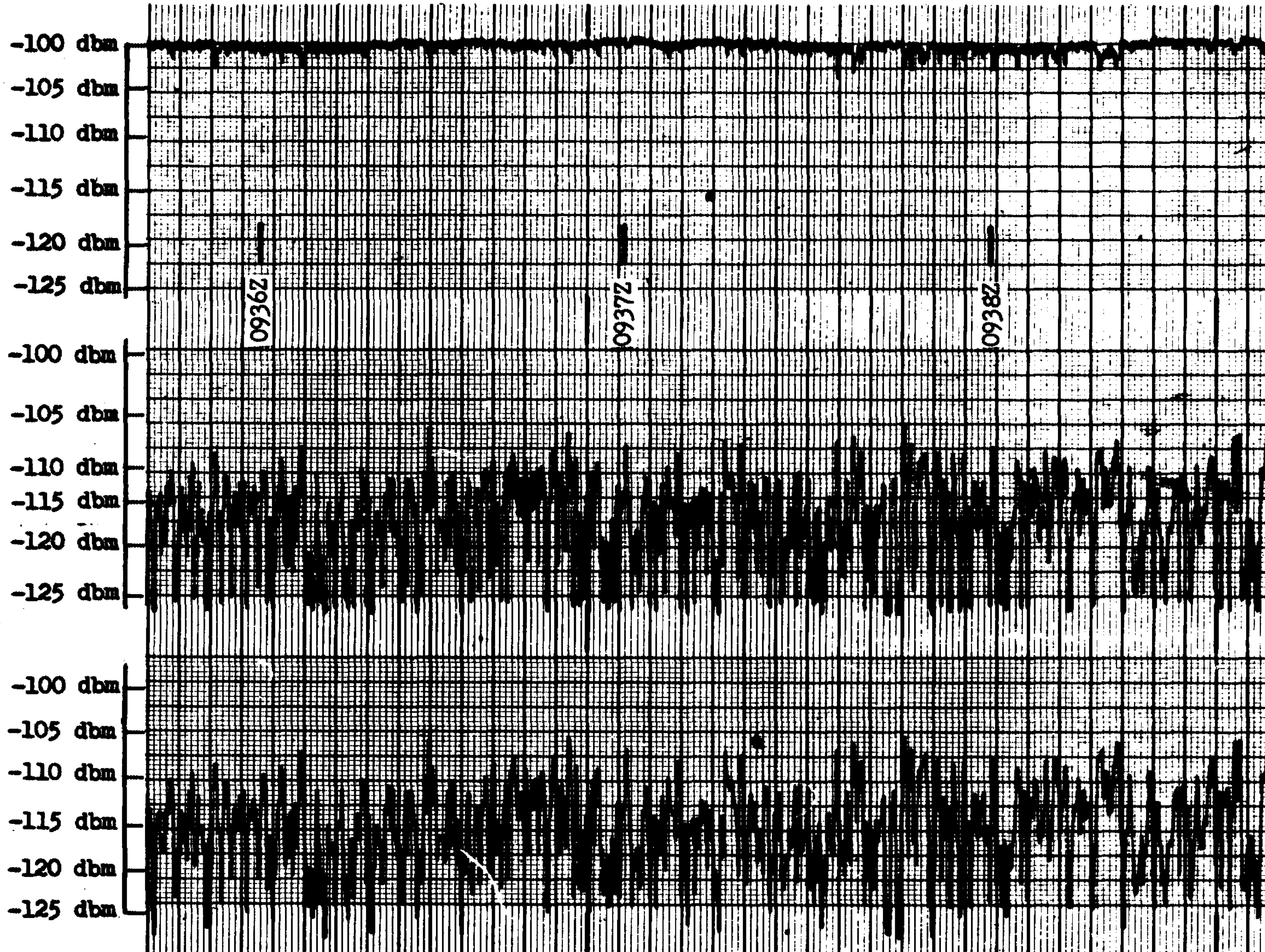


Figure 2. Signal Level of Mojave and U.S.S. Hornet (Sheet 5 of 6)

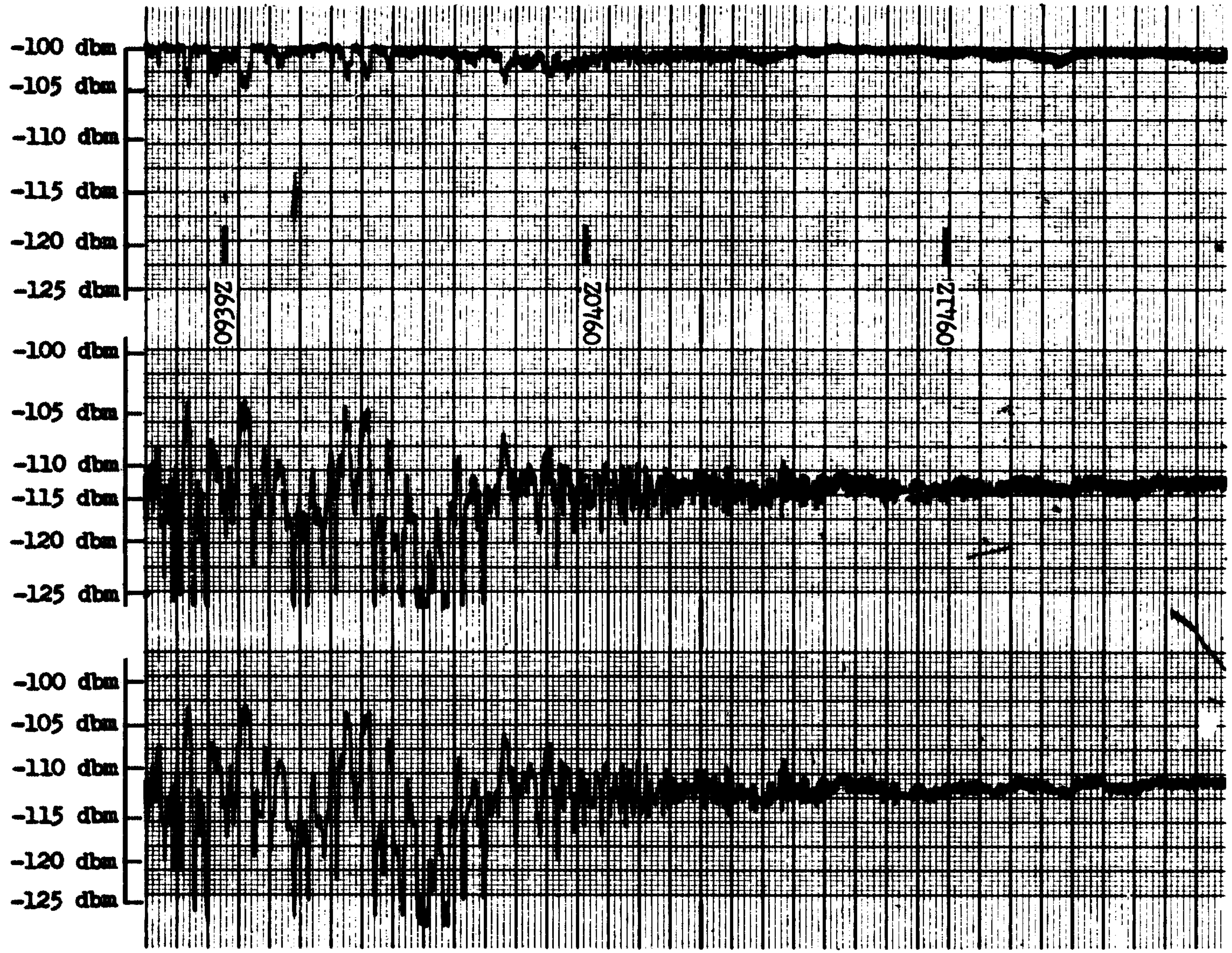


Figure 2. Signal Level of Mojave and U.S.S. Hornet (Sheet 6 of 6)

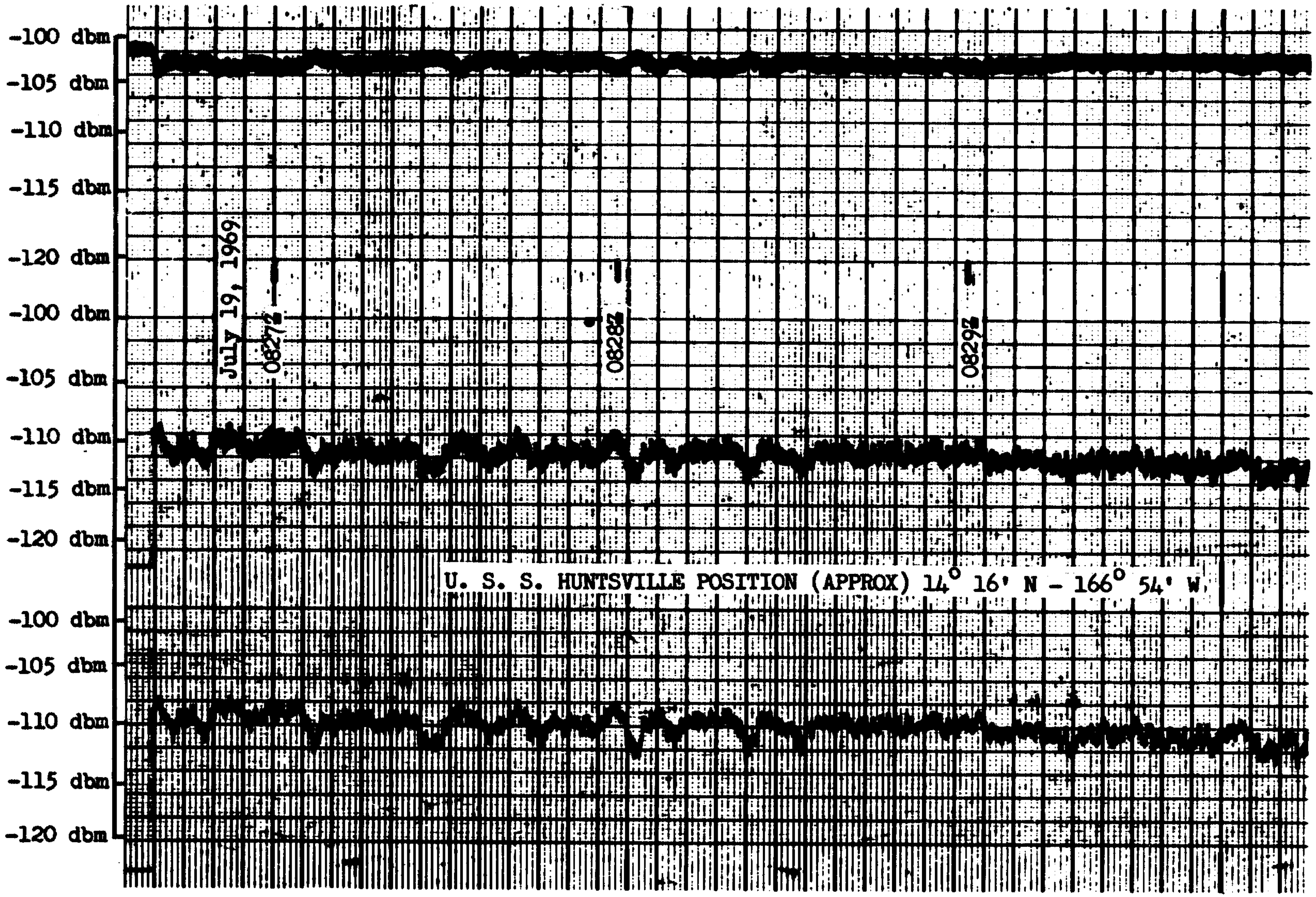


Figure 3. Signal Level of Mojave, U.S.S. Huntsville and U.S.S. Hornet
(Sheet 1 of 4)

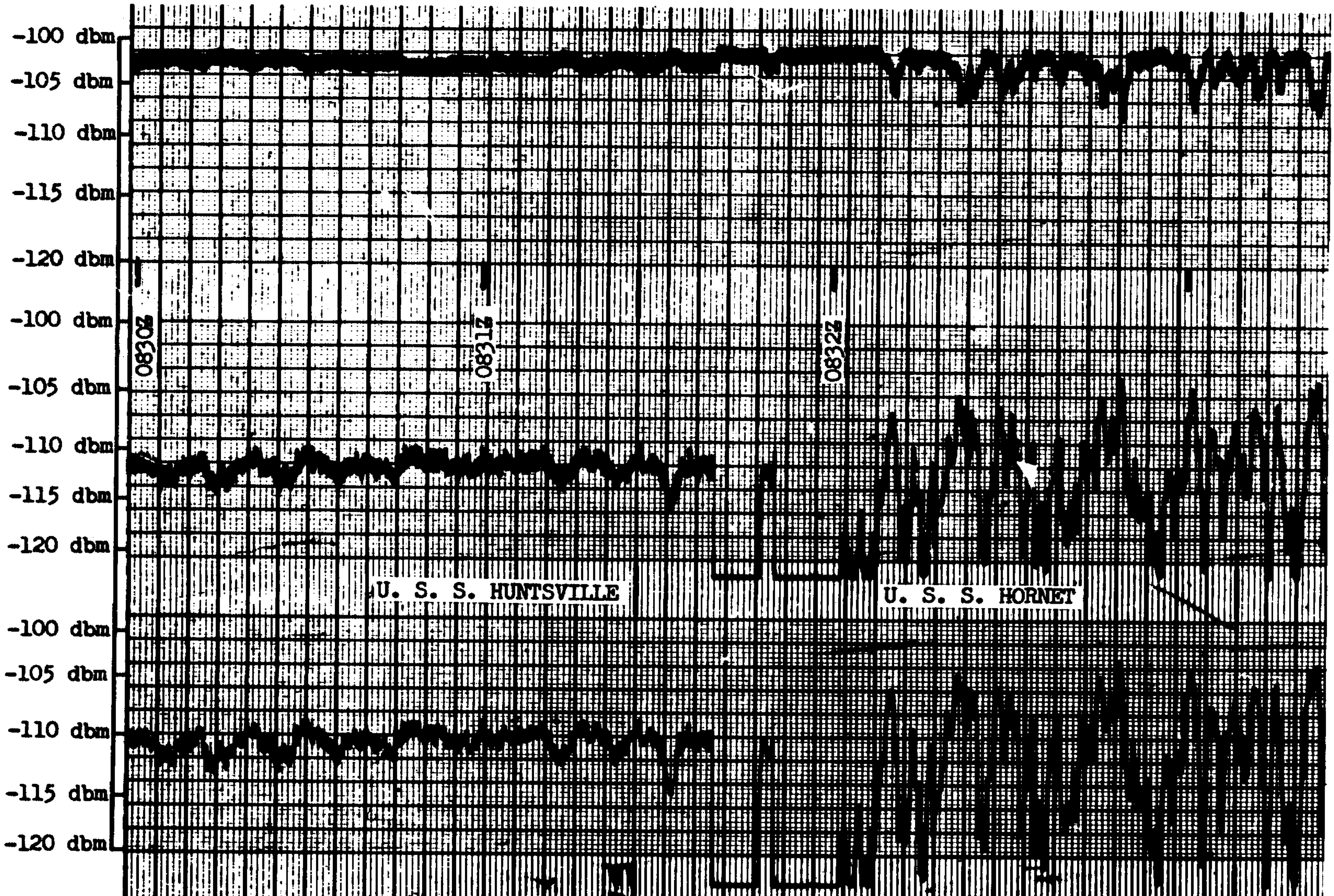


Figure 3. Signal Level of Mojave, U.S.S Huntsville and U.S.S. Hornet
(Sheet 2 of 4)

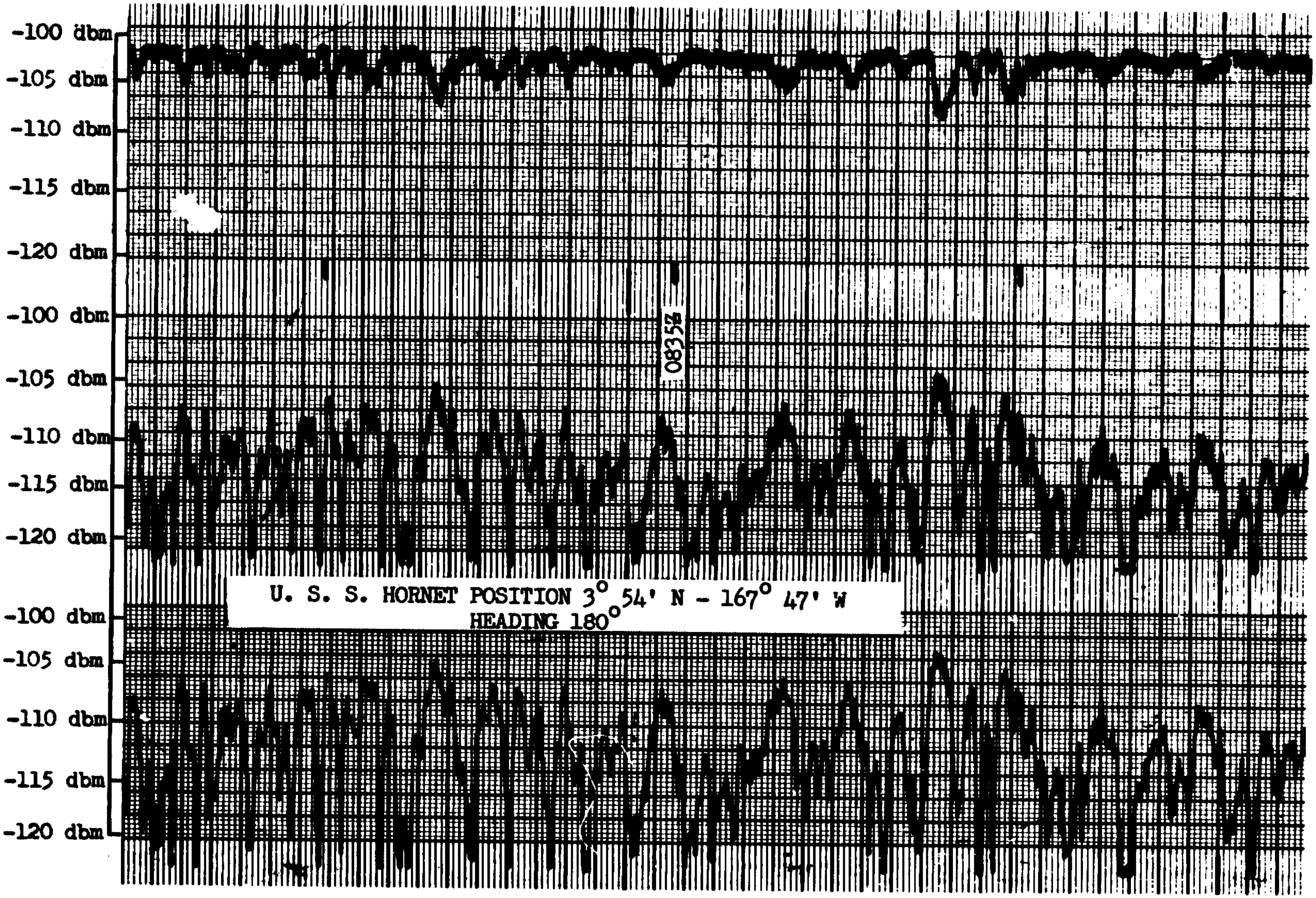


Figure 3. Signal Level of Mojave, U.S.S. Huntsville and U.S.S Hornet
(Sheet 3 of 4)

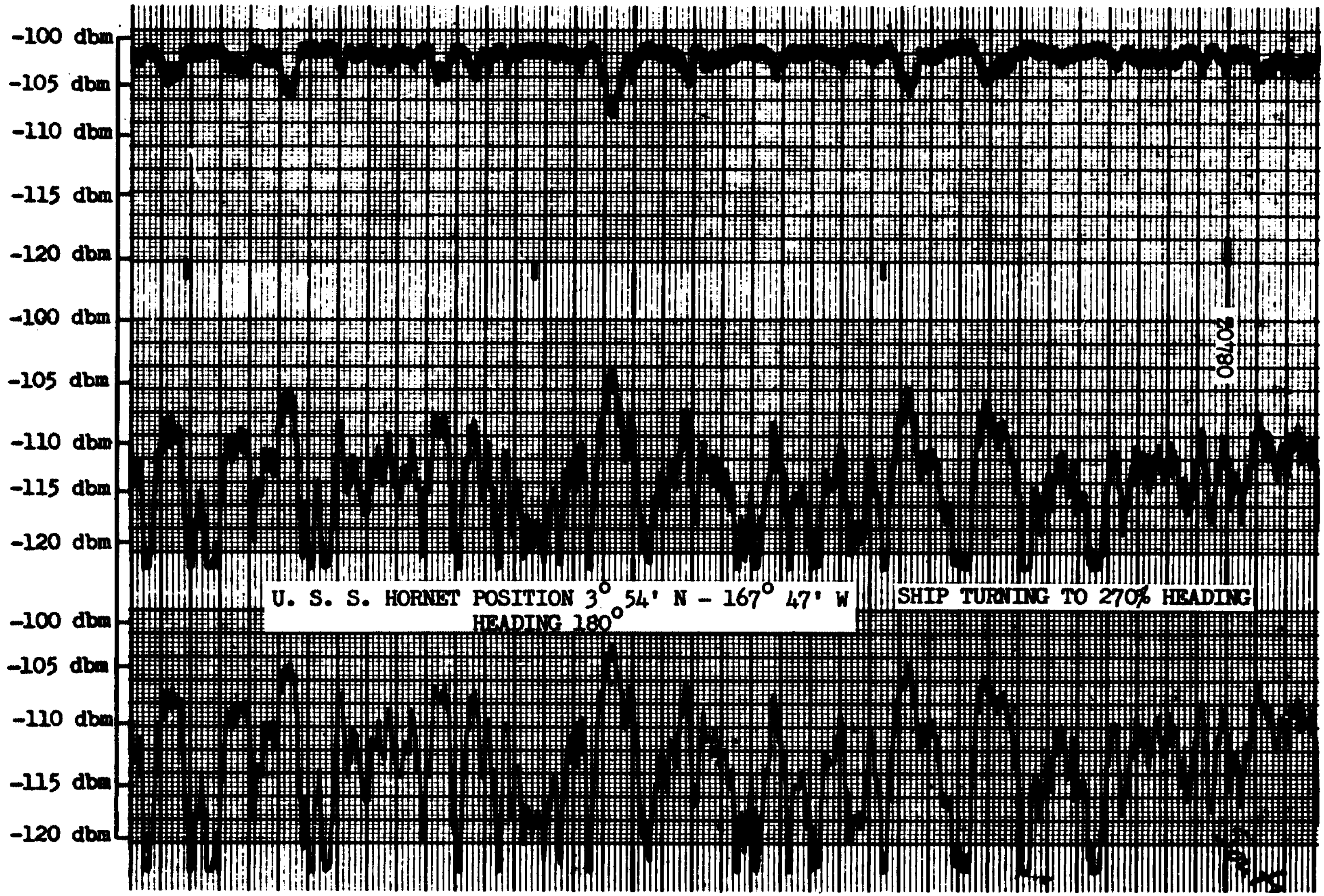


Figure 3. Signal Level of Mojave, U.S.S. Huntsville and U.S.S. Hornet (Sheet 4 of 4)

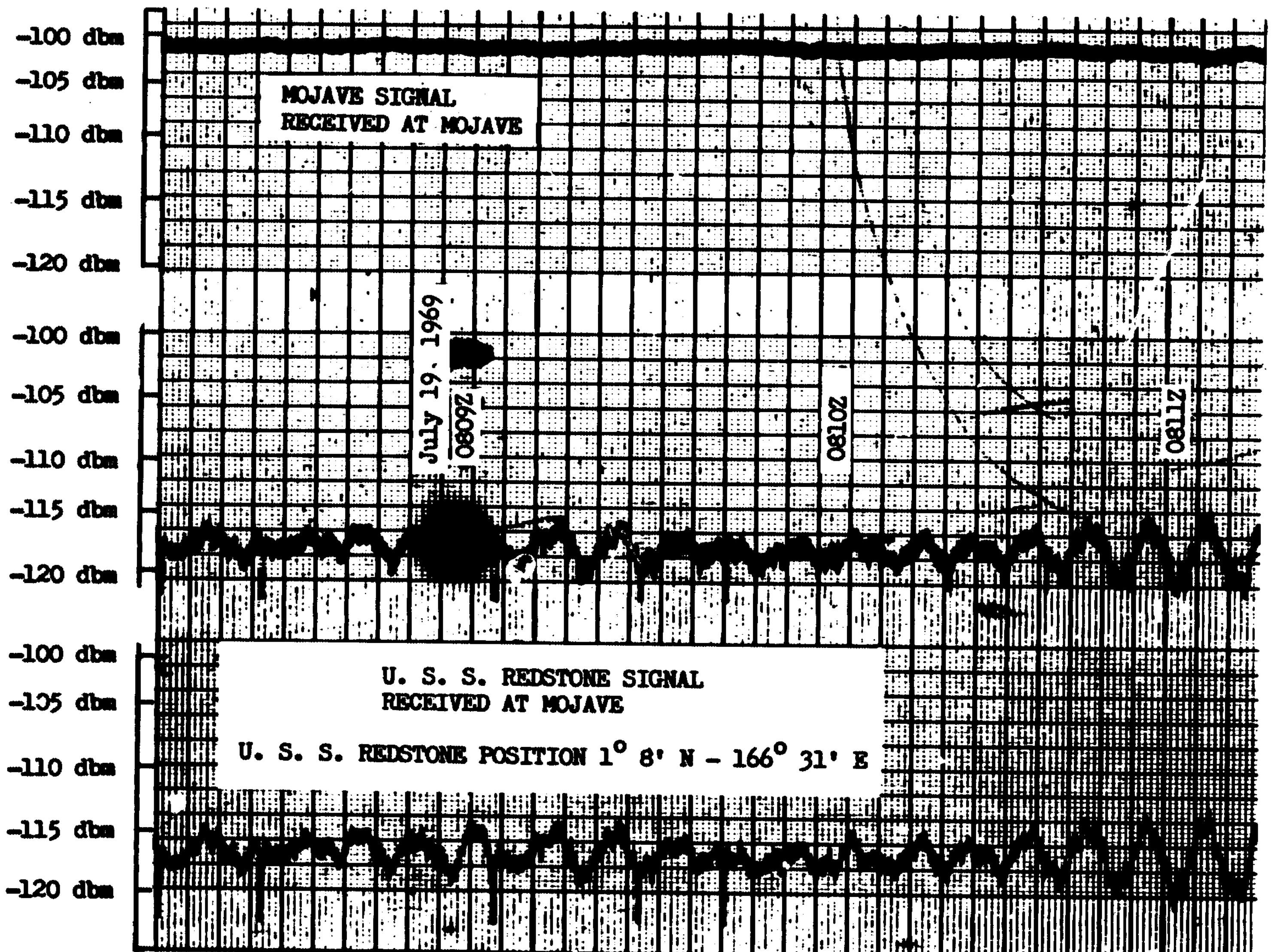
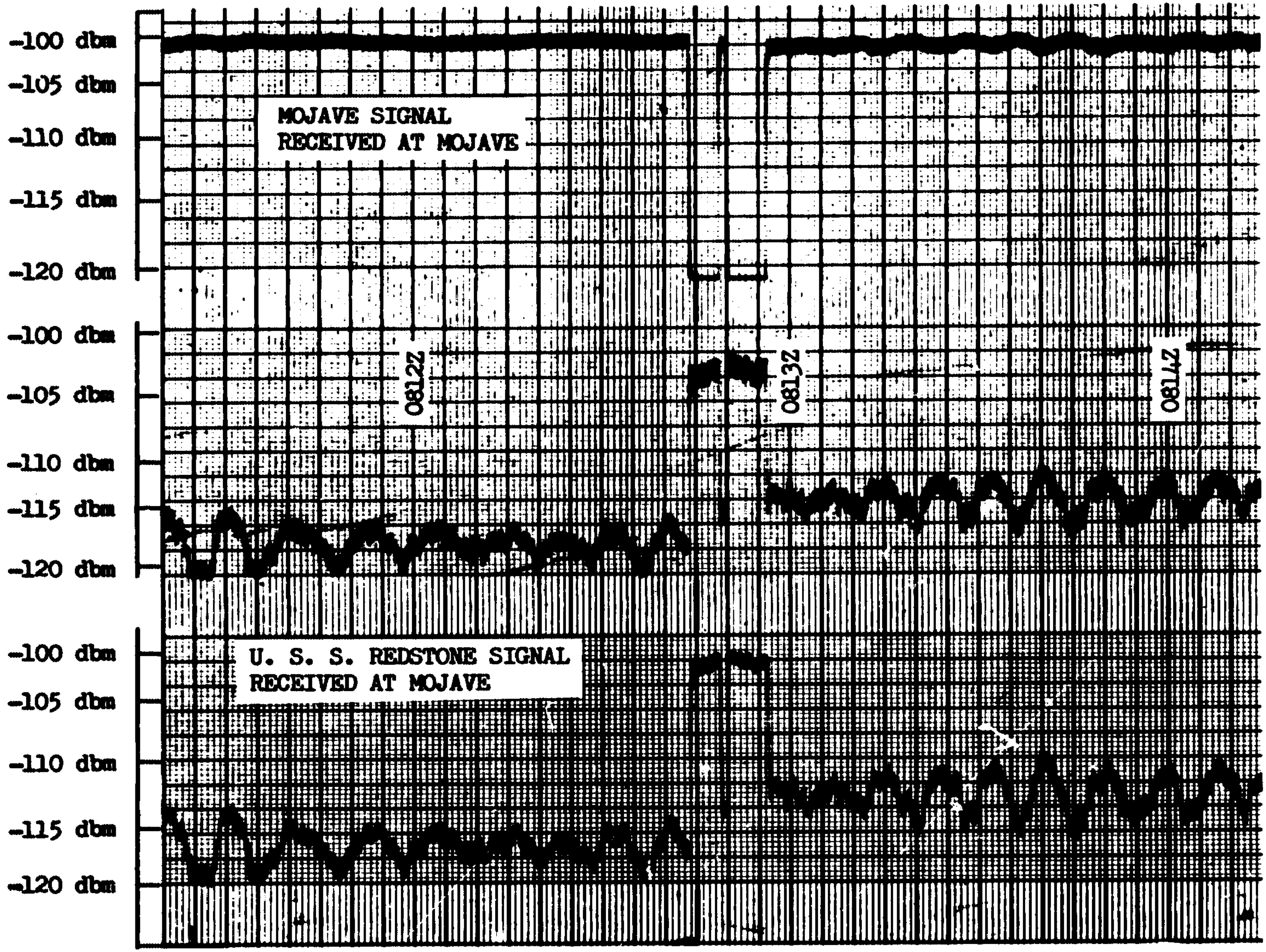


Figure 4. Signal Level of Mojave and U.S.S. Redstone (Sheet 1 of 5)



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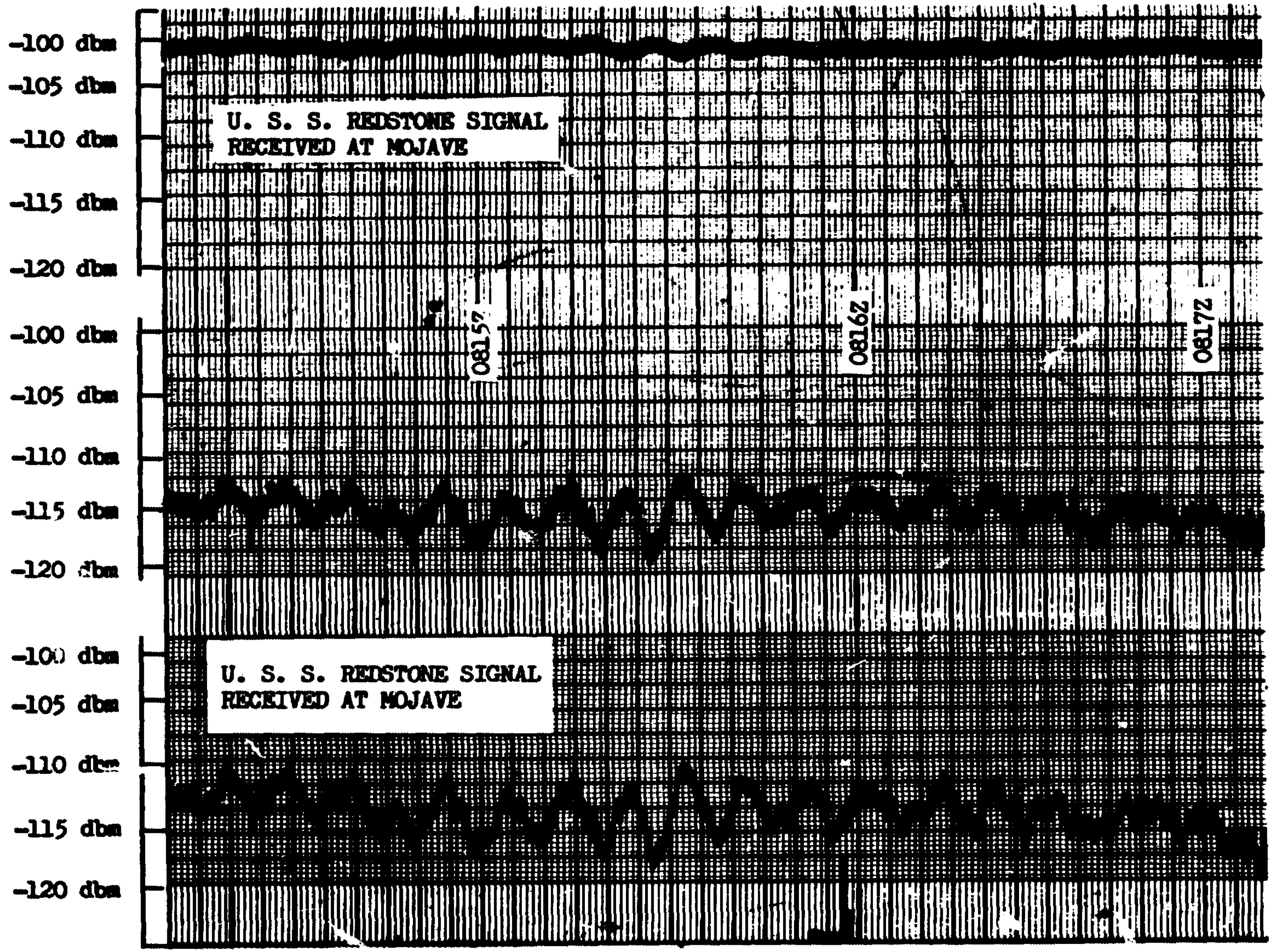

Figure 4. Signal Level of Mojave and U.S.S. Redstone (Sheet 3 of 5)

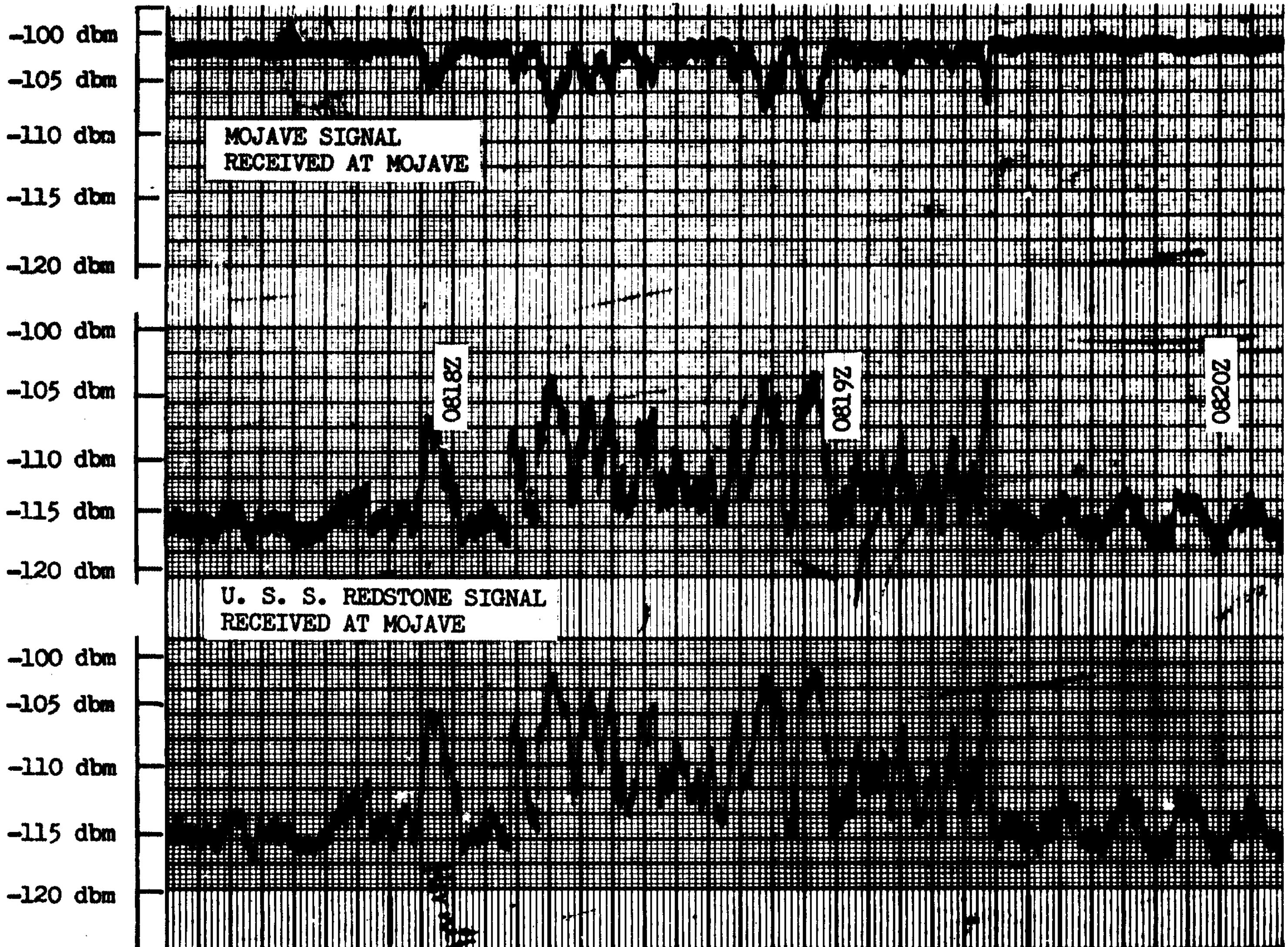

Figure 4. Signal Level of Mojave and U.S.S. Redstone (Sheet 4 of 5)

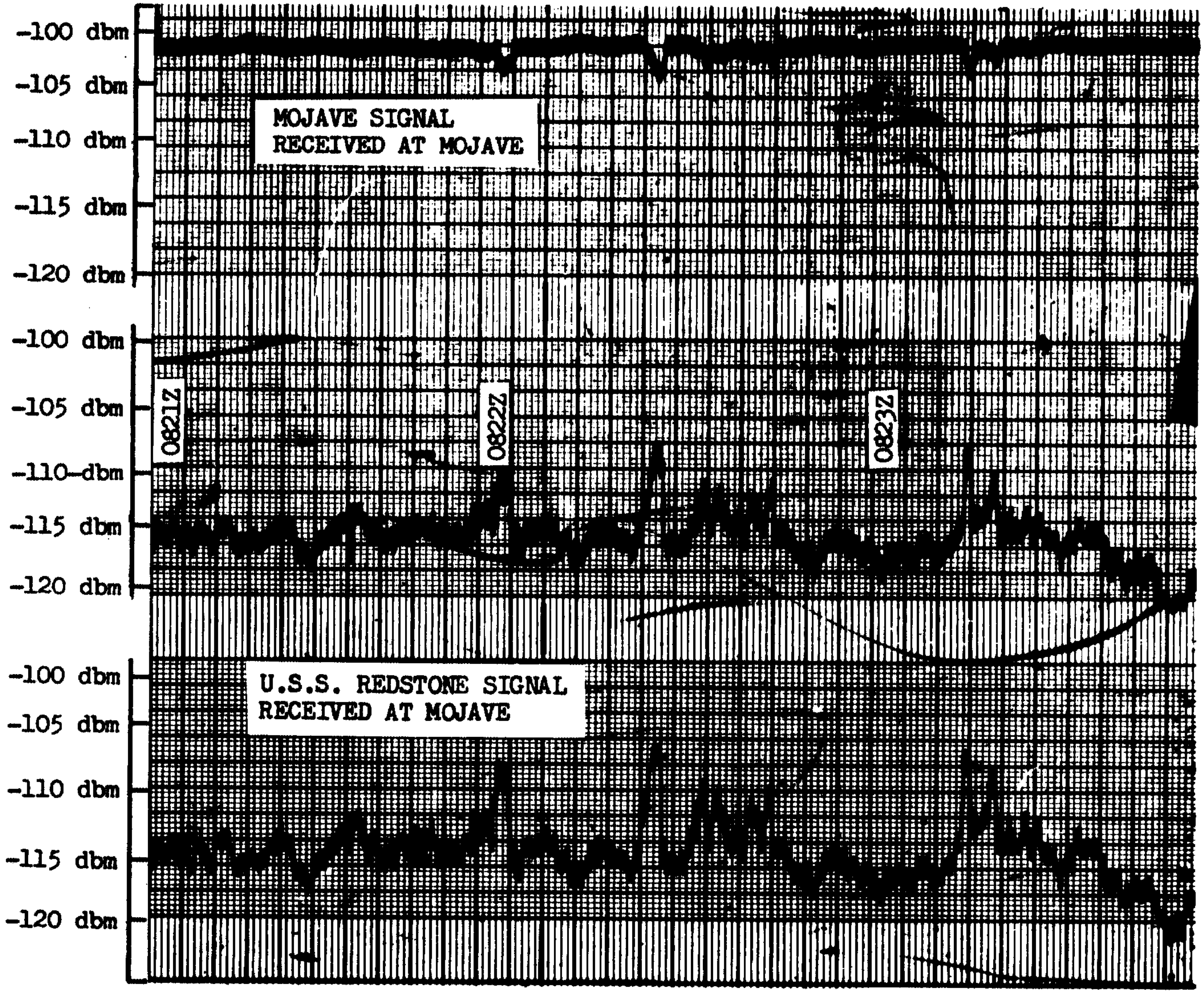

Figure 4. Signal Level of Mojave and U.S.S. Redstone (Sheet 5 of 5)

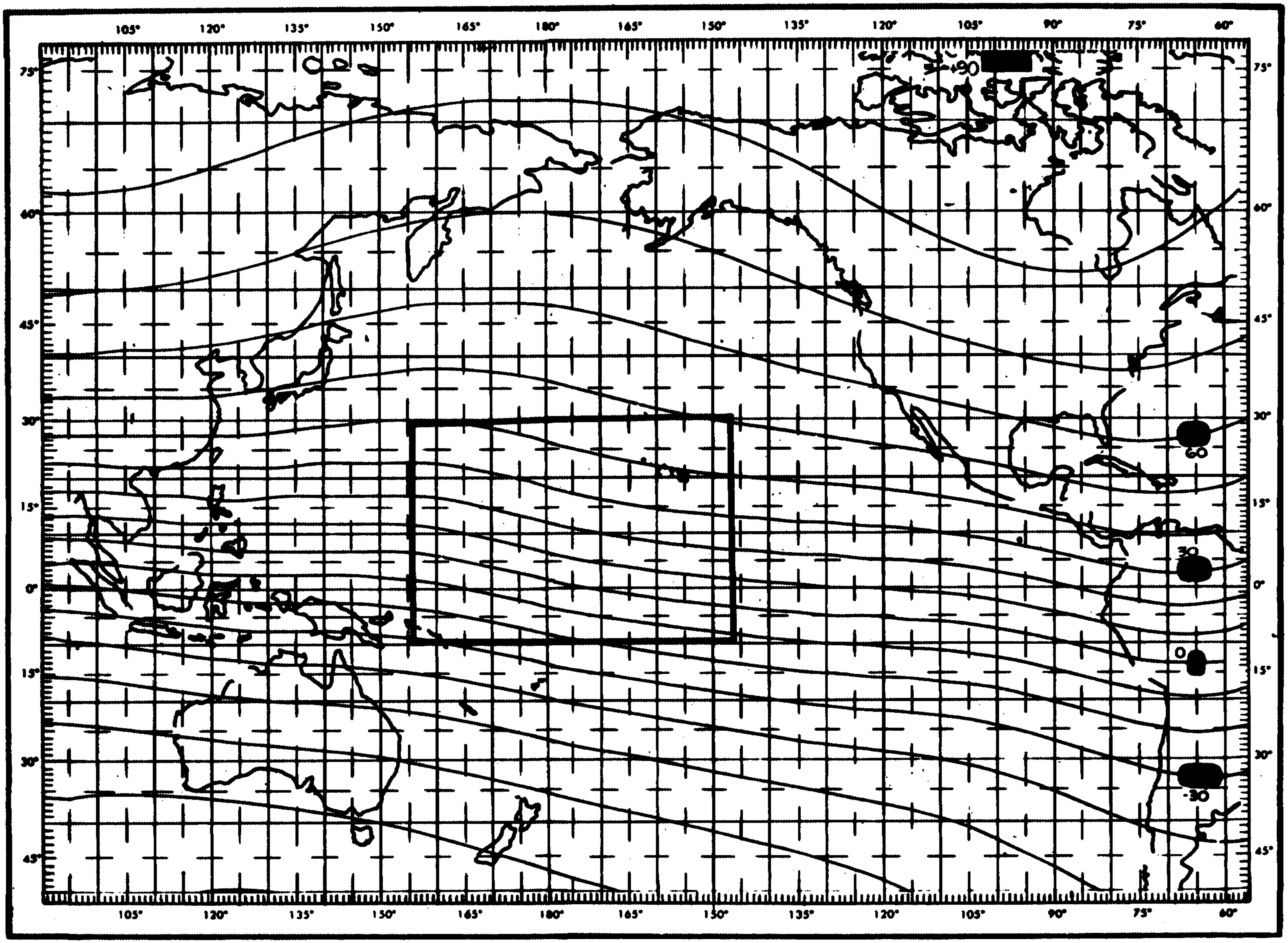

Figure 5. General Location of Apollo 11 Task Force

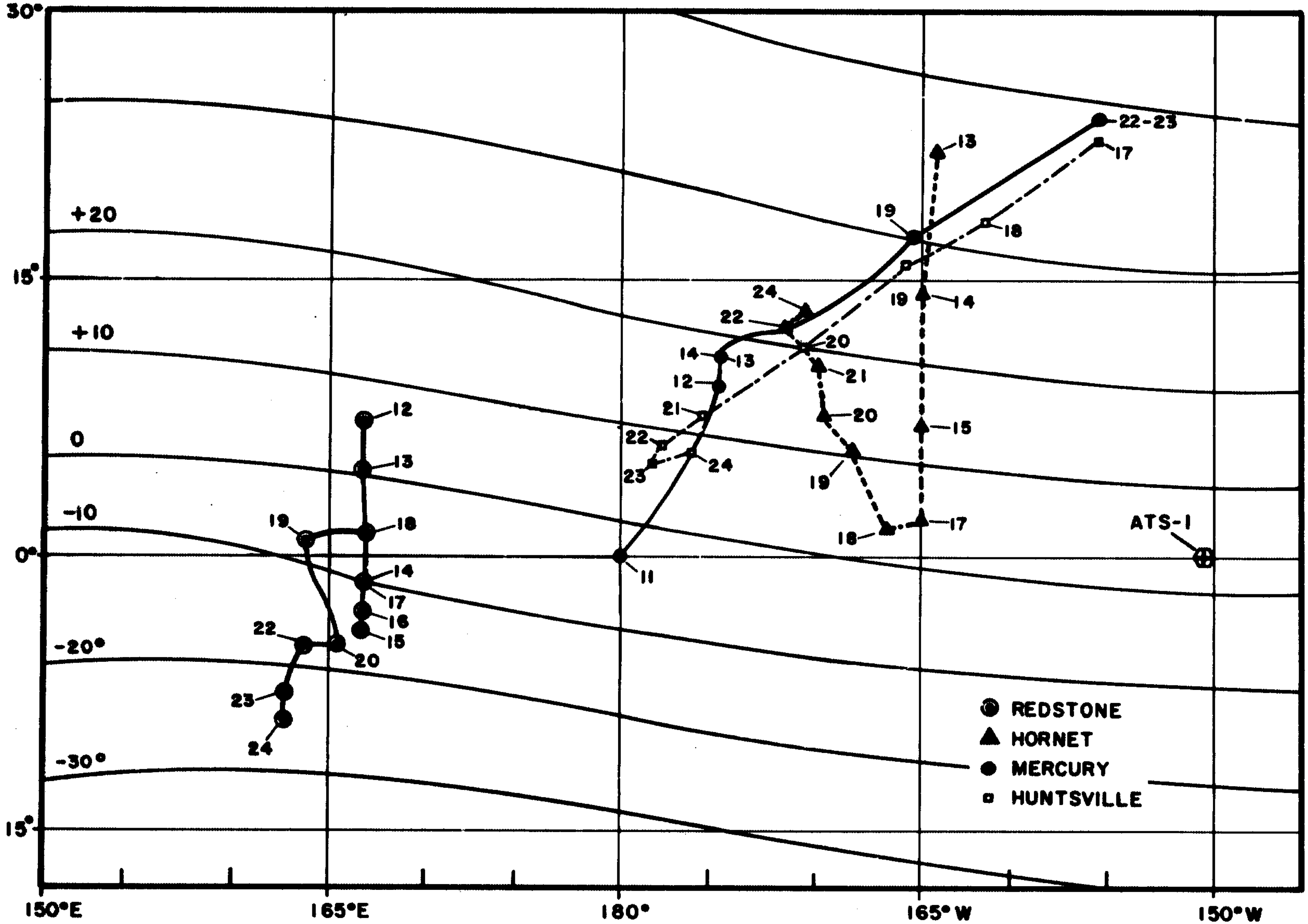

Figure 6. Detailed Location of Apollo 11 Task Force (July 12-24,1969)

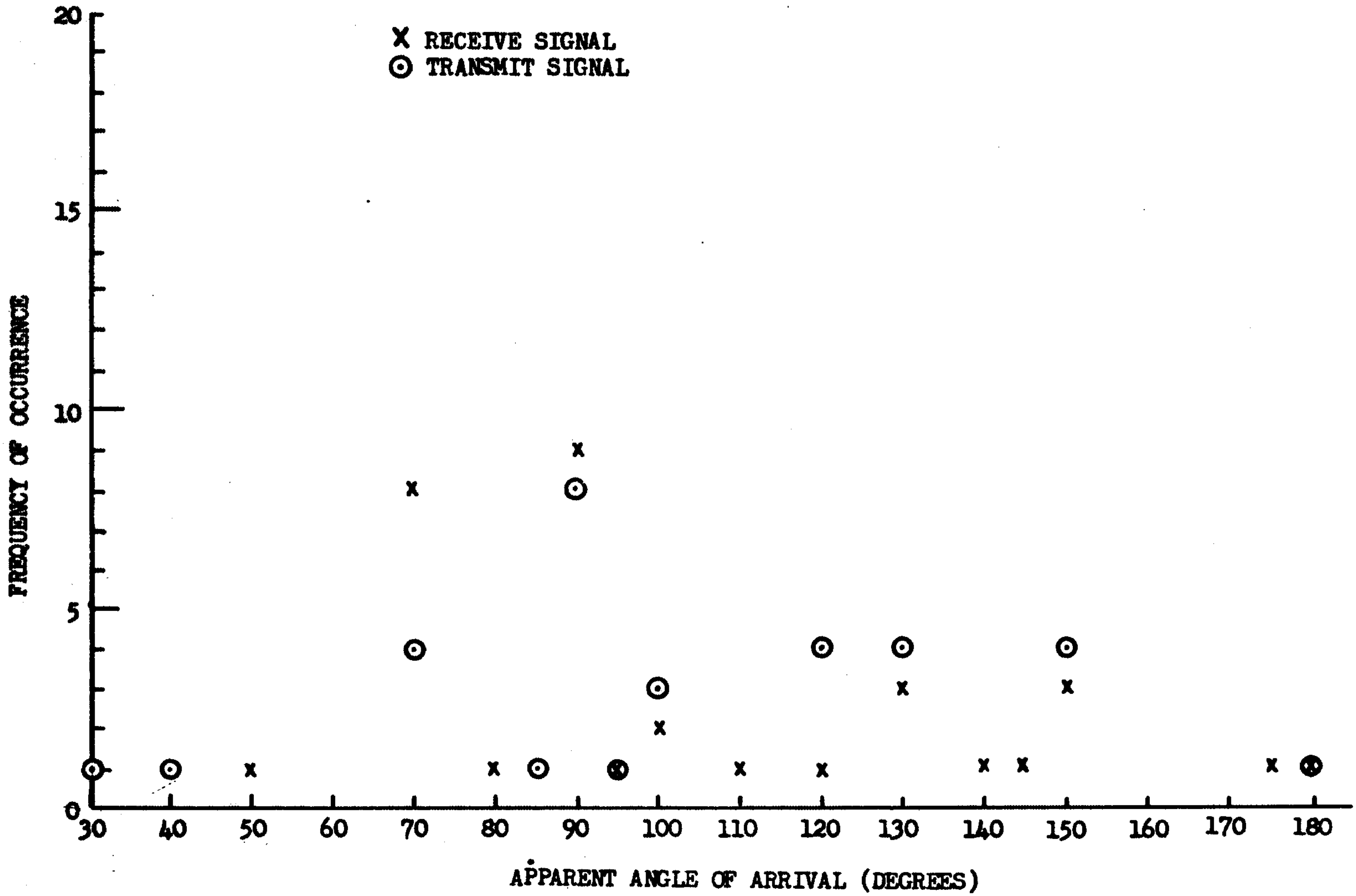

Figure 7. Frequency of Occurrence of Angles of Arrival

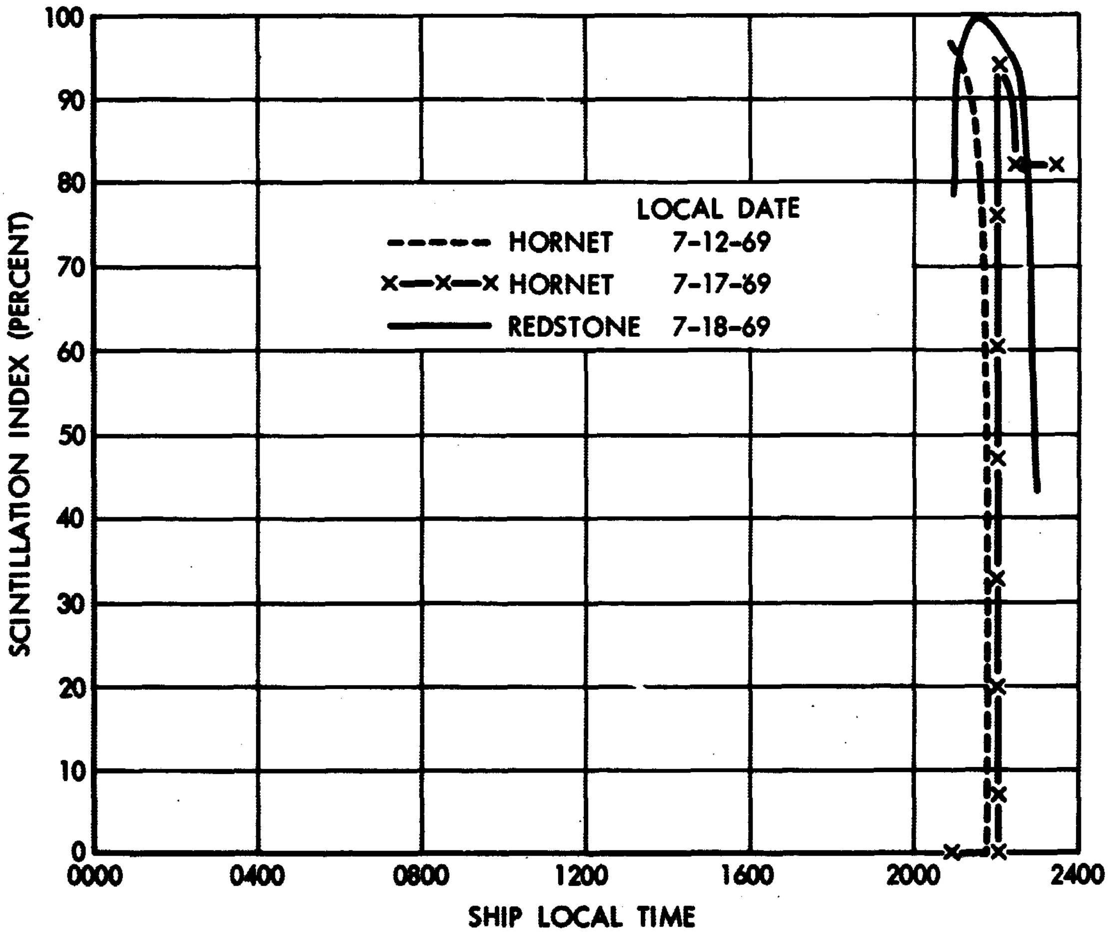

Figure 8. Scintillation Index vs Ship Local Time

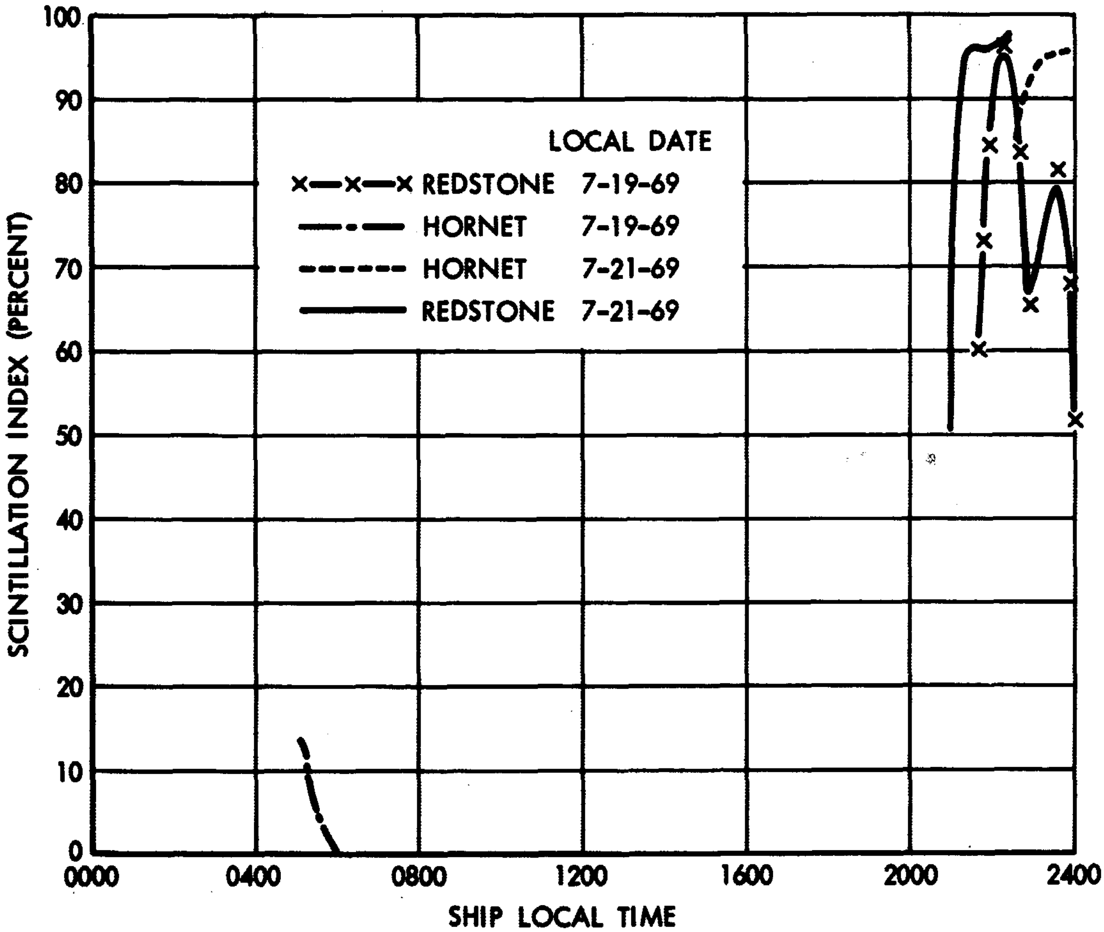

Figure 9. Scintillation Index vs Ship Local Time

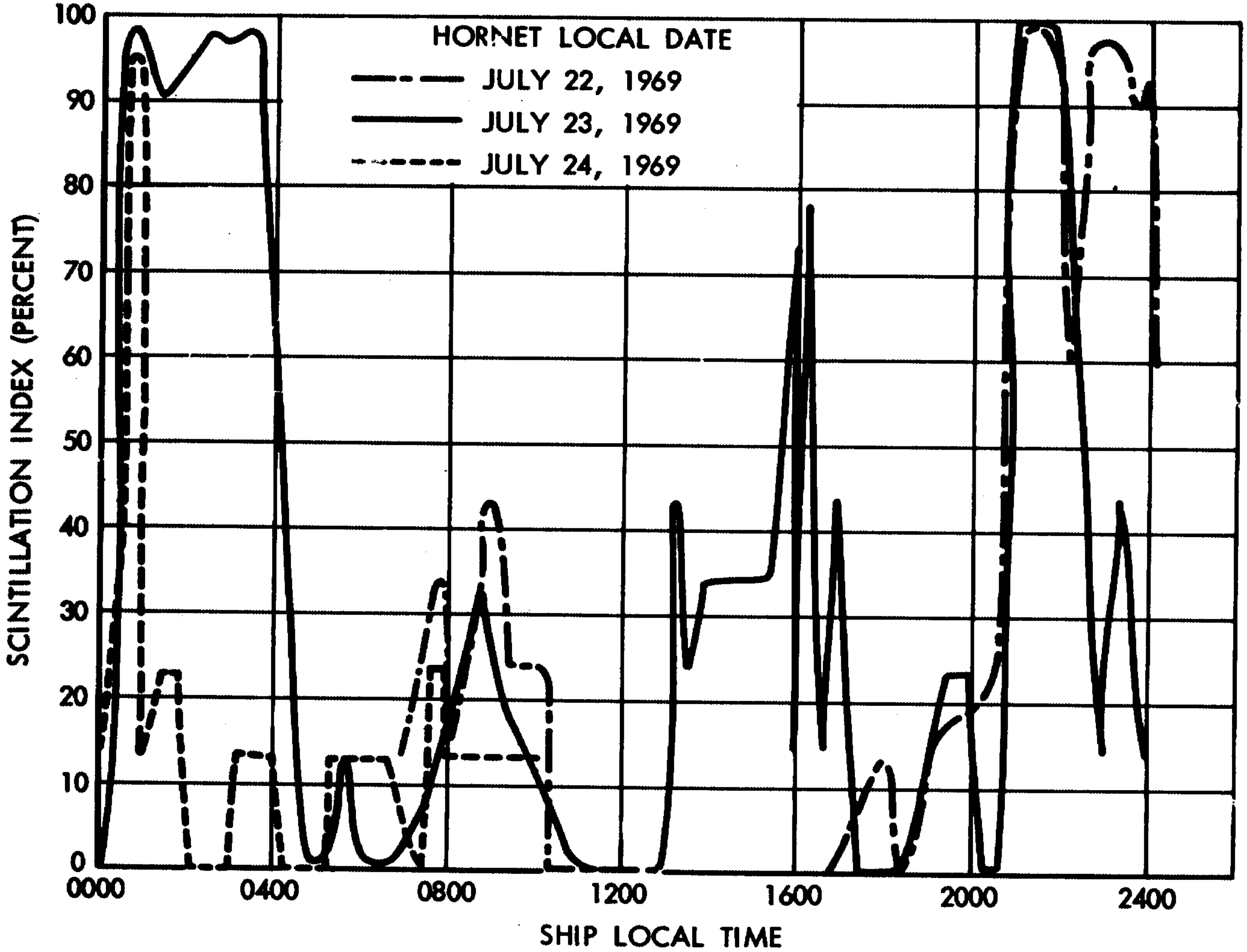

Figure 10. Scintillation Index vs Ship Local Time

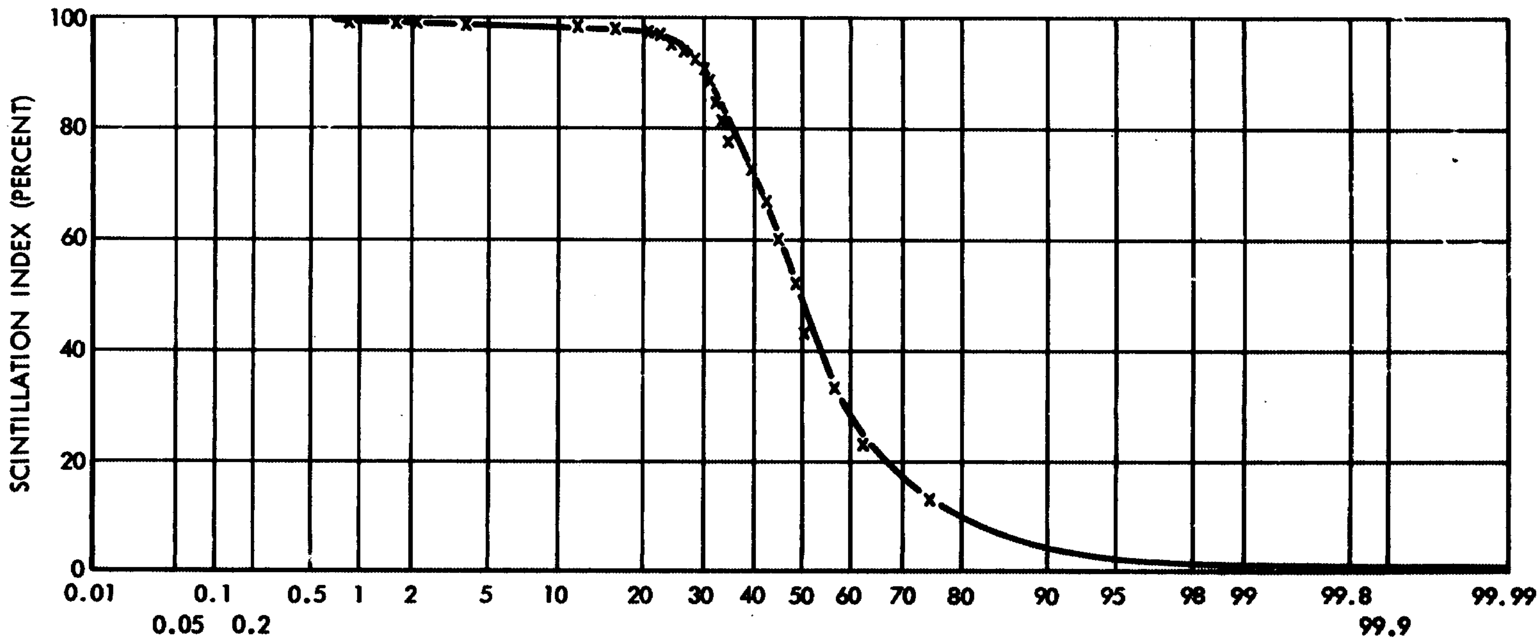

Figure 11. Cumulative Distribution of Scintillation Index U.S.S. Hornet to ATS-1, July 23, 1969

APPENDIX I

SYSTEM CALCULATIONS

A. GROUND STATION TO S/C

Ground Station Tx. output power (1 KW)	+60 dbm
Ground Station Tx. Antenna Gain	+14 db
Free space loss	-168 db
Feeder loss	-2 db
Polarization loss	-3 db
Signal level out of an isotropic radiator at 22,300 mi.	-99 dbm

B. SHIPBOARD STATION TO S/C

Shipboard Tx. Output Power (250 watts)	+54 dbm
Shipboard Tx. Antenna Gain	+12 db
Free space loss	-168 db
Feeder loss	-2 db
Polarization loss	-3 db
Signal level output of an isotropic radiator at 22,300 mi.	-107 dbm

C. S/C EIRP

S/C TX output grower (2 watts)	+43 dbm
Feeder loss	-2.4 db
Antenna gain	+8.5 db
S/C EIRP	+49.1 dbm

D. SPACECRAFT TO GROUND LINK CALCULATIONS

Since the S/C transponder is a power sharing devise and the two input signals differ by 8 db, then because of compression the output signals differ by 12 db. Therefore the output signals are S_1 and $15.8S_1$.

Total S/C output power (80.5 watts) EIRP		+49.1 dbm
Power sharing signals	(S_1) 75.7 watts EIRP	+48.8 dbm
	(S_2) 4.78 watts EIRP	+36.8 dbm

E. SIGNAL NO. 1 ANALYSIS

S/C Output power ERP	+48.8 dbm
Free Space loss	-167.0 db
Polarization loss	-3.0 db
Feeder loss	-2.0 db
Signal level output of an isotropic radiator	-123.8 dbm

F. SIGNAL NO. 2 ANALYSIS

S/C Output power EIRP	+36.8 dbm
Free space loss	-167.0 db
Polarization loss	-3.0 db
Feeder loss	-2.0 db
Signal level output of an isotropic radiator	-135.8 dbm

G. Signal No. 1 received by the Ground Station with antenna gain of +21 db has received carrier level of: -102.8 dbm

H. Signal No. 1 received by the shipboard station with an antenna gain of +12 db has a received carrier level of: -111.8 dbm

I. Signal No. 2 received by the ground station with an antenna gain of +21 db has a received carrier level of: -114.8 dbm

J. Signal No. 2 received by the Shipboard Station with an antenna gain of +12 db has a received carrier level of: -123.8 dbm