NATIONAL BUREAU OF STANDARDS REPORT

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WWVB/WWVL FIELD STUDIES

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NBS

U.S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

FOREWORD

This NBS Report on Project 2730424 covers work performed by the Frequency-Time Broadcast Services Section of the Time and Frequency Division, National Bureau of Standards, Boulder, Colorado. The project covered the period June 1964 to July 1968, and was sponsored by the Office of Civil Defense and the U. S. Army Strategic Communications Command.

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Project 2730424, WWVB/WWVL Field Studies, was a cooperative effort between the National Bureau of Standards, the Office of Civil Defense, and the U. S. Army Strategic Communications Command. The effort included aiding in producing a field strength map of the United States at 20 kHz and 60 kHz; upgrading the WWVL and WWVB antenna systems; providing a standby transmitter for WWVB; evaluating some FSK receiving systems; cooperating in FSK transmission tests; and providing, through a private contractor, a preliminary study of a joint NBS-OCD high power transmitting facility.

Key Words: Emergency broadcasts, VLF transmissions, Field mapping, OCD (Office of Civil Defense), FSK (frequency shift keying)

1. INTRODUCTION

1.1 The OCD and Emergency Communications

The Office of Civil Defense is, as part of its effort, responsible for alert and warning communications in case of national emergency. These communications have utilized such systems as CONELRAD, the Emergency Broadcast System, and the Emergency Action Notification System.

A more comprehensive system has been proposed, and will utilize a highly reliable system of radio links on three levels. A LF broadcasting system will communicate directly with elements of state and local government, police, and fire protection groups, civil defense local headquarters, and a series of low or medium frequency relay stations. It will be the responsibility of these relay stations to communicate directly with the populus as well as to actuate alarms and sirens for those people out of radio communication.

1.2 Project Purposes

This project has been a cooperative effort between the OCD and NBS aimed at determining the feasibility of this LF emergency communication system. The NBS has:

a. Provided upgraded facilities at WWVB and WWVL. This has included replacing obsolete and deteriorated equipment and components.

b. Aided in a field mapping project conducted by a private contractor. Field strength on nine radial lines from WWVL and on nine radial lines from WWVB was measured in this work. Distances from the transmitter ranged up to 1743 miles.

c. Evaluated various VLF and LF receiving techniques--coherent versus non-coherent detection, frequencies, data rates, etc., and

d. Provided, through a subcontractor, a preliminary engineering study for a high power VLF/LF transmitting facility.

2. FIELD STUDIES

2.1 Calibration Services by NBS

The radiated power from WWVL and WWVB was measured by the Electronic Calibration Center, Division 272.00, of the NBS. A plot of antenna versus radiated power was obtained for use in the field mapping work.

2.2 Field Mapping

Gautney and Jones Communications, Incorporated, conducted the actual mapping work. Nine radial lines from WWVB and WWVL were utilized and were directed as follows:

Radial #	Directed Toward
1	Seattle, Washington
2	San Francisco, California
3	Los Angeles, California
4	Douglas, Arizona
5	Brownsville, Texas
6	Jupiter, Florida
7	Cape Fear, North Carolina
8	Nantucket, Massachusetts
9	Fargo, North Dakota

Distances ranged up to over 1700 miles from the station. The data thus obtained and the field strength map that resulted are listed in Appendix A. The data contained in this appendix is part of Gautney and Jones Communications, Inc., "Measured Daytime Field Intensities in the United States at VLF, FL and MF," Interim Report for the Department of the Army and the Office of Civil Defense, May 1966.

3. UPGRADING EXISTING FACILITIES

3.1 WWVL Antenna and Transmitter

The original WWVL helix and variometer were wound with litz wire of a very early ventage. Sufficient new wire was purchased to rewind both the helix and the variometer with two parallel conductors. Each conductor has a capacity of 100 rf amperes.

The antenna was lowered and all connections upgraded to allow for a higher current carrying capacity. The antenna is capable of about 1.8 kw radiated power, 33.4 kw input to the antenna and an antenna current of 183 amperes. The limiting factor now is the flashover voltage of the antenna bushing, this voltage being approximately 100 kv.

The 20 kHz final tank circuit was redesigned to provide the proper load impedance for the final amplifier, and the proper coupling to the antenna and transmission line. The tank coils were rewound with new 75 ampere capacity litz wire.

3.2 WWVB Antenna and Transmitter

The various operations performed on the WWVL antenna were also repeated on the WWVB antenna. The 60 kHz helix and variometer were also rewound. In this case, these units were triple-wound. Since the terminal reactance of the 60 kHz antenna is much lower than that of the 20 kHz antenna, the WWVB antenna current could be raised to a full 300 rf amperes before the bushing flashover voltage was reached. The original grid-type ground system was improved by the addition of a radial ground screen. This system of 300 radials, increased the efficiency of the antenna from 14% to 30%.

WWVB is a fixed service and as such could not be interrupted during the helix and antenna modification work. STRATCOM, through project 2510421, provided for the construction of a spare antenna utilizing two of the WWVB/VL masts. With this antenna, and in operating at somewhat reduced power, WWVB was able to continue operations.

As in the case of the WWVL transmitter, the 60 kHz tank circuit was redesigned and rebuilt with the new litz wire.

4. NEW FACILITIES

4.1 Standby WWVB Transmitter

A standby 50 kw power amplifier has been constructed utilizing the power supply, frame and some parts of a surplus AN/FRT-6 high frequency transmitter. This standby unit utilizes an iron-core output transformer in place of the more conventional tank circuit. The transmitter is operated at zero-bias in the class "B" mode, and the bandwidth is ± 5 kHz.

The original WWVL transmitter that had been operated at Sunset, Colorado, is being modified for use as a driver for the new 60 kHz transmitter. This modification is nearly complete as of this writing.

4.2 Provision for Switching Antenna and Transmitters

The new 60 kHz untuned transmitter has an output impedance that is equal to the Z_0 of the transmission line, but the original tuned unit operates with a standing wave on the transmission line. When service is changed from one transmitter to the other, vacuum switches are used to change the line from one unit to the other as well as switching the coupling configuration at the helix.

4.3 Provision for OCD Frequency Generation and Control

In the early days of this project, special FSK keyers were obtained from a manufacturer of VLF phase tracking receivers. These units were deemed adequate for test pruposes but they required tedious adjustment. For use at a less experimental stage of the work, it is recommended that these keyers be replaced. This is especially true in light of the change from ± 100 Hz to ± 50 Hz in the FSK mode.

It is recommended that the new keyers be capable of full coherent transmission capability. This will not only conserve bandwidth and enhance both the effective transmitted power and receiver bandwidth requirements, but will permit the maximum utilization of the OCD transmitters by other government agencies for the transmission of standard frequency signals which can be used for ionospheric experiments, timing tests, etc. The small additional cost to obtain fully coherent keyers is fully justified both for OCD reception improvement and civilian use of their transmitters.

4.4 Radio Teletype Control Equipment and Switching Gear

Equipment intended for operation, but not yet obtained, will allow the OCD to have access to the WWVB transmission system. Upon a signal from OCD, a vacuum switch at the helix house (installed) will change the antenna resonance from 60 kHz to the OCD center frequency of 61.15 kHz. At the same time the 60 kHz driving frequency will be removed and the OCD FSK generator activated. If the tuned transmitter is in service, switches will automatically actuate the untuned amplifier. Radio teletype transmissions will begin within some 30 seconds of the initial OCD signal. The text of the transmissions will be remotely controlled by OCD and station personnel will in no way be involved. It is intended that for test purposes, the OCD may use up to five minutes per hour for FSK tests. (See Appendix B for equipment drawings.)

5. RECEPTION STUDIES

5.1 Evaluating the Radio Teletype Capability

Following the field mapping work by Gautney and Jones, tests were performed to determine the reception quality of the FSK transmissions. Receivers were set up at various locations and experimental transmissions were instituted. The receiving work was carried out by Gautney and Jones Communications, Inc. The results were considered satisfactory.

5.2 Coherent versus Non-Coherent Detection

Using the same FSK generators, some receiver studies were performed at NBS Boulder Laboratories. Two coherent receiver systems did operate satisfactorily. They were able to receive perfect copy and the technique can be considered sound. All tests on the receivers were performed at the ± 50 Hz shift.

The TMC Research receiver supplied by the OCD on loan was used as a standard of comparison. It, too, operated satisfactorily and did so at both the narrow and wide frequency shift ranges. It required repairs twice during the tests. Both failures were minor, but they gave rise to a recommendation that the manufacturer be consulted on solutions to the problem by redesign of the solid state switch used to drive the teleprinter line. It is possible that only this receiver has had this problem and, if so, the recommendation should be qualified to say that this problem is noted and should be investigated further if trouble is reported from other receivers of this type.

None of the receivers were tested with noisy signals. The project effort was limited to testing only the practicality and feasibility of the coherent receiver technique. The benefits of coherent detection are well known under extremely noisy conditions and it was not felt justified to make any noise tests on this project. However, one advantage of receivers of this type should be mentioned here. The coherent receiver does not manifest the "threshold" effect of the ordinary FSK receiver. With a suitable time constant, the receivers developed on this task effort can indeed approach their design limit of tracking a weak signal buried in noise. The procurement specification for these receivers was that they should produce good copy within 30 seconds of start of transmission. They did meet that specification. Note, however, that the present OCD requirement precludes being able to wait for that period of time.

5.3 Recommendations on Receiver Types

The original coherent reception technique as proposed does work and can be exploited by OCD for those locations where a time delay in reception can be tolerated. Experience gained from field tests of the NBS station WWVB would suggest a time constant of at least 50 seconds on the receivers. This would mean that a delay of from one to ten minutes could be expected at sites using these receivers. If, in fact, the OCD does not feel there is sufficient need for receivers at sites that can wait for dependable communication to be established, then the coherent receiver technique should be abandoned in favor of the alternatives of increased transmitter power. At the receiving sites where only a short delay in communication can be tolerated, the non-coherent reception method will be a requirement.

6. PROJECT WORK BY OTHER GROUPS

6.1 Joint Facility Study

Early in the project it was proposed that NBS and OCD colaborate in the design, construction and use of a high power LF/VLF facility. At that time, a preliminary study for such a facility was provided by Deco Electronics, Division of General Electric. Appendix C contains that study.

7. SUMMARY

During the four-year duration of this project, NBS and the OCD have cooperated in an important venture. The reliability, power, and quality of the NBS LF and VLF facility have been markedly increased. The OCD has benefited by having access to a transmitting system that allowed Gautney and Jones Communications, Inc., to complete a field strength mapping of the United States at both 20 kHz and 60 kHz. FSK tests were run and proved reliable enough for OCD to continue their work on the LF emergency broadcasting network for the United States. Continued testing on WWVB is planned for the future. The 60 kHz broadcasting facility will soon be readily accessible to the OCD for continued experiments.

The receiver evaluation has concluded that non-coherent detection is probably best for the requirements of the OCD. It is, however, recommended that the new OCD FSK keyers provide coherent keying with provision for cw operation at either mark or space.

As stated in the previous section, Appendix C contains a preliminary study for a joint NBS-OCD facility. This study is dated 1966. At that time, it was felt by NBS that a higher power VLF time and frequency station should be acquired in order to provide worldwide timing. Support came from NASA, JPL, USNO, foreign standards laboratories, and others.

In 1968, it became apparent that the financial resources of NBS would not support such a venture. Also, work in the timing area by other government agencies in the fields of LF and VLF broadcasting, satellites, and portable clocks made any NBS effort toward a higher power station scientifically questionable. It was then decided that NBS would officially withdraw from any cooperative effort toward a joint facility.

APPENDIX A

MEASURED DAYTIME FIELD INTENSITIES IN THE UNITED STATES AT VLF, LF, AND MF

Prepared for:

The Office of Civil Defense

and

The Department of the Army

Prepared by:

Gautney and Jones Communications, Incorporated

MEASURED FIELD INTENSITY
SEATTLE, WASHINGTON RADIAL
WWVL - 20 KHz

POINT NO.	FIELD (DBU)	DISTANCE (MI.)
1	90.1	9.0
2	83.0	15.0
3	80.7	23.0
4	76.4	30.0
5	76.6	35.0
6	74.8	42.0
7	76.4	45.0
8	73.4	60
9	72.0	70
10	71.3	80
11	67.6	90
12	67.2	100
13	67.1	110
14	65.7	120
15	65.7	140
16	61.1	160
17	61.7	180
18	62.3	200
19	61.7	230
20	58.6	260
21	54.7	280
22	50.1	300
23	45.8	325
24	45.1	340
25	43.0	360
26	50.1	380
27	52.2	400
28	53.1	450
29	51.8	490
30	53.0	535
31	55.5	560
32	55.8	580
33	55.0	635
34	53.1	660
35	53.4	715
36	53.4	785
37	51.1	850
38	47.2	900
39	45.8	950
40	44.4	1010
41	37.5	1075

MEASURED FIELD INTENSITY
SAN FRANCISCO, CALIFORNIA RADIAL
WWVL - 20 KHz

POINT NO.	FIELD (DBU)	DISTANCE (MI.)
1	86.3	12.6
2	83.6	17.1
3	77.3	26.1
4	74.6	44.2
5	73.0	53
6	72.0	63
7	70.5	72
8	67.3	93
9	63.8	103
10	66.9	116
11	62.8	136
12	60.1	146
13	59.3	159
14	60.5	173
15	61.5	183
16	59.8	189
17	58.4	198
18	58.3	208
19	58.3	224
20	57.8	243
21	58.8	262
22	51.3	291
23	43.3	326
24	44.3	377
25	49.3	397
26	54.3	446
27	53.6	472
28	53.0	505
29	54.3	534
30	55.3	578
31	54.3	616
32	52.8	653
33	55.3	695
34	54.3	741
35	49.3	781
36	48.3	829
37	49.3	897
38	48.8	918
39	47.3	963

MEASURED FIELD INTENSITY
LOS ANGELES, CALIFORNIA RADIAL
WWVL - 20 KHz

POINT NO.	FIELD (DBU)	DISTANCE (MI.)
1	89.3	9.0
2	86.3	15.5
3	78.0	24.3
4	74.3	34.3
5	72.7	50.0
6	72.4	61
7	68.6	89
8	64.8	107
9	61.0	120
10	63.3	138
11	62.2	156
12	60.9	164
13	60.5	186
14	60.2	198
15	60.7	215
16	60.6	229
17	59.5	268
18	56.8	287
19	56.3	337
20	45.2	347
21	39.0	375
22	48.8	402
23	54.3	437
24	50.9	478
25	49.3	500
26	47.9	562
27	51.6	630
28	53.4	660
29	53.2	682
30	51.5	707
31	51.6	750
32	52.3	797
33	51.1	847
34	48.3	874

MEASURED FIELD INTENSITY
DOUGLAS, ARIZONA RADIAL
WWVL - 20 KHz

POINT NO.	FIELD (DBU)	DISTANCE (MI.)
1	86.9	10.0
2	86.8	13.0
3	83.2	16.0
4	81.7	20.0
5	80.4	25.0
6	75.7	33.0
7	73.3	40.0
8	73.3	43.0
9	75.1	47.0
10	72.3	51
11	71.1	60
12	67.5	70
13	68.3	78
14	70.3	92
15	64.9	100
16	64.8	110
17	68.3	120
18	65.5	130
19	65.3	145
20	64.3	162
21	64.6	170
22	62.8	180
23	63.7	190
24	64.9	200
25	63.5	220
26	61.1	260
27	50.7	280
28	48.8	300
29	48.6	320
30	44.3	340
31	43.5	360
32	50.2	380
33	52.7	400
34	52.6	450
35	52.5	500
36	53.9	550
37	54.5	600
38	54.2	650

MEASURED FIELD INTENSITY
BROWNSVILLE, TEXAS RADIAL
WWVL - 20 KHz

POINT NO.	FIELD (DBU)	DISTANCE (MI.)
1	85.2	10.6
2	82.4	17.2
3	79.4	23.0
4	77.4	26.5
5	76.8	31.0
6	76.6	35.1
7	76.1	40.8
8	75.6	48.7
9	73.2	60
10	70.2	70
11	69.3	80
12	67.0	90
13	65.5	110
14	64.6	120
15	64.2	140
16	64.2	150
17	60.4	165
18	60.5	185
19	62.2	200
20	63.7	220
21	63.6	240
22	61.0	260
23	60.2	280
24	58.6	310
25	51.0	325
26	47.6	340
27	40.1	365
28	38.7	380
29	43.6	400
30	52.1	450
31	51.0	500
32	53.1	525
33	54.1	575
34	55.7	625
35	53.1	675
36	53.1	700
37	53.3	750
38	52.1	800
39	54.1	875
40	52.1	900
41	51.6	950
42	46.4	1025
43	43.6	1100

MEASURED FIELD INTENSITY
PALM BEACH, FLORIDA RADIAL
WWVL - 20 KHz

POINT NO.	FIELD (DBU)	DISTANCE (MI.)
1	87.7	10.0
2	83.4	15.0
3	80.7	21.0
4	77.3	26.0
5	77.3	31.0
6	75.0	43.0
7	74.1	50.0
8	72.6	55
9	67.9	70
10	67.4	85
11	67.4	95
12	64.2	110
13	64.2	125
14	63.7	145
15	59.8	165
16	59.8	190
17	62.3	200
18	64.3	230
19	63.0	250
20	59.8	270
21	57.4	290
22	49.6	320
23	48.2	340
24	38.9	360
25	35.0	380
26	49.2	400
27	52.1	450
28	50.1	500
29	54.1	550
30	55.7	600
31	56.9	660
32	53.6	700
33	51.5	715
34	52.1	750
35	53.1	800
36	51.5	840
37	49.6	890
38	47.3	950
39	47.8	1000
40	46.3	1050

PALM BEACH, FLORIDA RADIAL
WWVL - 20 KHz Cont'd.

POINT NO.	FIELD (DBU)	DISTANCE (MI.)
41	42.7	1110
42	40.9	1150
43	42.3	1190
44	45.4	1240
45	46.3	1300
46	45.0	1350
47	46.9	1400
48	43.2	1440
49	42.7	1465
50	43.6	1500
51	43.2	1550
52	45.4	1600

MEASURED FIELD INTENSITY
CAPE FEAR, NORTH CAROLINA RADIAL
WWVL - 20 KHz

POINT NO.	FIELD (DBU)	DISTANCE (MI.)
1	85.6	10.2
2	84.8	15.0
3	81.4	19.0
4	78.3	25.0
5	76.4	29.0
6	76.1	35.0
7	75.5	40.0
8	74.2	45.0
9	73.5	50.0
10	71.6	65
11	69.5	71
12	69.2	87
13	68.4	96
14	67.0	108
15	66.3	122
16	65.7	133
17	64.4	147
18	61.8	174
19	60.0	185
20	61.6	200
21	61.4	211
22	61.2	237
23	60.2	255
24	59.3	273
25	55.5	287
26	51.4	304
27	52.6	314
28	50.3	324
29	48.3	333
30	45.8	346
31	42.5	356
32	35.5	363
33	40.3	375
34	46.3	384
35	49.2	396
36	51.8	440
37	52.3	473
38	52.0	530
39	53.5	573
40	49.3	608

CAPE FEAR, NORTH CAROLINA RADIAL Cont'd.
WWVL - 20 KHz

POINT NO.	FIELD (DBU)	DISTANCE (MI.)
41	54.3	627
42	56.9	642
43	55.6	652
44	53.5	662
45	54.1	675
46	53.5	690
47	54.9	712
48	55.8	727
49	54.3	753
50	53.1	780
51	50.4	800
52	49.5	850
53	48.6	900
54	47.7	950
55	46.9	1000
56	44.4	1050
57	40.0	1100
58	42.6	1150
59	47.4	1200
60	44.4	1300
61	40.0	1350
62	41.7	1400

MEASURED FIELD INTENSITY
NANTUCKET, MASSACHUSETTS RADIAL
WWVL - 20 KHz

POINT NO.	FIELD (DBU)	DISTANCE (MI.)
1	86.1	10.0
2	82.3	15.0
3	79.9	20.0
4	77.2	25.0
5	75.9	30.0
6	75.6	35.0
7	74.6	40.0
8	75.2	44.0
9	74.0	51
10	73.6	60
11	70.9	70
12	69.8	80
13	70.5	90
14	67.5	100
15	64.7	110
16	66.1	120
17	67.5	130
18	67.4	140
19	65.3	150
20	62.8	160
21	62.4	170
22	63.3	180
23	63.5	190
24	63.5	200
25	62.5	220
26	60.4	260
27	54.2	280
28	51.9	300
29	50.1	320
30	43.0	340
31	37.5	360
32	38.0	380
33	43.0	400
34	48.0	450
35	55.8	490
36	53.0	530
37	53.9	570
38	55.3	610
39	55.8	650

NANTUCKET, MASSACHUSETTS RADIAL Cont'd.
WWVL - 20 KHz

POINT NO.	FIELD (DBU)	DISTANCE (MI.)
40	54.8	690
41	53.5	770
42	52.0	800
43	47.0	850
44	46.0	900
45	43.5	1000
46	45.0	1050
47	44.5	1100
48	43.2	1318
49	41.2	1350
50	39.0	1460
51	39.0	1500
52	38.0	1630
53	38.0	1743

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MEASURED FIELD INTENSITY
FARGO, NORTH DAKOTA RADIAL
WWVL - 20 KHz

POINT NO.	FIELD (DBU)	DISTANCE (MI.)
1	88.4	10.0
2	84.3	15.0
3	81.8	20.0
4	80.6	26.0
5	77.9	32.0
6	77.0	36.0
7	75.6	41.0
8	75.1	46.0
9	74.6	50.0
10	71.6	60
11	69.9	70
12	68.8	90
13	66.2	110
14	65.7	122
15	63.7	140
16	64.1	150
17	62.8	160
18	60.8	170
19	62.5	180
20	62.4	190
21	63.6	200
22	63.9	220
23	61.6	240
24	60.4	260
25	59.4	282
26	58.9	300
27	54.4	320
28	49.2	340
29	44.4	360
30	43.4	380
31	52.0	485
32	52.0	550
33	56.0	600
34	56.1	650
35	54.7	700
36	53.8	750

SEPTEMBER, 1964

MEASURED FIELD INTENSITY
SEATTLE, WASHINGTON RADIAL
WWVB - 60 KHz

POINT NO.	FIELD (DBU)	DISTANCE (MI.)
1	97.6	9.0
2	91.4	15.0
3	88.4	23.0
4	85.9	30.0
5	84.3	35.0
6	81.2	42.0
7	80.7	45.0
8	78.6	60
9	77.7	70
10	77.6	80
11	72.7	90
12	72.0	100
13	72.3	110
14	71.5	120
15	70.5	140
16	69.2	160
17	67.5	180
18	66.9	200
19	63.6	230
20	64.4	260
21	62.3	280
22	60.4	300
23	56.9	325
24	58.6	340
25	57.4	360
26	56.9	380
27	57.4	400
28	55.2	450
29	56.6	490
30	47.8	535
31	34.0	560
32	42.9	580
33	44.3	635
34	44.4	660
35	44.3	715
36	45.7	785
37	40.6	850
38	42.6	900
39	37.2	950
40	41.6	1010
41	35.6	1075

MEASURED FIELD INTENSITY
SAN FRANCISCO, CALIFORNIA RADIAL
WWVB - 60 KHz

POINT NO.	FIELD (DBU)	DISTANCE (MI.)
1	94.5	12.6
2	92.1	17.1
3	85.2	26.1
4	82.7	44.2
5	79.8	53
6	79.9	63
7	77.4	72
8	74.1	93
9	73.4	103
10	73.0	116
11	69.6	136
12	68.9	146
13	68.8	159
14	68.2	173
15	66.7	183
16	64.2	189
17	62.3	198
18	65.1	208
19	64.8	224
20	64.6	243
21	64.1	262
22	61.1	291
23	58.6	326
24	58.6	377
25	56.1	397
26	51.3	446
27	49.3	472
28	47.4	505
29	47.1	534
30	48.6	578
31	44.1	616
32	42.6	653
33	40.3	695
34	46.3	741
35	45.0	781
36	49.1	829
37	45.1	897
38	46.6	918
39	46.2	963

MEASURED FIELD INTENSITY
LOS ANGELES, CALIFORNIA RADIAL
WWVB - 60 KHz

POINT NO.	FIELD (DBU)	DISTANCE (MI.)
1	97.6	9.0
2	94.3	15.5
3	85.3	24.3
4	84.2	34.3
5	81.1	50.0
6	79.3	61
7	74.8	89
8	73.8	107
9	68.8	120
10	71.4	138
11	70.0	156
12	70.2	164
13	68.3	186
14	66.8	198
15	66.8	215
16	64.6	229
17	63.2	268
18	60.8	287
19	62.2	337
20	60.6	347
21	60.2	375
22	59.7	402
23	60.1	437
24	55.8	478
25	55.3	500
26	56.3	562
27	43.3	630
28	42.3	660
29	44.1	682
30	45.8	707
31	45.5	750
32	47.8	797
33	45.7	847
34	46.1	874

MEASURED FIELD INTENSITY
DOUGLAS, ARIZONA RADIAL
WWVB - 60 KHz

POINT NO.	FIELD (DBU)	DISTANCE (MI.)
1	97.0	10.0
2	96.2	13.0
3	92.3	16.0
4	89.8	20.0
5	87.2	25.0
6	84.1	33.0
7	84.1	40.0
8	79.9	43.0
9	82.0	47.0
10	80.0	51
11	78.3	60
12	75.3	70
13	72.9	78
14	72.2	92
15	66.9	100
16	70.2	110
17	68.3	120
18	66.8	130
19	63.4	145
20	65.2	162
21	64.2	170
22	61.1	180
23	61.7	190
24	64.3	200
25	59.9	220
26	58.3	260
27	53.7	280
28	51.1	300
29	55.3	320
30	55.3	340
31	54.3	360
32	55.5	380
33	52.7	400
34	53.3	450
35	45.6	500
36	41.3	550
37	38.8	600
38	40.8	650

MEASURED FIELD INTENSITY
BROWNSVILLE, TEXAS RADIAL
WWVB - 60 KHz

POINT NO.	FIELD (DBU)	DISTANCE (MI.)
1	94.5	10.6
2	91.6	17.2
3	89.2	23.0
4	86.8	26.5
5	85.7	31.0
6	84.8	35.1
7	83.7	40.8
8	82.9	48.7
9	81.1	60
10	78.7	70
11	75.7	80
12	75.2	90
13	74.7	110
14	74.1	120
15	73.6	140
16	72.3	150
17	69.9	165
18	70.3	185
19	69.4	200
20	66.9	220
21	66.4	240
22	65.5	260
23	64.1	280
24	62.7	310
25	62.7	325
26	58.5	340
27	59.4	365
28	59.4	380
29	58.3	400
30	58.6	450
31	59.3	500
32	59.8	525
33	57.1	575
34	51.1	625
35	47.3	675
36	36.7	700
37	28.5	750
38	39.9	800
39	47.3	875
40	45.5	900
41	41.0	950
42	39.1	1025
43	41.0	1100

SEPTEMBER, 1965

MEASURED FIELD INTENSITY
PALM BEACH, FLORIDA RADIAL
WWVB - 60 KHz

POINT NO.	FIELD (DBU)	DISTANCE (MI.)
1	96.3	10.0
2	92.1	15.0
3	89.7	21.0
4	87.7	26.0
5	85.1	31.0
6	82.7	43.0
7	82.1	50.0
8	82.3	55
9	77.9	70
10	76.3	85
11	74.1	95
12	74.7	110
13	72.5	125
14	71.0	145
15	69.2	165
16	67.8	190
17	67.8	200
18	65.9	230
19	64.5	250
20	63.6	270
21	63.0	290
22	59.8	320
23	62.3	340
24	59.2	360
25	59.2	380
26	59.8	400
27	59.8	450
28	55.2	500
29	54.1	550
30	49.2	600
31	45.0	660
32	40.4	700
33	36.7	715
34	40.4	750
35	42.2	800
36	44.3	840
37	45.4	890
38	44.5	950
39	44.5	1000

PALM BEACH, FLORIDA RADIAL
WWVB - 60 KHz Cont'd.

POINT NO.	FIELD (DBU)	DISTANCE (MI.)
40	45.0	1050
41	42.7	1110
42	41.8	1150
43	43.6	1190
44	46.9	1240
45	45.4	1300
46	43.2	1350
47	41.8	1400
48	39.3	1440
49	40.1	1465
50	40.9	1500
51	37.7	1550
52	36.9	1600
53	32.9	1670

MEASURED FIELD INTENSITY
CAPE FEAR, NORTH CAROLINA RADIAL
WWVB - 60 KHz

POINT NO.	FIELD (DBU)	DISTANCE (MI.)
1	94.7	10.2
2	93.1	15.0
3	89.3	19.0
4	87.7	25.0
5	86.3	29.0
6	85.1	35.0
7	83.8	40.0
8	82.5	45.0
9	81.7	50.0
10	78.7	65
11	77.4	71
12	75.8	87
13	75.7	96
14	74.2	108
15	74.1	122
16	73.4	133
17	72.3	147
18	69.9	174
19	69.5	185
20	68.9	200
21	66.8	211
22	66.9	237
23	65.6	255
24	64.1	273
25	63.5	287
26	63.2	304
27	62.1	314
28	62.1	324
29	61.6	333
30	61.1	346
31	61.1	356
32	60.9	363
33	59.9	375
34	60.0	384
35	59.9	396
36	59.9	440
37	59.1	473
38	56.6	530
39	56.1	573
40	55.1	608

CAPE FEAR, NORTH CAROLINA RADIAL Cont'd.
WWVB - 60 KHz

POINT NO.	FIELD (DBU)	DISTANCE (MI.)
41	56.5	627
42	55.5	642
43	47.0	652
44	42.1	662
45	41.1	675
46	41.2	690
47	36.6	712
48	35.5	727
49	39.6	753
50	41.1	780
51	43.6	800
52	46.5	850
53	46.5	900
54	45.5	950
55	46.5	1000
56	46.5	1050
57	44.7	1100
58	44.7	1150
59	46.0	1200
60	39.5	1300
61	44.7	1350
62	43.0	1400

MEASURED FIELD INTENSITY
NANTUCKET, MASSACHUSETTS RADIAL
WWVB - 60 KHz

POINT NO.	FIELD (DBU)	DISTANCE (MI.)
1	95.5	10.0
2	91.4	15.0
3	90.0	20.0
4	87.3	25.0
5	86.5	30.0
6	84.5	35.0
7	83.3	40.0
8	83.4	44.0
9	81.5	51
10	80.6	60
11	78.8	70
12	77.3	80
13	77.5	90
14	75.9	100
15	74.3	110
16	68.2	120
17	69.4	130
18	69.5	140
19	69.5	150
20	68.3	160
21	59.8	170
22	67.5	180
23	67.5	190
24	64.1	200
25	63.3	220
26	62.9	260
27	61.2	280
28	62.0	300
29	59.8	320
30	59.2	340
31	58.5	360
32	57.8	380
33	57.5	400
34	56.6	450
35	57.2	490
36	52.3	530
37	50.3	570
38	46.9	610
39	44.7	650
40	40.8	690

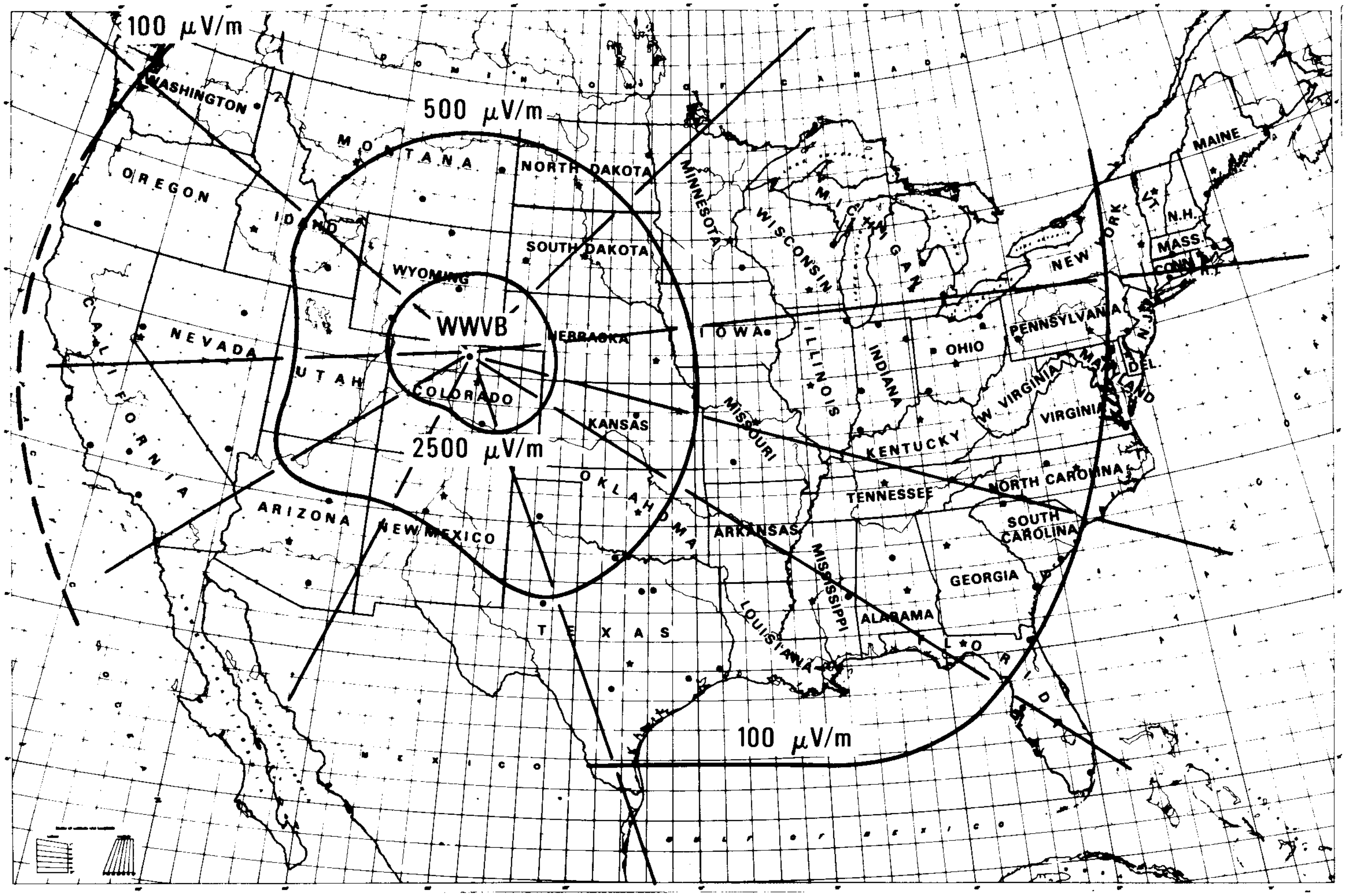
NANTUCKET, MASSACHUSETTS RADIAL Cont'd.
WWVB - 60 KHz

POINT NO.	FIELD (DBU)	DISTANCE (MI.)
41	36.0	770
42	39.5	800
43	44.0	850
44	46.5	900
45	46.5	1000
46	52.5	1050
47	50.0	1100
48	43.8	1318
49	43.0	1350
50	41.0	1460
51	40.7	1500
52	38.0	1630
53	36.0	1743

MEASURED FIELD INTENSITY
FARGO, NORTH DAKOTA RADIAL
WWVB - 60 KHz

POINT NO.	FIELD (DBU)	DISTANCE (MI.)
1	96.9	10.0
2	93.2	15.0
3	91.6	20.0
4	90.1	26.0
5	87.5	32.0
6	85.3	36.0
7	84.9	41.0
8	83.1	46.0
9	81.2	50.0
10	79.5	60
11	77.6	70
12	72.7	90
13	71.3	110
14	71.1	122
15	67.3	140
16	68.5	150
17	68.0	160
18	65.4	170
19	65.8	180
20	64.4	190
21	65.6	200
22	66.1	220
23	63.8	240
24	61.0	260
25	61.0	282
26	60.5	300
27	60.1	320
28	59.7	340
29	57.8	360
30	55.4	380
31	56.5	400
32	56.2	440
33	56.5	485
34	53.1	550
35	49.1	600
36	44.9	650
37	36.6	700
38	33.8	750

SEPTEMBER, 1964



MEASURED FIELD INTENSITY CONTOURS: WWVB @13 kW ERP

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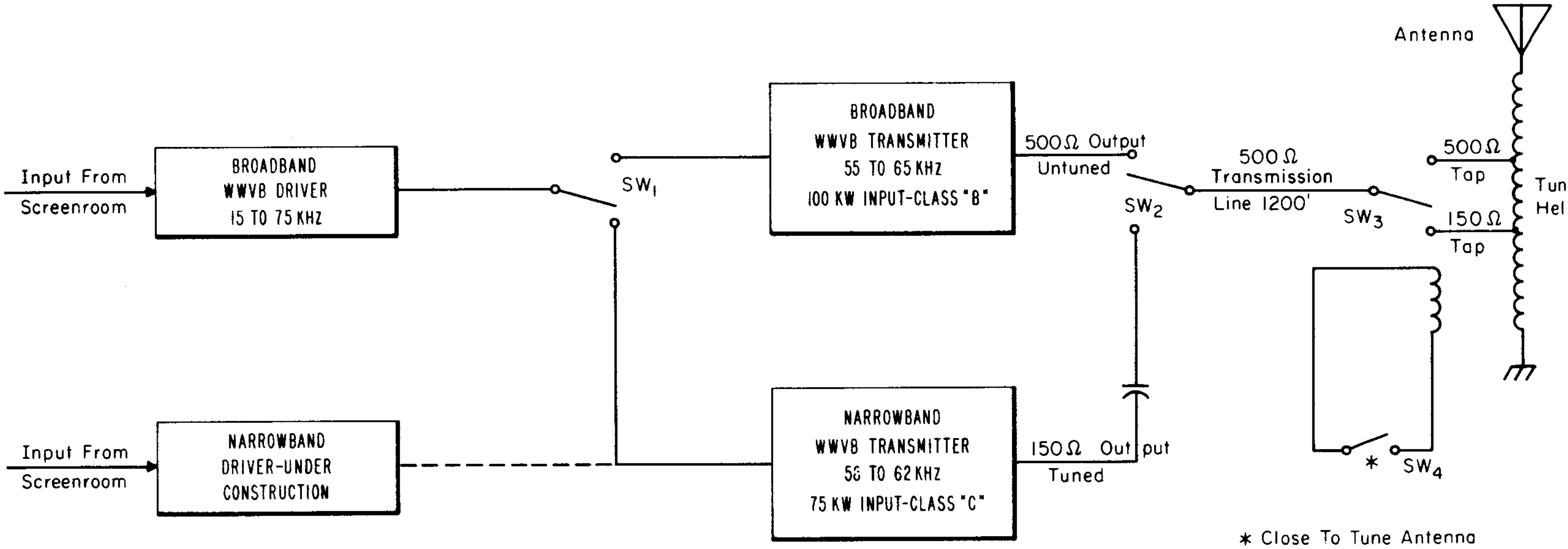
APPENDIX B

SIMPLIFIED DRAWINGS AND BLOCK DIAGRAMS

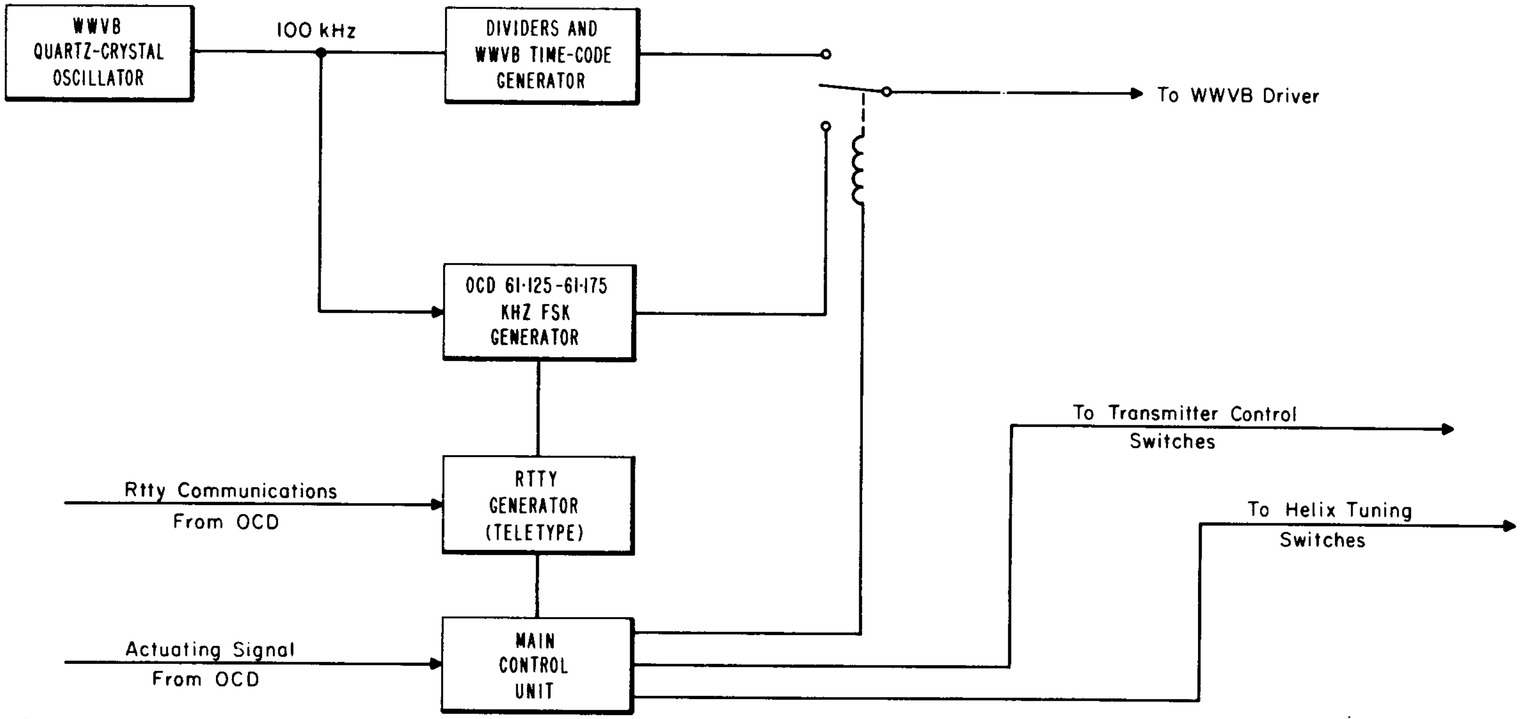
SIMPLIFIED DRAWING OF WWVB TRANSMITTER AND ANTENNA SYSTEM



SW_{1-4} Vacuum Switches To Be Remotely Controlled By OCD For Tests.

* Close To Tune Antenna To 61.15 kHz OCD Center Frequency.

SIMPLIFIED CONTROL-ROOM UNITS
FOR OCD TESTS AND EXPERIMENTS



APPENDIX C

PRELIMINARY ENGINEERING AND COST STUDY OF VLF/LF TRANSMISSION FACILITY FOR NBS AND OCD

Prepared for:

The National Bureau of Standards

Prepared by:

DECO Electronics, Incorporated

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

GLOSSARY AND DEFINITIONS OF SYMBOLS

Terms have been defined as they were used in the text, but some important definitions and symbols are collected for convenience here.

bit	The unit of measure of information content. It will not be used to refer to a binary element unless that element is worth one bit of information.
character	Sequence of elements transmitting a basic function or unit of the message. Here the term is loosely used as is the term "word." A word may be one or more characters as in real languages and a message may be one or more words.
coding	Translation of language or numerical symbols into sequences of electrical signals.
element	An interval during which one frequency, phase or amplitude is transmitted. One element may contain more or less than one bit of information, depending upon the choice of coding.
false alarm	The wrong interpretation by the receiver that environmental noise is a transmitted message.
grade of service	Quality of message translation as measured over a short period of time.
message reception	The combined functions of recognizing and translating a message.
message recognition	The proper determination by the receiver that a message is present. Message recognition can occur only if a message was sent; otherwise the determination represents a false alarm or reaction to an interfering signal.
message translation	Correct interpretation of the received message. This is not message recognition, but correct translation can take place only after recognition.

system performance, E/N_o	One measure of the system's capabilities in terms of quality not cost. Indicative of the signaling power required to achieve a specified grade of service at a given rate.
service probability	Probability of achieving or exceeding specified grade of service for a given percentage of the time.
time availability	Percent time during which a specified grade of service will be achieved with a certain probability.

E/N_a = ratio of energy per bit to atmospheric noise spectral power density. Usually expressed in db.

m = number of unique messages or symbols it is possible or required to send.

m_f = frequency modulation index.

M = size of the signaling alphabet or number of frequencies.

n = number of elements or signaling intervals per symbol.

P_c = character error rates for teletypewriter.

p_s = error rate for an alert message or switching function.

S/N_a = required signal power to atmospheric noise power density ratio to achieve a given grade of service.

$\overline{S}/\overline{N}_a$ = mean value of available signal power to atmospheric noise power density ratio at a reception point.

ABSTRACT

An LF transmitting station for the Office of Civil Defense is described, which is capable of meeting the stringent requirements of extreme reliability for special control and warning messages during a national emergency. The station's emergency operating frequency is 60 kHz, but it is planned that it may also be operated on a regular basis at 20 kHz by the National Bureau of Standards as a high-powered outlet for standard frequency and timing signals. This joint operation increases the economic feasibility and provides added insurance of continuous availability for emergency use.

The station capabilities and a budget estimate are outlined in the first part of the report. Later sections give the preliminary engineering support data and cost-trade figures for the recommended facility.

1. INTRODUCTION

The Office of Civil Defense has a requirement to transmit reliably, and at any time, certain control signals and warning messages to the Emergency Broadcast Industry and local government agencies in the event of a national emergency. Low frequency transmission facilities can provide such service with coverage over large areas from a single station. A properly implemented station can provide extremely high communications reliability and time availability with an extremely small probability of false alarm.

Since such stations would involve a large initial investment and have limited emergency use, it seems reasonable to consider a joint operation whereby another agency could operate and maintain the station on a regular basis. This arrangement of dual-purpose station use increases the economic feasibility and the probability of proper operation when required by OCD.

The National Bureau of Standards is presently disseminating frequency and time interval standards on allocated frequencies of 20 kHz and 60 kHz. This service could be substantially improved by increasing the radiated power at these frequencies. The antenna and transmitter which meet OCD's requirements can provide increased radiation capabilities at 20 kHz. The "cost-trades" for a station compatible to both NBS and OCD, and for OCD use only, are included.

One recommended facility and the corresponding budget estimate is given in Section 2 of this report. Section 3 indicates the preliminary engineering work and support data which form the basis for this selection. Using the information of Section 3, it is also possible to define other similar facilities in terms of performance and cost.

2. RECOMMENDED FACILITY

2.1 Description of station performance characteristics

The transmitter station recommended here has the approximate characteristics listed below. The station operates in the neighborhood of 61 kHz when under OCD control during test and emergency use. Normal operation is assumed to be at 20 kHz by NBS.

Operating Frequency	≈ 60 kHz	20 kHz
Radiated Power	500 kw	30 kw
Bandwidth (Antenna System)	1200 Hz	40 Hz
Antenna System Efficiency	.83	.30
Transmitter Output Power Required	600 kw	100 kw
Total Facility Input Power	1000 kw	200 kw

The OCD portion of the system has the following assumed operational characteristics. Performance specifications apply for worst time noise over the poorest path assuming the transmitters located in the vicinity of Washington, D.C. and Fort Collins, Colorado. Noise is assumed to have a rms-to-average ratio, (V_d), of 10 db in a 300 Hz effective bandwidth.

ALERT MESSAGE MODE:

Code	8 element
Signaling Rate	1 baud
Time per message	8 seconds
Total number of messages possible	256
Modulation	FSK, $m_f = 50$ ($\Delta f = \pm 25$ Hz)

ALERT MESSAGE MODE: (continued)

Probability of message error	10^{-4}
Probability of false alarm	1 in 3 years for 300 receivers
Service probability	0.9
Time availability (with noise suppression)	> 99.95%
Time availability (no noise suppression)	98.8%
Message recognition	Determined by noise threshold exceedances
Synchronization	Element synchronization established during test periods and held between such periods using adequate oscillator stability. Character synchronization established by message recognition, storage and threshold logic.

TELETYPEWRITER MODE:

Code	7 element start-stop
Signaling rate	50 baud
Information rate	35.7 bits/sec.
Word rate	71.4 words/min.
Modulation	FSK, $m_f = 1$ ($\Delta f = \pm 25$ Hz)
Detection	Limiter-Discriminator
Percent character errors	0.1%
Service probability	0.9
Time availability (with noise suppression)	93%

The performance specifications apply for reception only and do not include the input control links. This assumes that two transmitters will be used, one near

Fort Collins, Colorado, covering the West-Central and Western portion of the continental United States, and the other near Washington, D.C., for Eastern and East-Central portions. Switching control functions and message selection, originating at warning centers, will be received via microwave at the station for automatic OCD operation. The most critical reception area is that in southern Louisiana. A worst case noise occurs between 1200 and 1600 hours during the summer. CCIR predictions indicate this noise will have an rms-to-average ratio, V_d, of 10 db in a 300 Hz bandwidth. The noise suppression is assumed to be a simple diode clipper set to clip the noise 10% or more of the time.

Various receiver configurations were considered to establish performance characterization of the system. The recommended type for the alert mode of operation incorporates narrow band filters and dual envelope detectors for message interpretation and a noise threshold for message recognition. The performance of a noncoherent detector of this type is not as good as a coherent receiver, but the complexity and cost is reduced by a substantial amount.

The synchronization problems for OCD receivers have not been worked out in detail. Some general concepts should be noted. Coherent detection is not recommended partly because of cost considerations for the more complex receiver and because of the required lock-up times which reduced the time available for element detection and increased signal-to-noise requirements. Since signals will not be continuously available, element synchronization should preferably be inherent in the receiver itself and could be achieved during OCD test periods and maintained between such periods. Generally, nearly optimum performance is realized if element synchronization is established within 10% of an element length. For a 1 baud system this means element synchronization should be established within ± 100 milliseconds. Such timing can easily be checked between OCD test periods by using independent means such as NBS timing signals from WWV.

The station is expected to be a manned operation, although it is possible that remote monitor and control sites could be located a very short distance away. With any station of this size it is desirable to have personnel available at the site on short notice.

A diagram showing the basic functions to be performed by the transmitter station is shown in Figure 2-1. Normal station operation is at 20 kHz by NBS. Periodic testing and test messages may be sent by OCD by remote switching via the microwave link. This also serves as the station control during an emergency, and such switching functions must override any NBS operations. Since NBS requires only 100 kw of transmitter output, the other transmitter power amplifier modules will be switched to standby during normal operation. NBS may alternate the use of 100 kw modules to check operating status.

2.2 Proposed antenna system

A 1200' base insulated, toploaded tower is proposed for the station. The toploading consists of 16 cables approximately 1000' long, which also serve as part of the length of the uppermost set of support guys. This tower is similar to that being supplied to the Air Force for an LF survivable communications system. Detail design studies are not included here, but performance is based on the Air Force design and provide for an antenna system capable of withstanding five psi or 150 mile per hour winds with 1/2" of radial ice.

The pertinent antenna characteristics are:

		Approximate Values
Land area required		300-400 acres
Design voltage limits		160 kv
Radiation resistance	60 kHz	3.0 Ω
	20 kHz	0.33 Ω
Static antenna capacitance		0.014 μfd

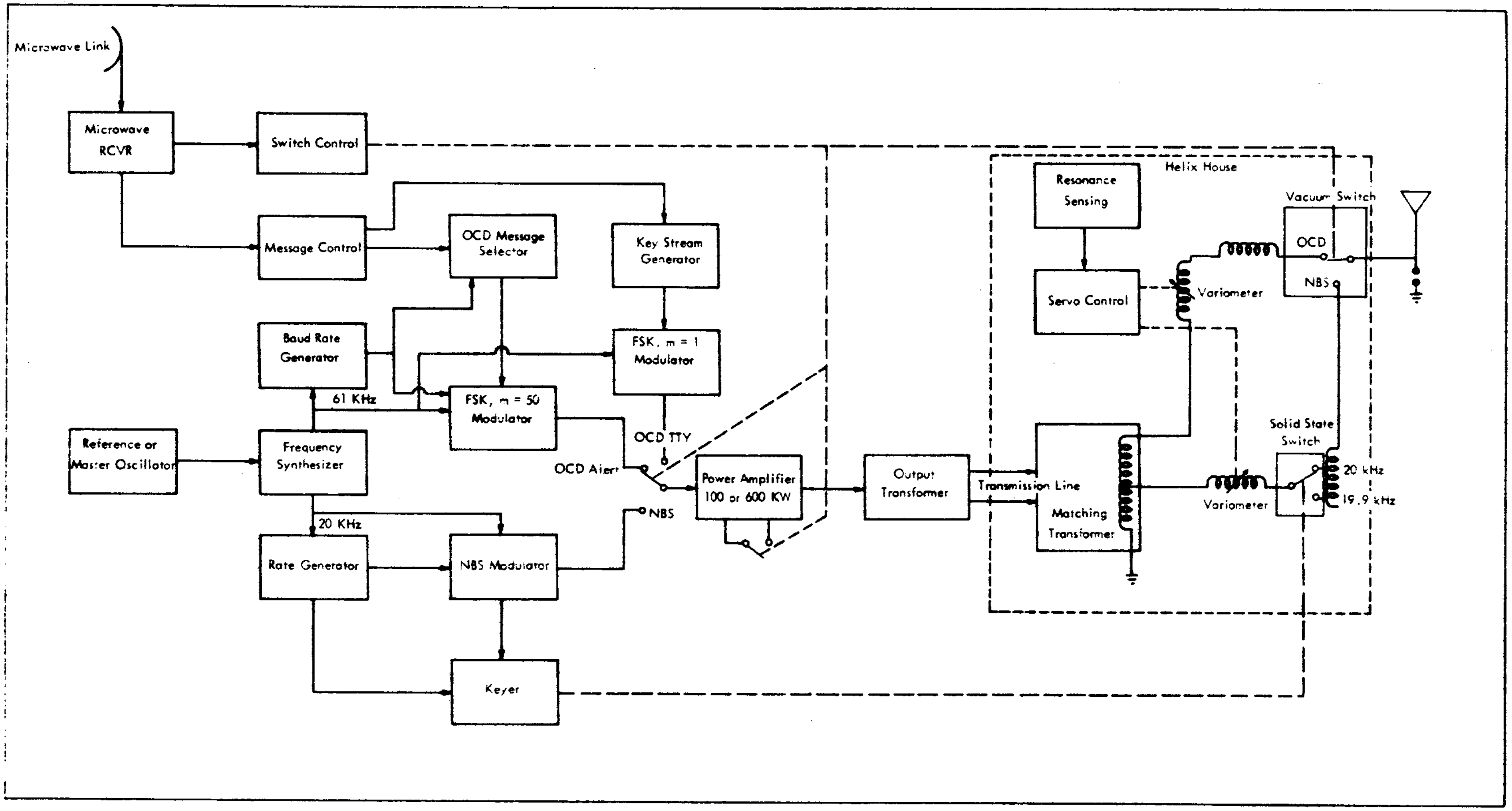


Figure 2-1 Joint NBS OCD Facility Functional Diagram

Antenna base current (for 30 kw at 20 kHz)	300 amps
Efficiency @ 20 kHz	.30
Efficiency @ 60 kHz	.83
Actual height	1220 feet
Effective height	220 meters
Inherent bandwidth 20 kHz	12 Hz
Inherent bandwidth 60 kHz	980 Hz
Inductance to tune 20 kHz	4.2 mh
60 kHz	0.17 mh
Helix Q	1300
Resonant frequency	74 kHz

2.3 Facility layout

A perspective view of the recommended facility is shown in Figure 2-2. Details of a tentative antenna system, transmitter and helix house are shown in Figures 2-2, 2-3 and 2-4. These figures should not be construed as engineering drawings, but do show the conceptual magnitude of the envisioned facility.

The antenna is essentially the same as that being implemented for the Air Force 487 L program. The transmitter power amplifier consists of six 100 kw RF modules, each occupying a 4 x 4 x 6 foot space. Each module includes built-in power supply, and is water cooled.

2.4 Station costs

The criteria used for the cost breakdown is outlined in Section 3.6.

The minimum antenna height which meets all the requirements is chosen since this results in minimum total station costs. The costs for the NBS/OCD station which meets the required 500 kw near 60 kHz and 30 kw @ 20 kHz are given below.

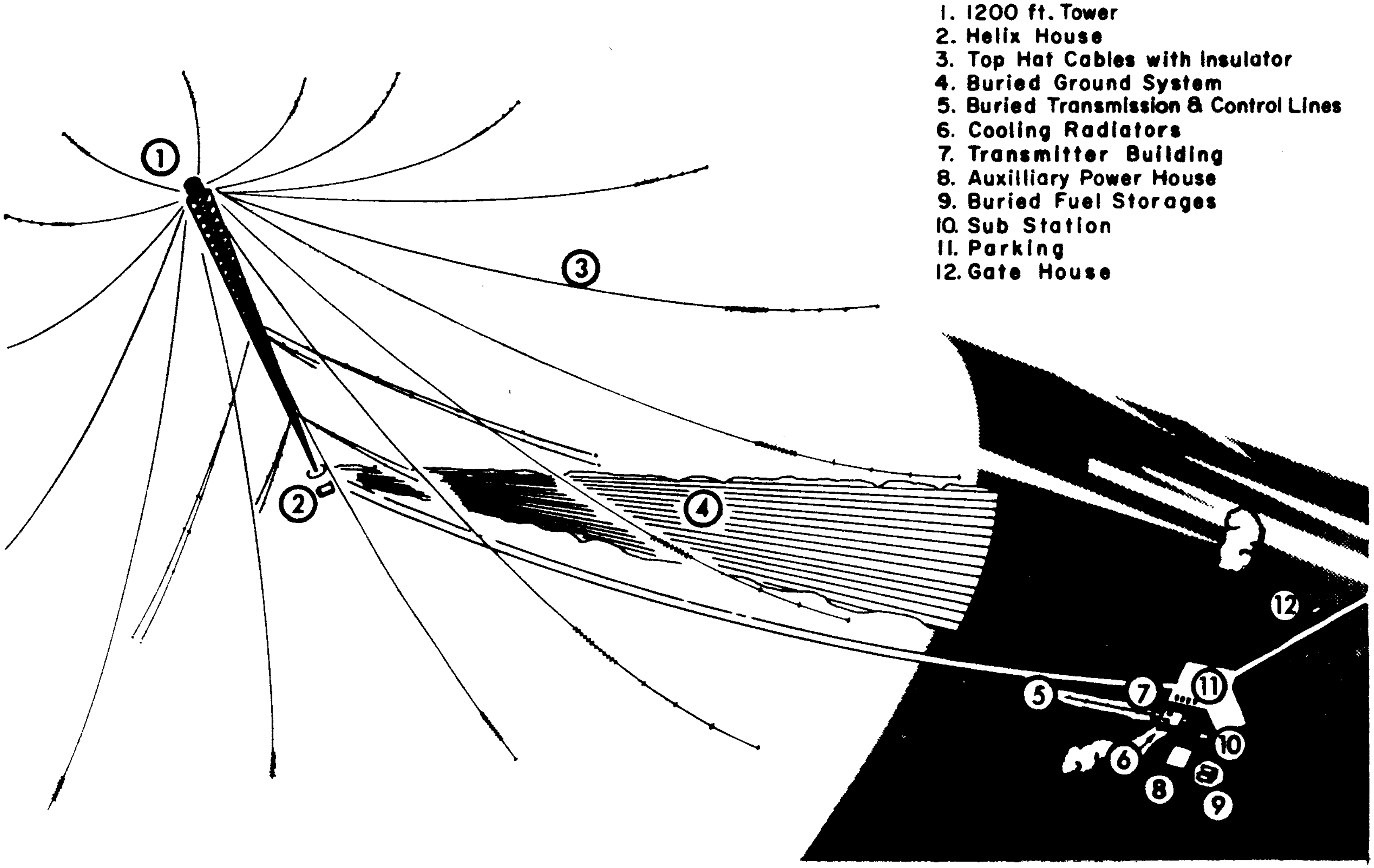


Figure 2-2

Conceptual Layout, Station Area

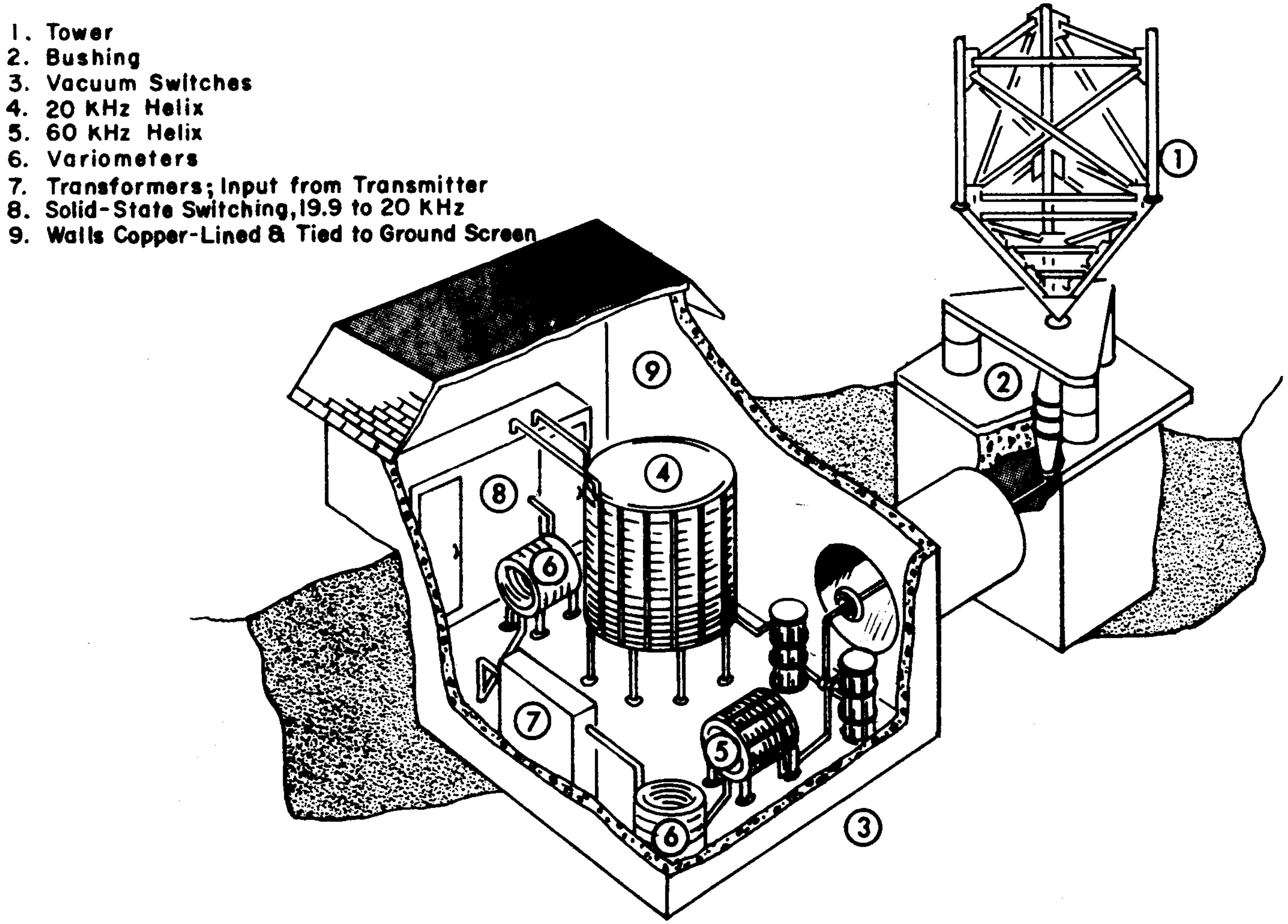


Figure 2-3

Conceptual Layout, Helix House and Antenna Base

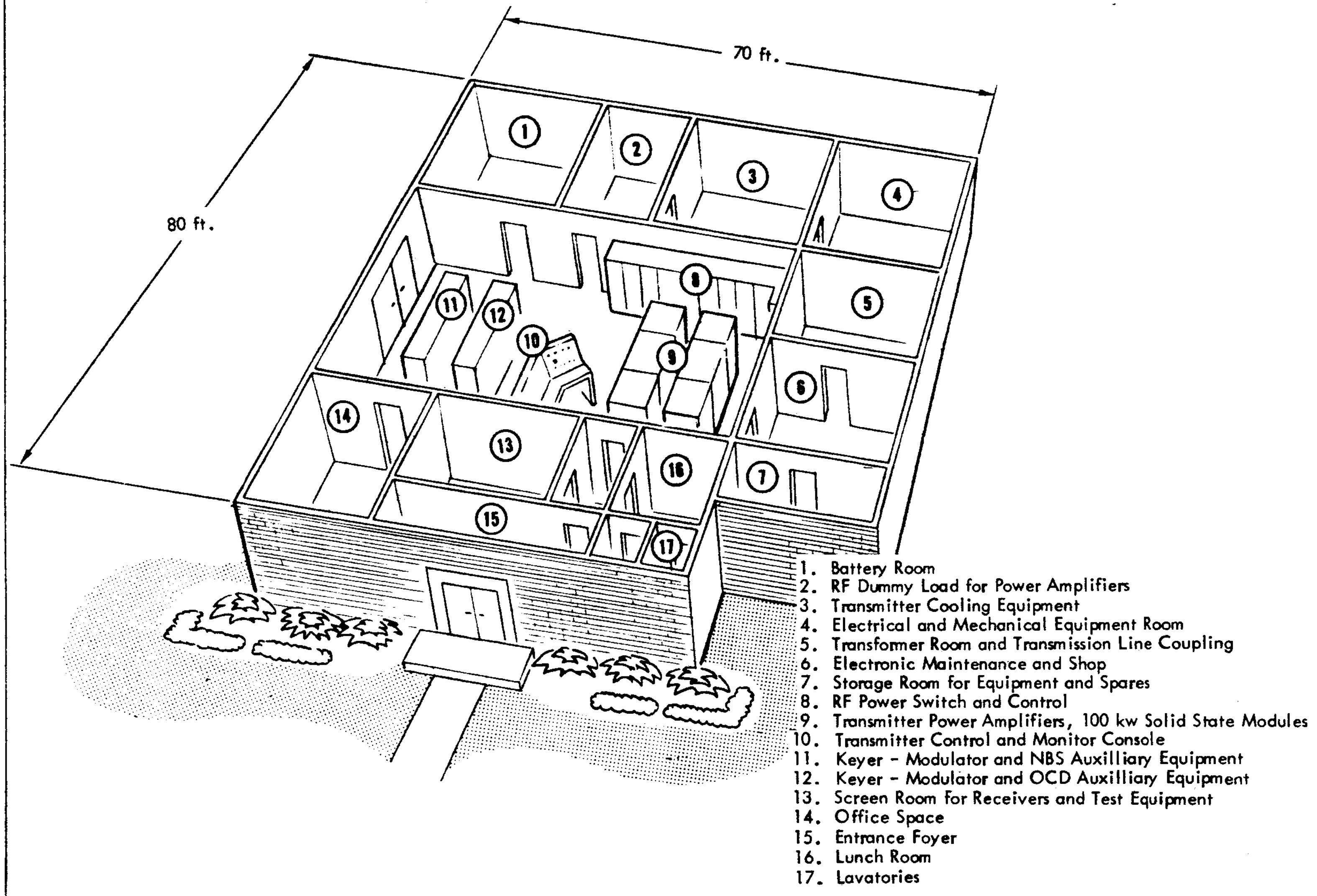


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Figure 2-4 Conceptual Layout, Transmitter Building

1. Land - 400 acres @ $750/acre	$ 300,000
2. Antenna system (includes feed, tower, guys, lightning protection, top-hat, insulators, foundation, anchors and installation)	1,670,000
3. Ground radial system (resistance = 0.1 ohms, Dia ≈ 4200')	70,000
4. Tuning inductors (helix house and inductors only)	110,000
5. Solid-state transmitter (600 kw) @ $2.00/watt installed	1,200,000
6. Transmitter building and auxiliary equipment (see breakdown that follows)	575,000
7. Auxiliary power (2-500 kw generators) (includes complete installation, building and fuel storage, switching and remote control, auto start and monitoring capabilities)	290,000
Total Station Costs	--$4,215,000

Costs shown here include allowances for plans and specifications of the complete station, but do not include provisions for personnel housing since this requirement may not be essential. Some savings may result by using the 1200' tower antenna system of the Air Force system presently being implemented. Curves and data, which form the basis of these estimates, are given in Section 3.

For a 500 kw station for OCD operation only, or for joint operation with NBS at 60 kHz, the cost is as follows for a station with the same performance capabilities. Actual costs may differ somewhat. For example, transmitter modules may only be available in 100 kw units. It would ordinarily be more realistic to start with available power output and let the radiation capabilities, and thus the performance characteristics, be degraded slightly.

1. Land - 280 acres @ $750/acre	$ 210,000
2. Antenna system - 1000' toploaded tower	1,050,000
3. Ground radial system	80,000
4. Tuning inductors and housing	20,000
5. Transmitter power amplifiers	1,250,000
6. Building	625,000
7. Auxiliary power	315,000
Total Station Costs	--$3,550,000

The costs for the transmitter building include not only the structure but all of the equipment auxiliary to, but excluding the power amplifier. An estimated cost breakdown for the principal auxiliary equipment is tabulated below for the joint station.

Auxiliary Equipment Costs

Item	Estimated Installed Cost
Microwave link (2)	$ 50,000
Message logic circuits (2)	10,000
OCD-FSK modulators (2)	20,000
Frequency standard (cesium) (3)	75,000
Frequency synthesizer (2)	50,000
Switch control (2)	15,000
NBS signal generator (1)	10,000
Dummy load (1)	30,000
Monitor and control console (1)	35,000
Matching transformer (2)	30,000
Variometers (2)	20,000
Solid state switch (500 amps) (1)	75,000
Vacuum switch (2)	10,000
Sensing and servo control (2)	15,000
Total Auxiliary --	$445,000
Building - 5200' @ $25 sq. ft.	130,000
Total Building and Auxiliary --	$575,000

The total provides $130,000 for the 5200 square foot building, or $25 per square foot. This $25 per square foot building costs should be sufficient to allow for the following special features.

1. Temperature and humidity control.
2. CO_2 fire-extinguishing system.
3. Sub-floor space in transmitter room and associated areas for cable-tray interconnection.

4. Screened room.
5. Special plumbing for liquid cooling of solid state transmitter.
6. Special shielding and grounding requirements.

2.5 Prime power costs

Electric rates are generally based on a demand charge plus the energy charge. Intermittent operation of the station by OCD increases the demand and thus the operating costs by a considerable amount. For 1000 kw of demand prime power and using typical rate schedules the cost per month is approximately $2500. This is approximately five times the cost/month for the station operating at normal power levels for 20 kHz required by NBS.

3. ENGINEERING SUPPORT DATA

In Section 2 the characteristics and costs were given for the recommended station. This recommendation was based on preliminary engineering studies using station criteria given by OCD and NBS and using certain essential and reasonable assumptions. These operational criteria are given in the following sections along with the preliminary engineering data.

3.1 Siting

The selection of a location for the VLF/LF facility is partly dependent on factors which do not necessarily affect the performance of the station itself, but will determine its operational capabilities. These include:

1) Input or control link requirements
2) Isolation from prime targets
3) Radioactive fallout danger
4) Availability of primary power and other servicing requirements
5) Protection of facility and control links from sabotage

Factors which do affect performance, and therefore costs, and should be considered when the specific site is chosen include:

1) Ground conductivity which affects the electrical performance of the radiation system
2) Site terrain and geological features in proximity
3) Natural hazards such as wind, icing, and frequency of local thunderstorm activity
4) Propagation paths to desired reception points
5) The altitude which affects the voltage limits on the antenna

Location of the transmitting antenna and station operating personnel with respect to targets liable to atomic attack may be determined from Figure 3-1. A distance of four miles, for example, gives adequate protection from 1 megaton blast and nuclear radiation for tower and personnel, providing the tower has been designed to withstand 75 mph gusts of wind. A distance of 15 miles is required to limit exposed persons to first degree burns from the resulting thermal radiation. These curves are quite dependent upon effects of air density, altitude of explosion and intervening objects, so a safety factor of three should probably be considered in actual siting.

This study assumes the antenna is located at sea level. Although two transmitting sites are required only the one in Virginia is expected to be used by NBS for 20 kHz where the antenna voltage limits restrict the radiated power. The antenna system at Ft. Collins, Colorado will be approximately 5000 feet above sea level and will be operated by NBS only at 60 kHz. The antenna at this site is expected to be input-power limited and the altitude affect can be neglected.

3.2 Frequency dependence of radiated power requirements

An initial task on the contract was to calculate the radiated power requirements as a function of frequency for a typical TTY system during the worst case time-block and over paths selected by the Government.

For this study transmission facilities were assumed to be located at Winchester, Virginia and near Fort Collins, Colorado. The receiver sites selected for the analysis were Natick, Massachusetts; Minneapolis, Minnesota; Denton, Texas; Olney, Maryland; and Seattle, Washington. See Figure 3-2. The sites shown in this figure include all those originally given from which six will be shown as representative for calculating the radiated power vs frequency requirements. The approximate distance from each transmitter is tabulated below.

APPROXIMATE PATH LENGTH IN MEGAMETERS

Receiving Sites	Winchester, Va.	Ft. Collins, Colo.
Denton, Texas	1.8	1.1
Olney, Maryland	0.1	2.3
Natick, Massachusetts	.7	2.7
Minneapolis, Minnesota	1.4	1.0
Salt Lake City, Utah	2.8	0.6
Ely, Nevada	3.0	0.8
Seattle, Washington	3.0	1.5
Billings, Montana	2.5	0.6

The distance between the transmitters is 2.2 megameters.

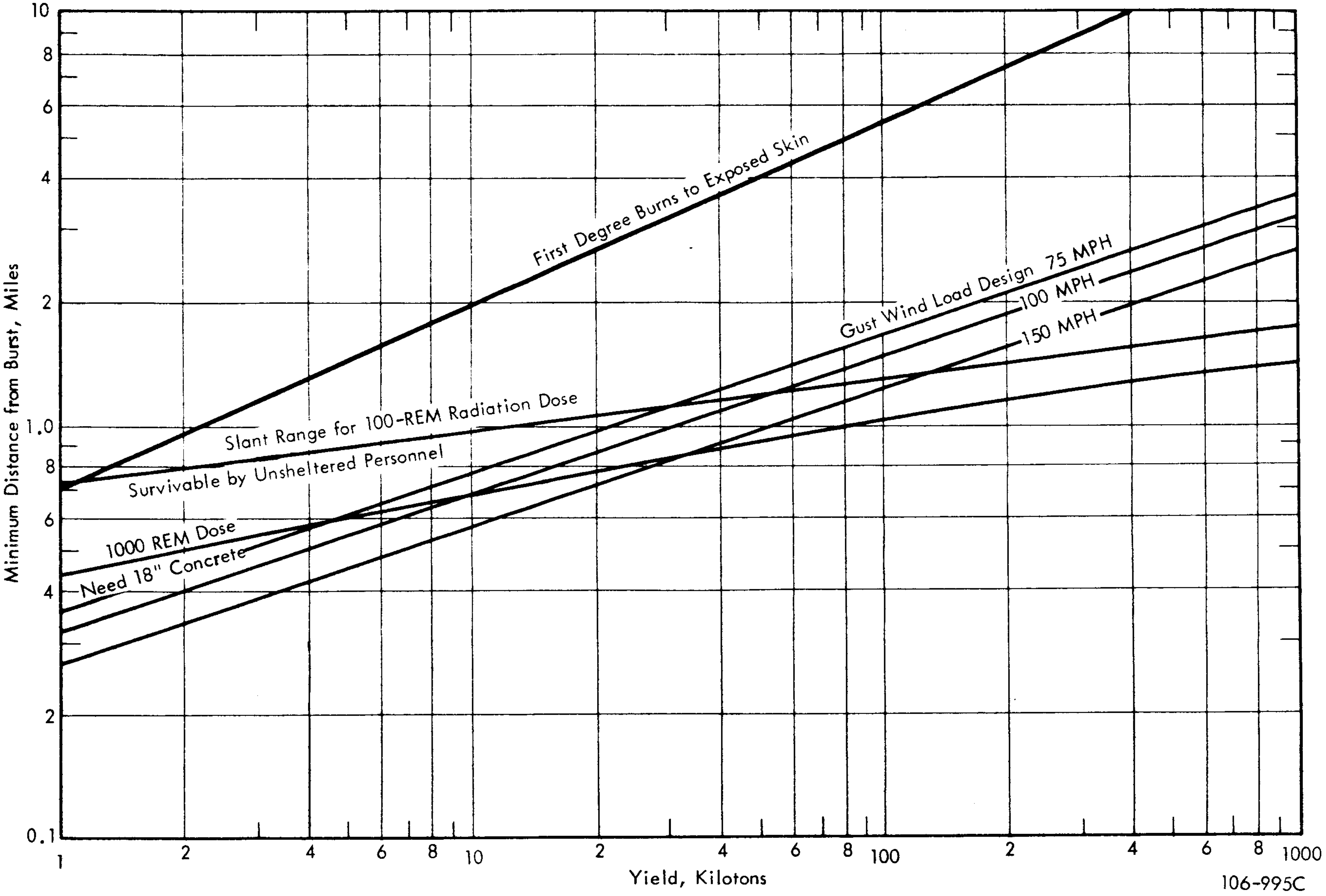

Figure 3-1 Minimum Distance From Targets for Antenna Tower and Personnel Nuclear Effects Survival

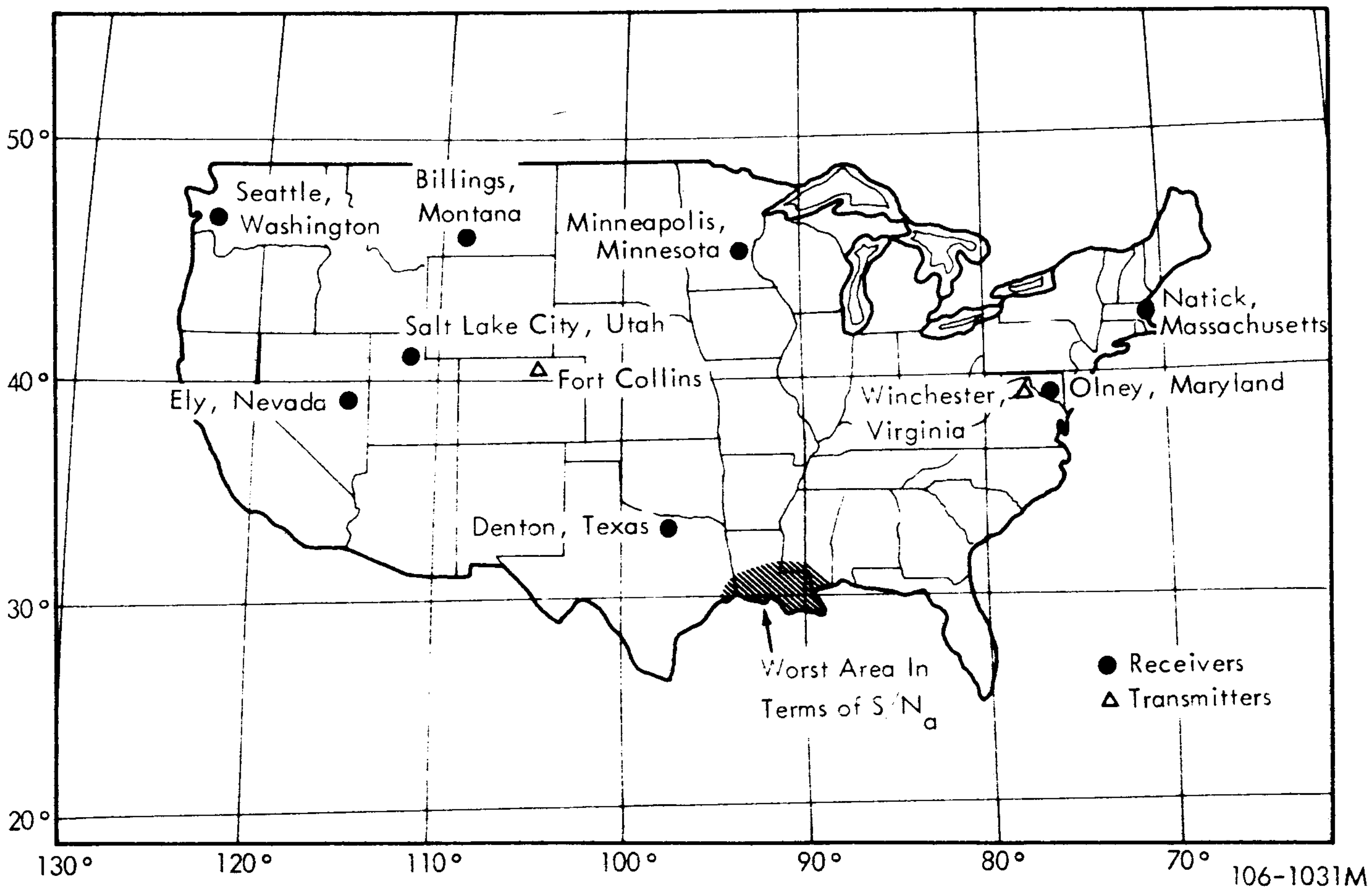

Figure 3-2 Transmitter and Receiver Sites

Signal levels were computed for only six paths and for different frequencies in the LF band from the ground wave equation,

$$\overline{S}\ (\text{ground wave, db}) = 109.5 - 20 \log d + W_g$$

where

d = path distance on the surface of the earth in km;

W_g = amplitude loss in db associated with the effect of the earth on the radiated field;

and the sky wave equation,

$$\overline{S}\ (\text{sky wave, db}) = 103.6 - D_p + A_t + 20 \log \cos \Psi - L_t - L_r + C'_m - mI_i - (m-1)\, I_g$$

where

D_p = inverse distance attenuation in db relative to unit ray distance;

A_t = transmitting antenna free-space gain in db at the launching angle, Ψ;

L_t = transmitting antenna launching loss in db relative to a loop in free space;

L_r = receiving antenna launching loss in db relative to a loop in free space;

C'_m = total effective convergence due to a curved ionosphere and earth, in db;

m = number of ray hops;

I_i = ionospheric reflection loss in db;

I_g = ground reflection or diffraction loss over a homogeneous earth in db.

The mean noise level at each frequency was obtained from CCIR Report 322 [1]. The mean value of available signal-to-noise-density ratio, $\overline{S}/\overline{N}_a$ can then be determined. This was done by normalizing transmitter radiated power to 1 kw. The required transmitter power, relative to 1 kw at a given frequency, can then be obtained from:

$$P_r(\text{db}) = 20 \log S/N_a - 20 \log \overline{S}/\overline{N}_a + T_x$$

where S/N_a is the signal-to-noise-density voltage ratio required by the receiver to give the desired grade of service and $\overline{S}/\overline{N}_a$ is the signal-to-noise-density ratio available at the receiver for 1 kw radiated by the transmitter. T_x is the variability factor to account for the temporal and spatial variations of S, N_a, $\overline{S}$ and $\overline{N}_a$. The magnitude of T_x is a function of the time availability (T. A.), the service probability (S. P.), i. e., the repeatability and predictability of the signal-to-noise ratio. Thus

$$T_x = x_1 \ \sigma (\overline{S}/\overline{N}_a) + x_2 \ \sigma_p(E)$$

where $\sigma (\overline{S}/\overline{N}_a)$ depends on the signal fading and noise variation over a given path and within a particular time block. $\sigma_p(E)$ combines statistically the uncertainties of all the parameters involved in the prediction processes. x_1 and x_2 can be read from Figure 3-3 for a particular time availability or service probability of interest. Techniques for deriving $\sigma (\overline{S}/\overline{N}_a)$ and $\sigma_p(E)$ are given in reference [2], and will not be described here.

Since T_x is a function of x_1 and x_2, which are determined by an arbitrary choice of time availability and service probability, there is a trade-off available between these two factors. The variation in time availability and service probability possible by changing the radiated power ΔP_r db is shown for three frequencies: 25, 50 and 75 kHz in Figures 3-4, 3-5, and 3-6. Curves are parametric in ΔP_r, the amount which must be added to the P_r that was calculated for $T_x = 0$.

A specific radiated power requirement can now be determined as a function of frequency for any given T. A. and S. P. if the ratio of energy per information bit-to-noise power density required for a specified error rate at the receiver is given. This ratio depends on the information content of the source, the signal design, the information, the modulation, and the detection scheme used.

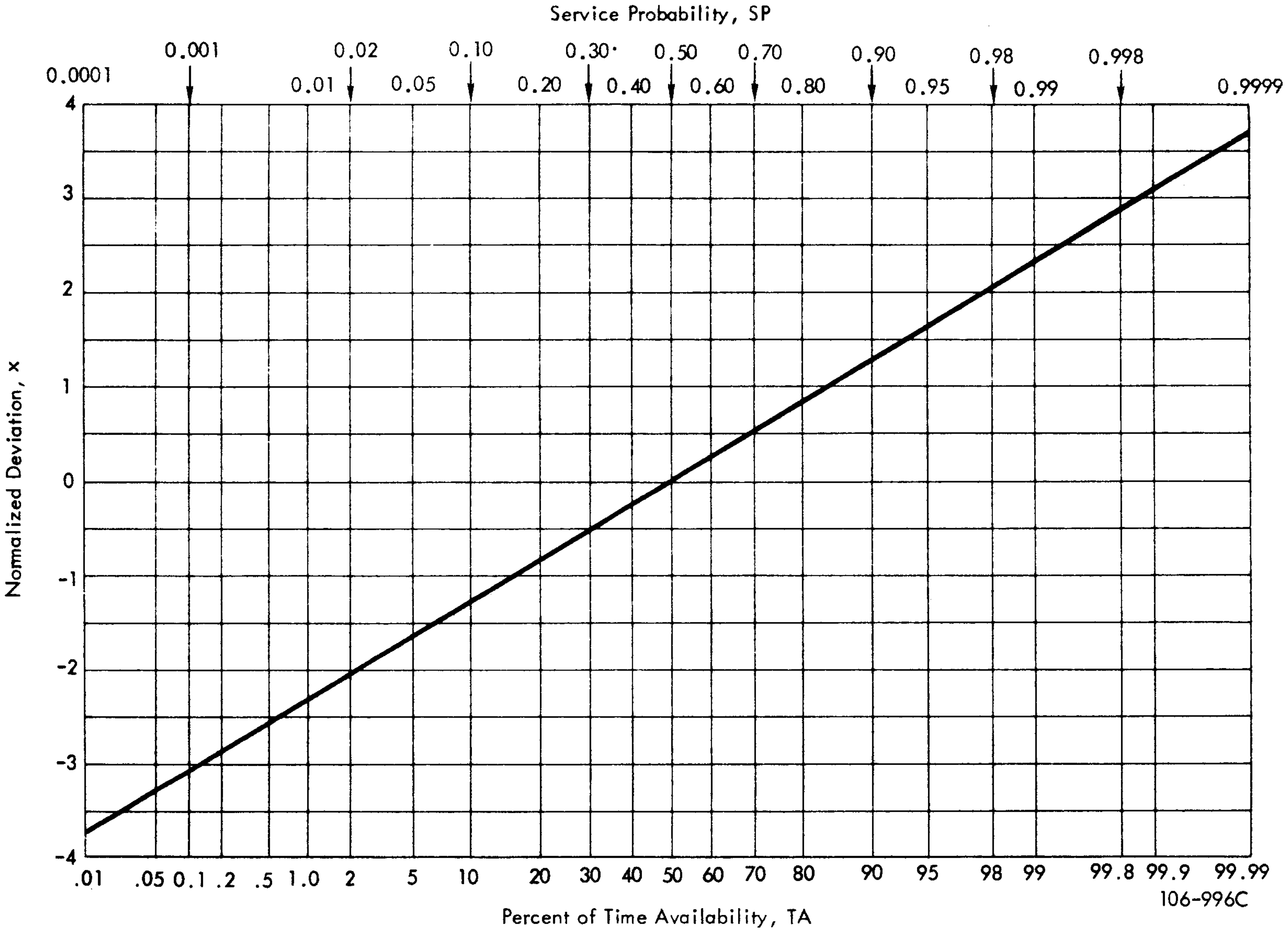

Figure 3-3 Relationship Between Percent of Time Availability or Service Probability and Nomalized Deviation

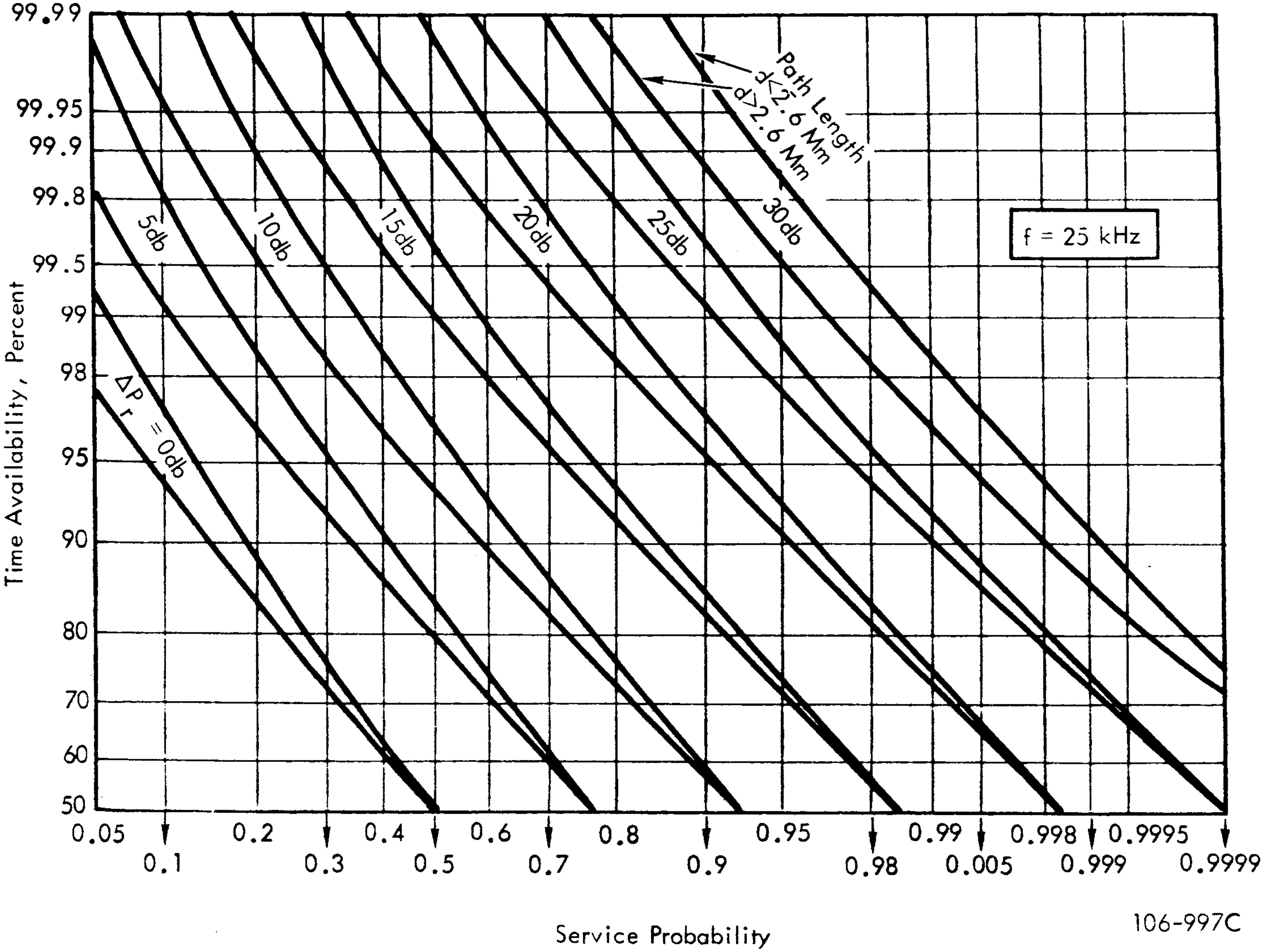

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Figure 3-4 The Variations in T.A. and S.P. Possible by Changing Radiated Power ΔP_r db

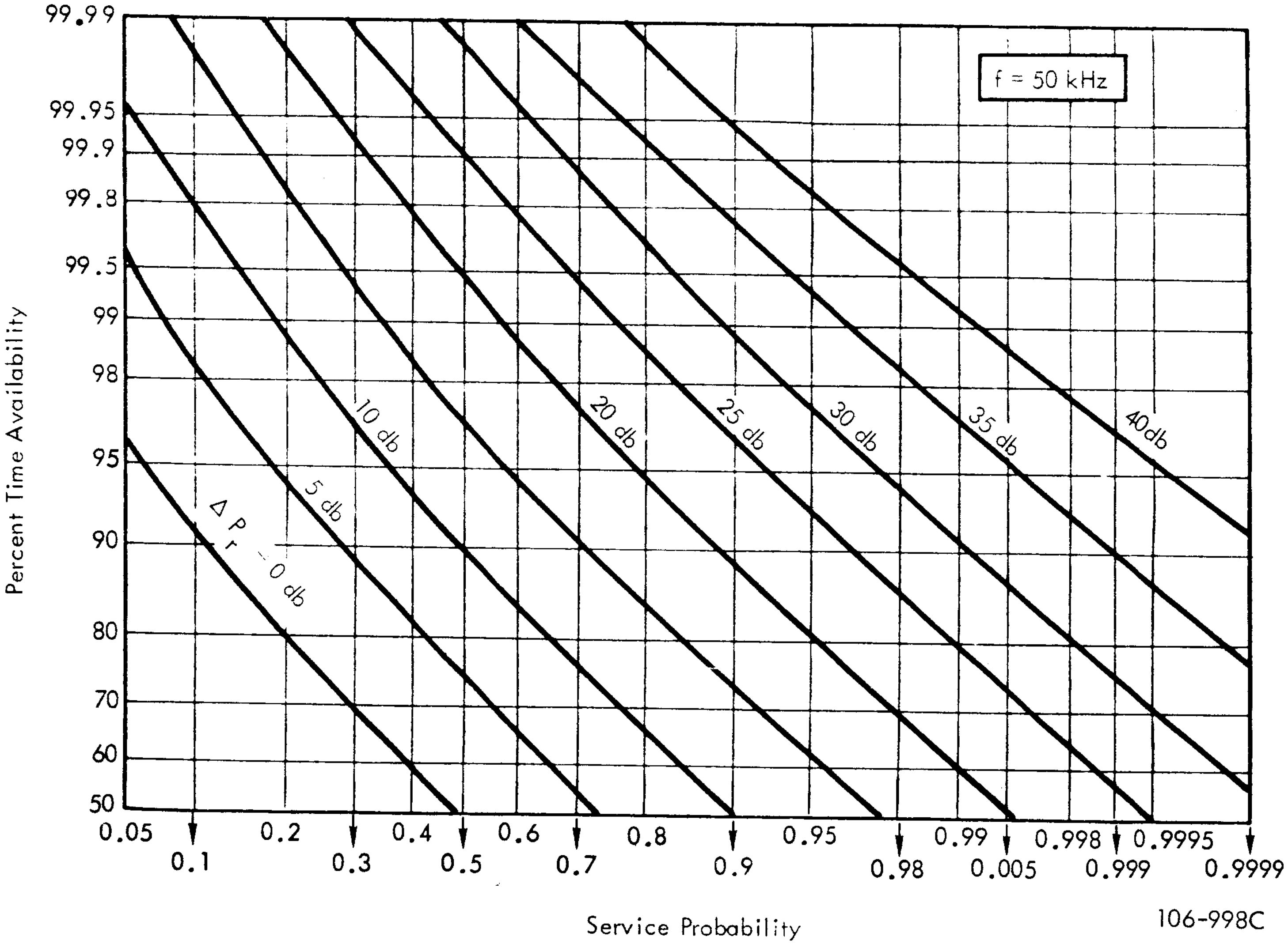

Figure 3-5 The Variations in T.A. and S.P. Possible by Changing Radiated Power ΔP_r db

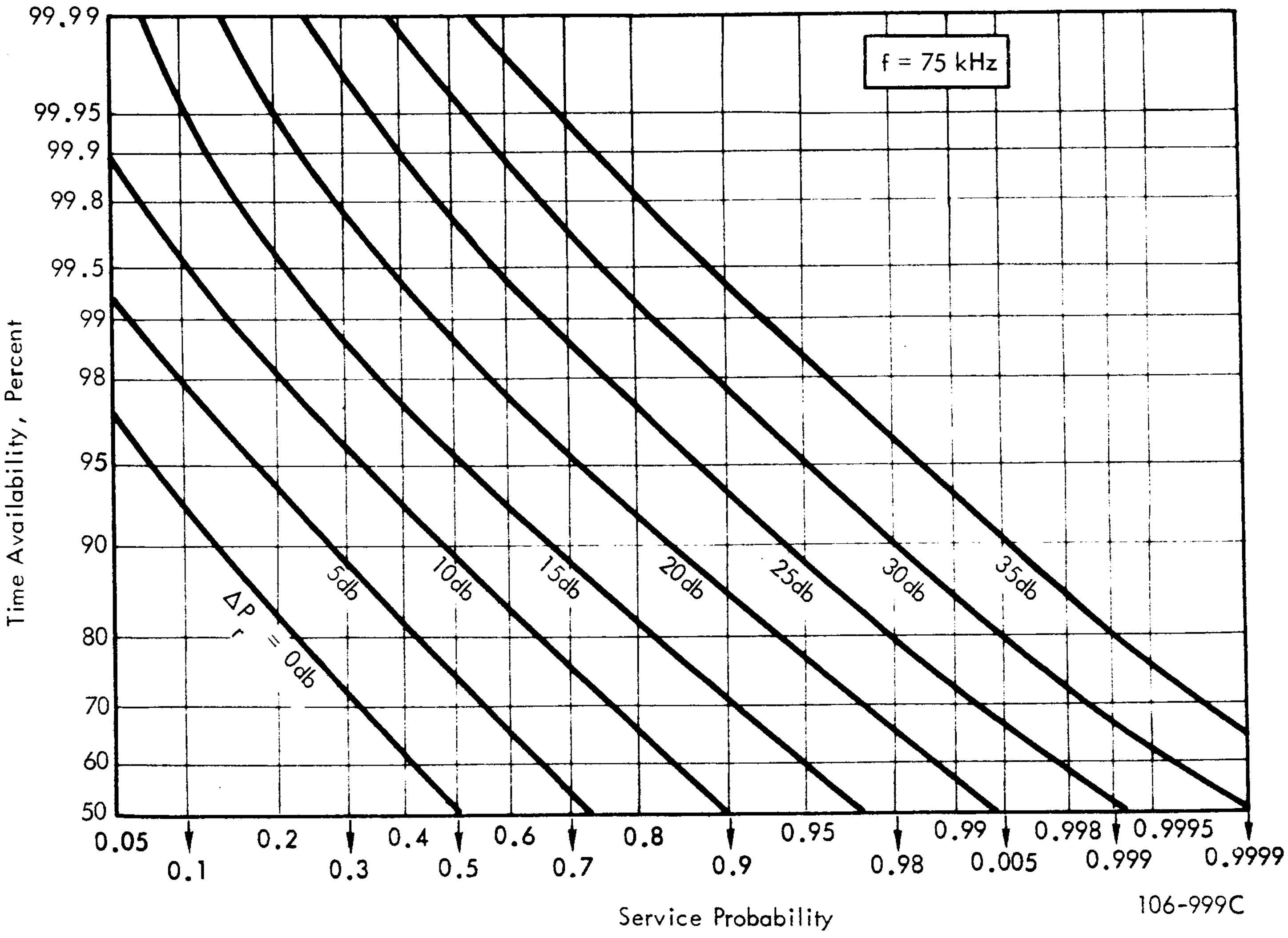

Figure 3-6 The Variations in T.A. and S.P. Possible by Changing Radiated Power ΔP_r db

Examples are given for certain paths in Figures 3-7 through 3-12 for a teletype system operating at 75 baud. The performance of the system is assumed to require $E/N_a = +3$ db for 0.1% character errors. This is achievable with an optimum FSK system and a modulation index of 1/2 operating with noise clipping in the atmospheric noise environment.* Typical of the worst time block, the curves are plotted in db relative to 1 kw of radiated power and also in db relative to 1 kw of antenna input power. The latter set of curves is most indicative of the performance cost of the station. These input power curves are obtained by dividing those relative to radiated power by the antenna efficiency which changes considerably with frequency. Points are indicated for both a six tower triatic type of antenna and a single, toploaded 1220' tower. Also shown by dashed lines are the power radiation capabilities with 150 and 200 kv voltage limits on the triatic antenna. For the tower these voltage-limit curves should be increased approximately 0.8 db at 20 Hz and 2.1 db at 60 Hz.

Based on this data alone it would appear that the optimum frequency for the OCD system would be at the lower end of the LF band. For the longest paths and for the higher time availability and service probability the power versus frequency curve shows a fairly broad minimum around 30 kHz. Discussions with OCD personnel, however, indicated a preference for the 60 kHz region because of frequency allocation considerations and also because more is known about the propagating media in this region. This knowledge is available largely because of measurements on the existing NBS 60 kHz standard frequency station located in Colorado. The lower end of the band (around 30 kHz) is a transition

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*The optimum FSK system performance can be realized when $m_f = \frac{1}{2}$ using a correlation type detector. Such a system is compatible(sometimes denoted CSK) or incompatible (denoted MSK) with simple limiter discriminator detectors depending on the keying logic at the transmitter. If mark-space references rather than a correlation detector **are** used with FSK, $m = \frac{1}{2}$ signaling then the performance is degraded approximately 3 db or essentially the same as FSK, $m = 1$ systems. The value of $E/N_a = +3$ db is for a 75 baud system in typical atmospheric noise with a reasonable amount of clipping. This same system is shown later in Section 3.3.6 as $E/N_a = +1$ db, but here it is for 50 baud at a specific noise environment and clipping level.

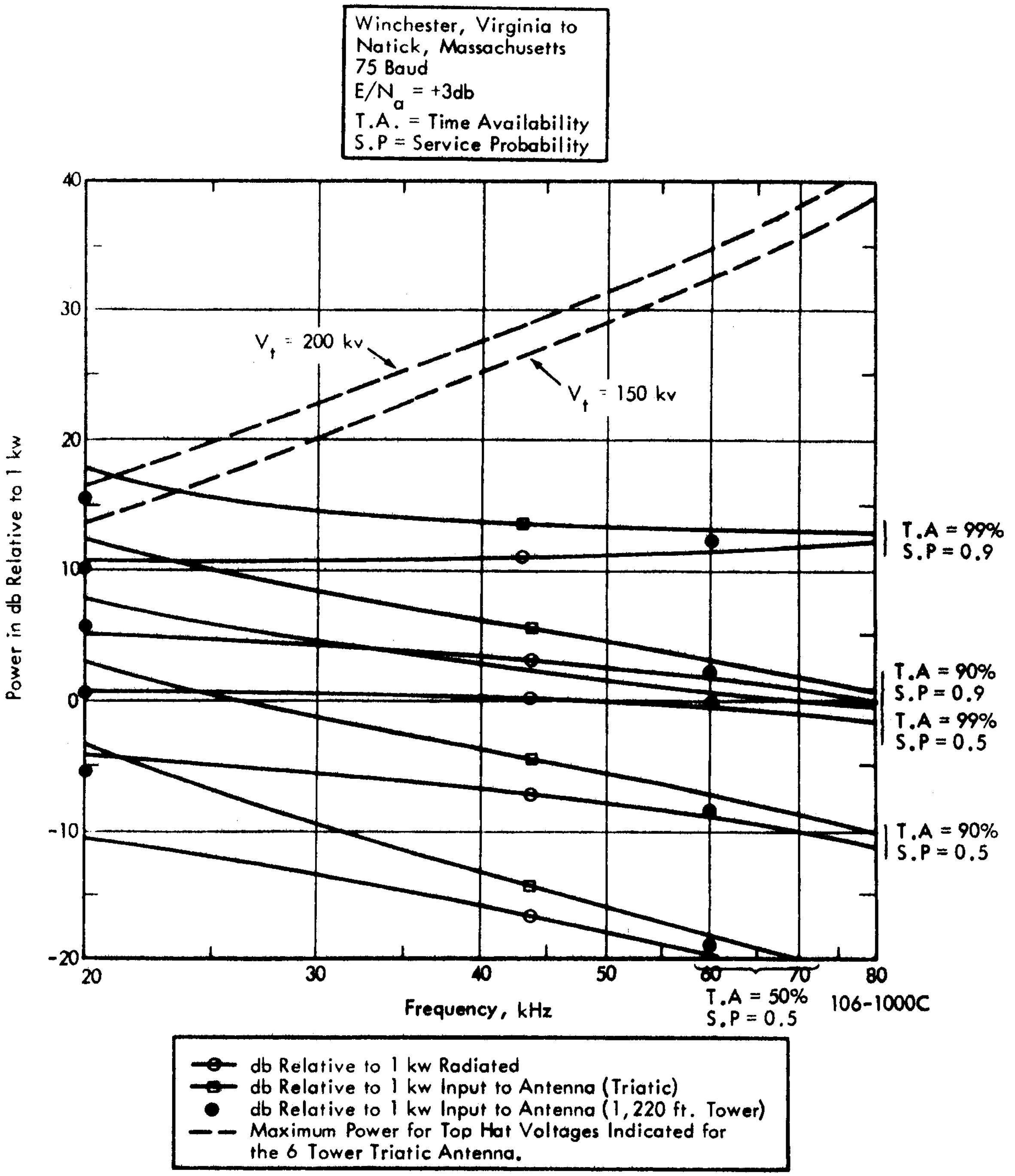

Figure 3-7 Power Requirements vs. Frequency

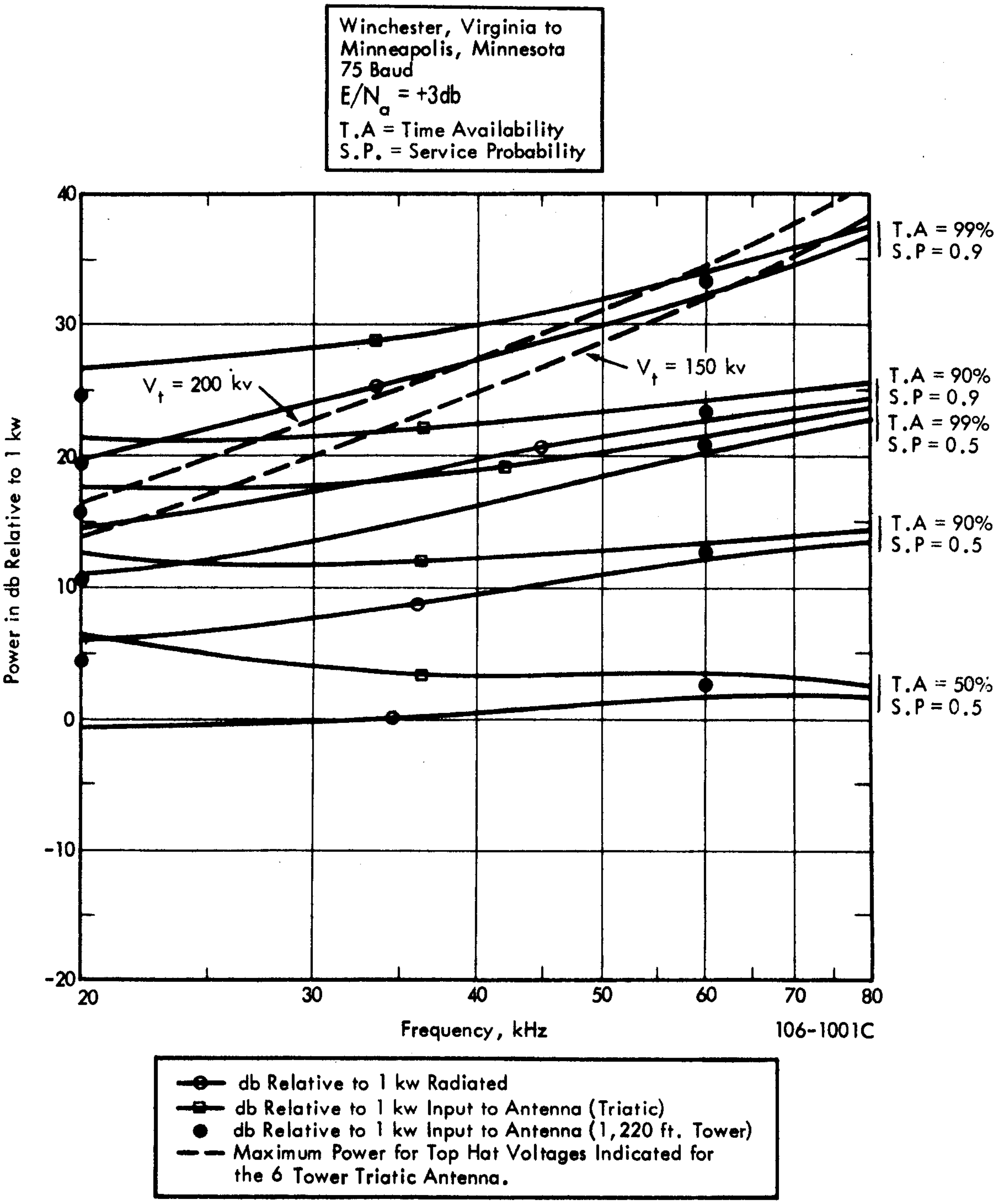

Figure 3-8 Power Requirements vs. Frequency

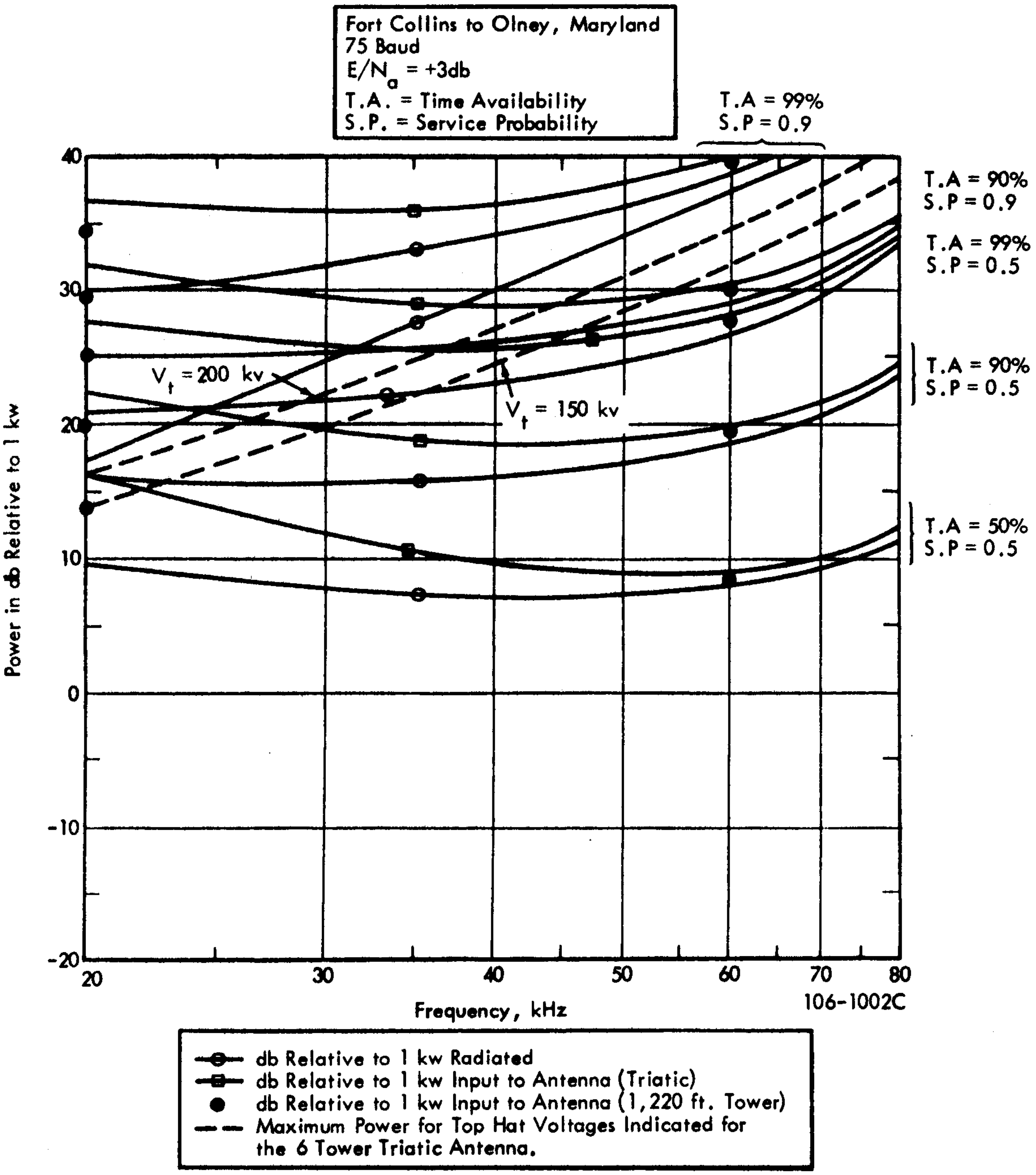

Figure 3-9 Power Requirements vs. Frequency

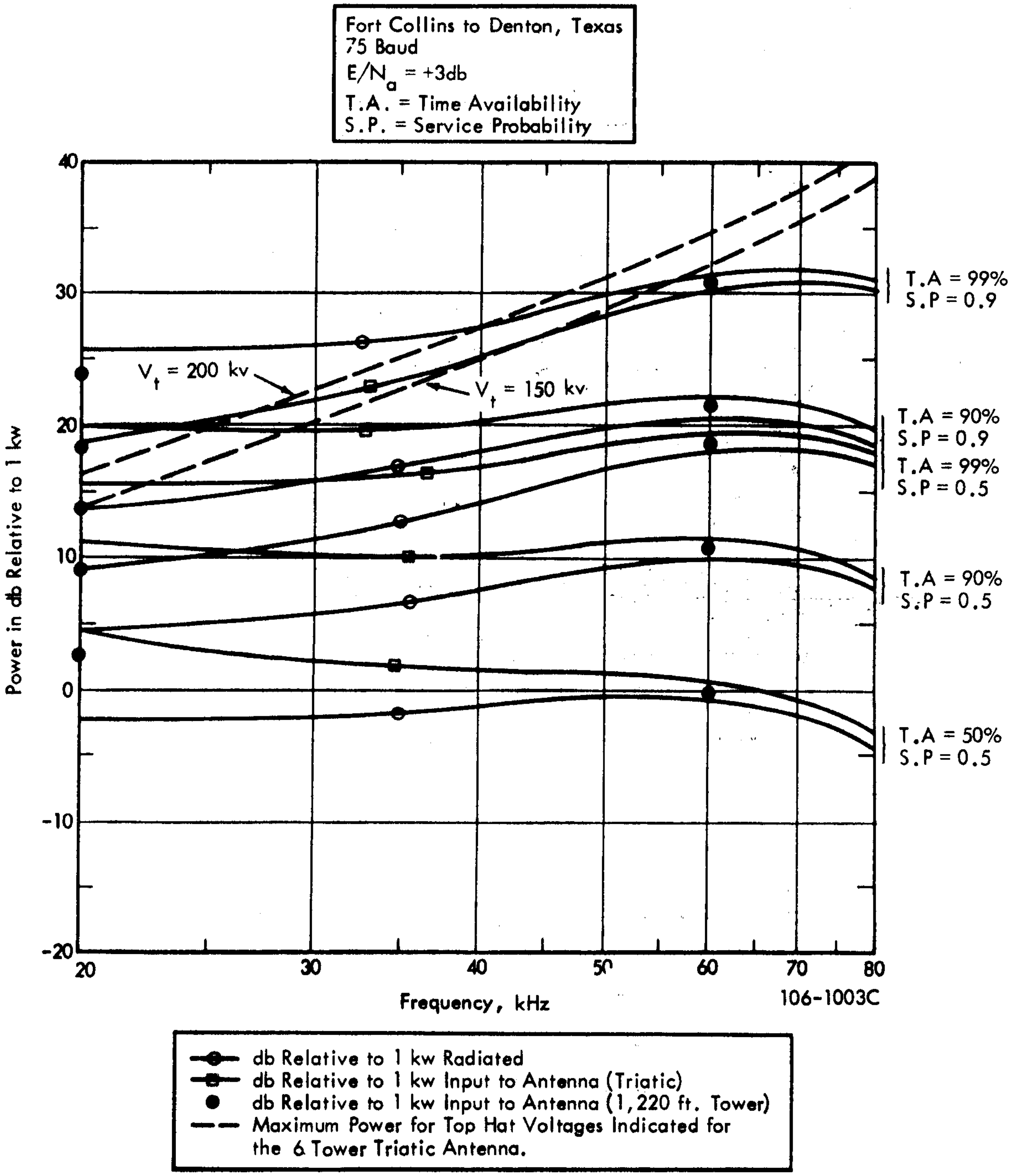

Figure 3-10 Power Requirements vs. Frequency

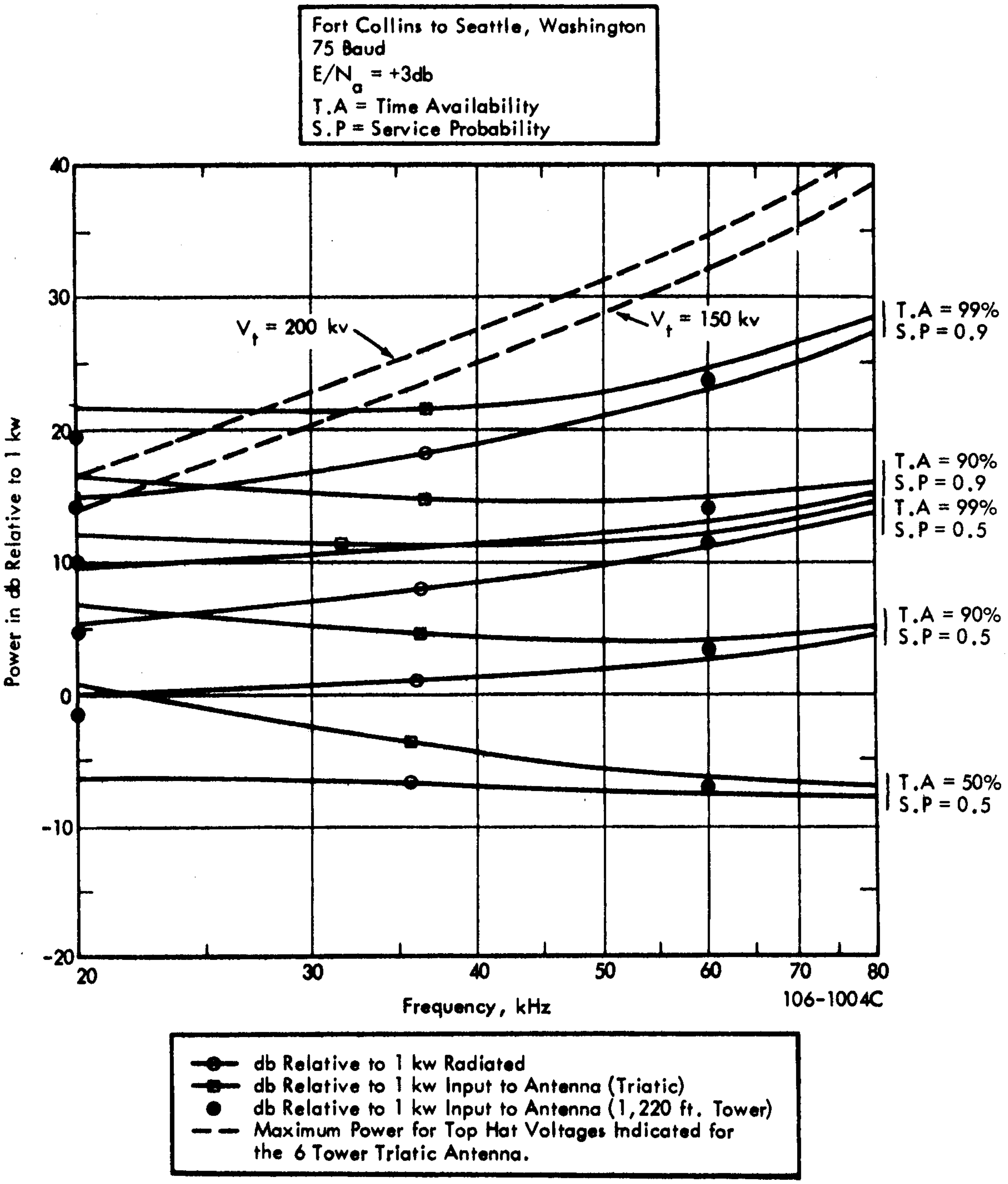

Figure 3-11 Power Requirements vs. Frequency

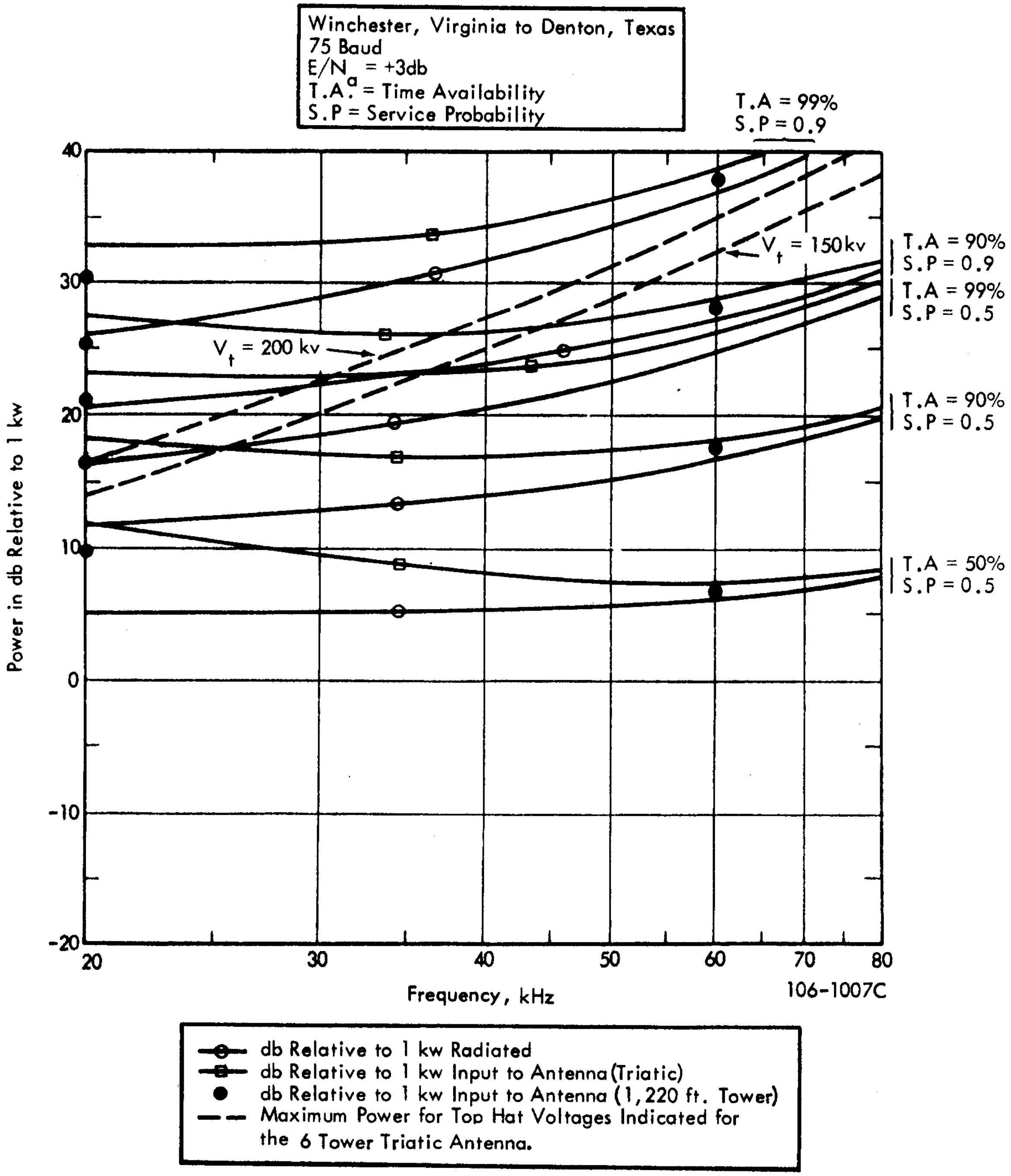

Figure 3-12 Power Requirements vs. Frequency

region where both mode and ray theory have certain limitations, and prediction techniques may not be as reliable as indicated by these curves. Thus it was felt that using a frequency near 60 kHz would be preferable and would minimize the amount of power required to achieve a reasonable confidence in system performanc

Subsequent analysis has assumed an OCD operation near 60 kHz and is limited to the toploaded tower configuration.[*]

Figures 3-7 through 3-12 are plotted for a specific system operating at a data rate of 75 baud and having a E/N_a of +3 db for 0. 1% character errors. Power requirements for other baud and systems with different E/N_a requirements at this error rate can also be determined using Figures 3-13 and 3-14. These show the increase or decrease in power required in db relative to the 75 baud system. Figure 3-13 shows the power trade as a function of transmission rate in baud, and Figure 3-14 gives the power trade as a function of E/N_a.

The following sections describe some of the operational requirements of the OCD system and some techniques for minimizing the power requirements by proper signal design to meet these needs. The performance characteristics of the recommended system are then shown. In Section 3. 5 cost-per-radiated-watt curves are derived for a transmitting facility with a toploaded tower by evaluating the costs of each major section as a function of antenna heights. These curves are then used to determine over-all costs of some typical station configurations. It is then possible to combine this cost information with performance data and make reasonable choices of suitable facilities.

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[*] Actually three different types of antennas were included in the initial studies of optimum frequency, namely the toploaded tower, a triatic type of antenna similar to that used by the Navy at Annapolis, Maryland, and the supported toploaded antenna similar to that used at Cutler, Maine. At a meeting between OCD, NBS, and DECO personnel late in 1965 some cost trades between several antenna configurations were shown. The Cutler type was originally developed for radiating megawatts at frequencies as low as 14 kHz and appeared high in cost relative to the more simple topload tower for a few 100 kw capability at 60 kHz. Similar arguments apply, but to a lesser extent, when comparing costs of the triatic type. Thus only the toploaded tower was considered in later studies once a frequency near 60 kHz was selected and it appeared the radiation requirements would be on the order of hundreds of kilowatts.

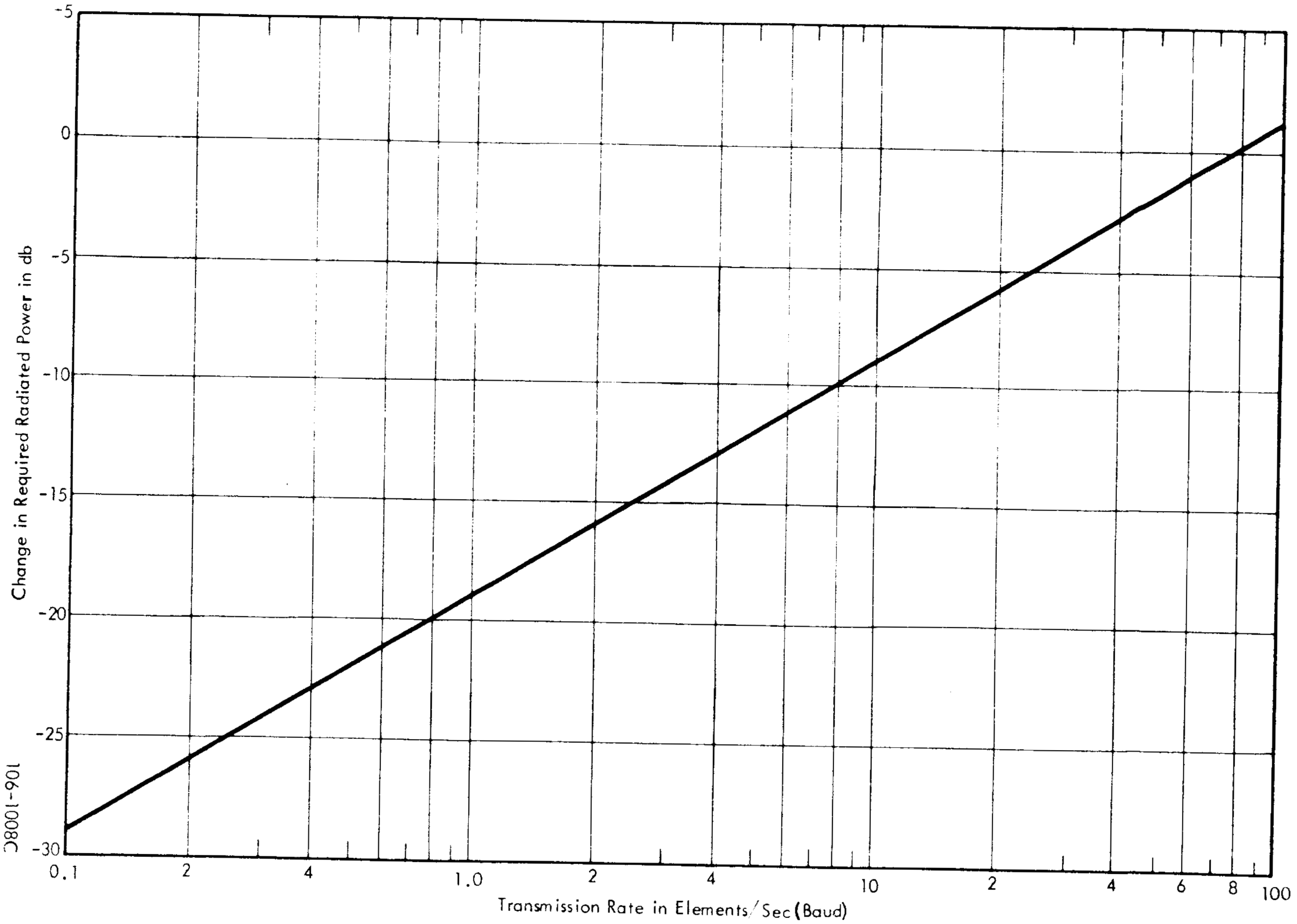

Figure 3-13 Radiated Power and Transmission Rate Trade Relative to System Operating at 75 Baud

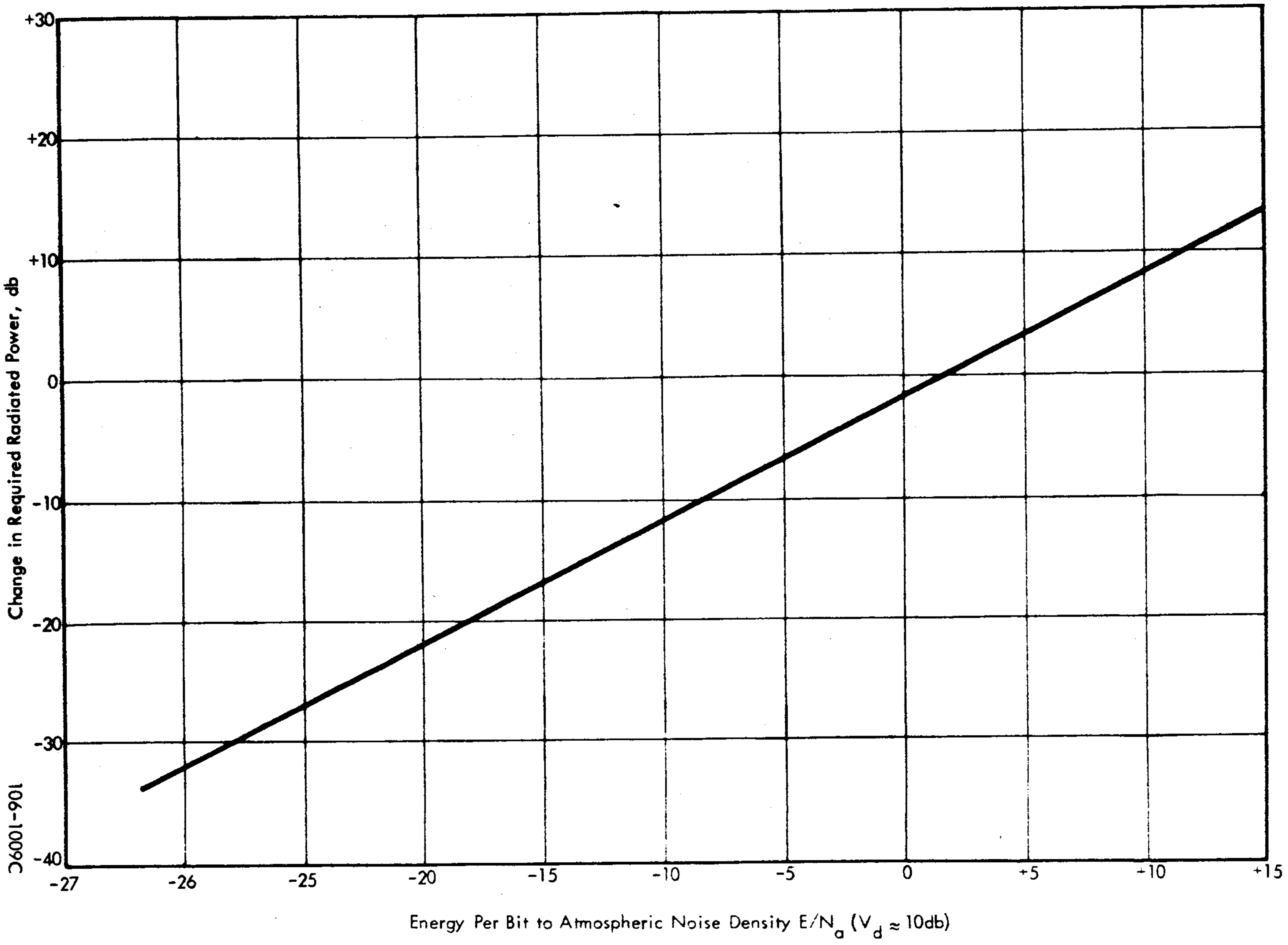

Figure 3-14 Radiated Power and Receiver Performance Trade Relative to Near Optimum System Operating in Atmospheric Noise With Hard Clipping and 0.1% Character Errors

3.3 OCD requirements and system concepts

The OCD operational requirements for a radio warning system involve basically three types of service, namely:

1. A highly reliable switching service. For example, provisions to turn on civil defense warning sirens and operate other automatic portions of the radio warning system from the National Warning Center.
2. Teletype traffic to the civil defense substructure and to federal and state government agencies.
3. Voice information to the general public.

The two stations operating near 60 kHz are expected to provide service of type 1 and 2. Voice service to the public will be supplied by other stations. The highly reliable switching service is the primary link to various warning centers and must be capable of instantaneous service, extremely high time availability and minimum false alarm rate throughout the day and night and for all seasons of the year. The optimum system, which can provide this service at minimum cost, will depend on a number of factors including the total number of different messages required, the time available to send one message, the allowable false alarm rate, the desired reliability, the permissible time availability, the number and location of receivers to which information must be supplied, and the transmitter location and power radiation capabilities. The magnitude of some of these parameters were based on discussions with OCD. Other numerical values were assigned arbitrarily as noted below.

The total number of warning or switching messages required lies somewhere between 16 and 256. The higher number is required if special reliable teletypewriter (TTY) addressing is desired. A maximum time for transmitting one of these messages is 12 seconds. This assumes that transmitter switching has already taken place, but some allowance must still be made for synchronizing and performing other operations. A false alarm rate of 1 in 300 receivers in 3 years and a message reliability of 1 message error in 10,000 are assumed.

Following the warning message the station should be capable of converting to standard TTY format operating at 50 or 75 baud, using 7-unit, start-stop code to transmit general information and instructions to the various agencies. Teletype error rates should be on the order of 0.1% character errors.

It should be noted that the stated or proposed values for service probability, time availability, false alarm rate and probabilities of message and element error apply to the expected condition for only the worst signal-to-noise ratio. Most of the receivers will be situated in a better performance environment, and those in the least favorable locations will see the worst noise conditions only a rather small part of the time.

When the station is normally operated by NBS, periodic tests will be required by OCD. These tests are expected to involve a few minutes out of every one or two hours, and should include the entire line from control center to the station via microwave link and to all reception points.

3.3.1 Coding and modulation

Coding precedes modulation and concerns the choice of means for translating the verbal or numeric information into electrical variations. A code using two or more discrete levels or signals rather than continuous variation improves reliability of reception if bandwidth is restricted, but, more important, it provides for machine operations to be easily understood and carried out at unmanned stations.

Modulation involves the application of the coded message to a carrier wave by varying carrier amplitude, phase or frequency. A choice of carrier frequency often restricts the choice of modulation methods that are practicable. The limitations are generally based on reasonable transmitter and antenna designs and available frequency space. In the vicinity of 60 kHz, transmitter voltage limitations for large radiated powers make practical the use of single channel (or possibly time-multiplexed) frequency-shift keying with phase continuity at element transitions. The system need not be limited to using only two frequencies, however. See Figure 3-15 for an example of coding and modulation.

3.3.2 Information content

To increase the efficiency of information transfer it is necessary to have some measure of the information content of each message that might be sent. Frequently this is rather easy to do if some restricting assumptions can be made. For example, if there is a finite number of possible messages and all messages are equally likely to be sent, the information content of each is:

$$I = \log_2 m \text{ bits}$$

where m is the number of possible messages. If no other factors were to be considered, the most reasonable coding would make all these messages of equal length and complexity.

The simplest example is the binary waveform where a detector must decide whether frequency f_1 or f_2 was sent. If one is as likely as the other to be sent, the information content in each decision is one bit. To build on this example, if there are 32 possible messages the detector must make only $\log_2 (32) = 5$ binary decisions in order to determine which message was sent. (Inversely, with five binary decisions made, up to $2^5 = 32$ combinations or different words may be transmitted.) Of course, if noise is present there is uncertainty in the decision and hence some probability of making one or more decisions incorrectly.

Another possibility would be to send only one of 32 different frequencies. Then there is only one decision to be made, but that decision provides five bits of information. In this case, the detector may have five times as long in which to make the decision and still deliver information at the same rate as for the previous case of five separate decisions. Generally, for a

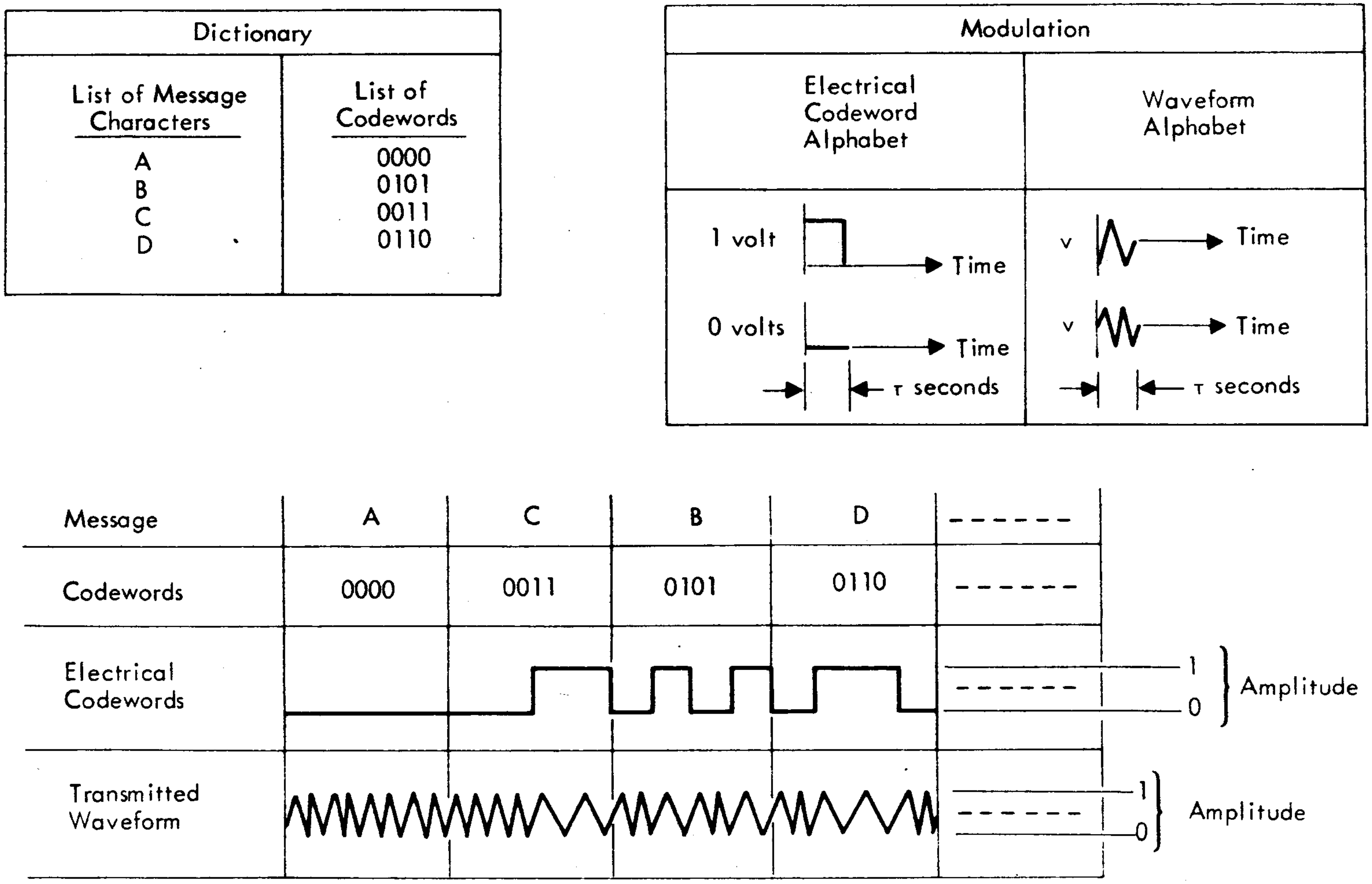

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Figure 3-15 Example of Coding and Modulation given signal-to-noise-density ratio, increased time in which to make the decision can be used to increase the quality of the decision. Conversely, for a given quality of decision, increased decision time will reduce the required signal-to-noise-density ratio.

3.3.3 Some available trade-offs

In order to evaluate various signal designs and detection methods, two ratios will be called upon. The first is signal-to-noise-density ratio, S/N_o where S is average signal power received by the antenna and N_o is the noise power density referred to the same place in the circuit as the signal power measurement. The second ratio is energy-to-noise-density ratio, E/N_o where E is signal energy per bit of information and N_o is as above. The two ratios are related by:

$$\frac{E}{N_o} = \frac{S}{N_o} T$$

where T is the time required to send one bit of information. Consideration of these quantities leads to several useful conclusions. When it is understood that for a given detection scheme an increase in available E/N_o increases the probability of correct decision,

1. Increasing transmitter power is equivalent to increasing the time to send each bit of information (that is, the time in which the detector has to make a decision).
2. The detection method which required the least E/N_o for a given probability of message error is most efficient of transmitter power.

For the data rates that need to be considered here, available bandwidth is not a problem, but in the detection process, reduction of bandwidth (to a minimum of $1/\tau$, where τ is the duration of an element) improves performance by excluding noise.

It was assumed in an example above that all messages that could be sent were equally likely to be sent and thus all were assumed to be equal in length and complexity of coding. Whether or not the messages have equal likelihood, it may be that some messages are more important than others and should have higher probability of correct reception. If a fixed length of time is allowed for each message, the coding of the important messages should be made simpler than for the less important ones; that is, fewer decisions to be made in a given time in order that those decisions may be made more reliably. On the other hand the simpler the message coding the easier it will be for unintentional jamming to cause the received message to be in error or to cause the receiver to believe a message was present when it was not. However, the simpler message need not make it easier for noise to cause mistaken identification of the presence of a message. It can be shown that the use of multiple frequencies reduces the signal-to-noise density requirements for a fixed date rate and grade of service. Details can be found in the bibliography given in Section 3. 7.

3. 3. 4 Detector and signal design considerations

Performance of a detector is related to the accuracy by which the detector knows time respective to the transmitter and path delay or travel time of the signal. Specifically, the decision process in the presence of noise is most reliable if exact phase of the message waveform is known by the detector. Without that much accuracy, the detector may be designed to perform reasonably well if it only knows when each element begins or when the frequency is changed, but the receiver is useless unless it can determine when each word or message began. Each of the time determinations will be referred to as synchronization or sync. That is, phase sync improves performance but is not required, element sync is required to some degree for correct interpretation, and message sync is absolutely required.

A receiver which is not handling continuous traffic or is not in some manner synchronized on the message is at quite a disadvantage and is subject to interpreting noise and interfering signals as message information and producing false alarms. A receiver designed to react with a binary decision to whatever it receives will produce a random stream of such decisions. There is some probability that a sequence of such decisions will look like some particular message. For example, if a 50 baud, 7-unit teletype printer is operated entirely by noise it will print any particular sequence of three letters or symbols an average of once every three hours and in the process use yards of paper. For 100 such printers the false alarm would be produced at an average rate of one every two minutes.

If additional factors are considered such as setting threshold levels or sending added, redundant symbols and if more sophisticated processing is applied to the detector output, the probability of false alarm may be made arbitrarily small, but with added cost and possibly some sacrifice in allowable minimum S/N_o.

Some consideration should be given to coding in such a way that unintentional interfering signals are not likely to be interpreted as messages. This is generally not difficult if intuitive notions are used. If there is a possibility of intentional interference or intelligent jamming the problems are complicated but also solvable.

3.3.5 Characteristics of some practical systems

It is useful to compare several general ways the coding might be handled and the advantages and disadvantages that obtain for a particular case. The assumed conditions upon the message and detector are as follows:

1. It will be assumed that there are 256 separate functions which may be sent, including address and message. Each message may be considered to contain $\log_2 256 = 8$ bits of information.

2. The maximum total time for message or information transfer will be eight seconds. This excludes time for alerting and synchronizing receivers and time for the receiver to operate upon and translate the received message.

3. The receiver will not know time accurately enough to synchronize on signal phase, but it will know the beginning and duration of elements. This requires knowing the start of each element accurate to about one-tenth of the element duration.

4. Since the receiver does not know when a message will begin, it must not misinterpret environmental noise as a message. It will be arbitrarily required that less than once in three years will one of 300 such receivers produce a false alarm by interpreting the noise as any of the 256 possible messages. In practice, the receivers in fringe areas will be most susceptible to error and particularly during times of the year when the signal-to-noise ratio is the worst. The frequency of false alarms is still expected to be in proportion to the total number of receivers, if the threshold is determined by noise only.

5. It will be assumed that the receiver must be able to recognize the presence of a message and find the most probable beginning and end for the message. There is, then, some probability of message recognition which is the probability that if a message is present, the receiver will correctly recognize the fact. This may be a different number, in general, from the probability that the message is correctly translated. It is assumed that the receiver must recognize the presence of a message and translate it with a probability of error of only one in 10, 000.

Two general types of coding will be compared below and discussed in terms of preventing false alarms.

(a) Sending 50 baud teletype, two letters or characters comprising a message.

    (1) To detect the presence of a message and prevent false alarms, a certain sequence may be sent to alert the receiver to the fact that a message is coming.

    (2) Alternatively, false alarms may be avoided if the average signal levels are compared to noise to watch for exceedance of a threshold value.

(b) Sending only one 8-bit word to represent one of the 256 possible messages, and utilizing more of the allowed message time to improve reliability.

(1) Eight binary decisions could be required; one of four frequencies could be used requiring four decisions, or one of 16 frequencies could be used requiring only two decisions.

(2) Again a threshold would be established which average signal levels must exceed.

The following table compares the required S/N_o for message error probabilities of 10^{-4} and false alarm rates of one receiver (of 300) in three years. Allowed message transmission time is eight seconds.

TABLE 3.3.5

System	S/N_o, db (Message Reliability)	S/N_o db (False Alarm Prevention)	Number of Possible Messages
Teletype, 7-unit, 50 baud			
1. Alert message & two characters	32.4	32.4	$32^8 \simeq 1.1\,(10)^{12}$
2. Two character sequence	32.0	24.0	$32^2 = 1024$
One 8-bit word			
1. Binary; 8 decisions	13.3	8.0	$2^8 = 256$
2. Quarternary; 4 decisions	10.4	6.7	$4^4 = 256$
3. 16-ary; 2 decisions	7.8	6.0	$16^2 = 256$

Three important general principles follow which are useful in this situation where messages are infrequent, transmitted in a fixed length of time and require high reliability.

1. Do not send more information than necessary. With n binary elements, 2^n different messages could be sent. Conversely, average information content of each of m messages is

$$I = \log_2 m \text{ bits.}$$

2. Allow as long as possible to make each decision. If good detection methods are used, transmitter power required for a fixed message

reliability is approximately inversely proportional to time, τ_d, available to make a decision.

$$S/N_o \cong \frac{K_1}{\tau_d} \quad \text{for message reliability.}$$

Figures 3-16 and 3-17 show the relationship between the number of possible messages, time to send the message and S/N_o required for message errors of 1 in 10,000.

3. Set some threshold which signal must exceed for a message to be recognized. Establishment of a threshold requires an S/N_o value which is approximately inversely proportional to total message time.

$$S/N_o \cong \frac{K_1}{\tau_m} \quad \text{for low false alarm rate.}$$

Required S/N_o increases slightly as the number of decisions increases, as shown by Figure 3-18 and also the preceding table, but that effect is secondary.

As an example relating to the conclusions above, if an alerting message like that mentioned for teletype operation were used to prevent false alarm and if it were followed by a sequence of eight message bits, instead of two teletype characters, a S/N_o of 13.3 db would be adequate to achieve message reliability if 58 seconds were used to send the whole sequence. In other words, it would require 58 times as long for each decision as for decisions at the 50 baud rate. In addition, just to prevent false alarm, many more elements were sent than were required for message information. The threshold method of preventing false alarm is much more conservative of time and signal power.

3.3.6 Performance of certain systems in atmospheric noise

The radiated power required to achieve a certain quality of message reception depends on the available energy per bit of information relative to the noise power spectral density at a reception point and the ability of the receiver to make correct decisions under these conditions. The available

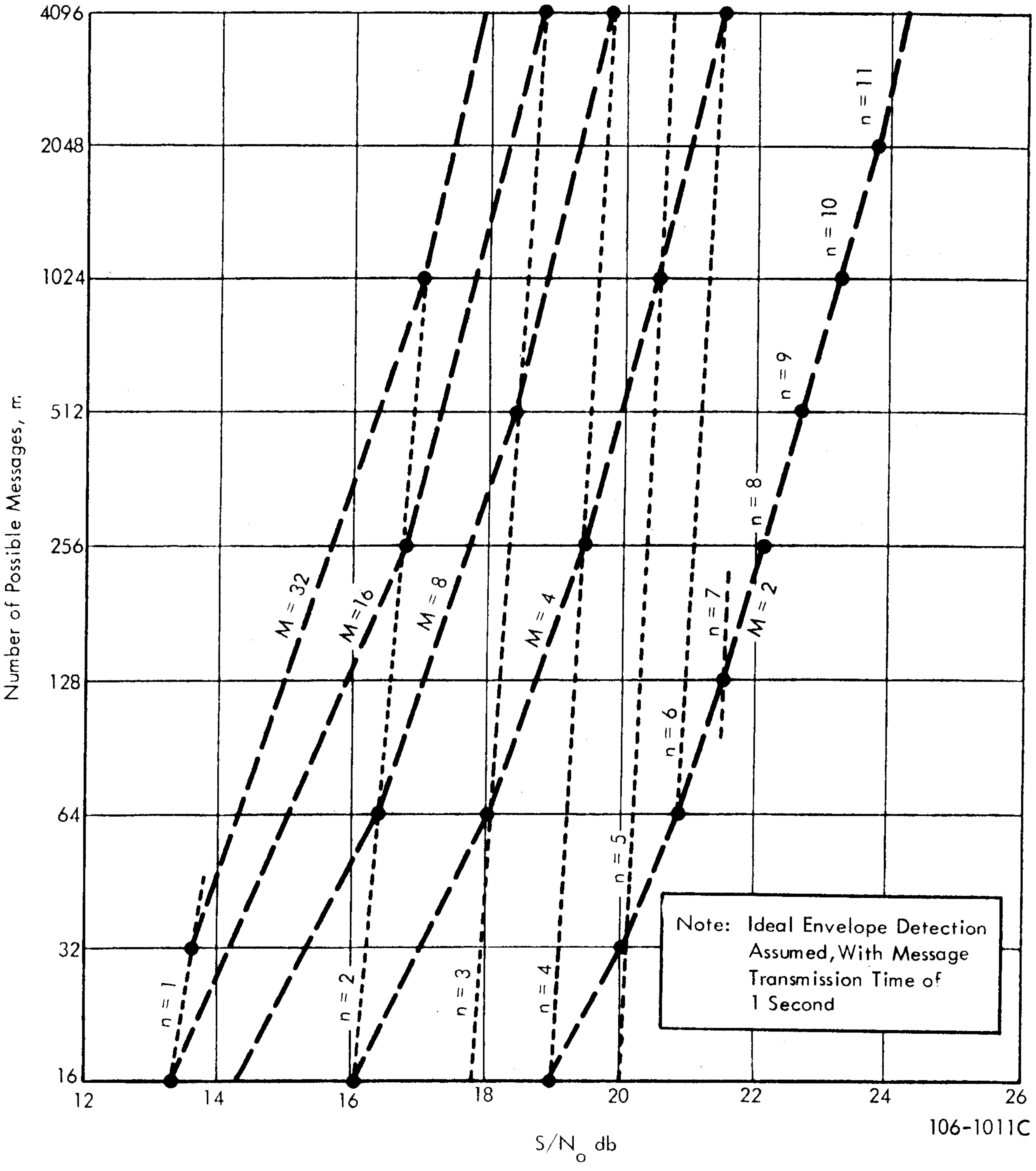

Figure 3-16 Number of Possible Messages, m; Number of Different Frequencies M; Elements in the Message n; and Required Signal-to-Noise-Density for Probability of Message Error Equal to 10^{-4}

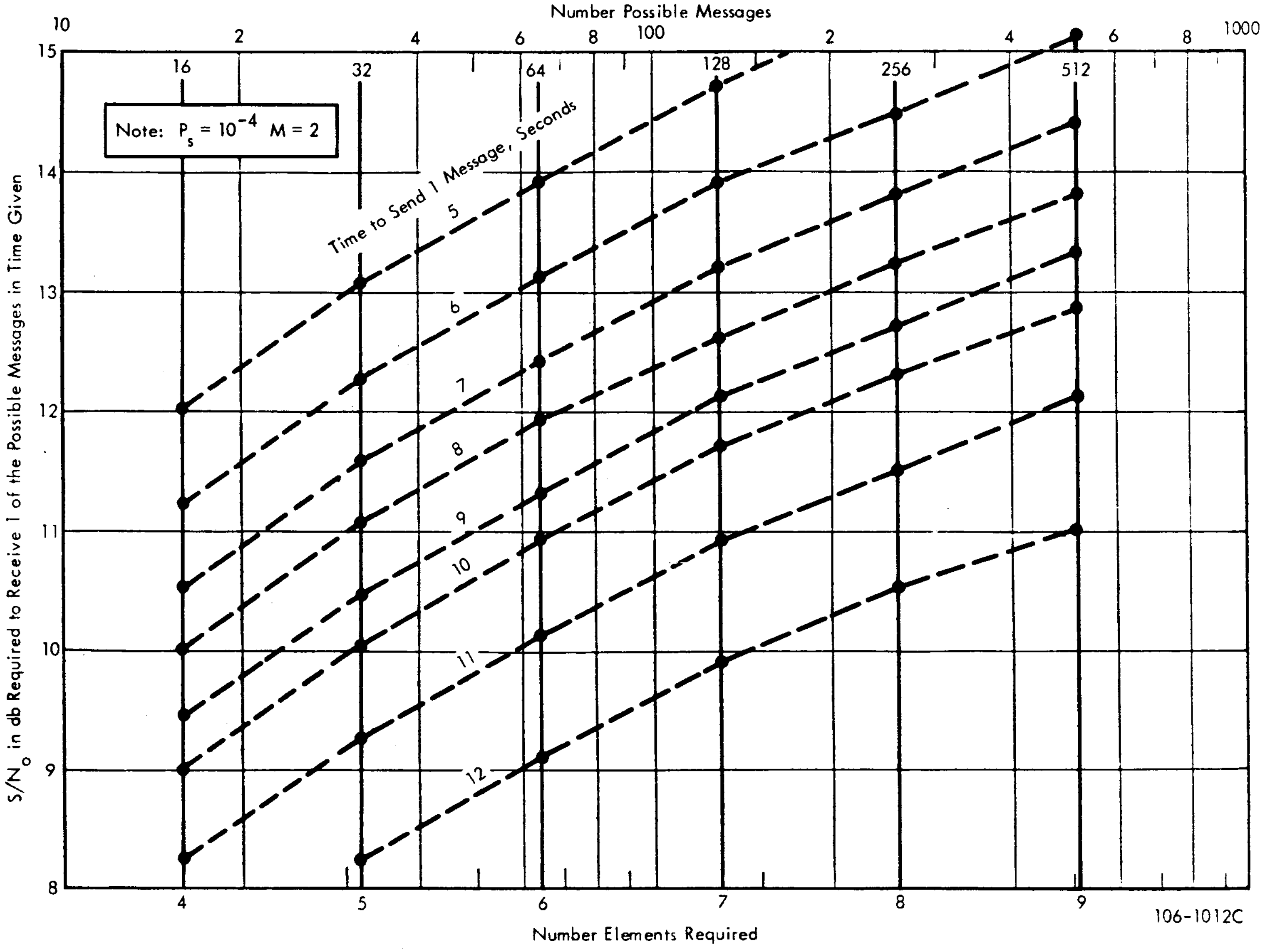

Figure 3-17 Relation of Message Time and Required Signal-to-Noise-Density

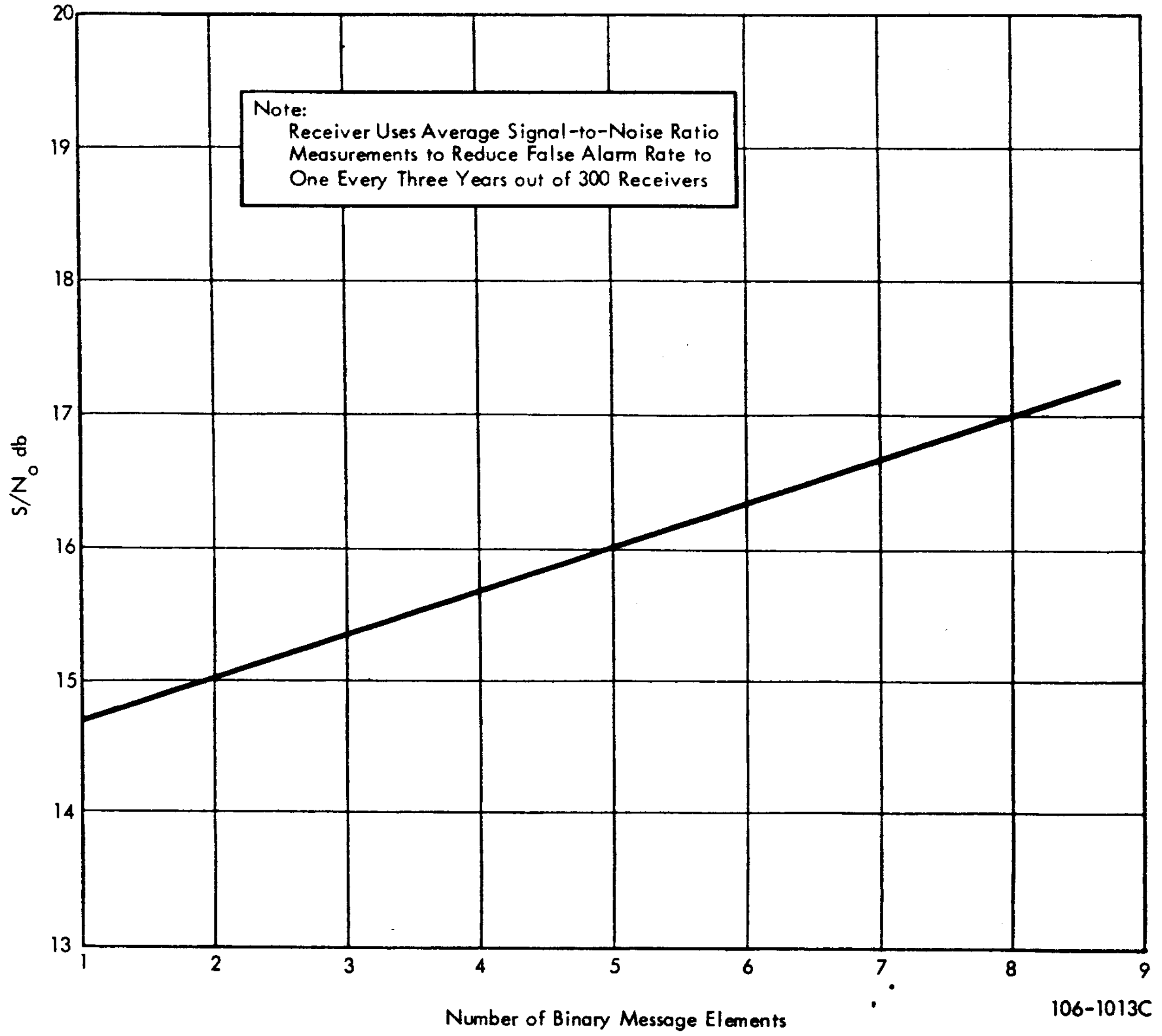

Figure 3-18 Required Signal-to-Noise Density Ratio as a Function of Message Length for Message Recognition

signal-energy-to-noise-power density ratio, E/N_o, can be determined from measurements or prediction. E depends on the information rate, the radiated signal power and the characteristics of the propagating medium. The noise at VLF and LF is primarily atmospheric noise with statistical characteristics determined by world-wide thunderstorm activity and the geographic location of the receiver.

The E/N required by a receiver to achieve a given reliability depends on signal design and the detection methods used. E/N for different systems operating in Gaussian noise can be determined theoretically and also demonstrated with practical systems. See Section 3. 2. 3. However, the E/N_a required by a receiver operating in atmospheric noise may be quite different. With a linear receiver the E/N_a can be made to approach, but never be less than, that obtained in Gaussian noise. This is accomplished by a reduction in information rate and thus reception bandwidth. With noise reduction circuits, however (and this generally implies a nonlinear receiver), the E/N_a required for a given error rate may be considerably less than that achieved in Gaussian noise. The amount of improvement depends primarily on (1) the input noise characteristics; (2) the presuppression and post suppression bandwidths; (3) the suppression technique itself; (4) the detection scheme, and (5) interfering signal levels. It is useful to demonstrate the improvement in required E/N_a which can be realized under typical conditions.

The rms value, N_a, and form factor, V_d, of the input noise envelope will be used to describe the noise. A V_d = 10 db in a presuppression bandwidth of 300 Hz is typical and will be used for comparison purposes. The presuppression to post suppression bandwidth ratio is assumed to be 10 or more. A simple symmetrical clipping circuit is employed. This normally gives good suppression if the noise voltage is clipped 10 percent or more of the time. The effects of using different detection schemes are not large and will be neglected. Interfering signals will be assumed nonexistent, but it must be noted that most suppression techniques require wide input bandwidths and therefore are quite susceptible to interference. Results are shown for two types of 50 baud, 7-unit code teletype systems operating with 0.1 percent character errors and for one highly reliable warning system using one eight-bit word to send one of 256 possible messages in eight seconds with a message error probability of 10^{-4} and a false alarm rate of one receiver out of 300 in three years.

TABLE 3.3.6

System	Code	Baud	Error Rate	E/N_o (Gaussian)	E/N_a (Atmos.)	S/N_a
TTY (correlation detector, $m_f = \frac{1}{2}$)	7 unit (start-stop)	50	$P_c = 10^{-3}$	8 db	1 db	16.5 db
TTY (non-coherent, $m_f = 1$ or $\frac{1}{2}$)	7 unit (start-stop)	50	$P_c = 10^{-3}$	12 db	5 db	20.5 db
8-bit word	8 unit (synchronous)	1	$p_s = 10^{-4}$	13 db	3 db	3.0 db

The improvement noted for atmospheric noise is a conservative estimate based on an input noise with $V_d = 10$ db and clipping 10 percent or more of the time. The last column indicates the S/N_a required to obtain the grade of service indicated. The S/N_a which must be available can be obtained from the predicted values of E/N_a and the information rate since

$$E/N_a = \frac{ST}{N_a}$$

where T is the time required to send one bit of information. For the worst case paths the $\overline{S}/\overline{N}_a$ has been predicted assuming 1 kw radiated as follows:

	$\overline{S}/\overline{N}_a$
Fort Collins to Denton, Texas	21.5 db
Winchester to Denton, Texas	15.5 db
Either transmitter to south Louisiana	13.5 db

This is for a summer daytime path during the worst time block 1200 - 1600. These, of course, are the mean values and do not necessarily exist at all times. The percent of time during which a given $\overline{S}/\overline{N}_a$ ratio is available or exceeded, i.e., the time availability, is a function of the variations of the signal and noise with time and can be estimated. The probability that the given $\overline{S}/\overline{N}_a$ of better will be available involves the predictability or service probability of S/N_a. Generally, the service probability can be improved (greater confidence in the predicted time availability) by actual path measurements. Such measurement, however, must cover all seasons of the year and many paths in the coverage area.

Because of their statistical nature, it is possible to interrelate time availability and service probability and this is a convenient method of characterizing the performance of a system. (See Section 3.2.) Figure 3-19 shows the percent time availability versus service probability for a 60 kHz circuit during the worst-case noise time block. Curves are given parametric in relative radiated power expressed in db for a typical summer daytime path.

3.4 Radiated power, requirements and performance characterizations

Using the curves of Section 3.3.6, the S/N_a required by a particular receiver and the $\overline{S}/\overline{N}_a$ available over a particular path it is now possible to characterize some actual systems.

Results are shown in Figure 3-20 for the three types of systems given in Table 3.3.6 and for reception in southern Louisiana. This reception area is approximately equidistant from the Fort Collins and the Winchester transmitters. It becomes obvious that the reliability required for the 50-baud teletype circuit may be a determining factor in choice of radiated power.

For 500 kw radiated and a reasonable value of 0.9 for service probability the highly reliable 1-baud circuit has a time availability of about 99.97 percent for the worst-case noise time block. The best 50-baud teletype circuit for this same path and time has a time availability of 96.5 percent.

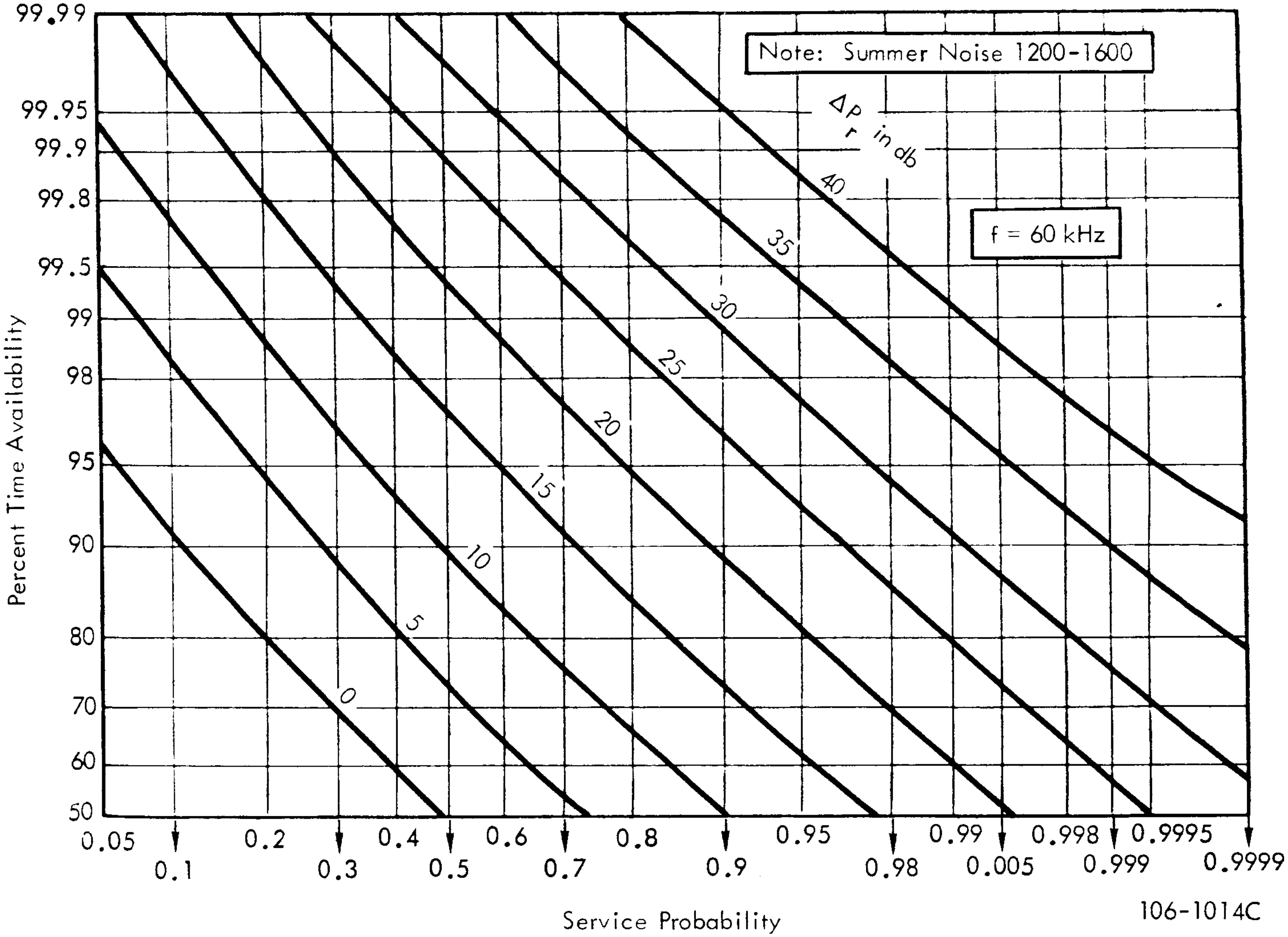

Figure 3-19 Time Availability vs. Service Probability for 60 kHz

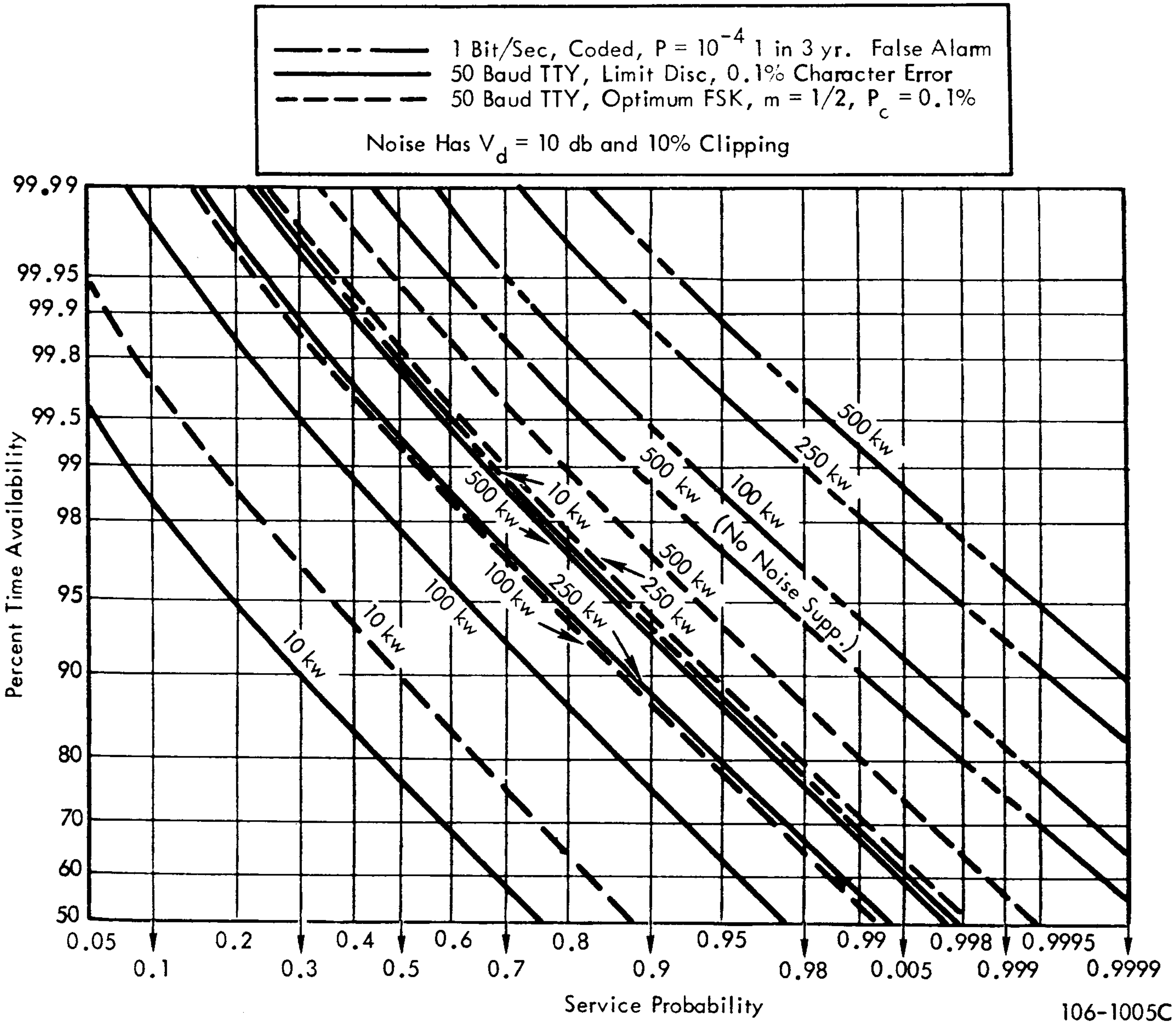

Figure 3-20 Time Availability - Service Probability Trade-Off for Different Transmitter Powers, Codes and Detectors

It is interesting to note that for the case where an interfering signal prohibits the use of noise suppression, the minimum E/N_a is 13 db for the high reliability circuit. The T.A. versus S.P. for this case is also shown on Figure 3-20 for 500 kw radiated. Time availability for 0.9 service probability and 500 kw radiated is now reduced to 98.8% from the suppressed noise value of 99.97%.

3.5 Radiation system

3.5.1 Antenna design

The antenna characteristics were obtained by scaling data obtained from modeling a 1200' toploaded tower. The frequency and effective height dependency of some of the parameters are tabulated below.

Radiation resistance $R_r \propto f^2 h_e^2$

Copper loss $R_{cu} \propto f^{1/2} h_e$

Ground loss $R_g \propto f^{1/2} h_e^2$

Dielectric loss $R_{di} \propto f^{-1}$

Helix loss $R_h \propto f^{-1} h_e^{-1}$

The Q of the antenna tuning inductor was assumed to be constant at 1300 and constant with frequency. A fixed antenna configuration was assumed with $h_e \propto s$ and $C_a \propto s$, when antenna size varies in all linear dimensions with scale factor s.

The radiated power in kw is given by;

$$P_r = 2.82 \times 10^{-13} V_t^2 C^2 h_e^2 f_r^2 f^2 \sin^2(\pi/2 \cdot f/f_r)$$

and the antenna system bandwidth by;

$$b_{as}(3\text{ db}) = 1.11 \times 10^{-13} C h_e^2 f^4/\eta_{as}$$

and antenna system efficiency;

$$\eta_{as} = \frac{R_r}{R_r + R_{cu} + R_g + R_{di} + R_h}$$

where MKS units are used.

The ratio of actual height to effective height was determined from modeling data, and is given by

$$\frac{h_a}{h_e} \doteq 1.575.$$

The antenna capacitance for various heights is tabulated below.

h_a (ft.)	h_e(meters)	C_a (μfds.)
206	40	.0025
284	55	.0034
387	75	.0047
516	100	.0062
725	140	.0087
1060	200	.0123
1550	300	.0190

For these values of h_e and C_a and a fixed frequency, it is possible to calculate the voltage-limited radiation capability of the antenna versus actual height. This is shown in Figure 3-21 for 20 kHz and 60 kHz and for 50, 100, 150 and 200 kv voltage limits. The bandwidth and efficiency versus height for 20 and 60 kHz curves are shown in Figure 3-22. Capacitance, effective height and radiation resistance versus actual height are given in Figure 3-23.

Using Figure 3-21, it is possible to choose antenna heights which are capable of meeting various combinations of radiated power capabilities at one or both frequencies and then to develop costs versus antenna heights by combining this with the corresponding efficiency curves to determine

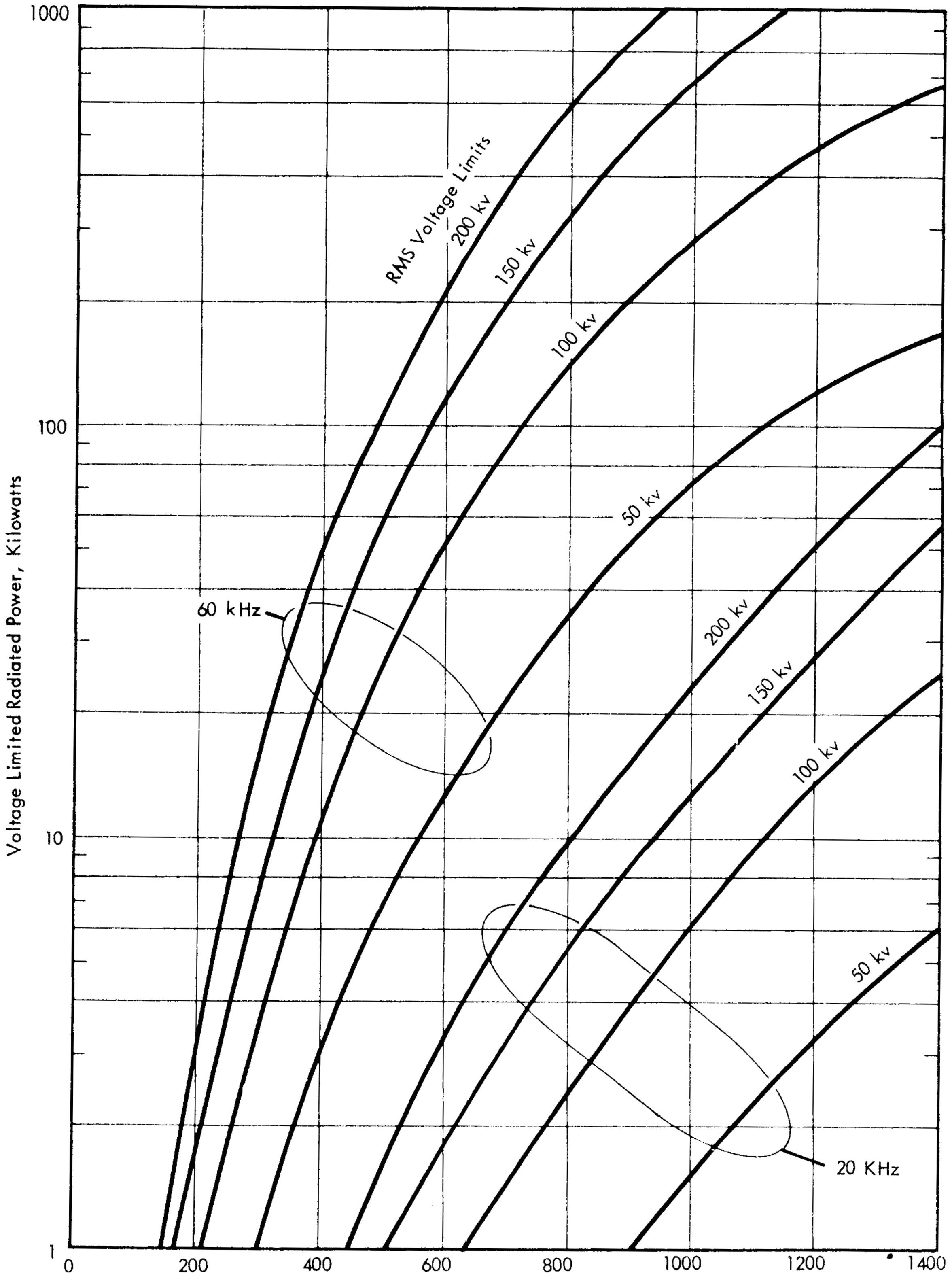

Figure 3-21 Radiation Capabilities vs. Tower Height (Assumes Top Loading Consisting of 16 Radials)

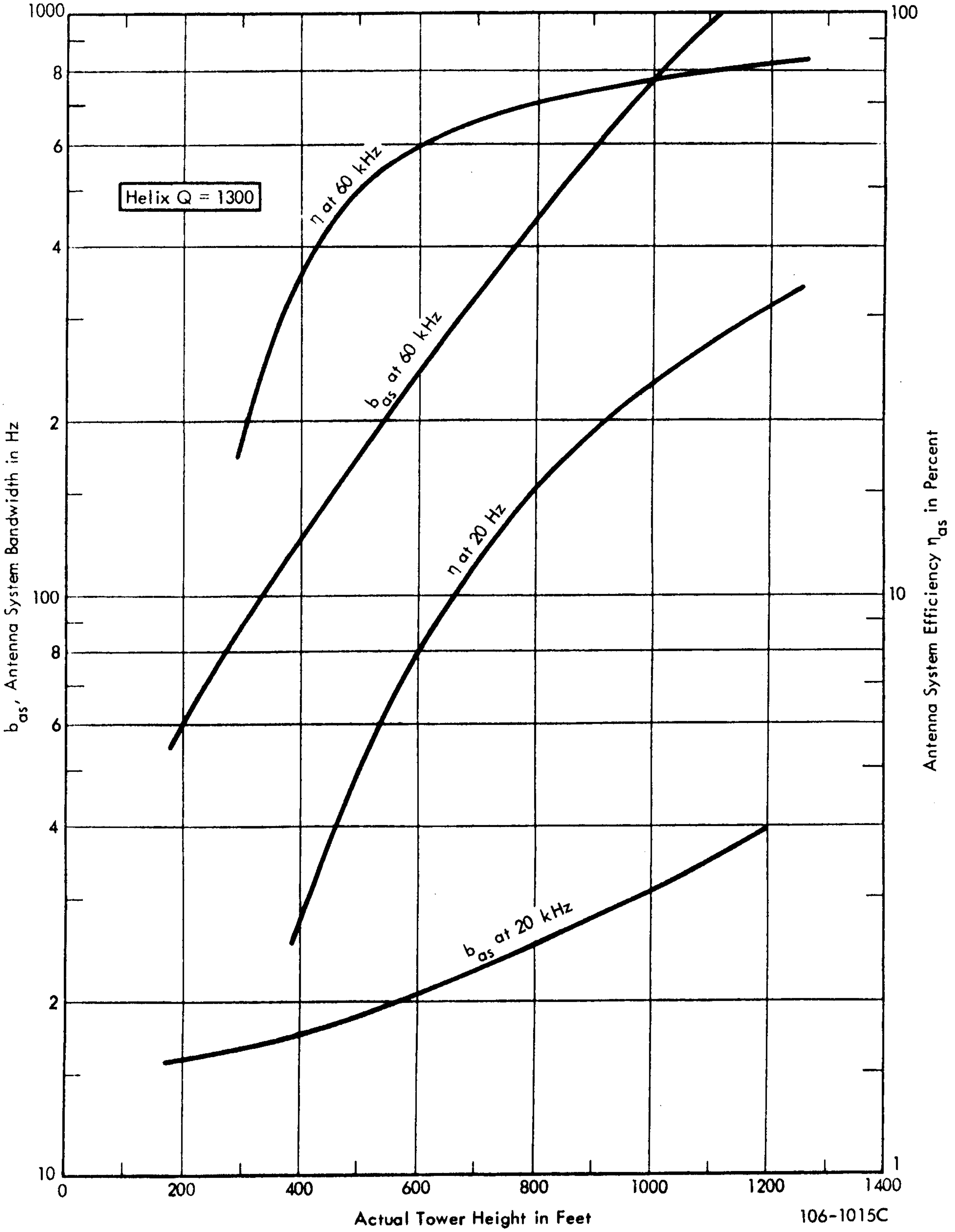

Figure 3-22 Antenna System Bandwidth and Efficiency

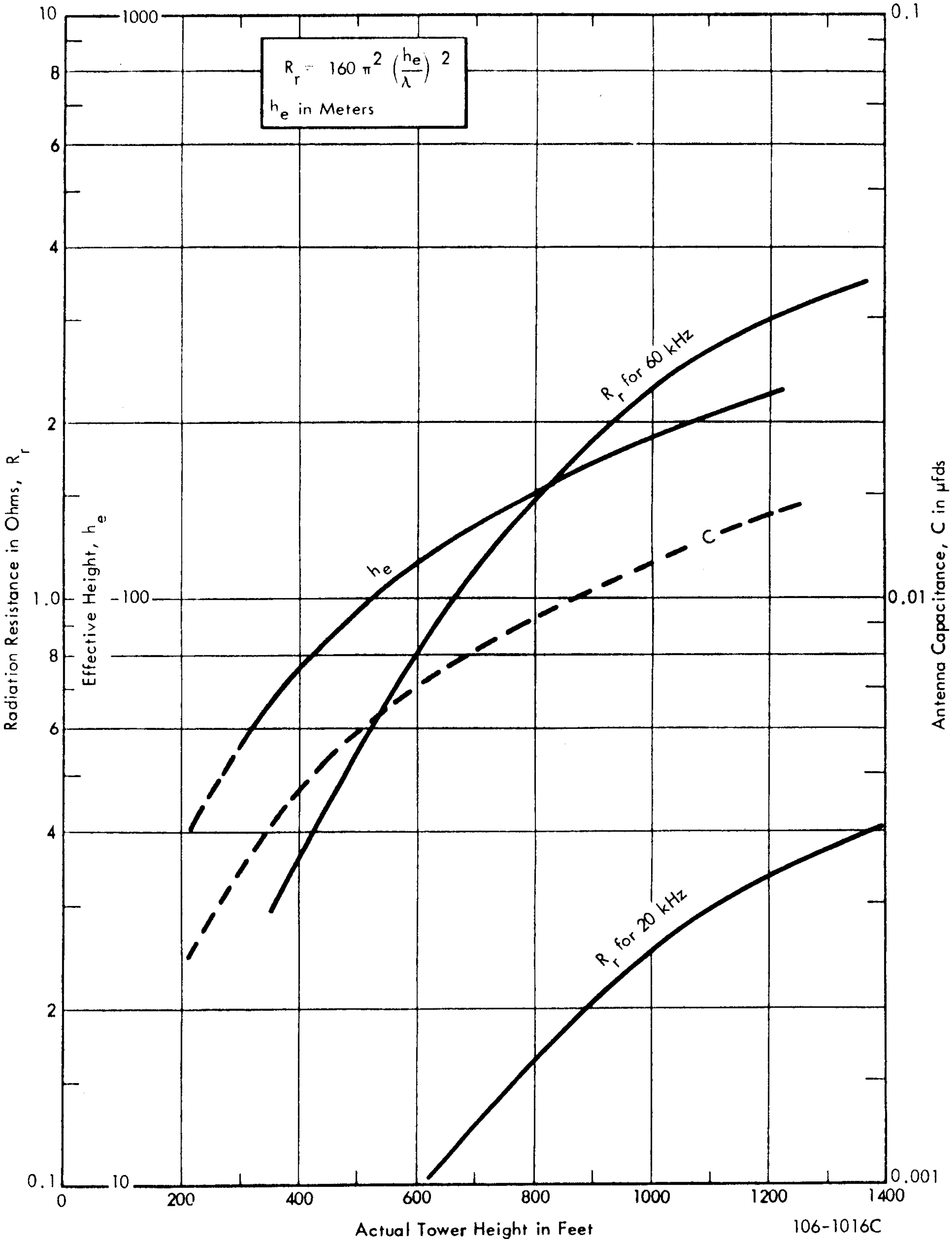

Figure 3-23 Radiation Resistance, Capacitance, and Effective Height of Antenna

transmitter requirements. This is done in Section 3.6.2 for several possible combinations of joint NBS/OCD operations and also for stations meeting only OCD requirements.

3.5.2 Ground system design and cost considerations

This cost analysis assumes a simple ground screen configuration consisting of N radial wires with length L and uniform angular spacing throughout. The length and number of wires were allowed to vary to find minimum cost solutions for different values of ground conductivity. A fixed total effective ground loss resistance of 0.1 ohm was allowed and is consistant with the antenna system efficiencies given previously.

Two solutions arise; one achieves a minimum wire length and cost of wire placement, while the other, more pertinent solution, gives minimum total cost, including land. Because land cost varies as L^2 while wire cost is proportional to L, the land cost controls if the unit cost is greater than $50 an acre. Thus the total required wire length passes through an actual minimum within the range of allowed values of L and N. The minimum total cost, however, is found for the least amount of land that can be used and still have the ground resistance less than 0.1 ohm. The required land was assumed to be a square area 2L on each side. The two solutions are shown in Figure 3-24 as a function of ground conductivity.

The total cost of land and ground system is shown by Figure 3-25 as it varies with unit cost of land. Actual practical designs may have the number of radials change beyond some given distance from the center, but in such a case the cost figures given here would probably be affected by only a small percentage.

3.6 Cost trades

The economics of a communication service play a large part in selecting the means to provide that service. The reliability or grade of service will be determined by the radiated signaling power of the transmitter

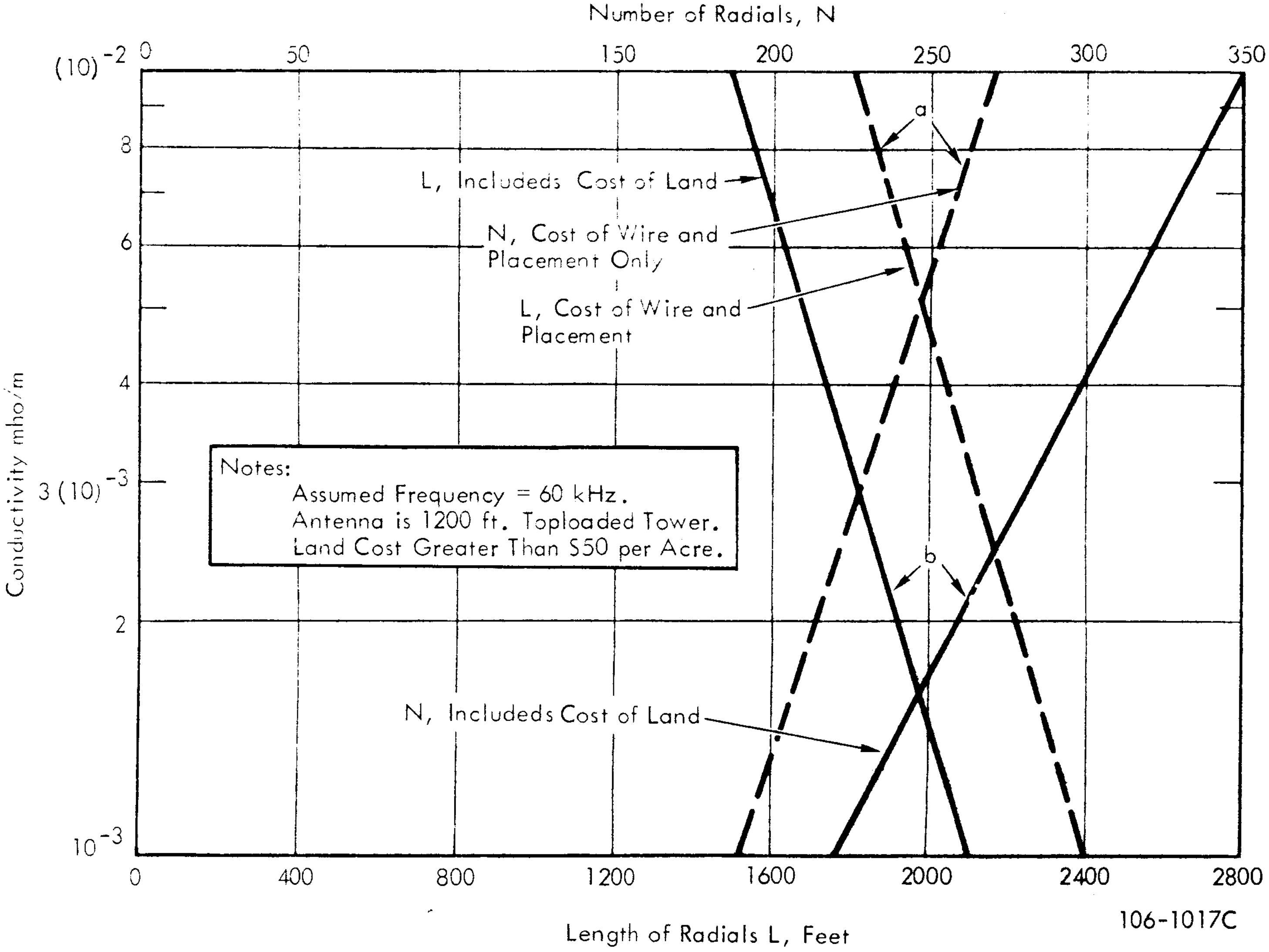

Figure 3-24 Ground Configuration to: (a) Minimize Cost of Wire Only
(b) Minimize Total Cost, Wire and Land Area

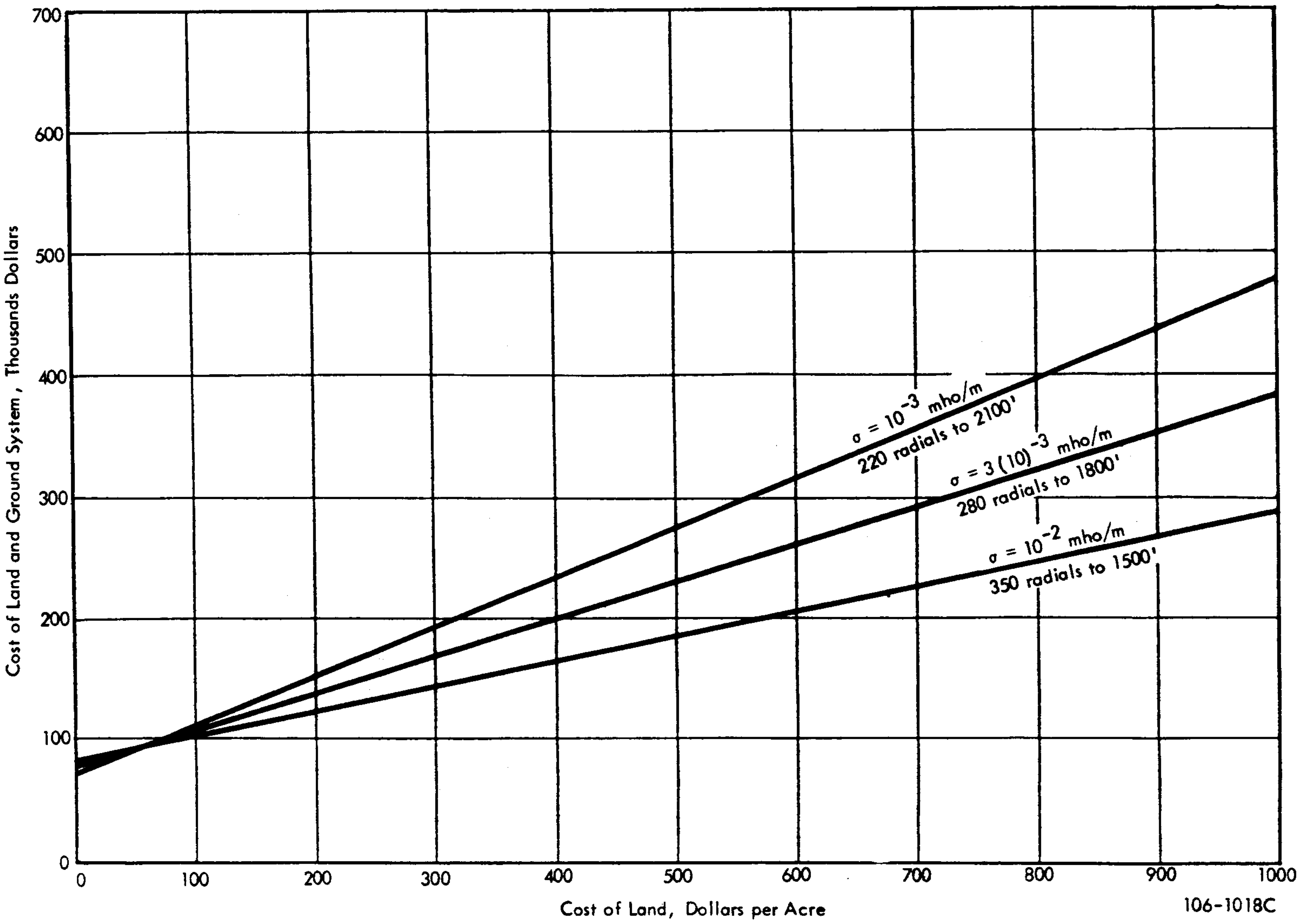

Figure 3-25 Ground System Cost and Configuration for Total Ground Resistance = 0.1 ohm at 60 KHz., 1200 ft. Tower

and the performance characterization of the receiver. Increasing the capabilities of the transmitter, the receiver or both generally implies an increase in costs. It is useful to examine these costs and note the economic trade-offs available between increasing power at the transmitter and increasing performance at the receiver.

Since the concern here is also a possible joint use of the facility by NBS and OCD, the relative costs for this joint type of service must also be examined in order to arrive at the most economical station which meets the needs of both users.

3.6.1 Basis for cost estimates

These budget estimates are based on experience at DECO with such stations as VLF PAC, Omega-Trinidad, Omega-Haiku, Omega-Norway, Air Force SLFCS (487L), and Cutler, Maine, The station costs are a tentative estimate based on a preliminary engineering phase of the station design. The relative costs of different station configurations are quite useful in determining the minimum cost station which meets the desired operational capabilities. Because of certain factors, the absolute costs may vary from those given here and in some cases by a considerable amount. Average or typical values have been used. For instance, the station ground system cost is a function of the land area and the number of radials required to meet a specified ground plane resistance, and this will depend on the site chosen. Land costs are difficult to predict accurately. The antenna system itself may cost less than estimated here because of present development work. All the estimates are believed to be fairly conservative. Allowances have been made for the following items.

1. Detailed plans and specifications.
2. Acceptance testing.
3. Sufficient redundancy to insure high component reliability.

4. Extremely reliable OCD warning, although possibly at reduced power if a power amplifier module fails.
5. Most items include a contingency to cover unforeseen requirements.

Items not included are:

1. Personnel support facilities.
2. Allowance for proof testing.
3. Budget factor to allow for inflationary trends. 1966 U.S. dollars were assumed.

3.6.2 Station cost breakdown

The costs involved in the station can be broken into several major categories each a function of the actual height of the antenna employed. These major breakdowns are antenna, ground system, including land area, tuning inductance with enclosure, transmitter power amplifier, transmitter building and auxiliary equipment, and auxiliary power costs.

Land costs are difficult to assess, being dependent on the location chosen and the site conductivity, since poor conductivity would require that a greater area be covered by the ground system. The required area is related also to tower height, and for this tower configuration the area can be assumed to be a square which encloses the circular ground system. A poor conductivity, 0.001 mho/meter, and expensive land are assumed here for cost purposes. As shown by Figure 3-25, an improvement in conductivity by a factor of 10 and reduction in land cost to $500 per acre would result in half the ground system cost, or a reduction of 13 percent in total estimated cost.

For 0.001 mho/m ground, the required land area is $3.5\ h_a$ on a side, where h_a is the actual antenna height. Thus, the area in square feet is given by

$$\text{Area in square feet} = (3.5\ h_a)^2$$

where h_a is in feet.

The area required in acres is then

$$A = 12.25\, h_a^2 \times 2.296 \times 10^{-5} \approx 2.8 \times 10^{-4}\, h_a^2 \,.$$

Figure 3-26 shows the total land costs for typical costs/acre. Estimated antenna and ground system costs versus antenna height are shown in Figure 3-27. The antenna costs include the tower, feed system, guys, top hat, insulators, foundation, anchors and installation costs. They are shown parametric in rms voltage limits.

The tuning inductor and enclosure costs are given in Figure 3-28 for 20 kHz and 60 kHz. For joint operation two inductors will be required, but the major costs are involved in the lower frequency unit. It is assumed that helix Q's on the order of 1000 - 1500 are required.

Transmitter power amplifier costs per radiated watt versus antenna height were obtained starting with the basic assumption of $2 per watt of amplifier output power. This is a typical installed cost for either air-cooled, vacuum-tube power amplifier, or liquid-cooled, solid-state units. The curve actually shows costs per radiated watt and accounts for variations in antenna system efficiency with antenna height at 20 kHz and 60kHz. This cost per radiated watt is given by

$$\text{Dollar cost per radiated watt} = \frac{\$2}{\eta_{as}}$$

where η_{as} is the antenna system efficiency at a given frequency and antenna height. This is shown in Figure 3-29.

The transmitter building and auxiliary equipment costs in dollars per radiated watt versus antenna height are given in Figure 3-30. These costs can be expected to be related to required transmitter output power. This, in turn, is related to radiated power by the antenna system efficiency which is a function of frequency. Examination of the costs of other stations such as

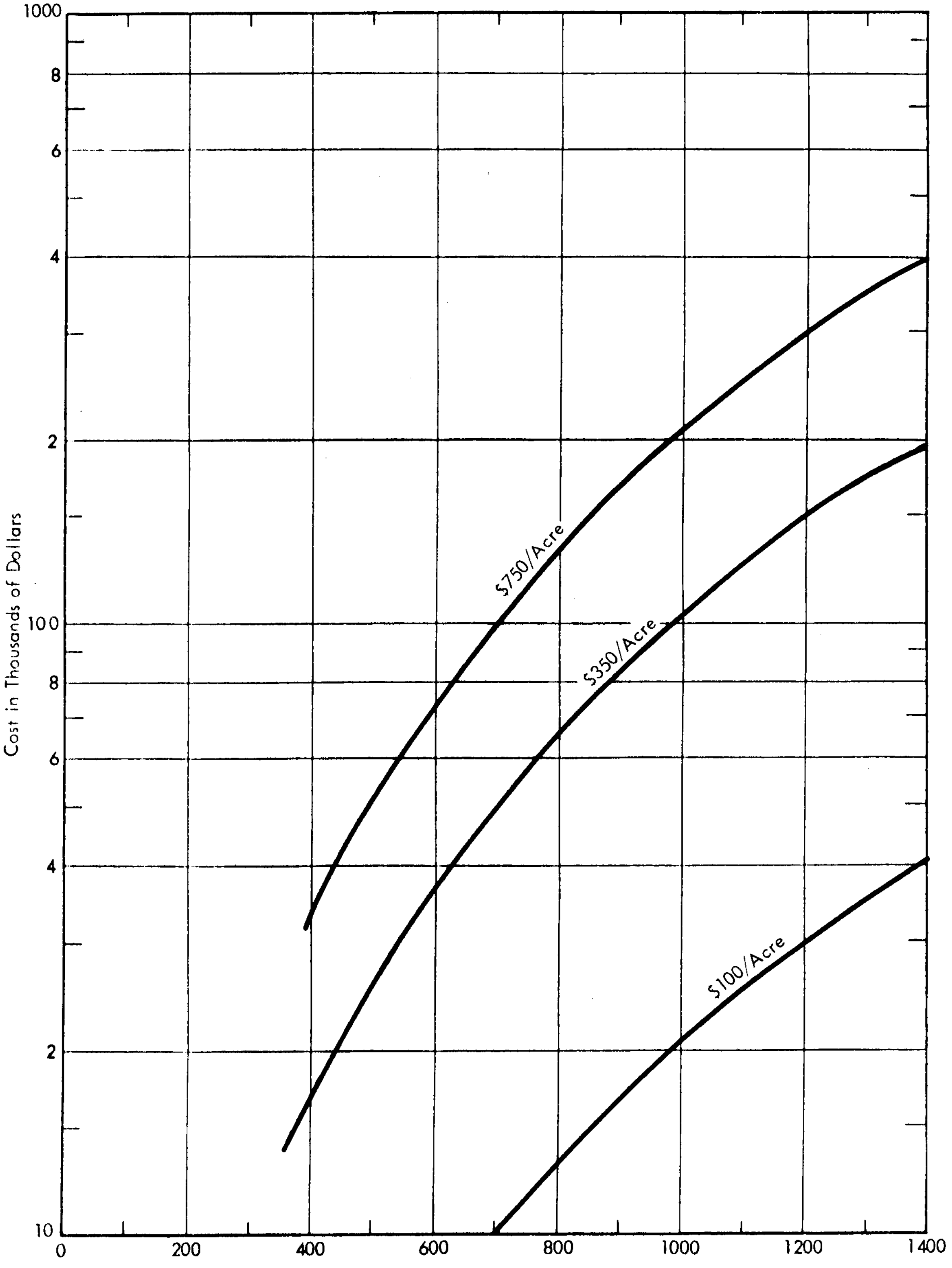

Figure 3-26 Estimated Land Costs for Top Loaded Towers, Ground Conductivity 10^{-3} mho/m

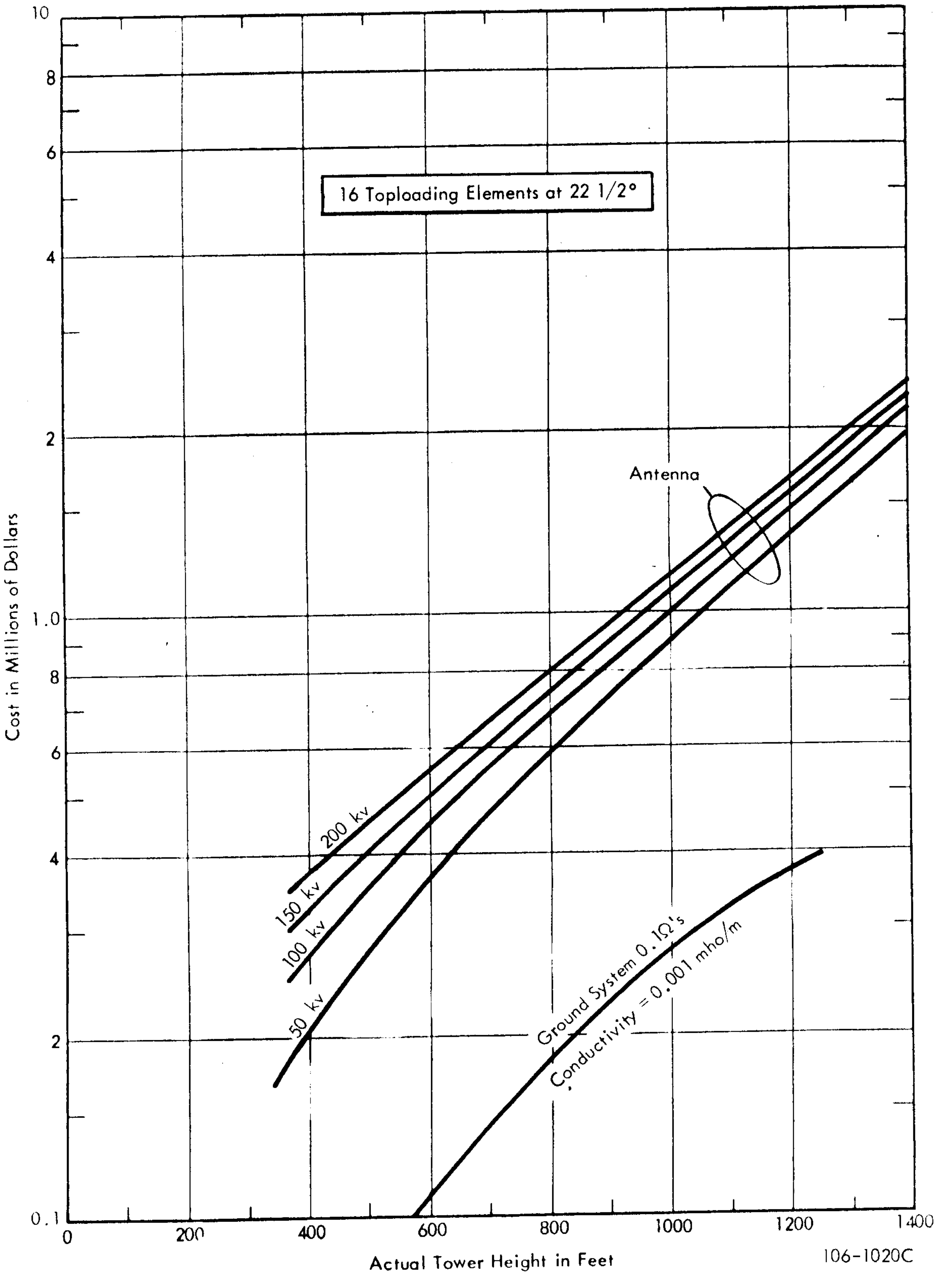

Figure 3-27 VLF-LF Antenna and Ground System
Cost for Toploaded Tower

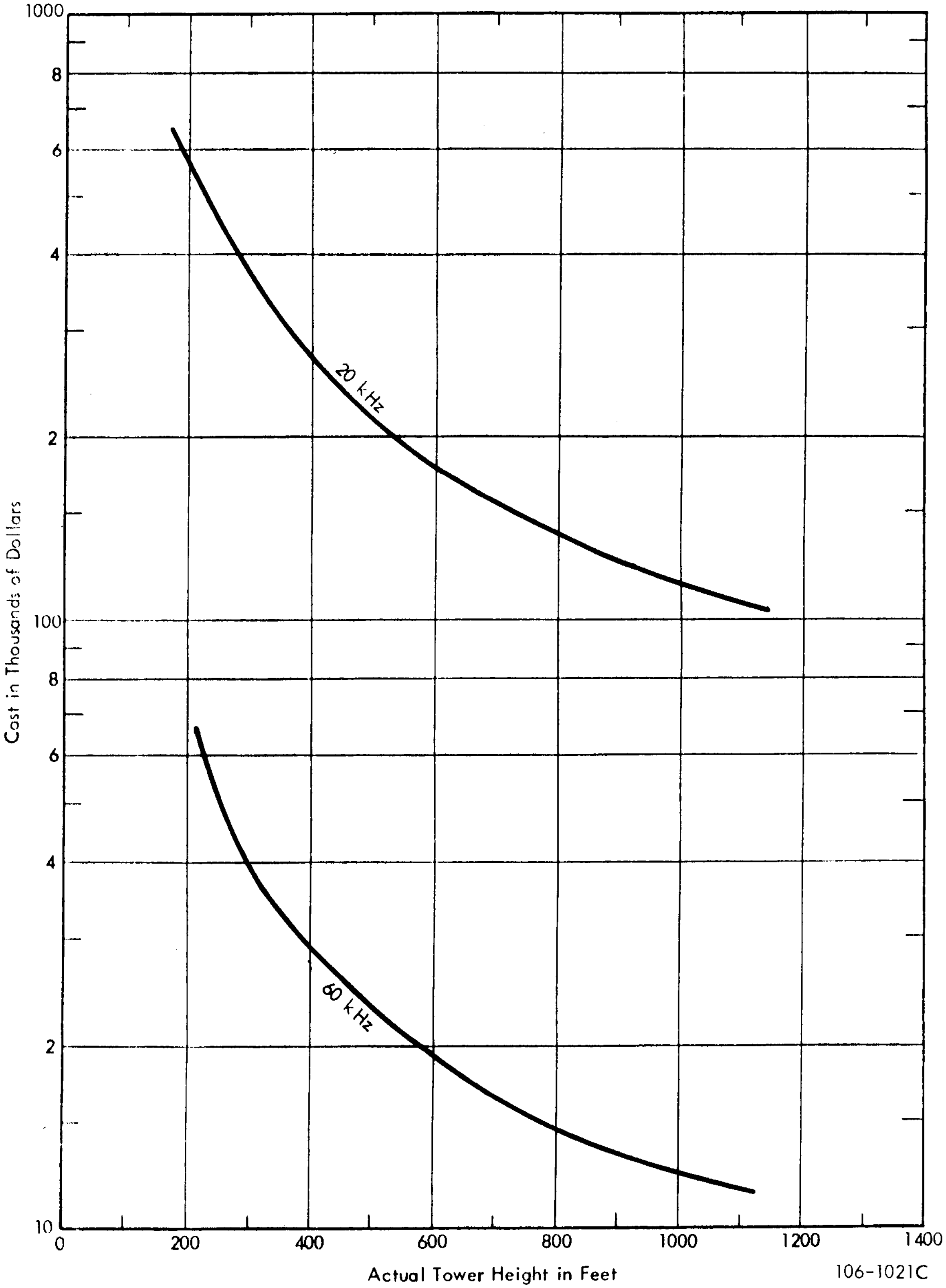

Figure 3-28 Cost of Tuning Inductor and Enclosure

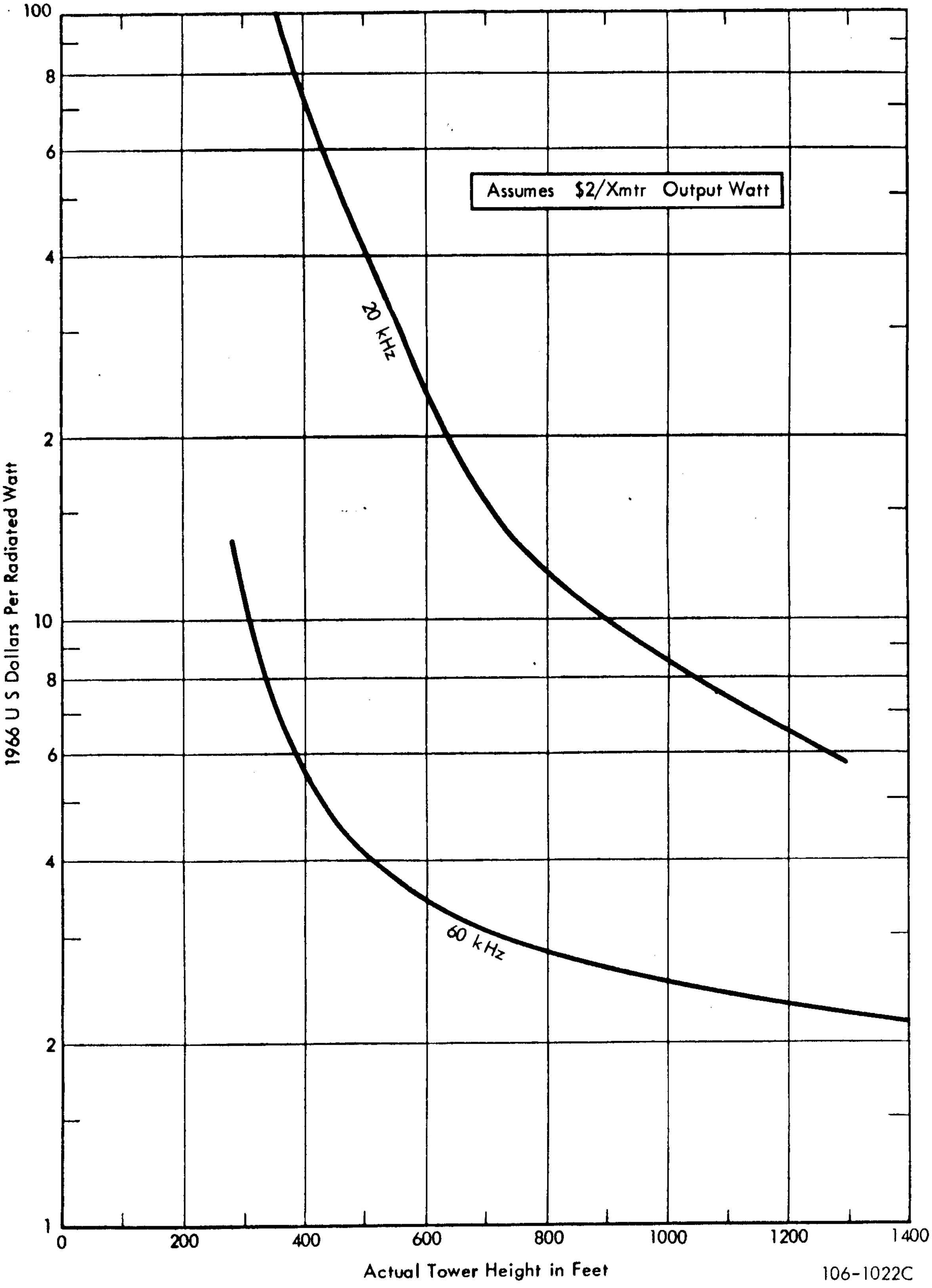

Figure 3-29 Estimated Transmitter Costs per Watt Radiated

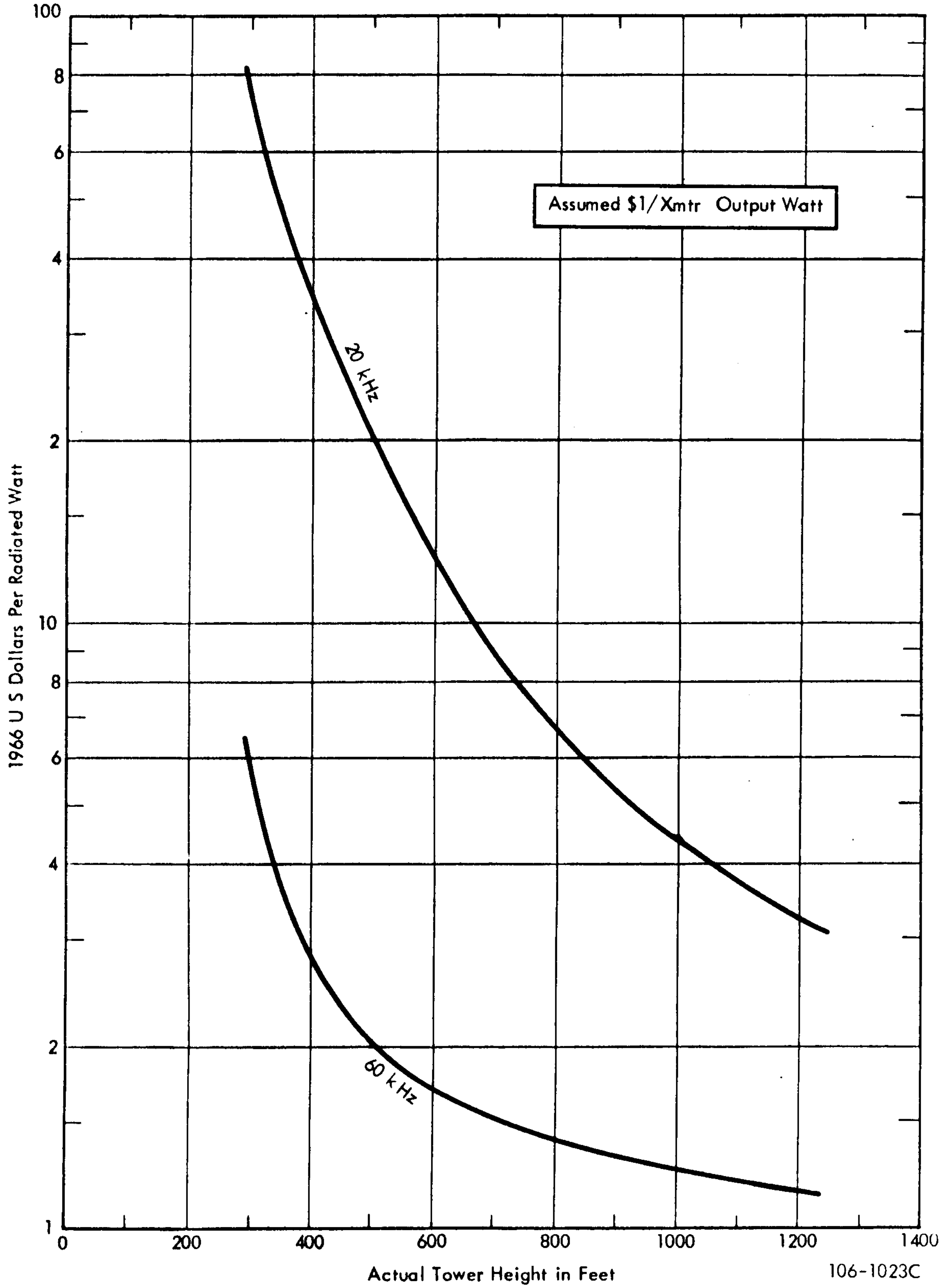

Figure 3-30 Estimated Transmitter Building and Auxilliary Equipment Costs

VLF PAC, Omega-Haiku, and the Air Force 487 L system, showed that $1 per transmitter output watt is a typical value. The curves show cost per radiated watt as obtained from

$$\text{Dollar cost} = \frac{\$1}{\eta_{as}}$$

where η_{as} is antenna system efficiency at the desired frequency and antenna height.

Auxiliary power costs are based on a quoted figure of $320/kw. This includes building, switch gear and all equipment associated with the generating equipment. In order to convert this to costs per radiated watt it is necessary to include not only antenna system efficiency but the transmitter system efficiency and the power supply efficiency. The power supply efficiency is assumed to be 0.8. Solid-state transmitter efficiencies approach 0.9 and vacuum tube systems average around 0.6. The cost per output watt for solid-state transmitters is given by,

$$\text{Cost per transmitter output watt} = \frac{\$.32}{0.8 \times 0.9} \approx \$0.45,$$

For vacuum tube transmitters the cost is,

$$\text{Cost per transmitter output watt} = \frac{\$.32}{0.8 \times 0.6} \approx \$0.67.$$

In terms of radiated power this gives

$$\text{Cost per radiated watt} = \frac{\text{Cost/output watt}}{\eta_{as}} .$$

Values for 60 and 20 kHz are shown in Figure 3-31 as a function of antenna height for both types of transmitters.

3.6.3 Examples of station cost trade with antenna height

As an example of the use of these curves a typical station will be assumed and the antenna height and voltage limit which results in a minimum

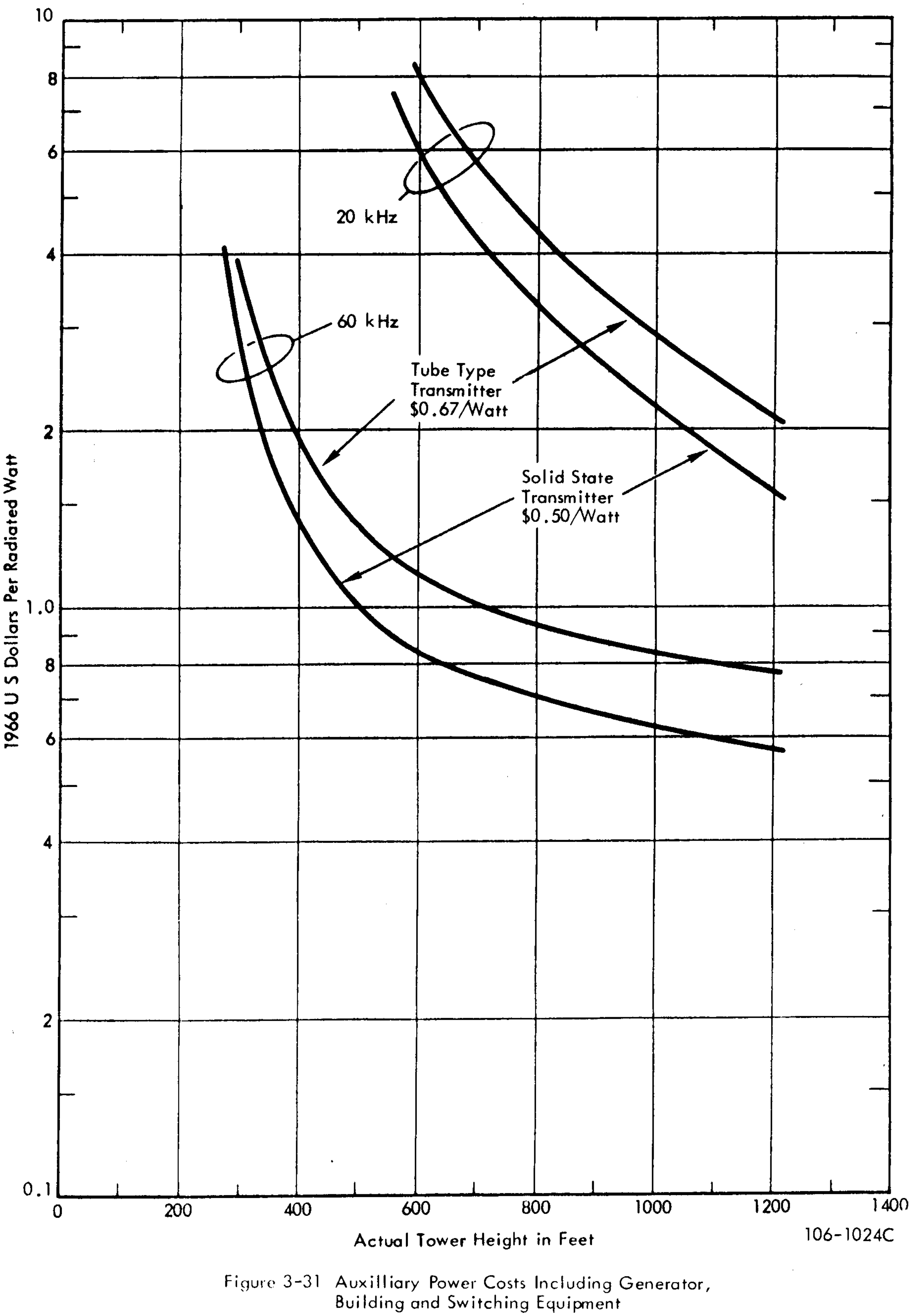

Figure 3-31 Auxilliary Power Costs Including Generator, Building and Switching Equipment

cost determined. For OCD station capable of radiating 100 kw the minimum antenna heights are from Figure 3-21, 490 feet with 200 kv, 580 feet with 150 kv, 730 feet with 100 kv, and 1110 feet with 50 kv.

Costs of the major portions are obtained from Figures 3-26 through 3-31 by multiplying the appropriate curves by the radiated power required which is 100 kw for this specific case. For this example the following table results:

	Tower Height and Operating Voltage			
	490'@ 200 kv	580'@ 150 kv	730'@ 100 kv	1110'@ 50 kv
Antenna	$ 450,000	$ 485,000	$ 595,000	$1,110,000
Ground system + land @ $750/acre	75,000	105,000	155,000	325,000
Tuning & enclosure	25,000	20,000	16,000	12,000
Trans. power ampl.	430,000	350,000	300,000	240,000
Bldg. & aux. equip.	215,000	175,000	150,000	120,000
Auxiliary Power	105,000	88,000	75,000	60,000
TOTAL facility costs	$1,300,000	$1,223,000	$1,291,000	$1,867,000

Thus for this type of antenna and 100 kw radiated at 60 kHz there is a broad minimum in station costs with tower heights of 600 to 700 feet. Similar tables have been made for other radiated powers and for stations meeting various combined capabilities of both OCD and NBS. Data has been plotted and is shown in Figure 3-32. Costs of personnel support facilities were not included in the Figure. The solid lines indicate cost trades for OCD operation only. The minimum cost occurs at increasing antenna heights as the radiation capability increases. Dashed lines are for joint operations with noted radiation capabilities for each frequency.

Though a 1200' tower is not consistent with cost minimization at the chosen output powers, such a tower requires a voltage over 150 kv for the NBS

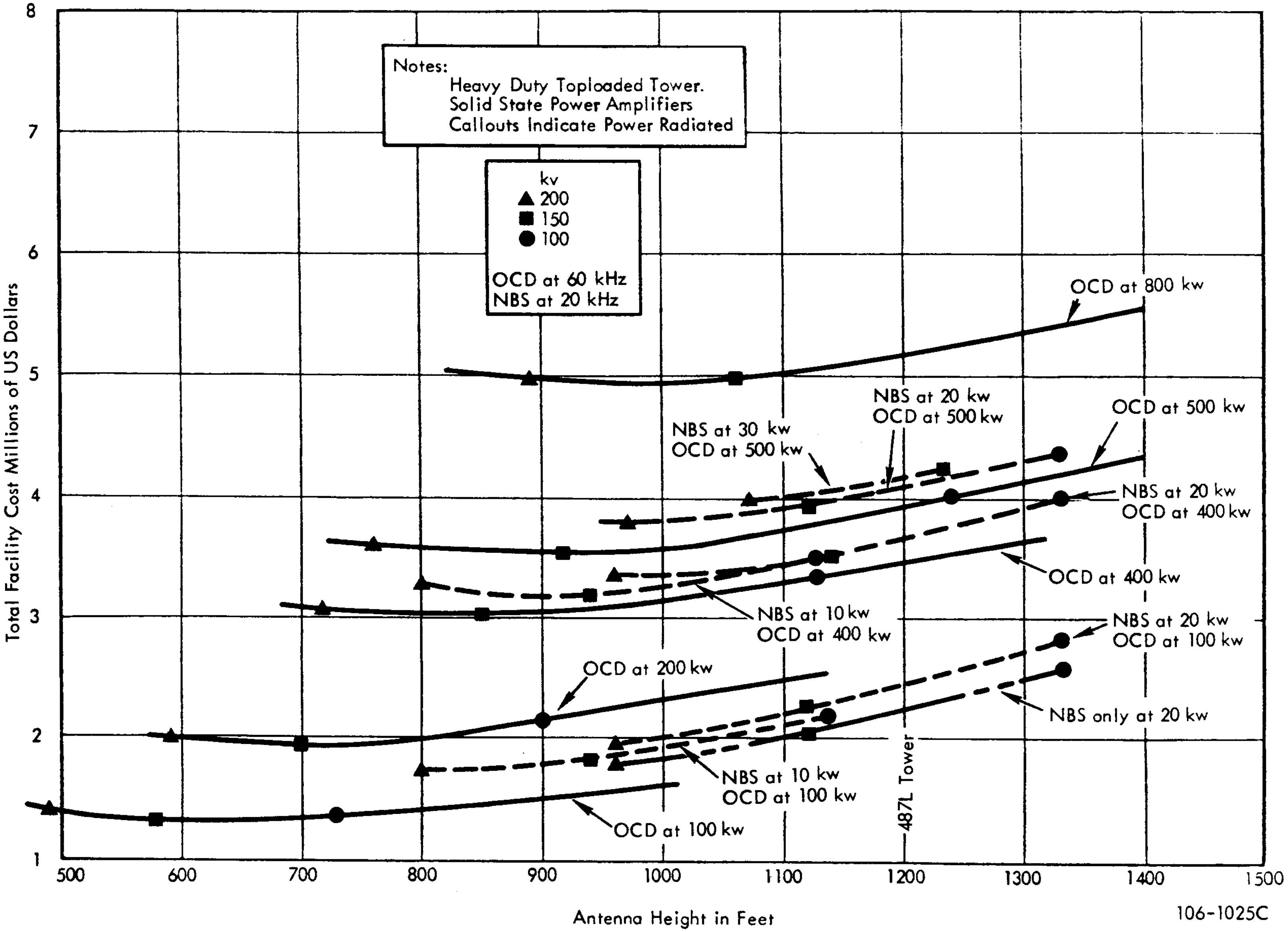

Figure 3-32 Total Station Costs vs. Antenna Height

operation. Cost increases effected by extremely high voltages are difficult to show in such a plot, but it is thought wise to choose here the solution calling for the higher tower rather than operating voltages approaching 200 kv.

3.6.4 Receiver cost trades

It is reasonable to expect that the more receivers that are served by a given transmitter, the more worthwhile it is to simplify the receiver. Generally, the simplification process will degrade the system's performance and require increased radiation capabilities to insure adequate coverage. This trade between receiver costs and signaling costs is worth examination.

The transmitting facility cost differential incurred by doubling the radiation capabilities of a station meeting OCD requirements is indicated in Figure 3-32. This shows, for example, that doubling the radiated power from 200 kw to 400 kw would cost approximately 1 million additional dollars. If, rather than doubling the transmitter power to provide acceptable performance, the receiver performance itself was improved by a factor of two, then the same operational capabilities would result. This may be accomplished through the use of more sophisticated coding, modulation, and detection techniques. Increasing receiver performance will generally increase the cost because of more sophisticated signaling concepts and increased complexity of the decoding schemes. The cost per improved receiver must be less than $\frac{\Delta D}{r}$, (where ΔD is the cost difference of an increased radiated power and r the number of receivers served), in order for this method to result in the most economical over-all communication system. Figure 3-33 shows some transmitter station and receiver cost trades for 3 db improvement and parametric in the number of receivers. For example, the cost of doubling the power of a 200 kw station is comparable to doubling the performance of 50 receivers at $20,000 per receiver. It is informative to examine some single receiver performance and cost relationships using various M-ary codes. For a

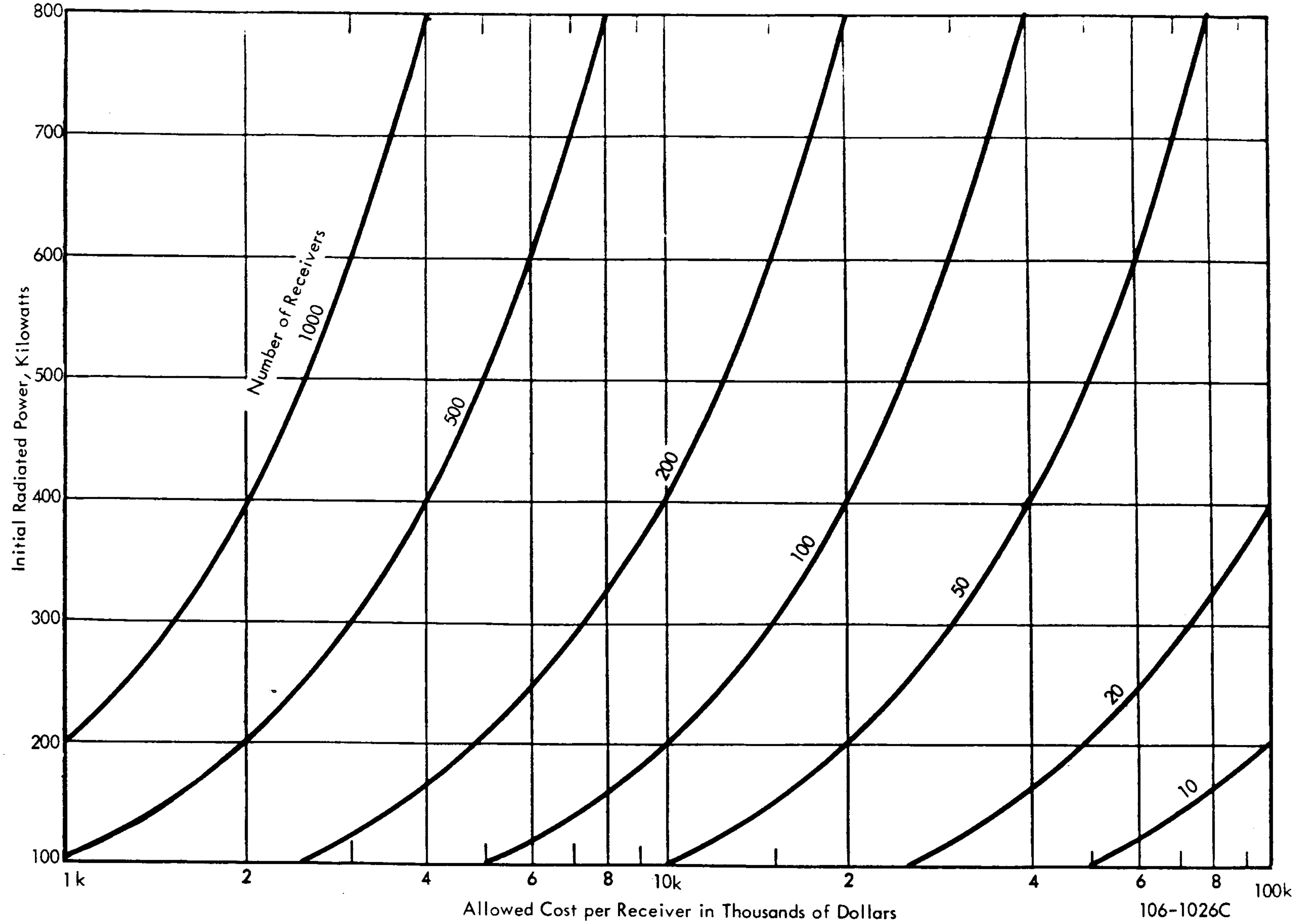

Figure 3-33 Transmitter-Receiver Cost Trades: Number of Receivers and Cost of 3db Improvement Which Equals Cost of Doubling Transmitter Power

binary system with a synchronous eight-element code capable of 256 message symbols, the element error rate must be slightly less for the same message error rate since more elements are required to produce each symbol. The symbol error rate p_s in terms of the element error rate, p_e, is given by

$$p_s = 1 - (1-p)^n$$

For a p_s of 10^{-4} assumed here, $p_e = 1.25 \times 10^{-5}$ for the 8-element code. This amounts to an additional difference of about 0.2 db in performance. Thus for a 16-ary code capable of 256 messages the improvement over the binary (m = 256) is 5.4 db. The binary 8-element code receiver using envelope detection and post detection logic to define a symbol is assumed to cost approximately $10,000.* A coherent system can be expected to cost considerably more (possibly a factor of 3 or 4) because of the necessity for phase lock and correlation detectors. The alphabet size, M, is expected to be a primary factor in determining cost. However, cost is not expected to increase directly with M since certain portions of the receiver are the same regardless of M. Thus the cost of an M-ary receiver can be expected to be somewhere between the binary cost and M times the binary cost. A value of $\left(\frac{M}{2}\right)^{1/2}$ × binary cost appears to be a reasonable assumption. This cost versus M is shown in Figure 3-34.

As one example assume that a quartenary alphabet were used with four elements per symbol. This gives a total message capability of 256 and approximately a 3 db improvement in required S/N_a over the 8-element binary. (See Figure 3-16.) The cost increase per receiver is $4,000 from Figure 3-33. This increase could be applied to 250 receivers and the system would give the same operational capability as doubling the transmitter power from 200 kw to 400 kw.

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* This figure includes antenna, sync circuits, false alarm protection, installation and checkout; in fact, the complete receiving system.

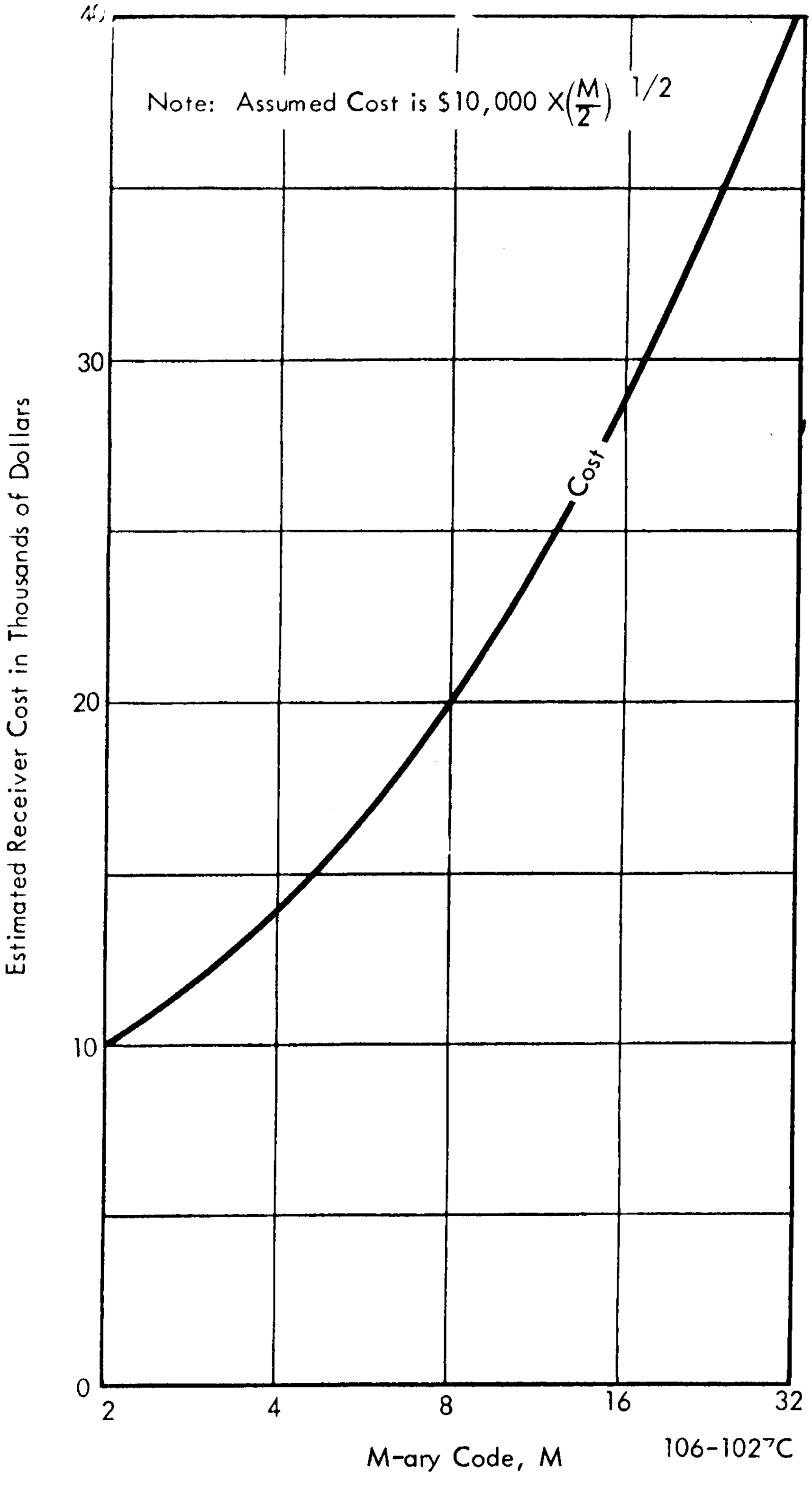

Figure 3-34 Receiver Cost as a Function of Sophistication of Performance

If the 3 db performance improvement was obtained by a coherent correlation type of detection, rather than the M-ary coding methods and non-coherent detection, the added cost per receiver is expected to be greater (possibly $20,000 or more), and only 50 or fewer improved receivers could be obtained for the same total cost. Also, the 3 db improvement may be difficult to actually realize for an intermittent communicating link, since the carrier sync time required will subtract from the total allowed message time.

It should be noted that if the coverage area of a given transmitting station is serviced by a certain number of receivers they certainly will not all necessarily require the same performance capability. Generally, however, because of logistics and maintenance problems, it is desirable to make all units essentially the same or at least to limit the type of receivers to be used.

3.6.5 Manned versus unmanned operation and reliability requirements

In the original effort as proposed, manned operation and joint NBS/OCD operation of the station were assumed synonymous. Unmanned operations were to be considered for operation by OCD only. This single user situation was not considered in detail since 1) the added cost for unmanned operation would be but a small portion of the total station cost, 2) for a station of this magnitude and the extremely high reliability requirement the unmanned operation does not seem feasible. A one-hour repair or replacement time was allowed for most substations.

Component and subsystem reliabilities were assumed throughout to be commensurate with power amplifier specifications. Redundancy may be required to achieve this capability. The specifications for each solid-state 100 kw module are as follows:

Mean-time-between-failure	$\approx$ 3000 hours
Mean-time-to-repair	$\approx$ 1 hour

No standby power amplifier units were included, because of this low failure rate and repair time. Even if one module should fail the system would still operate at reduced radiated power. This reduction does not appear sufficient to warrant standby units.

3.7 Additional Background Material

The optimum design of any radio communication system requires basic information, both experimental and theoretical, from many diverse fields including information theory, modulation, radio propagation, noise, antennas and instrumentation. Much of this material is beyond the scope of this report but was used in developing the concepts and general design features that were given. Much of the basic work was actually accomplished by DECO on other contracts. The following list of reports may be useful to individuals who desire more detailed information than given in the text. In addition, there are many pertinent reports available in the literature. These are not all listed here but others can also be found in the references given in DECO reports.

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