

The Empire State Building Master FM Antenna

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Abstract—A Master FM Antenna and multiplexing system has recently been installed on the Empire State Building which allows any number of FM stations up to a maximum of seventeen to simultaneously broadcast from a single antenna, without interference, an essentially omnidirectional signal in the horizontal plane with approximately equal horizontal and vertical polarization components.

The antenna consists of two layers of sixteen dipoles each with each dipole tilted at an angle of approximately 45° with respect to the horizontal plane. An interconnecting feed system allows each dipole to be fed its share of the input power while introducing a phase rotation of $22\frac{1}{2}^\circ$ between adjacent dipoles. This phase rotation results in an extremely low input SWR over a wide range of frequencies by allowing the reflections from groups of dipoles to cancel mutually.

The multiplexing system utilizes individual combining units, one for each station using the antenna. Each combining unit consists of an all-pass variable-phase RF network which operates in conjunction with two hybrids in such a manner as to add the signal being combined to those signals previously combined with essentially no interaction or phase nonlinearity.

IN THE FALL of 1959, the management of the Empire State Building Company requested several companies, including the Alford Manufacturing Company, to make a study of the possibility of installing a master antenna on the Empire State Building for joint use by a number of FM broadcasting stations. There were at that time upwards of twenty FM assignments in the New York area, all of which were either in use or in hearing status. Five licensees were already operating from the Empire State Building employing FM antennas associated with or in proximity to their television antenna systems. Six additional FM licensees and one FM applicant had shown evidence of interest in broadcasting from the Empire State Building provided a suitable radiating system could be designed. It was not until March of 1965, however, that the first three stations, WQXR, WHOM, and WLIB, agreed to lease space on the Master FM Antenna, and construction began.

The specifications for the Master FM Antenna are given in Table I. Item 10 was included because it was apparent that the order in which the stations might lease space as well as the number of stations, would be unknown to the very end.

Figure 1 shows the Empire State Building before the project began. As may be seen from this figure, the space on the tower protruding above the Empire State Building

itself was already well occupied. It would have been difficult, if not impossible, to accommodate a two-level 100-MHz antenna on the tower without disturbing the performance of the existing antennas and certainly without causing a great deal of commotion. The space on the cone immediately below the tower was also well occupied by standby antennas. The space below the Channel 13 antenna is below the 900-foot level and seemed less desirable than the two bands, one above and one below the 102nd floor observatory. It was these two bands that were first suggested by the management of the Empire State Building. At these points, the building is approximately 35 feet in diameter. The bands are made of stainless steel.

The Alford Manufacturing Company had had previous experience with broadcasting an omnidirectional pattern from an antenna installed on a large cylinder. In fact, the Alford Manufacturing Company designed and built the WOR-TV Channel 9 Antenna, mounted just above the bands offered for the Master FM Antenna, in 1953. Using this experience as well as other previous experiences with large cylinders, some calculations of the number of dipoles that would be required were made. Sixteen dipoles around a circle appeared to be a satisfactory number. Eight and then twelve dipoles were nevertheless tried with a model in order to be certain that the smaller number could not be used.

The scale model shown in Fig. 2 was used during the model studies. To start with, as shown in this figure, horizontal dipoles were used. A subsequent decision by the FCC permitted a dual polarized antenna system. The addition of vertical polarization (obtained by tilting the dipoles) was desired primarily in order to increase the signal that could be readily received in automobiles with conventional whip antennas.

The model was made to 1/11 scale so that the actual band of frequencies between 88 and 108 MHz corresponded to model frequencies between 968 and 1199 MHz. This was found to be a convenient frequency range in which to work.

The model was used to determine the following characteristics:

- 1) Radiation patterns in the horizontal plane.
- 2) Radiation patterns in the vertical plane.
- 3) The RMS power gain in horizontal and vertical polarizations.
- 4) The most desirable angle at which the dipoles should be tilted.

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TABLE I
REQUIREMENTS TO BE MET BY THE MASTER FM ANTENNA
AND MULTIPLEXER SYSTEM

- 1) System should accept the output of seventeen different FM station transmitters at a power level of 10 kW each.
- 2) The antenna should radiate an essentially omnidirectional signal in both horizontal and vertical polarizations in approximately equal amounts.
- 3) The antenna gain and multiplexer losses should be such that each station can achieve an ERP of approximately 5.5 kW in both polarizations (the maximum power presently authorized by the FCC for that height above ground and that location).
- 4) The antenna system should be well matched over the entire frequency band from at least 92 to 108 MHz and preferably from 88 to 108 MHz.
- 5) The external portions of the antenna should be deiced.
- 6) System VSWR should be 1.1 or less at each station's input over a 200 kHz band centered at each station's carrier frequency.
- 7) Isolation between antenna and other antennas on building should be at least 40 dB.
- 8) Isolation between FM transmitters connected to the system should be at least 40 dB for adjacent FM carrier frequencies and at least 36 dB for non-adjacent FM carrier frequencies.
- 9) The frequency-phase characteristic of the system as measured at each station's input should be linear within $\pm 5^\circ$ throughout a 200 kHz band centered at each station's carrier frequency.
- 10) System should allow for any number of stations to participate at the beginning and should allow for additional stations to be added from time to time as required up to a maximum of seventeen in any arbitrary order of carrier frequencies.

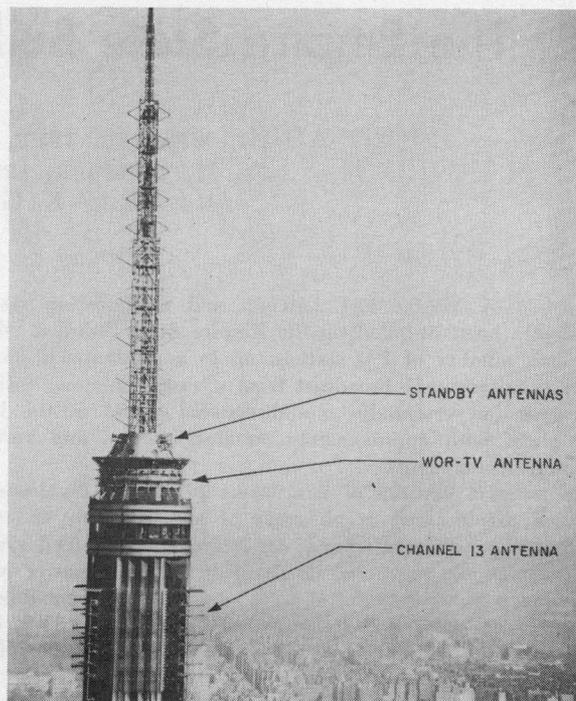


Fig. 1. Empire State Building before installation of the Master FM Antenna.

The gain of the antenna was determined by two methods. It was measured directly by comparing the signal from the model with the signal from a standard antenna, the gain of which was known. The gain was also computed from the radiation patterns.

During direct gain measurements, the feeders were matched not only at the dipoles themselves, but also at each power divider. The attenuation in the model harness was also measured and accounted for in determining the gain of the antenna.

The bandwidth of the individual dipole as a function of its dimensions as well as the various parameters which resulted in impedance compensation were also studied with the aid of models.

The tilt of the dipoles was found to result in elliptical polarization with one large and one small axis. This type of polarization results in the desired horizontal and vertical components.

Several different feeding arrangements were considered:

Arrangement A, in which all dipoles would be fed in the same phase with equal amounts of power, was quite satisfactory from the point of view of patterns but it resulted in a relatively large input standing wave ratio which appeared to be difficult to compensate over the entire FM band.

Arrangement B, in which the phase from dipole to dipole would be increased by 90° in a cyclical manner from 0° to 360° and then repeated, worked very well in the case of the WOR-TV antenna where two layers consisting of twenty-four dipoles each were used around a circle. It was found that with sixteen dipoles, however, this arrangement resulted in relatively poor horizontal patterns.

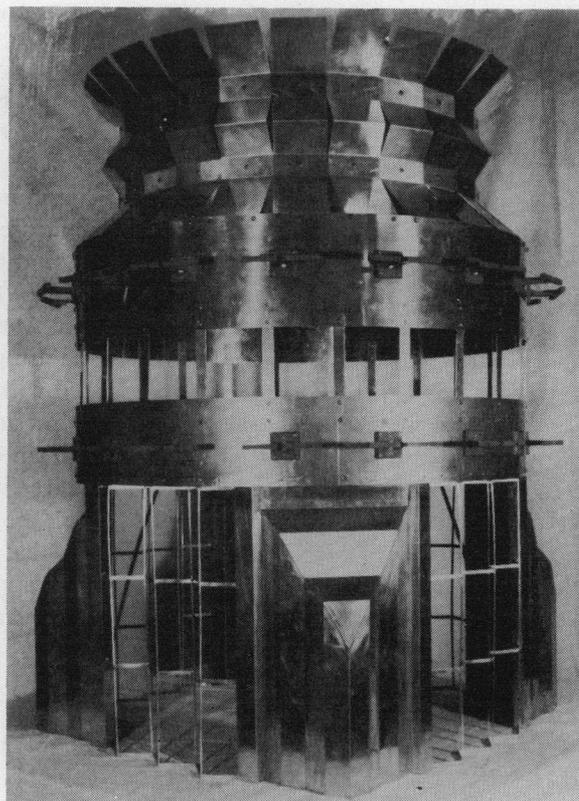


Fig. 2. Early scale model showing horizontal dipoles.

It had to be abandoned in spite of its desirability from the point of view of low input standing wave ratio.

Arrangement C, in which the adjacent dipoles differed in phase by 22.5° , was found to give satisfactory patterns and resulted in a low input standing wave ratio. It was this arrangement that was adopted.

The final antenna is shown in Fig. 3 and its characteristics are given in Figs. 4 and 5. Figure 4 shows the horizontal radiation patterns at three frequencies. These frequencies correspond to 92, 100 and 108 MHz. Figure 5 shows the SWR of the upper and lower levels of the antenna taken separately and of the entire array consisting of both levels.

A schematic diagram of the feeding system is shown in Fig. 6. Groups of dipoles were fed with multiple four-way forks because of the phasing sequence. Dipoles 1, 2, 3, and 4 were fed from one single four-way star fitting with cables having lengths designed to supply signals with 0° , -22.5° , -45° , and -67.5° phases at the midband frequency. The next four-way star supplied the following 90° sector, and so on. The four sectors were connected together by three T fittings.

As small branches were connected into the main branches, the transmission line size was increased. The smallest transmission lines used were $\frac{7}{8}$ -inch diameter semi-rigid Spirolines.¹ The $1\frac{1}{8}$ -inch diameter and $3\frac{1}{8}$ -inch diameter transmission lines were of conventional rigid design except for two-stage transformers. The upper and lower levels of dipoles were fed with $4\frac{1}{8}$ -inch diameter transmission lines which met at the transfer panel shown in Fig. 7. The main feeder which supplies RF power to this panel is $6\frac{1}{8}$ -inches in diameter. The transfer panel is designed in such a way that both levels of dipoles can be used in normal operation but either level can be taken out of service when desired. This arrangement was adopted to increase the reliability by providing the possibility of operation in spite of a failure in one of the levels. The transfer panel is equipped with an interlock switch such that if a patch should be pulled, the switch would result in high voltage being removed from all transmitters before any RF contact is broken.

The multiplexer system which is used to supply the Master FM Antenna, is diagrammatically shown in Fig. 8. The main feeder to which the multiplexer units deliver their power is the same feeder which feeds the input of the transfer panel. This feeder is $6\frac{1}{8}$ inches in diameter.

Each multiplexer unit is based on the principle illustrated in Fig. 9. In this figure, there are two hybrids, one at the input and one at the output of the circuit. At the input hybrid, the main line divides into two $4\frac{1}{8}$ -inch diameter branches. One branch is a length of $4\frac{1}{8}$ -inch diameter transmission line equipped with a U-shaped adjustable section which provides for small adjustments in line lengths (about two or three inches). The second branch passes through a double tank circuit. Both of these tanks are tuned to the frequency f_0 which is to be injected into the main line. Frequency f_0 is the carrier frequency supplied by a particular FM station. One tank in the two-tank system is equipped with two loops, an input loop and an output loop. The second tank has only one loop. The first tank is called the "series tank" because at the frequency to which it is tuned, the power goes directly

through the tank. The second tank is called the "shunt tank" because it is hung across a bypass line. The lengths of lines supplying the loops in the tanks are chosen so that the impedances seen, looking into them at frequencies other than f_0 , are as high as possible. In addition, the relatively small effect of these three subfeeders can be almost fully compensated by the effect of a stub shunted across Branch I. The bypass around the series tank and the U-shaped section in Branch I are made $\frac{1}{2}$ -wavelength long at the frequency f_0 . At frequencies other than f_0 , branches, I and II are identical in length so that a wave split at the hybrid arrives at the output hybrid by two equal length paths. Since the phase difference between these two signals is adjusted to be essentially zero, the two waves recombine and the power is delivered to the sum output of the hybrid and hence into the continuation of the main line. The slight difference between the two branches appears at the difference branch of the hybrid. This very small amount of power is dissipated in a dummy load connected to the difference branch of the output hybrid.

At frequency f_0 , the shunt tank is in tune. Instead of the impedance looking into the subfeeder of the shunt tank being very large, it becomes very small and essentially short circuits the bypass line. Since this apparent short circuit occurs a $\frac{1}{4}$ wavelength away from the subfeeders of the series tank, which is now in tune and is able to transmit f_0 , all of the signal passes through the series tank. The loops in the series tank are so oriented that the power transmitted through the series tank arrives in 180° phase with respect to the power which would be transmitted around the bypass. The two-tank circuit transmits all frequencies including those near the transition frequency f_0 to which the tanks are tuned. Further, when the circuit is properly adjusted, this transmission takes place without reflection right through the transition region. When terminated in 50 ohms, the input standing-wave ratio can be made to remain under 1.05 right through the transition region while the phase behaves as shown in Fig. 9. If power of frequency f_0 were to arrive at the common input of the input hybrid, the two-tank circuit would reverse the phase of this signal in such a way that it would enter the output hybrid in opposite phase to the signal arriving via Branch I and thus would cancel in the direction of the antenna but would add in the direction of the dummy load and would be entirely dissipated therein. When power of frequency f_0 is delivered to the input hybrid via its difference branch, it starts out of phase along Branch II and, having undergone the reversal referred to previously, gets corrected in phase in the two tank circuit and arrives at the output hybrid in the same phase as the power arriving via Branch I. Thus, the two branches again supply power in the same phase so that the signal emerges at the sum output and proceeds toward the antenna along the main line. The multiplexer unit is thus able to inject frequency f_0 into the main feeder while transmitting all other frequencies via this same main feeder. It not only transmits other channels but it even intercepts and absorbs any signal that might come along

¹ Trademark of Prodelin Incorporated.

the main line at the proprietary frequency f_0 .

It makes essentially no difference in which order the multiplexer units are arranged. Frequencies above f_0 as well as frequencies below are treated alike.

Typical characteristics of a multiplexer unit are given in Fig. 10. The SWR presented to an FM transmitter is shown in Fig. 11. Figures 12 and 13 show, respectively, a single multiplexer unit and two units installed close to each other in the Empire State Building. All of the multiplexer units are located on several levels below the 102nd-floor observation deck. These levels are not floors in the ordinary sense, but are steel gratings connected with stairways. A typical view of one of the levels is shown in Fig. 14. It may be seen from this figure that the space was quite limited, not only for the multiplexer units but even for the $6\frac{1}{8}$ -inch diameter transmission lines.

The inputs and outputs of a multiplexer unit are arranged side by side in such a way that they can be fed from two vertical transmission lines with the aid of two special elbows that can be turned about their vertical axes. This arrangement enables one to replace any multiplexer unit with a U-shaped section on short notice. The arrangement also enables one to test the unit by itself while other stations are on the air. Any station whose multiplexer unit is taken out of service can be put back on the air by connecting its transmission line to the end of the main line. This feature provides an added flexibility as well as a built-in standby facility in the system.

The Master FM Antenna system is equipped with several safety devices. In the main feeder at the transfer panel, there is a directional coupler. The output of this coupler is connected to a circuit which can be preset to throw out interlocks of all FM transmitters when the wave reflected from the antenna exceeds a chosen value.

In each individual line which connects an FM transmitter unit, there is a directional coupler which is also provided with a circuit to trip the interlock circuit of the particular FM transmitter when the reflected wave exceeds a chosen value.

Each multiplexer unit is provided with a blower which is used to cool the inner conductors of the two half-wave tanks. In cool weather these blowers are not operated. On particularly warm days, when the temperature of the top end plates of the tanks exceeds a certain value, the blowers automatically go on and stay on only as long as necessary to keep the temperature below the preset value. All tanks are temperature compensated and the temperature compensation of each tank has been tested by making heat runs in a special chamber in which the ambient was varied up to 180°F .

Since the system was installed, other FM stations have joined the group. As of January, 1967, there were nine stations actually operating from the Master FM Antenna.

For a period of some weeks, Station WOR-FM was operated at full power by using the emergency input because its multiplexer unit was then being manufactured together with several others. The emergency arrangements



Fig. 3. Empire State Building Master FM Antenna.

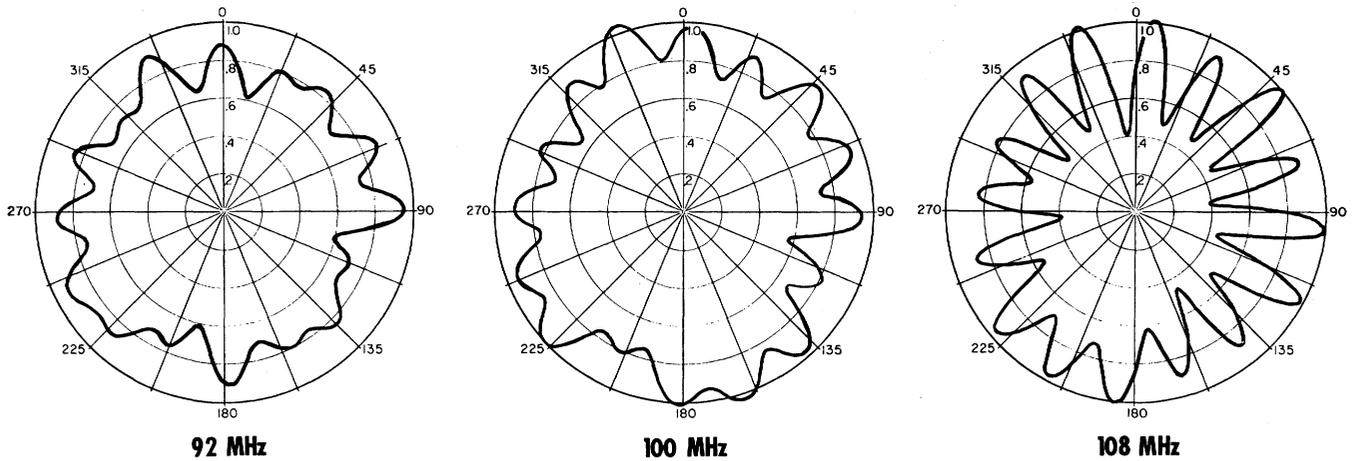
of this system have thus been clearly demonstrated.

Some interesting engineering questions arose in connection with the multiple station operation. One of the questions asked was whether or not there is any discernible cross modulation resulting in sidebands that should not be radiated. Such sidebands have been looked for with determination using sensitive receivers together with a sharply tuned tank that was slowly tuned over the frequency range. No sidebands were found even though the exploration was made below the FCC prescribed level.

It should be noted at this point that the multiplexer system is such that in addition to providing the isolation between FM transmitters, it is also such that it would intercept the sidebands due to cross modulation and dissipate them in the dummy load. This does not happen to useful sidebands because they are very close to the carrier frequency. This additional safety factor is apparently not necessary because even during emergency operation, where Station WOR-FM was not provided with its multiplexer unit, the sideband level was still well below the FCC requirement.

The Empire State Building Master FM Antenna, we believe, provides clear evidence that it is possible to operate a large number of high power FM stations from a single antenna.

E-PLANE



H-PLANE

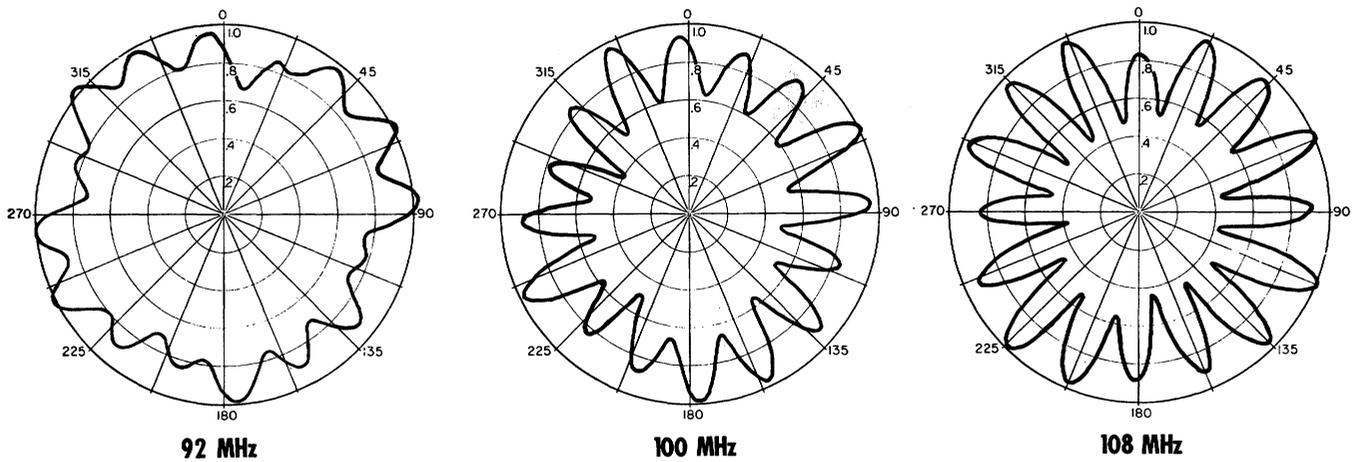


Fig. 4. Horizontal radiation patterns of the Empire State Master FM Antenna.

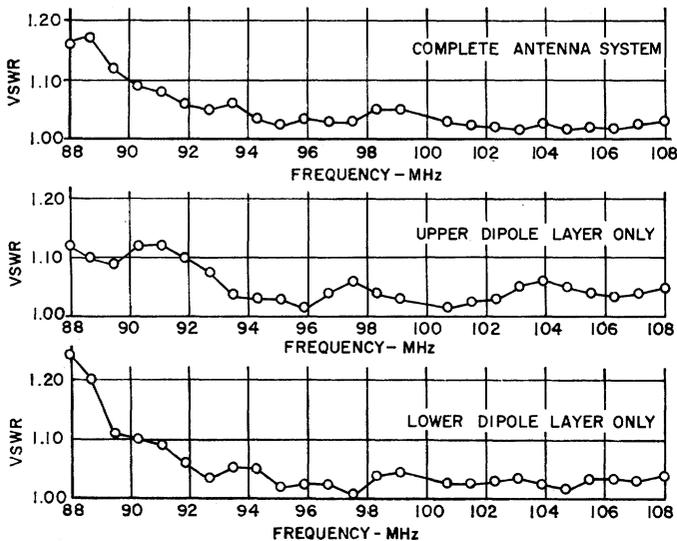


Fig. 5. Master FM Antenna input VSWR.

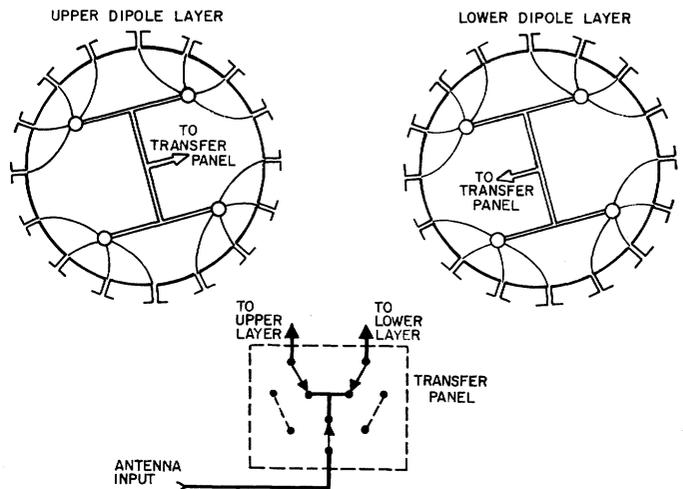


Fig. 6. Schematic diagram of the feeding system for the Empire State Master FM Antenna.

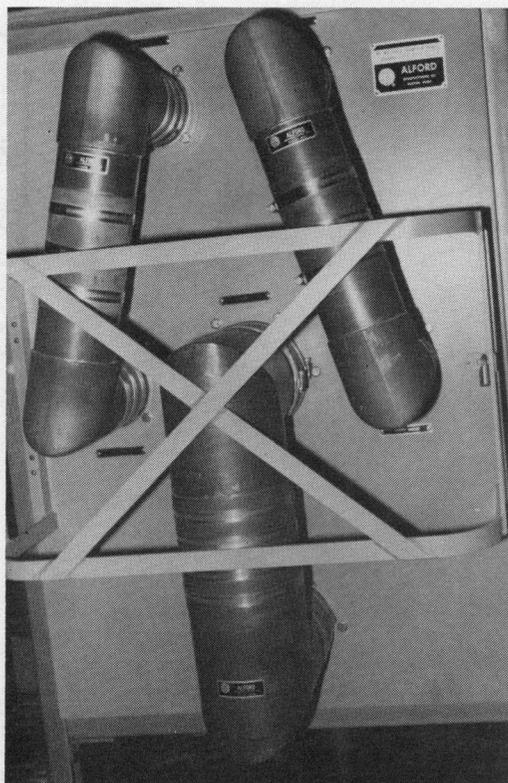


Fig. 7. Transfer panel for the Empire State Master FM Antenna.

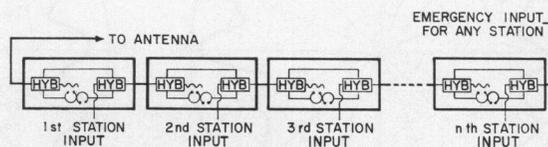


Fig. 8. Multiplexer system used to supply the Empire State Master FM Antenna.

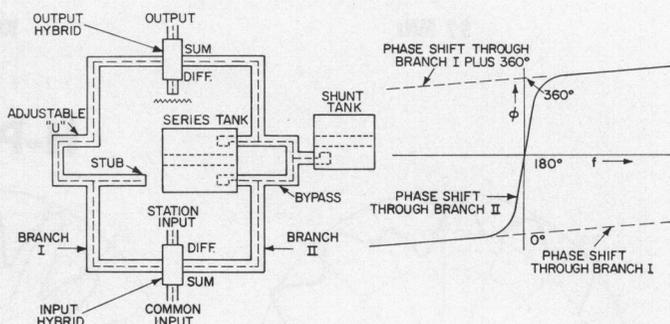
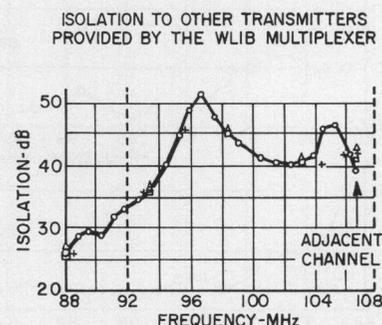
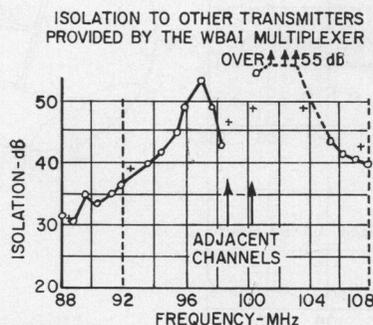
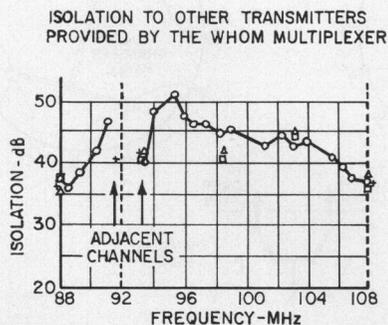
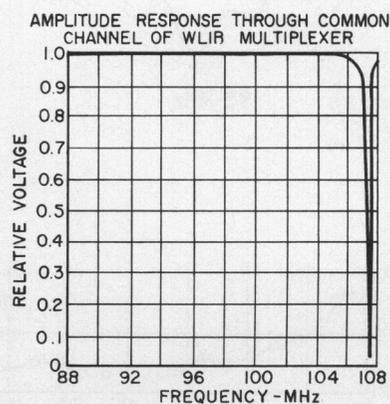
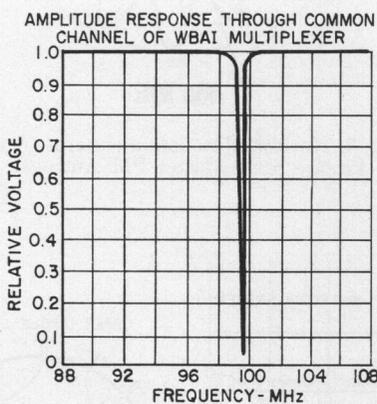
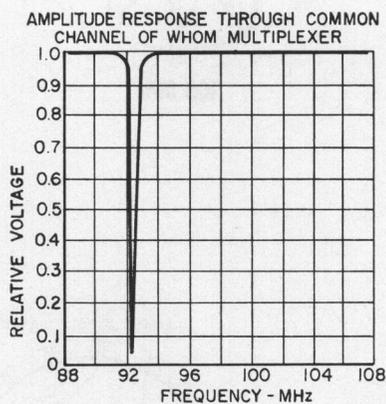


Fig. 9. Multiplexer unit schematic diagram.



○ - SYSTEM TERMINATED IN COMPLETE ANTENNA
 + - MULTIPLEXER TERMINATED IN A 50 OHM LOAD

Δ - SYSTEM TERMINATED IN UPPER DIPOLE LAYER ONLY
 □ - SYSTEM TERMINATED IN LOWER DIPOLE LAYER ONLY

Fig. 10. Typical multiplexer unit characteristics.

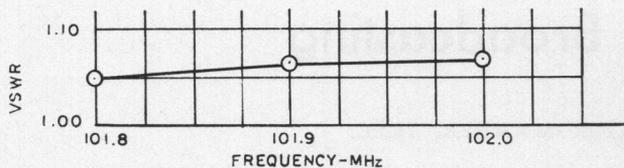


Fig. 11. VSWR of Master FM Antenna at the station WPIX input.

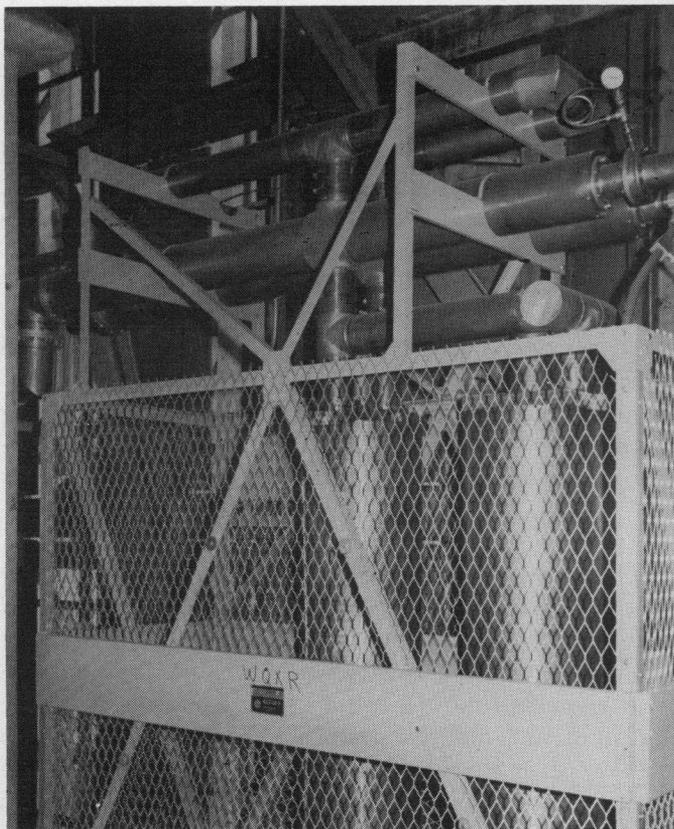


Fig. 12. Single multiplexer unit installed in the Empire State Building.

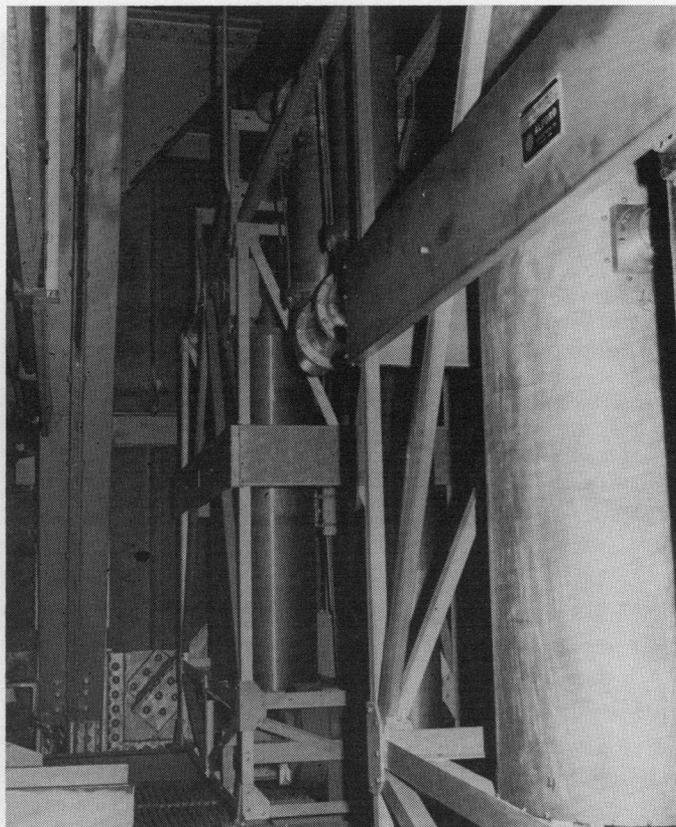


Fig. 13. Two adjacent multiplexer units installed in the Empire State Building.

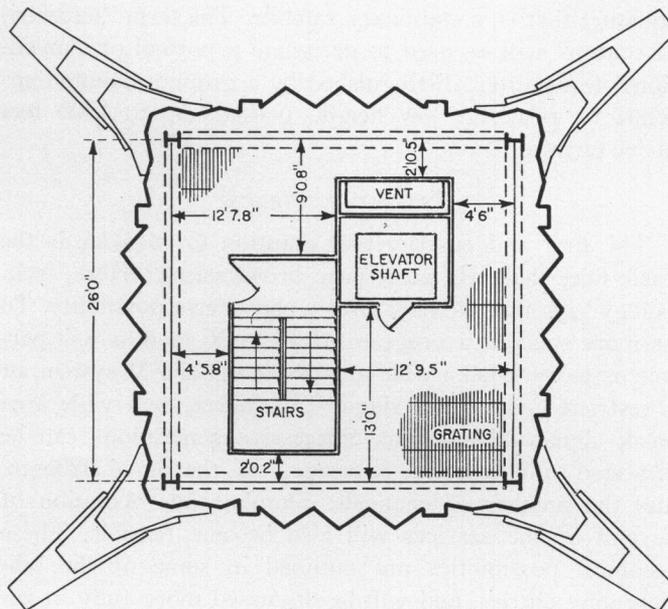


Fig. 14. Typical plan view.

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