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Output Tube Emission Characteristics of Operational Radars

R.J. Matheson
J.D. Smilley
G.D. Falcon
V.S. Lawrence

U.S. DEPARTMENT OF COMMERCE
Malcolm Baldrige, Secretary

Bernard J. Wunder, Jr., Assistant Secretary
for Communications and Information

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OUTPUT TUBE EMISSION CHARACTERISTICS OF OPERATIONAL RADARS

R. J. Matheson, J. D. Smilley, G. D. Falcon, and V. S. Lawrence*

During the past several years, the Radio Spectrum Measurement System (RSMS) of the National Telecommunications and Information Administration (NTIA) has measured the emission spectra and other characteristics of many radars operating in the government frequency bands. This report contains the emission spectra of 19 different types of radars, selected to show the different emission spectrum characteristics produced by a variety of radar output tube technologies. The radars include examples of ground-based search, airport surveillance, weather, and height-finding radars operating in L-band, S-band, or C-band.

The RSMS, contained within a mobile van, is described, along with the measurement techniques used for obtaining radar emission characteristics. The emission limits imposed by the Radar Spectrum Engineering Criteria (RSEC) are displayed with each emission spectrum.

Key words: Radar, Emission Spectrum, Magnetron, Radar Measurements.

1. INTRODUCTION

Since 1973, the Radio Spectrum Measurement System (RSMS) has been making measurements of the emission spectra of a large number of radars. About 200 radar spectra have been measured in a nominal fashion as part of the general spectrum occupancy measurements which the RSMS has made throughout the country. Possibly 75 radar spectra have been measured in greater detail, with additional dynamic range and frequency range. These radar measurements were begun under the Office of Telecommunications Policy (OTP) and have continued under the National Telecommunications and Information Administration (NTIA) as part of on-going studies of radar band usage (Hinkle et al., 1976). These measured radar spectra represent a considerable source of data which might be helpful in reaching optimum decisions for spectrum engineering in the radar bands. Since many of the measured radar spectra are not available in widely circulated publications, this report has been prepared as a summary of radar spectra which we believe are pertinent to the problem of spectrum conservation in radar bands. The Federal Government radio spectrum contains many frequency bands allocated to radars, and several of these are severely crowded. Several types of radar output tubes are relatively miserly in their use of the spectrum and would substantially relieve the present crowding; some are outrageous spectrum spendthrifts. In many cases, good spectrum qualities

The authors are with the Institute for Telecommunication Sciences, National Telecommunications and Information Administration, U. S. Department of Commerce, 325 Broadway, Boulder, Colorado 80303.

may be outweighed by features which are disadvantegeous to specific mission requirements. Therefore, the choice of a high-power output tube is not straightforward, but represents a series of tradeoffs to see what type of radar technology is best for a particular circumstance.

This report is not to imply that spectrum conservation should outweigh other operational and economic considerations in the choice of a radar output tube; but, to emphasize that spectrum conservation must be considered--along with other factors--and that considerable data are available on radar spectra to aid in the considerations.

We have made no attempt in this report to rank the desirability of output tube characteristic in any manner. On the contrary, this report contains spectrum data in as unbiased a form as possible. A Radar Spectrum Engineering Criteria (RSEC) limit has been plotted on the individual radar spectra. Even this October 1977 RSEC (NTIA, 1980) should not be regarded as a value judgment on a particular radar spectrum, because the particular radar many not be subject to the limits implied by that RSEC. The same RSEC limit was drawn on all of the radar spectra--regardless of what RSEC limits actually apply to that radar--to provide a single technical reference for comparison between radars. This RSEC contains some measurement bandwidth correction factors, described in a later section, which must be included if a valid comparison is to be made between radars. Merely observing the amplitude of the sidebands relative to the peak will often give misleading interpretation of these spectrum data.

We have selected an assortment of radar spectra for this report that give a representative view of the emission spectra available from various currently operational output tube technologies. In some cases, the selected radar spectra were chosen from among many examples of measurements made on a particular nomenclature. In these cases, the spectra were selected to show a spread of characteristics that were encountered. In other cases, we have only a very few (even single) examples of a spectrum. from a particular nomenclature. We would have no way of evaluating the degree to which these spectra are typical; however, we have not knowingly selected atypical data for inclusion here.

2. MEASUREMENT TECHNIQUES

2.1. The Radio Spectrum Measurement System (RSMS)

The RSMS is a computerized multi-stage superheterodyne receiver, tunable between 100 kHz and 18 GHz, that is integrated into a motorhome-type van for easy transportation and operation at remote sites. The van contains environmental controls and two 6-KVA RFI-shielded motor-generator sets to allow for operation independent of other logistic support.

Essentially all functions of the receiving system (Fig. 1.) are under computer control, and a very flexible digital data processing system is used to process real-time information or to record data for later analysis.

The antenna subsystem includes noise diodes to calibrate the system in absolute amplitude at the antenna terminals. Relays are used to select either a desired measurement antenna or the noise diode for calibration. This technique automatically accounts for switching or transmission losses involved in bringing the received signal from the antennas to the signal processing inputs of the receiver.

As required, 0-70 dB input attenuation may be inserted to bring the input signal within the measurement range of the receiver. The system software automatically connects the proper preselector/preamplifier, based on the frequency of the signal being measured. Below 500 MHz, fixed-tuned bandpass filters are used to keep out-of-band signals from interfering with measurement of the desired signals. The system uses YIG-tuned tracking preselectors and post selectors for received frequencies above 500 MHz. Preamplifiers are used to decrease system noise figure for frequencies below 12 GHz.

The signal is converted to an IF signal after several mixing stages. All of the local oscillators are derived from a single synthesized reference frequency, so that received signal frequencies can be tuned very accurately. Several IF/detector units are used for various types of measurements. A 3 MHz, narrowband IF unit allows a choice of ten bandwidths between 10 Hz and 300 kHz and gain adjustment from O to 50 dB in 10 dB steps. A 50 MHz wideband IF unit allows a choice of 1 MHz or 3 MHz bandwidths. Video bandwidths in excess of 10 MHz are available from a detector/log amplifier module driven directly from the preamplifiers. The AM, FM, cw, and SSB demodulator circuits are available to monitor the aural content of the signal. Peak and quasi-peak detectors are available to assist in making measurements of radar and broadband impulsive noise signals.

A pulse-blanking system is used to isolate a single radar from a multiradar environment, so that measurements may be made on that radar only. A pulse train separator and a pulse repetition frequency filter provide a means of determining when the desired radar pulses are present. This equipment operates with a high-speed switch to gate only the desired radar pulses into the measurement circuits. A peak detector is used to measure the amplitude of the selected

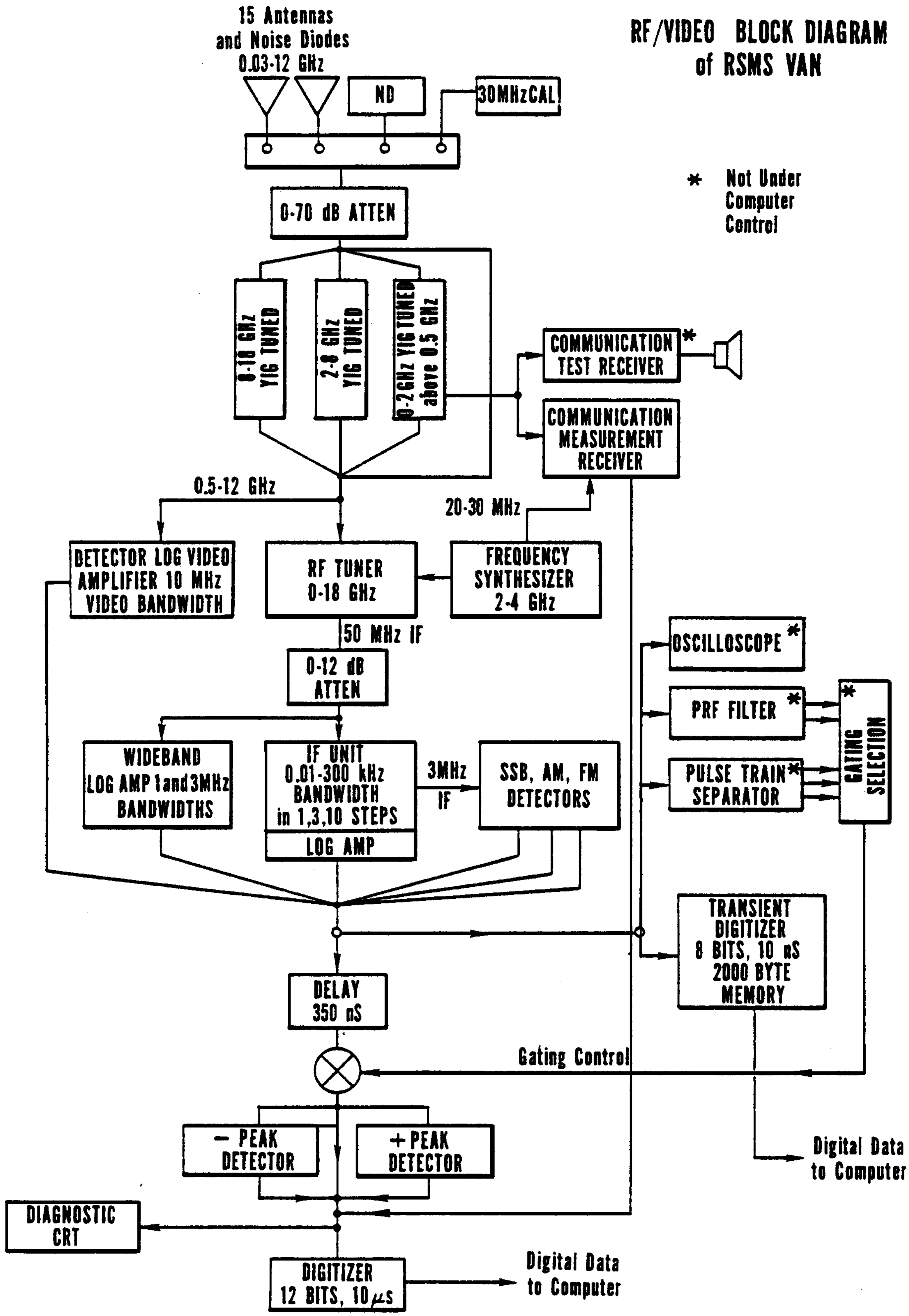


Figure 1. Rf/video block diagram of RSMS van.

pulses.

For additional information on the RSMS capabilities, refer to the references at the end of this report.

2.2. Radar Emission Spectra Measurements

The emission spectra measurements presented in this report were collected as part of a several-year series of radar band spectrum occupancy surveys and special radar measurements conducted as part of the NTIA frequency management program.

Some of the radar spectra were measured with a direct connection to a suitable coupler on the radar output. This technique usually provided the best dynamic range, though often entailed some feedthrough problems due to the high signal levels. In other cases, the RSMS was located at a distance from the radar and used an antenna to obtain a sample of the radar spectrum. This allows working with smaller signal amplitudes but introduces the problem of isolating the radar spectrum from other signals in the environment.

In this case, several techniques were used to minimize the influence of other radars on the measurement. A parabolic dish antenna was usually used for these measurements. The dish provided considerable angular discrimination against other radars, in addition to giving extra system gain necessary to measure farther down on the skirts of the radar spectrum. If necessary, the pulse blanking capability could be used to help eliminate other radars from the measured emission spectrum.

The radar spectra measurements utilize a program (Wide Band Scan) that allows the specification of many operating parameters, including frequency range, number of frequency steps within the specified range, dwell time on each frequency step, bandwidth, rf attenuation, IF gain, peak hold, and receiving antenna. The program steps across a selected band of frequencies, starting at the lower end of the frequency range and continuing until the upper end of the frequency range is reached. A typical frequency range selected is 200 MHz, with 200 steps within this range. If a l-MHz or greater measurement bandwidth is also selected, the entire 200-MHz segment is sure to be measured. At each frequency, the system waits for a specified dwell time (typically 5 seconds for S-band radars) continually measuring the peak amplitude of the signal and updating its measurement when a stronger pulse occurs. The dwell time is chosen somewhat longer than the rotation period of the radar antenna, to ensure that the peak measurement recorded for each frequency will contain the period of time during which the radar antenna's main lobe was aimed directly at the RSMS. Of course, if operational constraints allow it, the radar can be continuously pointed at the RSMS, permitting a very short dwell time, reducing the time required to complete the measurement. As the measurements are made, the measured data are graphed. The operator may add or subtract rf attenuation in 10-dB steps as required to keep the signal within the linear measurement range of the system. Software compensates for rf attenuation so that the graphed data are continuous and appear to have been measured by a system with larger dynamic range. In some extreme situations where the combination of preelection and attenuation did not' provide sufficient dynamic range, a notch filter--tuned to the radar center frequency--was inserted at the measurement system input. The insertion loss of the filter is compensated by the noise diode system calibration routine to give a correct center frequency power measurement for the radar spectra. Whenever operational constraints permitted, sequential frequency segments were measured until the received radar signal fell below system noise as illustrated by Figure 3a.

3. DATA ANALYSIS

The RSEC was established to help ensure an acceptable degree of electromagnetic compatibility among radar systems. A detailed explanation of the RSEC is found in section 5.3. of the Manual of Regulations and Procedures for Federal Radio Frequency Management (NTIA, 1980).

The RSEC bases an allowable emission bandwidth, B, on certain radar operational parameters including the radar type, transmitted power, pulse characteristics, frequency, and procurement or major overhaul date. For purposes of technical comparability, the same RSEC was applied to the spectra of all radars presented in this report, even though a different RSEC category may correctly apply to the spectra. For the -40 dB bandwidth we selected:

$$B_{(-40\ dB)} = \frac{7.6}{\sqrt{t\ t_r}}\ ,\ \text{or}\ \frac{64}{t}\ ,\ \text{whichever is less,}$$

where t = radar pulse width and t_r = radar pulse risetime.

It will be noted, Figure 5, for example, that the RSEC limit often starts several decibels above the peak response of the radar. This difference is from a correction factor that was added because the measurement bandwidth was larger than the emission bandwidth.

The data in the emission spectra measurements must be converted to power density (dBm/kHz) before the measurements can be compared to the RSEC. Since the RSEC is in relative terms (sidebands must be suppressed a certain number of dB below the power level at the fundamental frequency), it might seem reasonable to apply the RSEC directly to the measured and graphed emission spectra. This may be incorrect, however, if the radar is measured with bandwidths larger than l/t, because the peak detector operates on a different pulse shape at the fundamental than it does at the sidebands.

The net result of this phenomenon is that the peak energy in the sidebands is sometimes measured several decibels too high compared to the energy measured at the fundamental frequency.

The RSEC limits are shown as dashed lines on the emission spectra presented in sections 4, 5, 6, and 7. Additional information concerning the RSEC selection and computation is contained in the Appendix. Values from tables 1 through 4 were used to compute the RSEC for all of the radar spectra presented.

It should be noted that some of the parameters in the tables were not obtained by direct measurements on the listed radar. Logistic and time constraints did not permit the RSMS crew opportunities to make all of the measurements at every radar site. In the tables, wherever a measured parameter is required, a code letter from the following list is used to indicate where the value was obtained.

CODE

M - Measured by RSMS personnel

E - Estimated from best data available (radar operators or maintenance personnel, Radar Standards Handbook, etc.)

G - Government Master File (GMF) listings.

4. SPECTRA OF S-BAND SURVEILLANCE RADARS

The S-band surveillance radars represent the largest population of fixed radars in the United States. They are the primary users of the crowded 2700-2900 MHz band, and are the radars typically seen at most large airports and military air bases.

In this section are several spectra of older airport surveillance radars (ASR'S) using conventional magnetrons and one example of a more recent ASR using a klystron amplifier. Also included in this section is one example of a military tactical 3D surveillance radar. Note that, except for the GPN-20, all of the radars using a conventional magnetron exhibit the characteristic "porch", on the lower side of the fundamental frequency, caused by frequency-pulling at the leading and trailing edges of the transmitted pulse. Although the "porches" of the FPN-47, ASR-5, and TPN-19 radars tend to exceed the reference RSEC, these radars' sideband frequencies are relatively well suppressed. The CPN-4, on the other hand, tends to exceed the RSEC over its entire frequency range. One factor which is, unfortunately, not known is the extent to which tube aging may be a factor in these differences. The CPN-4 was an older radar and was measured at a relatively inactive Naval Air Station where it was operated only occasionally by military reserve units.

The GPN-20 also uses conventional magnetrons, but additionally uses a diplexer filter for two-channel operation. The most recent ASR illustrated in this section is the ASR-8. It uses a klystron amplifier and a diplexer filter, and provides the cleanest spectrum of all the ASR'S. The TPN-19, GPN-20, and the. ASR-8 are modern ASR'S which transmit on two frequencies simultaneously to give more protection against an effect called "target scintillation", whereby an echo from a target can occasionally disappear at a particular frequency. There is less likelihood of simultaneous disappearance at two frequencies. Frequency diversity operation gives a small improvement in detection range, and an improvement in probability of detection equivalent to a 3-5 dB increase in transmitter power.

The TPS-43E is included in this section to show the influence it may have on the crowded 2700-2900 MHz band and also to provide an example of the twystron (TWT/klystron) amplifier. The TPS-43E measured was under operational constraints not to transmit all sixteen channels at one time, and--in fact--many channels had not recently been used and were not peaked up for the measurements. To provide a representative example, however, measurements were made on all channels individually and graphically combined. An extended spectrum of the radar operating on only channel 1 is also included.

Measurement and analysis parameters, plus additional information about the radar spectra presented in this section, are listed in table 1.

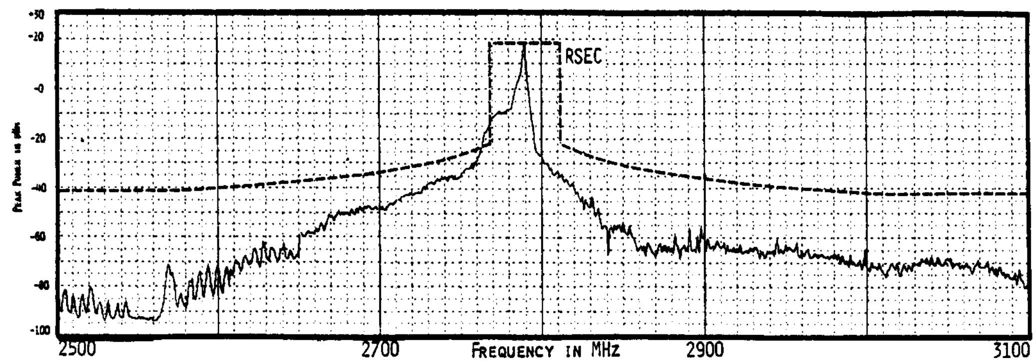
<u>ASR-5 (Fig. 2a).</u> The ASR-5 is an older FAA two-dimensional, medium-range (lllkm, 60nmi), S-band airport-surveillance radar with a conventional magnetron. It is also used at military airfields where it is designated as an FPN-47/55.

<u>CPN-4 (Fig. 2b).</u> The CPN-4 is an older, self-contained, mobile ground-control-approach (GCA) radar that functions as an Air Traffic Control Central for landing aircraft during periods of reduced visibility. The search (surveillance) portion is a medium range (56 km, 30 nmi), S-band (2700-2900 MHz) radar with a

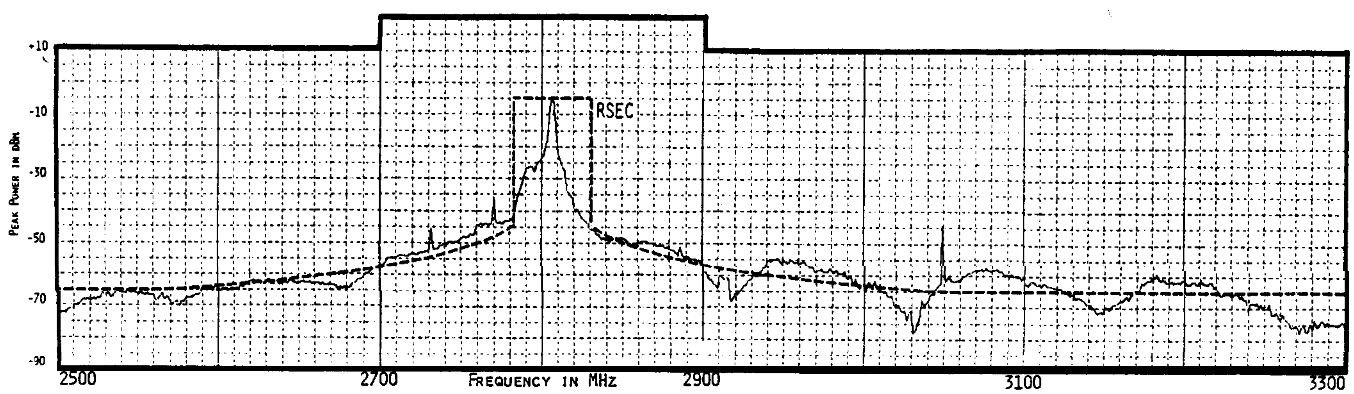
Table 1. Selected Operational and Measurement Parameters for S-band Surveillance Radars

Radar Equipment	Amplifier Type	Operating Frequency (MHz)	Pulse Repetition Rate (pps)	Pulse Duration (μs)	Pulse Rise Time (ns)	Peak Power (dBm)	Measurement Bandwidth(s) (kHz)	Figure Number
FPN-47 (Channel A)	Conventional Magnetron	2800 [M]	1142 [M]	0.96 [M]	90 [M]	86 [G]	1000	4a
FPN-47 (Channel B)	Conventional Magnetron	2813 [M]	1142 [M]	0.92 [M]	80 [M]	86 [G]	1000	4b
GPN-20 (Channel A)	Conventional Mag. (Filtered)	2885 [M]	1000 [E]	1 [E]	100 [E]	87 [E]	1000	3a
GPN-20 (Channel B)	Conventional Mag. (Filtered)	2808 [M]	1000 [E]	1 [M]	100 [M]	87 [E]	1000	3a
TPN-19 (Channel A)	Conventional Magnetron	2827 [M]	1050 [E]	1 [E]	150 [E]	87 [E]	1000	3b
TPN-19 (Channel B)	Conventional Magnetron	2719 [M]	1050 [E]	1 [E]	150 [E]	87 [E]	1000	3b
ASR-5	Conventional Magnetron	2790 [M]	1130 [M]	1.02 [M]	30 [M]	89 [G]	1000	2a
CPN-4A	Conventional Magnetron	2807 [M]	1200 [M]	0.5 [G]	50 [E]	88 [G]	1500	2b
ASR-8 (Channel A)	Klystron	2885 [M]	1008 [M]	0.69 [E]	100 [E]	90.5 [G]	3000	5
ASR-8 (Channel B)	Klystron	2825 [M]	1008 [M]	0.69 [M]	100 [M]	90.5 [G]	3000	5
TPS-43E	Twystron	2902 [M]	250 [M]	5.6 [E]	500 [E]	94.5 [E]	300	6

[M] - Measured
[E] - Estimated
[G] - From Government Master File



a. ASR-5, conventional magnetron.



b. CPN-4, conventional magnetron.

Figure 2. Airport surveillance radars, ASR-5, CPN-4.

conventional magnetron.

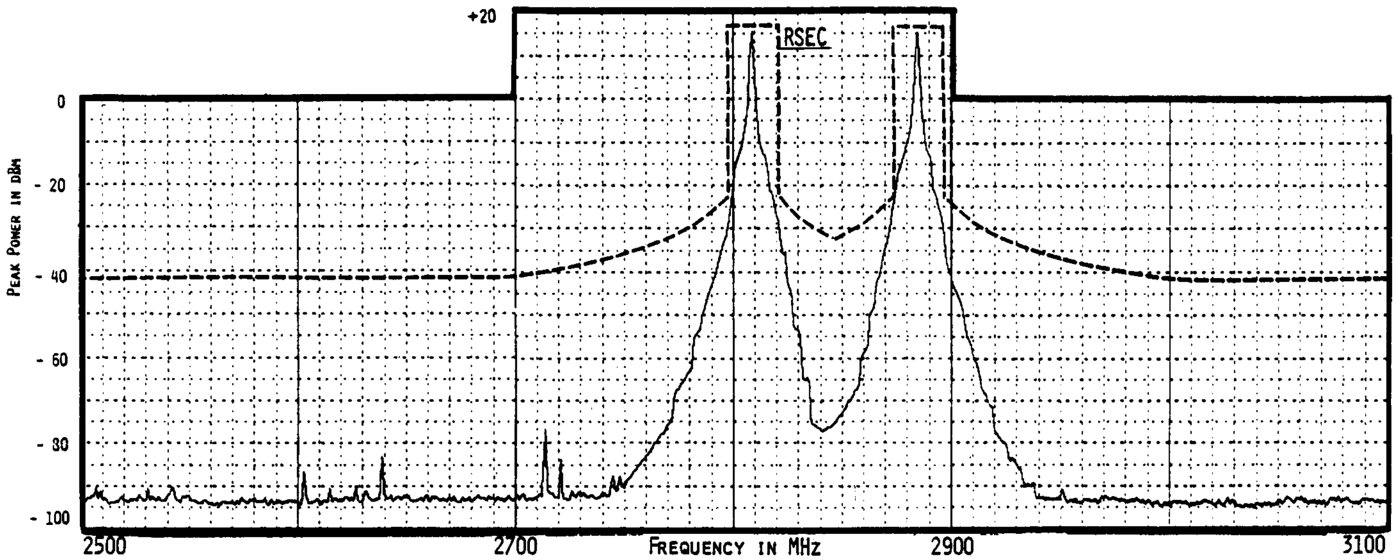
GPN-20 (Fig. 3a). The GPN-20 is a modern Air Force S-band two dimensional radar used for airport surveillance, It is essentially identical to the ASR-8, but uses conventional magnetrons instead of klystrons. The radar is normally used in the diplex mode with the two center frequencies 70 to 90 MHz apart. The diplexer's narrow band pass characteristic substantially reduces the sidebands from the conventional magnetrons, and the resulting spectrum falls off very rapidly. The range is 111 kilometers (60 nautical miles) using 500 kW peak power. The radar is used in conjunction with an integrated Precision-Approach-Radar (PAR) .

TPN-19 (Fig. 3b). The TPN-19 Air Traffic Control (ATC) system consists of a TPN-24, S-band, airport surveillance radar and a TPN-25, X-band, precision approach radar. The TPN-24 (measured) is a two-dimensional ASR using conventional magnetrons. Unlike the GPN-20, however, the TPN-19 does not use a narrowband diplexer to combine the two channels, but uses a broadband diplexer with a notch at the frequency of the other channel. This configuration does not provide the extra rejection of magnetron sidebands, and the TPN-19 output spectrum is that of a conventional magnetron. The system is often used as a temporary replacement while a permanent system is being installed. The range is 111 km (60 nmi), transmitting 450 kW using a magnetron in a diplex mode. Stacked horns are used to shape a vertical fan beam (about 20°) without resorting to extra antenna height.

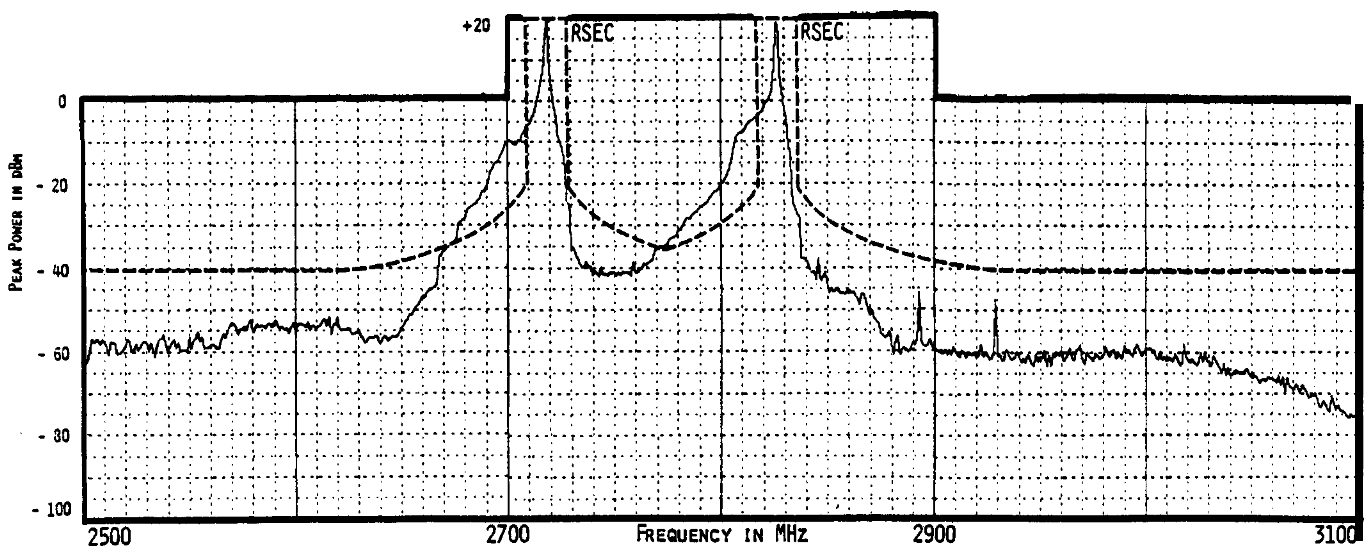
FPN-47 (Fig. 4). The FPN-47 is an Air Force S-band two-dimensional radar (same as FAA's ASR-5) used for airport surveillance and is a part of an air traffic control system. The range is 111 kilometers (60 nmi) using 400 kW peak power. Similar military radars are the FPN-51, and the FPN-55. Channels A and B are shown separately to illustrate substantial differences between channels. Measurement system noise is at -94 dBm, shown as a relatively straight line near the lower frequency end of the displayed spectrum.

ASR-8 (Fig. 5). The ASR-8 is a recent FAA air traffic control two-dimensional, medium range 111 kilometers (6O nmi) S-band airport-surveillance radar using two klystron amplifiers each transmitting 1 MW in a diplex mode. The radar has an exceptionally clean spectrum due to the use of klystrons and the narrowband diplexer filter. Other measurements, not shown here, indicate that the diplexer characteristics provide significant improvement to the klystron output sidebands.

TPS-43E (Fig. 6). The TPS-43E is an Air Force 3-D, stacked-beam, surveillance radar and is air and ground transportable. The range of the TPS-43E is

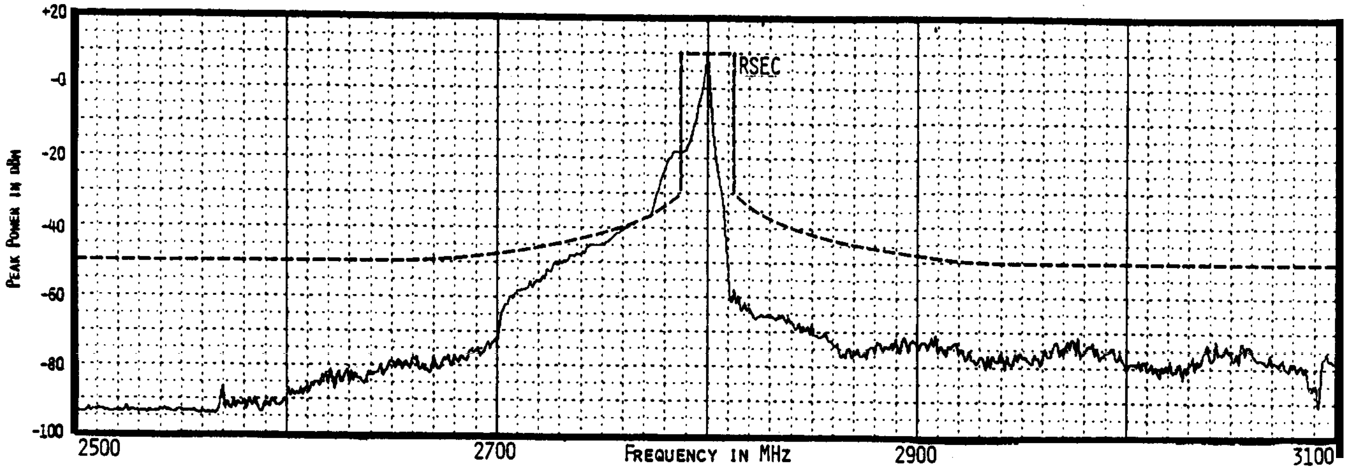


a. GPN-20, conventional magnetron, diplexer filtered.

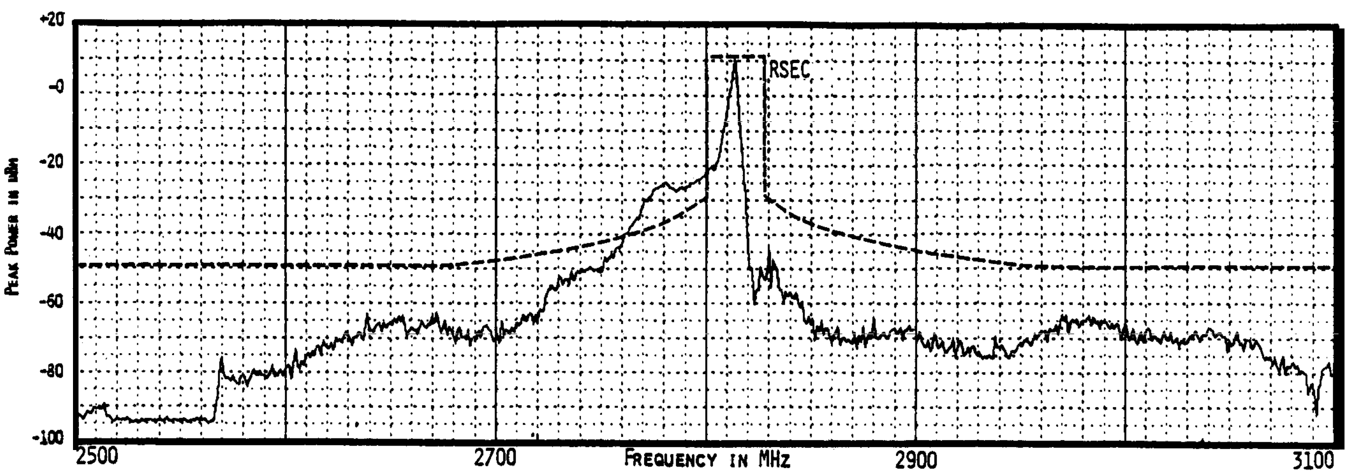


b. TPN-19, conventional magnetron.

Figure 3. Airport surveillance radars, GPN-20, TPN-19.



a. FPN-47 (Ch. A), conventional magnetron.



b. FPN-47 (Ch. B), conventional magnetron.

Figure 4. Airport surveillance radar, FPN-47.

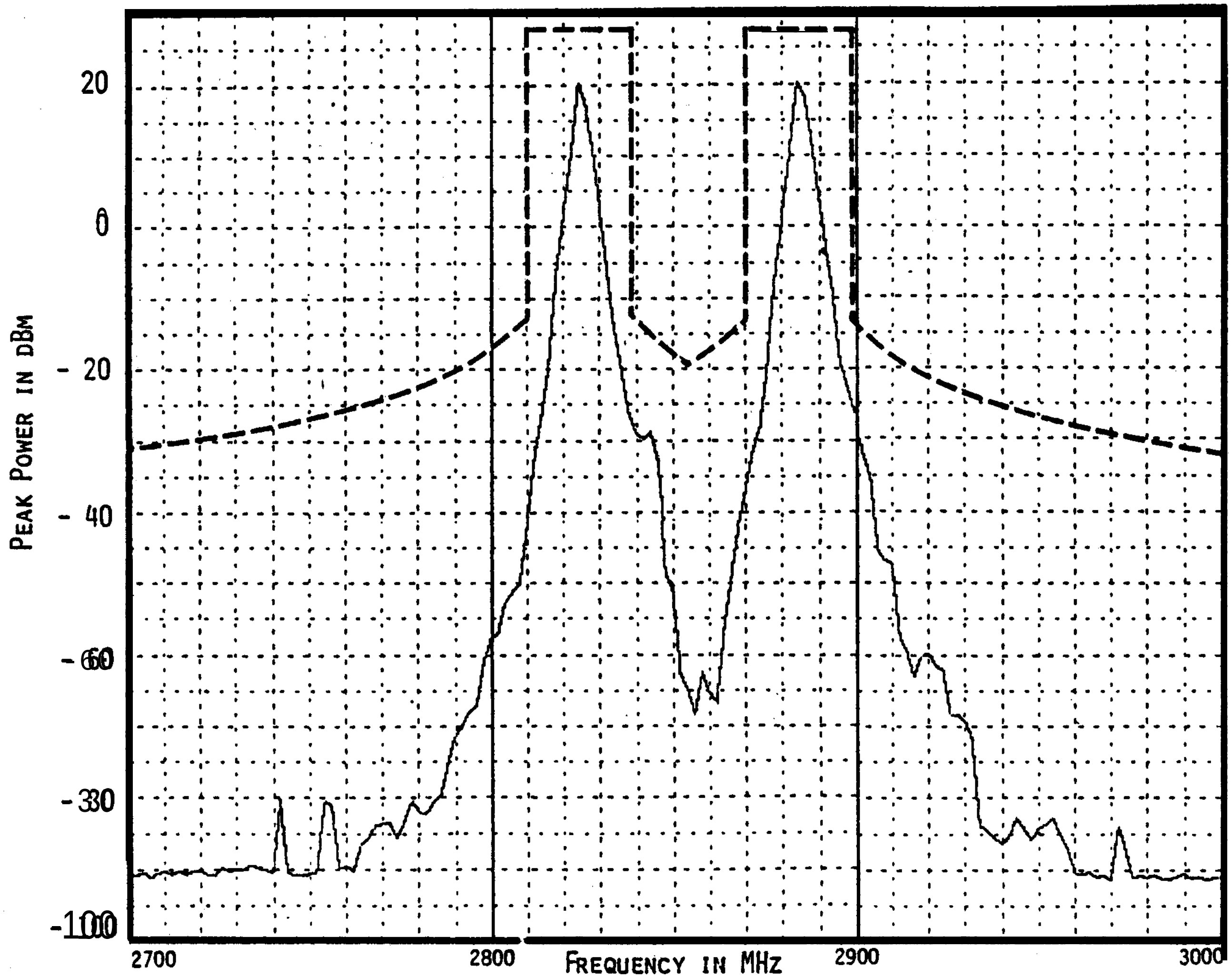
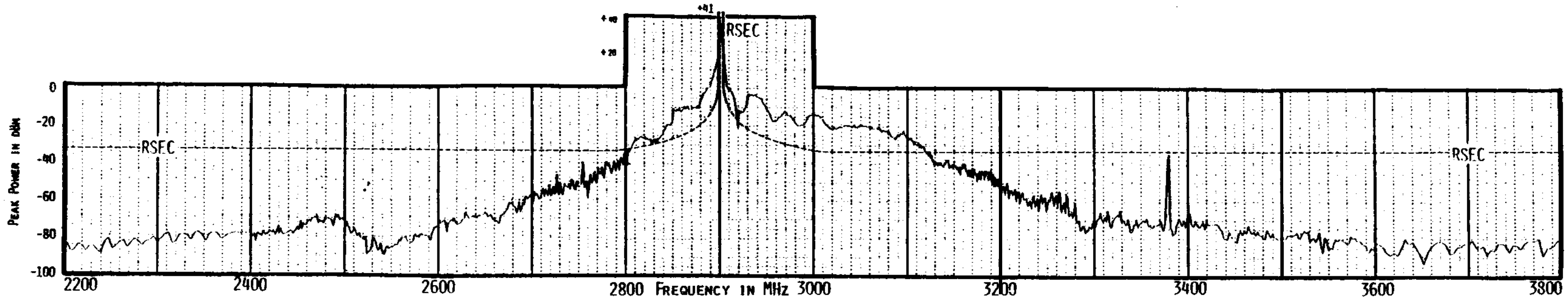
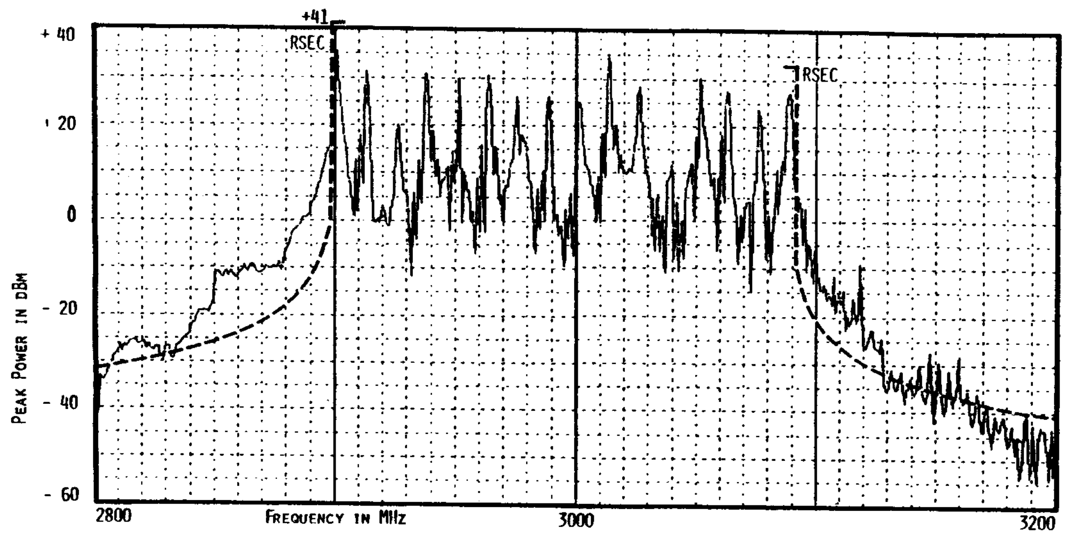


Figure 5. Airport surveillance radar, ASR-8, Klystron, diplexer filtered (Ch. A-2884 MHz, Ch. B-2824 MHz).



a. Extended spectrum, channel 1 only.



b. Detailed spectrum, all 16 channels.

Figure 6. TPS-43E, twystron, long-range tactical radar.

481 kilometers (260 nmi), transmitting 4 MW using a linear beam twystron. The transmitter control can select any one of 16 frequencies in the range from 2900 to 3100 MHz. It can operate on six different PRR's; the average PRR is 250 Hz using a 6.5 us pulse. The antenna uses six stacked feed horns to determine target height. The TPS-43E is designed for simultaneous long range search and height finding. The radar system is highly mobile and effective in severe weather and/or jamming environments. The radar uses Barker Phase Coded pulses to increase range accuracy and resolution. Pulse-to-pulse frequency diversity is used to decrease vulnerability to jamming. Figure 6a is an extended spectrum of the TPS-43E operating on only one channel. The measured response at 3380 MHz is an emission from the radar. Figure 6b is a graphically created composite produced by using an individual spectrum of each channel. A spectrum illustrating actual operation of all 16 channels could not be made because of operational constraints on the radar.

5. SPECTRA OF L-BAND LONG RANGE RADARS

The radars in this section are all used for long range detection (185 to 555 kilometers, or 100 to 300 nautical miles). Generally, they are used by the FAA for air route surveillance between air traffic control areas and by the military as part of the air defense early warning system. Near U.S. borders these radars are usually cosited with a long range height-finding radar such as the FPS-90. Often the AF and FAA maintain joint surveillance sites (JSS) to satisfy both responsibilities.

Measurement and analysis parameters, plus additional information about the radar spectra presented in this section, are listed in table 2.

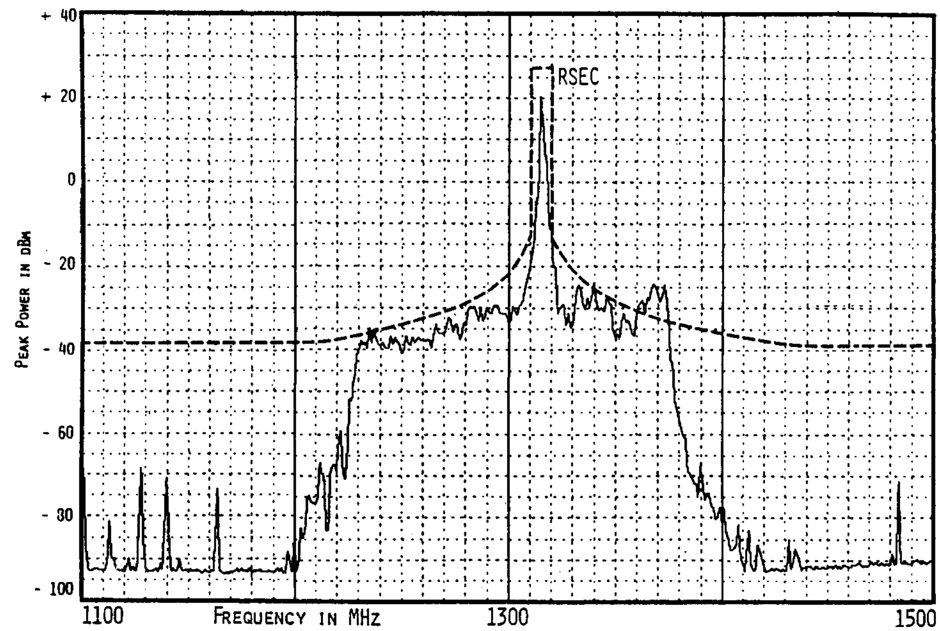
ARSR-1E (Fig. 7a). The ARSR-lE is an FAA two dimensional L-band (1215-1400 MHz) air-route-surveillance radar (ARSR) with a conventional magnetron feeding 400 kW peak power into an amplitron (crossed-field amplifier) to provide an additional 10 dB gain. The amplitron may be switched in or out as required by the operator. Amplitrons are characterized by a very wide noise floor only 40-60 dB below the fundamental. In many ARSR'S, including this one, a bandpass filter has been used to reduce the spurious sidebands outside the 1220-1380 MHz range.

ARSR-1E (Fig. 7b). This ARSR-lE does not use the 1220-1380 MHz bandpass filter often installed with ARSR-lE'S to reduce energy radiated by the crossed-field amplifier (amplitron) outside the frequency of operation. Above 1500 MHz, 7 dB should be added to the measured values to correct for a missing

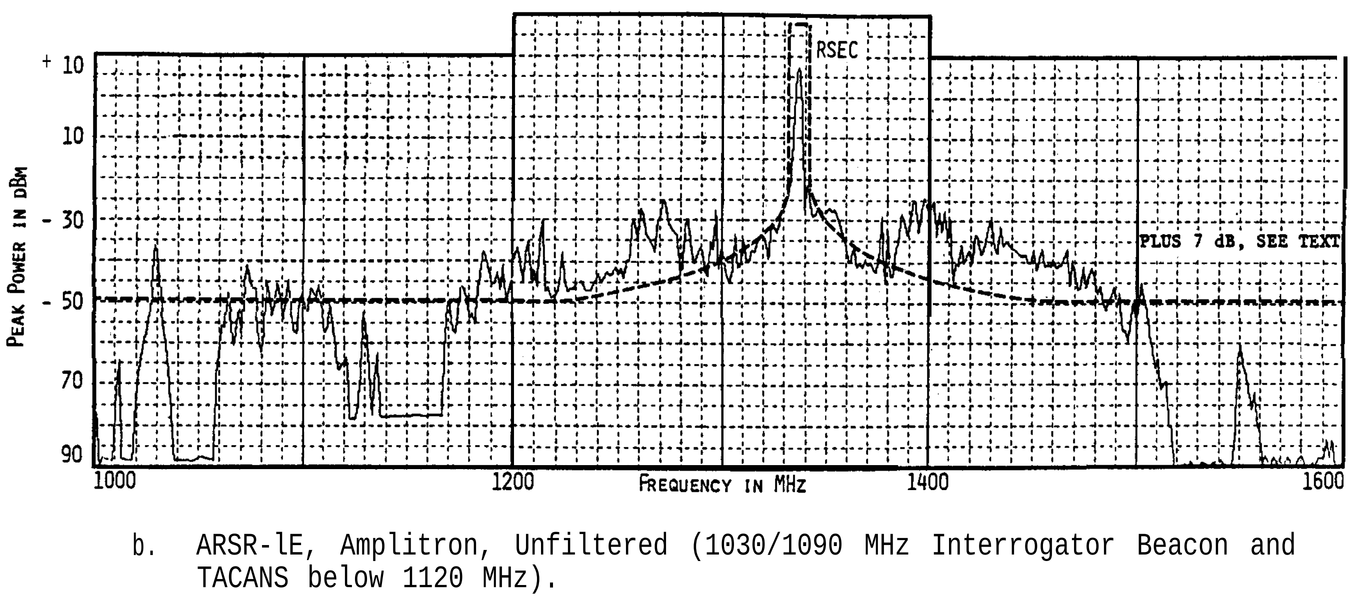
Table 2. Selected Operational and Measurement Parameters for L-band Long-Range Radars

Radar Equipment	Amplifier Type	Operating Frequency (MHz)	Pulse Repetition Rate (pps)	Pulse Duration (μs)	Pulse Rise Time (ns)	Peak Power (dBm)	Measurement Bandwidth(s) (kHz)	Figure Number
ARSR-1E	Amplitron (Filtered)	1315 [M]	359 [M]	2 [E]	300 [E]	96 [G]	1000	7a
ARSR-1E	Amplitron (Unfiltered)	1336 [M]	350 [M]	2 [E]	300 [E]	96 [E]	1500	7b
ARSR-1E	Amplitron (Filtered)	1316 [M]	348 [M]	2 [E]	300 [E]	96 [G]	1000 300	8
FPS-107	Klystron	1290 [M]	241 [M]	6.8 [M]	600 [M]	100 [G]	1000	9a
ARSR-3	Klystron	1268 [M]	340 [M]	2.2 [M]	150 [M]	77 [G]	3000	9b

[M] - Measured
[E] - Estimated
[G] - From Government Master File



a. ARSR-lE, Amplitron With Waveguide Filter.



b. ARSR-lE, Amplitron, Unfiltered (1030/1090 MHz Interrogator Beacon and TACANS below 1120 MHz).

Figure 7. Long-range air route surveillance radar, ARSR-lE.

calibration factor. The peaks at 1000 MHz, 1010 MHz, and 1030 MHz are from TACAN and interrogator beacons. The responses around 1090 MHz represent interrogator beacon replies.

ARSR-lE (Fig. 8). The spectrum shown here was selected from among the worst of the filtered amplitron ARSR-lE spectra that were measured. Figure 8b shows more detail in the middle 20 MHz of spectrum; note the decrease in measured amplitude caused by the more narrow 300 kHz measurement bandwidth.

FPS-107 (Fig. 9a). The FPS-107 is a two dimensional L-band long-range search radar designed for ground-controlled-intercept (GCI) applications in the air defense system. The FPS-107 uses a klystron, providing 10 MW peak power, and a 481 kilometer (260 nmi) range. The klystron, as illustrated here, is an impressive example of spectrum conservation.

ARSR-3 (Fig. 9b). The ARSR-3 is a two dimensional L-band air-route-surveillance radar with a detection range of 444 kilometers (240 nmi)--when operating in the diplex mode. Its klystron output provides 5 MW peak power with 3.3 kW average power. The radar can be operated in a non-stagger or stagger mode with 5, 7, or 8 discrete periods about the selected average PRR. When measured, the radar was still in a developmental stage and only one channel was operational.

6. SPECTRA OF HEIGHT-FINDING RADARS

All of the radars in this section are long-range, high-power, air-transportable, height-finders with a maximum range near 370 kilometers (200 nmi) and a height-finding capability of about 22,500 m (75,000 ft). They are normally collocated with an L-band search radar of comparable range--an ARSR-lE, for example. The height-finding radars operate in the 2700-2900" MHz band and in many areas contribute substantially to the spectrum crowding in this band. The older height-finders used conventional magnetrons, but many are being equipped with newer coaxial magnetrons whenever a major overhaul is scheduled. Several examples of conventional and coaxial magnetron radars are included in this section for comparison. The RSMS has been used to measure radar spectra for both types of output tube and in one case was able to measure the same radar both before and after it was converted from conventional to coaxial magnetron. The before-and-after measurements were made on an FPS-90, and care was taken to ensure that all measurement parameters were the same for each example including the measurement site location of the RSMS. Figure 10a shows the conventional magnetron radar spectrum, and figure 12a shows the coaxial magnetron spectrum for comparison. The conventional magnetron clearly displays the characteristic “porch” just prior to

a. ARSR-1E, Amplitron (1000 kHz measurement bandwidth), waveguide filtered.

b. ARSR-1E, Amplitron (300 kHz measurement bandwidth).

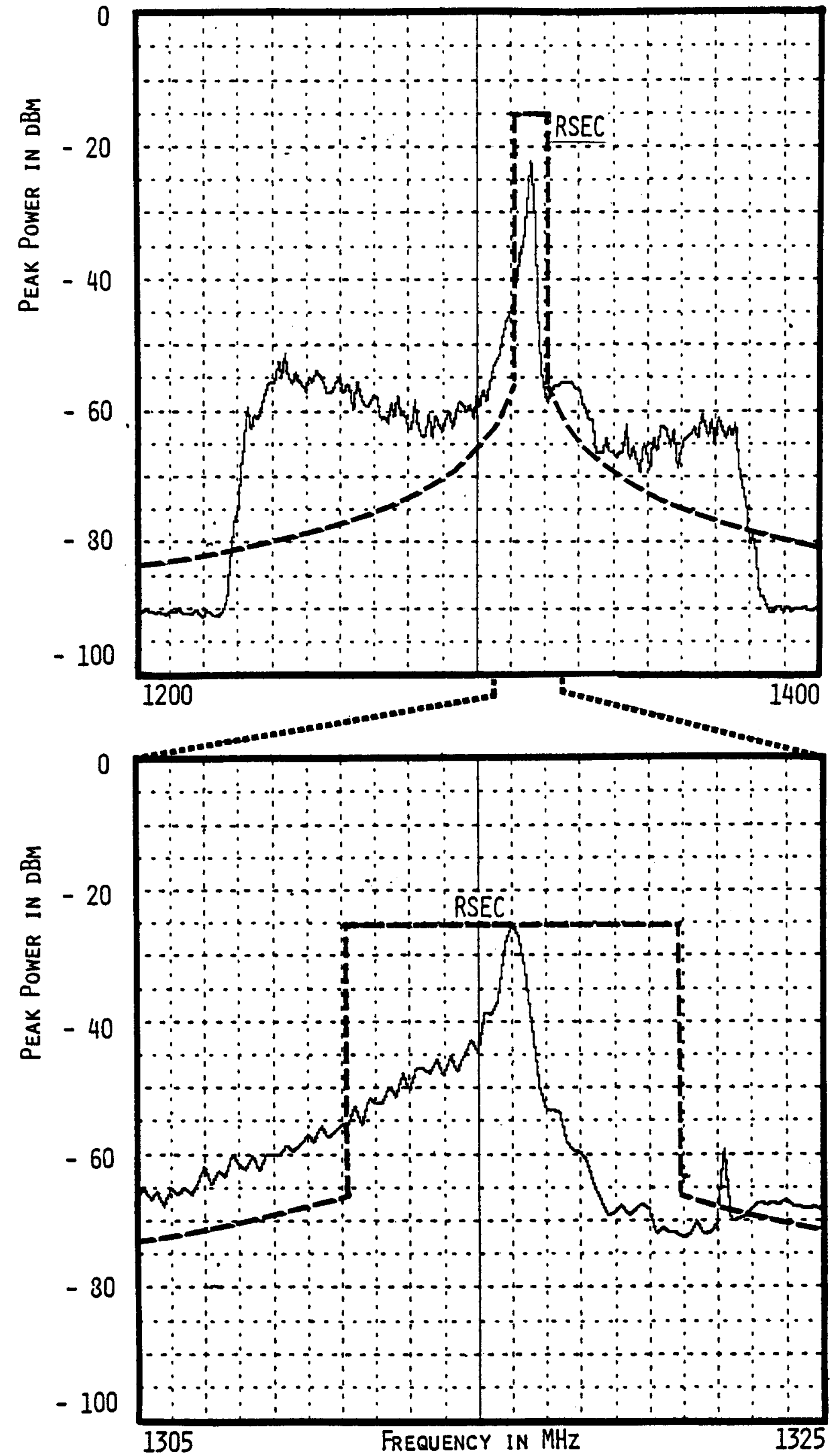
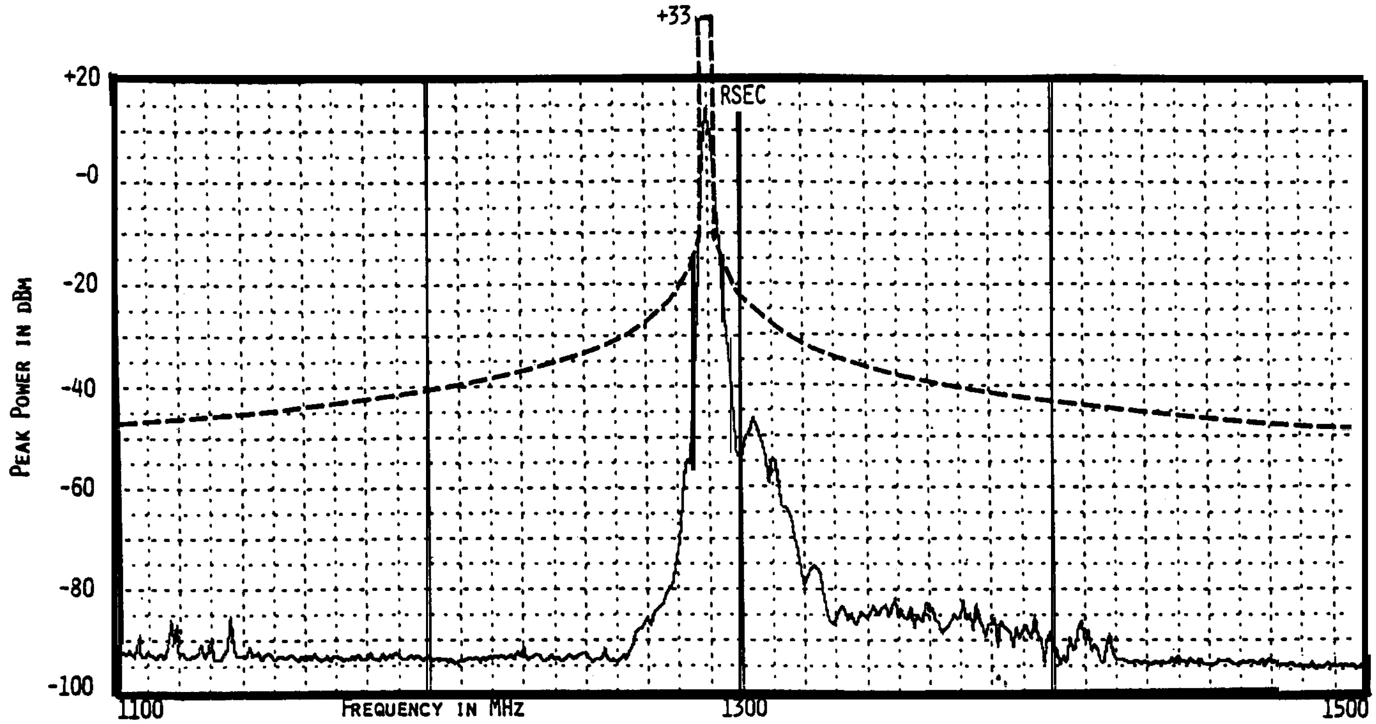
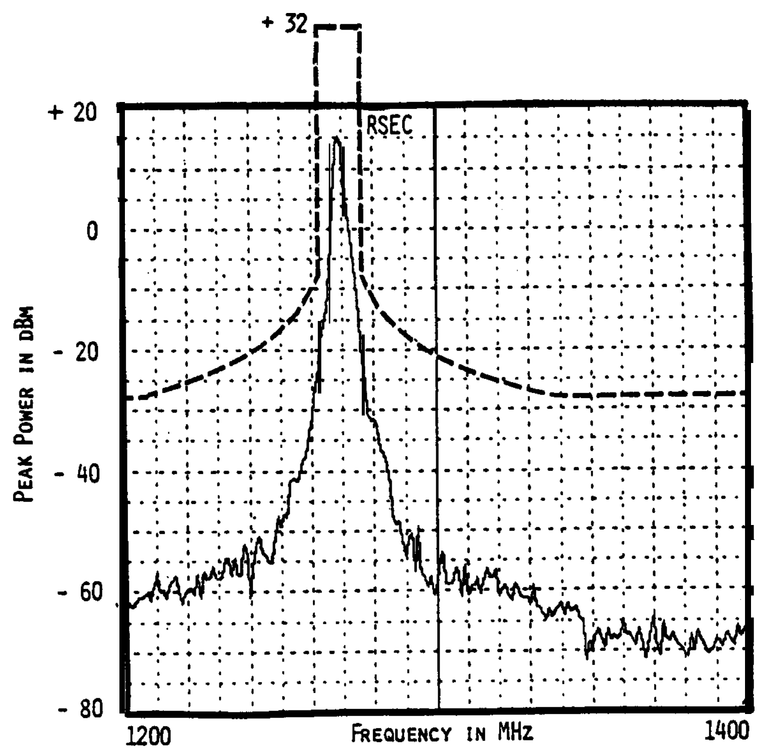


Figure 8. Long-range air route surveillance radar, ARSR-1E.



a. FPS-107, klystron.



b. ARSR-3, klystron.

Figure 9. Long-range search and air route surveillance radars, FPS-107, ARSR-3;

the fundamental frequency. It should be noted that the conventional magnetron was near the end of its recommended operational life when measured, and the coaxial magnetron was measured soon after installation. When comparing the two spectra, some questions are raised. The coaxial magnetron spectrum seems to be an improvement relative to the conventional magnetron. Would a new conventional magnetron have had an equal improvement, except in the “porch area?” Was any other maintenance performed which might have caused a change in output spectra? Above 3380 MHz the coaxial magnetron output is still measurable where the conventional magnetron output has fallen below the measurement system noise level.

A comparison of all of the S-band coaxial magnetron spectra in this section reveals another interesting phenomenon. The coaxial magnetrons also exhibit a characteristic [1, 2, 1] mode “hump” centered approximately 80 MHz above the fundamental. With the exception of the radar in Figure 12a (measured almost immediately after installation), all of the radars fail to meet the RSEC in the “hump” area. This coaxial magnetron characteristic will be discussed further in the next section.

Measurement and analysis parameters, plus additional information about the radar spectra presented in this section, are listed in table 3.

<u>FPS-90 (Fig. 10a). Conventional magnetron</u>. The spectrum of this radar may be compared with the spectrum of figure 12a, which is the same radar after overhaul and installation of a coaxial magnetron.

<u>FPS-90 (Fig. 10b). Conventional magnetron</u>. At the time this spectrum was measured, the radar was nearing its overhaul date and this conventional magnetron was replaced shortly afterwards by a coaxial magnetron.

<u>FPS-90 (Fig. 11a). Conventional magnetron</u>. This spectrum and figure llb represent classic examples of conventional magnetron spectra.

<u>FPS-90 (Fig. 11b). Conventional magnetron</u>. Note that this spectrum was measured in a 300 KHz bandwidth, and there is no correction necessary for the RSEC at the fundamental frequency.

<u>FPS-90 (Fig. 12a). Coaxial magnetron</u>. This spectrum may be compared with figure 10a which is the same radar, prior to modification, when it used a conventional magnetron.

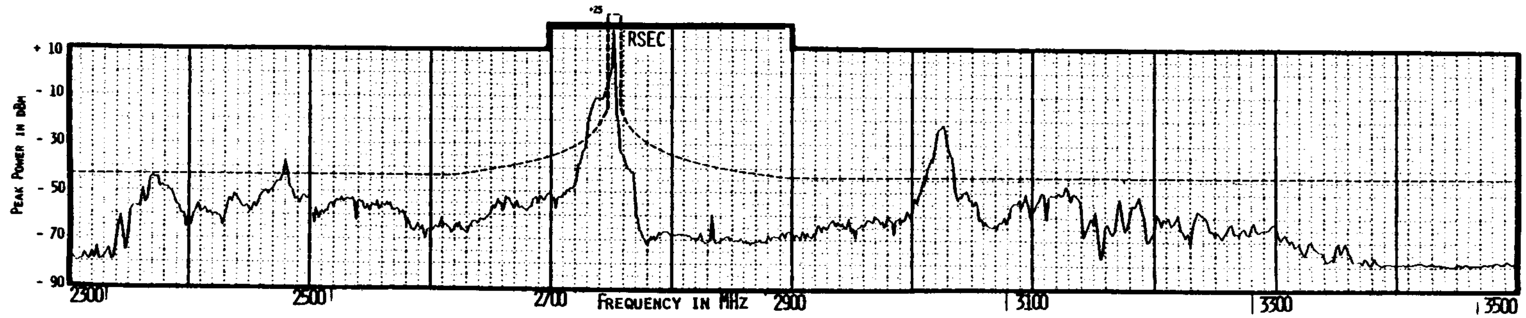
<u>FPS-90 (Fig. 12b). Coaxial magnetron</u>. To save measurement time, fewer data points were used above 3300 MHz hence the less detailed fine structure on the spectrum plot.

<u>FPS-6 (Fig. 13a). Coaxial magnetron</u>. The FPS-6 height-finding radar is essentially the same as the FPS-90 radar except for a mechanical variable-nod

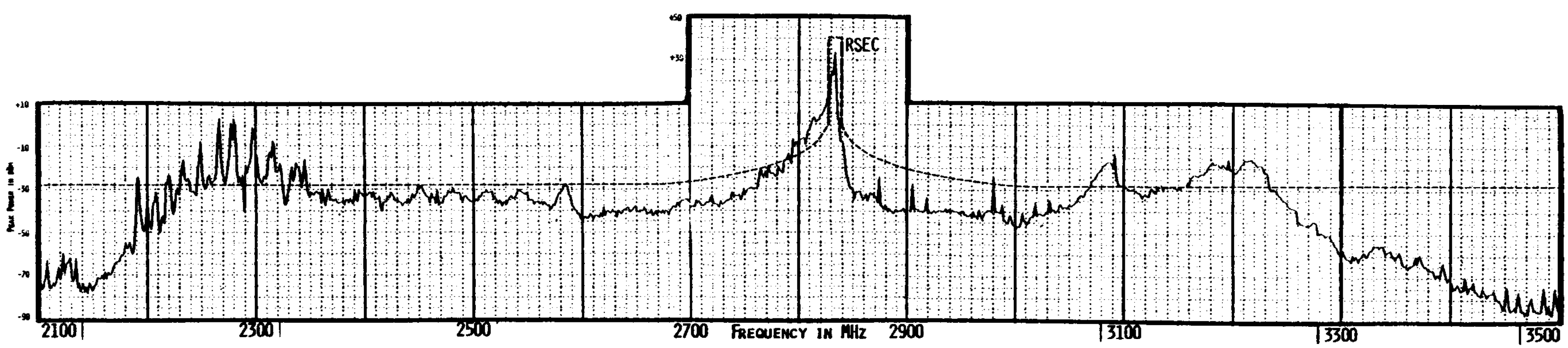
Table 3. **Selected Operational and Measurement Parameters for Height-Finding Radars**

Radar Equipment	Amplifier Type	Operating Frequency (MHz)	Pulse Repetition Rate (pps)	Pulse Duration (μs)	Pulse Rise Time (ns)	Peak Power (dBm)	Measurement Bandwidth(s) (kHz)	Figure Number
FPS-90	Conventional Magnetron	2737 [M]	354 [M]	2 [E]	200 [E]	97 [E]	1000	11a
FPS-90	Conventional Magnetron	2777 [M]	278 [M]	2 [E]	200 [E]	97 [G]	300	11b
FPS-90	Conventional Magnetron	2833 [M]	370 [G]	2 [G]	200 [E]	97 [G]	1000	10b
FPS-90	Conventional Magnetron	2752 [M]	360 [E]	2 [E]	200 [E]	95.5 [E]	1000	10a
FPS-90	Coaxial Magnetron	2752 [M]	363 [M]	2.75 [M]	300 [M]	95.5 [E]	1000	12a
FPS-6	Coaxial Magnetron	2750 [M]	360 [M]	3.6 [M]	275 [M]	95.5 [G]	1000	13a
FPS-90	Coaxial Magnetron	2745 [M]	370 [M]	3 [M]	530 [M]	96 [E]	1000	13b
FPS-90	Coaxial Magnetron	2808 [M]	354 [M]	3.15 [M]	400 [M]	96 [E]	1000	13c
FPS-90	Coaxial Magnetron	2787 [M]	369 [M]	3 [M]	400 [M]	96.5 [G]	3000	12b

[M] – Measured
[E] – Estimated
[G] – From Government Master File

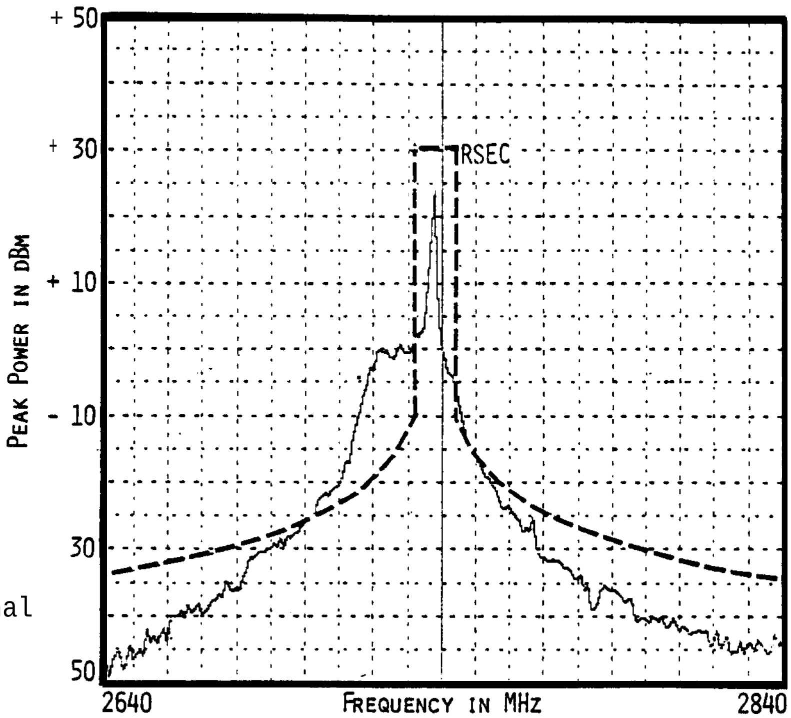


a. FPS-90, conventional magnetron.

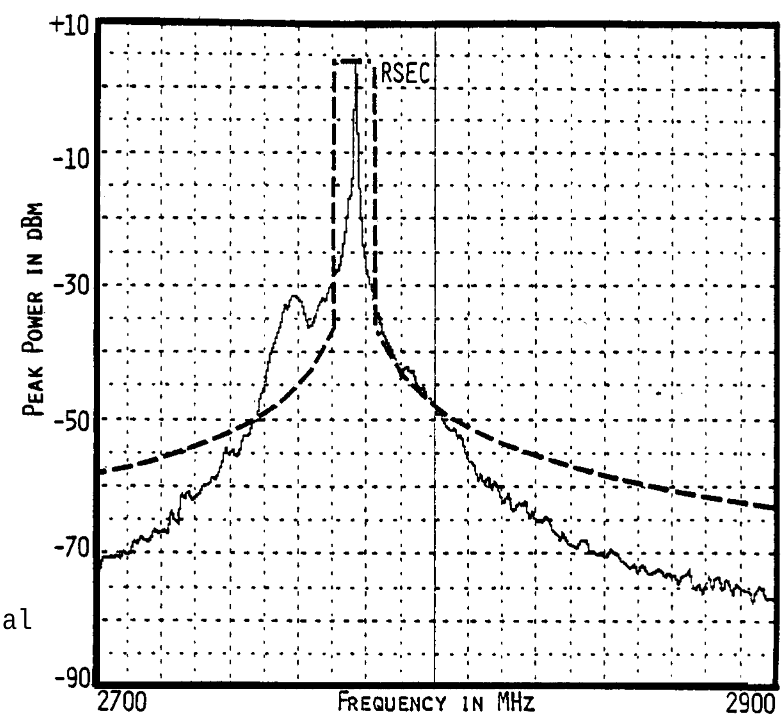


b. FPS-90, conventional magnetron.

Figure 10. Height-finding radars, FPS-90.

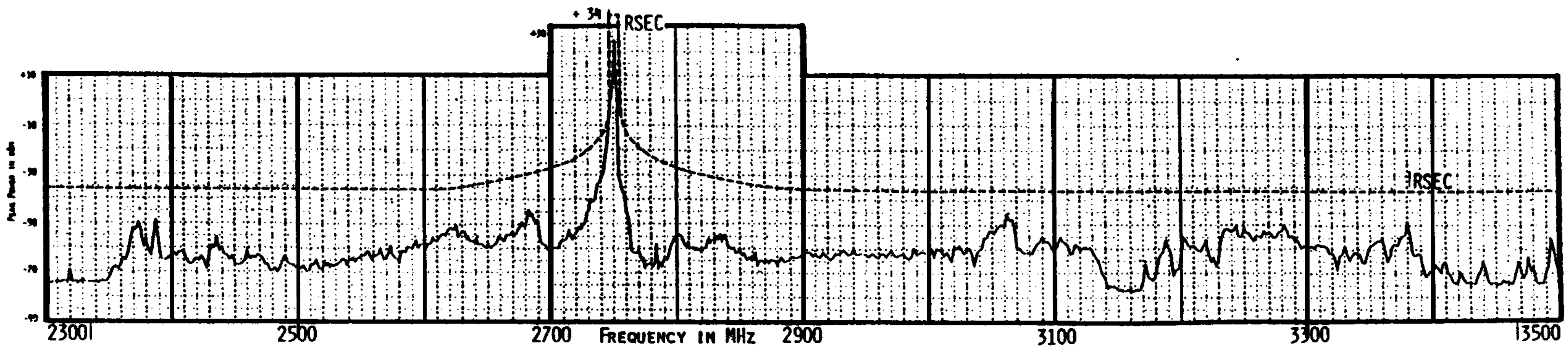


a. FPS-90, conventional magnetron.

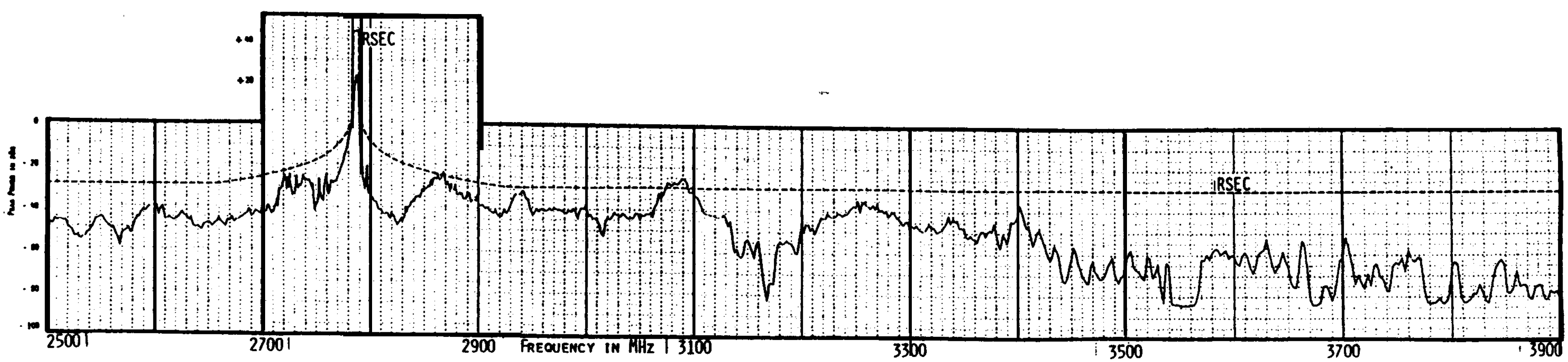


b. FPS-90, conventional magnetron.

Figure 11. Height-finding radars, FPS-90.

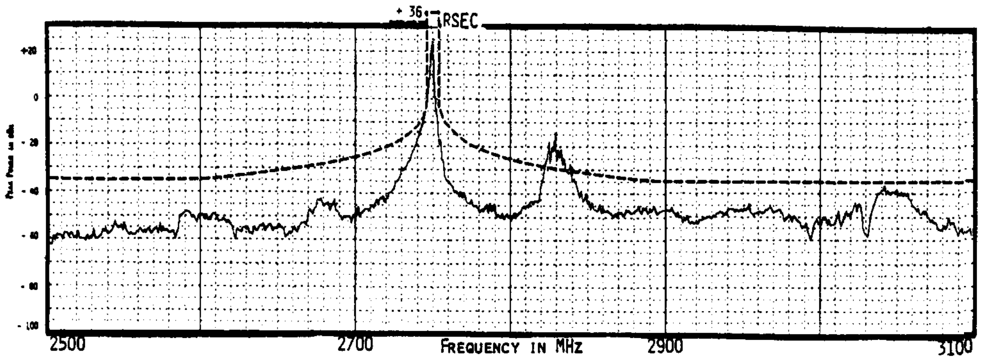


a. FPS-90, coaxial magnetron.

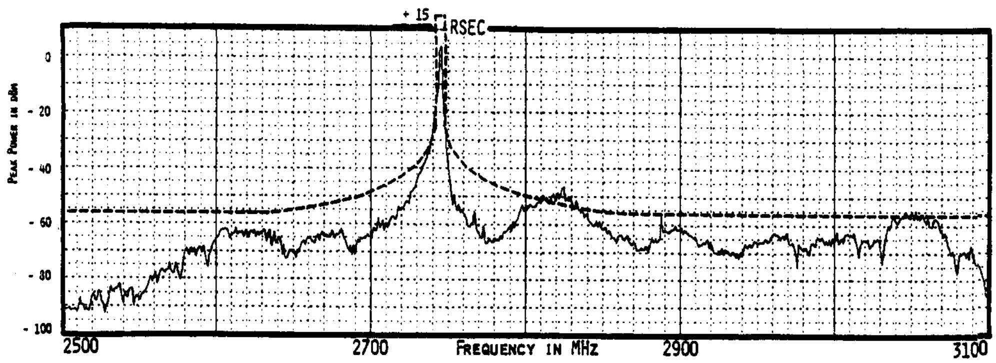


b. FPS-90, coaxial magnetron.

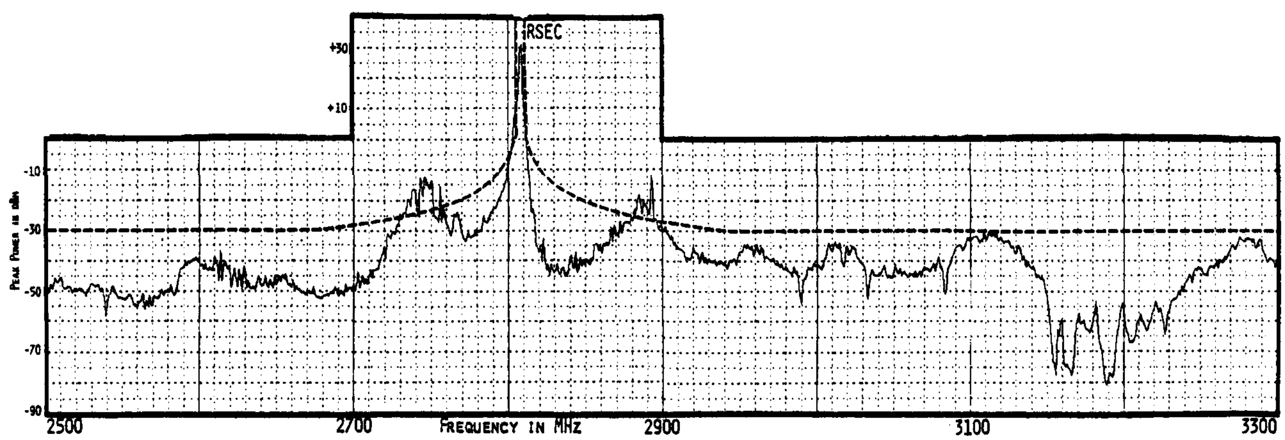
Figure 12. Height-finding radars, FPS-90.



a. FPS-6, coaxial magnetron.



b. FPS-90, coaxial magnetron.



c. FPS-90, coaxial magnetron.

Figure 13. Height-finding radars, FPS-6, FPS-90.

feature in the elevation drive mechanism of the antenna.

FPS-90 (Fig. 13b and c). Coaxial magnetrons. The FPS-90 in figure 13c is distinctive because it exhibits an additional "hump" centered approximately 60 MHz below the fundamental. This characteristic of coaxial magnetrons has been noted, to a lesser extent, on other S-band coaxial magnetrons.

7. SPECTRA OF WEATHER RADARS

This section contains spectra of C-band and S-band weather radars using both conventional and coaxial magnetrons. There are three conventional magnetron spectra, one S-band and two C-band, and ten coaxial magnetron spectra included here. Two of the coaxial spectra (Figs, 15a and b) are measurements of the same radar and were included to show the spectral differences between the long and short transmitted pulse width. Figure 17 contains extended emission spectra of three different radars and illustrates the large amount of spectrum containing potential interference energy. Figures 17a and d are different radars with similar magnetrons and were measured across the frequency spectrum until the received signal level dropped below the measurement system noise level. Figures 17b and 17c are the same radar, measured twice, illustrating the effectiveness of a band reject filter installed to protect a selected portion of the spectrum (5950-6450 MHz).

An area of concern with coaxial magnetrons is the "hump" about 100 MHz (80 MHz, S-band) above the fundamental frequency. This hump is caused by a spurious oscillation mode in the' coaxial magnetron. It should be noted that the character of the emission changes significantly in this area, and that the particular measurement method which was used here overemphasized the average energy amplitude of the emission spectra for this region. For example, using a minimum measurement period of 0.5 s at each frequency, and a typical PRR of 260 pps, a measurement period at each frequency contained about 130 pulses. Over most of the frequency range each radar pulse produced about the same amount of energy, and it made no difference whether the peak power was measured from one pulse or from 130 pulses. In the "hump" region, however, there was a significant spread in the amount of energy from pulse to pulse, often as much as 20 dB. This spread was easily visible by observing the instantaneous video waveforms before they were processed by the peak detectors. Since the measured spectrum was determined by the peak amplitude of the highest pulse out of the 130 pulses at each frequency in the "hump" region (instead of the peak amplitude of the average pulse for 130 pulses), the measurements emphasized the occasional high amplitude pulse. The intermittent nature of the high amplitude pulses is especially visible in the spectra of the WSR-74C. For purposes of comparison with the rest of the spectrum, it would be quite believable to suggest that the “hump” region should be reduced by as much as 10 dB. However, we do not have any more specific quantitative data to support this adjustment.

Measurement and analysis parameters, plus additional information about the radar spectra presented in this section, are listed in table 4.

WSR-57 (Fig. 14a). Conventional magnetron. The WSR-57 is an S-band weather radar using a conventional magnetron with 500 kW peak power for an effective range of 463 kilometers (250 nmi). It can be used to establish height, distance, density, and course of a storm area.

FPS-77 (Fig. 14b). Conventional magnetron. The FPS-77 is a C-band weather radar using a conventional magnetron with 350 kW peak power for an effective range of 370 kilometers (200 nmi). As noted with other conventional magnetrons, this radar does not meet the RSEC in the “porch” region.

FPS-77 (Fig. 14c). Conventional magnetron. This radar does not meet the RSEC in the “porch” region.

WSR-74S (Fig. 15a). Coaxial magnetron. The WSR-74S is an S-band weather radar using a coaxial magnetron. The National Weather Service 74C and 74S series weather-surveillance-radars (WSR) are essentially the same except for operating frequency. They are meteorological radars generally employed to establish cloud height, distance, density, rainfall (cm/hr), and position of a storm area for weather observation, storm warning, hydrology, airways weather briefing, and weather research. This spectrum and that of Figure 15b, are from the same radar. They are shown together here to illustrate the differences that occur when the transmitted pulse width is changed. This spectrum was made while the radar operated in the 4 us (nominal) pulse width mode.

WSR-74S (Fig. 15b). Coaxial magnetron. This spectrum and Figure 15a, are from the same radar. They are together here to illustrate the differences that occur when the transmitted pulse width is changed. This spectrum was made while the radar operated in the 1.15 us (nominal) pulse width mode.

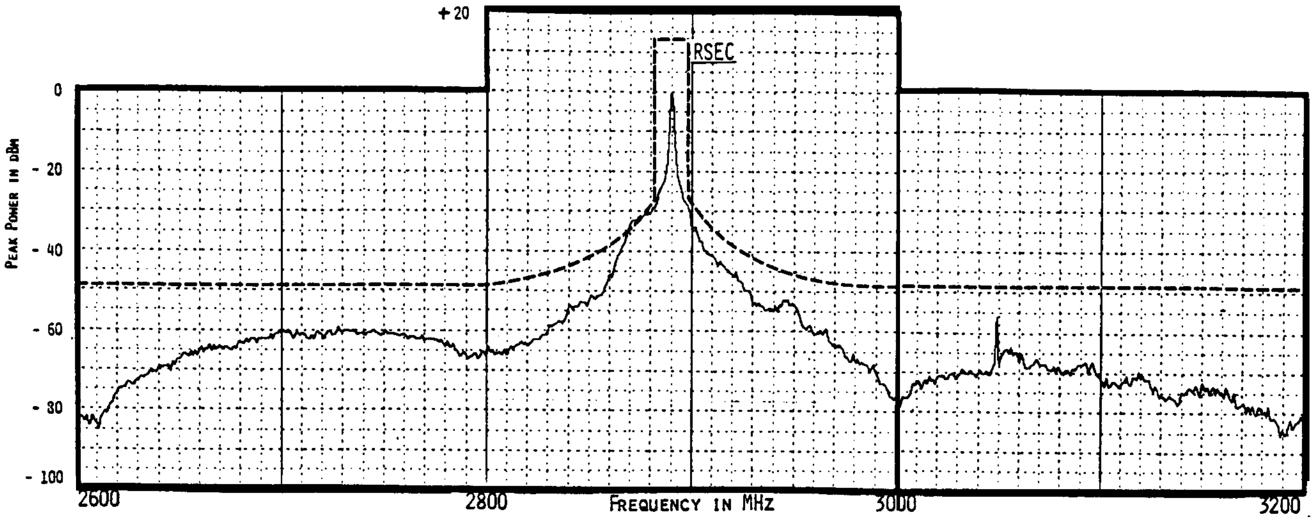
WSR-74S (Fig. 15c). Coaxial magnetron. This spectrum clearly illustrates the coaxial magnetron “hump” discussed at the beginning of this section.

WSR-74C (Fig. 16a). Coaxial magnetron. The WSR-74C is a C-band weather radar using a coaxial magnetron. This spectrum and Figures 16b and c, show the variability that occurs in the "hump" region, as discussed at the beginning of this section.

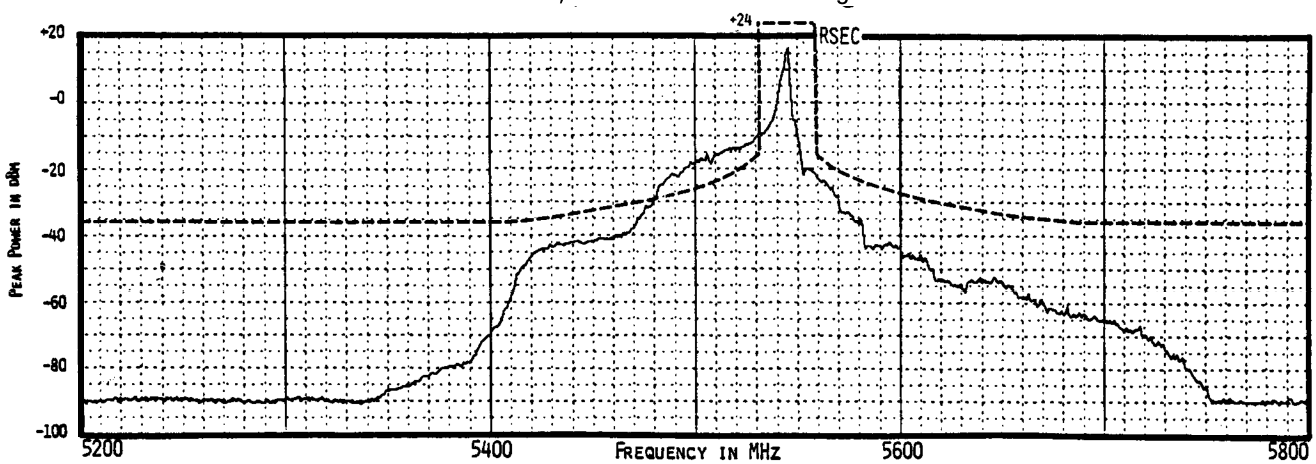
Table 4. Selected Operational and Measurement Parameters for Weather Radars

Radar Equipment	Amplifier Type	Operating Frequency (MHz)	Pulse Repetition Rate (pps)	Pulse Duration (μs)	Pulse Rise Time (ns)	Peak Power (dBm)	Measurement Bandwidth(s) (kHz)	Figure Number
WSR-57	Conventional Magnetron	2890 [M]	163 [M]	4.1 [M]	50 [M]	87 [G]	1000	14a
FPS-77	Conventional Magnetron	5545 [M]	323 [M]	2.3 [M]	30 [M]	85.5 [G]	1000	14b
FPS-77	Conventional Magnetron	5637 [M]	324 [M]	2.1 [E]	50 [E]	85.5 [E]	1000	14c
WSR-74S	Coaxial Magnetron	2890 [M]	259 [E]	4.3 [M]	300 [M]	84 [E]	1000	15a
WSR-74S	Coaxial Magnetron	2890 [M]	259 [E]	1.15 [E]	500 [E]	84 [E]	1000	15b
WSR-74S	Coaxial Magnetron	2848 [M]	259 [E]	4.3 [M]	150 [E]	84 [E]	1000	15c
WSR-74C	Coaxial Magnetron	5623 [M]	259 [M]	3.3 [M]	36 [M]	84 [E]	1000	16a
WSR-74C	Coaxial Magnetron	5622 [M]	259 [E]	3.3 [M]	30 [M]	84 [E]	1000	16b
WSR-74C	Coaxial Magnetron	5608 [M]	259 [E]	3.3 [M]	33 [M]	84 [E]	1000	16c
WSR-74C	Coaxial Magnetron	5627 [M]	299 [M]	3.25 [M]	50 [M]	84 [G]	1000	17a
WSR-74C	Coaxial Magnetron	5629 [M]	259 [E]	3.3 [E]	40 [E]	84 [E]	1000	17b
WSR-74C	Coaxial Magnetron	5627 [M]	259 [E]	3.3 [E]	40 [E]	84 [E]	1000	17c
WR100-2/77	Coaxial Magnetron	5570 [M]	254 [M]	2.1 [M]	40 [M]	84 [M]	1000	17d

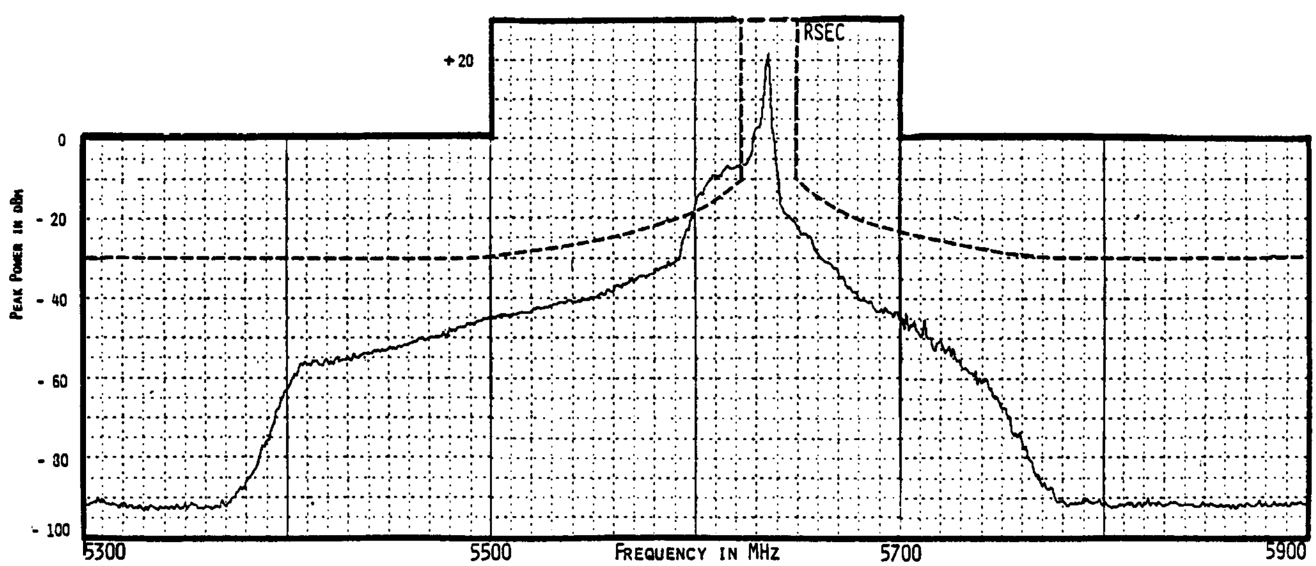
[M] - Measured
[E] - Estimated
[G] - From Government Master File



a. WSR-57, conventional magnetron.

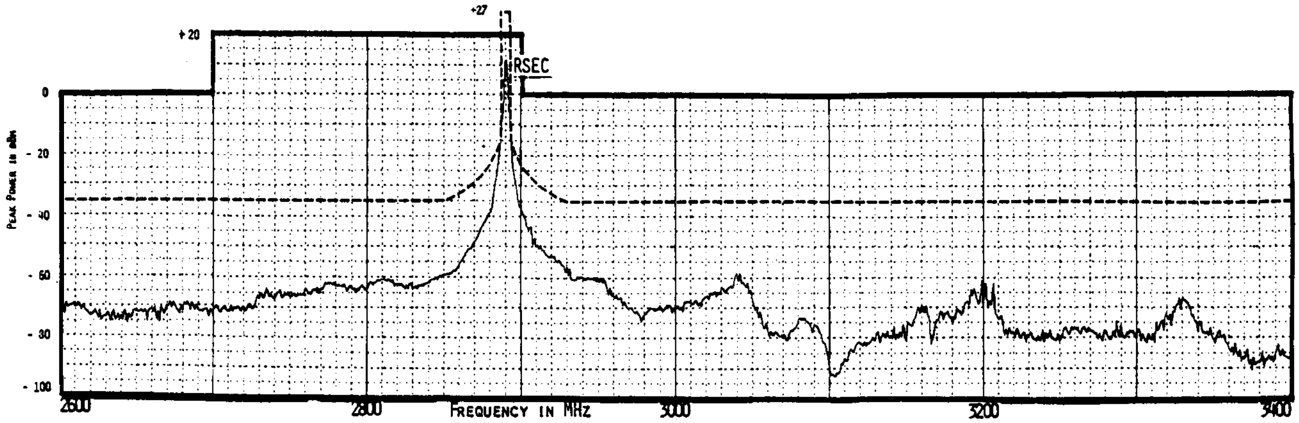


b. FPS-77, conventional magnetron.

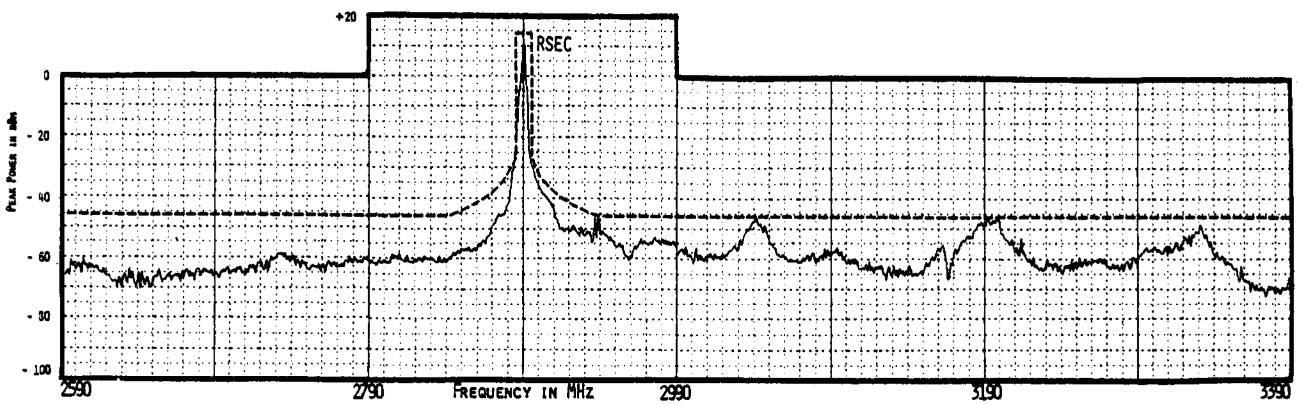


c. FPS-77, conventional magnetron.

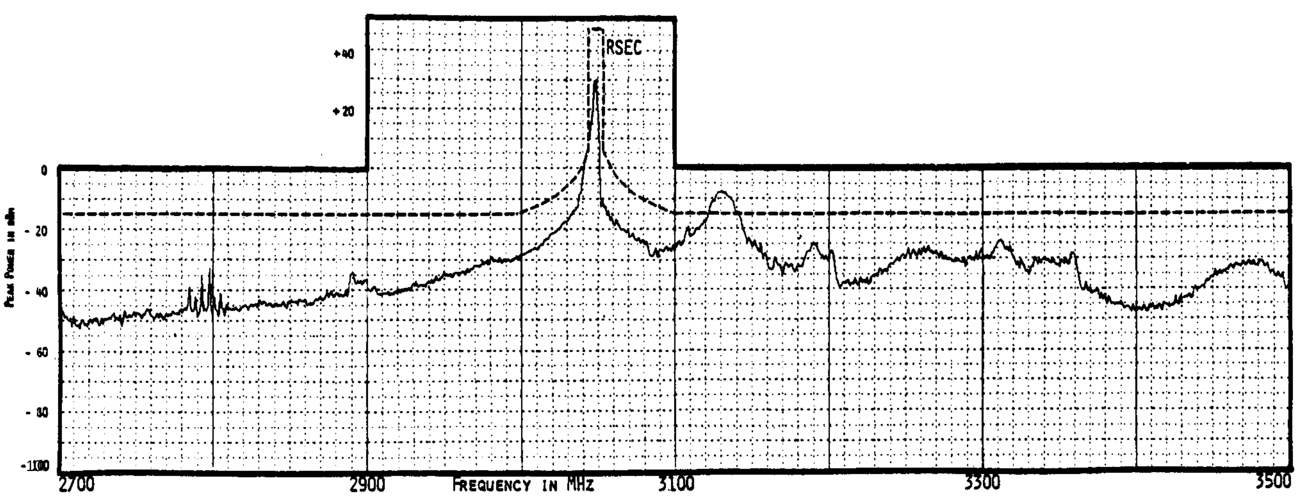
Figure 14. Weather radars, WSR-57, FPS-77.



a. WSR-74S, coaxial magnetron (long pulse width).

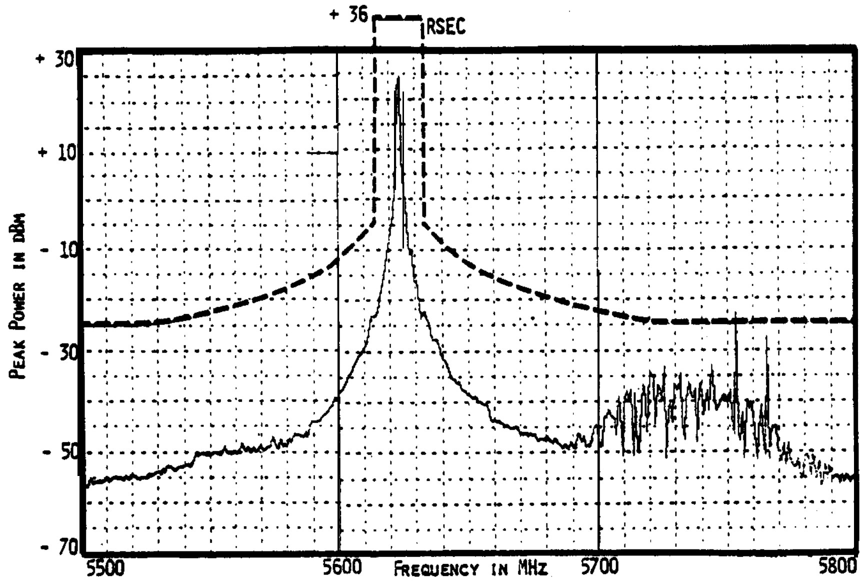


b. WSR-74S, coaxial magnetron (short pulse width).

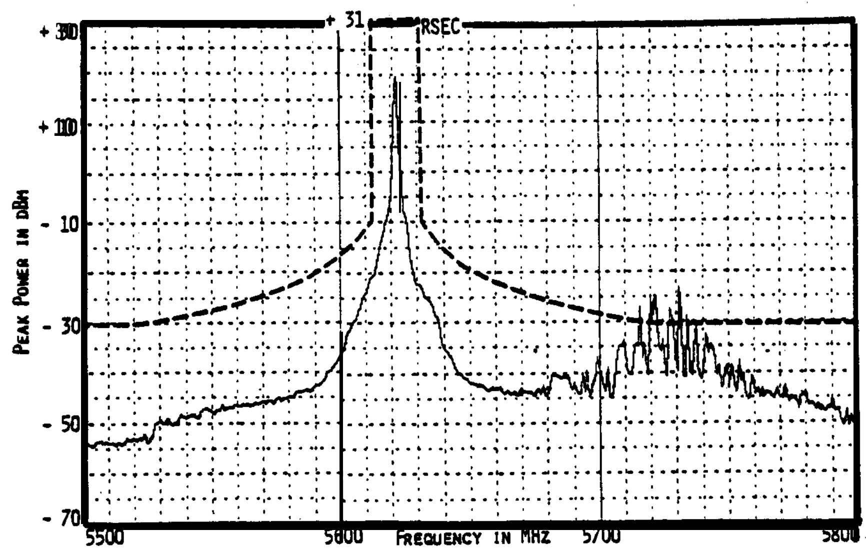


c. WSR-74S, coaxial magnetron.

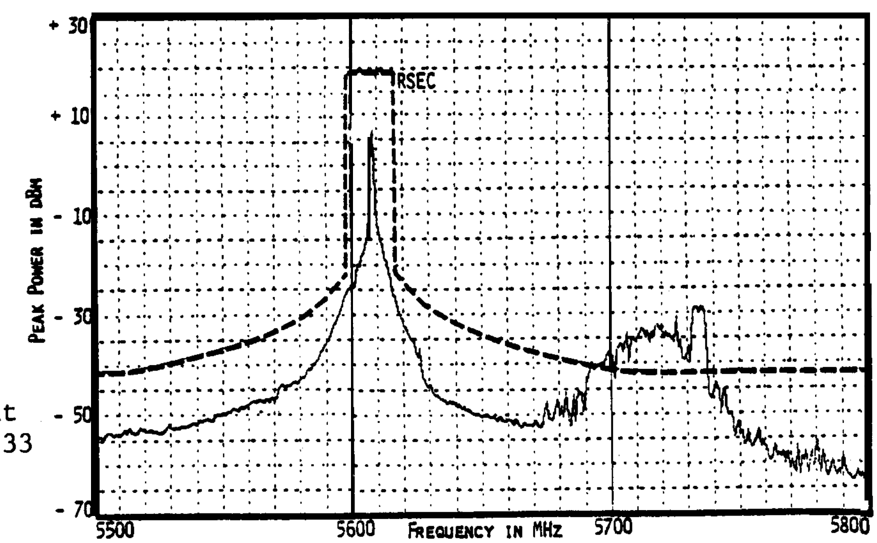
Figure 15. Weather Radars, WSR-74S.



a. WSR-74C coaxial magnetron.

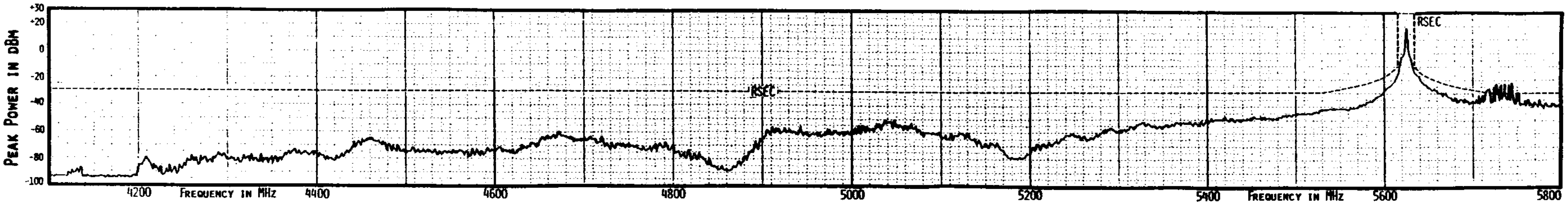


b. WSR-74C, coaxial magnetron.



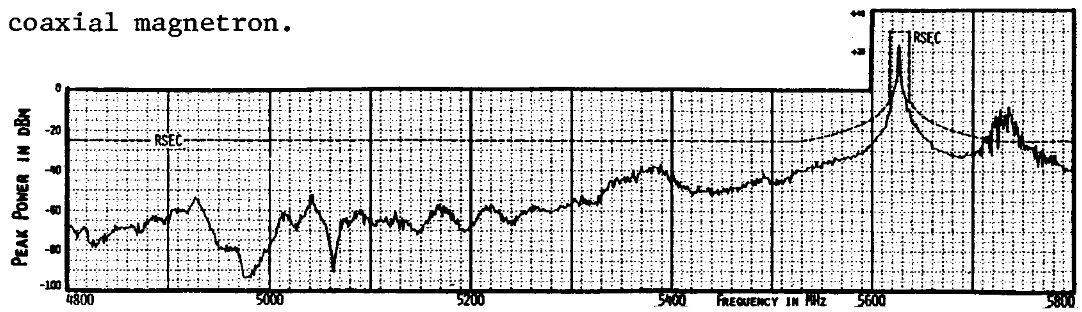
c, **WSR-74C, coaxial magnetron (measurement error at 5733 MHz).**

Figure 16. Weather radars, WSR-74C.

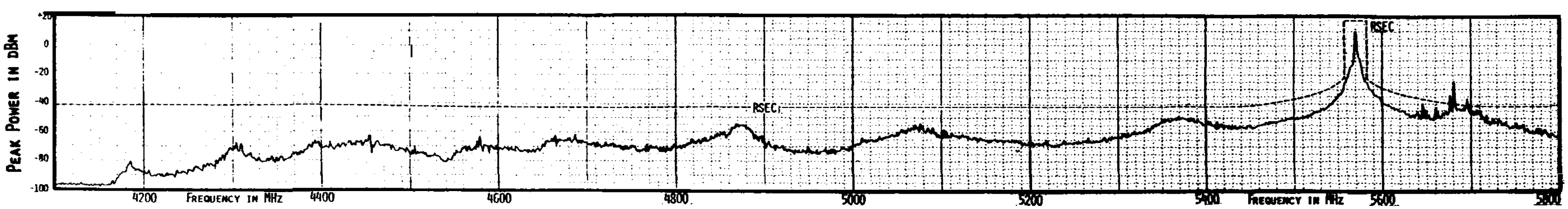


a. WSR-74C, coaxial magnetron.

b. WSR-74C, coaxial magnetron.

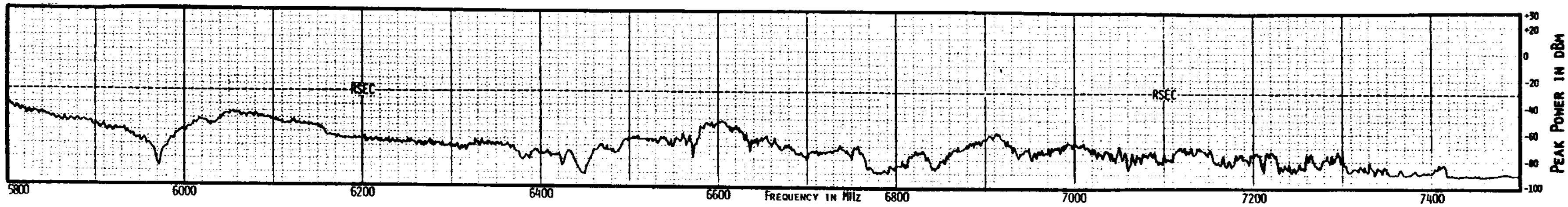


c. WSR-74C, coaxial magnetron, with band reject filter (5950-6450 MHz).

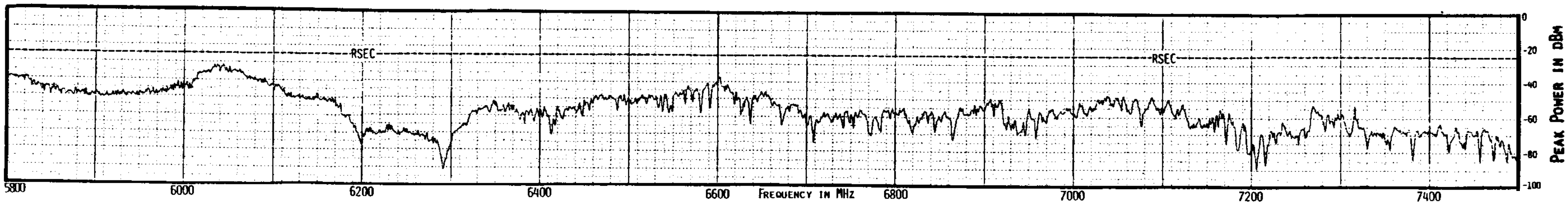


d. WR 100-2/77, coaxial magnetron.

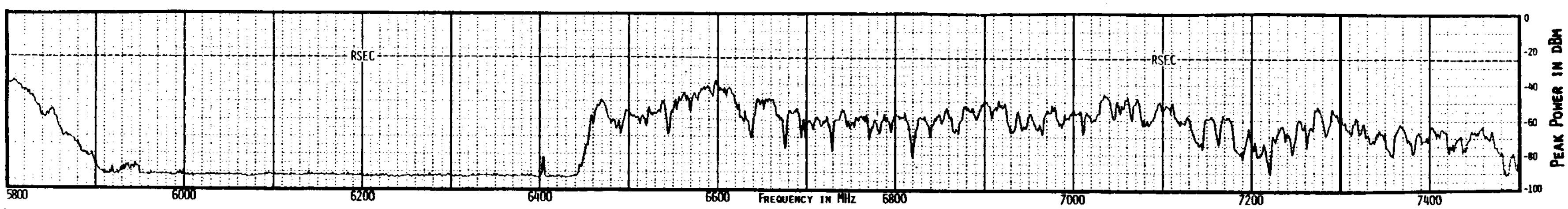
Figure 17. Weather radars, WSR-74C, WR 100-2/77.



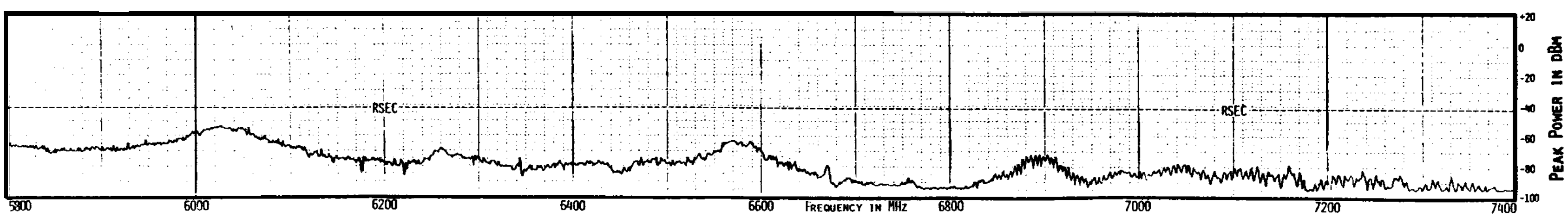
a. WSR-74C (continued).



b. WSR-74C (continued).



c. WSR-74C, with filter (continued).



d. WR 100-2/77 (continued).

Figure 17. Weather radars (continued).

The radars had all been recently installed and are presumed to have been identical in all respects.

WSR-74C (Figs. 16b and c). Coaxial magnetrons. A measurement error (fig. 16c) occurred at 5732 MHz causing the 5 MHz wide peak in that region.

WSR-74C (Fig. 17a). Coaxial magnetron. This extended radar spectrum of a C-band weather radar was continued until the received signal level dropped below the measurement system noise level.

WSR-74C (Fig. 17b). Coaxial magnetron. This figure and figure 17C, following, illustrate the same radar measured with (figure 17b) and without (figure 17c) a band reject filter at 6200 MHz.

WSR-74C (Fig. 17c). Coaxial magnetron. A feature of this spectrum is the attenuation of the radar emission over 5950-6450 MHz, resulting from use of a special filter designed to protect a local microwave link. Comparing this spectrum with Figure 17b illustrates the effectiveness of using filters to protect collocated users of the frequency spectrum.

WR100-2/77 (Figure 17d). Coaxial magnetron. This C-band weather radar is operated by a local television station, and is described by the manufacturer as being essentially the same as a WSR-74C. The extended spectrum was made in full cooperation with the television station personnel and spectrum data collection was continued until the signal level fell below the measurement system noise level.

8. CONCLUSIONS

Different types of radar output tubes vary markedly in the amount of spectrum they “consume” in normal operation. In many cases, much more spectrum is used than is needed for proper radar operation. The extra spectrum is consumed by spurious sidebands produced by radar output tube operation. The amplitrons and twystrons are particularly “dirty” and generally do not meet the RSEC limits used in this report. On the other hand, they can produce high-power, frequency-agile outputs with high efficiency in a small package. Bandpass filters can be used to reduce out-of-band emissions, but this could hamper frequency agility in some operations.

Klystrons produce very clean spectra. When klystrons are combined with narrowband diplexers, the spectra are improved even more. The rapid fall-off and the deep suppression of sidebands make it possible to site radars closer together in frequency and space than would be possible with other types of output tubes. Klystrons, however, are large and expensive and possibly best suited to fixed installations.

The conventional magnetron is small and cheap, and is extensively used in many types of equipment. There is a wide range of spectra produced by conventional magnetrons, compare the spectra of Figure 2a and 2b, for example. This may be because conventional magnetrons are subject to wide variations in equipment design and operational maintenance. When the conventional magnetron is combined with narrowband filters or diplexers, as in the GPN-20, excellent spectrum characteristics are possible.

The coaxial magnetron produces a cleaner spectrum (near center frequency) than the conventional magnetron, completely eliminating the "porch" which is present with conventional magnetrons. Farther away in frequency, however, the improvement is not particularly noticeable. A "hump" about 100 MHz above the fundamental frequency is present in many coaxial magnetron spectra. Whether the [1, 2, 1] mode "hump" of a coaxial magnetron spectrum is more objectionable than the frequency pulling "porch" (produced by conventional magnetrons) is a matter of question.

The spectrum used by various combinations of output tubes and bandpass filters is one factor in determining how much value is gained from the spectrum allocated to radar. Many factors besides the level of unnecessary sidebands must obviously be included in the choice of radar output tubes. However, the difference between the amount of spectra used by various tube types is very substantial and must not be totally ignored. A majority of the frequency spectrum allocated to radar is currently filled by unnecessary spurious sidebands produced by dirty radar output tube technology. The widespread use of cleaner output tube technology would provide room for many more radars in existing bands.

9. REFERENCES

NTIA (1980), Manual. of Regulations and Procedures for Federal Radio Channel Frequency Management, Revised Edition, Chapter 5, January.

Hinkle, R. L., R. M. Pratt, and R. J. Matheson (1976), Spectrum resource assessment in the 2.7 to 2.9 GHz band phase II: measurements and model validation (Report No. 1), OT Report 76-97.

Hinkle, R. L. (1980), Spectrum resource assessment in the 2.7 to 2.9 GHz band phase II: LSR deployment in the Los Angeles and San Francisco areas (Report No. 3), NTIA Report 80-38.

Matheson, R. J. (1977), A radio spectrum measurement system for frequency management data, IEEE Transactions, Electromagnetic Compatibility, EMC-19, No. 3, pp. 225-230.

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APPENDIX: RADAR SPECTRUM ENGINEERING CRITERIA (RSEC) CALCULATIONS

The RSEC to be applied to each radar spectrum is defined in section 5.3 of the NTIA Manual of Regulations and Procedures for Federal Radio Frequency Management. Several radar parameters--operating frequency, peak power, transmitting pulse shape, type of radar, and procurement or overhaul date--determine the RSEC emission bandwidth and levels to be applied to the radar spectra. Based on these parameters, some of the radars presented in this report were in a different RSEC category at the time the measurements were made; however, for purposes of technical comparability, the same RSEC is applied to all of the spectra. The criteria we selected do apply to non-FM pulse radars having a rated peak power of more than one kilowatt and operating at less than 40 GHz, and do properly apply to many of the radars included in this report.

The RSEC is concerned with the difference between spectral energy measured at f_o and at sideband frequencies. As long as the measurement system is handling the spectral energy at f_o and at sideband frequencies identically, the RSEC may be compared directly to the measurements. As noted before, Figure 5 for example, the RSEC limit often starts several decibels above the peak response of the radar. This difference is caused by a correction factor that must be added when the spectrum is measured with a bandwidth larger than l/t, where t is the pulse width of the radar being measured. For measurement bandwidths greater than l/t, but smaller than l/t_r, where t_r is the radar pulse rise time, the measurement system responds accurately to the emission at f_o but sees an impulse at sideband frequencies. As bandwidth, B, is increased, the measured value of signal at f_o will remain constant while the signal at sideband frequencies will increase at a 20 log B rate. For measurement bandwidths less than l/t, the sideband spectra fall below system noise. For measurement bandwidths outside the range between l/t and l/t_r, no correction is necessary. However, use of measurement bandwidths greater than l/t offer advantages in measurement system sensitivity in the sideband areas of the radar and allow accurate measurement of received radar peak power and pulse width.

For a measurement bandwidth between l/t and l/t_r, the correction factor may be computed from some well-known relationships between impulse bandwidth and peak response.

From the RSEC:

$$P_t = P_p + 20 \log (Nt) + 10 \log (PRR) - PG - 90 \quad (1)$$

where, P_p = peak transmitted power (dBm)
t = emitted pulse duration (us)
PRR = pulse repetition rate (pulses per second)
P_t = maximum spectral level (dBm/kHz)
PG = processing gain (dB)
N = total number of chips (subpulses) contained in the pulse.

assuming that the processing gain is 0 and the number of chips is 1 (for radars in this report) we can convert to:

$$P_t = P_p + 20 \log t + 10 \log (PRR) - 90 \quad (2)$$

If t is expressed in s instead of us and P_t is expressed in dBm/Hz instead of dBm/kHz, this becomes:

$$P_t = P_p + 20 \log t + 10 \log (PRR).$$

Converting from dBm to absolute units gives:

$$P_t = P_p \times t^2 \times PRR, \quad (3)$$

where P_t is in mW/Hz, P_p is transmitted power in mW, t is pulse width in s, and PRR is in pulses/s.

Another equation relates impulse bandwidth and system responses to P_t at a frequency in the sidebands of the radar:

$$P_t \times b_p = p_i \times l/b_i \times PRR,$$

where b_p is the power bandwidth of the system; p_1 is the peak response from an impulse, and b_i is the impulse bandwidth.

This can be solved to give:

$$P_t = l/b_p \times l/b_i \times p_i \times PRR \quad (4)$$

Equations (3) and (4) can be combined by assuming that the P_t is equal for measurements made at f_o and the sidebands, then comparing the value of P_p and P_i. From (3) and(4):

$$P_p \times PRR^2 \times t^2 \times 1/PRR = 1/b_p \times 1/b_i \times p_i \times PRR$$

simplifying: $$P_p \times t^2 = l/b_p \times l/h_i \times P_i$$

$$P_i / P_p = t^2 \times b_p \times b_i. \quad (5)$$

The above calculations assume that the measurements are made with a bandwidth larger than l/t, so that the measured value for p_P is actually the peak power of the radar. They also assume that the measurement bandwidth is less than $1/t_r$, because equation (4) assumes that the signal looks impulsive in the measurement bandpass. These equations work for the asymptotic cases; they give no correct answers when near f_o or when using bandwidths near l/t. Careful calibration of the RSMS has not been performed to determine the exact power bandwidth b_p and impulse bandwidth b_i for the measurements. However, a general rule of thumb lets us say that $b_i = 1.25\ b_p$.

From Table 4, measured values for the WSR-57 radar were: t = 4.1 us; t_r = 50 ns. Then l/t = 244 kHz and l/t_r = 20 MHz, and for a measurement bandwidth, b_P = 1 MHz, the above equation (5) for p_i/p_p applies.

$$P_i/P_p = (4.1 \times 10^{-6})^2 \times 1 \times 10^6 \times 1.25 \times 10^6$$

= 21 correction factor

= 13 dB correction

This means that the power at the sidebands (p_i) is being measured 13 dB too high, compared to the value measured at the fundamental (P_p).

This correction could have been applied by either: a) drawing a dashed line 13 dB below the measured sideband spectra and using the dashed line values to compare with the RSEC for sideband suppression below the peak value, or b) adding 13 dB to the peak value at the fundamental frequency and start the RSEC comparison 13 dB above the fundamental frequency. The latter method was chosen because of the simpler graphical procedure involved.

The current RSEC stipulates that the emission levels at the antenna input must be at least 40 dB below the maximum value (emission level at the fundamental frequency, f_o) at frequencies f_o+ or - 1/2 $B_{-40\ dB}$, and at frequencies, f, displaced by more than 1/2 $B_{-40\ dB}$ from f_o, the suppression (dB) shall be at least

$$-20 \log \left| \frac{f - f_o}{\frac{1}{2} B_{-40\ dB}} \right| -40,$$

where B = emission bandwidth in MHz. This latter suppression is to continue until the ultimate value of 60 dB or P_t + 30, whichever is the larger value, is attained, where p_t may be measured or calculated from:

$$p_t = P_p + 20 \log (Nt) + 10 \log (PRR) - PG - 90.$$

Using the same WSR-57 as an example, the allowable emission bandwidth at 40 dB below the level at the fundamental frequency is:

$$B_{(-40\ dB)} = \frac{7.6}{\sqrt{t\ t_r}} \quad \text{, or } 64/t$$

whichever is less.

$$B_{(-40\ dB)} = \frac{7.6}{\sqrt{4.1 \times 10^{-6} \times .05 \times 10^{-6}}} = 16.8 \text{ MHz}$$

$$B_{(-40\ dB)} = 64/t = 15.6 \text{ MHz}$$

Thus, at f_o+ or - 7.8 MHz, the emission level must be at least 40 dB below the peak level (peak received signal plus 13 dB correction).

The roll-off from the -40 dB points must be at the 20 dB per decade rate, so that at the required level of 60 dB below the peak, the bandwidth is

$$B_{(-60\ dB)} = B_{(-40\ dB)} \times 10^{\frac{60-40}{20}} = 156 \text{ MHz.}$$