RECOMMENDATION ITU-R M.1314-1*

Reduction of unwanted emissions of radar systems operating above 400 MHz

(Question ITU-R 202/8)

(1997-2005)

Scope

This Recommendation provides information on the design factors affecting unwanted emission characteristics of radar transmitters to be taken into account during the design of radars. It also recommends certain types of transmitter output devices that should be used when practicable to minimize unwanted emissions.

The ITU Radiocommunication Assembly,

considering

a) that the radio spectrum available for use by the radiodetermination service is limited;

b) that the radionavigation service is a safety service as delineated in No. 4.10 of the Radio Regulations (RR), and in addition that some other types of radar systems such as weather radars may perform safety-of-life functions;

c) that the necessary bandwidth of emissions from radar stations in the radiodetermination service is large in order to effectively perform their function;

d) that new emerging technology systems may use digital or other technologies that are more susceptible to interference from radars' unwanted emissions due to their high peak envelope power;

e) that the ITU-R has been studying the question of efficient use of the radio spectrum by radar systems;

f) that unwanted emissions from radar systems may in some cases cause interference to systems in other radio services operating in the adjacent and harmonically related bands;

g) that RR Appendix 3 specifies maximum permitted power levels for spurious or spurious domain emissions, and that Recommendation ITU-R SM.1541 specifies out-of-band limits for radiodetermination radars,

recommends

1 that the information on radar transmitter design factors affecting unwanted emission characteristics of radars contained in Annex 1 should be used to reduce unwanted emissions;

2 that, when practical, the best available output device technology should be used in radars to reduce non-harmonic radar spurious emission levels;

---

[*] This Recommendation should be brought to the attention of the International Maritime Organization (IMO), the International Civil Aviation Organization (ICAO), the International Maritime Radio Committee (CIRM), and the World Meteorological Organization (WMO) and Radiocommunication Study Groups 1 and 9.

3 that, when necessary and when possible, radar output filters should be used to reduce radar unwanted emissions.

Annex 1

Reduction of unwanted emissions of radar systems

1 Introduction

To maximize future efficiency of spectrum use, radar transmitters should be chosen, designed, and constructed such that the emission spectrum falls off as rapidly as possible, given the constraints on radar performance, size, cost, weight, reliability, maintainability, etc. The emission-spectrum skirt fall-off rate (out-of-band emission characteristics), and the emission floor level (spurious emissions) are determined by the transmitter hardware and architecture and by the transmitted waveform. Those influences are discussed below.

2 Radar design factors

The function or mission of a radar largely determines the design of the radar. Radar missions are widely varied (such as: navigation, weather observation, wind velocity determination, surveillance, imagery and mapping, terrain following, altimeter, etc.) and generally require unique performance specifications. These missions determine some parameters that are not under the control of the radar designer which directly impacts upon radar design factors such as: required transmitter power, transmitter waveform selection, transmitter output device selection, antenna gain, receiver sensitivity, range and azimuth resolution, and Doppler coverage. The judicious trade-off of radar design factors to improve emission spectrum control is key in enhancing compatibility between radar systems and other services.

3 Waveform selection and shaping

The choice of pulse waveform type and the way in which the waveform is shaped can also have important influences on spectrum control and hence on compatibility. Most radars, especially those using a single power oscillator or power amplifier, are constrained by considerations of energy efficiency and heat dissipation to use pulses having essentially constant-amplitude except during brief transitions between subpulses. That limits the types of waveforms that can be chosen. Even when that constraint applies, however, choices remain that can have a major effect on the emission spectrum.

Radar waveforms can be categorized, at the first level, into plain-pulse, or unmodulated-pulse, waveforms (having the emission designator of “P0”) and intra-pulse-modulated waveforms. Intra-pulse modulation usually serves as a means for implementing pulse compression, although an exception occurs in the case of waveforms used to drive frequency-steered arrays. Intra-pulse modulations can thus be divided further into the following subcategories:

- continuous FM, or “chirp” pulses;
- stepped-chirp pulses;

- stepped-frequency pulses used in frequency-steered radars;
- discretely-coded pulses.

From the standpoint of emission-spectrum control, a guiding principle in selecting and shaping a waveform is to remove discontinuities in as many derivatives of the waveform as possible, since that determines the ultimate spectrum fall-off slope, in dB/decade of frequency offset, that is achieved. The various pulse waveforms are therefore distinguished by the differences among their transitions of amplitude, phase, and frequency within the pulse.

All pulse waveforms, of course, contain rise and fall ramps on the overall envelope. Other things being equal, it is desirable to have gradual and smooth rise and fall ramps. However, other things are not always equal. In particular, pulses generated in crossed-field devices require quick rise ramps to avoid excitation of spurious oscillatory modes that would worsen the spectrum. When amplifiers other than crossed-field devices are used, smooth, gradual rise ramps are helpful to spectrum control when they can be implemented. Such implementation might still be difficult because power-amplifier dissipation is usually high when the amplifiers are not driven close to saturation; that can motivate use of fast rise and fall ramps even when spurious oscillations are not a concern.

Continuous frequency modulation, or chirp, waveforms with high pulse-compression ratio, or bandwidth-pulsewidth product, have very steep spectrum fall-off rates. This applies to both linear FM and nonlinear FM waveforms. The main contribution to undesired spectral components of these waveforms arise from the use of short rise ramps on the pulses.

Stepped-chirp waveforms have piecewise-constant frequencies that increment or decrement monotonically throughout the pulse. They can be considered as a subset of continuous-frequency-modulation chirp. However, stepped-chirp waveforms, as well as non-monotonic stepped-frequency waveforms that are used with frequency-steered antenna arrays, have poorer emission spectra than continuous-FM chirp waveforms have. This is a consequence of discontinuities in the waveform. It might be feasible to remove those discontinuities by implementing the stepped chirp in a way that maintains continuity of phase at the junctions between frequency steps. Even if that is so, however, discontinuities in the first derivative, which do not occur in true continuous-FM waveforms, will remain, so the spectrum will not be as good as that of a continuous-FM pulse with comparable pulse-compression ratio.

There are also certain polyphase-coded waveforms, of which the Frank polyphase-coded waveform is the prototype, that effectively approximate chirp waveforms; i.e., they approximate "continuously-coded" waveforms[1]. However, these contain abrupt steps in phase, so their spectra do not fall-off nearly as steeply as those of continuous-FM chirp waveforms.

Herein, discretely-coded radar waveforms refer to those that do not resemble continuous-FM waveforms in any way. Since that excludes the polyphase codes, most discretely-coded radar waveforms can be subdivided into bi-phase-coded and frequency-coded types. Waveforms in either of these categories can use Barker codes and pseudo-random binary sequence codes.

In the absence of refinements, discretely phase-coded waveforms have abrupt transitions between constant-phase "chips". (The same is true of Frank codes and other polyphase codes.) As a consequence, their spectra fall off at only 20 dB/decade. However, some options are available that can improve the spectra of phase-coded waveforms.

In principle, the spectrum of the RF drive (excitation) waveform can be made to fall-off arbitrarily fast by filtering the modulating waveforms or the modulated low-level drive waveforms (either IF or RF) themselves. However, those gains can be eroded in practice by spectral regrowth that occurs in both the transmitter power amplifier and in receivers in the environment. When premodulation

---

[1] Chirp waveforms are sometimes referred to as coded waveforms even though their "coding" is not discrete.

filtering is used, the chip-to-chip transitions are gradual instead of abrupt, but on bi-phase waveforms and those polyphase waveforms that contain 180° phase transitions, nulls or dimples remain in the waveform envelope because that envelope passes through zero during transitions from one phase to the other. That is not a problem in itself, but the advantages gained are reduced by two factors. One factor is AM-to-PM conversion that occurs in power-amplifier devices. The extraneous phase modulation that results widens the spectrum. Another disadvantage is that any limiting that occurs in either the power-amplifier transmitter stages or in victim receivers tends to reintroduce abrupt transitions into the dimpled waveform. Those abrupt steps translate into unwanted spectral sidebands with spectrum skirts that again fall at only 20 dB/decade.

It is possible to mitigate that spectral regrowth to a considerable extent. This can be done by constructing exciter (low-level, driver) waveforms that maintain a nearly constant envelope not only during the subpulse dwell intervals but also during phase transitions. In such waveforms, 180° phase transitions consist of rotations of carrier phase through a semicircle in the I-Q, or real-imaginary plane instead of movements along the I or Q axis that pass through the origin. This can be implemented by means of quadrature modulators and suitable waveform-shaping circuitry.

An alternative discretely coded waveform category is continuous-phase frequency-shift keying. These waveforms are essentially the same as so-called minimum-shift-key (MSK) waveforms used in some communication systems. Although sometimes referred to as phase-shift-keyed waveforms, these are really frequency-coded because the phase changes continuously while, in their basic unfiltered form, the instantaneous frequency changes abruptly and remains constant throughout each subpulse. There are no discontinuities in the waveform itself, but there are discontinuities in the first derivative. Consequently, the spectra approach asymptotes that fall at a rate of 40 dB/decade. Furthermore, these waveforms have constant envelope even during their subpulse transitions, so they are intrinsically immune to the spectral-regrowth problems that occur with phase-coded waveforms. (Since swept-frequency waveforms have no subpulses, they too are immune from spectral regrowth due to limiting and AM-to-PM conversion.) In communication systems, premodulation-filtering of MSK waveforms is widely used. It is expected that such filtering could also be applied in radars, in which event the emission spectrum fall-off would theoretically become steeper than 40 dB/decade.

While steep fall-off of the emission spectrum is desirable, it cannot be pursued without regard for the consequences in range resolution and Doppler coverage, usually expressed by the shape of the "ambiguity function". That function represents the magnitude of the output signal evoked by return from a point target and produced by a filter matched to the transmitted signal. The ambiguity function is a function of both the range (time delay) and the Doppler shift of the target return. As one extreme example, a linear-FM rectangular pulse waveform with infinite time-bandwidth product (i.e., infinite compression ratio) would have a perfectly rectangular spectrum, except for the contribution from the rise and fall ramps. But the response of a matched filter to such a waveform would have a $\sin(t)/t$ response for a constant-Doppler target return. Such a response has time (i.e., range) side-lobes only about 13 dB below the main response, which is inadequate in some applications that require a high degree of multiple-target resolution. The matched-filter response is not simply the Fourier transform of the emission spectrum. However, there is a tendency for abrupt fall-off of emission spectrum to be accompanied by high range side-lobes in the response, much as abrupt steps in the time waveform are accompanied by high side-lobes in the emission spectrum. To some extent, range side-lobe suppression can be improved by mismatching the receiver signal processor to the transmitted pulse, but this incurs a loss of sensitivity relative to that of a matched filter. It is therefore necessary to choose a waveform that makes a good trade-off among spectrum control, range side-lobe suppression, and sensitivity. (Swept-frequency waveforms using a slightly non-linear FM profile are good compromises for some applications.) In general, however, the need for good resolution and sensitivity narrows the designers' options. In addition, many radar applications require nearly uniform response over a substantial span of Doppler frequencies; i.e., they are required to have low "Doppler sensitivity". This introduces another constraint on the designers' choice of waveform.

In communication systems, the improvement of spectrum fall-off that is gained by premodulation filtering comes at the expense of worsening inter-symbol interference. Nevertheless, considerable improvement in spectrum control can often be achieved before intersymbol interference becomes unacceptable. In a radar, the spectrum improvement that can be gained by use of premodulation filtering comes at the cost of degrading the radar's resolution. It is also to be expected that a slight loss of detection sensitivity will be incurred due to the difficulty of constructing a perfectly matched filter (or correlation process) for waveforms containing rounded corners (resulting from premodulation filtering) instead of sharp discontinuities. As with the analogous communication-system case, however, it is reasonable to expect that considerable improvement in spectrum control can often be achieved before the ambiguity function or sensitivity is degraded significantly. As indicated above, removing discontinuities in as many derivatives of the waveform as possible is what determines the ultimate spectrum fall-off slope that is achieved at large frequency offsets. That does not necessarily require that the filtering have a narrow bandwidth, although that bandwidth determines the frequency offset at which the ultimate spectrum slope is attained.

The preceding discussion applies when the waveform has constant amplitude within its subpulse dwells. The use of multiple power-amplifier modules (usually solid-state amplifiers) in either in-guide-combiner or spatial-power-combining architectures, opens up possibilities for use of smooth amplitude-modulated waveforms. These are not known to be used in currently-deployed radars, but such waveforms might be used in the future. This would establish another degree of design freedom that could be exploited in part to help control radar emission spectra.

4 Selection of radar output devices

The selection of the radar transmitter output device affects the design of not only the transmitter, but also the radar receiver and antenna systems. Also, the design of multifunction radar systems can even further complicate the selection of a radar output device. Other major design factors in selecting an output device include: energy efficiency (conversion of DC energy to RF), instantaneous bandwidth (available tuning bandwidth without adjustments), and pulse-to-pulse coherency (relative phase of each pulse which is important for Doppler processing), weight, size, mechanical ruggedness, life of the device and cost.

Table 1 shows the output device performance for major design factors considered in the design of radar systems. As seen in Table 1, there is a wide variation in the output device characteristics for the major design factors of peak power, instantaneous bandwidth and energy efficiency. It should be noted that the above design factors must be given primary consideration in the selection of the radar output device to ensure that the radar mission(s) can be achieved. Radar output device spurious emission characteristics are considered only after all mission objectives are satisfied.

TABLE 1

Radar output device characteristics considered in the design of radar systems

Output device	Peak output power range (kW)	Energy efficiency (%)	Instantaneous 1 dB bandwidth (% of carrier frequency)	Pulse-to-pulse coherency	Weight (kg)	Size	Mechanical ruggedness	Relative life expectancy(1)	Relative cost(2)
Crossed-field:(3)									
Crossed-field amplifiers	60-5 000	40-65	5-12	Yes	25-65	Small	Good	1.0	Low
Magnetrons (unlocked)	20-1 000	35-75	(4)	No	1-25			1.0	
Magnetrons (locked)	20-1 000	35-75	(4)	Yes	1-25			1.0	
Coaxial magnetrons	10-3 000	35-50	(4)	No	2-55			5.4	
Linear beam:									
Coupled cavity travelling wave tube	25-200	20-40	10-15	Yes	10-135	Large	Good	7.4	High
Klystron	20-10 000	30-50	1-12	Yes	25-270			13.5	Medium
Twystron	2 000-5 000	30-40	1-12	Yes	55-65			10.4	High
Solid state transistors (Parallel-class C modules):		(6)							
Si bipolar	10-90	20-30	10-30	Yes	0.5-2.5 per module	Small	Excellent	15	High
GaAs field effect transistor (5)	0.5-5.0	10-25	10-30						

(1) Life expectancy is normalized relative to a 1970s conventional magnetron and does not reflect the longer life expectancy of newer technology conventional magnetrons.

(2) Depends on production volume.

(3) Crossed-field output devices will most likely be phased out in future radar designs; however, their use is expected to continue in maritime radionavigation systems.

(4) Although magnetrons do not have an instantaneous bandwidth capability, tuning frequency ranges up to 10% of the operating frequency can be achieved.

(5) Silicon (Si) bipolar modules are generally used below 3.5 GHz and Gallium Arsenide (GaAs) modules in the 5 GHz band.

(6) Depends on the number of modules combined in the output stage.

The levels of spurious emissions from radar transmitters are dependent upon the output device used in the radar transmitter. Knowledge of the inherent spurious emission characteristics of the various output devices used in radar transmitters is essential in promoting efficient use of the spectrum and minimizing interference to services operating in adjacent bands.

Table 2 lists the spurious emission characteristics (non-harmonic and harmonic) for output devices used in radar systems. Radar systems using crossed-field output devices have inherent non-harmonic spurious emission levels that would require filtering if spurious emission limits are greater than about −60 dBc. Both linear-beam tubes and solid-state output devices have inherent non-harmonic spurious that are below −100 dBc. All radar output devices have harmonic spurious emissions in the range of –15 to –55 dBc, and thus require filtering to suppress the harmonic spurious emissions. For radars employing distributed output devices (phased arrays) filtering may not be practical.

TABLE 2

Radiodetermination pulsed output device spurious emission characteristics for systems in the 3 and 5 GHz bands

Output device(1)	Spurious emission level			
	Non-harmonic (dBc) in 1 MHz	Harmonic (2), (3) (dBc)		
		2nd	3rd	4th
Crossed-field:				
Crossed-field amplifiers	–35 to –50 (5)	–25	–30	–45
Magnetrons (unlocked) (4)	–65 to –80 (5)	–40	–20	–45
Magnetrons (locked) (4)	–75 to –90 (5)	–40	–20	–45
Coaxial magnetrons (4)	–60 to –75 (5)	–40	–20	–45
Linear beam:	(6)			
Coupled cavity TWT	–105 to –115	–20	–25	–35
Klystron	–110 to –120	–20	–25	–35
Twystron	–105 to –115	–20	–25	–35
Solid state transistors (Parallel-class C modules):				
Si bipolar	–100 to –110	–45	–55	–65
GaAs FET	–100 to –110	–35	–45	–55

(1) Alternative output devices may be more applicable for systems operating above 5 GHz. These options include, but are not limited to, helix/ring bar travelling wave tubes and newer technology magnetrons.

(2) Harmonic spurious emission levels listed are nominal values. The range of harmonic spurious emissions is typically +5 to −10 dB of the nominal values.

(3) Harmonic emission levels can be reduced below –100 dBc with a harmonic (low pass) filter.

(4) Older magnetron output devices can have inherent $\pi - 1$ modes which may be only 40 dB below the carrier. These modes are intermittent and of short duration occurring during the start-up of oscillations. New technology magnetrons are designed to suppress these emissions.

(5) Non-harmonic emissions levels in crossed-field devices can be reduced below –100 dBc with a waveguide bandpass filter. These filters generally have a few tenths of a dB in insertion loss.

(6) Linear beam output devices may have non-harmonic spurious emissions close to the carrier in the order of –80 to –90 dBc depending on the characteristics of the overall cavity selectivity.

5 Radar output filters

RF filters at the transmitter output can be very helpful in suppressing harmonic emissions. RF filters can also be used to suppress out-of-band and non-harmonic spurious emissions that lie closer to the fundamental emission than the harmonics do. However, their utility for controlling relatively close-in portions of the emission spectrum is limited. This is due partly to their additional cost, weight, and size, and also to the fact that many radars are tunable and/or use multiple waveforms, some of which have much wider necessary bandwidths than others have. It is scarcely practical to implement high-power RF filters that can be reconfigured to accommodate changes in carrier frequency or pulse waveform, especially when it is considered that such changes are likely to occur within milliseconds.

Transmitter architecture is also an important determinant of the achievable degree of spectrum control. Where multiple power amplifiers are used, emission-spectrum fall-off rate and level are influenced by whether the outputs from those power amplifiers are combined within the transmitter waveguide or only in space after being radiated. In-guide combining effectively creates a severe impedance mismatch for the mutually incoherent components of the output waveforms from the power amplifiers, which can dramatically lower the radiated noise power relative to the sum of the available noise powers of the amplifiers. With array radars fed by multiple amplifiers, on the other hand, spatial power combining is an attractive architecture, but it allows all the noise power of the amplifiers to be radiated. Opportunities for RF filtering are also limited in such arrays. This is partly because a separate filter would be needed for each amplifier, where the number of amplifiers can be in the hundreds or thousands. It is also partly because the space between filters would need to be on the order of half a wavelength, since the radiating elements are normally that close together to avoid occurrence of unacceptable lobes in the antenna gain pattern. That space is insufficient for very effective filtering.

As shown in Table 2, the selection of the radar output device has a major effect on the requirement for filtering non-harmonic spurious emissions. However, as mentioned earlier, the selection of the radar output device can not be made entirely on spurious emission characteristics. Because of the inherently high levels of harmonic spurious emissions of all output devices, the suppression of harmonic spurious emissions by the use of harmonic (low pass) filters is generally performed when practical. To mitigate radar non-harmonic spurious emissions bands from some moderate and high-power radars in bands adjacent to radiodetermination, bandpass filters after the radar transmitter would also be required for some radar output devices. These would typically have to be separate from the harmonic filter, since the wide-stop-band characteristics of harmonic-suppression filters can not ordinarily be achieved along with the sharp cutoff characteristic of adjacent-band-suppression filters. The number of filters required can be much greater than two, however; in active-array radars, one or two filters would need to be interposed between each power-output device and the antenna element or subarray that it feeds. Thousands of filters could be required altogether.

The monetary cost of these filters can be significant, since unconventional filter types, sometimes requiring pressurization or evacuation, are required to handle the high powers and maintain the desired suppression over a wide stopband. Use of such filters also imposes trade-offs in radar system performance. The insertion loss of transmitter harmonic filters and bandpass filters for radars in these bands ranges from 0.1 to 0.7 dB. If both harmonic and bandpass filters are required, the insertion loss would be roughly double. Due to the many variables in radar operation, the attendant decrement in detection and tracking performance usually goes unnoticed, but the fact is that even 0.2 dB represents a major loss of RF power (for example, 47 kW of peak power in the case of a 1 MW radar). The transmitter would need to be that much more powerful to recover the performance loss, since it must be assumed that more cost effective means of improving the performance would already have been exploited. A loss of 0.4 dB, for example, corresponds to a 2.3% reduction of detection range, which is inconsequential for most radars but significant for some. The voltage standing wave ratio of both types of filters is in the range of 1.1 to 1.3.

Also, power handling, size, and weight of the filter are factors to be considered in the feasibility of using an output filter on the radar, particularly in mobile radars. Size and weight can be overriding considerations in the case of mobile, active-array radars. Filtering bands close to the radar operating band requires steep selectivity skirts and hence high energy storage, which raises the risk of breakdown (or lowers the power-handling capacity) and can also introduce phase distortion in the passband – another major consideration for active-array radars. The higher the radar power, the more attenuation is needed to suppress spurious outputs to a given level, so the more sections the filters will need, and hence the higher their insertion loss, size, and weight will tend to be.

Transmitter filtering is best implemented during the original design of the radar. The addition of transmitter filters to existing radars has been achieved with minimal impact on system performance in many cases, but there have been other cases in which breakdown problems have occurred when a bandpass filter was added to suppress adjacent-band emissions.

6 Radar trends

Major areas of advance driving the direction of the selection of radar output devices are:

– digital radar signal processing which is leading to rapid growth in Doppler radars which require high pulse-to-pulse coherency (linear beam and solid state output devices),

– the development of higher power solid-state transmitter devices (modular/bottled and distributed (phased array) configurations),

– the development of new technology magnetrons that have been specifically designed to reduce unwanted emissions and also offer substantially longer operational lives than older conventional types.

These trends will have an influence on reducing the unwanted emission levels of the newer generation of radars.