3-2 Measurement of Unwanted Emissions of Marine Radar System

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To consider the effective use of the frequency, it is asked to reduce the unwanted emissions. With regard to the measurement method of the spurious emission of primary radars, the spurious regulation of World Radiocommunication Conference (WRC-03) requests to measure the spurious emissions which are radiated from the radar antenna. NICT has been developing the measurement system which enables wide dynamic range, and high-speed measurement based on ITU-R recommendation M.1177 to regulate the measurement of unwanted emissions of radar systems.

1 Background and history

For effective use of radio waves, the reduction of unwanted emissions in radio waves to the extent possible is needed internationally. The International Telecommunication Union (ITU) revised its regulations and values for unwanted emissions, changing the requirement from non-modulated status to modulated status (performed during actual operation). Radio Regulations (RR) and related recommendations were amended around 1997 and have been applied since 2003[1]. Unwanted emissions consist of spurious emissions and out-of-band emissions. Spurious emissions are defined as emission on a frequency or frequencies outside the necessary bandwidth and the level of which may be reduced without affecting the corresponding transmission of information. Spurious emissions include harmonic emissions, parasitic emissions, intermodulation products and frequency conversion products, but exclude out-of-band emissions. Out-of-band emissions are defined as emissions on a frequency or frequencies immediately outside the necessary bandwidth that result from the modulation process.

In Japan, a legal revision was carried out in December 2005, under which more stringent regulation of unwanted emissions is applied to radio equipment. Especially for radar, unlike other communication systems, the level of emissions radiated from the antenna must be measured, and unwanted emissions in out-of-band (OoB) domains are restricted by an “OoB mask.” An OoB mask is formed by a 40 decibel bandwidth (B-40) and a 30 dB/decade roll-off curve from each edge; the frequency where the roll-off curve intersects with the spurious value according to the regulation forms the boundary between the out-of-band domain and spurious domain (Fig. 1).

Unwanted emissions in out-of-bound domains are described in ITU-R Recommendation SM.1541, which shows the design objectives of OoB masks for radar systems. The application of stricter regulatory values is being studied (regulatory value of 40 dB/decade roll-off in the out-of-band domain)[2].

The use of a measurement method established in ITU-R Recommendation M.1177[3] is required for the measurement of unwanted emissions from a radar system. Two types of measurement methods are described in M.1177: The direct method (for radio waves radiated from the radar antenna) and the indirect method (for separate measurement of the spectrum at the feed point of the transceiver and the characteristics of antenna emission followed by combination of the values). RR specifies regulatory values of unwanted emissions from radar systems in terms of equivalent isotropically radiated power (EIRP), and with the indirect method, it is very difficult to measure across the entire measurement frequency range including frequency characteristic changes of the device being measured or the measurement system that are generated when the feed point is cut off from the antenna. This is why NICT has used the direct method in investigating measurement.

The direct method requires far-field conditions (at a scale of several hundred meters for marine radar and several kilometers for terrestrial radar) as measurement conditions. Therefore, for precise measurement, it is necessary to accurately establish a measurement site. At present, only QinetiQ in the UK maintains credible uncertainties of measurement sites or measurement systems and can perform accurate far-field measurement according to M.1177. Considering that Japan's regulations concerning spurious emissions are also applied according to RR, it is necessary to construct a measurement site in Japan.

Regarding a method to measure unwanted emissions of a radar system, M.1177 requires radar antenna measurements across the full circumference of directions, but it is not possible to pinpoint the radiation direction and value of unwanted emissions from radar antennae as they rotate during usual operation. Therefore, complete measurement takes a very long time (approximately 20 hours for marine radar), and it is possible that the measurement results are affected by changes in the ambient environment. Under these circumstances, NICT has carried out research and development of measurement equipment, and investigation of candidate measurement sites, from the perspective of establishing measurement sites and preparing measurement equipment.

2 Unwanted emission regulations for radar systems

2.1 History of regulations

Regarding unwanted emissions, permitted values for spurious emissions from radar systems were unclear until 1997, when, at WRC-97, the ITU revised RR. The permitted values are specified in Appendix 3, Table I, of RR. For radiodetermination service, the category in which radar systems belong, "43 + 10 log (PEP), or 60 dB, whichever is less stringent" (PEP: Peak Envelope Power) became the permitted value for spurious emissions. This permitted value is relative to PEP at the transmission frequency. Also, RR Appendix 3 describes that the frequency range of that measurement is from 9 kHz to 110 GHz or the second harmonic if higher, but actually, a more realistic measurement range is described in the latest version of ITU-R Recommendation SM.329[4], which shows the regulation values and measurement method for unwanted emissions in the spurious domain quoted from RR. Measurement is performed in compliance with ITU-R Recommendation SM.329. The frequency ranges that should be measured are clearly described in SM.329 (SM.329 -7: section 2.6), revised in 1997, and are classified into fundamental frequency ranges as shown in a table in SM.329 (SM.329 -8: Table 1), revised in 2000. According to this, 3 GHz band radar is from 30 MHz to the 5th harmonic, and 9 GHz band radar is from 30 MHz to 26 GHz; if a waveguide is used in the transmission line, then spurious domain emission measurements of frequencies below 0.7 times the waveguide cut-off frequency are not required (Table 1).

For regulation values (permitted values) of unwanted emissions, the concept of "domain" was added to WRC-03 in 2003. Permitted power, etc., in spurious domains are shown in RR Appendix 3, Table I and ITU-R Recommendation SM.239, as described above. Regulatory values of unwanted emissions in out of band domains are shown in ITU-R Recommendation SM.1541, Annex 8.

RR also mentions the enforcement date of the revised regulations. It was decided at WRC-2000 and specified in Appendix 3 that the revised regulation are to be enforced from the date of transmitter installation. New regulations in RR on spurious emission apply to radar installed on or after January 1, 2003, and to all radar (including those already installed) from January 1, 2012. Currently (June 2016), the transition period has expired, and the revised regulations apply to all radars.

The measurement point of unwanted emissions from radar systems (location where measurement equipment is connected) was the antenna transmission line until WRC-97, but this condition was changed significantly at WRC-2000, which added incidental conditions to the classification of radiodetermination service, so the strength of unwanted

Table 1 Frequency range for measurement of unwanted emissions (Extract from ITU-R Recommendation SM.329-12 [5])

Fundamental frequency range	Frequency range for measurements: Lower limit	Frequency range for measurements: Upper limit (The test should include the entire harmonic band and not be truncated at the precise upper frequency limited stated)
9 kHz-100 MHz	9 kHz	1 GHz
100 MHz-300 MHz	9 kHz	10th harmonic
300 MHz-600 MHz	30 MHz	3 GHz
600 MHz-5.2 GHz	30 MHz	5th harmonic
5.2 GHz-13 GHz	30 MHz	26 GHz
13 GHz-150 GHz	30 MHz	2nd harmonic
150 GHz-300 GHz	30 MHz	300 GHz

emissions from radar (radar as defined in No.1.100 of RR) is now restricted to the antenna radiation level, not the antenna transmission line. This change has a major impact on the measurement of unwanted emissions: now it is necessary to measure the power radiated from a radar antenna across the entire specified frequency range and compare that to the peak envelope power of center frequency when investigating whether spurious regulations are satisfied. However, it is very difficult to predict the power and radiation angles of unwanted emissions across the entire range of measurement frequencies required. Therefore, special considerations are required in order to enable accurate capture of all unwanted emissions radiated from a rotating radar antenna. For this purpose, ITU-R Recommendation M.1177 was established as an exception regarding measurement methods for radar systems, and RR requires the measurement of unwanted emissions from radar based on this recommendation.

2.2 Latest unwanted emission regulations

The previous sections have described the history of unwanted emission regulations. From here, unwanted emission regulation values for radar systems as of June 2016 are summarized.

- Unwanted emission permitted values: 43 + 10 log (PEP), or 60 dB, whichever is less stringent
- Unwanted emission of out of band (OoB) domain permitted values: According to determination of 40 dB bandwidth, and OoB mask.
- In principle, the OoB mask, with classified by modulation method, attenuates at 30 dB/decade from each edge of a 40 dB bandwidth, and is an out-of-band domain until it reaches the permitted values of spurious emissions.
- ITU-R Recommendation SM.1541 clearly stipulates that the design objective mask is 40 dB/decade. Study on the enforcement of this stipulation was to be finished by 2016, but no report on study results has been released yet.

Table 1 provides a summary of unwanted emission regulation values.

2.3 Unwanted emission measurement method for radar systems

The measurement of unwanted emissions from radar systems is described in ITU-R Recommendation M.1177. Figure 2 is a block diagram representing the measurement system using the direct method described in this recommendation.

The settings of the spectrum analyzer used in this measurement system are listed below.

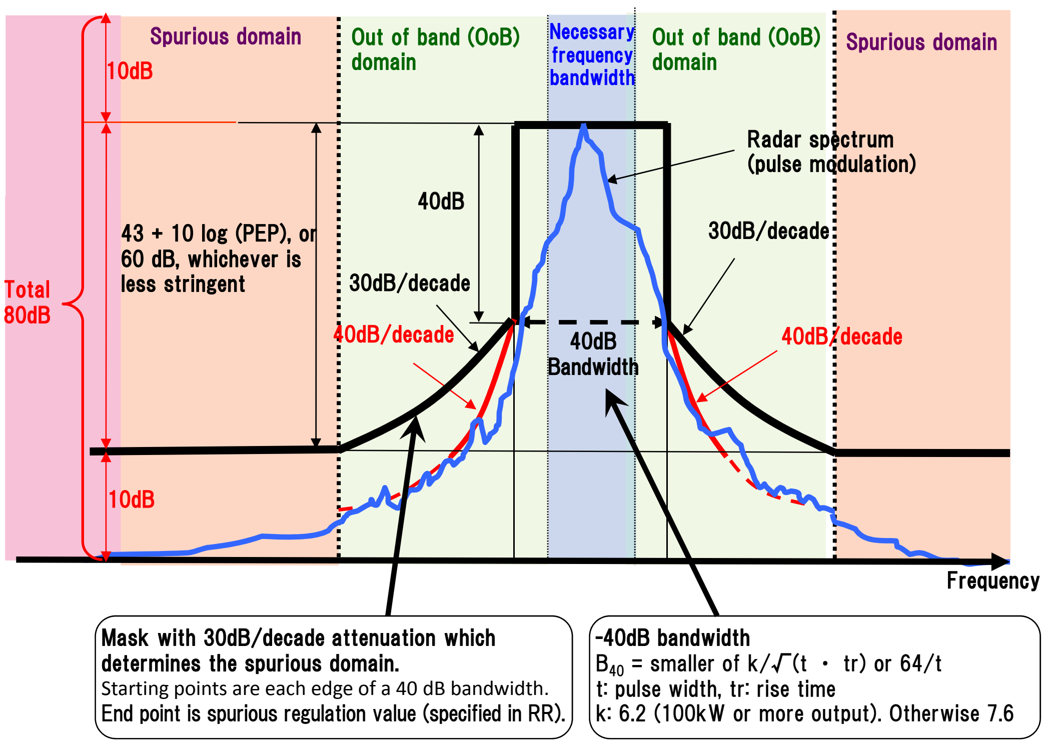

Fig. 1 Diagram summarizing radar system (pulse modulation) unwanted emission regulation values

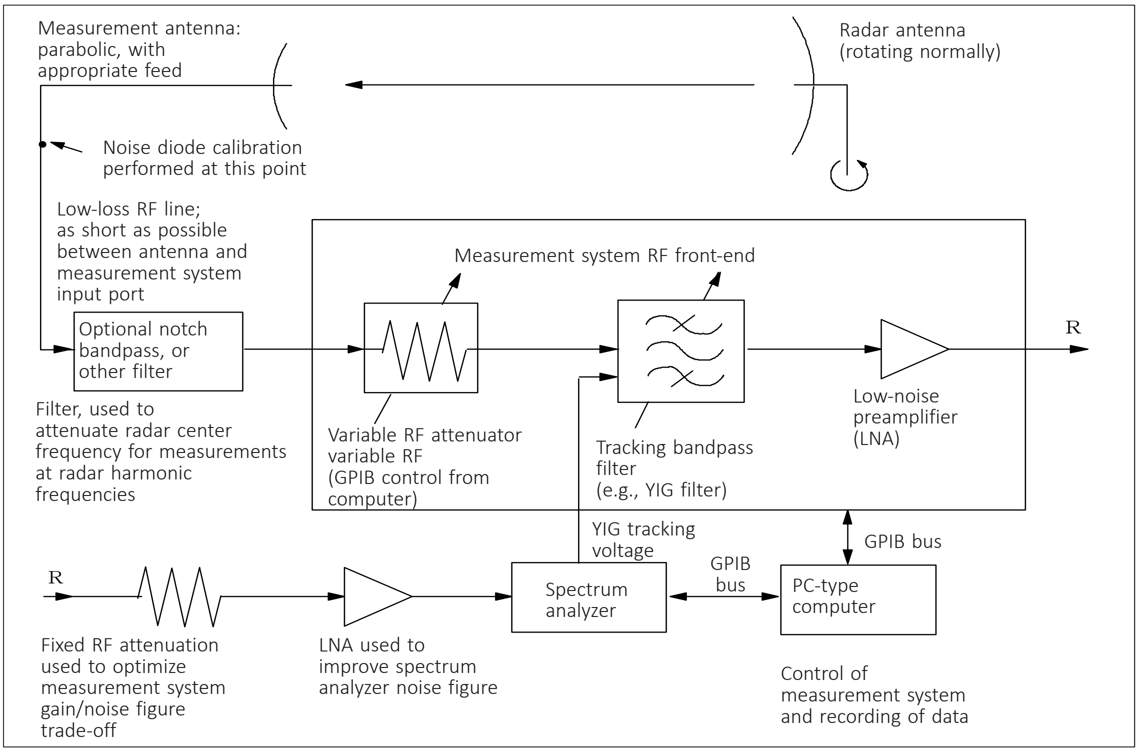

Fig. 2 Measurement system block diagram

Center frequency	: Frequency range defined in SM.329, Table 1 * If a waveguide is used in the antenna system, then measurements below 70% of the waveguide cut-off frequency are not required
Frequency span	: 0 Hz
Sweep time	: Equal to or greater than the radar antenna rotation period
Frequency steps	: RBW value
Resolution bandwidth (RBW)	: 1 MHz or less * Bandwidth defined by the modulation method. In the case of pulse modulation, RBW is 1/τ (τ is pulse width). However, if the result of calculation exceeds 1 MHz, then 1 MHz.
Video bandwidth (VBW)	: Same as RBW or greater

We developed and prepared the measurement equipment described above, in compliance with the content in M.1177.

3 Measurement equipment development in compliance with M.1177

M.1177 specifies a method for measuring unwanted emissions from radar systems. As shown in Fig. 1, a measurement dynamic range greater than 80 dB is required.

However, the secure dynamic range of existing spectrum analyzers with the settings shown above (center frequency = 9 GHz, RBW = 1 MHz, VBW = 1 MHz) is limited to just over 60dB. Therefore, when using such a spectrum analyzer, it is necessary to use of an RF front-end block connected directly before the spectrum analyzer in order to secure a dynamic range greater than 80dB, as shown in Fig. 2. The purpose of the front-end block is to enlarge the dynamic range of the whole measurement system by adjusting the signal level input into the spectrum analyzer. It does so by planning the improvement of the noise figure of the receiving block, and by preventing the saturation of the receiving block by frequencies outside the measurement subject. Specifically, to assemble the RF front end block it is necessary to prepare parts that have the following functions.

(1) Band restriction by a band rejection filter (BRF) or band pass filter (BPF)
(2) Signal amplification by a low-noise amp (LNA)

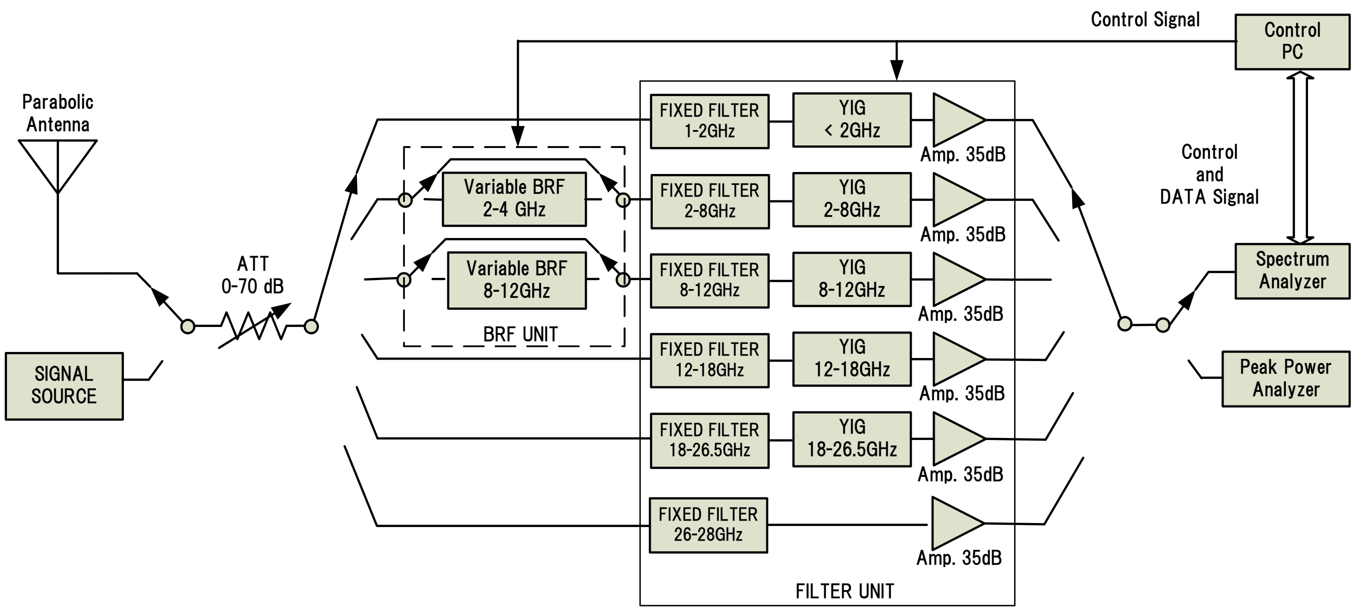

Fig. 3 Developed measurement system block diagram

(3) Control of the optimal input power to the yttrium iron garnet (YIG) filter, LNA, etc. with an attenuator (ATT)

The BRF or BPF in (1) is used to limit the total power input into the measuring system by limiting the band to the measured spectrum. Also, the LNA in (2) improves the noise figure of the measurement system, while (3) adjusts the optimal input into the YIG filter, LNA and spectrum analyzer, to avoid distortion in measurement results.

To achieve these functions, we developed a front end (broadband YIG BPF unit) using a YIG, LNA and ATT. The specifications of the measurement equipment we developed are shown below. Figure 3 is an overview in the form of a block diagram.

<u>Main Specifications of Developed Measurement Equipment</u>

Frequency range	: 1 to 28 GHz (expandable up to 40 GHz)
BPF frequency range	: 1 to 28 GHz (comprised of 6 bands)
BPF bandwidth	: 100 MHz or less
AMP band gain	: 35 dB or more
I/O terminals	: APC3.5 type (f) connectors

The measurement equipment we developed (Fig. 4) is controlled by a computer to perform measurements of spurious emissions from a radar system, and uses an M.1177 compliant method. By using the front-end block we developed, we achieved a dynamic range of approximately 100 dB.

Fig. 4 Developed measurement equipment (RF front end part)

Figure 5 shows an example result of measurement of a marine radar's spectrum using the equipment shown in Fig. 4. The radar (marine radar) measured in Fig. 5 uses a magnetron without unwanted emissions countermeasures, and these results reveal that the amount of unwanted emissions are much more than those of marine radar systems currently sold.

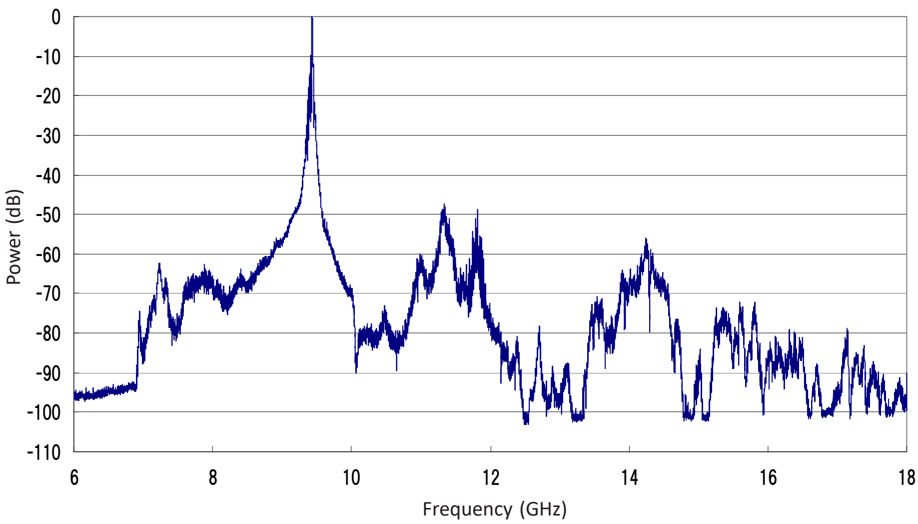

Fig. 5 Example of measurement results (spectrum of magnetron radar normalized at fundamental frequency peak power)

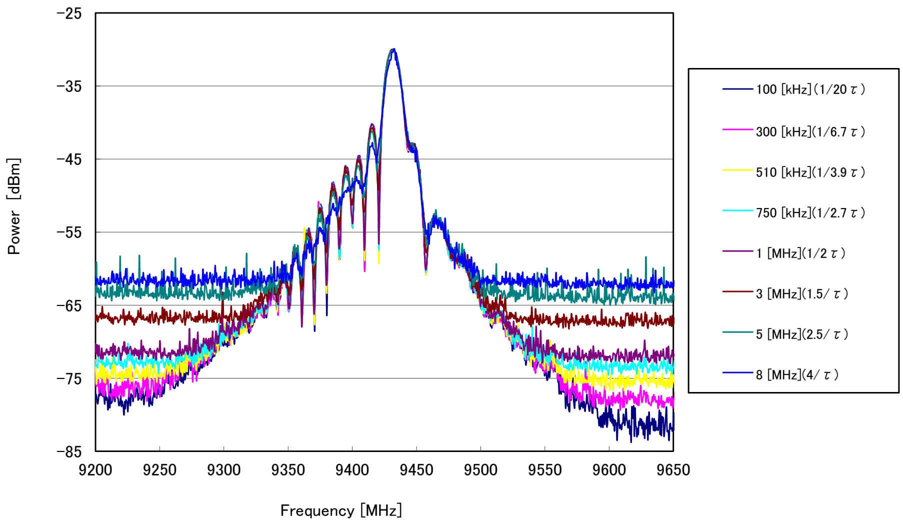

Fig. 6 Radar system spectrum example

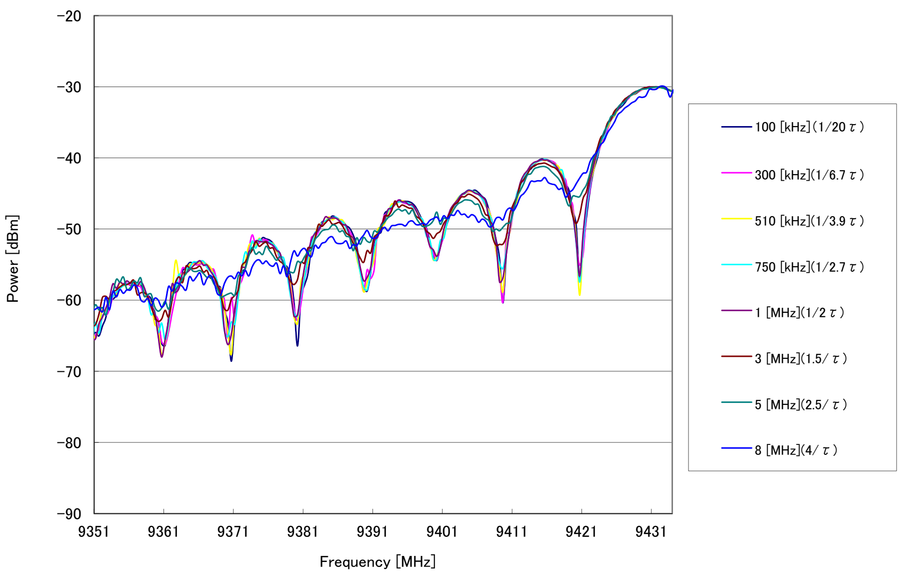

Fig. 7 Spectrum expansion at or below center frequency

4 Development of high-speed measurement equipment

As described above, M.1177 requires measurement of emission power from an antenna at a measurement site that satisfies far-field conditions. In addition, it stipulates the following settings for measurement equipment (spectrum analyzer): "Measurement bandwidth (RBW) is 1/τ (maximum 1 MHz) for pulse width τ. During one or more rotations of the antenna at span 0 Hz, it records the maximum value of receiving power, and measures the measurement frequency range in steps of measurement band (for example, if X-band radar, then 30 MHz to 26 GHz.)." Taking account of these conditions, it usually takes about 22 hours to measure an X-band radar rotating at 24 rpm. Therefore, there are concerns about what may affect measurement results, such as changes in the radio environment during measurements, or changes in propagation characteristics due to weather conditions. Shorter measurement time is one way to solve these problems when using the M.1177 measurement method.

Using the M.1177 direct method, the maximum RBW setting of the spectrum analyzer is 1 MHz even though the RBW is 1/τ when the pulse width is τ. The ITU working group that studied M.1177 suggested the possibility that a wider RBW can be used as a means to shorten measurement time. To investigate measurement errors if RBW is wider than the value specified in M.1177, NICT performed simulation and spectrum measurement of radar waves. However, we confirmed that, depending which RBW we used, differences between the measurement values of the main lobe and the side lobe can vary, and to keep those measurement errors within approximately 0.5 dB, the condition of RBW < 1/(4 τ) is required [5]. As an example, Figs. 6 and 7 show spectrum results obtained when operating a marine radar system that uses a magnetron, changing the RBW settings of the spectrum analyzer, and then taking measurements. When it comes to higher speed unwanted emission measurements, there are problems in simply widening RBW alone. Considering even more precise measurements, it is necessary to adopt an even narrower RBW compared to the current specifications. That, however, would mean an even longer measurement time, so our RBW setting is a maximum of 1 MHz, which conforms to the latest version of M.1177.

As shown in Fig. 8, we developed a method that uses high frequency down converters, A/D converters, programmable DSPs that implement signal processing (FFT calculations, etc.; similar to the implementation of multiple parallel filters of the specified bandwidth [specified RBW]), and a MAX hold function. With this method, we widen the band of frequencies measured simultaneously in order to perform high-speed measurements[6][7]. We also add a function that synchronizes the process of received signals

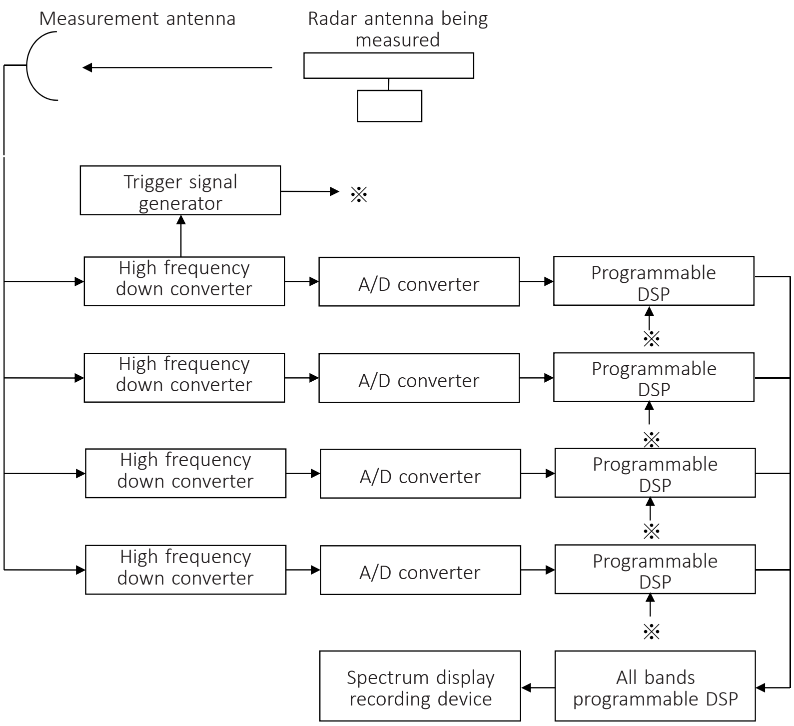

Fig. 8 High-speed measurement method by multi-channel programmable DSPs

with arriving radio waves (synchronized to the repetition frequency of measured radar), a function that analyzes signal level and frequency information, etc. We also devised a function that performs settings to distinguish signals to be measured from unwanted waves (waves arriving from outside, etc.). Then we developed equipment to perform high-speed measurement of unwanted emissions. The characteristics of this equipment (Fig. 9) are as follows.

- Parallel filters by programmable DSPs, and high-speed measurement by a MAX hold function.
- Based on information on the pulse width of the measured radar, pulse repetition frequency and the maximum pulse level, the equipment can synchronize with signals to be measured, and remove unwanted external waves.
- As the equipment is multi-channel, it can constantly monitor the fundamental frequency, and constantly measure the relative values of unwanted emissions and peak power of fundamental frequency.
- As the equipment is multi-channel, it can measure many frequency bands simultaneously, for even higher-speed measurements.

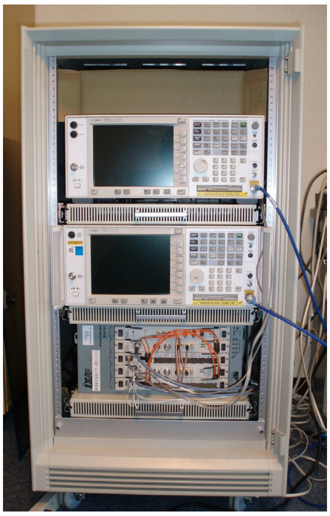

Fig. 9 Developed high-speed measurement equipment (when configured for 2 channels)

Figure 10 shows a comparison, in the vicinity of the fundamental frequency, between measurement results produced with a conventional measurement method according to M.1177 and measurement results produced with the equipment we developed based on the high-speed measurement method. The high-speed measurement equipment enabled a much shorter measurement time compared to equipment using the conventional measurement method (we used programmable DSPs to construct 32 parallel filters of 1 MHz band per channel, and a tri-channel configuration, enabling us to shorten measurement time to approximately 1/60th the conventional time; here, one channel was used for carrier sensing). Also, in the vicinity of the fundamental frequency, the difference in measurement results between the conventional method and the high-speed measurement method was kept to within approximately 1 dB, so we confirmed good matching.

As described above, we found that a high-speed measurement method using programmable DSPs is useful for measurements of unwanted emissions from radar. In particular, as illustrated by the RBW's effects on measurement results described above, it would be advantageous to im-

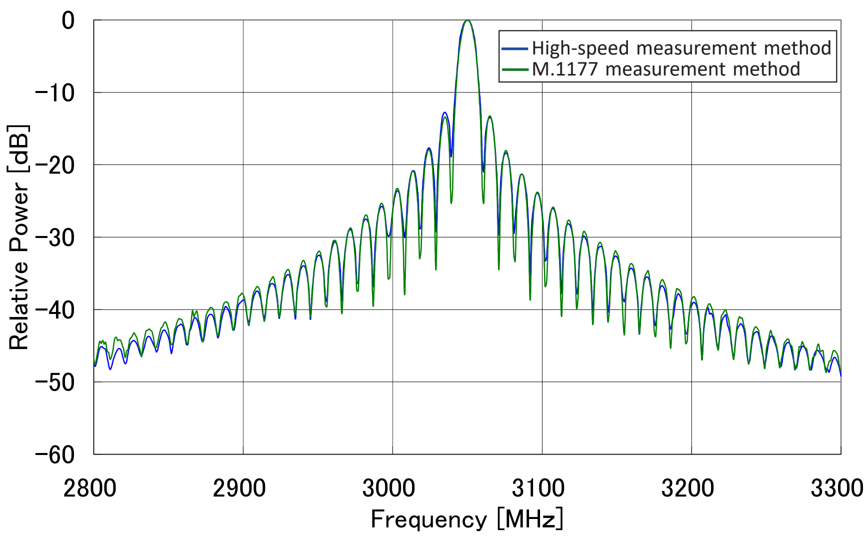

Fig. 10 Measurement results of M.1177 and high-speed measurement equipment (fundamental frequency vicinity)

prove measurement precision by satisfying the condition of RBW < 1/(4τ). If we use the condition of RBW < 1/(4τ), the measurement takes even longer when using the conventional method, but the high-speed measurement method is also effective in this case.

On the other hand, we found the following problems with the high-speed measurement equipment we developed.

(1) The high frequency down converter has insufficient dynamic range
(2) The arriving radio wave synchronization system (function to synchronize pulse repetitions of the radar being measured) cannot maintain synchronization (insufficient time resolution, caused by the maximum clock frequency of the receiving system)

Both problems are caused by performance limitations of the hardware we were able to obtain during development. To solve these issues, we believe we need to revise the level chart of the overall system, improve the performance of the high frequency down converter (increase its dynamic range, etc.), and develop a new method and technology to completely synchronize the receiving system during the time the antenna takes to rotate once or more.

5 Conclusion

The 2003 WRC revised the permitted values of spurious emissions for radar systems. This revision changed the measurement method for unwanted emissions, including spurious emissions, and Japan's Radio Act (radio equipment regulations) was accordingly revised in 2005. NICT developed a measurement system enabling the measurement of unwanted emissions in Japan in compliance with ITU recommendations, and made progress in improving the measurement method. As a result, we developed equipment to measure unwanted emissions with a dynamic range of approximately 100 dB that complies with ITU-R Recommendation M.1177, which describes a measurement method for radar systems. Regarding the problem of long measurement time with respect to the measurement method stipulated in M.1177, we also made progress in investigating high-speed equipment, and showed that high-speed measurement of unwanted emissions appears to be technically possible.

However, the measurement methods for unwanted emissions that we developed entail the following five main issues:

(1) Reducing the size and weight of measurement equipment
(2) Achieving a measurement distance that satisfies far-field conditions
(3) Considering radar antenna patterns, and obtaining a measurement site that suppresses multi-path propagation
(4) Developing high-speed measurement equipment with a wider dynamic range
(5) Shortening measurement time to reduce the effects from the external environment to the extent possible

Regarding issue (1), as shown in Figures 3 and 4, the measurement equipment we developed does not all fit into one 19-inch rack, and its size and weight make it very difficult to carry. Some radar systems cannot be brought onto the measurement site (cannot be moved where they are installed), so it is necessary to consider how to move the measurement equipment to the radar system, and perform the measurement there. If we are to do that, the equipment must be made smaller and lighter. Regarding issues (2) and (3), we must obtain a measurement site that satisfies the conditions. We have been investigating and doing other selection work for candidate measurement sites that we could occupy exclusively for multiple years, but due to various restrictions, we have still not established a measurement site. For measurements of spurious emissions from radar, the necessary conditions are a measurement site that satisfies far-field conditions, and a measurement system that has a wide dynamic range, as described in (4) above. In addition, technology standards for solid-state device radar systems have recently been applied to marine radar. Consequently, marine radar systems' oscillation devices have been converted to solid-state devices, resulting in decreased output. Moreover, reduced power supply to the measurement system has led to measurement systems with insufficient dynamic range. There are also many causes of reduced measurement precision of long-term measurements on outdoor measurement sites, such as changes in the radio wave environment. To reduce these effects on unwanted emission measurements to the extent possible, investigation of a means to shorten measurement time as mentioned in (5) above is also an issue we need to address.

Acknowledgments

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