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University of Applied Sciences

Radio Monitoring Station Munich

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Compatibility Measurements

DRM120, DRM+ and HD Radio interfering with
FM Broadcast, Narrowband FM (BOS) and Aeronautical Radionavigation

Thomas Hasenpusch
BNetzA Station Munich
P.O. Box 65 00 10
D-81213 München
Germany
Phone: (+49) 89 386 06 216
Fax: (+49) 89 386 06 183
e-mail: Thomas.Hasenpusch@BnetzA.de

Roland Effinger
BNetzA Station Konstanz
P.O. Box 5466
D-78433 Konstanz
Germany
Phone: (+49) 7531 935 205
Fax: (+49) 7531 935 183
e-mail: Roland.Effinger@BNetzA.de

Felix Schad
Fachhochschule Kaiserslautern
Morlautererstrasse 31
D-67657 Kaiserslautern
Germany
Phone: (+49) 631 3724 226
e-mail: Felix.Schad@FH-KL.de

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Contents

0 Executive Summary

This document describes the results of protection ratio measurements between the following radio services:

- FM stereo reception interfered by DRM+ / DRM120 and HD-Radio
- Narrowband FM reception interfered by DRM+ / DRM120 and HD-Radio
- Aeronautical Radionavigation (VOR and ILS) interfered by DRM+ / DRM120 and HD-Radio

The main motivation for this measurement series was to assess the interference potential of the planned new digital broadcast systems DRM+ and HD-Radio into existing in-band services and services in adjacent frequency bands. To enable the comparison of these results with the interference potential of the standard FM broadcast signal, the protection ratios with this analogue signal into the services listed above was also measured.

The main results can be summarized as follows:

1. Provided sufficient additional band pass filtering of the output of the transmitter is applied, the interference potential of HD-Radio and DRM+ / DRM120 into narrowband FM (BOS) reception is not substantially higher than that of a standard FM broadcast signal.
2. The interference potential of DRM+ / DRM120 into FM stereo reception is depending on the frequency separation between wanted and interfering signals. For offsets of less than +/-300 kHz, DRM+ / DRM120 produces roughly the same interference than an FM broadcast signal. For offsets above +/- 300 kHz, the interference potential of DRM+ / DRM120 is tentatively higher but strongly depends on the receiver design. Results range from about 30 dB more critical to equal protection ratios.
3. The interference potential of HD-Radio into FM stereo reception also depends on the frequency separation: For separations of more than +/-300 kHz, the same interference as from a standard FM broadcast signal can be expected. For Offsets between +/-100 and +/-300 kHz, however, the protection ratios are up to 20 dB higher (i. e. more critical). This is not surprising because the digital frequency blocks of the HD-Radio signal cause the spectrum to exceed the current transmitter mask for FM broadcast substantially.
4. For frequency offsets of less than 200 kHz, the interference potential of DRM+ / DRM120 into VOR and ILS localizer reception is much less than of a standard FM broadcast signal (up to 30 dB less). For larger frequency offsets, both signals produce roughly the same interference, provided sufficient additional band pass filtering of the output of the transmitter is deployed.
5. The interference potential of HD-Radio into VOR and ILS reception is generally much higher for frequency offsets up to 500 kHz and little more than from a standard FM broadcast signal for larger offsets, provided the levels of remaining sideband emissions are the same. HD-Radio could not be used in the upper FM channels 107.8 and 107.9 MHz, because then even parts of the normal emission fall inside the aeronautical band.

1 Introduction, aim of measurements

The planned test transmissions of several new digital audio broadcast systems in the frequency range 87.6 to 108 MHz raised the question about their compatibility with other radio applications both inband and in adjacent bands.

In Germany, the above mentioned frequency range is allocated to the FM broadcast service. The lower adjacent band is allocated to narrowband FM used for official and public safety purposes (BOS) which is equal to private mobile radio (PMR) in terms of protection ratios. The upper adjacent band is allocated to aeronautical radionavigation.

The following digital broadcast systems were investigated as “interferers”:

- DRM120
- DRM+
- HD-Radio

The main purpose of these compatibility measurements was to assess the interference potential of all three systems into analogue FM broadcast receivers, narrowband FM receivers, VOR and ILS receivers, compared to the interference potential of an analogue FM emission. To enable this comparison, additional measurements were made with an analogue FM broadcast signal as the interferer.

The measurements took place in the laboratories of Fachhochschule Kaiserslautern (FH) and Deutsche Flugsicherung Langen (DFS), Germany between May and August, 2007 with the majority of measurements between June 25th and August 23th.

Active participants:

Name	Organisation
Hasenpusch, Thomas	BNetzA Munich
Effinger, Roland	BNetzA Konstanz
Schad, Felix	FH Kaiserslautern
Rosenbaum, Mark	Technical University Kaiserslautern
Steil, Prof. Dr. Andreas	FH Kaiserslautern
Günzel, Helmut	DFS
Waal, Albert	University of Hannover

Tab. 1: Participants list

The main body of this document provides a description of the measurement process and a result summary. Detailed information as well as every single measurement result can be found in the annexes.

2 Receiver selection

2.1 Narrowband FM / BOS

A total of 6 narrowband FM / BOS transceivers were provided by the “Zentralstelle für Polizeitechnik” Rheinland Pfalz. They can be regarded as a representative variety of narrowband FM receivers used by public safety services in the 4 meter band in Germany today.

A detailed list of the receivers can be found in Annex 2.

The protection ratios resulting from these compatibility measurements can therefore be regarded as typical for the 4 meter BOS service in Germany.

2.2 FM Broadcast

A total of 7 analogue FM broadcast receivers were available. A detailed list can be found in Annex 2.

Due to the limited amount of time, not all receivers were tested for all interference signals. Protection ratio measurements with FM broadcast as the interferer have shown, however, that Rx 1 has a representative behaviour against neighbouring signals when compared with the relevant curve published in ITU-R BS.412-9 and other receivers tested.

2.3 Aeronautical Radionavigation

The frequency range directly above the FM broadcast band is used for ILS localizer (108.1 to 111.95 MHz) and VOR (108.0 to 117.95 MHz).

Since the extension of the FM broadcast band to 108 MHz, all aeronautical navigation receivers have to fulfil special requirements concerning the FM immunity that are set by ICAO. For the present compatibility measurements, only one ILS and one VOR receiver were available. It is important to note that the results presented here are only valid for the investigated receiver and can not easily be generalized. To determine the average or worst case protection ratios against VOR and ILS reception, a representative set of receivers has to be measured.

Details of the measured receiver can be seen in Annex 2.

Because aeronautical communication frequencies are above 118 MHz, this service was not investigated during these measurements because no harmful interference potential beyond that of normal analogue FM broadcast emissions can be expected.

3 Wanted signals

3.1 FM Broadcast

3.1.1 Description

FM broadcast signals can be mono or stereophonic and may include additional components in the baseband such as RDS. For compatibility measurements, the stereophonic reception is far more critical compared to mono. Therefore, a stereo signal was used during these measurements. Since the protection ratio results into FM reception should be made comparable to the existing compatibility situation (FM broadcast against FM broadcast), the wanted signal as well as the measurement procedure was taken from Recommendation ITU-R BS.641. For the first part of the measurement (maximum Audio level), this is a carrier which is FM modulated by the following signals:

Audio frequency	Deviation	Description
19 kHz	6.7 kHz	Stereo pilot tone
500 Hz	75 kHz	Audio signal

Tab. 2: FM wanted signal modulation

When the remaining noise in the S/N test is measured the 500 Hz audio modulation is switched off.

RDS data was provided by an external RDS coder. The following settings were used:

Program Service name (PS): RadioEIT

Alternative Frequencies List (AF): - no entry -

Programme Identification Code (PI): D0AA

Traffic Program ID (TP): 0

Traffic Announcement (TA): 0

Music / Speech (MS): 1

Program type: Pop medium

Date / Time: - not set -

Group sequence sent: 2A 0B 0B 0B (continuous repetition)

3.1.2 Failure criteria

Recommendation ITU-R BS.641 defines the failure criteria for the scenario FM broadcast against FM broadcast as the degradation of the weighted audio S/N from 56 dB to 50 dB. Because these measurements should allow to compare this scenario with the others (DRM120, DRM+ and HD-Radio against FM broadcast), this failure criteria was used throughout the compatibility measurements. The audio S/N is measured with a psophometer that includes a weighting filter according to Recommendation ITU-R BS.468.

Where available, RDS reception was also examined. For this service, the first occurrence of bit errors was taken as the failure criterion. This is evaluated by comparing the sent bit stream data from the receiver decoded by the “Franken” software running on a PC.

3.1.3 Signal generation

The wanted FM broadcast signal was generated using one of the following setups:

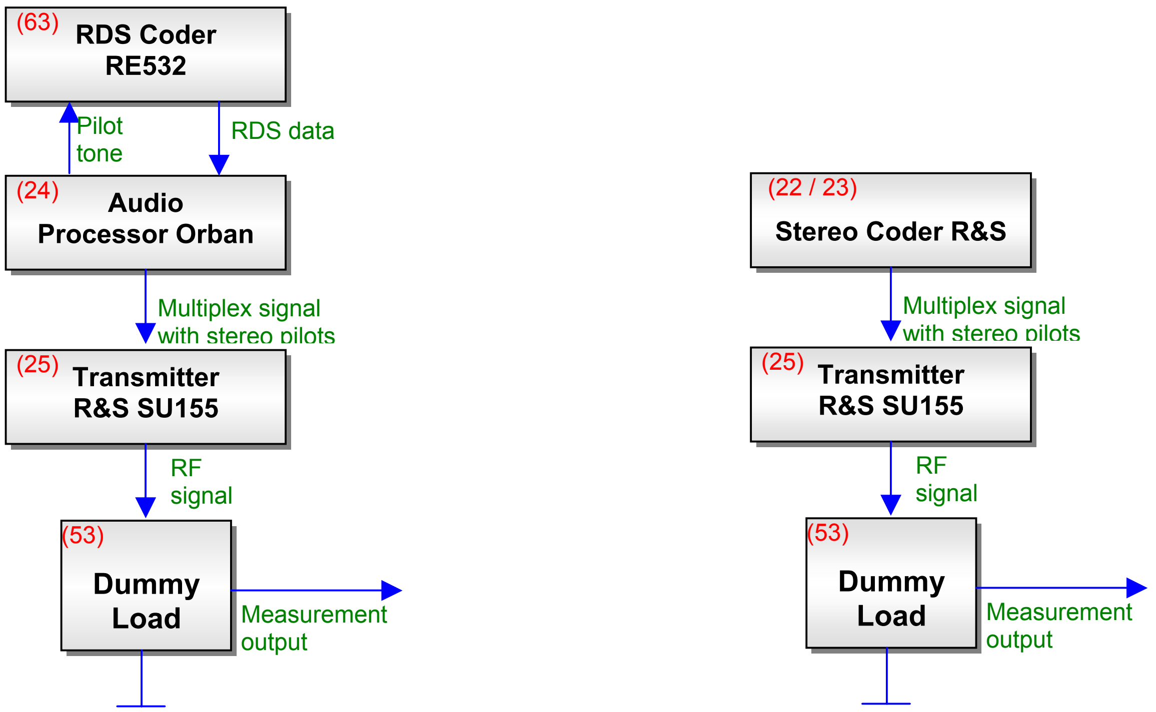

Fig. 1a / 1b: Wanted FM broadcast signal generation
No. in brackets refer to the equipment list in Annex 1

The frequency of the FM transmitter was set to 87.6 MHz. The power was adjusted by a variable attenuator following the measurement output.

3.2 Narrowband FM / BOS

3.2.1 Description

According to FTZ 17TR2049, the test signal for narrowband FM measurements is a carrier which is FM modulated with a 1 kHz sinusoidal audio tone. In Germany, the 4 m Band for public safety services (BOS) uses 20 kHz channel spacing. In this case, the deviation of the test signal is 2.4 kHz.

3.2.2 Failure criteria

Interference from noise-like sources such as digitally modulated signals into narrowband FM receivers may result in the following effects:

- The audio quality decreases due to background noise
- The squelch does not open although sufficient wanted signal level is present
- The interfering signal opens the squelch even without the presence of a wanted signal

The first effect occurs in any case. This effect is assessed by measuring the SINAD. In Germany, FTZ 17TR2049 states a minimum SINAD of 20 dB as necessary for a given percentage of understandable syllables. This SINAD is measured with a CCITT filter that emphasizes frequencies around 500 Hz and suppresses very high and low frequencies. This interference effect was called “SINAD interference”. The failure criteria is fulfilled when the interfering signal decreases the audio SINAD below 20 dB (target value = 19 dB).

Depending on the design of the receiver, it shows either the second or the third effect. The second effect was called “Squelch interference”. It was measured as follows:

First, a wanted signal level was adjusted so that the squelch safely opens. The interfering signal level was increased until the wanted signal can no longer open the squelch immediately (delayed squelch). This was confirmed by constantly switching the wanted signal on and off.

The third criteria “Squelch opens” was measured without wanted signal present.

When comparing the different interference effects it should be noted that the squelch interference is the most serious one because the user can not notice that interference is present. Moreover, he cannot even notice that he was called and has no chance of getting the information repeated.

3.2.3 Signal generation

The wanted narrowband FM test signal was taken directly out of the Radio Test Rack CMS48 (No. 11 in Annex 1). Frequency and level can be adjusted freely.

3.3 Aeronautical Radionavigation

3.3.1 Description

Aeronautical radionavigation in the frequency bands directly starting at 108 MHz consist of two different systems: VOR and ILS localizer.

VOR uses a combination of AM and FM with one fixed and one rotating antenna (the rotation is simulated electronically): The main carrier is AM modulated with a 30 Hz variable signal, and a 9960 Hz subcarrier that is frequency modulated by a 30 Hz reference signal. This reference signal is emitted from the onmidirectional part of the antenna whereas the AM signal is emitted from the part of the antenna that rotates at 30 Hz per second. Comparison of the phase between this rotating part and the reference signal allows the airborne receiver to determine its horizontal position (in degrees) relative to the direction of the ground antenna. VOR frequencies are the even hundreds of kilohertz starting at 108.0 MHz.

Recommendation ITU-R IS.1140 describes the nominal modulation parameters for the VOR signal during compatibility tests which were used during the measurements: The modulation degree is set to 30%, phase offset is set to 0 which corresponds to a course of 0° relative to the VOR.

The instrument landing system ILS consists of two parts: One part delivers the horizontal offset from the ideal glidepath ("localizer"), the second part gives the vertical offset ("glideslope"). Both carriers are amplitude modulated with two sinusoidal tones, one with 90 Hz and one with 150 Hz. The transmitter antenna patterns are different for both tones. The aircraft receiver compares the signal strength from the components modulated with 90 and 150 Hz (difference in depth of modulation or DDM). If the aircraft is exactly on the glidepath, both tones will be received equally strong. From the difference in receiving strength between the two components the receiver can determine the vertical and horizontal offset relative to the ideal glidepath.

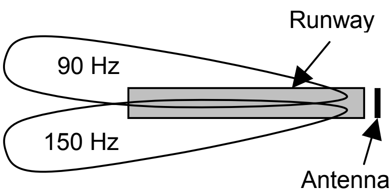

Fig. 2a: ILS localizer emissions

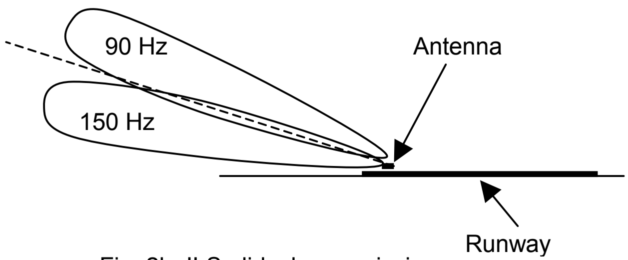

Fig. 2b: ILS glideslope emissions

Localizer and glideslope frequencies are paired but reside in different bands. While the localizer frequencies are the uneven hundreds of kilohertz starting at 108.1 MHz, glideslope frequencies are in the UHF range, starting at 329.15 MHz. Due to this, only the localizer part of ILS was investigated here.

Recommendation ITU-R IS.1140 describes the nominal modulation parameters for the ILS signal during compatibility tests which were used during the measurements: Both 90 and 150 Hz tones were modulated with a degree of 20%. The nominal offset from the ideal glidepath (DDM) was set to 0.093.

3.3.2 Failure criteria

Failure criteria for analogue aeronautical radionavigation receivers are defined in recommendation ITU-R IS.1009. According to this recommendation, the maximum allowable error in course display for VOR is 0.5°. For the ILS course component the error is defined as 7.5 µA in the analogue course indicator display which is equal to 7% of the total scale, measured at a nominal course deflection of 2/3 of the total scale.

Most modern receivers, like the one used here, are digital. Their output is data telegrams with course information that is passed to the board computer to be shown on a (multifunction) display. To have a similar interference criterion, ITU-R IS.1140 states a statistical method for determining the maximum on-course errors of ILS localizer receivers based on a 95% probability and limits centring error to 5% of the standard deflection. Five per cent of the standard localizer deflection is given by (0.05 * 0.093 DDM) or 4.5 µA (0.00465 DDM) and a 95% probability may be achieved by utilizing plus or minus two standard deviations, 2σ, of the normal distribution. An equivalent deflection of 4.5 µA for the VOR is 0.3° change in bearing indication.

Reaching these criteria due to the interfering signal being present was called “course interference”.

In addition to this, the so-called “flag signal” was monitored. Whenever the received wanted signal is too weak or too heavily distorted for the receiver to decode properly, this is indicated to the pilot by a red flag that is lowered over the instrument indicating that the current reading is unreliable. Although this situation usually occurs long after the criteria for course interference, this “flag interference” was also recorded during the measurements.

3.3.3 Signal generation

Both VOR and ILS wanted signals could be derived directly from the signal generator R&S SME03 (No. 12 in Annex 1).

4 Unwanted signals

4.1 Documentation of spectra

The limits for unwanted emissions outside the used channel are usually defined in the relevant standards. Because the level of unwanted out of band emissions has significant influence on the adjacent channel protection ratio, much effort was made to carefully document the emitted spectra. If possible, the spectrum of the unwanted emissions was shaped in a way that it closely matches the transmitter mask, because this situation represents the worst case in the sight of the victim receiver

To measure the sideband emissions even far below the wanted signal level, it is necessary to enhance the measurement dynamics beyond the normal capabilities of a spectrum analyzer. Therefore, all spectrum plots of the unwanted signals were recorded with the following setup:

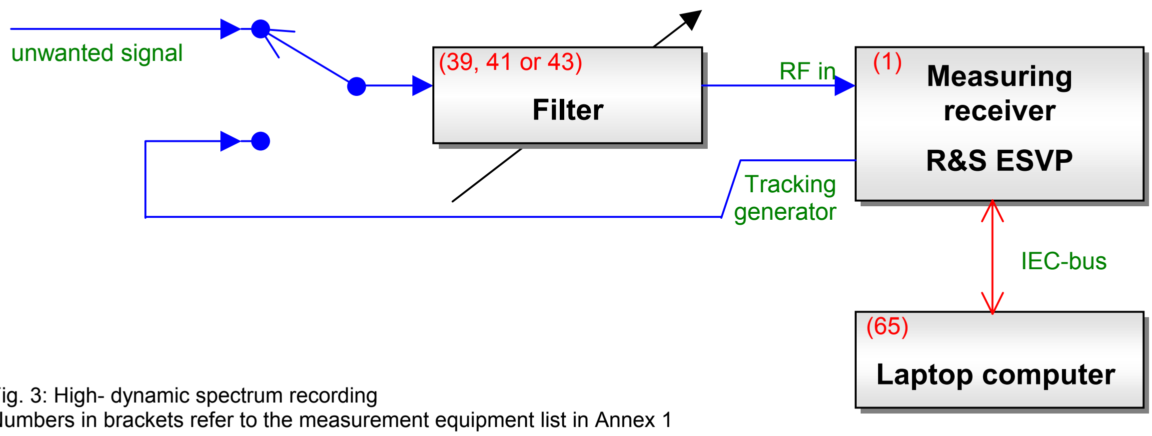

Fig. 3: High- dynamic spectrum recording
Numbers in brackets refer to the measurement equipment list in Annex 1

The filter is either a band pass or notch filter used to attenuate the main signal so that the receiver is not overloaded while still passing the interesting range of sideband emissions with little attenuation. The measurement receiver is controlled by a laptop computer to perform a frequency scan with narrow bandwidth (7.5 kHz) and store the measured level results. First, the filter curve for the frequency range concerned is measured, then the filtered signal is gradually scanned. The sum of the two level/frequency curves is equal to the actual emitted spectrum with a dynamic range of more than 85 dB (corrected for a 1 kHz measurement bandwidth). Sideband spectra of all used unwanted signals can be found in Annex 3.

4.2 FM Broadcast

4.2.1 Description

The deviation of FM broadcast signals and hence their interference potential into adjacent channels depends on the deviation which under normal operating conditions varies constantly. Although ETSI EN 302 018-1 defines a transmitter mask for FM broadcast signals (see Fig. 6), in this case one cannot generate a signal that constantly follows this mask as this would place an unrealistic interference potential to neighbouring channels in terms of time. Instead, the unwanted signal consists of a carrier which is FM modulated with a coloured noise and a deviation that should result in an average bandwidth of the signal comparable to a normal programme modulation. Recommendation ITU-R BS.641 describes the unwanted signal that has to be used for protection ratio measurements in detail. This modulation was used for the measurements against FM broadcast and narrowband FM / BOS.

For aeronautical radionavigation, ITU-R IS.1140 describes a different unwanted FM signal: The transmitter is operated in stereo mode and the coloured noise is modulated on both audio channels with a fixed level ratio of ½. This signal was used for the protection ratio measurements against ILS and VOR reception.

4.2.2 Signal generation

The unwanted FM broadcast signal was generated using one of the following setups:

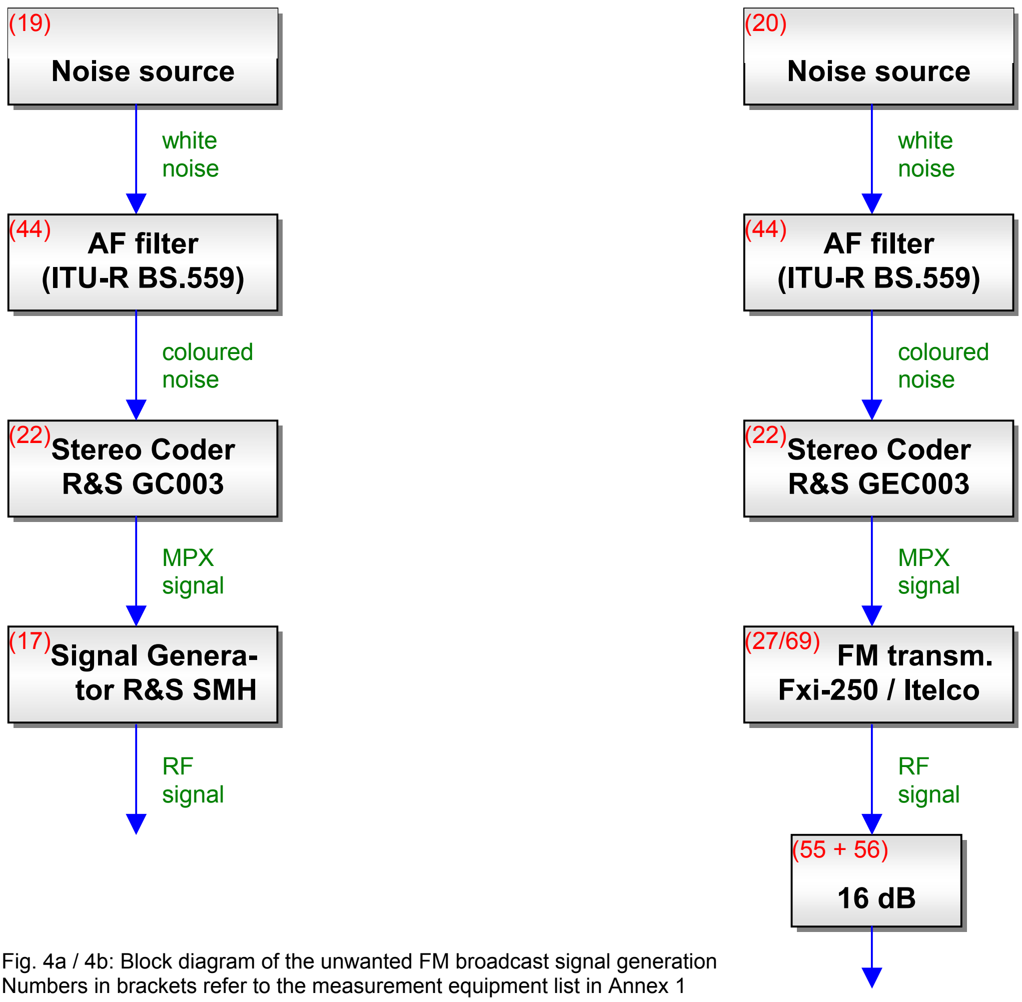

Fig. 4a / 4b: Block diagram of the unwanted FM broadcast signal generation
Numbers in brackets refer to the measurement equipment list in Annex 1

Modulation settings for measurements against FM broadcast and narrowband FM / BOS:

The transmitter is operated in mono mode because according to Recommendation ITU-R BS.641 this gives the worst case effect of disturbance. The deviation of the coloured noise was adjusted as follows: first, the transmitter is modulated with a sinusoidal tone of 500 Hz until a deviation of +/- 32 kHz (non-weighted) is reached. The AF voltage at the input of the stereo coder is measured. Then the noise source is used instead of the sinusoidal tone and adjusted to the same quasi-peak voltage at the stereo coder input. The resulting FM signal is a coloured noise with a quasi-peak deviation of 32 kHz. Throughout this adjustment process, the preemphasis is switched off. The deviation of the actual unwanted signal is higher due to the preemphasis being switched on again for the measurements.

The following figure shows the resulting spectrum of this unwanted FM broadcast signal.

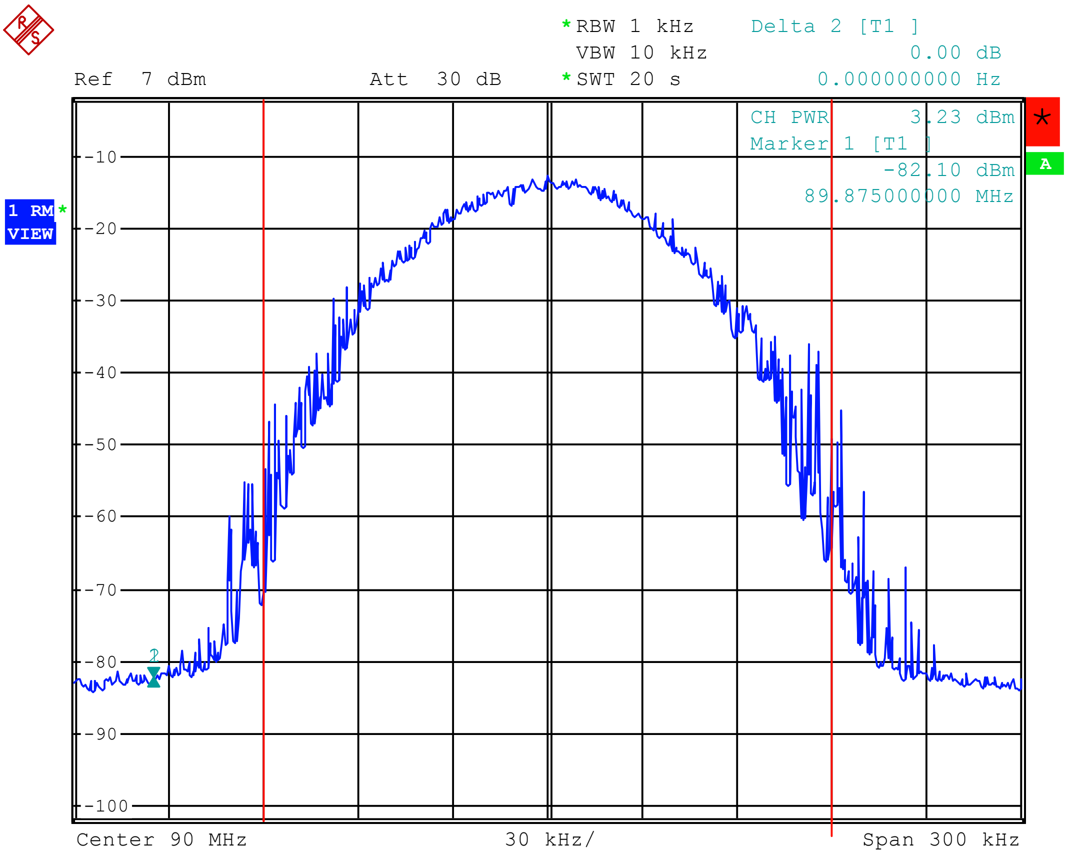

Fig. 5a: ClearWrite RMS spectrum of the FM broadcast unwanted signal according to ITU-R BS.641.

It was found that the peak level of this signal, when measured with 1 kHz RBW, is 15.5 dB below the total overall power.

Modulation settings for measurements against VOR and ILS reception:

The settings are taken out of Recommendation ITU-R IS.1140. The transmitter is operated in stereo mode. Both audio channels are modulated with coloured noise, but the level of the signal modulating the left channel is 6 dB lower (half the voltage) than the level that modulates the right channel. The deviation of the resulting signal was adjusted to +/- 32 kHz with the preemphasis switched on.

The following figure shows the resulting spectrum of this unwanted FM broadcast signal.

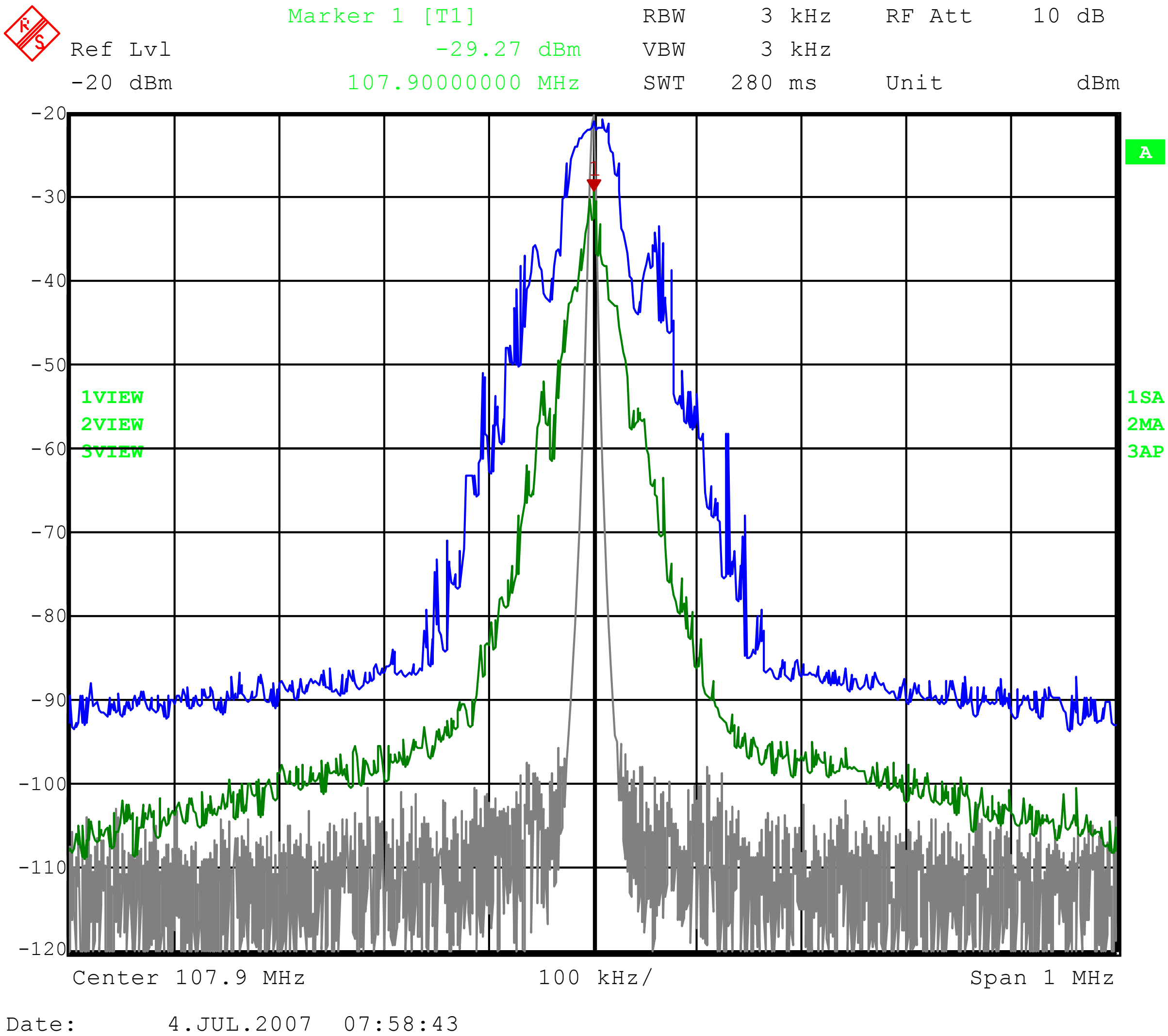

Fig. 5b: Spectrum of the FM broadcast unwanted signal according to ITU-R IS.1140.
Upper (blue) trace: MaxHold
Middle (green) trace: ClearWrite
Lower (grey) trace): unmodulated carrier as level reference

The high dynamic recording of the sideband emissions can be found in Annex 3.

4.3 DRM120

4.3.1 Description

DRM120 is a working title for a digital broadcast system using OFDM modulation that is similar to the planned new standard DRM+. It is a further development of the DRM system which is used below 30 MHz. The key parameters are as follows:

Modulation (main carrier): COFDM

Number of subcarriers: 111

Subcarrier spacing: 857 Hz

Bandwidth: 100 kHz

Modulation (data carriers): 16QAM (used), QPSK or 64QAM also possible

CREST factor: 11.5 dB

A transmitter mask for this signal is not standardized, but from the intention not to overshoot the existing mask for FM broadcast from ETSI EN 302 018-1, the following mask was used:

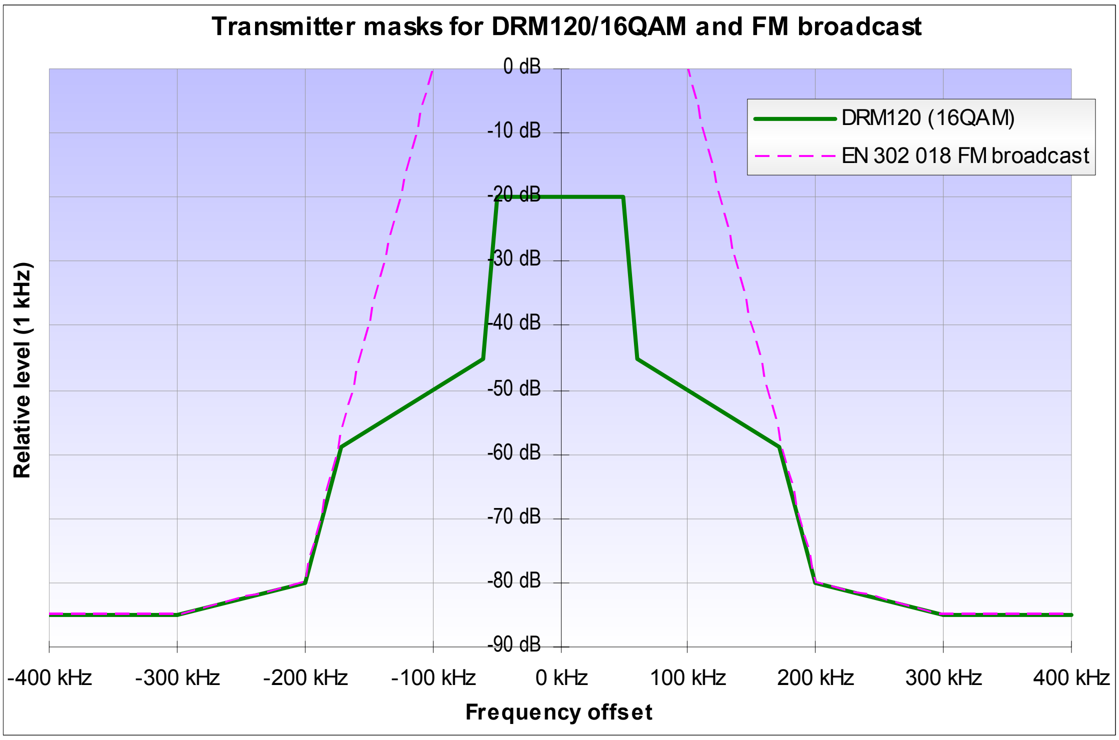

Fig. 6: Transmitter masks for DRM120 and FM broadcast

ETSI mask for FM:

Offset	rel. level (1 kHz)
-400 kHz	-85,0 dB
-300 kHz	-85,0 dB
-200 kHz	-80,0 dB
-100 kHz	0,0 dB
100 kHz	0,0 dB
200 kHz	-80,0 dB
300 kHz	-85,0 dB
400 kHz	-85,0 dB

DRM120 mask:

Offset	rel. level (1 kHz)	Attenuation
-400,00 kHz	-85,0 dB	-65,0 dB
-300,00 kHz	-85,0 dB	-65,0 dB
-200,00 kHz	-80,0 dB	-60,0 dB
-172,00 kHz	-59,0 dB	-39,0 dB
-60,00 kHz	-45,0 dB	-25,0 dB
-50,00 kHz	-20,0 dB	0,0 dB
50,00 kHz	-20,0 dB	0,0 dB
60,00 kHz	-45,0 dB	-25,0 dB
172,00 kHz	-59,0 dB	-39,0 dB
200,00 kHz	-80,0 dB	-60,0 dB
300,00 kHz	-85,0 dB	-65,0 dB
400,00 kHz	-85,0 dB	-65,0 dB

4.3.2 Signal generation

Generation of the digital baseband is done by software written by the FH Kaiserslautern that is running on a standard Windows-PC. The data transmitted consisted of a pseudo random bit sequence. Output of the analogue I and Q components of the baseband is provided by a 24 bit digital-analogue converter interface card. The dynamic range of the baseband was measured to be better than 75 dB. Transferring the baseband into the RF range was done by a signal generator that was I-Q modulated. An RF amplifier following the output of the signal generator provided the necessary signal level for the measurements. Initial tests have shown that the spectral shape of the sideband emissions are mainly influenced by the power amplifiers used. Experience shows that when using high-power amplifiers, the relevant spectrum mask can only be met when additional filtering after the amplifier output is deployed. To assess the influence of such additional filtering on the protection ratios, both the unfiltered and filtered DRM120 signals were used as interferers.

The following setup was used to generate the DRM120 unwanted signals:

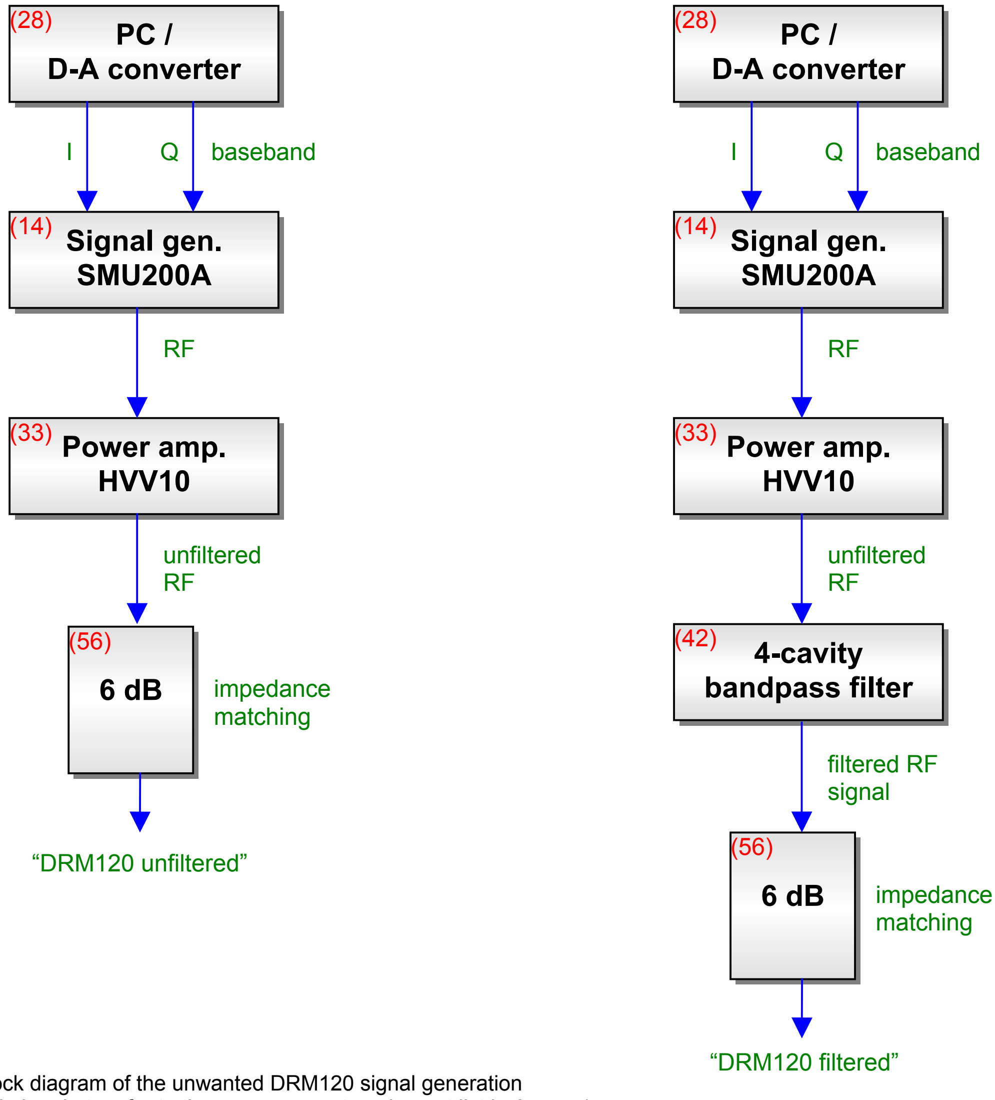

Fig. 7: Block diagram of the unwanted DRM120 signal generation
Numbers in brackets refer to the measurement equipment list in Annex 1

The following figure shows the spectrum of the DRM120 signal.

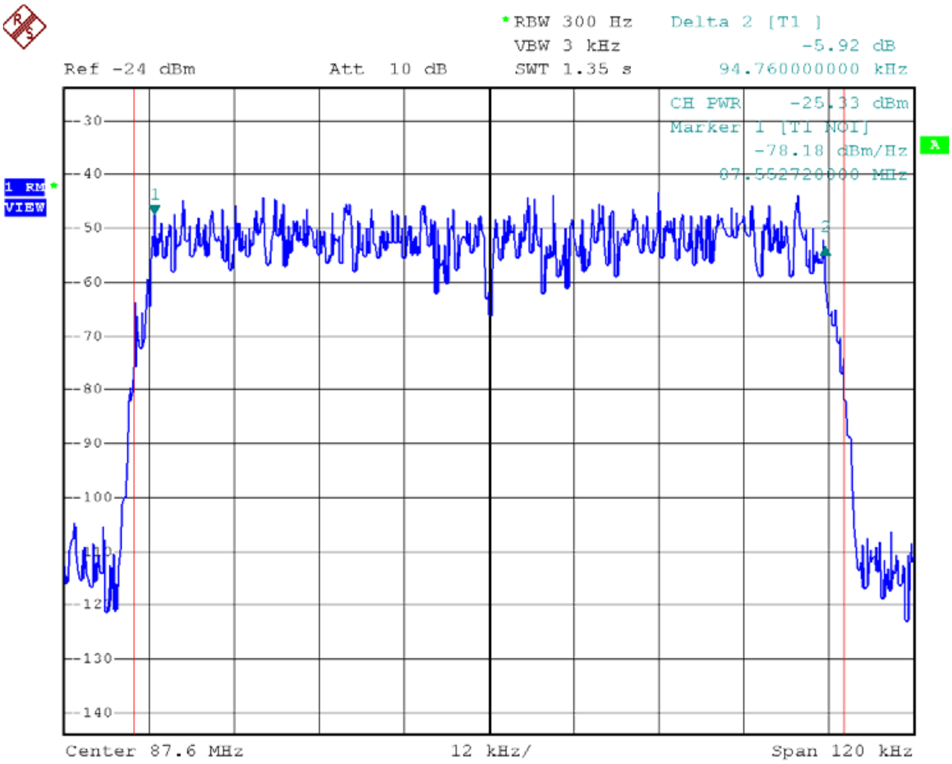

Fig. 8: ClearWrite RMS spectrum of the DRM120 unwanted signal.

High dynamic spectrum recordings of the sideband emissions can be found in Annex 3.

4.4 DRM+

4.4.1 Description

DRM+ is a digital sound broadcast system that has been developed by the DRM Forum. As far as the spectrum and transmitter masks are concerned it is equal to DRM120. However, the number of subcarriers and their spacing is different. Also, a different coding scheme is used resulting in a lower CREST factor which is expected to have influence on the protection ratios. The standardization process for DRM+ is likely to be finished during 2007.

The key parameters are as follows:

Modulation (main carrier): COFDM

Number of subcarriers: 213

Subcarrier spacing: 444 Hz

Bandwidth: 100 kHz

Modulation (data carriers): 16QAM (used), QPDSK or 64QAM also possible

CREST factor: 9 dB

The transmitter mask for DRM+ is still under discussion in the DRM forum. It can be expected to be comparable with the mask used for DRM120 as seen in Fig. 6. For the purpose of these measurements it has to be assumed that the DRM+ signal falls below the current ETSI mask for FM broadcast at all frequency offsets.

4.4.2 Signal generation

The DRM+ baseband signal was provided on an electronic circuit board developed by the University of Hannover. The data transmitted was a pseudo random bit sequence that was repeated in a loop. The board also included the D/A converter and RF mixer that shifts the baseband signal into the desired RF range with the help of an unmodulated RF carrier that was provided by a signal generator. An amplifier followed the mixer to provide enough signal level for the measurements.

The following setup was used to generate the DRM+ unwanted signal:

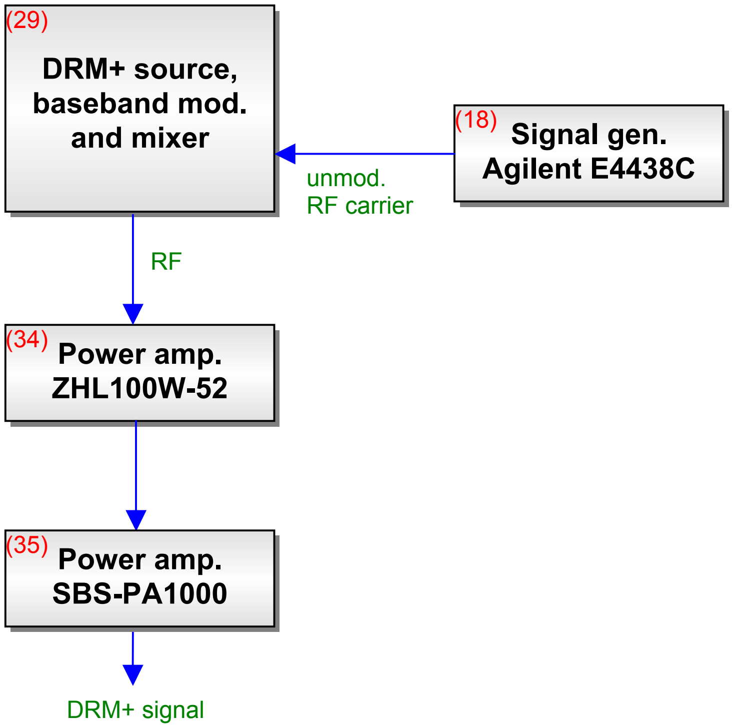

Fig. 7: Block diagram of the unwanted DRM+ signal generation
Numbers in brackets refer to the measurement equipment list in Annex 1

The spectrum of the DRM+ signal as seen on the analyzer was similar to the spectrum of the DRM120 signal.

The high dynamic spectrum recording of the DRM+ signal can be seen in Annex 3. It can be seen that the signal includes “peaks” at certain distinct frequencies in the OoB domain that go well above the level of the surrounding sideband emissions. These peaks may lead to sudden rise in protection ratio when the victim receiver is exactly on one of these peaks.

The power amplifier reduced the dynamic range of the signal relative to the sideband noise level. Although the signal still lies below the current FM broadcast mask the level of sideband emissions was higher than that of the other interferers, especially the FM broadcast unwanted signal. This has significant influence on the measured protection ratios at frequencies far off the centre frequency and is not due to the modulation of the unwanted signal.

4.5 HD-Radio

4.5.1 Description

HD Radio is a Broadcast system developed in the US that allows broadcast stations to transmit their programme in analogue and digital form simultaneously, also known as “IBOC DSB” or “digital System C”. It consists of the normal analogue FM broadcast spectrum with two additional OFDM blocks outside the RDS frequency range (between about +/- 130 kHz and +/- 200 kHz from the main carrier), resulting in an overall bandwidth of about 400 kHz:

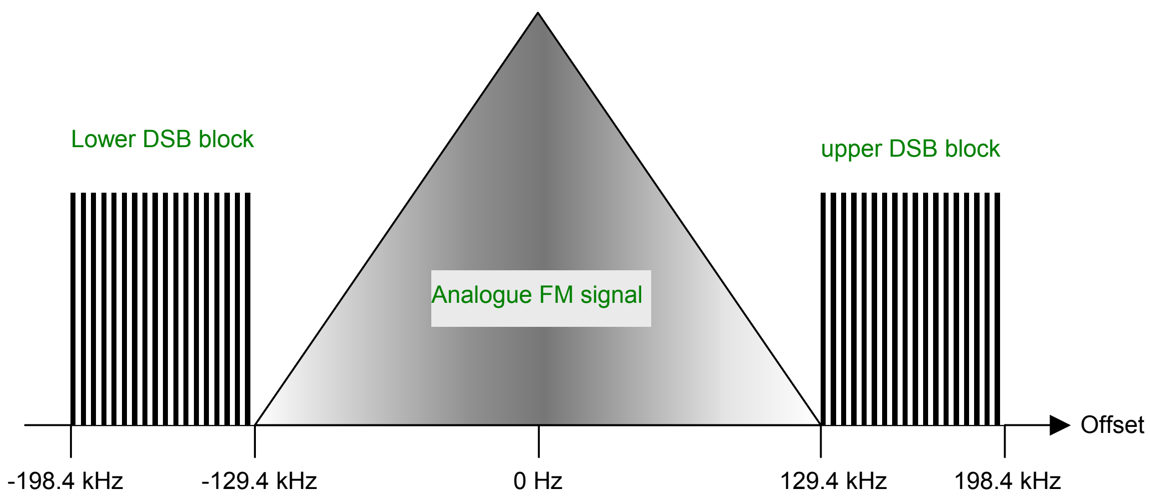

Fig. 9: Spectral components of the HD radio hybrid mode signal

The analogue component of the HD radio unwanted signal was modulated with the coloured noise according to ITU-R BS.641 to be in accordance with the FM broadcast unwanted signal. Key parameters for the DSB blocks are:

Modulation (main carrier):	COFDM
Number of subcarriers:	2 x 191
Subcarrier spacing:	363 Hz
Bandwidth:	2 x 69 kHz
Modulation (data carriers):	QPSK
CREST factor of OFDM blocks:	8.5 dB (measured)

The spectrum mask is developed from ITU-R BS.1114-5. The applicable mask is a combination of the mask for FM broadcast (ETSI EN 302 018-1) and the mask for the digital sidebands in hybrid mode according to ITU-R BS.1114-5 section 8.1.1:

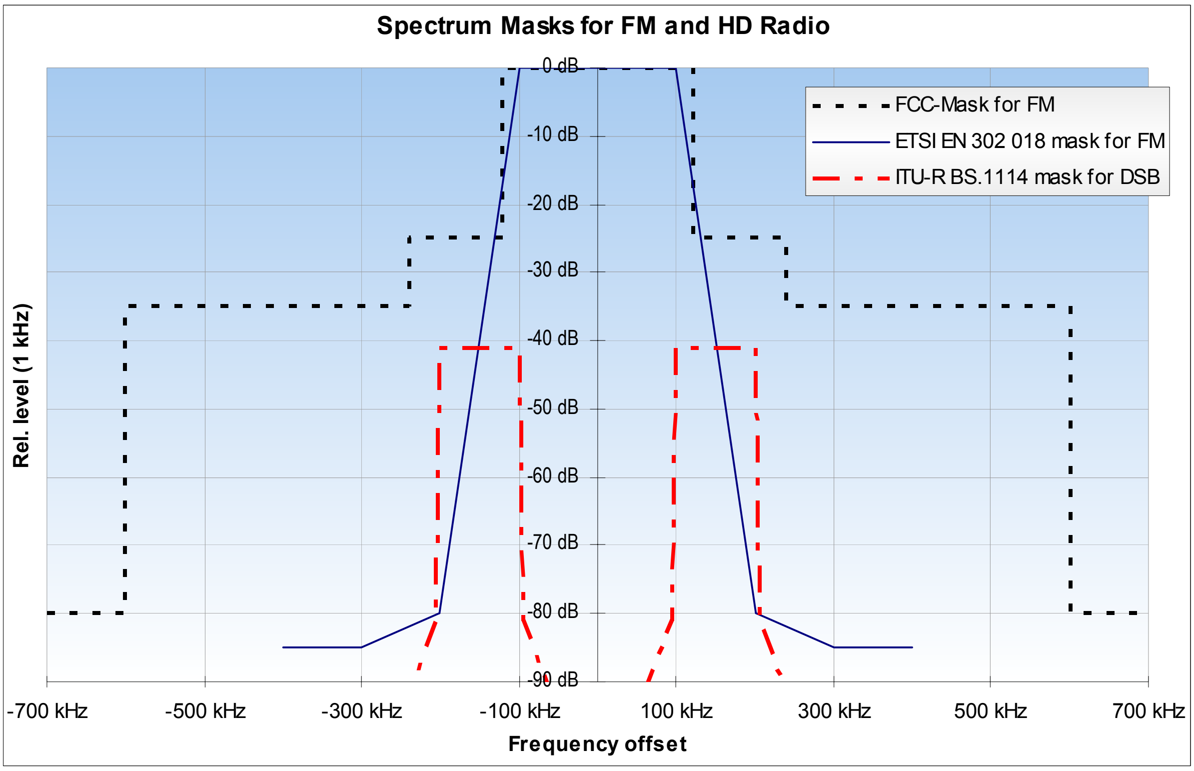

Fig. 10: Spectrum masks for FM and HD radio

FCC mask for FM:

Offset	rel. level (1 kHz)
-600 kHz	-80,0 dB
-600 kHz	-35,0 dB
-240 kHz	-35,0 dB
-240 kHz	-25,0 dB
-120 kHz	-25,0 dB
-120 kHz	0,0 dB
120 kHz	0,0 dB
120 kHz	-25,0 dB
240 kHz	-25,0 dB
240 kHz	-35,0 dB
600 kHz	-35,0 dB
600 kHz	-80,0 dB

ITU-R BS.1114 mask for DSB:

Offset	Atten.	rel. level (1 kHz)
-270 kHz	-60,0 dB	-101,0 dB
-205 kHz	-40,0 dB	-81,0 dB
-200 kHz	0,0 dB	-41,0 dB
-100 kHz	0,0 dB	-41,0 dB
-95 kHz	-40,0 dB	-81,0 dB
-30 kHz	-60,0 dB	-101,0 dB
30 kHz	-60,0 dB	-101,0 dB
95 kHz	-40,0 dB	-81,0 dB
100 kHz	0,0 dB	-41,0 dB
200 kHz	0,0 dB	-41,0 dB
205 kHz	-40,0 dB	-81,0 dB
270 kHz	-60,0 dB	-101,0 dB

ETSI mask for FM:

Offset	rel. level (1 kHz)
-400 kHz	-85,0 dB
-300 kHz	-85,0 dB
-200 kHz	-80,0 dB
-100 kHz	0,0 dB
100 kHz	0,0 dB
200 kHz	-80,0 dB
300 kHz	-85,0 dB
400 kHz	-85,0 dB

Tab. 3: Spectrum masks for FM and HD radio

The spectral power of the DSB blocks measured with 1 kHz RBW is 41 dB below total power. The total power of each DSB block over its full bandwidth is 23 dB below the total emitted power. Therefore the overall emitted power is nearly the same, regardless of whether the DSB blocks are switched on or off, in which case only the analogue FM component remains.

4.5.2 Signal generation

The HD radio signal was readily provided and consists of two units, one of which provided the DSB blocks. The other unit included an FM modulator and RF amplifier that produced sufficient signal level for the measurements. Coloured noise for the analogue FM component was provided by a noise source followed by an audio filter. In the digital DSP blocks, pseudo random data was transmitted.

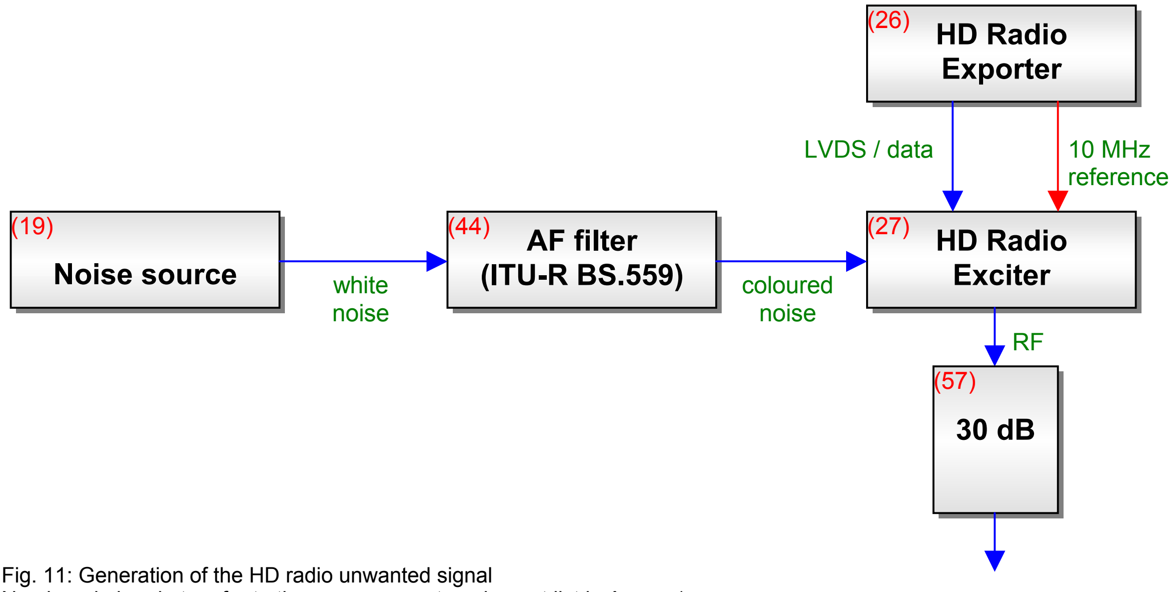

Fig. 11: Generation of the HD radio unwanted signal
Numbers in brackets refer to the measurement equipment list in Annex 1

This setup produced the following spectrum:

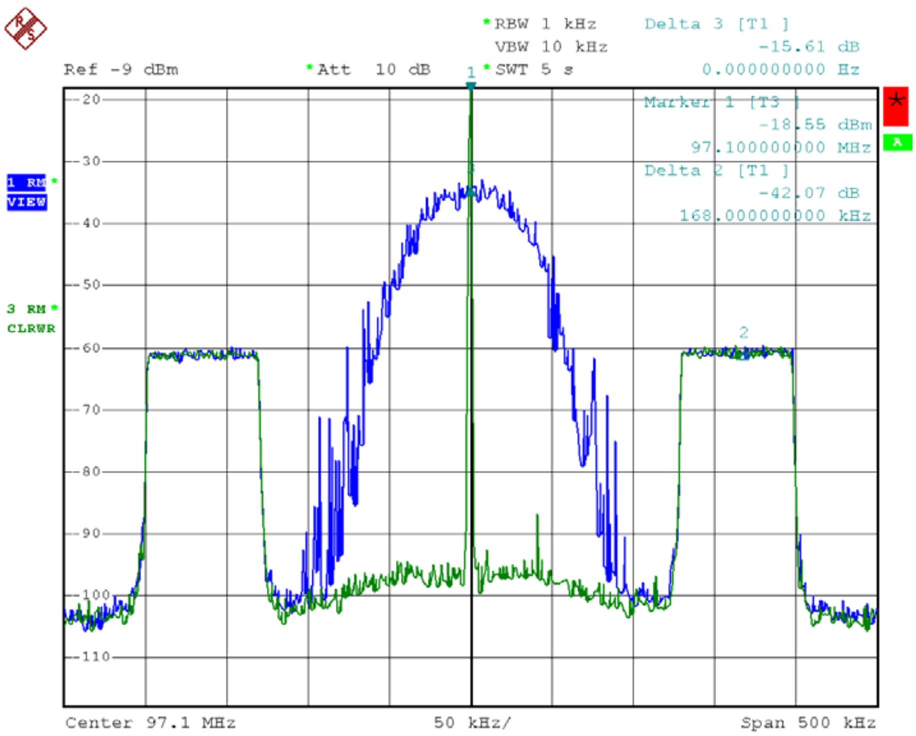

Fig. 12: HD radio spectrum.
Upper (blue) trace: FM carrier modulated with coloured noise.
Lower (green) trace: FM carrier unmodulated (used as level reference).

High dynamic spectrum recordings of the sideband emissions can be found in Annex 3.

5 Protection ratio measurements

5.1 General

The general procedure followed for the protection ratio measurements was to supply sufficient wanted signal level to the receiver and then increase the unwanted signal level until the failure criteria occurs. The difference between wanted and unwanted signal levels is the protection ratio. This measurement is repeated for various offsets between wanted and unwanted signal frequencies.

All signal levels throughout this report are given in RMS over the whole signal bandwidth.

For narrowband FM / BOS no minimum wanted signal level is defined. In this case, the wanted signal level for the protection ratio measurements was adjusted to about 10 dB above the measured receiver sensitivity in order to be well away from influences of receiver noise, but still low enough to simulate a situation near the coverage border. Because the variation in sensitivities was quite high, the wanted signal level for each receiver was different. However, the protection ratio is independent of this level as long as we are inside the "linear range" of the receiver. This range usually begins about 7 to 10 dB above the sensitivity and ends where the receiver input stage is overloaded, usually in the range of 0 dBm. Therefore, a setting of about 10 dB above the sensitivity provides the highest level margin for the interfering signal before overloading occurs.

For FM broadcast, ITU-R BS.641 says that the wanted signal level to be used in protection ratio measurements is the lowest level at which the receiver under test reaches an audio S/N of 56 dB. For the investigated FM receivers here, minimum wanted signal levels range from -55 dBm to -51 dBm. To assess the linearity of the receivers, additional measurements were made with an increased wanted signal level (+10 and +20 dB).

For VOR and ILS, ITU-R IS.1140 describes a set of levels at which protection ratios are to be made: The minimum level listed for VOR where the tested receiver works is -79 dBm, for ILS this level was -86 dBm. To assess the linearity of the receiver, most measurements have been repeated with the next higher signal level listed in the recommendation, which was -63 dBm for VOR and -70 dBm for ILS.

The level of the unwanted signal was always adjusted by means of an external attenuator to ensure that the ratio of main signal to sideband emissions remained unchanged.

The following subchapters state only result summaries. The detailed results of all protection ratio measurements for each receiver can be seen in Annex 4.

When interpreting the results, it is most important to note that when the receiver is not overloaded, the protection ratio mainly depends on the level of sideband emissions on the receive frequency. Since the main aim of these measurements was to obtain practically realistic results, standard transmitters for the generation of FM broadcast unwanted signals and state of the art transmitters for DRM+ and HD-Radio signals were used. It is much easier to produce a clean FM spectrum that an OFDM spectrum with low sideband emissions. FM transmitters used nowadays often produce sideband emissions that fall 40 dB or more below the defined FM spectrum mask. Without additional output filtering, OFDM transmitters can only just meet the mask. This fact is the main reason for the seemingly higher interference potential of the digital signals measured over the standard FM broadcast emission for high frequency offsets.

5.2 FM Broadcast as the interferer

5.2.1 FM broadcast -> FM broadcast reception

To have a reference for the interfering effect of all digital systems investigated here, a series of protection ratio measurements FM broadcast against FM broadcast was made.

The following setup was used:

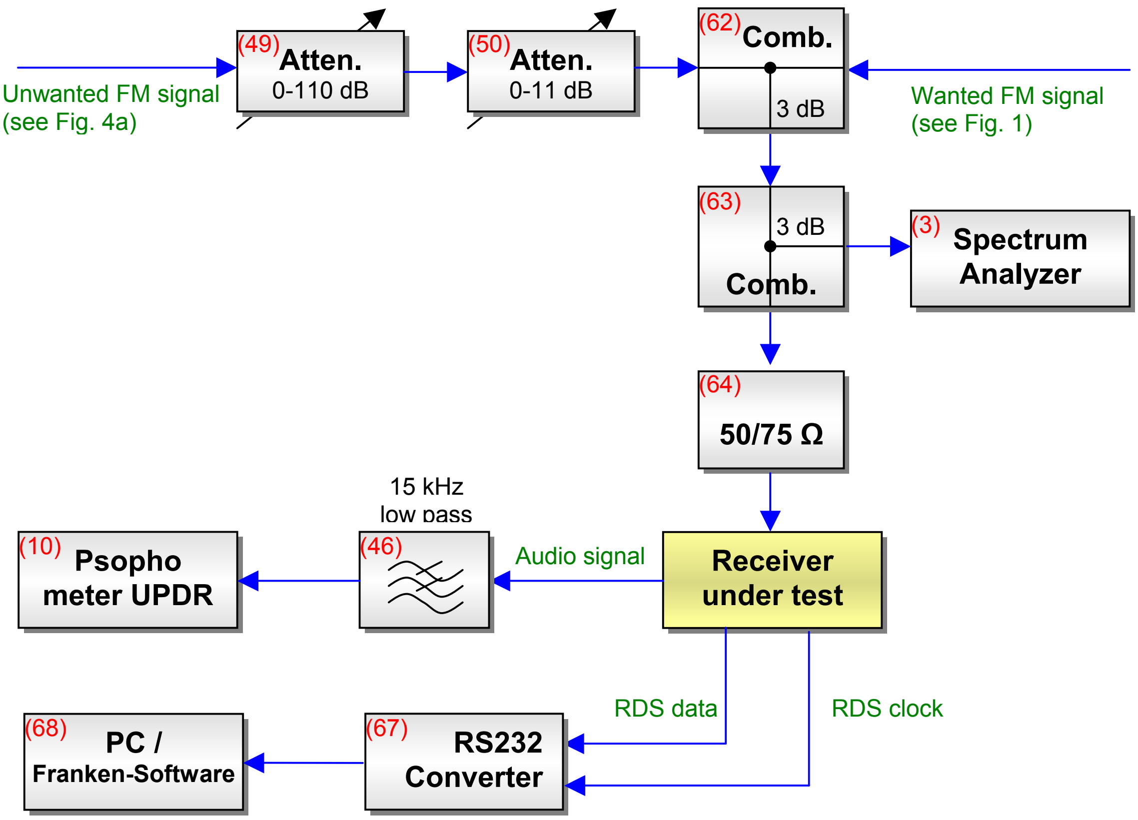

Fig. 13: Setup for FM -> FM S/N protection ratio measurements
Numbers in brackets refer to the measurement equipment list in Annex 1

A summary of the results for the S/N interference is given in the following figure. Measurements with increased wanted signal level are marked “Rx2 +20 dB”, “Rx4 +10 db” and “Rx4 +20 dB”.

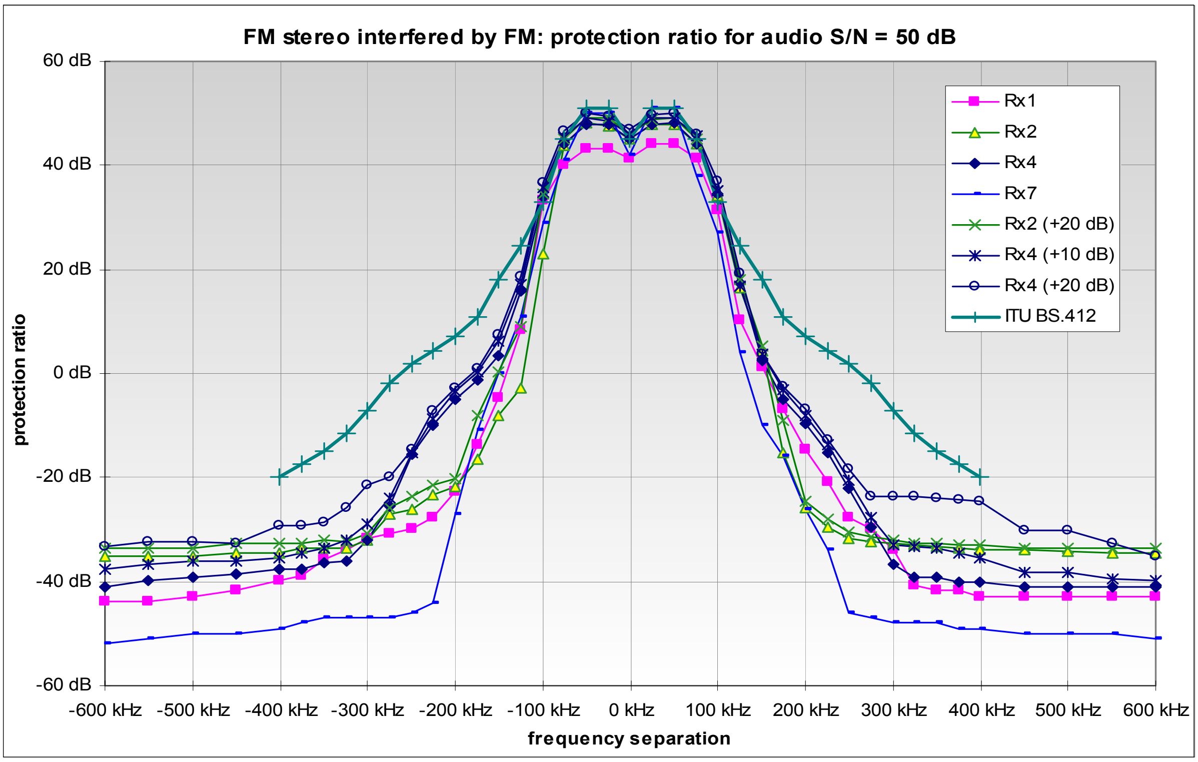

Fig. 14: Summary of protection ratio results for FM stereo interfered by FM (S/N interference)

As a reference, the protection ratio curve for steady interference into FM stereo reception given in ITU-R BS.412, Table 3, is also included in the graph.

It can be seen that the shape of the results equals the reference protection ratio curve, although the receivers used generally have a better selection.

Apart from a small rise in protection ratio between 250 and 500 kHz offset for Rx 4 at wanted signal level increased by 20 dB, the receivers show relatively good linearity.

5.2.2 FM broadcast -> Narrowband FM / BOS reception

The usable frequency range of the supplied BOS receivers was 84.015 MHz to 87.255 MHz. The lowest frequency possible for any FM transmitter in Germany is 87.6 MHz, so a minimum frequency separation of -345 kHz is always guaranteed. Although the determination of protection ratios FM broadcast into BOS was not a key issue for this series, one receiver was still measured for the following reasons:

- The results should serve as a reference for comparison of protection ratios with the digital broadcast signals as interferers
- It should be determined whether the receivers are still in the linear range (not overloaded) even at wider frequency offsets.

The following measurement setup was used:

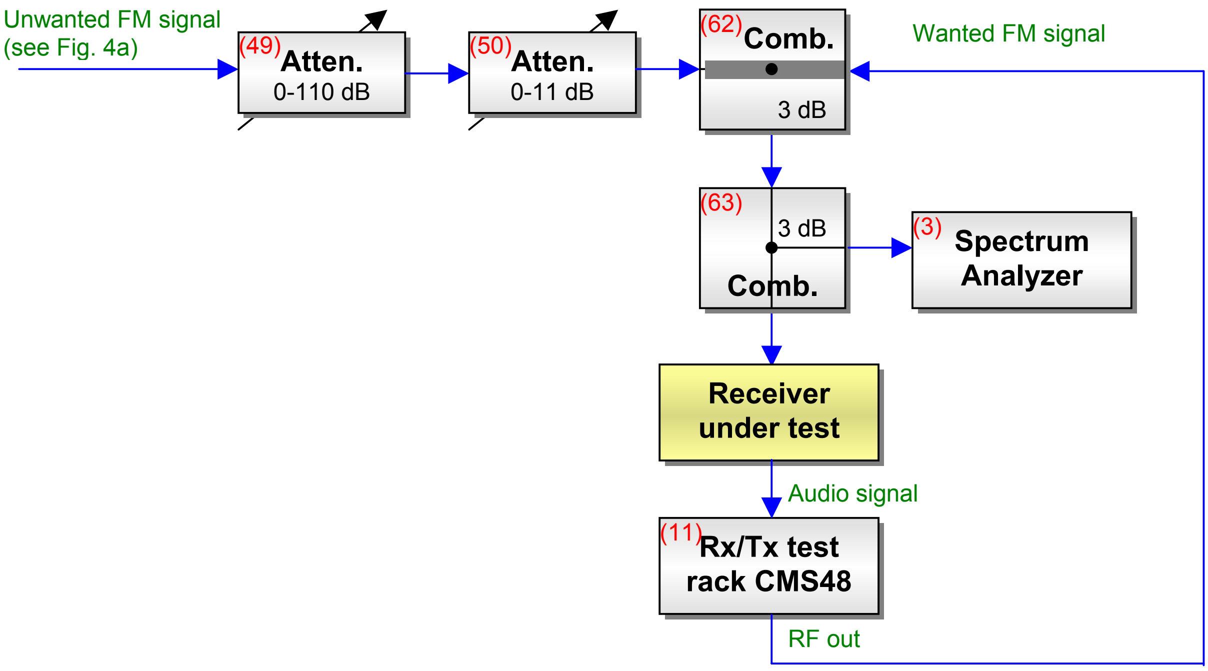

Fig. 15: Setup for FM -> narrowband FM protection ratio measurements
Numbers in brackets refer to the measurement equipment list in Annex 1

The result is summarized in the following figure.

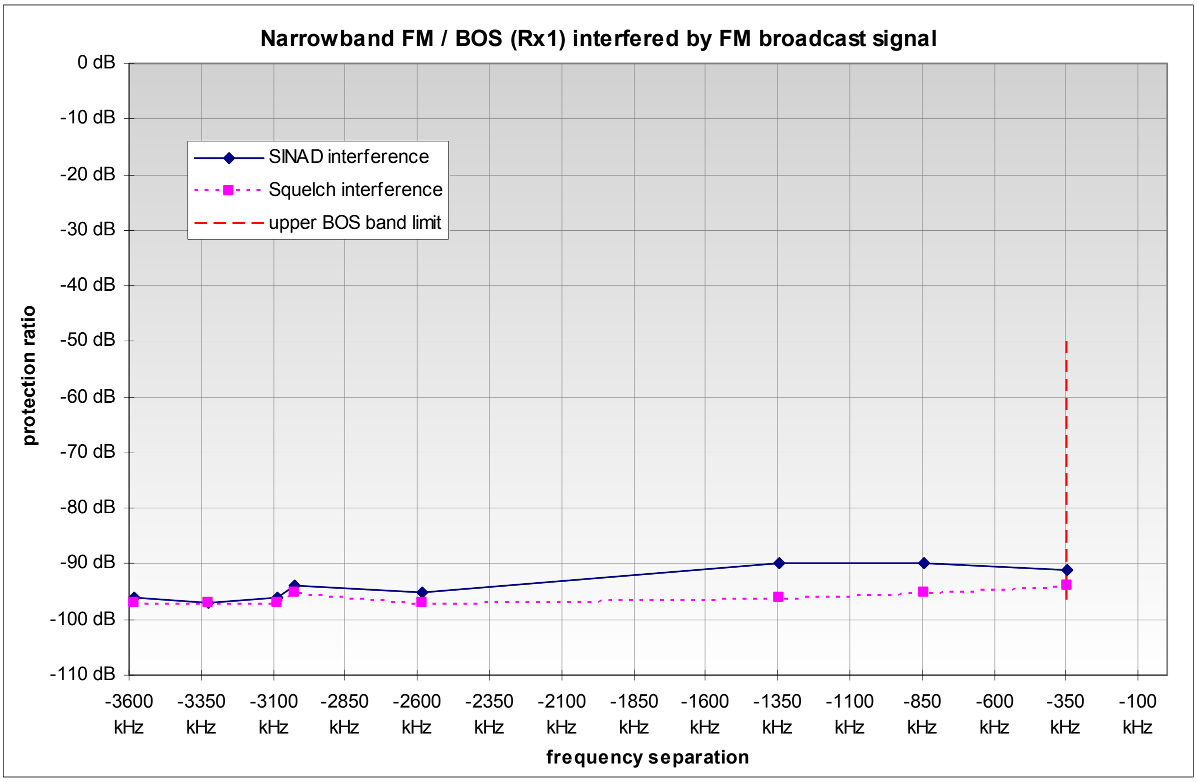

Fig. 16: Protection ratio results for narrowband FM / BOS interfered by FM broadcast.

The wanted signal level for the SINAD interference was -104 dBm, for the squelch interference -100 dBm. These levels are 10 dB above the measured sensitivity for an undistorted SINAD of 20 dB and undistorted squelch opening, respectively.

It can be seen that the receiver is still not overloaded because there are no sudden “steps” in protection ratio.

5.2.3 FM broadcast -> Aeronautical Radionavigation (VOR) reception

The lowest VOR frequency is 108.0 MHz, the highest FM broadcast frequency is 107.9 MHz. Starting from this constellation (Offset = -100 kHz), the FM broadcast signal was shifted down in frequency while the VOR receiver frequency was kept.

The following setup was used to measure the VOR protection ratios:

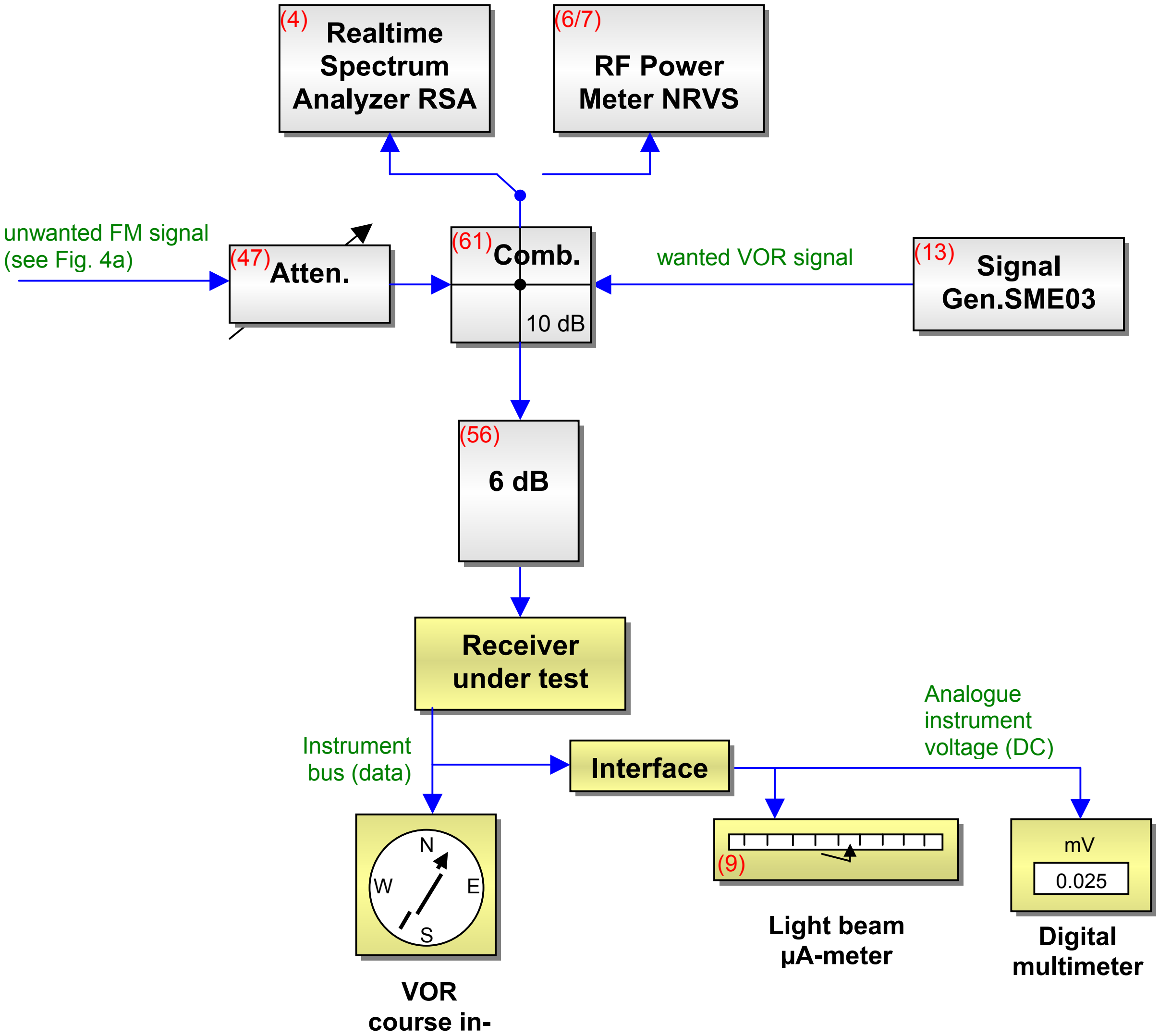

Fig. 17: Setup for FM -> narrowband VOR protection ratio measurements
Numbers in brackets refer to the measurement equipment list in Annex 1

The VOR course indicator was used to detect the “flag interference”. The course interference was measured using a method described in ITU-R IS.1140: A number of output-deflection samples from the ARINC-429 bus for digital receivers are collected and then the mean and standard deviation of the data is computed. The standard deviation for the baseline case (no interfering signals) is multiplied by two to get the baseline 2σ value and 4.5 µA (0.00465 DDM) is added to the baseline 2σ value to get an upper limit for the 2 σ value with interfering signals present. The interference threshold is defined as the point where the 2 σ value exceeds the upper limit. For practical reasons, a special interface was used that converts the serial data telegrams from the receiver into an adequate voltage that drives the analogue light beam instrument. The maximum allowable VOR course error corresponds to a variation of the current through the µA meter of 4.5 µA or +/- 2.25 mV on the multimeter. This was used to determine the “course interference”.

When interference from digital systems is present, the course indicator starts to shift around the true course value irregularly.

The result is summarized in the following figure. The wanted signal level was -79 dBm. ITU-R IS.1140 describes a total of four different wanted signal levels. -79 dBm was the lowest level in this list where the undistorted receiver was still able to meet the course criterion. The next higher level was -63 dBm. Protection ratios measured with this wanted signal level did not differ from those at -79 dBm.

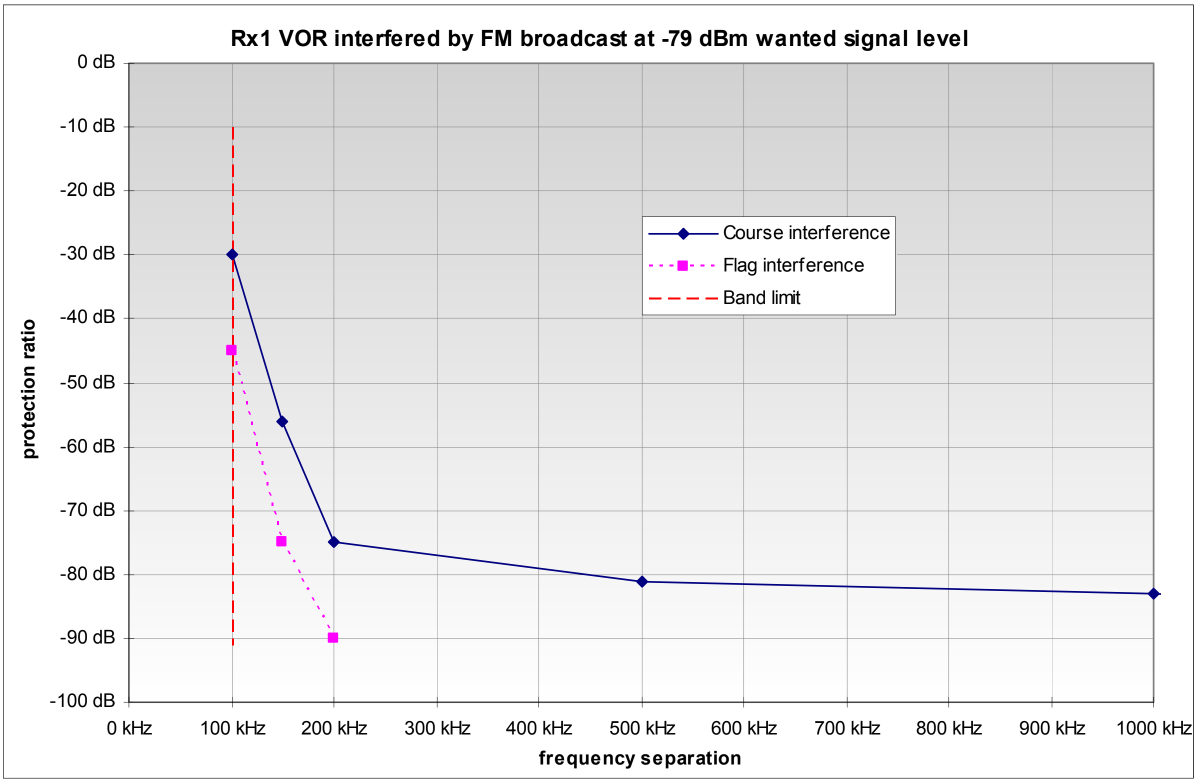

Fig. 18: Protection ratio results for VOR interfered by FM broadcast.

Annex 4 contains the detailed results of the measurements. Additional measurements were made with the unwanted FM transmitter being modulated with noise according to ITU-R BS.641 on the Fxi-250 FM transmitter. Comparison between these measurements and the ones made with modulations according to ITU-R IS.1140 with the ITELCO transmitter shows how much protection ratios depend on the exact modulation and on the level of sideband emissions.

5.2.4 FM broadcast -> Aeronautical Radionavigation (ILS) reception

The lowest ILS frequency is 108.1 MHz, the highest FM broadcast frequency is 107.9 MHz. Starting from this constellation (Offset = -200 kHz), the FM broadcast signal was shifted down in frequency while the ILS receiver frequency was kept.

The measurement setup used was the same as for VOR protection ratios (see Fig. 17) with the exception that the receiver data was displayed by an ILS course indicator instrument.

The ILS course indicator was used to detect the “flag interference”. The maximum allowable ILS course error according to ITU-R IS.1140 corresponds to a variation of the current through the µA meter of 4.5 µA. To measure this error, a standard deviation of 0.093 DDM was set in the Signal generator. This produced a default reading of 90 µA on the light beam instrument which was used to determine the “course interference”.

When interference from digital systems is present, the course indicator starts to shift around the true course value irregularly.

The result is summarized in the following figure. The wanted signal level was -86 dBm. ITU-R IS.1140 describes a total of four different wanted signal levels. -86 dBm was the lowest level in this list where the undistorted receiver was still able to meet the course criterion. The next higher level was -70 dBm. Protection ratios measured with this wanted signal level did not differ from those at -86 dBm.

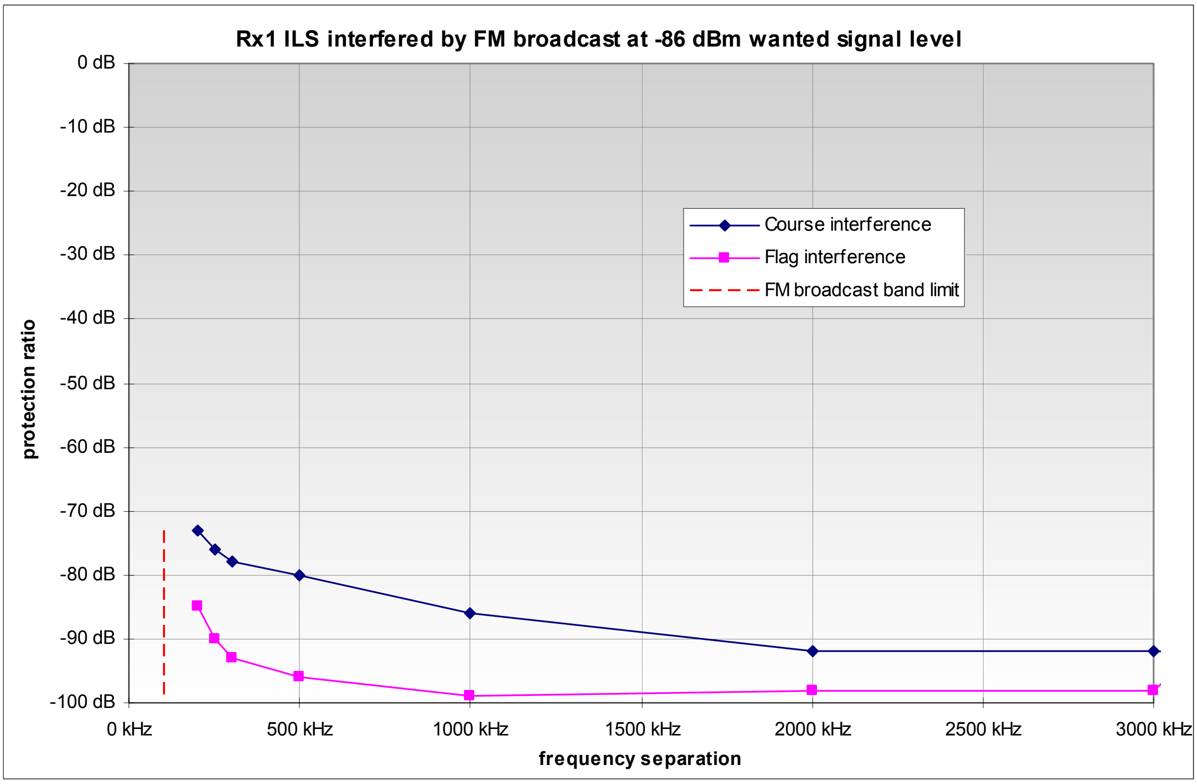

Fig. 19: Protection ratio results for ILS course interfered by FM broadcast.

Annex 4 contains the detailed results of the measurements. As with VOR, additional measurements were made with the unwanted FM transmitter being modulated with noise according to ITU-R BS.641 on the Fxi-250 FM transmitter. Comparison between these measurements and the ones made with modulations according to ITU-R IS.1140 with the ITELCO transmitter shows how much protection ratios depend on the exact modulation and on the level of sideband emissions.

5.3 DRM120 as the interferer

5.3.1 DRM120 -> FM broadcast reception

The same measurement setup as for FM broadcast -> FM broadcast (see fig. 13) was used. Protection ratio measurements were made by shifting the unwanted DRM120 frequency over the receiving range.

As said in chapter 4.3.2, the DRM120 signal was used as interferers with and without additional filtering after the transmitter output.

The following figures summarize the results for the “S/N interference” at the minimum wanted signal level (see chapter 5.1).

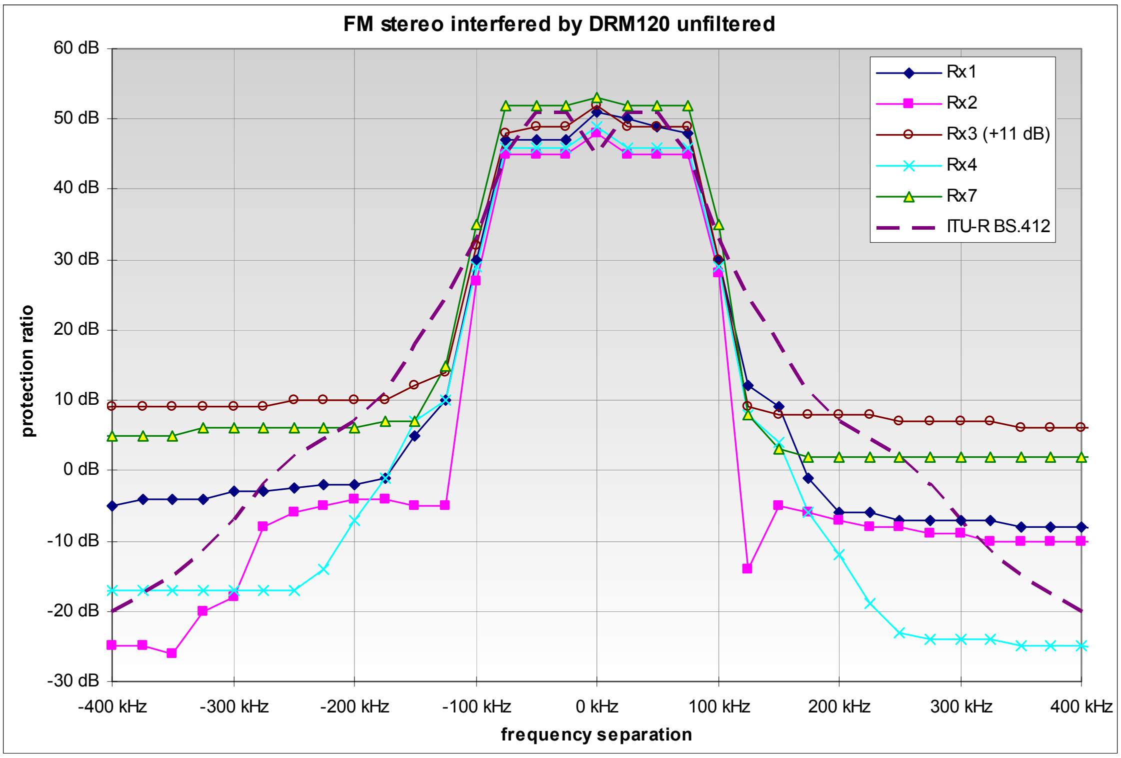

Fig. 20: Protection ratio results for FM stereo interfered by DRM120 unfiltered.

For comparison, the protection ratio curve for FM broadcast against FM broadcast from ITU-R BS.412 is included in the figure.

It can be seen that for offsets up to +/- 200 kHz the interfering effect of DRM120 unfiltered is nearly equal to an FM broadcast interference. For larger frequency offset there is a strong dependency on the receiver design: While Rx7 is up to 25 dB more sensitive to the DRM120 signal, Rx4 is still not more interfered by DRM120 than by FM broadcasting signals.

For DRM120 filtered as the interferer, only the protection ratios of Rx1 were measured:

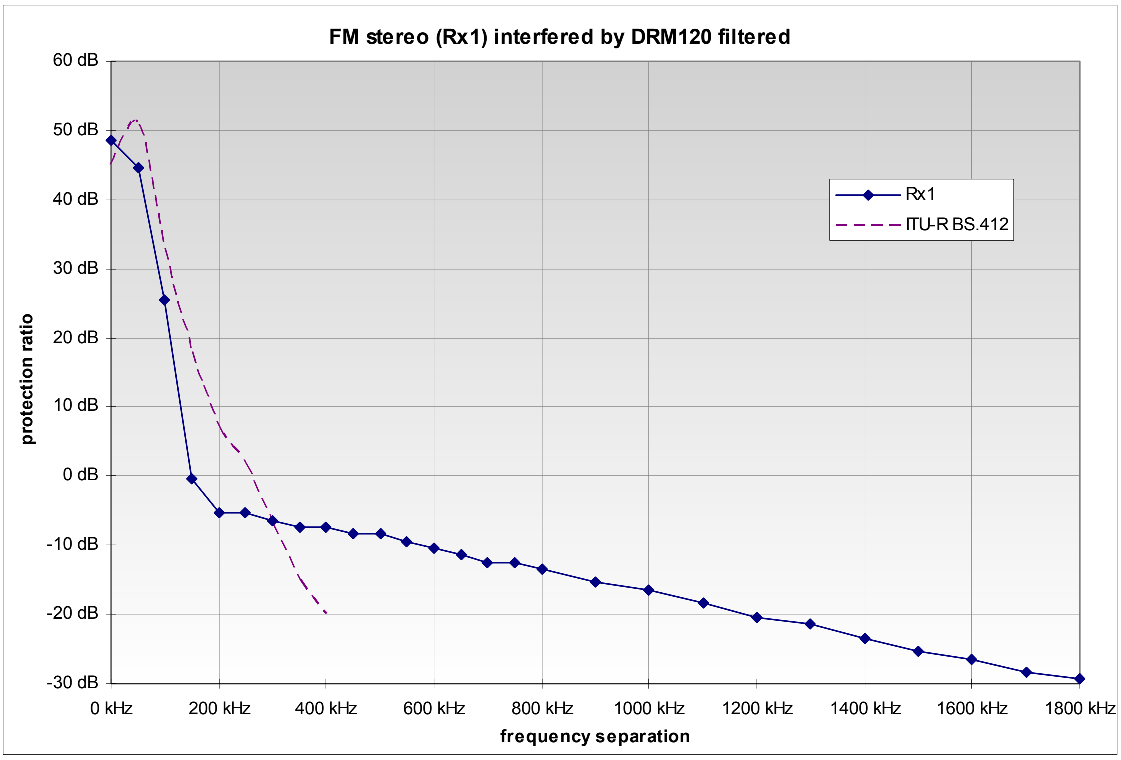

Fig. 21: Protection ratio results for FM stereo interfered by DRM120 filtered.

It can be seen that filtering affects the protection ratio only for larger frequency separations. At 400 kHz offset, the protection ratio from DRM120 is still about 12 dB higher compared to an FM broadcast interferer. Equal protection ratios are only reached for offsets of more than 1200 kHz.

Measurements of the protection ratios for RDS decoding showed that this service is generally less susceptive to interference from DRM120 than the audio S/N.

5.3.2 DRM120 -> Narrowband FM reception

The same setup as in Fig. 15 was used to measure the protection ratios of narrowband FM / BOS against DRM120 filtered and unfiltered. The following figure shows the results for the most critical interference criterion.

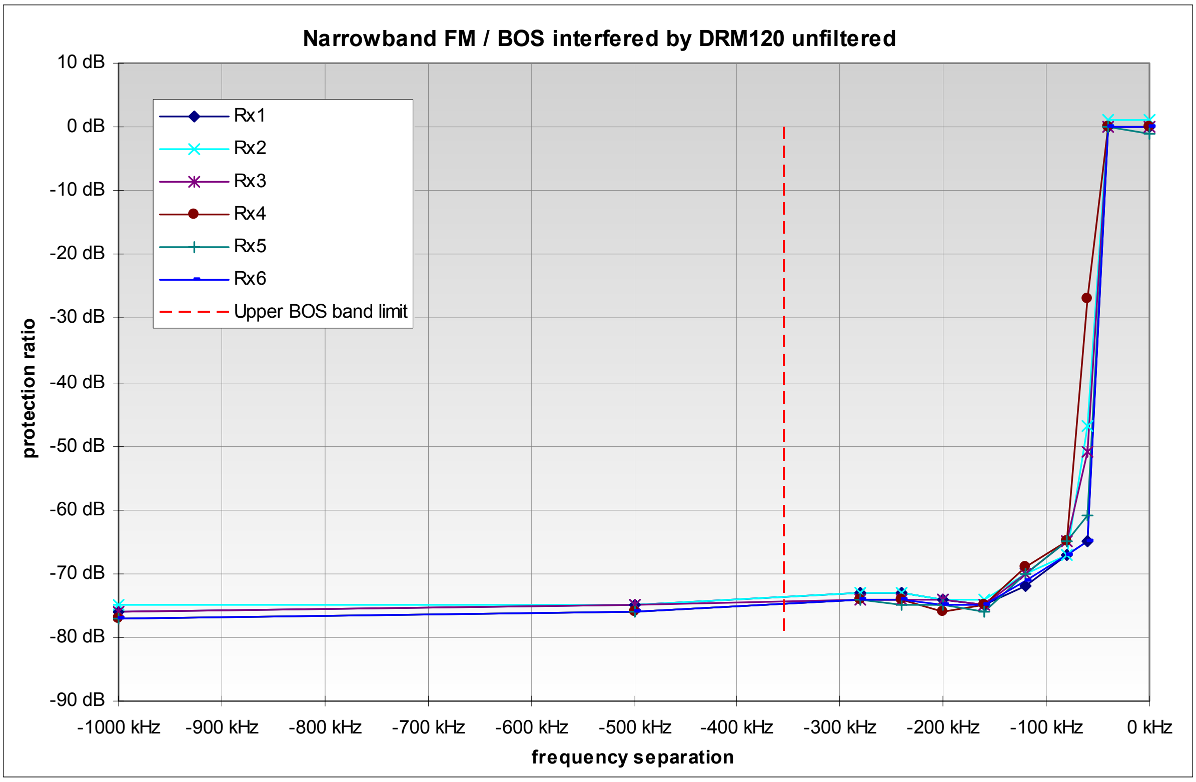

Fig. 22: Protection ratio results for narrowband FM / BOS interfered by DRM120 unfiltered.

It can be seen that the protection ratio of all receivers lie within a very narrow margin. The difference in protection ratio between co-channel and large frequency separations is roughly equal to the suppression of sideband emissions of the DRM120 signal. Therefore all receivers are within their linear range and the only interfering effect is the sideband noise emitted on the BOS channel.

Protection ratios with the DRM120 filtered signal could only be made for realistic frequency separations from -345 kHz up because the output filter for the DRM120 signal was fixed to a transmitter frequency of 87.6 MHz. The following figure shows the results for the most critical interference criterion.

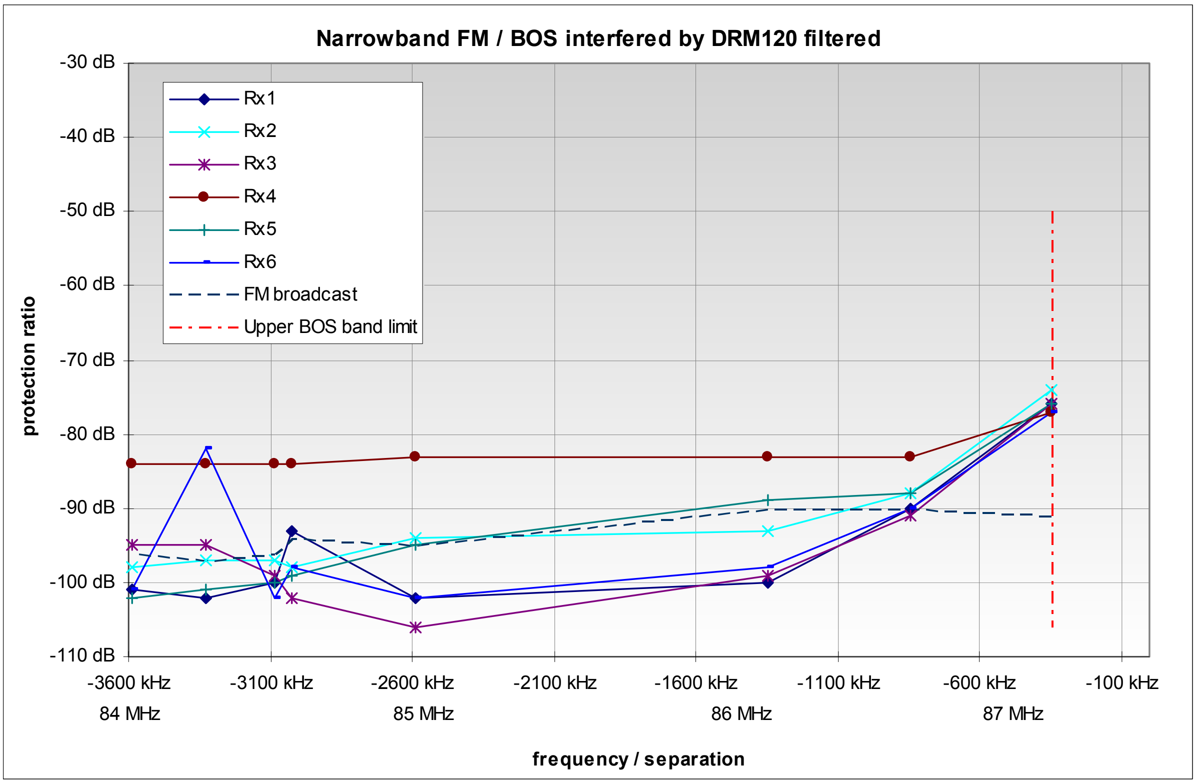

Fig. 23: Protection ratio results for narrowband FM / BOS interfered by DRM120 filtered.

It can be seen that when no substantial sideband emissions from DRM are present, the presence of the high- level DRM120 signal itself becomes an interfering factor. The extent to which this factor plays a role depends on the receiver design as some of them (especially Rx4) seem to get into non-linear states.

For comparison, the measured protection ratio from FM broadcast signals is included in the figure. Apart from the frequency range above 86.755 MHz and Rx4, the interfering effect of DRM120 filtered is roughly the same or less.

5.3.3 DRM120 -> Aeronautical Radionavigation (VOR) reception

The system setup for the protection ratio measurements DRM120 into VOR is the same as illustrated in Fig. 17. The wanted VOR frequency was kept at 108.0 MHz while the unwanted DRM120 signal was tuned from 107.9 MHz downwards.

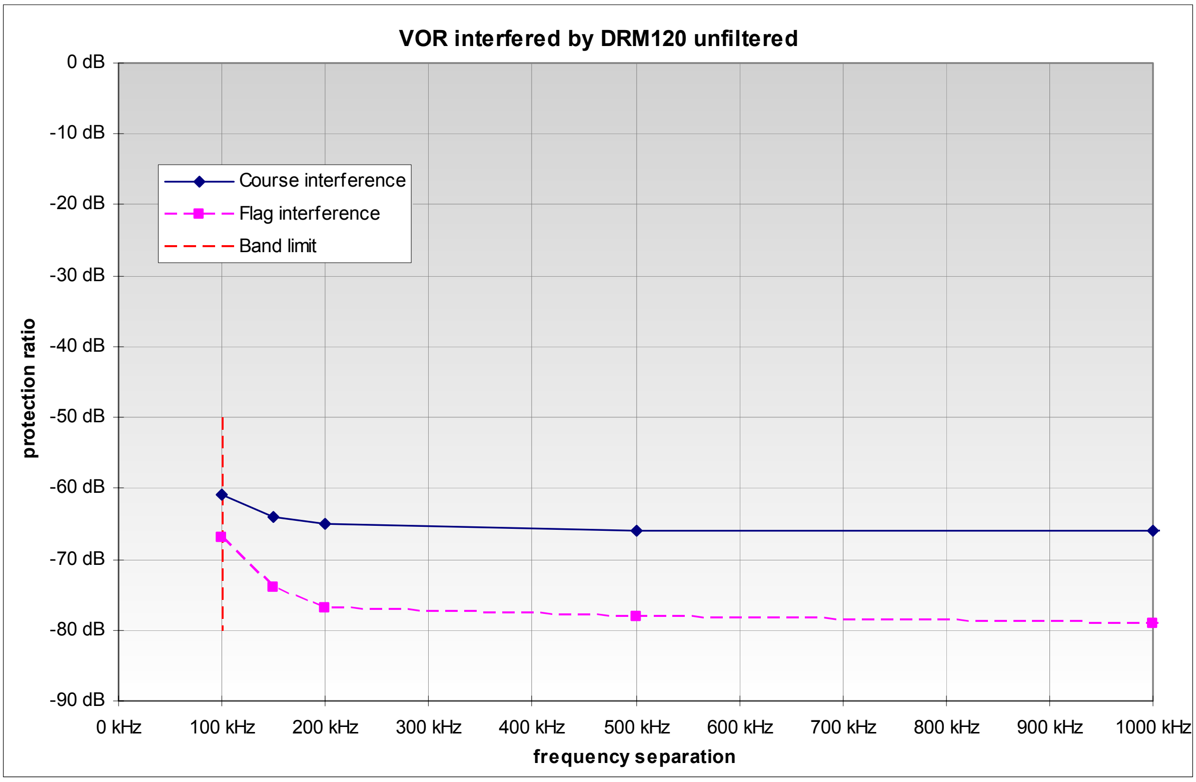

Fig. 24: Protection ratio results for VOR interfered by DRM120 unfiltered.

The protection ratios measured with increased wanted signal level were nearly identical. Therefore it can be assumed that the receiver is still in a linear state and the only interfering effect is the sideband emissions of the DRM120 signal.

For the protection ratio measurements with the DRM120 filtered signal, a tunable bandpass filter (No. 27 in Annex 1) was used as the output filter. At frequencies around 108 MHz, this filter has roughly similar pass range and shape as the filter used in the other measurements. This was necessary to have a free selection of the unwanted frequency which was again tuned from 108 MHz downwards.

Only the course interference is shown in the following figure as this is the more critical criterion.

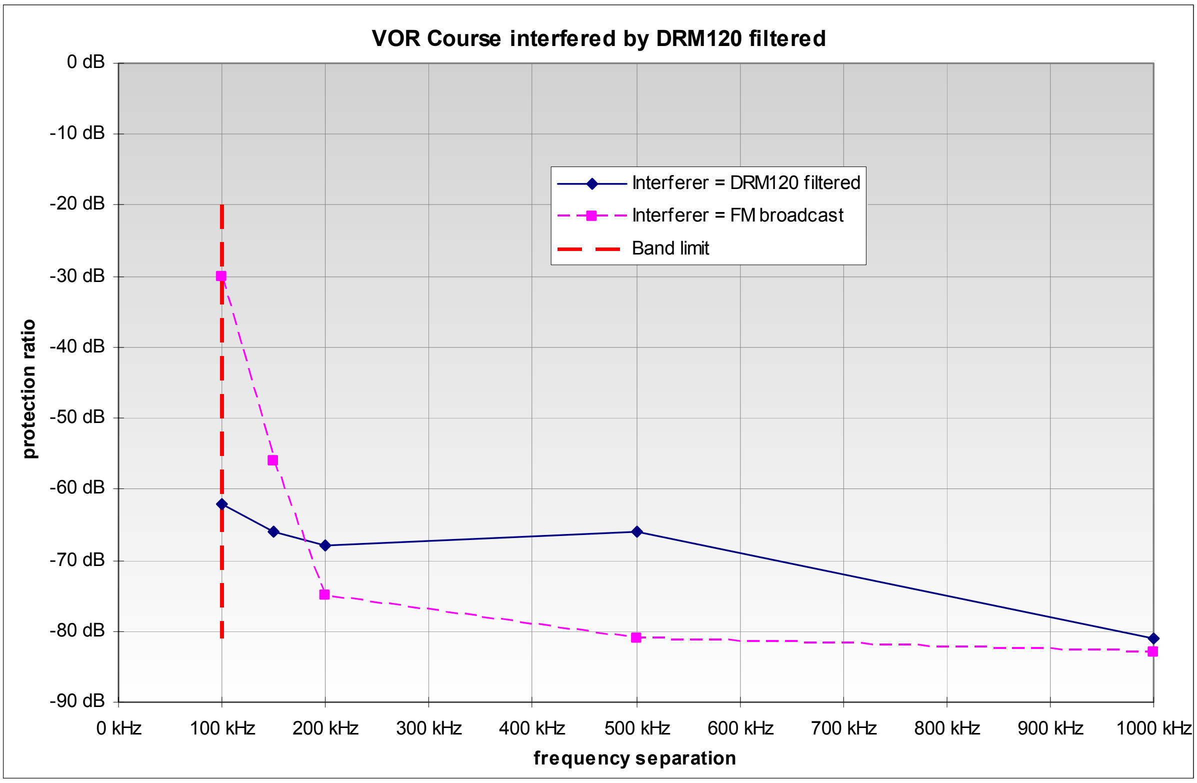

Fig. 25: Protection ratio results for VOR course criterion interfered by DRM120 filtered.

For comparison, the protection ratio curve from FM broadcast is included in the figure. It can be seen that the FM broadcast has more interfering effect for offsets up to 200 kHz (that is below 108.2 MHz) whereas the interference from DRM120 is more at frequency offsets between 200 and 1000 kHz (between 108.2 and 108.9 MHz). Above this frequency, both signals have the same interference potential. Note that the suppression of sideband emissions was best at the FM broadcast signal. This is the main reason for lower protection ratios.

To determine whether the exact offset of the VOR frequency to single subcarriers of the DRM120 signal has any effect, additional measurements have been made with offsets between 100.0 and 100.8 kHz in 20 kHz steps. There was no measurable difference in protection ratios. This proves that the DRM120 signal indeed is like random noise to the VOR receiver evenly spread over the whole signal bandwidth.

5.3.4 DRM120 -> Aeronautical Radionavigation (ILS) reception

The system setup for the protection ratio measurements DRM120 into ILS is the same as illustrated in Fig. 17 with the exception that the receiver data was displayed by an ILS course indicator instrument.

The wanted ILS frequency was kept at 108.1 MHz while the unwanted DRM120 signal was tuned from 107.9 MHz downwards.

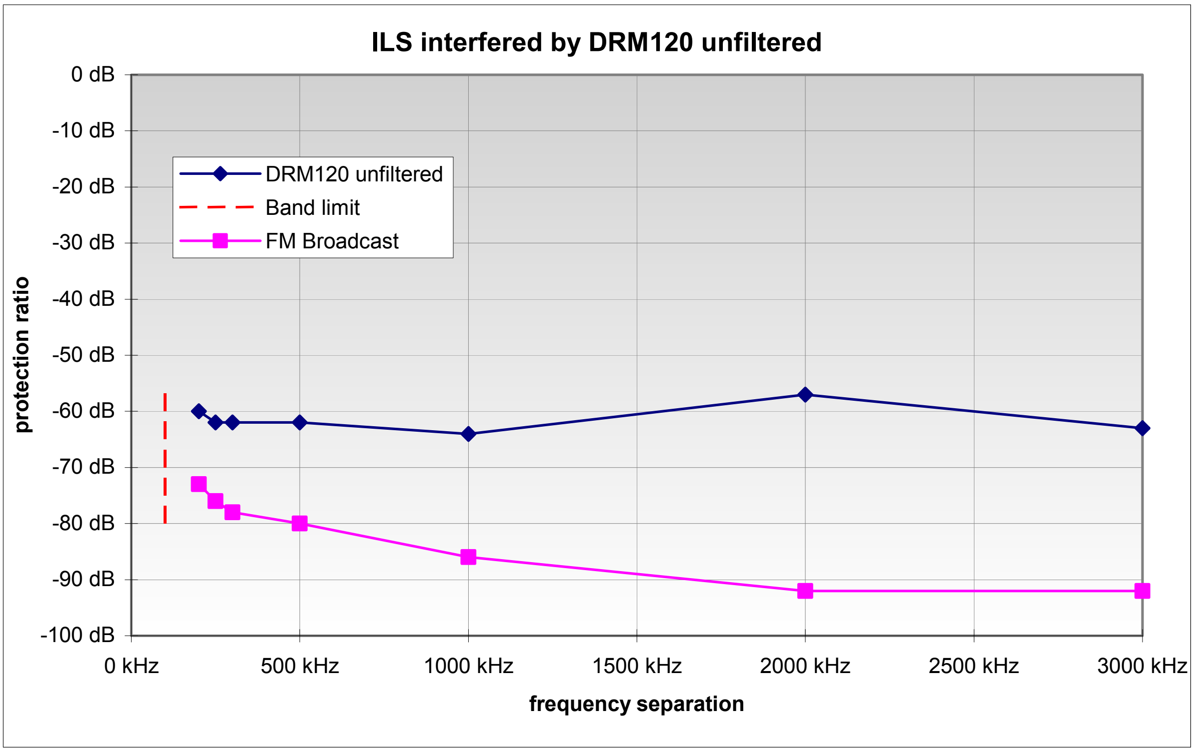

Fig. 26: Protection ratio results for ILS localizer interfered by DRM120 unfiltered.

Additional measurements with increased wanted signal level showed identical protection ratios, so the receiver is still in its linear stage and the only interfering effect is the sideband emissions of the DRM120 signal.

The following figure shows the summary of the protection ratio measurements with the filtered DRM120 Signal as the interferer. Only the course interference is shown as this is the more critical criterion.

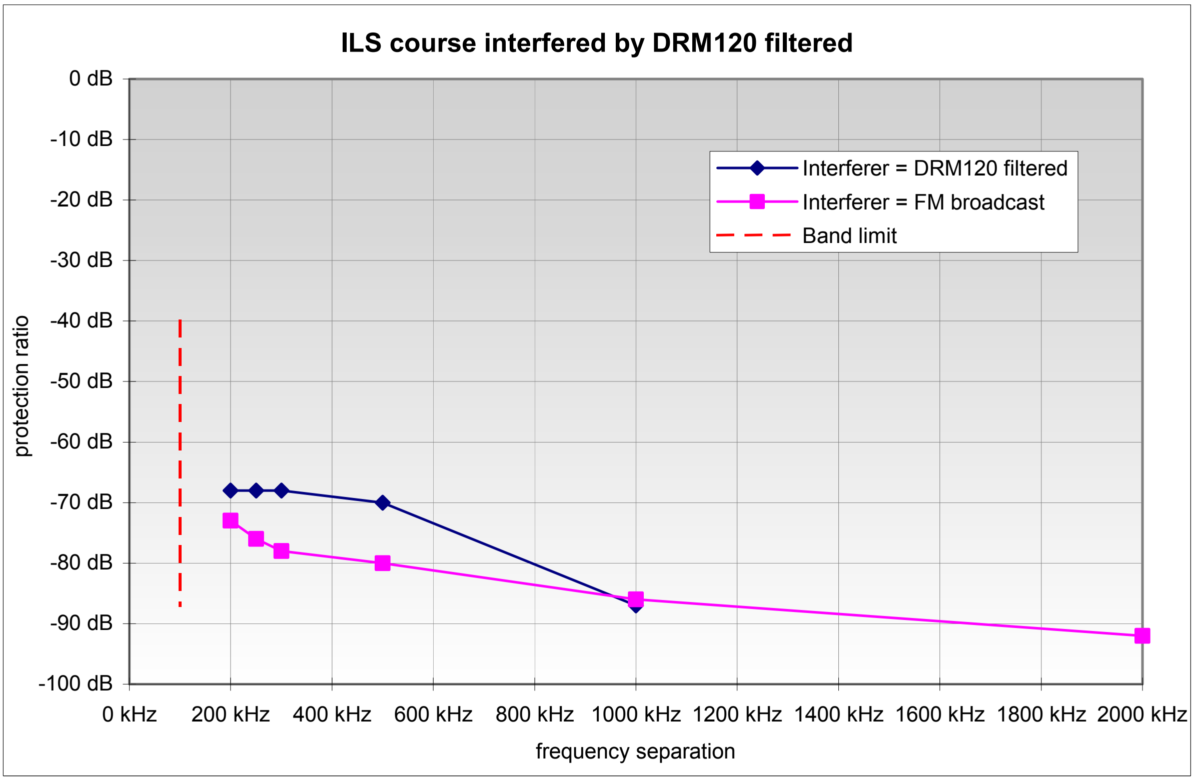

Fig. 27: Protection ratio results for ILS course criterion interfered by DRM120 filtered.

The interference potential of DRM120 on ILS seems to be higher than that of an FM broadcast signal. However, the dominating interference effect is again the level of sideband emissions which was generally lower from the FM broadcast signal.

To determine whether the exact offset of the ILS frequency to single subcarriers of the DRM120 signal has any effect, additional measurements have been made with offsets between 200.0 and 200.8 kHz in 20 kHz steps. There was no measurable difference in protection ratios. This proves that the DRM120 signal indeed is like random noise to the ILS receiver evenly spread over the whole signal bandwidth.

5.4 DRM+ as the interferer

5.4.1 DRM+ -> FM broadcast reception

The same setup as in Fig. 15 was used to measure the protection ratios of DRM+ against narrowband FM / BOS. Due to time constraints, only Rx1 could be measured. The following figure shows the results:

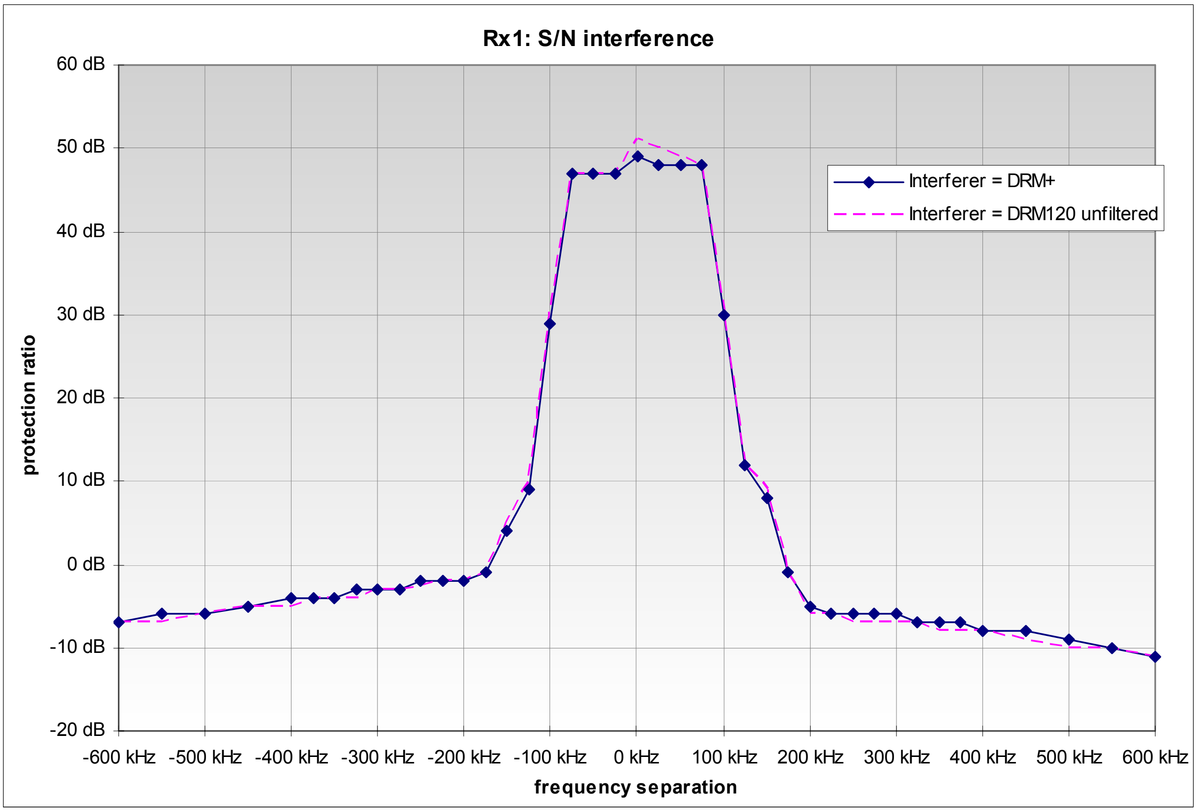

Fig. 29: Protection ratio results for FM broadcast interfered by DRM+.

For comparison, the protection ratios for DRM120 unfiltered as the interferer are also displayed. To facilitate the comparison, only this measurement was made with the power amplifier of the DRM+ signal switched off. With this setup, the sideband emissions of both signals were about equal and so is the protection ratio. This proves that the interference potential of both signals is the same.

5.4.2 DRM+ -> Narrowband FM reception

The same setup as in Fig. 15 was used to measure the protection ratios of DRM+ against narrowband FM / BOS.

Due to time constraints, only the protection ratios for one receiver could be measured. Rx4 was chosen because this was the most critical receiver when interfered by a DRM120 signal. The following figure summarizes the results:

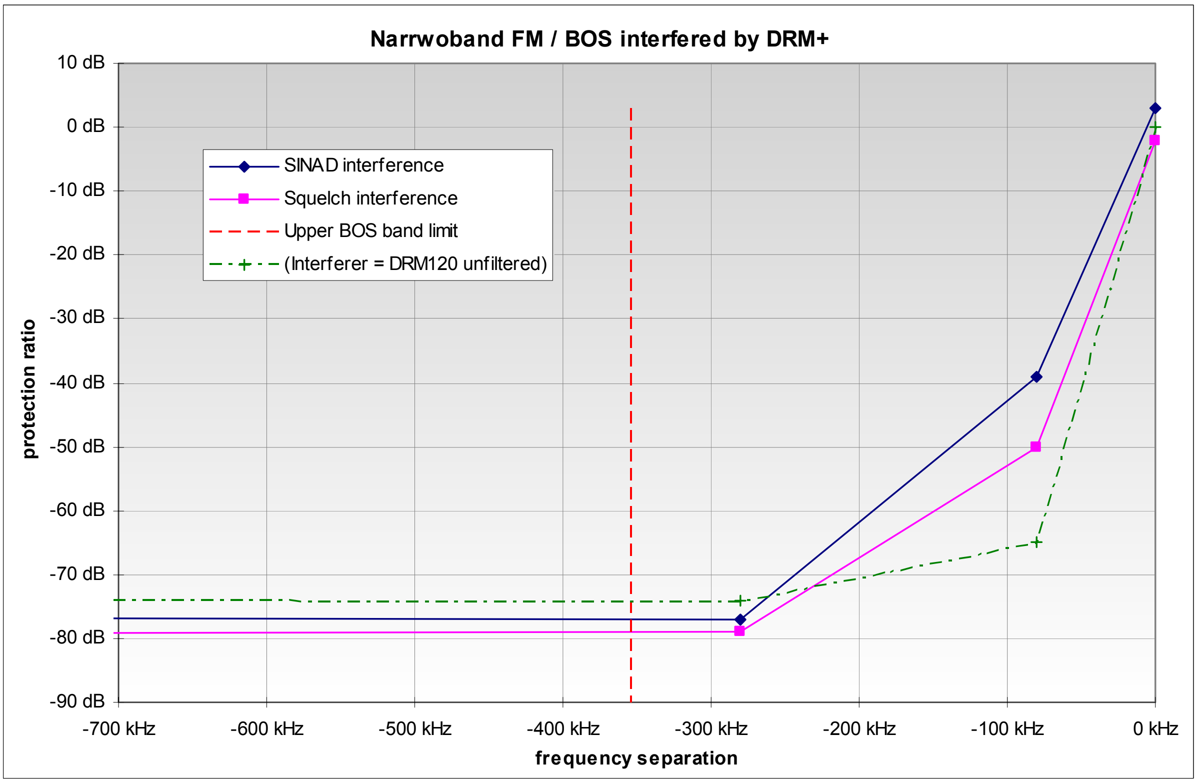

Fig. 30: Protection ratio results for narrowband FM / BOS interfered by DRM+.

For comparison, the protection ratio against DRM120 unfiltered is also included in the figure.

As with DRM120, the difference in protection ratio between co-channel and large frequency separations is roughly equal to the suppression of sideband emissions of the DRM+ signal. Therefore the receiver is within its linear range and the only interfering effect is the sideband noise emitted on the BOS channel.

5.4.3 DRM+ -> Aeronautical Radionavigation (VOR) reception

The system setup for the protection ratio measurements DRM+ into VOR is the same as illustrated in Fig. 17. The wanted VOR frequency was kept at 108.0 MHz while the unwanted DRM+ signal was tuned from 107.9 MHz downwards.

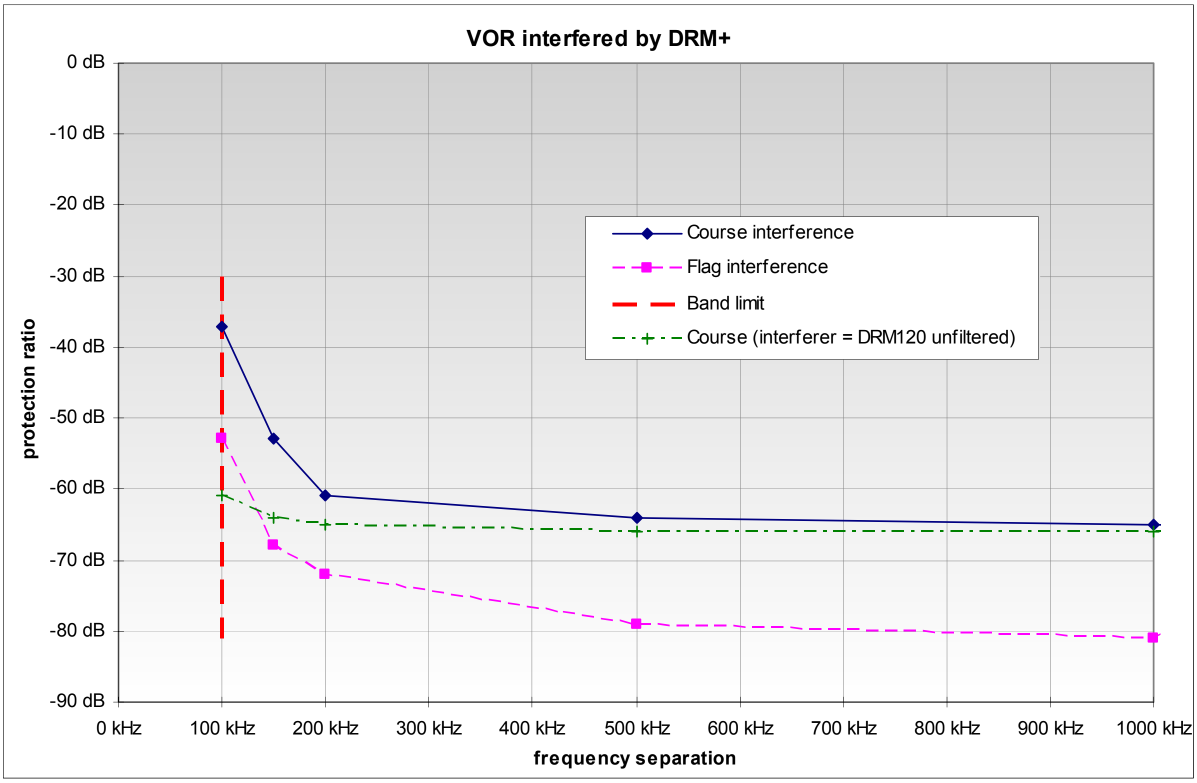

Fig. 31: Protection ratio results for VOR interfered by DRM+.

The protection ratios measured with increased wanted signal level were nearly identical. Therefore it can be assumed that the receiver is still in a linear state and the only interfering effect is the sideband emissions of the DRM+ signal.

For comparison, the course interference protection ratios against DRM120 unfiltered are included in the figure. It can be seen that, apart from the offsets less than 200 kHz, the interference from DRM+ is roughly the same as from DRM120. This, again, is a result of the slightly different sideband levels from both signals. The receiver is still in a linear stage. This has been proven by repeating the measurement at a higher wanted signal level with equal protection ratio results.

This proves that the interference potential of DRM+ to VOR is independent of signal parameters such as pilot tones, carrier spacing and CREST factor.

5.4.4 DRM+ -> Aeronautical Radionavigation (ILS localizer) reception

The system setup for the protection ratio measurements DRM+ into ILS is the same as illustrated in Fig. 17 with the exception that the receiver data was displayed by an ILS course indicator instrument.

The wanted ILS frequency was kept at 108.1 MHz while the unwanted DRM+ signal was tuned from 107.9 MHz downwards.

The result is shown in the following figure:

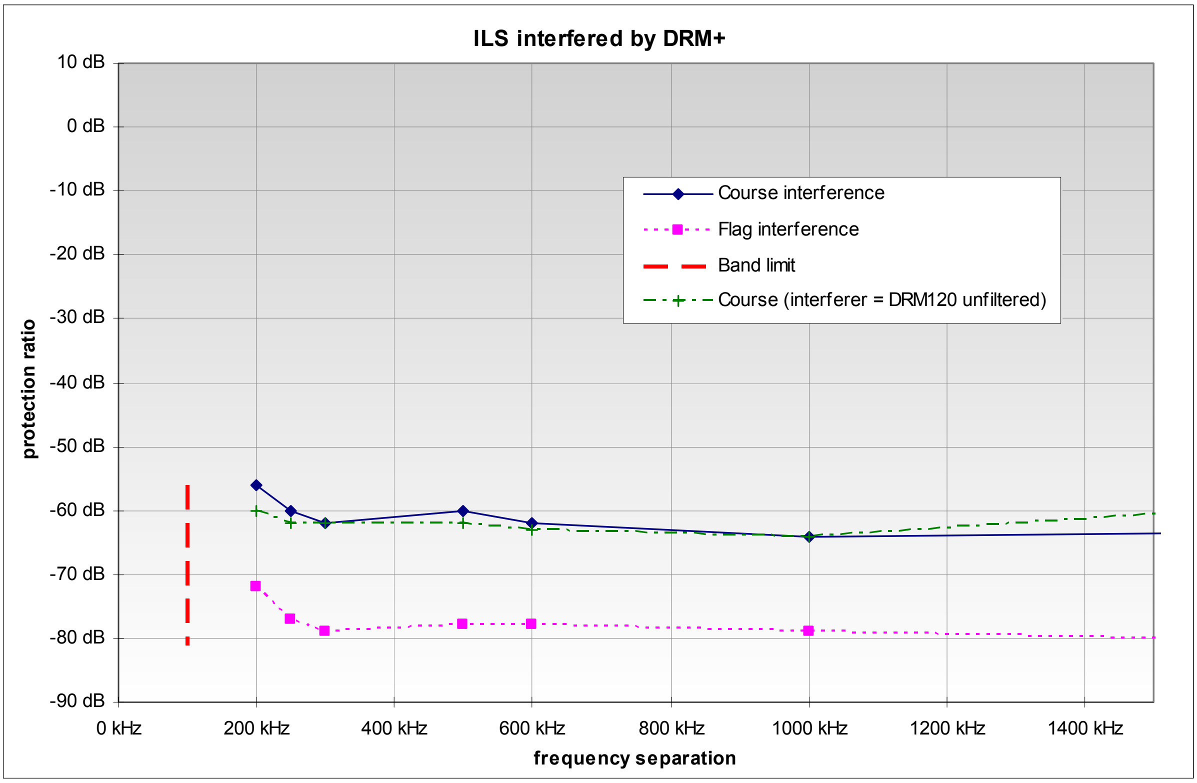

Fig. 32: Protection ratio results for ILS localizer interfered by DRM+.

Additional measurements with increased wanted signal level showed identical protection ratios, so the receiver is still in its linear stage and the only interfering effect is the sideband emissions of the DRM+ signal.

For comparison, the course interference protection ratio against DRM120 unfiltered are included in the figure. It can be seen that it is nearly the same as for DRM+. This proves that the interference potential of DRM+ to ILS is independent of signal parameters such as pilot tones, carrier spacing and CREST factor.

5.5 HD-Radio as the interferer

5.5.1 HD-Radio -> FM broadcast reception

The same measurement setup as for FM broadcast -> FM broadcast (see fig. 13) was used. Protection ratio measurements were made by shifting the unwanted HD-Radio frequency over the receiving range.

The following figures summarize the results for the “S/N interference” at the minimum wanted signal level (see chapter 5.1).

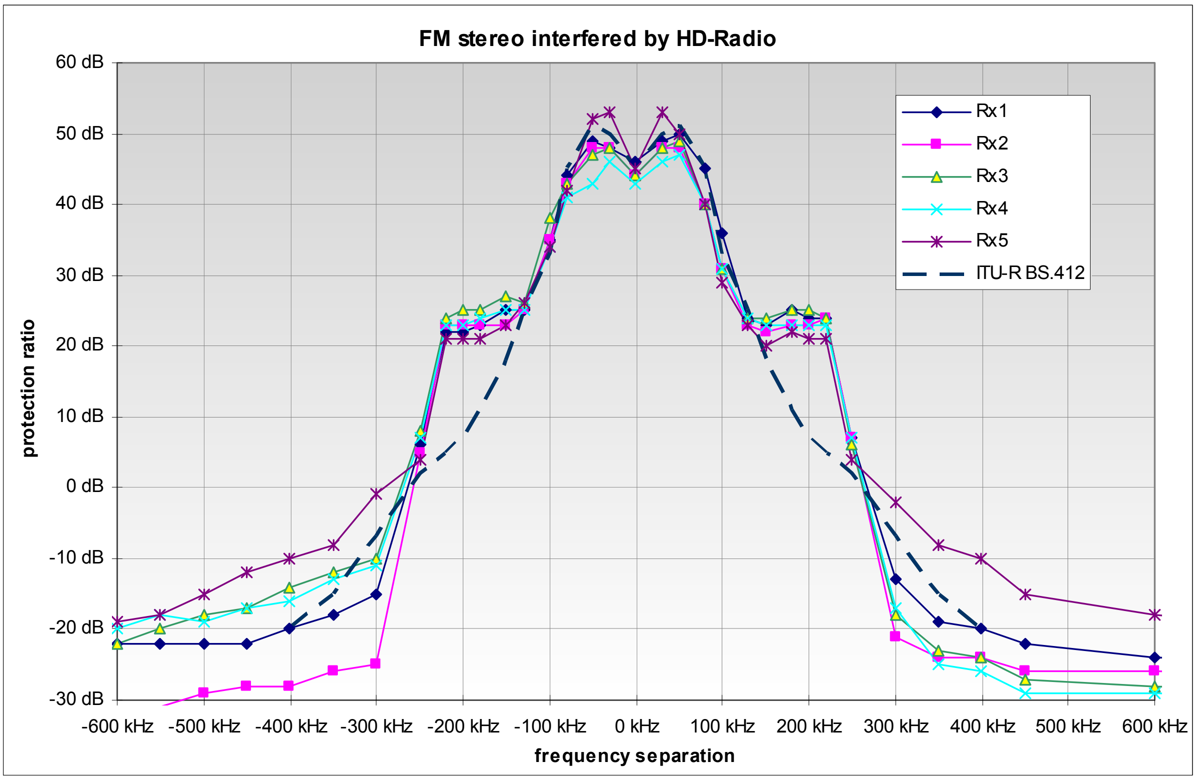

Fig. 33: Protection ratio results for FM stereo interfered by HD-Radio.

For comparison, the protection ratio curve for FM broadcast against FM broadcast from ITU-R BS.412 is included in the figure.

For offsets up to +/- 150 kHz the interfering effect of HD-Radio is nearly equal to an FM broadcast interference. Especially for offsets between +/- 150 kHz and +/- 250 kHz, however, the required protection ratio is up to 20 dB higher compared to an FM broadcast interferer. Keeping in mind that the average protection ratio of the measured receivers against FM broadcast interferers was much less than specified in ITU-R BS.412, the interference potential of HD-Radio is higher for all offsets between +/-100 kHz and +/-300 kHz.

Additional measurements for Rx4 with increased wanted signal level showed the same protection ratio, so the receivers are still in their linear range and the only interfering effect is the HD-Radio sideband emissions.

Measurements of the protection ratios for RDS decoding showed that this service is generally less susceptive to interference from HD-Radio than the audio S/N.

The following figure shows a situation with 200 kHz frequency separation at the beginning of interference. For comparison, both the interfering HD-Radio and FM broadcast signals are shown.

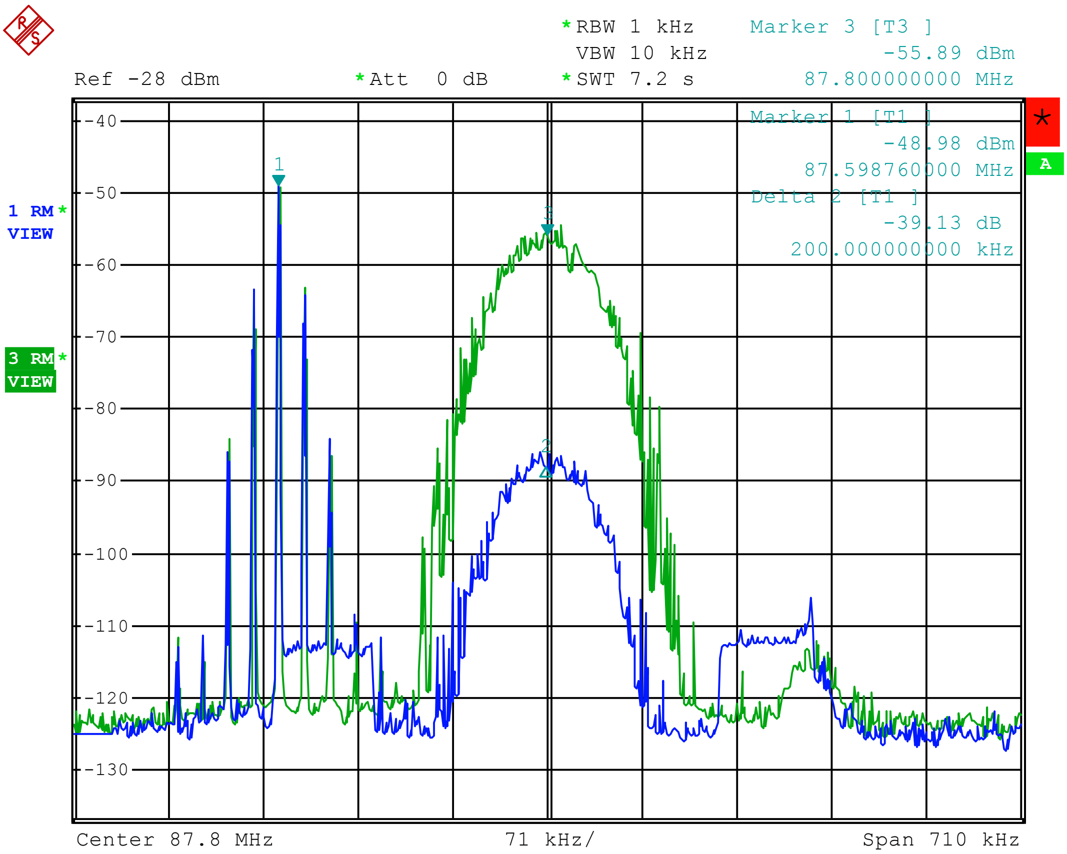

Fig. 34: ClearWrite spectrum for FM stereo on 87.6 MHz interfered by HD-Radio (blue) and FM broadcast (green) on 87.8 MHz at the beginning of the “S/N interference”.

In this critical situation it can be seen that the level of the interfering HD-Radio signal has to be 39 dB less than an interfering FM broadcast signal.

5.5.2 HD-Radio -> Narrowband FM / BOS reception

The same setup as in Fig. 15 was used to measure the protection ratios of narrowband FM / BOS against HD-Radio. The following figure shows the results for the most critical interference criterion.

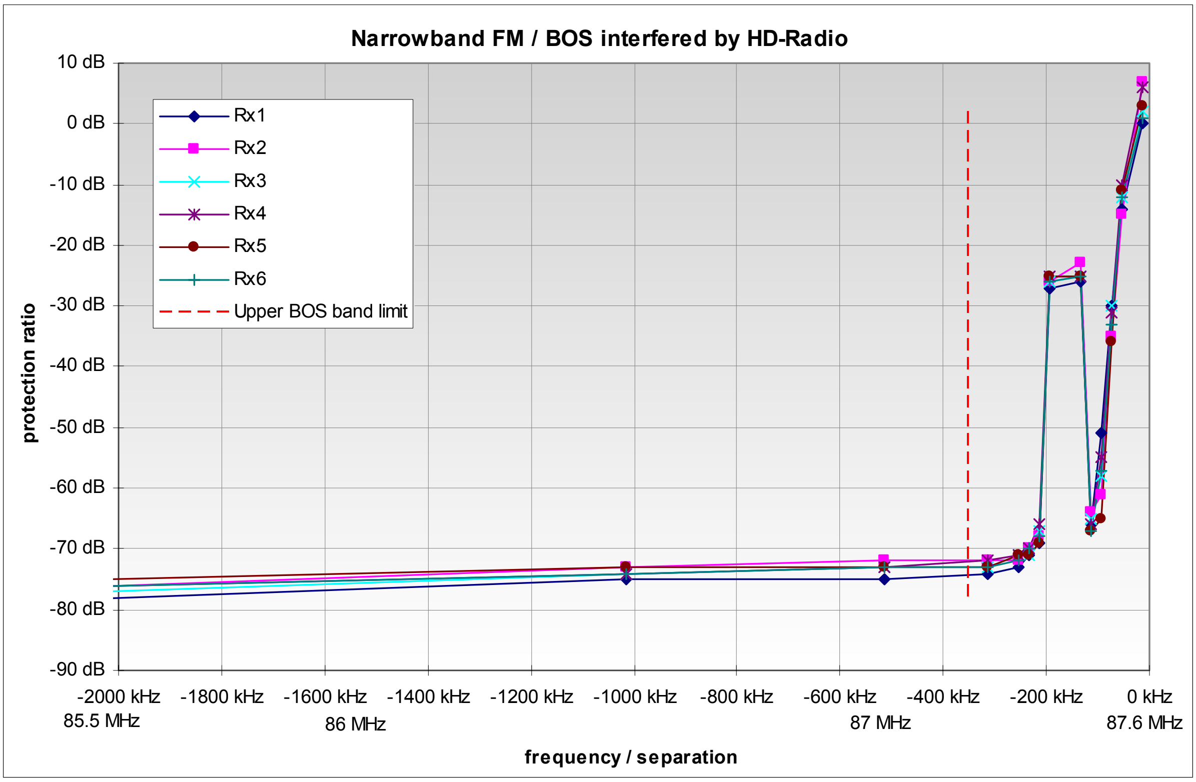

Fig. 35: Protection ratio results for narrowband FM / BOS interfered by HD-Radio.

The protection ratios of all receivers lie within a very narrow margin. The difference in protection ratio between co-channel and large frequency separations is roughly equal to the suppression of sideband emissions of the HD-Radio signal. Therefore all receivers are within their linear range and the only interfering effect is the sideband noise emitted on the BOS channel.

Compared with DRM120, HD-Radio has no additional interference effect on narrowband FM/BOS receivers.

5.5.3 HD-Radio -> Aeronautical Radionavigation (VOR) reception

The system setup for the protection ratio measurements HD radio into VOR is the same as illustrated in Fig. 17. The wanted VOR frequency was kept at 108.0 MHz while the unwanted HD-Radio signal was tuned from 107.9 MHz downwards.

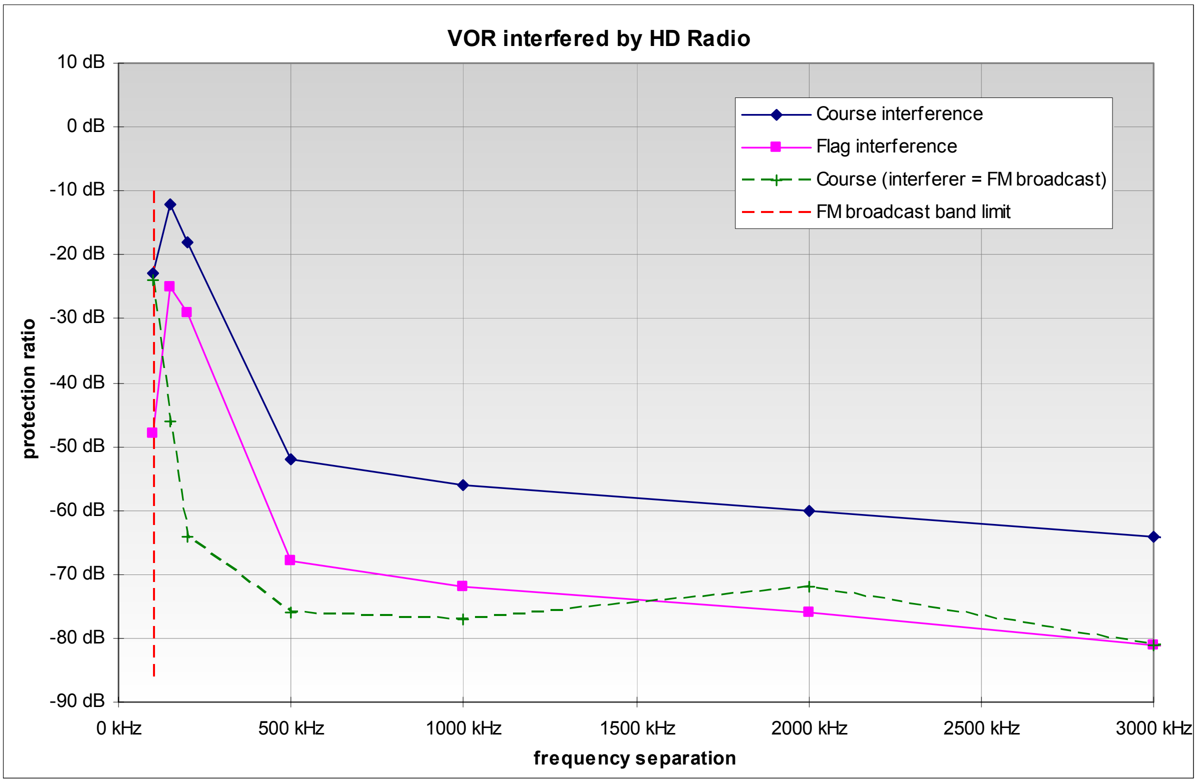

Fig. 36: Protection ratio results for VOR interfered by HD-Radio.

The protection ratios measured with increased wanted signal level were nearly identical. Therefore it can be assumed that the receiver is still in a linear state and the only interfering effects are the sideband emissions of the HD-Radio signal.

For comparison, the course interference protection ratio against FM broadcast is included in the figure. It can be seen that interference from HD-Radio is far more critical as from FM broadcast. It should be noted that for HD-Radio frequencies of 107.9 and 107.8 MHz, the first ILS frequency (108.0 MHz) is still inside the normal spectrum range of the HD-Radio emissions. It can be seen that interference from the upper DSB block goes up to an offset of 500 kHz. Even for higher offsets the interfering effect of HD-Radio is substantially higher than that of an FM broadcast signal, but this may be improved by additional filtering at the output of the HD-Radio transmitter.

The following figure shows the situation where the HD-Radio frequency is 107.8 MHz and the VOR frequency is 108.0 MHz. The levels are adjusted so that the course interference just begins.

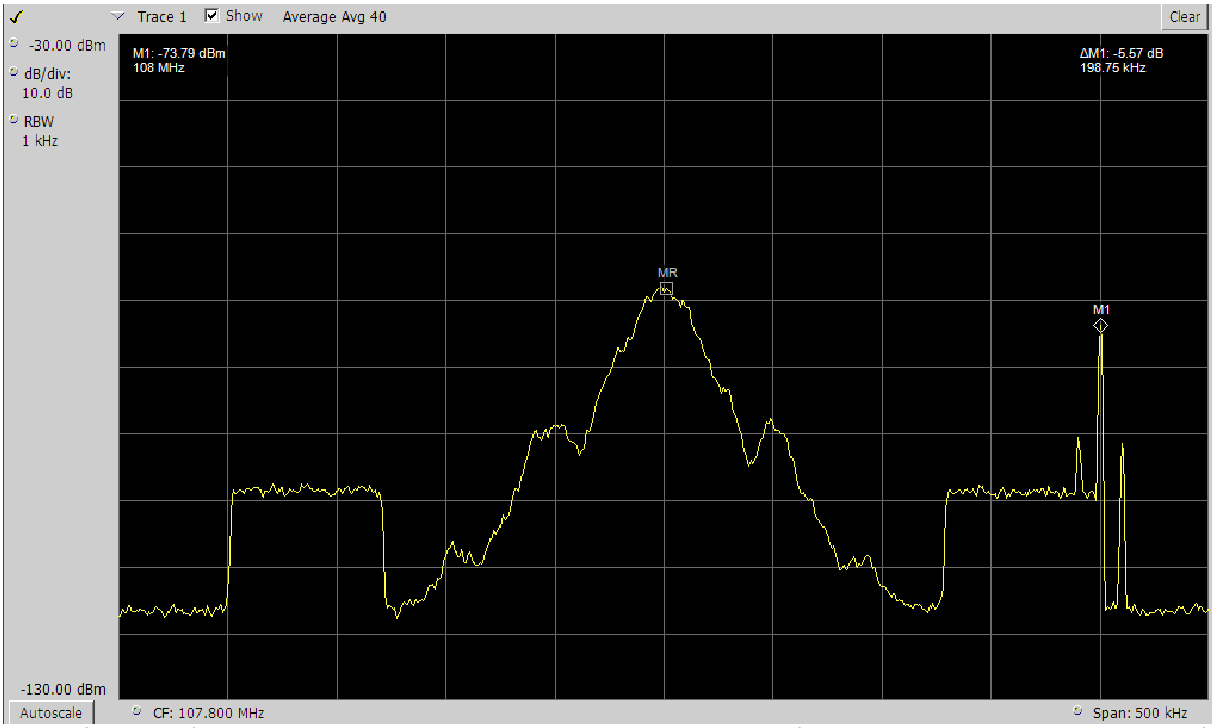

Fig. 37: Spectrum of the unwanted HD-radio signal on 107.8 MHz and the wanted VOR signal on 108.0 MHz at the beginning of the course interference.

It can be seen that even for this frequency setup the upper digital block of HD-Radio is well inside the aeronautical band.

5.5.4 HD-Radio -> Aeronautical Radionavigation (ILS localizer) reception

The system setup for the protection ratio measurements HD-Radio into ILS is the same as illustrated in Fig. 17 with the exception that the receiver data was displayed by an ILS course indicator instrument.

The wanted ILS frequency was kept at 108.1 MHz while the unwanted HD-Radio signal was tuned from 107.9 MHz downwards.

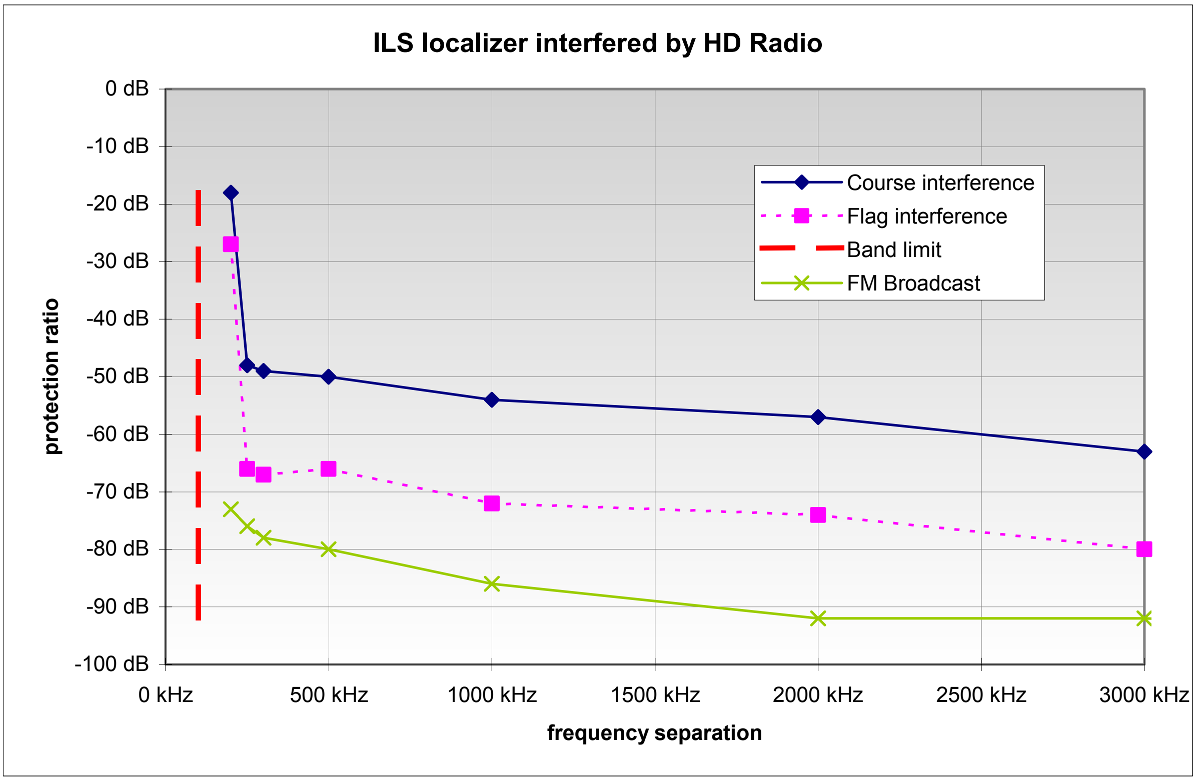

Fig. 38: Protection ratio results for ILS interfered by HD-Radio.

Additional measurements with increased wanted signal level showed identical protection ratios, so the receiver is still in its linear stage and the only interfering effects are the side-band emissions of the HD-Radio signal.

For comparison, the course interference protection ratio against FM broadcast is included in the figure. It can be seen that ILS localizer is much more affected by HD-Radio than by FM broadcast. This is especially true for frequency offsets up to 300 kHz. It should be noted that the first ILS frequency (108.1 MHz) is still well inside the normal emitted HD-Radio spectrum when this system is transmitted on 107.9 MHz.

The sideband emissions were much higher for the used HD-Radio signal than for FM broad-cast which is the reason for the seemingly higher interference potential of HD-Radio at larger frequency offsets.

6 Result comparison

6.1 FM Broadcast as the victim

The following figure shows the protection ratios for FM stereo reception when exposed to any of the investigated unwanted signals. The graph shows the measurement results for Rx 1 which was regarded representative.

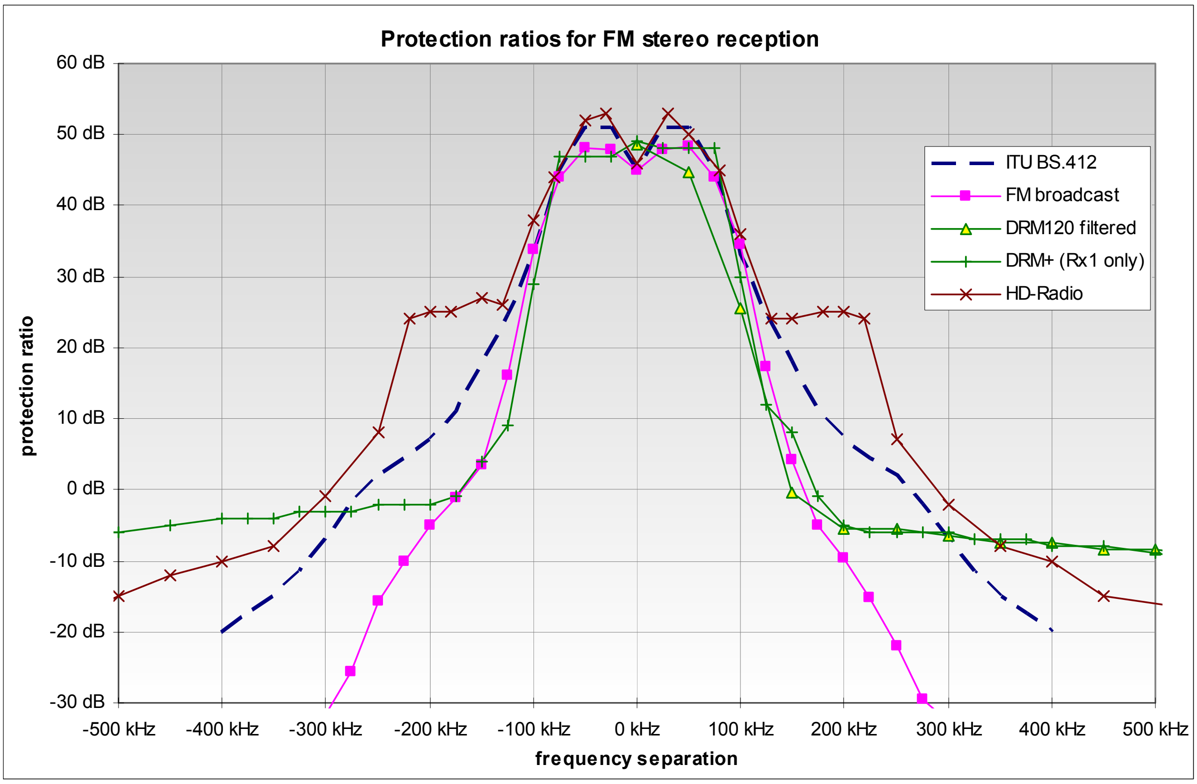

Fig. 39: Protection ratio summary for FM stereo reception.

It can be seen that HD-Radio has by far the most interference potential. DRM120 and DRM+ have less interference potential than FM broadcast for frequency offsets below +/-200 kHz, but tentatively more for larger frequency offsets. There is virtually no difference between the interference potential of DRM120 and DRM+.

All measured FM receivers have much better performance against FM interferers than stated in the curve from ITU-R BS.412.

6.2 Narrowband FM as the victim

The following figure shows the protection ratios for narrowband FM / BOS reception when exposed to any of the investigated unwanted signals. The graph shows the measurement results for the most critical receiver and interference criterion.

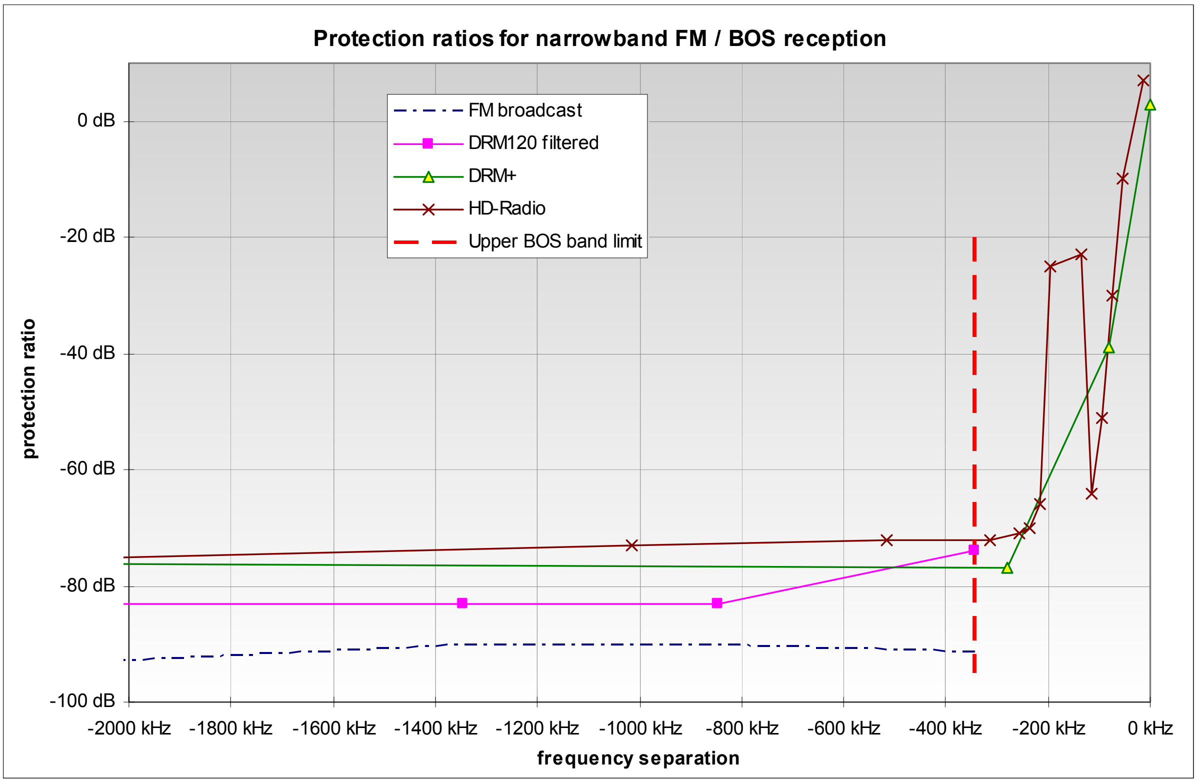

Fig. 40: Protection ratio summary for narrowband FM / BOS reception.

All digital systems tested seem to have more interference potential than the FM broadcast signal. However, measurements with increased signal level have shown that all receivers are still in their linear range. This means that the protection ratio is only determined by the remaining sideband emissions on the BOS frequency. Therefore, the situation can be improved by filtering at the output of the digital transmitter. This filtering was most effective on the FM broadcast signal.

6.3 Aeronautical Radionavigation (VOR) as the victim

The following figure shows the protection ratios for VOR reception when exposed to any of the investigated unwanted signals. The graph shows the measurement results for the "course interference" as this is the most critical criterion.

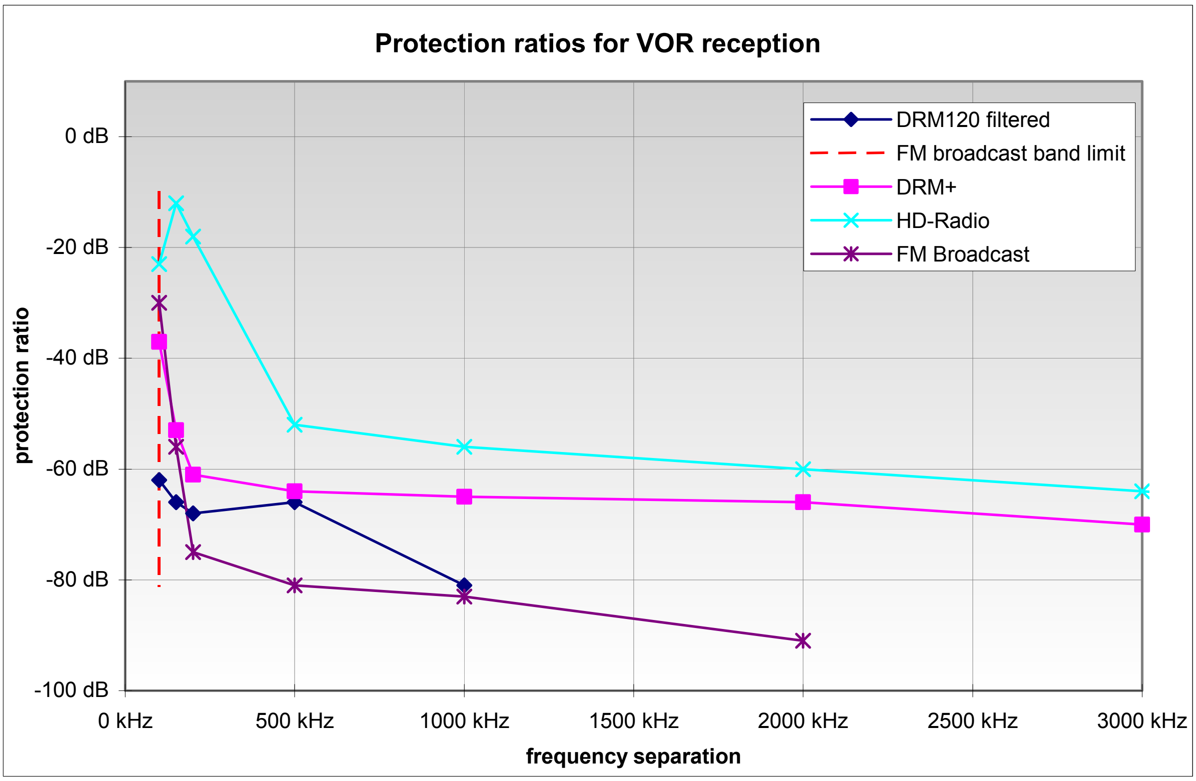

Fig. 41: Protection ratio summary for VOR reception.

It can be seen that the digital systems tested tend to have more interference potential than the FM broadcast signal. However, measurements with increased signal level have shown that the VOR receiver is still in its linear range. This means that the protection ratio is only determined by the remaining sideband emissions on the VOR frequency. Therefore, the situation can be improved by filtering at the output of the digital transmitter. This filtering was most effective on the FM broadcast signal.

For compatibility issues with VOR reception, HD-Radio can not be operated above 107.7 MHz because then the normal emitted spectrum falls inside the aeronautical band.

6.4 Aeronautical Radionavigation (ILS) as the victim

The following figure shows the protection ratios for ILS localizer reception when exposed to all of the investigated unwanted signals. The graph shows the measurement results for the "course interference" as this is most critical criterion.

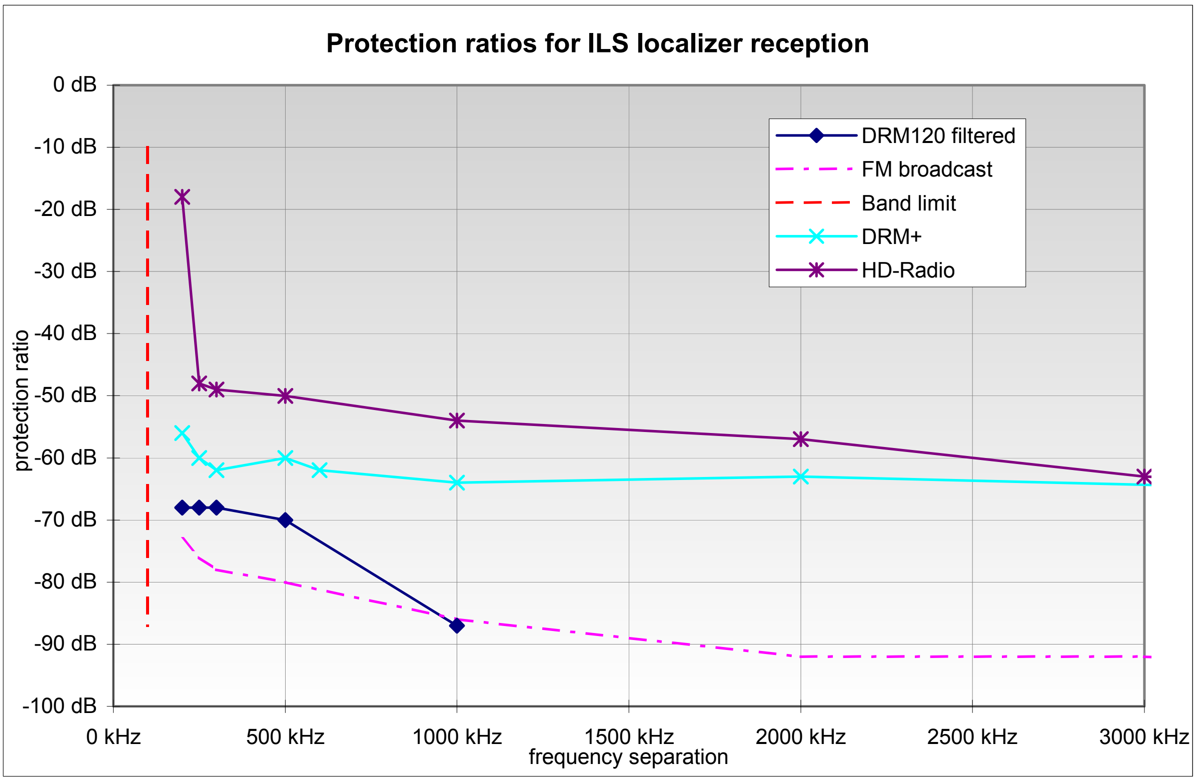

Fig. 42: Protection ratio summary for ILS localizer reception.

For the ILS localizer reception, only HD-Radio has substantially more interference potential than FM broadcast. It seems that DRM120 interferes less than FM broadcast. The same should be possible for DRM+ when it is as well filtered as the DRM120. Again, measurements with increased signal level have shown that the ILS receiver is still in its linear range. This means that the protection ratio is only determined by the remaining sideband emissions on the ILS frequency. Therefore, the situation can be improved by filtering at the output of the digital transmitter.

For compatibility issues with ILS reception, HD-Radio can not be operated above 107.8 MHz because then the normal emitted spectrum falls inside the aeronautical band.

7 Intermodulation measurements

7.1 General

High-level emissions in the FM broadcast band can overload the input stage of an aeronautical receiver and cause intermodulation products to rise inside the aeronautical band and interfere with the reception of the wanted ILS or VOR signal. The performance of an aeronautical receiver under these conditions is called "FM immunity". The frequencies of these intermodulation products can be calculated from the transmitter frequencies in the FM broadcast band. The most critical cases here are the 3rd order intermodulation products caused by three transmitters inside the FM broadcast band. To assess the influence of digital systems compared with analogue FM broadcast systems, several measurements of the FM immunity have been made.

7.2 Measurement setup and procedure

The measurement procedure and setup is described in ITU-R IS.1140. The following setup was used:

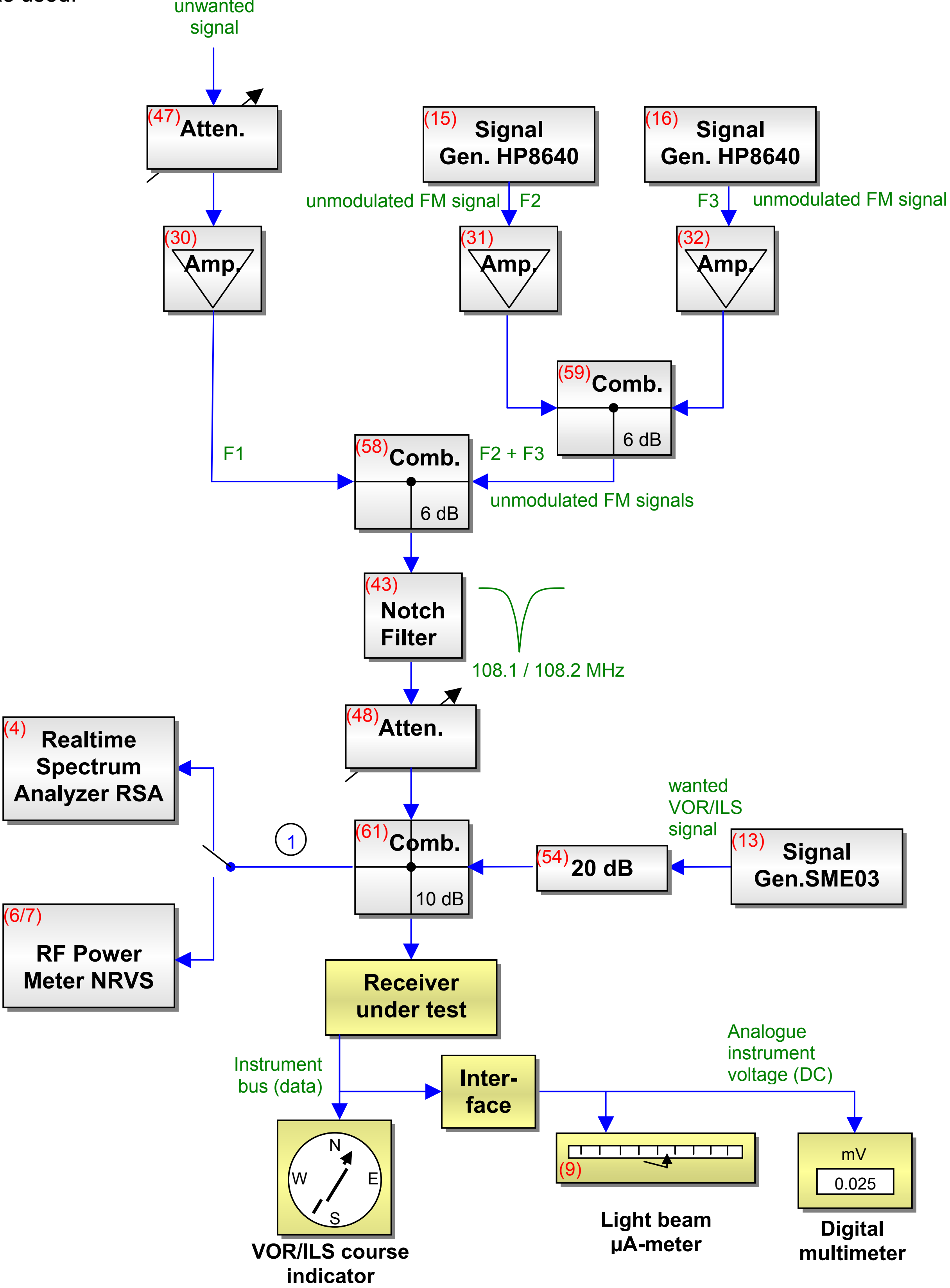

Fig. 43: Setup for FM immunity measurements according to ITU-R IS.1140 Fig. 1a and 1b

The frequencies in the FM broadcast band are called F1, F2 and F3. The most critical case occurs when F2 and F3 are unmodulated carriers, and only F1 is modulated. In our case, F1 is the interfering signal under investigation, which is either FM broadcast (for comparison), DRM120, DRM+ or HD-Radio.

Four possible frequency combinations for F1, F2 and F3 are given in ITU-R IS.1140. Only the most critical combinations with involved frequencies closest to 108.0 MHz were taken for these measurements, and only those combinations that produce intermodulation on these frequencies (108.1 or 108.2 MHz respectively).

The level of the wanted VOR / ILS signal is again adjusted to the lowest level mentioned in ITU-R IS.1140 where the receiver is capable of performing above the interference criteria. This level is -79 dBm for VOR and -86 dBm for ILS. A second measurement was also made with increased wanted signal levels (-63 dBm for VOR and -70 dBm for ILS).

By means of the signal generators (15) and (16) and the variable attenuator (47), the levels of the unwanted signal F1 and the unmodulated carriers on F2 and F3 are set to be equal at the output of the combiner (58) in Fig. 43.

The notch filter (43) blocks any sideband emissions and transmitter intermodulation on the VOR / ILS frequency under investigation.

Then the total level of the unwanted signals is increased with attenuator (48) until the failure criterion is reached (see 3.2.2. and 3.3.2). The difference between the unwanted and wanted signal level at this point is noted as the protection ratio.

7.3 VOR as the victim

The wanted VOR frequency was set to 108.2 MHz as this is the lowest usable channel given in Recommendation ITU-R IS.1140.The following figure contains the results for the FM immunity measurements for VOR reception. Only the course interference is shown as this is the more critical criterion, and only results for -79 dBm wanted signal level.

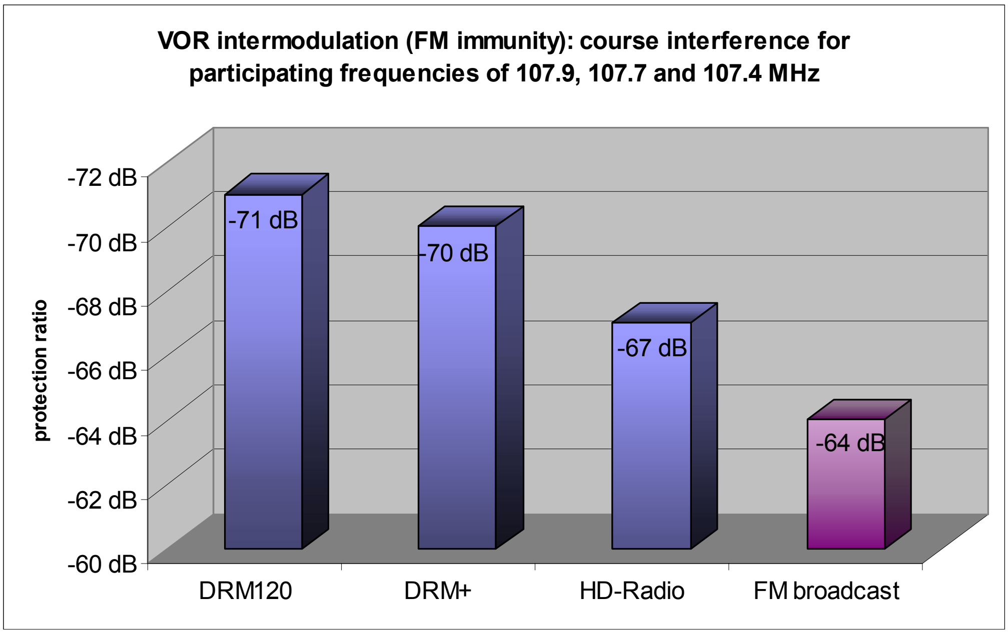

Fig. 44: „FM immunity“ of VOR in the presence of strong analogue and digital broadcast signals

It can be seen that the DRM120 and DRM+ signals have the least interference potential, even less than FM broadcast. The interference potential of HD-Radio should be nearly equal to FM broadcast because in this measurement it is the analogue part of the main carrier that causes interference. For HD-Radio and FM broadcast, this part of the spectrum is equal. The measured difference in protection ratio is to differences in the modulation of the main FM carrier (different FM transmitters were used).

Measurements with a higher wanted signal level (-63 dBm) showed that the results can not be scaled due to the non-linearity of the receiver. This means that the protection ratio will change when wanted signal level is increased by 16 dB.

The detailed measurement results are shown in Annex 5.

7.4 ILS as the victim

The wanted ILS frequency was set to 108.1 MHz as this is the lowest usable channel given in Recommendation ITU-R IS.1140.The following figure contains the results for the FM immunity measurements for ILS localizer reception. Only the course interference is shown as this is the more critical criterion.

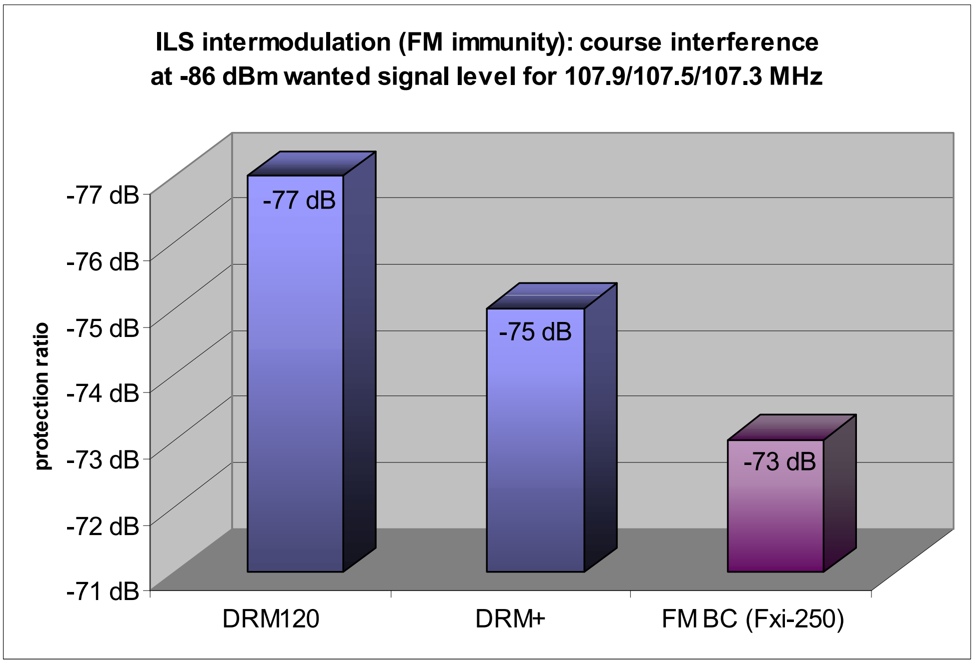

Fig. 45: „FM immunity" of the ILS localizer in the presence of strong analogue and digital broadcast signals

The most critical frequency combination given in ITU-R BS.1140 includes 107.9 MHz as F1. This combination, however, could not be measured with HD-Radio because the ILS receiving frequency is still inside the main HD-Radio spectrum. Instead, the second critical combination was measured with HD-Radio involved:

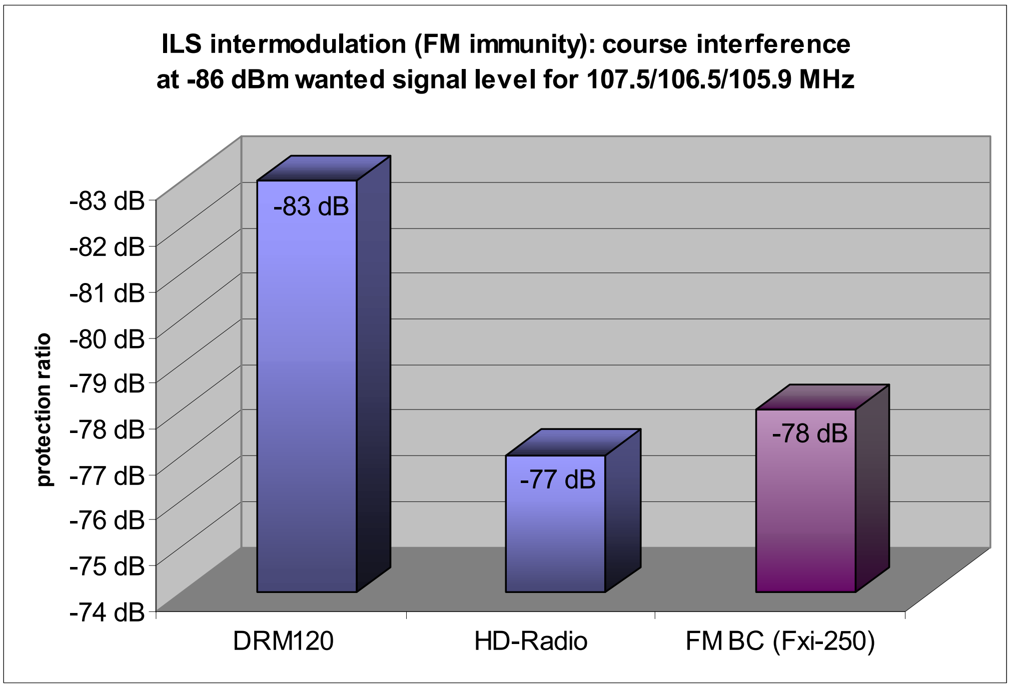

Fig. 46: „FM immunity" of the ILS localizer in the presence of strong analogue and digital broadcast signals

It can be seen that the DRM120 / DRM+ signals have the least interference potential, even less than FM broadcast. The interference potential of HD-Radio is nearly equal to FM broadcast which is not surprising because in this measurement it is the analogue part of the main carrier that causes interference. For HD-Radio and FM broadcast, this part of the spectrum is equal.

As with VOR, measurements with a higher wanted signal level (-70 dBm) showed that the results can not be scaled due to the non-linearity of the receiver. This means that the protection ratio will change when wanted signal level is increased by 16 dB.

The detailed measurement results are shown in Annex 5.

8 Conclusion

The measurements have shown that in principle DRM+ / DRM120 has nearly equal or even less interference potential to adjacent band services than a standard FM broadcast signal, provided that additional filtering at the transmitter output is deployed to reduce sideband emissions far outside the wanted channel. As mentioned earlier, however, producing a cleaner spectrum outside the used channel is much more difficult for a digital transmitter.

Inside the FM broadcast band, the interference potential of DRM120/DRM+ to FM stereo reception is substantially higher for some receivers than from a standard FM broadcast signal. This is especially true for frequency offsets larger than +/-200 kHz. Surprisingly the receiver that performs best when interfered by an FM broadcast signal is most susceptive against DRM120/DRM+.

The interference potential of HD-Radio to the Narrowband FM / BOS service in the lower adjacent band is equal to that of a standard FM broadcast signal, if additional filtering at the transmitter output is deployed. Interference to ILS and VOR reception is much higher if the HD-Radio frequency is above 107.5 MHz. Operating HD-Radio above 107.7 MHz is impossible because then parts of the HD-radio spectrum falls inside the aeronautical band.

Inside the FM broadcast band HD-Radio produces substantially higher interference especially to neighbouring channel reception at frequency offsets between +/-100 and +/-300 kHz. The current spectrum mask for FM transmissions can not be met. Therefore it seems impossible to fit systems like HD-Radio into the existing FM broadcast network in Germany.

RDS reception is less critical than S/N when digital interferers are present. This coincides with Recommendation ITU-R BS.643-2 where the same statement is made for FM broadcast interferers.

It should be noted that the protection ratio measurements against ILS and VOR reception made here are only valid for one certified aeronautical receiver. In so far, the results may give indication about the interference potential of DRM120/DRM+ and HD-Radio compared to that of an FM broadcast signal. To determine these protection ratios for general use, however, a more comprehensive measurement series has to be performed including a large range of aeronautical receivers.

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Thomas Hasenpusch

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Roland Effinger

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Felix Schad