®

Digital Audio Broadcasting

First results of field tests with the DAB single frequency network in Bavaria

A. Lau

M. Pausch

W. Wütschner

(Bayerischer Rundfunk)

This article presents a report on the DAB field test in the channel 12 single frequency network which forms one component of the Bavarian DAB Pilot Project.

Measurements results obtained using a specially–equipped monitoring van and computer software which has been specifically developed for mobile reception are compared with coverage predictions. The "gain" over individual transmitters, which is achievable in DAB SFNs, is demonstrated by way of an example.

The special features of coverage in mountainous regions are also discussed.

1. Introduction

In recent years, the bit–rate needed to digitize a stereo sound programme has drastically been reduced by techniques which exploit the psycho–acoustical effects of the human ear. By combining suitable source and channel–coding schemes as given by ISO–MPEG Layer II (MUSICAM) and coded orthogonal frequency–division multiplexing (COFDM) [1], it has become possible to plan for the introduction of terrestrial DAB. Progress in the microelectronics industry will allow DAB receivers to be offered to the public at acceptable prices in the very near future. The Eureka 147 DAB Project has finished nearly all the system specifications. Overviews and descriptions of the system are given in many publications [2, 3, 4, 5, 6] ; the full draft specification was published by the European Telecommunications Standards Institute (ETSI) in January 1994 [7].

DAB has been demonstrated successfully during various international meetings and in small field tests. In contrast to VHF/FM sound broadcasting which has been planned only for stationary reception, DAB will offer the reception of stereo programmes in CD–like quality and a broad variety of data broadcasting services especially for mobile and portable receivers. The problems in mobile reception associated with the Rayleigh channel have been overcome by using the COFDM technique which also allows the introduction of single frequency networks (SFN). In networks that cover large areas, SFNs are very attractive due to the inherent frequency economy. On the other hand, the new digital broadcasting system also has disadvantages; one of these is the relatively abrupt failure at the fringe of the coverage area. This has to be taken into account when DAB networks are planned. To investigate the network concept and verify the theoretical assumptions, the Bayerische Rundfunk (BR) has built up a large SFN in the VHF range, using television channel 12. The plan-

Original language: English
Manuscript received 26/9/94.

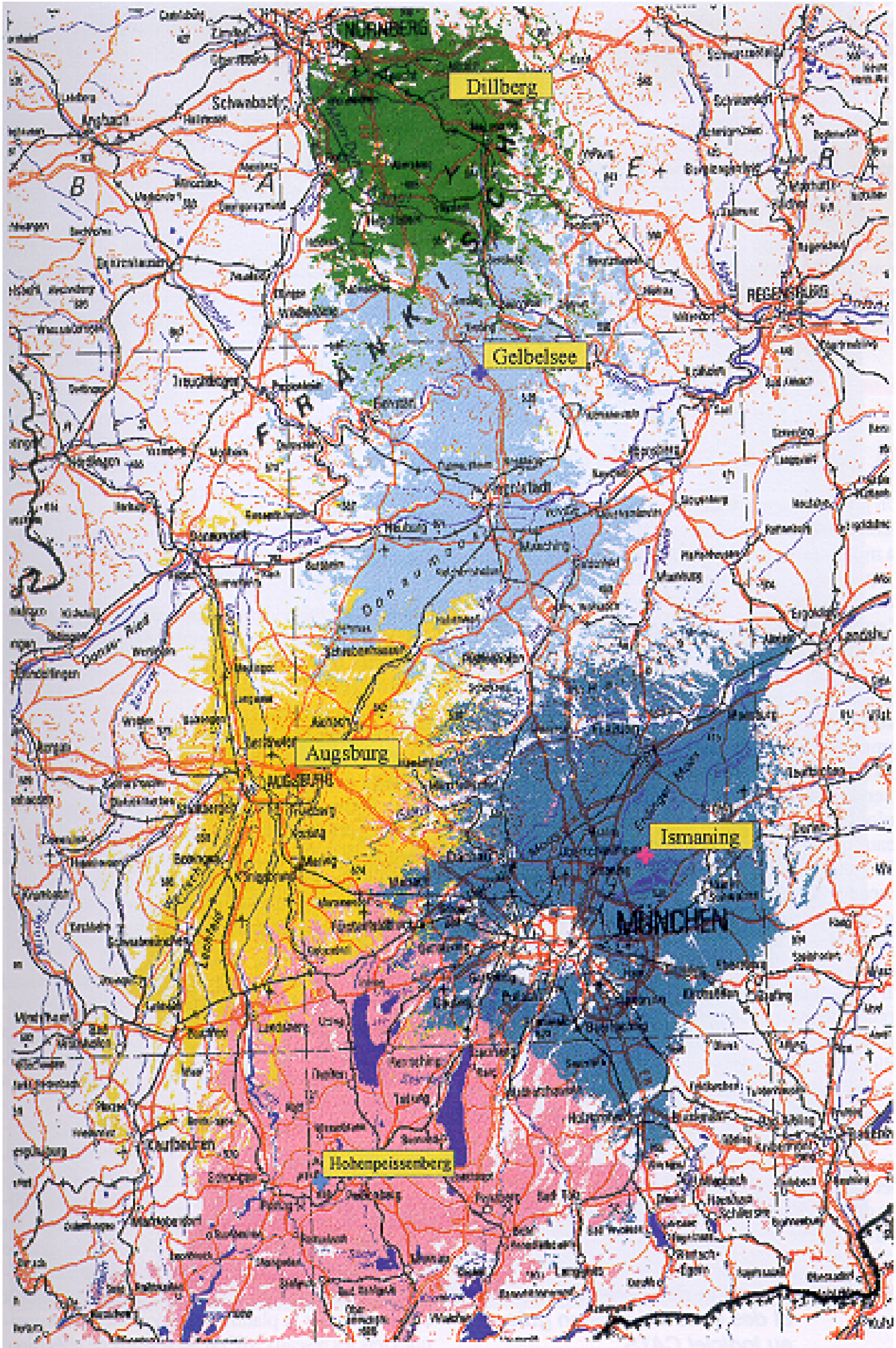


Fig. 1
Predicted coverage of the five individual DAB–transmitters on channel 12.
(Minimum wanted field–strength = 52 dBµV/m).

ning of the DAB transmitter network was based on experience gained during the field tests in 1992 and 1993 with a small SFN in Munich, operating in television channel 11. This network was established and operated in close co–operation with the Institut für Rundfunktechnik (IRT). During these two years a special measurement van for DAB was equipped and the software for mobile coverage measurements was developed and tested.

This article describes the SFN operated in channel 12. The predicted coverage of the SFN is shown, the measurement system used to evaluate the DAB coverage for mobile reception is described, and some measurement results are given.

2. Planning of the SFN for the field trials

2.1. Availability of frequencies for DAB

An expert group, with members from all relevant organizations connected with the introduction of DAB, decided that DAB should be introduced in Germany in television channel 12. In those areas where this is not possible due to the need to protect the service areas of high–power television stations, it was recommended that Band I should be used as the “fall back”. It was also agreed that the 1.5 GHz band should be used. In the meantime the receiver manufacturers have recommended that Band I should *not* be used, for technical and economical reasons. It is still unclear to what extent the network concept (i.e. the number of transmitter sites) differs between a DAB network in Band III and one in the 1.5 GHz range. Further field tests are planned to clarify this.

In Germany about 300 television fill–in (relay) stations are operated in channel 12, most of them by broadcasters of the ARD. The protection of existing television services in channel 12 in neighbouring countries had also to be taken into account. In the light of these constraints, it was decided to coordinate the field–test SFN transmitters for sites situated more or less in the middle of Bavaria. Only a few relay transmitters had to be moved to another channel, and these were all operated by the organization responsible for the field tests.

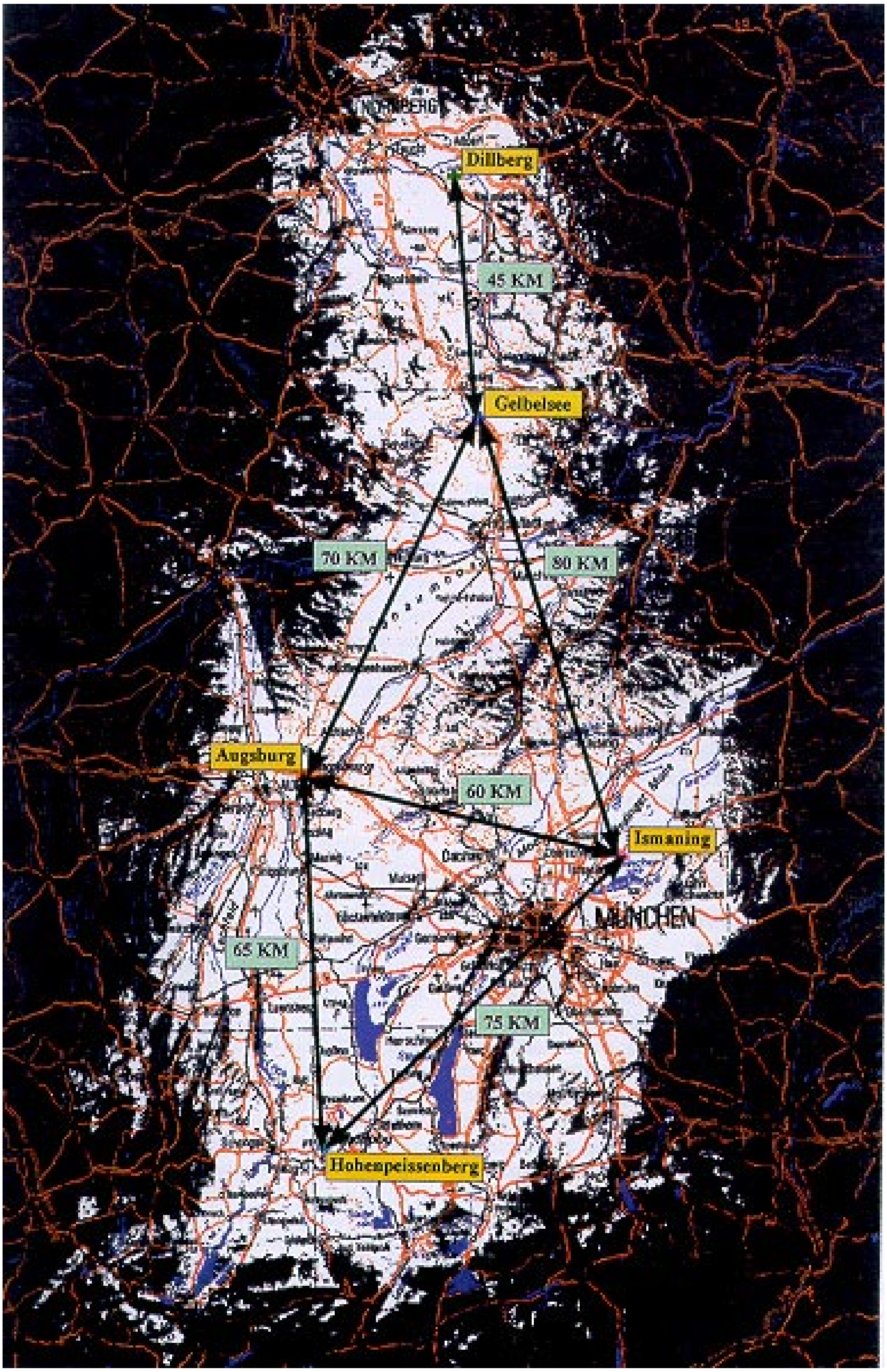
2.2. Selection of the transmitter sites and their characteristics with the planning tool CATS

The BR has developed a software package known as *CATS* for the planning of VHF/FM and television networks. The software runs on UNIX workstations and uses geographical information including topography, urban development, and woods, and data about the distribution of the population. The data are available in databases with a resolution of 100 x 100 m pixel size, as well as 200 x 200 m and 400 x 400 m. By means of different propagation models, coverage predictions can be performed for single transmitters or whole networks.

In recent years the CATS software has been adapted for DAB network planning. The measurement results that were gained during the field test with the small SFN on channel 11 in Munich were used as a basic for this development. Calculations with CATS for an SFN in channel 12 were carried out in 1992 and presented in [8, 9]. This planning exercise had been carried out with DAB transmitters mainly located at the existing VHF/FM transmitter sites of the BR. With an e.r.p. of 1 kW, the predicted coverage for mobile DAB reception of a 1.5 MHz block, able to carry about six stereo programmes and some data, looked already quite good.

In the meantime the propagation model and the software for calculating the DAB coverage have been refined. *Fig.* 1 shows the predicted coverage of the individual transmitters at Augsburg, Dillberg, Gelbelsee, Hohenpeißenberg and München–Ismaning. The main parameters of the transmitter sites are given in *Section 2.3.* The figure shows the strongest transmitter expected at the receiving location, a pixel of size 200 x 200 m. The minimum equivalent field strength is taken as 52 dBμV/m at a receiving antenna height of 1.5 m. The propagation model used here is based on a model of Epstein and Petersen [10] but takes additional attenuation in large cities and smaller towns into account.

In a DAB SFN, all signals, direct or reflected, add positively if they reach the receiver in the given guard interval. In the VHF range, DAB Mode I is used; this has 1536 carriers and a guard interval of 246 μsec between the COFDM symbols. The CATS program system offers the possibility of calculating the network gain of the SFN on a statistical basis, assuming a log–normal distribution of the signals, or by simply adding up the signals as a power sum. *Fig. 2* shows an example of the power sum method and gives the predicted coverage for mobile reception for 99% locations. This is in contrast to the planning of analogue networks like VHF/FM or television, where the service is planned for 50% location probability and 10 m receiving antenna height. The coverage for digital broadcasting systems has to be planned for a higher location probability of 99% because DAB does



White: undisturbed reception
Grey: no reception

Fig. 2
Predicted coverage of the DAB SFN on channel 12.
Addition of signals with power sum method; minimum wanted field–strength = 52 dBµV/m.

DAB

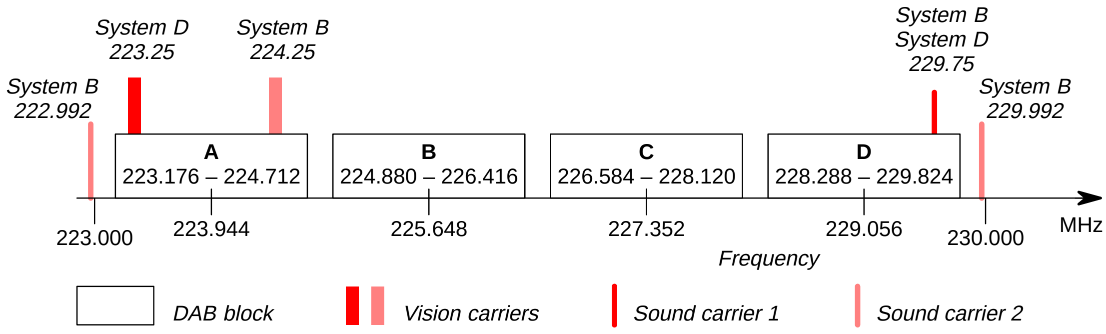


Fig. 3
Example of the accommodation of four DAB frequency blocks in channel 12.
(Receiver tuning steps of 8 kHz assumed).

not exhibit the graceful degradation associated with analogue broadcast transmissions. It should be noted that this prediction takes no account of self–interference or of interference from other sources. On the other hand, the model does not make use of the reflections coming from mountains or other obstacles which improve the coverage. The measurements described in *Section 5.4.* in the area of Garmisch–Partenkirchen show this effect.

The value used for the minimum field–strength is 6 dB lower than the value being discussed for VHF in the relevant EBU and CEPT working groups preparing for the CEPT DAB meeting scheduled for July 1995. It has to be realised that the model used there is that given in ITU–R Recommendation PN.370 [11] which does not take account of the specific terrain parameters. The CEPT DAB planning meeting will aim to establish an allotment plan for DAB; no individual network planning will be done so the approach will be different.

2.3. Technical parameters of the transmitters

The chosen parameters (e.r.p., antenna height, antenna pattern) of the DAB transmitters could only partly be realised. On the one hand the mechanical loading on the existing masts had to be taken into account; on the other hand, the existing television services in channel 12 in Austria, the Czech Republic and in Baden–Württemberg had to be protected. The television relay stations in Bavaria that were incompatible with the DAB transmitters were moved to other channels. The transmitters were taken into operation in the period from July 1993 to April 1994. Their characteristics are listed in *Table 1*. The Hohenpeißenberg transmitter is operated by the DBP–Telekom and all others by the BR. The SFN uses block "C" whose position can be seen in *Fig. 3*. The accommodation of the four DAB blocks in a television channel is not yet fixed. Here it was assumed that the receiver is capable of tuning in steps of 8 kHz as specified in [5]. As can be seen from *Fig. 3* the "guard band" between adjacent DAB blocks is 168 kHz, while the space at the edges is 176 kHz. It still has to be investigated whether this is sufficient to protect the television sound carriers in channel 11 and the mobile services in the band 230–240 MHz.

3. Signal distribution in the DAB SFN

For the operation of a DAB SFN it is essential to feed each individual transmitter with identical signals at an exactly defined time (but not necessarily at the same time). For larger SFNs the only economic solution to fulfil this technical requirement is a distribution via satellite.

For local or smaller regional networks, terrestrial fixed links could be an alternative, but the costs for this concept increase with each additional transmitter site, whereas the costs of a satellite distribution concept are nearly independant of the number

Table 1
Parameters of the DAB transmitters.

Transmitter	Max. e.r.p. (kW)	Antenna height a.g.l. (m)	Max. effective antenna height (m)	Azimuth of main direction(s) of radiation (degrees East from true North)
Dillberg	1	177	345	160 – 200
Gelbelsee	1	60	171 and 140	340 – 10 and 140 – 190
Augsburg	1	50	86	20 – 210
München–Ismanning	1	74	100	200 – 0
Herzogstand*	0.3	7	709	200
Hohenpeißenberg	1	90	450	1 – 240

* The Herzogstand transmitter was in operation only for a short period.

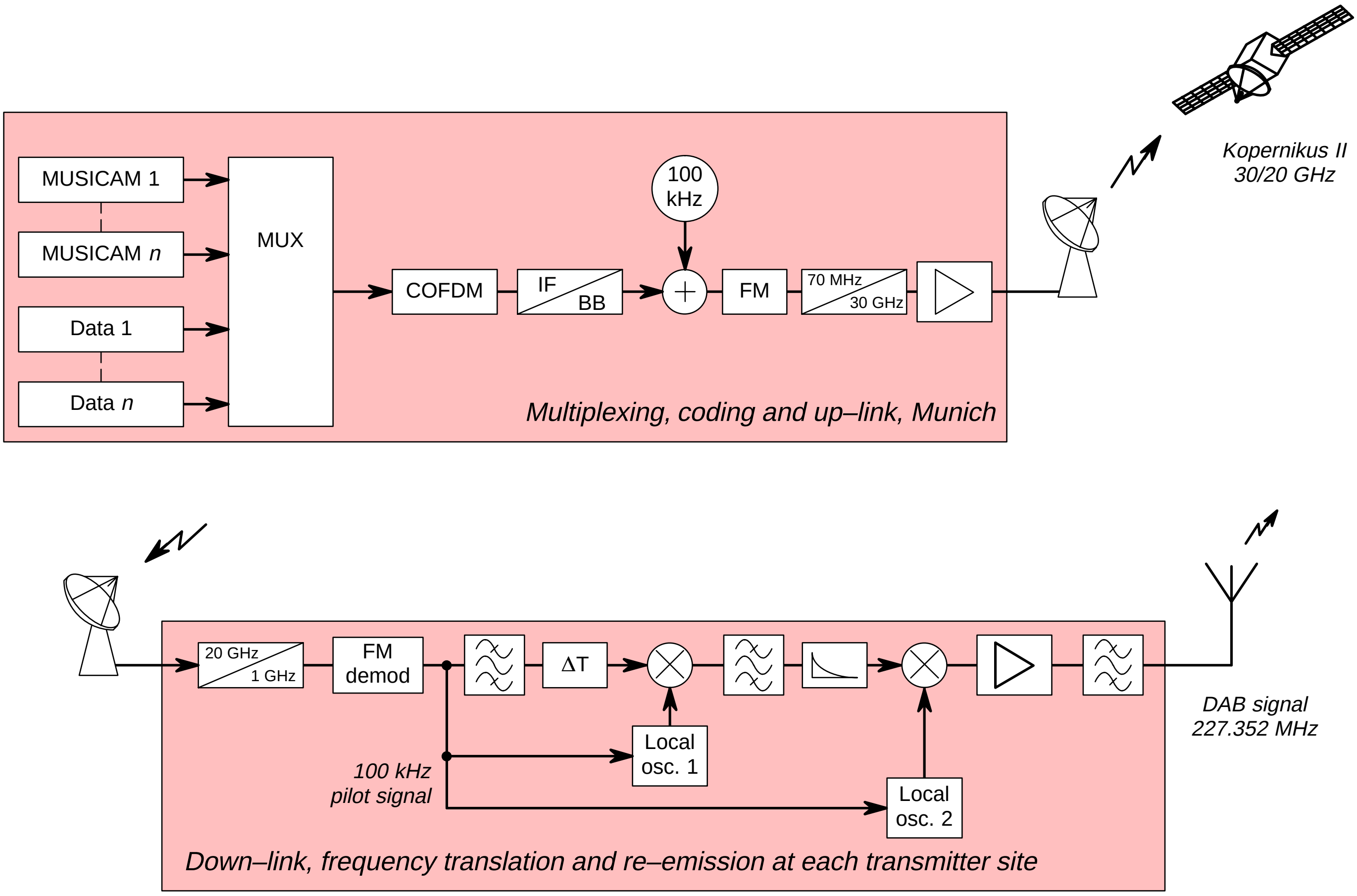


Fig. 4
Satellite distribution of the DAB programme multiplex to the SFN transmitters.

of transmitter sites. Nevertheless the costs for a transponder and the up–link are quite high compared with the costs for some terrestrial fixed links.

In *Fig. 4* the distribution system which is now in operation for DAB field trials in Germany and Switzerland is shown. The six MUSICAM sources and the data channels are coded and multiplexed at the IRT in Munich. The Eureka 147 DAB receiver (third generation) is not able to process a flexible multiplex, so the data rates are fixed (*Table 2*). The next DAB receiver generation will be able to evaluate the Fast Information Channel (FIC), so the transmission of flexible multiplex configurations will be possible.

After the multiplex, the signal is COFDM coded and a 100–kHz pilot signal is added. This is done because a very high frequency accuracy is needed throughout the network. The next step is the frequency modulation of the COFDM DAB signal for the analogue transmission via the 30/20 GHz transponder of the German Telekom satellite Kopernikus II.

At each transmitter site, the frequency–modulated COFDM DAB signal is received, FM–demodulated, filtered, converted to the VHF frequency range and amplified for transmission. This quite simple modulation concept is a suitable solution for field trials. For pilot projects or a real DAB service, analogue modulation with the FM technique is not sufficiently spectrum–efficient, bearing in mind the high cost of the satellite transponder.

Prog.	**Mono/ Stereo**	**Data rate** (kbit/s)	**Code rate**
1	S	256	0.6
2	S	224	0.5
3	S	224	0.6
4	S	192	0.5
5	S	192	0.6
6	M	64	0.5

Table 2
Data and code rates of the individual programmes in the field test.

For the Bavarian DAB Pilot Project, it is intended to use a digital modulation link with a 2 Mbit/s data stream which contains the DAB transport multiplex information (*Fig. 5*). This concept is more complicated than the analogue solution as regards the hard-

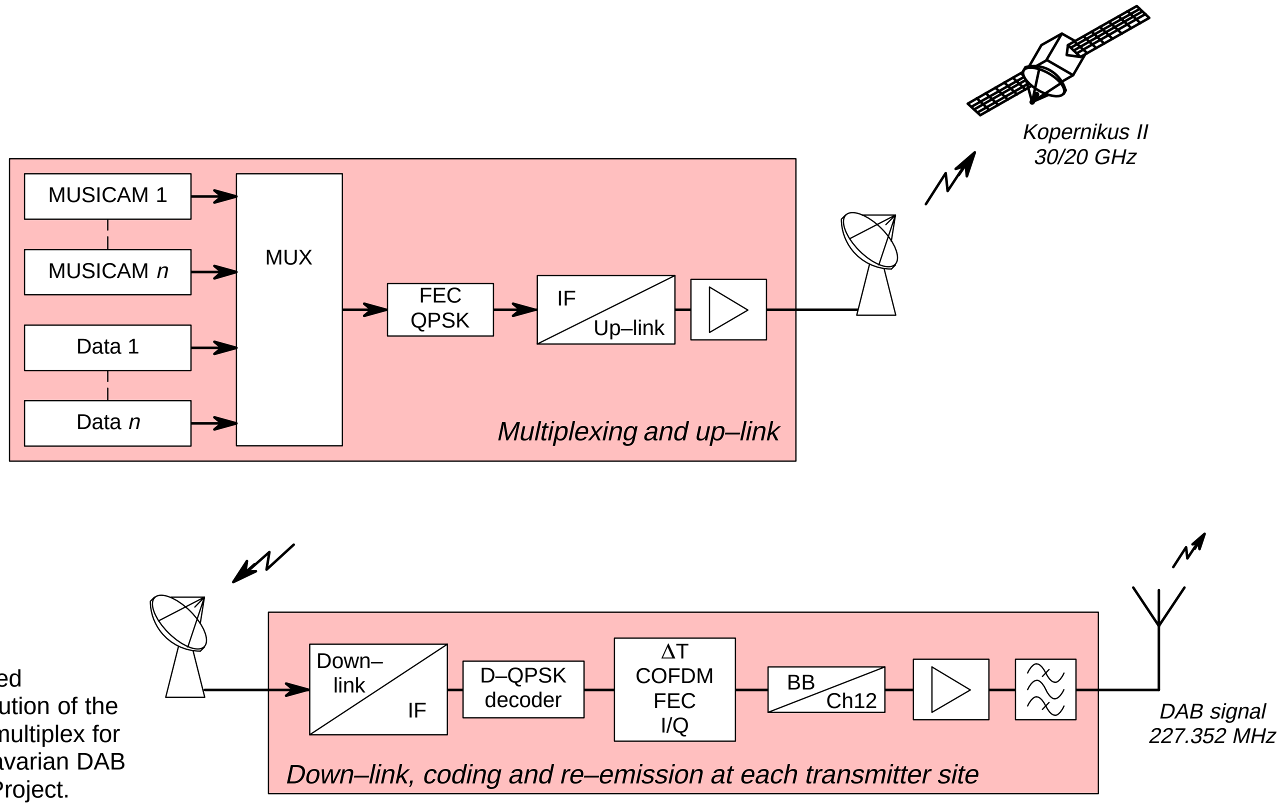


Fig. 5
Planned distribution of the DAB multiplex for the Bavarian DAB Pilot Project.

ware at the up–link and the transmitter sites, but the costs for the satellite transponder are lower.

4. Measuring equipment and software for DAB coverage assessment

4.1. The DAB monitoring van

The monitoring vans employed by the BR for television and VHF/FM measurements do not meet the special standards required for DAB coverage measurements, so a new van had to be designed. A Volkswagen bus has been chosen as the basic vehicle so that sufficient space is available for the necessary equipment.

Figs. 6 and *7* give an impression of the van. The block diagram in *Fig. 8* shows the equipment. The signal is supplied to the DAB receiver via a receiving aerial. For acoustic checking, the decoded bit flow is audible over loudspeakers by connecting the DAB receiver to the CD input of a commercially–available car radio. The third–generation DAB receiver also provides the channel impulse response which may be displayed on an oscilloscope. With these provisions it is possible to dis-

Fig. 6 ▼
The DAB measurement van.

Fig. 7 ▶
A look into the DAB measurement van.

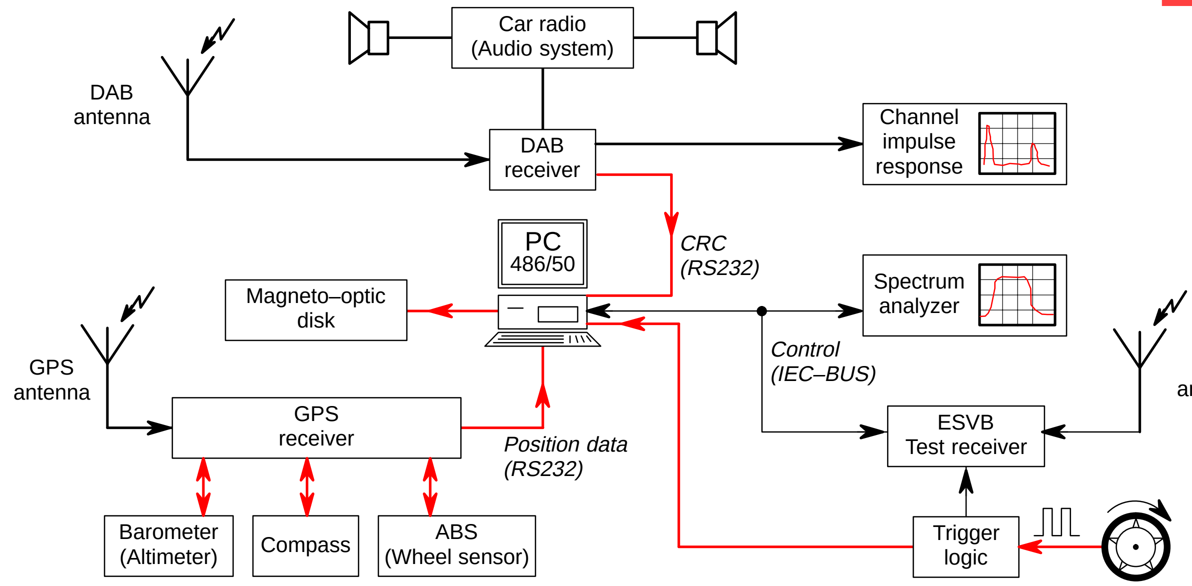
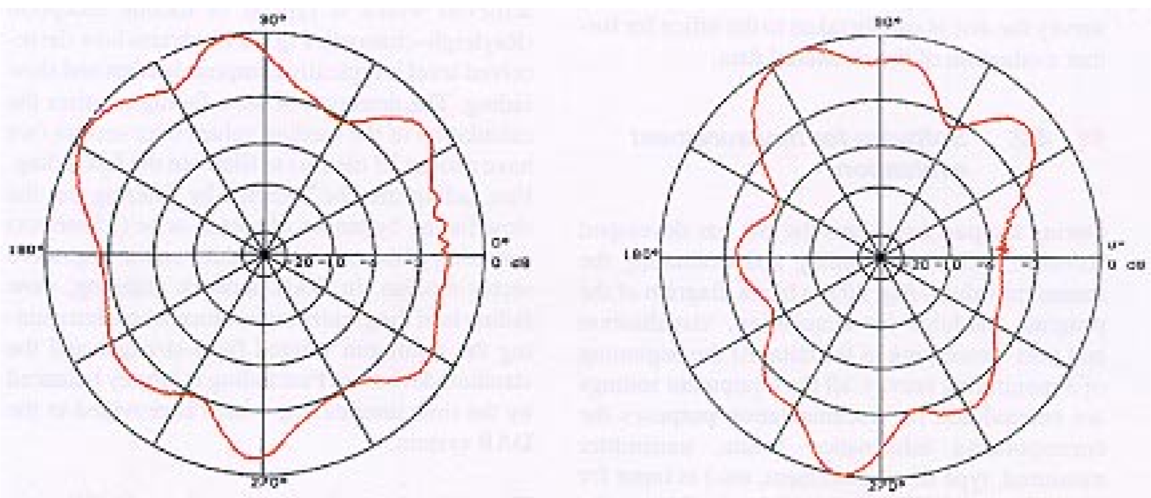


Fig. 8
Block diagram of the equipment in the DAB measurement van.

play the signal components of the individual transmitters and the reflections, and to measure the delays between these components.

When a specific chip produced by Philips is employed, the cyclic redundancy code check (CRC check) may be received via a serial interface (RS 232). This code is an 8–bit check word integrated into the MUSICAM data flow. This concept offers the possibility of quality control during normal programme operation. In the absence of any other provisions this is a good substitute for a complex bit–error rate measurement at different code–rates (unequal–error protection). The chip provides information about faults in the four scaling factors, frame errors and receiver muting. The checks are carried out every 24 msec, corresponding to the length of a DAB audio frame. CRC check measurements are also described in [12].

The signal level is measured using a separate aerial and an “ESVB” test receiver from Rhode & Schwarz. The measured radiation patterns of the vertical $\lambda/4$–aerials are illustrated in *Figs. 9a* and *9b*. A maximum of approximately 3000 level measurements can be taken per second (in the so–called “fast level mode”). A wheel–sensor with a high resolution is integrated for triggering the measurement cycles. The geographical coordinates, the instantaneous speed and the altitude of the actual vehicle position are provided once per second using a Global Positioning System (GPS) receiver which is backed up by directional information received from a gyro–compass, by altimetric information from an electronic barometer, and by a distance trigger driven from an additional sensor fitted to the vehicle’s ABS system. These additional sensors permit route determination by



a) Antenna for ESVB test receiver (227.25 MHz).

b) Antenna for DAB receiver (227.25 MHz).

Fig. 9
Measured antenna patterns of the vertically–polarized receiving antennas.

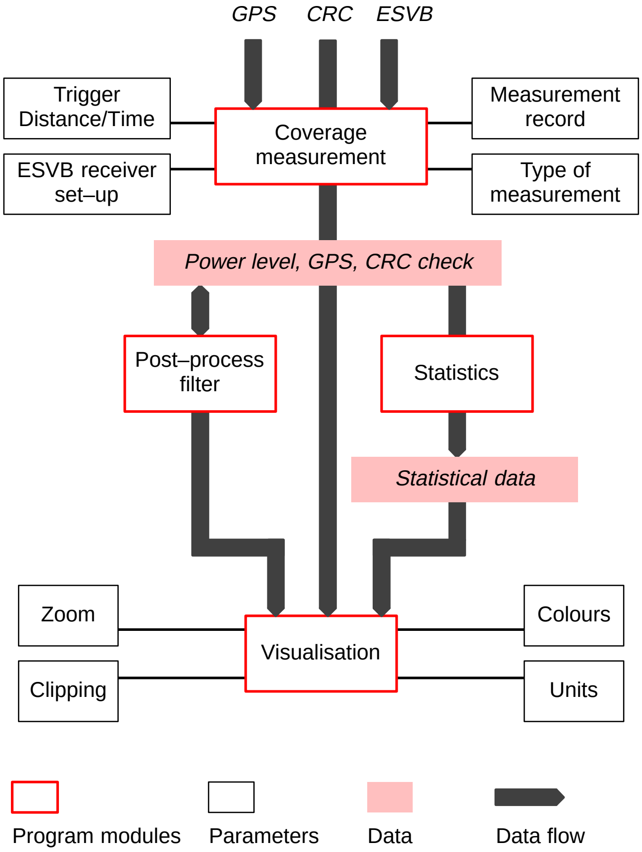


Fig. 10
Program modules of the software for DAB coverage measurements.

"dead reckoning", which is especially useful in dense urban areas, tunnels and forests.

A Personal Computer (486/50 MHz) with the interfaces illustrated in *Fig. 8* is installed to control the measuring equipment and data acquisition. As in the course of a day two to three million values may easily be sampled when high resolution is selected, a magneto–optical disk (3 1/2", 128 MB) is used for data storage. At the end of the monitoring survey the disc is simply taken to the office for further evaluation of the measured data.

4.2. Software for measurement evaluation

During the past two years the BR has developed software tools for recording and evaluating the measured values. *Fig. 10* is a block diagram of the program modules for acquisition, visualisation and post–processing of the data. At the beginning of a monitoring survey, all the equipment settings are entered and for documentation purposes the corresponding information (route, transmitter measured, type of measurement, etc.) is input for the envisaged measurements. It is possible to trigger measurements either in terms of time or in terms of distance. In addition to the power levels, the geographical coordinates which are received from the GPS and the CRC status bytes may optionally be recorded. The units of measurement can be selected in advance, or the detected power levels can be converted into field–strength values later on, according to equation (2) given in *Section 5*. Most evaluations are based on measurements of power levels, since these give a better representation of a signal of 1.5 MHz bandwidth than field–strength values.

The measured values are stored on the magneto–optical disk (MOD) via a buffer in the main memory so that it is not necessary to interrupt the current measurement while storing the previous one. In this manner, distances of any length may be recorded. Also during the measurement, some of the sampled values are continuously displayed on the screen for checking. When the measurement is complete, data can be post–processed either directly in the monitoring van using the PC or later, using a UNIX workstation in the office.

The software has been designed to produce either a distance/level diagram (*Fig. 11a*) or a time/power–level diagram for the entire measured route, or parts of it. The number of values may be reduced by averaging. It is possible to calculate and represent the probability density of the measured values (*Fig. 11c*), the probability with which specified limits are exceeded (cumulative distribution function, CDF), the median values and the standard deviation (*Fig. 11b*) for the distance under measurement.

In "fast level mode", a local resolution of 15 cm is selected for power level measurements (which corresponds to roughly 9 samples per wave–length), the combined (fast and slow) fading is achieved which is typical of mobile reception (Rayleigh–channel). *Fig. 12* illustrates how the received level is typically composed of fast and slow fading. The detection of slow fading requires the calculation of the median values over sectors (we have chosen 25 metres) to filter out the fast fading. Fast fading may be detected by filtering out the slow fading by means of sector–wise (25 metres) centering of the measured values on the respective sector median. In DAB network planning, slow fading is of the greater importance when determining the minimum wanted field–strength and the standard deviation. Fast fading is largely balanced by the time interleaving which is provided in the DAB system.

The evaluation software also allows for filtering, for instance to eliminate the measured null symbols which appear at the header of each COFDM frame.

If the status of the CRC code has been measured, it may be further evaluated with the software; examples are given in *Section 5.2.* below.

4.3. Third generation DAB receiver

About one hundred third–generation DAB receivers have been produced. The receiver (*Fig. 13*) is still comparatively large and it consumes much power, because of the numerous electronic parts. Moreover, the equipment has a modular structure so that the individual cards must be interconnected. As a consequence, the receiver emits a great number of interfering noise signals which may be coupled into the receiving aerial, particularly in the VHF range. It was only after improvements at the receiver, which were made by ourselves on two sets and by the manufacturer on one, that the self–interference could be substantially reduced. Additionally a location was chosen for the receiver in the monitoring van which allows for optimum decoupling from the receiving aerial. With these provisions, the minimum level required for error–free reception in the monitoring van could be reduced to approximately –88 dBm which, according to the conversion given in equation (2) in *Section 5.*, corresponds to a field–strength of roughly 35 dBμV/m.

These problems of self–interference will be less severe with the fourth–generation DAB receiver, envisaged for application in the Bavarian DAB Pilot Project; these reecivers will use a substantially higher level of chip integration (JESSI DAB–chip set), leading to smaller dimensions of the receiver and a substantial reduction of the power consumption. Moreover, they will be provided with a screened case so that potential noise will be radiated mainly via the inputs and outputs and the connecting cables.

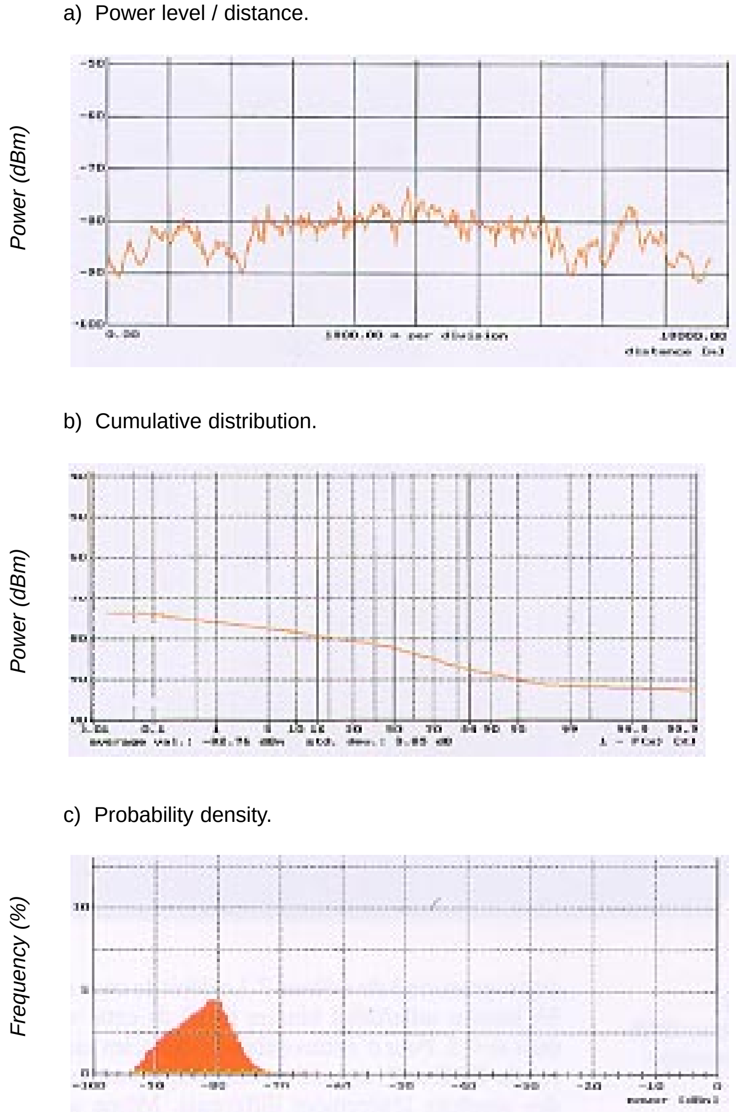
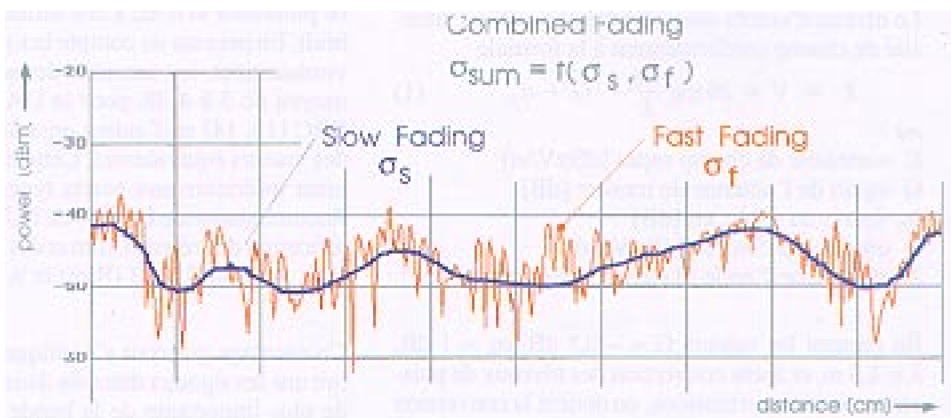


Fig. 11
Examples of DAB power level evaluations.



Trigger resolution: 15 cm (approx. λ/9), corresponding to about 185 measurements at 100 km/h
Sector size: 25 m (approx. 19λ)

Fig. 12
Typical form of the DAB power level measured along a short distance.

Fig. 13
A third–generation DAB receiver.

5. Results of measurements

During the past few months a large number of power level and CRC measurements have been carried out in the coverage area shown in *Figs. 1* and *2*. The audio channel, containing a stereo programme coded with a data–rate of 224 kbit/s, was used for any subjective assessment and for all CRC measurements. This channel corresponds to programme 2 in *Table 2*. The code–rate (i.e. the ratio of useful bit–rate to total bit–rate) was 0.5 on that channel. For other code–rates, slightly different results were obtained for the CRC measurements and in listening tests. Even with as few as five transmitters in operation, it was possible to derive interesting information about the DAB SFN operation from different transmitter combinations.

The measured input level was converted into a field–strength value according to equation (1):

$$E = V + 20 \log \frac{7.6}{\lambda} - G + \alpha_k \qquad (1)$$

where:

E = received field–strength, in dBμV/m
G = gain of the measuring aerial, in dB
α_k = cable loss, in dB
V = input voltage, in dBμV
λ = wave length at the measuring frequency, in m.

Substituting values of G = –0.5 dB, α_k = 1 dB, λ = 1.3 m, and after conversion of the output power levels into voltages, the following conversion from power level to field–strength is obtained:

$$E \text{ [dB}\mu\text{V/m]} = P \text{ [dBm]} + 123.7 \text{ [dB]} \qquad (2)$$

5.1. Standard deviation of power level measurements

Apart from the protection ratio, the minimum equivalent field–strength is one of the essential parameters in transmitter network planning. It has to be re–defined for DAB coverage. Starting from the minimum power level required at the receiver input, the minimum equivalent field–strength can be determined by an appropriate conversion. For transmitter network planning, certain increases are still required, e.g. to allow for the location variation of field–strength or for adaptation of the value to a propagation model.

As has been mentioned above in *Section 2.2.*, DAB must be planned for 99% of the locations. The propagation curve specified in ITU–R Recommendation PN.370 [11] apply to 50% of the locations. Assuming a log–normal distribution, the correction factor K for 50% to 99% location probability may be determined from the standard deviation σ as

$$K_{50\% \rightarrow 99\%} = 2.33\,\sigma \qquad (3)$$

Fig. 14a – c shows examples of the standard deviations of the power levels of single DAB transmitters, which were derived from the measuring sections (each 1 km long) for different distances and for different DAB transmitters. This evaluation was made only for slow fading.

The comparatively large standard deviations in the vicinity of a transmitter are not important since here the power level is sufficient. At large distances, the values of standard deviation are very small, owing to an insufficient power level and hence to an ever–increasing noise influence. Depending on the topography and the environment, a standard deviation of 3 to 4 dB may be derived from the measurements as a general mean value for DAB. Similar values have been established by the IRT [12], the BBC [13, 14] and other organizations. This value is definitely lower than the value specified in ITU–R Recommendation PN.370 for VHF/FM and television network plan-

Fig. 14a
Standard deviation of power level measurements taken from the Gelbelsee transmitter along the highway A9

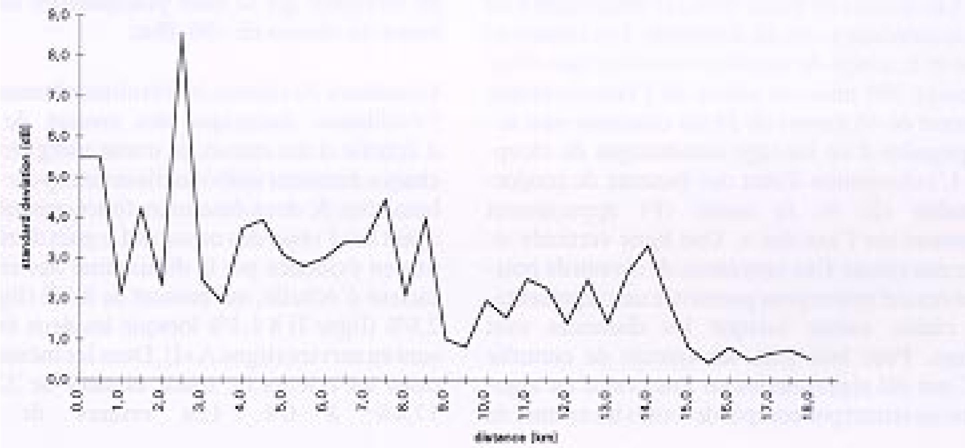


Fig. 14b
Standard deviation of power level measurements taken from the Augsburg transmitter along the highway A8

Fig. 14c
Standard deviation of power level measurements taken from the Augsburg transmitter along a country road

ning: standard deviations of 8.3 dB (VHF range) and 9.5 dB (UHF range).

One reason for this difference could be that for, the wider bandwidth of 1.5 MHz, less variation of the signals can be found than for narrow–band VHF/FM and television signals. On the other hand, it is not clear in Recommendation PN.370 how the field–strength was measured and evaluated; it might also be that combined fading, rather than slow fading, was evaluated. The values of standard deviation determined by the BBC, IRT and BR are between 4 dB and 6.5 dB for combined fading.

5.2. Network gain in the single frequency network

One advantage of DAB SFNs resides in the fact that the direct and reflected signal components of the individual transmitters, which are present at the receiving antenna, add up in a positive manner. This could be demonstrated on one of the measuring routes. The 8–km section between the exits at Sulzemoos and Fürstenfeldbruck, along the highway A8, was chosen. The prediction according to *Fig. 1*, indicates that contributions may be expected from the Hohenpeissenberg, Ismaning and Augsburg transmitters. The measuring van travelled along the measuring route, which is mapped in *Fig. 15* in the form of an enlarged extract from *Fig. 1*, from Fürstenfeldbruck to Sulzemoos, and in the opposite direction, at a constant speed of roughly 100 km/h. The power level was measured at 15 cm intervals and CRC checks were recorded every 24 ms.

Figs. 16 a – e reproduce the measured results. No disturbance was audible when the power level was sufficient (red graph). If scale factor errors occured (green) a slight "bubbling" was audible. Frame errors (black) occured at a level of less than –88 dBm approximately. Receiver muting occured both during the frame errors and for the time for re–synchronization (at least 384 ms, due to the time interleaving over 16 frames of 24 ms each). The status information of the scale factors (S) and the frame (F) are also shown, alongside the x–axis of the figures. A vertical line signifies an error. For a clear representation, even over long distances, mean values of the power levels were taken, while the CRC check errors were represented according to an algorithm which ignores some scale factor errors. As a first approach, this method fits well with the subjective impression of the audio under mobile reception conditions.

Figs. 16a, *b* and *c* illustrate cases where only the single transmitters at Ismaning, Augsburg and Hohenpeissenberg were in operation. The route is best served by the Hohenpeissenberg transmitter, and worst served from the Augsburg transmitter, as can be seen also from the different percentages of undisturbed audio reception indicated in the columns headed "No error" in *Table 3 a–b*. In the case shown in *Fig. 16d*, the Augsburg and Ismaning transmitters were in operation together. In comparison with *Figs. 16a* and *b*, there are definitely fewer unserved locations. If the Hohenpeissenberg transmitter is also brought into operation (*Fig. 16e*), CRC check errors no longer occur and the received level is almost always above –80 dBm.

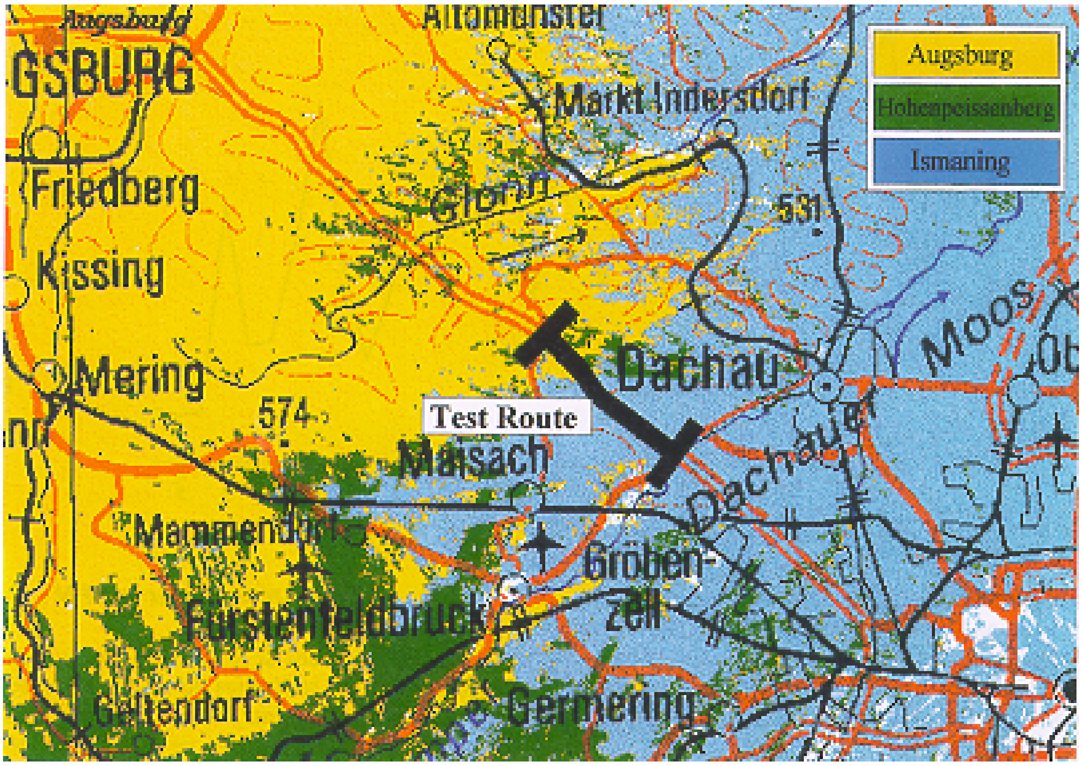
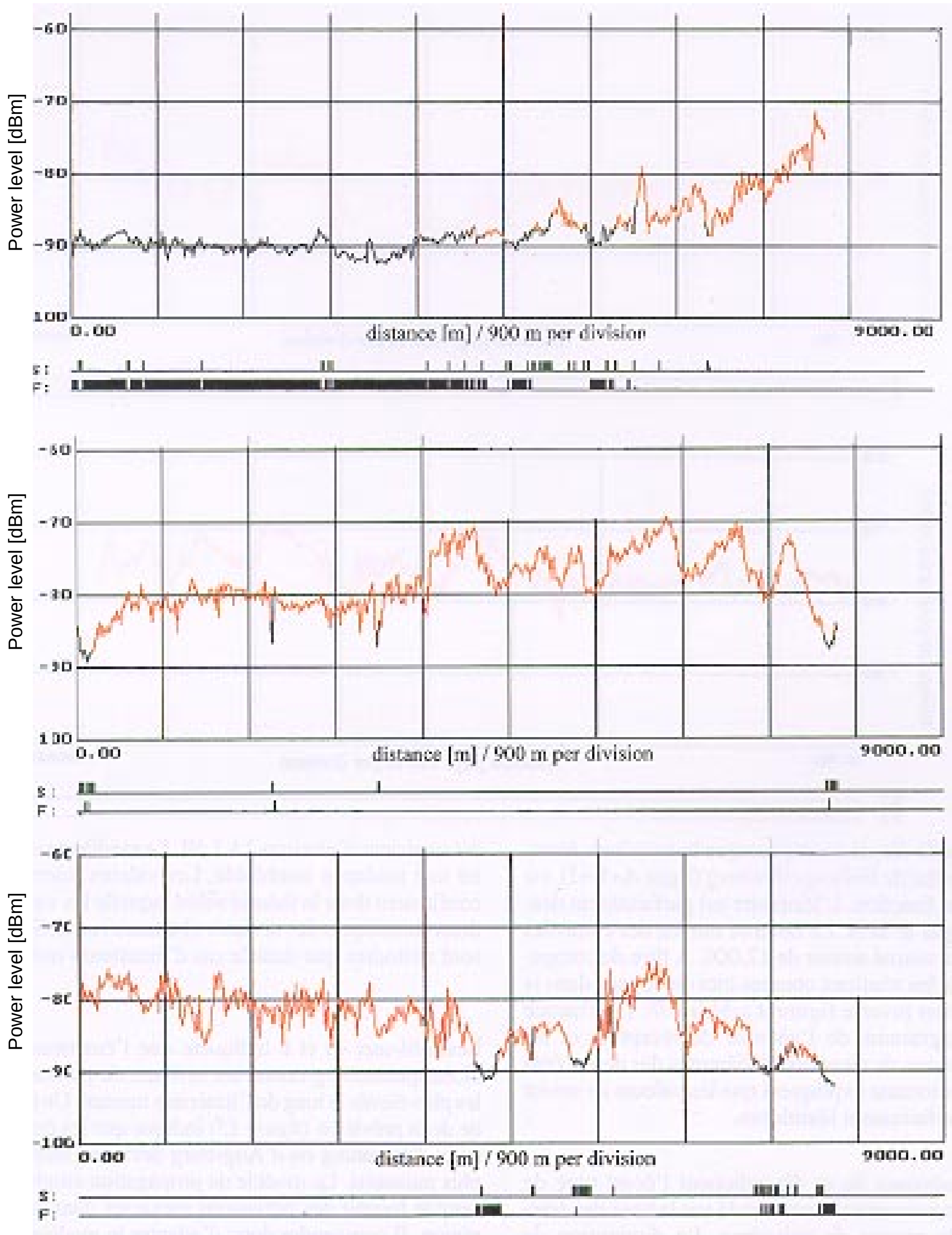


Fig. 15
Predicted DAB coverage and test route along the highway A8 from Sulzemoos to Fürstenfeldbruck.



a) Augsburg transmitter only.

b) Hohenpeißenberg transmitter only.

c) München–Ismaning transmitter only.

Fig. 16 a – c
Power level and CRC check, scale factor (S) and frame errors (F) measured with single transmitters.

Transmitter(s)	a) Sulzemoos → Fürstenfeldbruck			b) Fürstenfeldbruck → Sulzemoos		
	Scale factor error	Frame error	No error	Scale factor error	Frame error	No error
A	8.3	32.8	58.9	5.5	47.5	47.0
H	1.5	3.2	95.3	1.7	3.5	94.8
I	2.6	12.4	85.0	2.8	6.1	91.1
A + I	1.1	0.0	98.9	0.8	0.5	98.7
A + H + I	0.0	0.0	100.0	0.0	0.0	100.0

Table 3 a – b
CRC evaluations between Sulzemoos and Fürstenfeldbruck with single transmitters and in the single frequency network.

d) Augsburg and München–Ismaning transmitters.

e) Augsburg,Hohenpeißenberg and München–Ismaning transmitters.

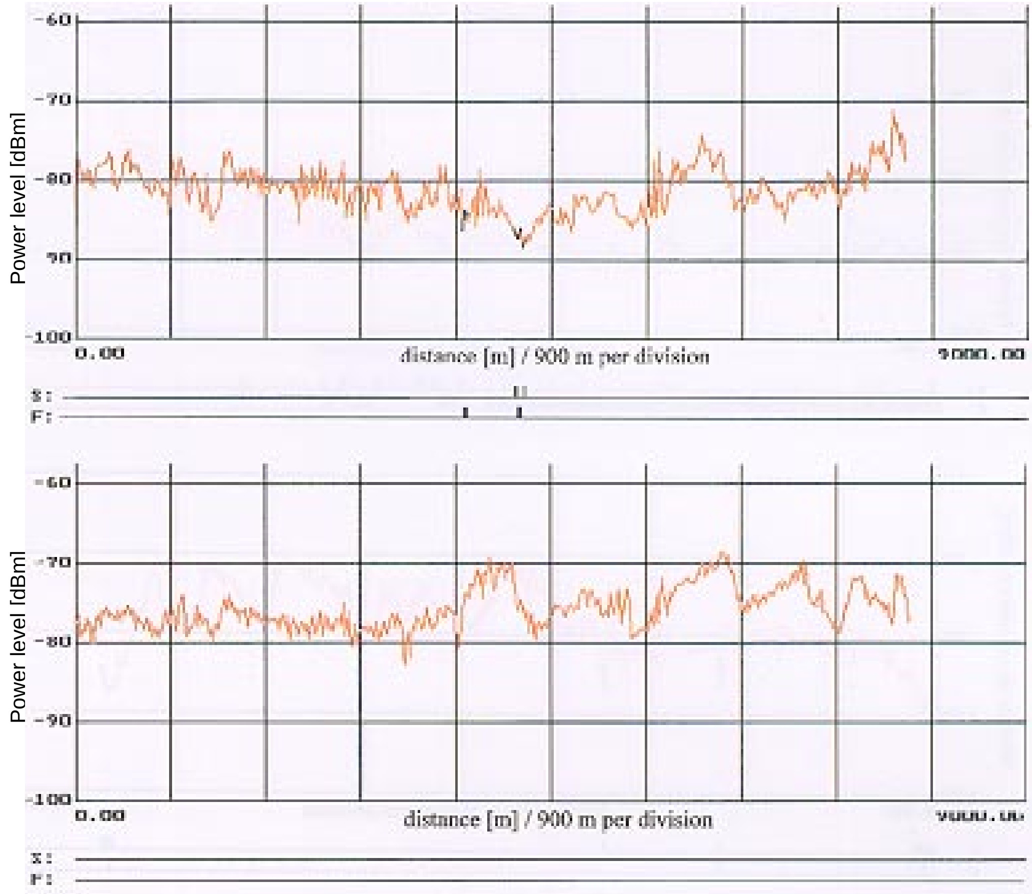


Fig. 16 d – e
Power level and CRC check, scale factor (S) and frame errors (F) measured with specified combinations of transmitters.

Table 3a summarises the results obtained from the statistical evaluation of the scale factor errors and the frame errors, for the individual transmitters and for the multi–transmitter combinations measured in SFN operation. The network gain can be clearly seen in the reduction of the scale factor errors from 8.3% (in line A) or 2.6% (line I) to 1.1% when both transmitters are operating (line A+I). The frame errors are reduced from 32.8% or 12.4%, respectively, to 0%. If the transmitter at Hohenpeissenberg is also operating (line A+H+I), scale factor errors no longer occur and the route is perfectly covered by the SFN. The mean number of CRC checks amounted to roughly 12 000. For comparison, results obtained when travelling in the opposite direction are indicated in *Table 3b*; due to the influence of the receiving aerial pattern and to the different receiving conditions on the two sides of the highway, the numerical values are slightly different.

Tables 4a and *4b* show the standard deviation of the slow fading, derived from the power level measurements. The lower values of standard deviation, in the range from 2.4 to 2.9 dB, can be clearly seen for the cases where two or more transmitters are operating simultaneously. For the individual transmitters, this value is higher by roughly 1 dB to 2 dB. The trend of the median is similar. Hence the measured values confirm the theory that the statistical variations of the levels in the SFN are smaller than those for single transmitters.

Table 4 a – b
Standard deviations of slow fading and medians between Sulzemoos and Fürstenfeldbruck.

Transmitter(s)	a) Sulzemoos → Fürstenfeldbruck		b) Fürstenfeldbruck → Sulzemoos	
	Standard deviation σ (dB)	Median of level measurement (dB)	Standard deviation σ (dB)	Median of level measurement (dB)
A	3.8	–87.5	4.0	–87.7
H	4.7	–78.3	4.1	–78.4
I	3.6	–82.9	4.0	–83.0
A + I	2.4	–80.8	2.8	–81.1
A + H + I	2.9	–75.6	2.7	–75.6

Tables 4a and *b* also show that the transmitter at Hohenpeissenberg makes the largest individual contribution to the power levels along the measured route. However, a study of the predicted levels, shown in *Fig. 15,* suggests that the Ismaning or Augsburg transmitters should be the strongest. The propagation model that was employed obviously furnishes incorrect predictions in this area. An adaptation of the prediction model is needed. However, small–area comparisons between predictions and measured power levels are required.

5.3. Coverage measurement along a long–distance route (highway / country road)

The route from Bad Tölz along the country road to Munich was chosen as another example of DAB coverage. The tour went via Grosshartpenning, Holzkirchen, Otterfing, Sauerlach and from there to the highway leading to the Mittlerer Ring in Munich. The route covers a total distance of 54 kilometres. The results of power level and CRC measurements are given in *Fig. 17*. All the transmitters of the SFN were in operation. It can be seen that there are some coverage problems (CRC errors) in areas with urban development, and these are also reflected in the prediction (*Fig. 2*). The attenuation chosen in the model for such areas is possibly too small. The reason is to be found, on the one hand, in the slightly higher "man–made noise" in developed areas [15], and, on the other hand, in the greater screening effect of the buildings. In addition, the time interleaving in cities is less effective because of the reduced driving speed. If the level is high, as is the case in Munich, failures occur only in strongly shaded areas, for ex-

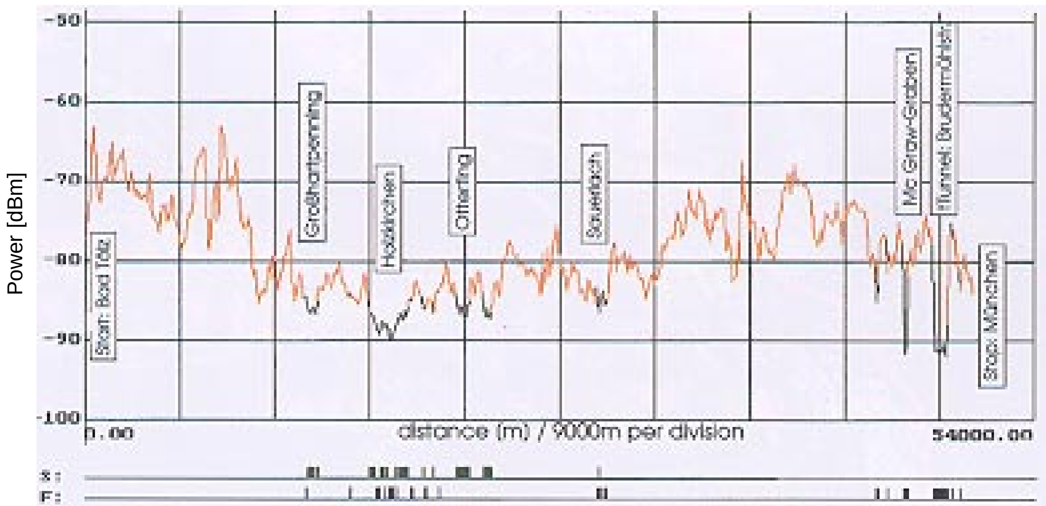


Fig. 17
Power level, CRC check, Scale factor (S) and Frame errors (F), measured along the road from Bad Tölz to Munich (all five transmitters of the SFN in operation).

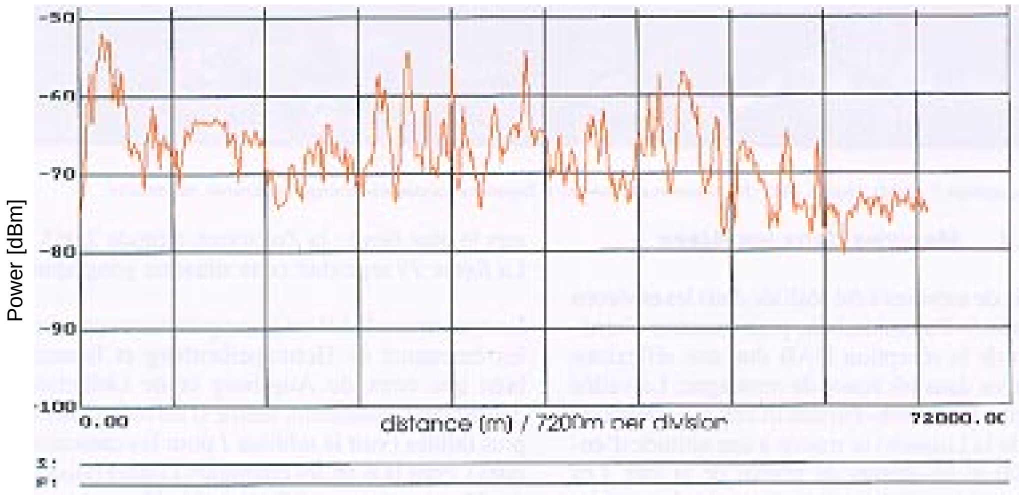


Fig. 18
Power level, CRC check, Scale factor (S) and Frame errors (F), measured along the road from Walchensee/Urfeld to Munich/Sendling (all five transmitters of the SFN in operation).

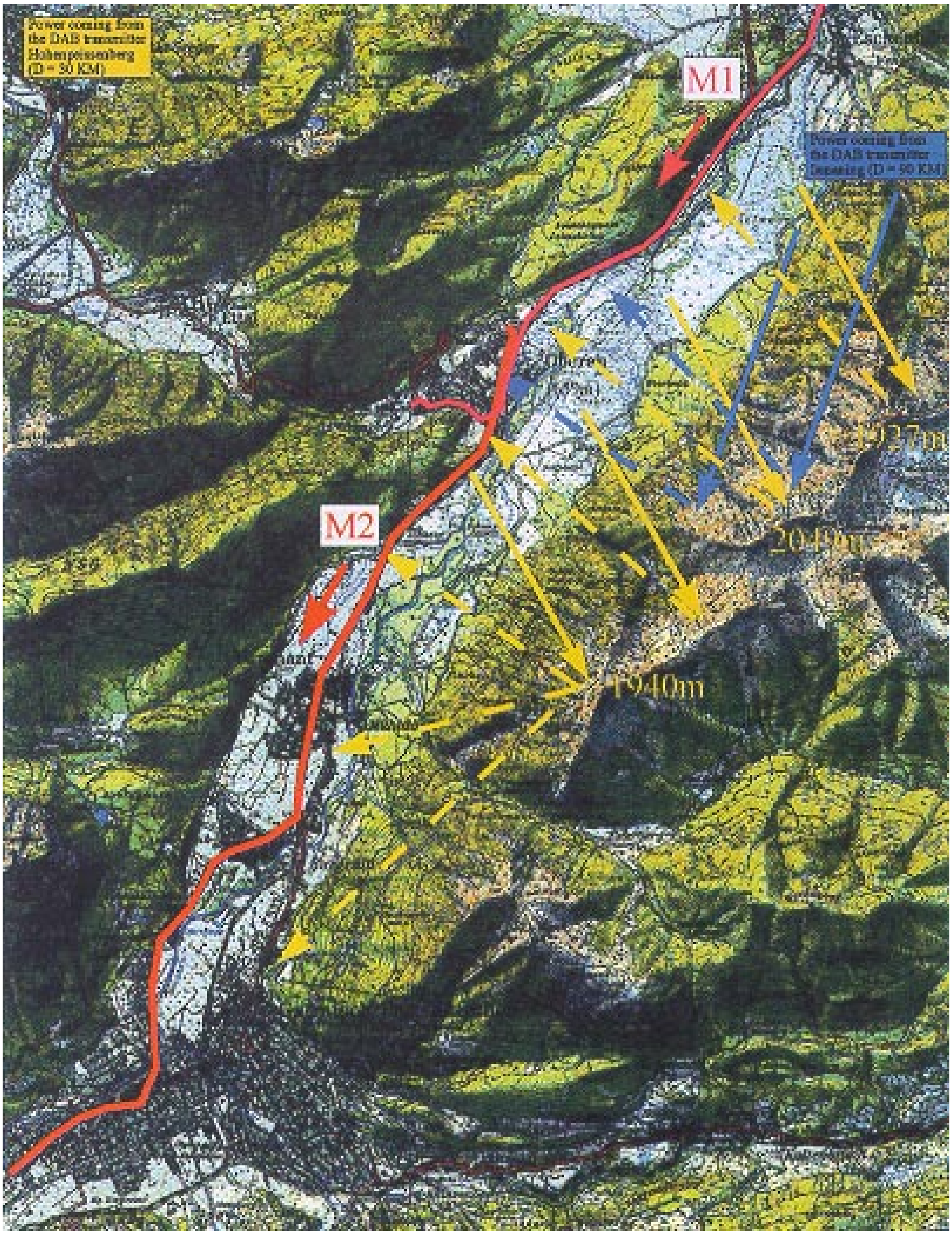


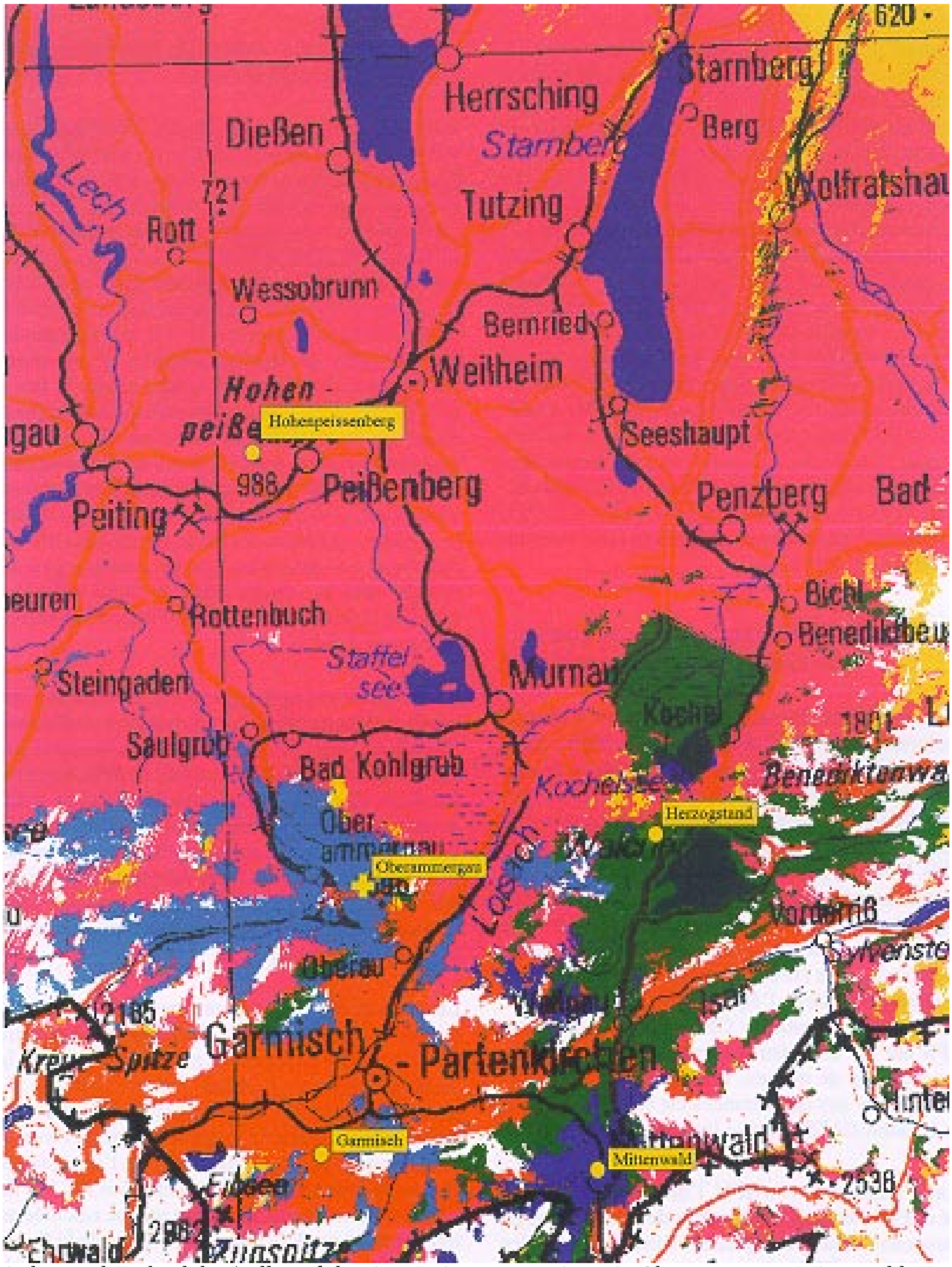
Fig. 19
Measurement route from Eschenlohe to Garmisch–Partenkirchen with topographical map and reflecting mountains.

ample on roads below the surrounding ground level or in tunnels.

The next example is a measurement along the route from Walchensee to Munich. The route started at Kesselberg/Urfeld, went through Kochel and Penzberg along the country road and continued then on the highway A 95 to Munich. The total distance of the route is 72 kilometres. The terrain is initially very mountainous, then hilly and near Munich it ends in a plain. The results of the power level and CRC measurements are given in *Fig. 18*. The coverage along the route is perfect and no CRC check errors were detected.

5.4. Measurements in the Alps

A series of measurements have been carried out near Garmisch–Partenkirchen to demonstrate how DAB reception is favoured by reflections in the mountains. The valley between Garmisch–Parten-



kirchen and Eschenlohe (valley of the river Loisach) is at an altitude of roughly 700 m above sea level. The surrounding mountains rise directly to altitudes above 2 000 metres (highest mountain: Zugspitze, 2963 m). *Fig. 19* shows the geographical situation there.

The Hohenpeissenberg and Ismaning transmitters provide the main DAB coverage here, although the Augsburg and Gelbelsee transmitters also contribute, albeit with weaker reflections (see *Table 1* for characteristics). For VHF/FM, the low–power transmitters in Oberammergau, Mittenwald, Herzogstand and Garmisch–Partenkirchen serve the valleys in that area, in addition to the high–power Hohenpeissenberg transmitter. *Fig. 20* illustrates the VHF/FM coverage predictions with a propagation model (GEG model) developed by a joint group of experts from ARD and DBP–Telekom. The colours (magenta, light blue, red, green, dark blue) identify the strongest VHF/FM transmitter at the receiving location (100 x 100 m pixel). White areas are predicted as being unserved. The fixed

Fig. 20
Predicted stereo coverage for 10 m antenna height of the VHF/FM transmitters serving the area around Garmisch–Partenkirchen.

VHF/FM reception is good but problems due to reflections occur in mobile reception.

In the DAB coverage prediction (see *Fig. 2*) no reception is expected for the Loisach valley between Oberau and Garmisch–Partenkirchen. The measurements, however, indicate perfect DAB coverage, an effect of reflections received from the Ester mountains and the Wetterstein range. No CRC errors occur along the route from Eschenlohe to the edge of Garmisch–Partenkirchen. In Oberau, for instance, a homogeneous DAB power level of –65 dBm is measured. The reflectors illustrated in *Fig. 19* could be verified by measurements with a directional antenna. It can be concluded that the coverage prediction for mountainous areas is much too pessimistic. The model should also consider the reflectors in order to arrive at better predictions. With such an approach, however, the computing time will be increased drastically. In mountainous regions (Austria, Switzerland, etc.) DAB is a very economic system since large numbers of low–power stations, which are necessary for VHF/FM, will most probably not be needed. One should be aware of the fact, however, that reflections with the strength noted here occur only when there is a line–of–sight link between the transmitter and the reflector. Similar results were obtained in studies carried out by the Swiss PTT in the Swiss Alps and were reported in international DAB working groups.

5.5. Comparison of calculated and measured field strength

In network planning, it is not only important to know the fringe of the coverage, but also to know the field–strength graduation inside the coverage area. Especially when using the SFN technique, this is of great interest for calculating the self–interference. Therefore comparisons were made between all measured power levels and the calculated field–strength values for every pixel along selected routes. The power levels were converted to field–strength values by using equation (2). The power levels, the CRC checks and the GPS coordinates were registered simultaneously during measurement tours. The expected field–strength values for these coordinates are calculated with the CATS software, as outlined in *Section 2.2*.

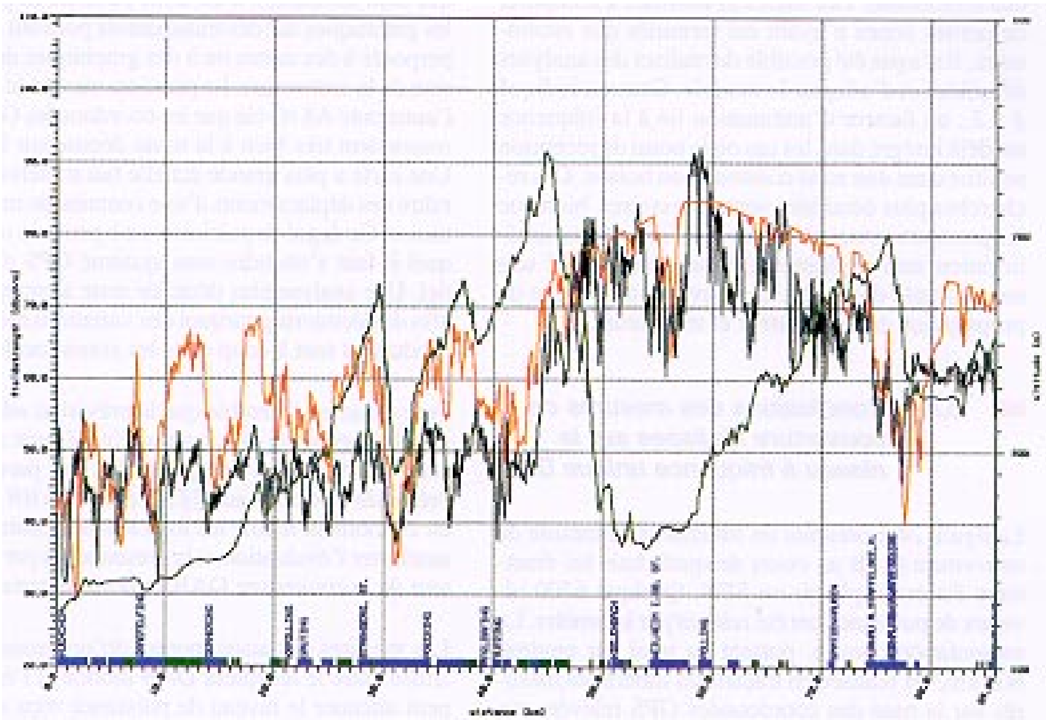
For SFN operation, the resulting field–strength was calculated by the power sum method. To compensate for inexact GPS coordinates and small errors in the topographical data, the field–strength was predicted for a block of 3 x 3 pixels, with the measurment coordinate point in the centre. Then the representative field–strength was calculated as the mean value of these 9 predicted values; the results are given in *Figs. 21* to *23* as a red curve. The black curve shows the median values of the measured field–strengths, calculated for a sector size of 100 m corresponding to 666 measured power level values with a resolution 15 cm. The green curve gives the height of the terrain along the route as stored in the database. At the bottom of these charts, built–up areas (blue, with name of the village or town) and forests (green) are marked.

The first example (*Fig. 21*), taken from a large set of measured routes (see also *Section 5.6.*), shows a comparison for the route from Kochel along the country road B 11 via Mittenwald to the Austrian border at Scharnitz; it is for the single transmitter at Herzogstand (The location of this transmitter can be seen in *Fig. 20* and the transmission parameters are given in *Table 1*.). In general, good compliance can be achieved between the measured and the calculated field–strengths. Remarkable differences can be seen for example at a distance of 8.8 km from the starting point, were a peak of 950 m a.s.l. is reached, before the terrain slopes to 860 m a.s.l. In this area, the predicted field–strength (red) is about 15 to 20 dB too low, because of reflected signals from the surrounding mountains, which are not predicted in the GEG DAB model used here (a model developed by the expert group mentioned in *Section 5.4.*).

The second example, shown in *Fig. 22*, is the route from Munich via Germering, Starnberg, Tutzing and Murnau to Eschenlohe, with all DAB transmitters operating as an SFN. The comparison is calculated with the GEG DAB model and shows that in several areas (from km 10 to km 37 and from km 67 to km 73, as well as at the end of the route) the predicted values (red) are much higher than the measured ones (black), but the general form of variation of the field–strength is well represented by the model that was used.

The measured values for this route were also compared with predictions gained with another model used by the BR. This model is based on the Deygout model and it subtracts the attenuation of the signals caused by the three highest knife edges along the path, from the free–space field–strength. In the case of a free line–of–sight, the model uses the field–strength given by ITU–R Recommendation PN.370. The predicted field–strength calculated with this model (see red curve in *Fig. 23*) fits a little better than the curve calculated with the GEG DAB model (*Fig. 22*). In just a few cases, the predicted field strength is more than 10 dB too high (at Feldafing, located from km 35 to km 38 and at Weilheim, located from km 54 to km 58). However the overall trend of field–strength variations is bet-

Fig. 21
Comparision of predicted and calculated field–strength.
Route with reflected signals from surrounding mountains.
(GEG DAB model, single transmitter)



Red: predicted field–strength
Black: measured field–strength
Green: terrain height

Fig. 22
Comparision of predicted and calculated field–strength.
(GEG DAB model, single frequency network with 5 transmitters)

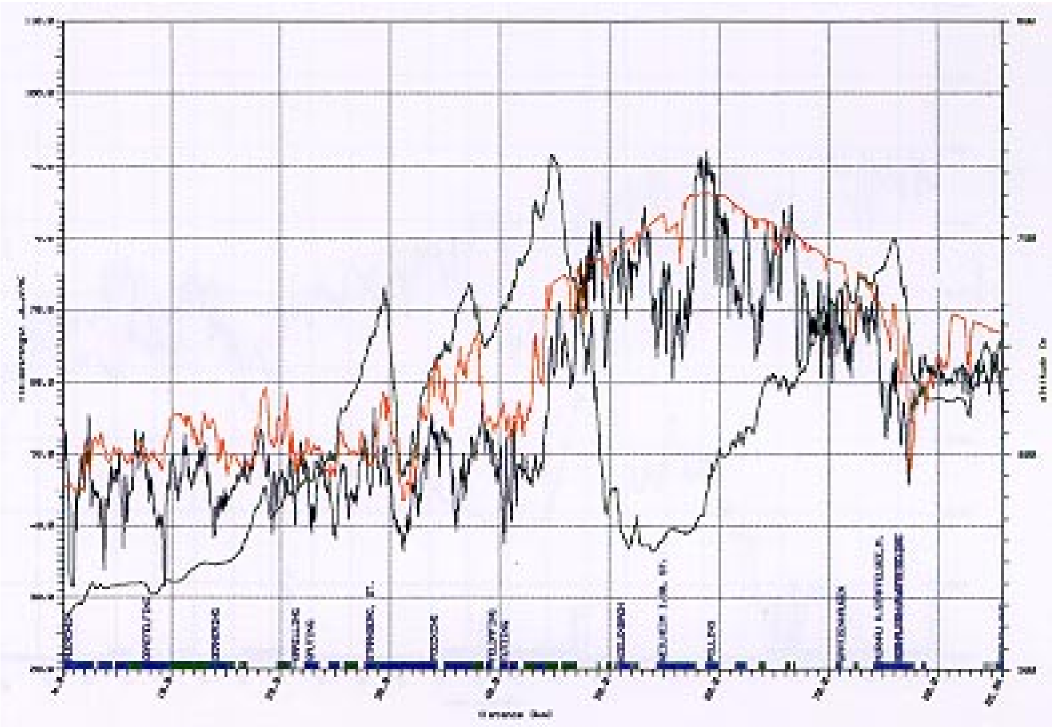


Fig. 23
Comparision of predicted and calculated field–strength.
Modified Deygout model, single frequency network with 5 transmitters.

Red: predicted field–strength
Black: measured field–strength
Green: terrain height

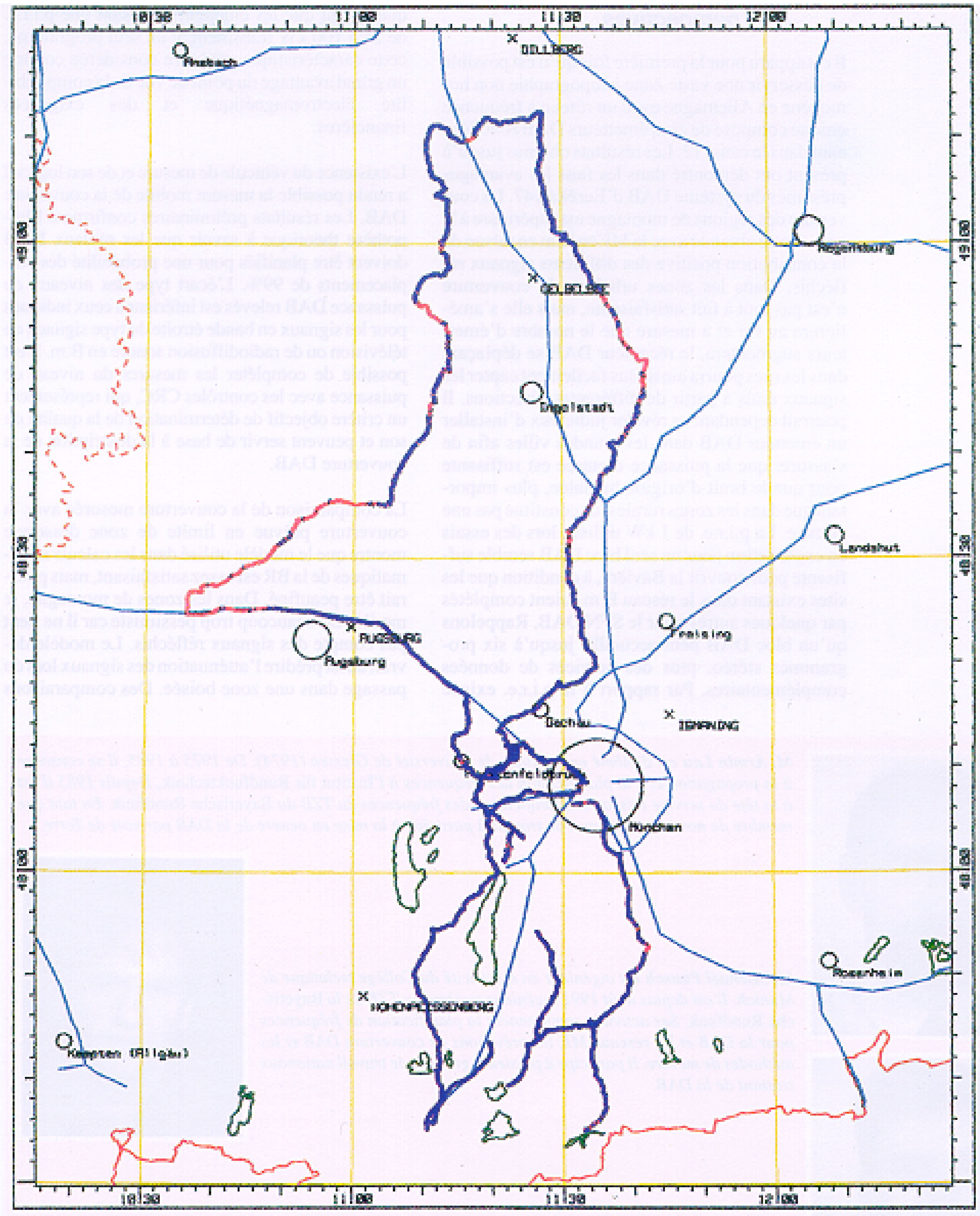
ter approximated by the GEG DAB model than by this BR model.

Comparisons calculated for other measured routes also show the effect that the predicted field–strength is often higher than the measured values (except in mountainous areas, where field–strength predictions are much too low, due to reflections). As the software tools for the small–area comparison have been finished only recently, it has not been possible to perform detailed analysis and to adapt the model. As indicated in *Section 2.2.*, a frequency–dependent attenuation factor is already taken into account if the reception point is in a built–up or wooded area. More detailed investigations are needed, although first tests have showed a significant improvement if allowance is made for forests along the propagation line between the transmitter and the receiver.

5.6. Concluding results of the coverage measurements in the DAB single frequency network

Fig. 24 shows routes on which DAB coverage measurements have so far been made with SFN operation involving all the transmitters. Some 6700 power level values have been measured per kilometre. The form of representation chosen here, which covers a total distance of approximately 605 km, has been obtained by plotting measured GPS coordinates along the various routes over a planning map available in the computer. The dark blue lines indicates error–free DAB reception while the magenta parts represent errors in the CRC check (Frame errors). The scales and the geographic reference system are optional, so it is also possible to plot the graphs on film sheets which may then be superimposed on maps or graphs of coverage predictions. The course of the measuring route along the highway A8 reveals that the GPS coordinates correspond very well with the road, as marked on the map. On a map having a larger scale, however, displacements of as much as some 100 metres become apparent. This corresponds approximately to the precision which may be achieved without a Differential GPS system. A more–detailed analysis is still required to find the reason why unexpectedly high variations occur in local areas.

In summary, it is apparent that the “served/not served” prediction is in acceptable agreement with the measurements, with the exception of the special cases discussed in *Sections 5.3.* and *5.4.* The BR is currently developing appropriate software to



Black: towns and cities
X (black): DAB transmitter
Light blue: highway
Green: lakes
Dark blue: DAB reception without any CRC check errors
Magenta: CRC check with frame errors

Fig. 24
A selected set of DAB measurements plotted against GPS coordinates taken during DAB coverage measurements with all transmitters of the SFN in operation.

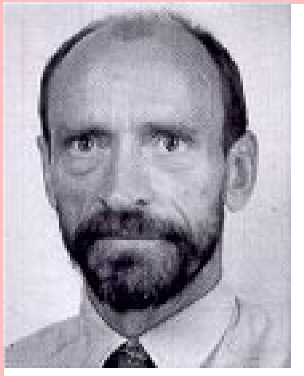
improve the computer–supported evaluation and the representation of the measured and the predicted DAB coverage.

The measurements have also shown that a wooded area between the mobile DAB receiver and the transmitter can attenuate the received power level so much that the reception fails. An appropriate modification of the model, which takes account of the attenuation caused by forests, is under development.

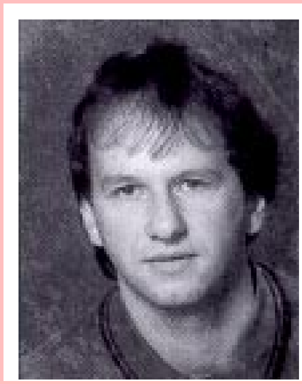
6. Conclusions and prospects

With the single frequency network of five DAB transmitters in television channel 12, it has for the first time been possible to cover a large non–homogeneous topographical area in Germany. The results gained so far have convincingly shown the expected advantages of the Eureka 147 DAB system. The coverage in mountainous areas is improved, compared to VHF/FM, due to the different reflected signals that contribute positively. In built–up areas, the coverage is not completely satisfactory but will be better when more transmitters are in operation because signals coming from different directions will more–easily reach a DAB receiver moving in the streets. Nevertheless it could be wise to install a DAB transmitter in larger cities to be sure of having enough input power to overcome the man–made noise which is higher than in rural areas. The e.r.p. of 1 kW that has been used in the field test for a single DAB block seems to be sufficient to cover Bavaria, if some additional sites are used for the DAB SFN to supplement those at existing sites of the VHF/FM network. It should be borne in mind that that up to six stereo programmes, plus additional data services, can be accommodated in a DAB block. Compared to the e.r.p. used in VHF/FM networks, where the transmitters often radiate a single programme with an e.r.p. of 25 kW to 100 kW, this can be regarded as a big advantage in respect of electromagnetic compatibility and economics.

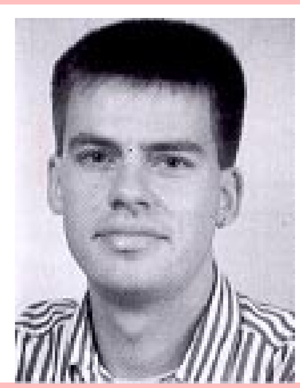
With the development of the measurement van together with its software, it has become possible to undertake mobile DAB coverage measurements. The first results underline the theoretical approach, that DAB networks should be planned for a location probability of 99%. The standard deviation of the measured DAB power–level values is lower than those reported for narrow–band signals like television or VHF/FM sound broadcasting. As an objective criteria for the audio quality, giving a basis for describing DAB coverage, the CRC checks can be used to supplement the power level measurements.



Mr. Armin Lau *graduated in physics at the University of Giessen in 1974. From 1975 – 1985 he worked on propagation and frequency planning related to broadcasting at the Institut für Rundfunktechnik. Since 1985 he has been Head of the Network and Frequency Planning Section of the TZB in the Bayerische Rundfunk. As a member of several national and international working groups he supports the introduction of terrestrial DAB.*



Mr. Michael Pausch *qualified in electrical engineering at the Technical College, Munich. Since August 1991 he has been working as a systems engineer at the TZB in the Bayerische Rundfunk. His activities include frequency and network planning for DAB and FM networks and DAB coverage prediction and measuring methods. He is member of several national working groups concerning DAB.*



Mr. Wolfgang Wütschner *qualified in electrical engineering at the Technical University, Munich. Since December 1991 he has been working as systems engineer at the TZB in the Bayerische Rundfunk. He has worked mainly on the development of a PC–based data acqusition system for mobile DAB measurements and the evaluation and visualisation of the data.*

The comparison of the measured and the predicted coverage at the fringe of the service area shows that the model used in the BR computer calculations fits relatively well but has to be refined. In mountainous areas the model is much too pessimistic due to the presence of useful reflected signals which are not taken into account. The model should also predict the attenuation of the signals passing through forests. More detailed comparisons over larger areas are needed to obtain a better overview.

DAB receivers of the 4th generation should produce less self–interference to guarantee good reception when used in “normal cars” in the different pilot projects foreseen for 1995.

It is planned to expand the Bavarian SFN with seven additional transmitters in order to improve and extend the coverage for the Pilot Project; this work will start in 1995. If the international coordination of these transmitters is successful, the SFN will cover about 30 000 km^2 and reach about 5 million people living in this area. This represents nearly 50 percent coverage of the Bavarian territory and a similar proportion of the population.

Acknowledgements

Numerous colleagues of the Bayerische Rundfunk have been actively involved in the planning and design of the DAB monitoring van and the DAB SFN. We want to address our thanks in particular to all these people and colleagues from Institut für Rundfunktechnik who have looked after the multiplexer and the up–link to DFS Kopernikus. Moreover, we thank DBP–Telekom here again for providing the 20/30 GHz transponder free of charge.

Bibliography

[1] Plenge, G.: **DAB – A new sound broadcasting system. Status of the development – Routes to its introduction**
EBU Technical Review, No. 246 (April 1991), pp. 87–112.

[2] Stoll, G.: **High quality audio coding for DAB: ISO/MPEG Layer II**
Proceedings, Second International Symposium on DAB, Toronto, March 1994. pp. 357–377.

[3] Ratliff, P.A.; Pommier, D.; Meier–Engelen, E.: **The coverage of satellite and terrestrial system approaches to digital audio broadcasting with mobile and portable receivers**
EBU Technical Review, No 241–242, 1990, pp. 82–94.

[4] Riley, J.L.: **The DAB multiplex and system support features**
EBU Technical Review No 259, Spring 1994, pp. 11–23.

[5] Le Floch, B.: **Channel coding and modulation for DAB**
Proceedings, EBU First International Symposium on DAB, Montreux, June 1992 pp. 99–110.

[6] **Advanced digital techniques for UHF satellite sound broadcasting (Collected papers on concepts for sound broadcasting into the 21st century)**
EBU, Geneva, August 1988.

[7] Draft European Telecommunication Standard pr ETS 300 401 (1994): **Radio broadcasting system; Digital Audio Broadcasting (DAB) to mobile, portable and fixed receivers**
ETSI, January 1994.

[8] Lau, A., Pausch, M., Wütschner, W.: **DAB SFNs – Computer aided planning and measurements**
Proceedings, Second International Symposium on DAB, Toronto, March 1994. pp. 146–155.

[9] Lau, A., Williams, W.F.: **Service planning for terrestrial Digital Audio Broadcasting**
EBU Technical Review No. 252, 1992 pp. 4–26.

[10] Epstein, J., Petersen, D.W.: **An experimental study of wave propagation at 850 Mc/s**
Proc. Inst. Radio Engineers 1993, 41,5 pp. 595 – 611.

[11] ITU–R Recommendation PN.370: **VHF and UHF propagation curves for the frequency range from 30 MHz to 1000 MHz. Broadcasting service**

[12] Großkopf,R., Schramm, R.: **Der DAB Funkkanal bei mobilem Empfang, Messungen in München, Vorhersagemodelle**
IRT, Techn. Bericht Nr. B132/93.

[13] Williams, W.F., Pullen, I.: **DAB: Location correction values for wide band transmissions**
BBC Technical Memorandum T–1139, October 1992.

[14] Maddocks, M.: **The measured performance of a High–Power, VHF Single Frequency Network for Digital Audio Broadcasting**
Proceedings, Second International Symposium on DAB, Toronto, March 1994. pp. 222 – 235.

[15] Williams, W.F., Moore, J.H.: **DAB: Man–made noise in various environments – The first results**
BBC Technical Memorandum T–1087, April 1992.