



*Research and  
Development  
Report*

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**THE CRYSTAL PALACE  
FM FILLER EXPERIMENT**

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**Research and Development Department  
Policy and Planning Directorate  
THE BRITISH BROADCASTING CORPORATION**

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### Summary

*In some areas of London, listeners to BBC Radio National FM services had suffered from poor reception for some time. The problem was particularly severe immediately south of the River Thames where around one million people suffered with unsatisfactory reception on portable and car receivers. This was due to path blocking of the direct signal from the BBC's Wrotham transmitter, located several miles south east of London, and also high levels of multipath propagation. The lack of spare frequencies in Band II meant that the problem could not be solved by using a conventional filler transmitter in the locality.*

*A novel solution was for a synchronised, low power filler transmitter to be set up at the BBC's Crystal Palace site, using a frequency offset of only 304 kHz away from the main Wrotham transmission. For this technique to be successful, the two transmitters need to transmit the same programme feed, the frequency offset needs to be accurate to within a few Hertz, and the timing difference of the two signals at the receiver needs to be minimised to within a few microseconds.*

*It was not known if the introduction of the filler would actually produce a worse service for a few listeners who were, at that time, adequately served by Wrotham, so test transmissions were established for one service only – BBC Radio 4, to allow trials of the technique. Due to the success of the experiment, the Crystal Palace filler has since been extended to all four national FM services.*

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## 1. INTRODUCTION

Poor reception of BBC Network Radio's FM services in parts of London has long been a cause for many complaints, both from listeners and from the BBC's own Network Radio staff. It was claimed that this was an important factor for a declining listener share, with the problem being particularly severe immediately south of the River Thames, where around a million people suffered from unsatisfactory portable and car radio reception; this was due to path blocking of the direct signal from the main transmitter located at Wrotham (see Fig.1), and high levels of multipath propagation. This was confirmed by the BBC R&D Service Planning Section when undertaking site tests of the BBC's national network FM transmitter coverage.

The conventional method of improving reception in such cases is simply to install a filler transmitter operating on an alternative frequency. However, in areas where the signals from both the main transmitter and the filler transmitter overlap, the frequency of the filler would need to be offset by at least 400 kHz. Unfortunately, in the London area no such frequency allocation was available. Though it was recognised that DAB would in the future take over from FM and thereby solve the problem, it was considered that this was not going to be a significant replacement service for many years; therefore, an interim solution was required.

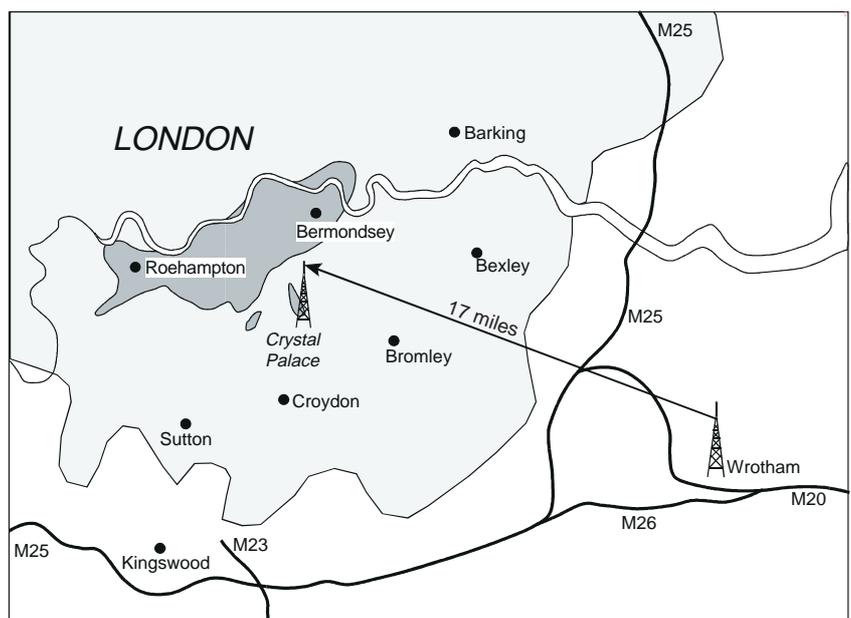
A novel solution was proposed for the installation of a filler transmitter which would use a frequency to be offset by just a few hundred kilohertz from the main Wrotham transmission. Earlier work by Development Department\* had shown that, provided the same programme was being transmitted from both the main and filler transmitters, the delay between the signals would be small; and that if the frequency offset was accurate, then adjacent channel interference protection requirement would be significantly reduced.

It was not known if the introduction of the filler transmitter would actually produce a worse service for a few listeners who were already being adequately served by Wrotham. For this reason, it was decided that test transmissions would be established on one service only (Radio 4) to prove the feasibility of the method, and be subsequently extended to all services if these tests proved successful. In November 1994, tests began with the Radio 4 service being radiated from Crystal Palace at a slightly lower frequency than the main transmission from Wrotham.

## 2. PROTECTION RATIO INVESTIGATIVE WORK

Work carried out on protection ratios for typical domestic receivers (towards the end of 1993) showed that for two transmitters carrying the same co-timed, programme feed, good rejection between adjacent

Fig. 1 - Map showing the location of the two transmitters and the main area of improved reception (hatched).



\* Now combined with Research Department as 'BBC Research & Development'.

channels occurred at around 300 kHz separation.

Further investigations revealed that a considerable improvement in the protection ratio could be obtained at a frequency offset of 304 kHz. The results of the protection ratio measurements are shown in Fig. 2. They are based on a selection of nine domestic stereo receivers, representing typical consumer equipment. The measurements were made with matched modulation on both the wanted and unwanted channels. For the ideal case of 304 kHz offset with no delay, the results vary widely between receivers, from the best at -24 dB to the worst at -8 dB. Fig. 2 shows that an improvement of at least 6 dB is achieved for an interferer at a level of 60 dB $\mu$ V/m.

The residual interference was found to comprise an audio tone of frequency equal to the difference between the adjacent interferer and an offset of 304 kHz relative to the wanted signal. It is caused by the eighth harmonic of the regenerated 38 kHz switching signal used within the receiver's stereo decoder, and an ensuing lack of suitable filtering. Such an interfering signal from an adjacent channel is converted down to base-band where it becomes audible. Therefore, to eliminate this tone, the two transmitters need to be exactly 304 kHz apart (i.e. exactly eight-times the 38 kHz switching frequency).

Therefore, for the case of the interferer being at a higher frequency than the wanted signal:

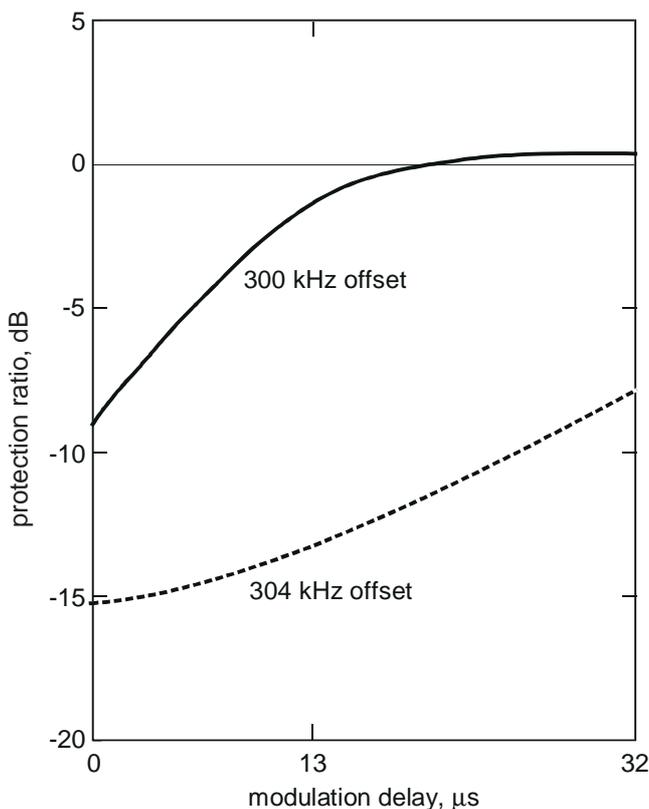


Fig. 2 - Average protection for a range of typical domestic receivers for a interfereer at 60 dB $\mu$ V/m.

$$f_{tone} = f_{adj} - f_{wanted} - 304 \text{ kHz}$$

Therefore, if the adjacent interferer is *exactly* 304 kHz, the tone will be 0 Hz, or in practical terms, below the audio passband of the receiver.

Note that the necessity for using this offset technique means that the filler frequency will not conform to the 1984 Geneva plan, and so needs to operate on a non-interference basis.

From Fig. 2, it can also be seen that, for received signals of equal strengths, the delay between the two signals at the receiver has to be reduced to within a few microseconds, so as to maintain the two signals in synchronism. (Excessive delay in one signal path effectively means that the two sources are decorrelated in the receiver.)

In addition, it was necessary to lock the pilot tones of the stereo coders to avoid a very audible 'beat' interference, which was found to be subjectively very annoying.

This work therefore showed three key factors to be considered when planning a real transmitter installation using the offset technique:

- The pilot tones in the two stereo coders must be locked together.
- The 304 kHz frequency offset between the two transmitters must be accurate.
- The delay between signals received from the two transmitters must be small.

### 3. THE DELAY BETWEEN THE RECEIVED SIGNALS

In order to co-time the programme audio as far possible, and also to provide a common source for local announcements regarding the start of the new filler service, Wrotham's transmitter input equipment (TIE) programme feed was relayed to Crystal Palace (CP) via a microwave communications SHF video link; a distance of around 17 miles (27 km). Figs. 1 and 3 show the initial arrangement. Note that the problem of locking separate pilot tones of different stereo coders is not an issue here, as both transmitters transmit the same multiplex – originating from a single stereo coder.

For the filler to work effectively, the signals transmitted from Wrotham and Crystal Palace should ideally arrive at the listener's receiver together. Therefore, the propagation delay, from Wrotham directly to the listener's receiver, needs to be approximately equal to the

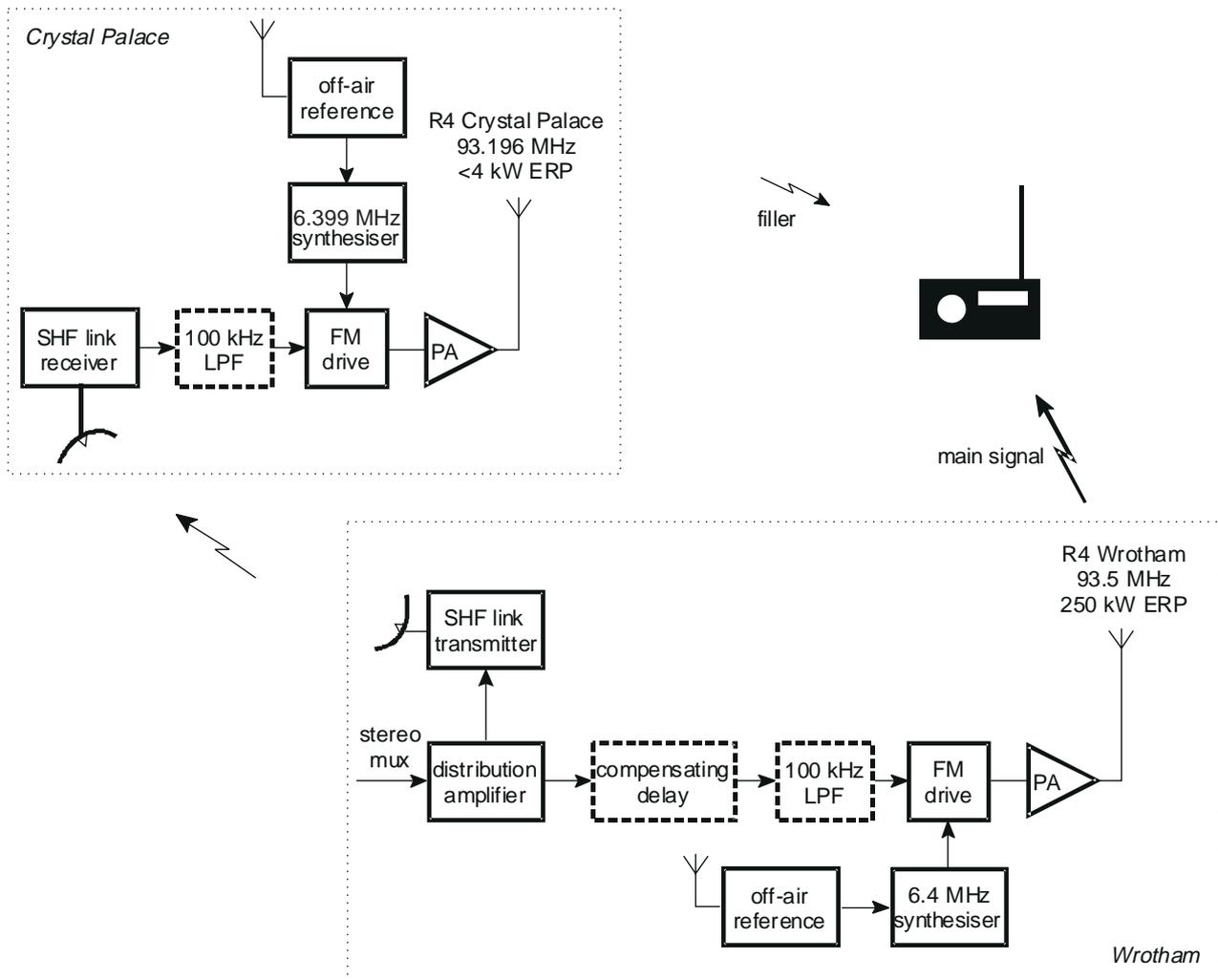


Fig. 3 - The initial arrangement, using the SHF link.  
 (The compensating delay and 100 kHz LP filters were not eventually required.)

sum of the delays of the signal paths as it is relayed from Wrotham via the SHF link, to Crystal Palace and then re-radiated at Crystal Palace to reach the listener's receiver.

A common misunderstanding of the delay problem is to believe that there is a need to compensate for the 17 mile propagation delay in the Band II transmission from Wrotham to Crystal Palace. In actual fact, this delay was already compensated for by the equal duration of the propagation delay of the SHF link from Wrotham to Crystal Palace over the same propagation path.

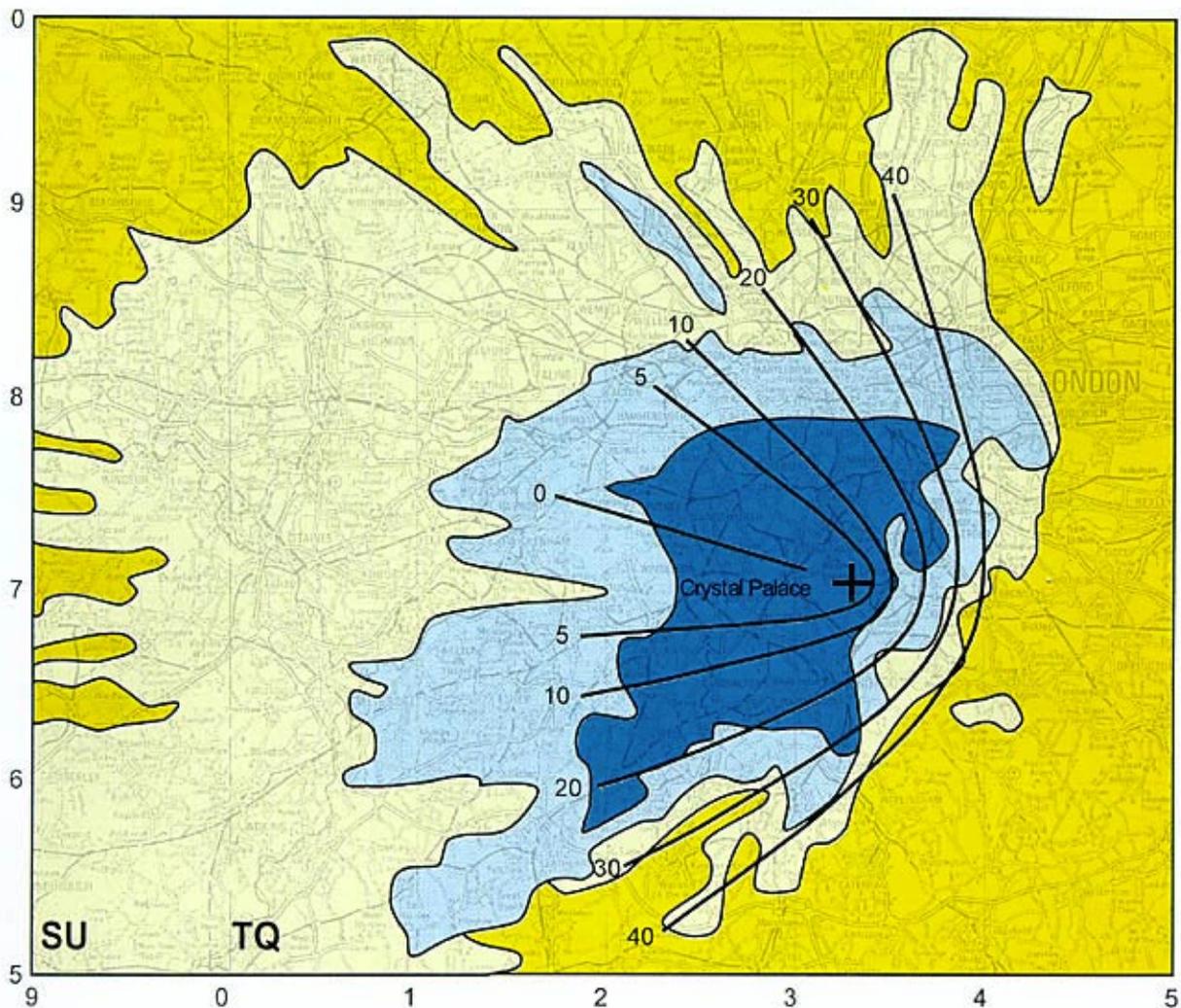
One cause for concern was the unknown delay through the SHF link equipment. For the test transmissions, an SHF link from BBC Television Outside Broadcast Department (Tel. OBs.) was to be used; so the delay of a similar unit was measured in the laboratory at BBC R&D and was found to introduce only around  $2\ \mu\text{s}$  of delay. As the propagation delay is  $3.4\ \mu\text{s}$  per kilometre, the delay introduced by the link equipment was considered to be negligible; so no compensating delay was therefore required in the Band II signal radiated from Wrotham.

Due to the size of the coverage area, it was not possible to produce an exact equalisation of the delay for all locations simultaneously. The goal was to approximately co-time the Crystal Palace transmission with the signal radiated from Wrotham as it passed over the Crystal Palace site.

For the areas where reception was likely to be greatly improved – mainly south of the River Thames, from Roehampton to Bermondsey – it was theoretically possible to match the delays from being approximately co-timed at Roehampton, while gradually increasing to around  $20\ \mu\text{s}$  at Bermondsey. In these key areas, the field strength due to the Crystal Palace filler signal was considerably higher than that from the main service originating from Wrotham as can be seen from Map 1 (*overleaf*)).

#### 4. FREQUENCY ACCURACY OF TRANSMITTERS

The 'beat tone' created by the error in the 304 kHz frequency offset between the two transmitters was



Map 1 Relative signal strengths and delay differences for BBC National FM services, from Crystal Palace and Wrotham

Crystal Palace stronger than Wrotham

by more than 7 dB

by between 0 and 7 dB

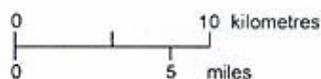
Wrotham stronger than Crystal Palace

by between 0 and 7 dB

by more than 7 dB

30 — Wrotham leads Crystal Palace by 30 μs

Note: Based on predictions of Radio-3 reception, vertically polarised, at 10m above the ground



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required to be kept below the pass band of the receiver's audio channel (< 20 Hz). This meant that the two transmitters needed to have a centre frequency accuracy of better than 10 Hz at Band II (around 100 MHz); that is, better than 0.1 ppm error, even though they are located many miles apart.

In order to achieve this tolerance of frequency matching, off-air frequency-standard equipment was installed at each site to provide a standard 10 MHz reference output (accurate to better than 0.01 ppm), which was then used as a common reference for each of the synthesisers. (The synthesisers provided the appropriate reference signals to the FM drive from which the final VHF frequencies were derived.) By using a common off-air frequency standard (the carrier of the BBC Radio 4 Droitwich long-wave transmitter) at both sites, the transmitters would then track the same reference, even though the short term accuracy of the reference might not have been (and clearly need not have been) perfect.

At Wrotham, considerable redundancy in the FM transmitter equipment provides a contingency for fault conditions, with two separate drives being available to the transmitter. Indeed, the drive changeover unit is switched between drives, often on a daily basis and so it was therefore necessary to provide two synthesisers at Wrotham, each with its own off-air reference.

## 5. WROTHAM TO CRYSTAL PALACE LINK

Initially, the link from Wrotham to Crystal Palace was a standard SHF video link. Although rather wasteful in bandwidth (20 MHz available bandwidth to convey a stereo multiplex of only 60 kHz bandwidth), it was a quick and simple solution. However, it was also realised that in the long term, and particularly if all *four* national services were to be provided with filler signals, this would not be practical.

In the event, the SHF link performance was disappointing, achieving a final audio signal-to-noise ratio of approximately 45 dBq0p's, whereas at least 50 dBq0p\* – same as 50 dB4W – would have been expected. Low pass filters had been purchased to assist with the anticipated noise problem but experimentation showed that these made little difference, indicating that the noise was mainly of a low-frequency nature. Another problem that occurred with the SHF link was that it introduced a spurious 8.45 kHz tone at an approximate level of -30 dB relative to the normal programme level.

\* Denotes the relative noise signal in a programme circuit as measured **weighted**. Suffix '0' (zero) indicates 0.775V as measured on a quasi-peak meter (the 'q' suffix) as specified by BS.468-4; it is therefore **not** an r.m.s. value. Suffix 'p' specifies the type of weighting as 'psophometric' – it uses the Rec. 468 weighting network.

Though it was argued that these two problems may have reduced the value of the test, the early listener reaction was very positive; but given that the SHF link was only a temporary solution and was soon to be replaced by an off-air link, these problems were accepted as an interim measure.

The SHF link was later replaced by a rebroadcast link (RBL) receiver (as shown in Fig. 4). This was fed from a directional antenna that received the Wrotham Band II signal directly, and was located sufficiently far away from the radiating antenna at Crystal Palace so that no feedback problems were created.

## 6. TRANSMITTER DRIVE MODIFICATIONS

### 6.1 Crystal Palace FM drives

The drives used in all the BBC's Band II transmitters are generally of similar design. Typically the output frequency is indirectly controlled by a 6.4 MHz reference oscillator. This is divided down by a fixed modulus counter to establish a 25 kHz reference for a phase locked loop (PLL). The other PLL input is derived from the final Band II output divided down by a programmable counter to give another (nominal) 25 kHz.

The PLL operating frequency establishes the resolution of the available frequency adjustment. However, the frequency required for the filler transmitter is not an integer multiple of 25 kHz and so a modification was necessary.

This was achieved by first setting the programmable divider to achieve the closest frequency possible, given the 25 kHz spacing, (as would normally be the case when installing a new transmitter) and then feeding an external reference to replace the internal 6.4 MHz.

As an example, for the Radio 4 trials:

Wrotham output for BBC Radio 4	= 93.5 MHz
CP filler therefore at 93.5 MHz – 304 kHz	= 93.196 MHz
Nearest channel at a multiple of 25 kHz	= 93.2 MHz

Therefore the reference will be:

$$6.4\text{MHz} \times \frac{93.196}{93.2} = 6.3997253\text{MHz}$$

In order to achieve the necessary tolerance, a synthesiser with 0.1 Hz resolution was used. This gave a theoretical maximum frequency error of ±4.7 Hz at Band II (which would result in a beat tone that should be below the audio bandwidth of a domestic FM receiver and hence inaudible).

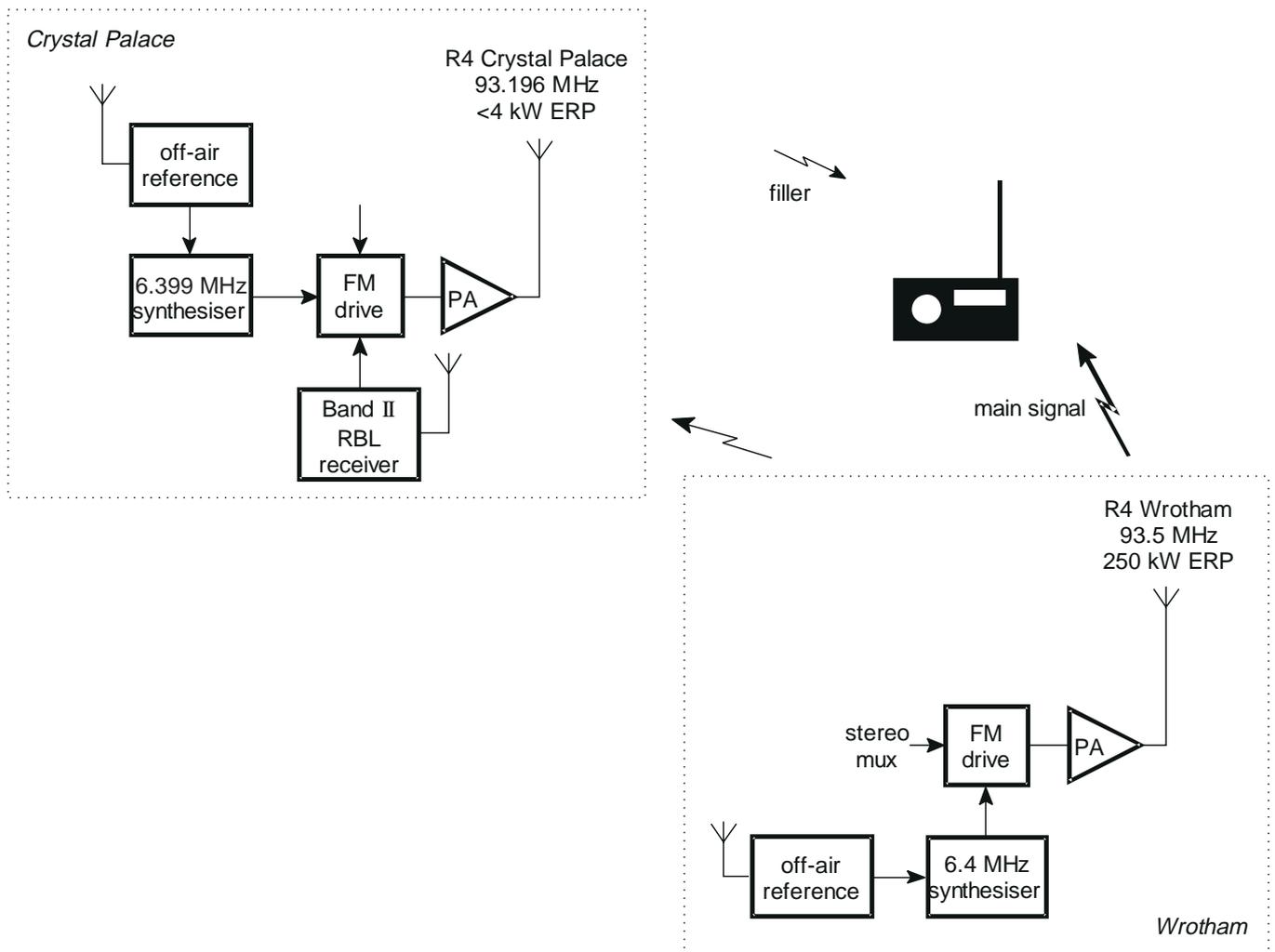


Fig. 4 - Using a RBL arrangement at Crystal Palace to receive the Radio 4 Wrotham signals directly off-air.

## 6.2 Wrotham FM Drives

Not only did the new Crystal Palace drive unit require a modification, but the Wrotham drives also required upgrading to achieve a similar performance. The original 6.4 MHz reference in the drive units employed a temperature-compensated crystal oscillator (TCXO) and had been perfectly adequate for 'normal' use; but in order to achieve the required accuracy of the frequency offset at Crystal Palace, it was necessary to ensure that the Wrotham drive was equally stable. For this reason, two further synthesisers were installed at Wrotham to externally reference the A and B drives there. These needed to be 6.4000000 MHz; again, to an accuracy within 0.1 Hz. Although the Wrotham synthesisers did not need to be capable of high resolution, they did require the absolute accuracy; hence, off-air frequency standards were again used.

## 6.3 Radio Data Service (RDS)

New RDS ROMs were installed at Wrotham so that mobile listeners in cars (one of the main reasons for undertaking the filler project) could automatically

benefit from the new FM filler service.

## 7. FURTHER DEVELOPMENTS

The Radio 4 filler proved very successful, and so the 304 kHz offset technique has since been applied to the other national network FM services from Crystal Palace/Wrotham. (A commercial company was contracted to assist in the completion of this work.)

At first, each drive at Crystal Palace and Wrotham was referenced to a frequency synthesiser, but these were later replaced by a separate high-accuracy oscillator with oven-controlled temperature regulation (for each drive in the A and B chains at the Wrotham site). This has subsequently ensured that an accurate offset has been maintained between Wrotham and Crystal Palace and that the equipment continues to have a degree of fault tolerance.

## 8. SUMMARY

The initial Crystal Palace FM filler experiment involv-

ing the rebroadcast of Radio 4 at a frequency offset of 304 kHz from the main transmitter (at Wrotham) was successful. The benefits of improved reception of National Network FM Radio Services in certain areas of London that had previously encountered poor reception, was appreciated by the listening public. Some of the problems anticipated (for example, compensating delays) did not emerge; other problems, such as transmitter frequency stability, were readily solved.

In March 1995, all four BBC national network FM radio services began rebroadcasting from the Crystal

Palace site at frequencies 304 kHz below their Wrotham counterparts; the operation has been highly successful and the filler now forms part of the operational network.

## **9. REFERENCE**

1. LEWIS, R., 1980. TM4L/5 VHF Transmitter Drive Equipment. Design & Equipment Department Handbook No. 5.153(80).



