TIME AND FREQUENCY BROADCAST WITH DCF77

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Abstract

For over fifty years the Physikalisch-Technische Bundesanstalt (PTB) has disseminated time signals and standard frequency by means of the low-frequency transmitter DCF77. In addition, since the 1970s legal time for Germany has been broadcast using coded time information by way of amplitude modulated second markers. This service, especially, has become very popular and DCF77 has developed to an important part of Germany's state funded infrastructure. In the 1980s binary phase shift keying using a pseudo random noise code sequence was added to enable a high precision and reliable time reception. In 2003, the feasibility of using vacant coding capacity of the DCF77 scheme for public warning messages was tested and since 2006 the same capacity has been used for the transmission of encrypted weather forecast information under responsibility of Meteo Time GmbH. The advantages of DCF77, in particular its wide range of reception with low cost receivers, have led through the years to the use of millions DCF77 radio-controlled clocks which provide exact time throughout central Europe. We briefly report on the current broadcast program including the features listed above and the current characteristics of the transmitted signals, and we give an overview of the technical equipment used for signal generation and monitoring.

INTRODUCTION

Entrusted by the German Act on Units and Time, PTB provides services to disseminate frequency and time within Germany, among which the low frequency transmitter DCF77 is the most prominent one. Other time services are the NTP servers and the telephone time service to synchronize computers via internet or modem connection, respectively (see e.g. **[1]**). DCF77 disseminates standard frequency and legal time as an infrastructure service of the Federal Government of Germany. A standard frequency of 77.5 kHz and coded time information, both generated on the transmitter site from PTB equipment, are currently broadcast via transmitter facilities operated by Media Broadcast GmbH under contract. Time information is broadcast as amplitude modulation (AM) and phase modulation (PM). While AM is widely used for applications with uncertainty requirements not below 1 ms, the PM code allows one to refer clocks to UTC(PTB) at the level of 10 µs.

Because DCF77 has been considered as a service for Germany there are only a few papers in the English language available, which are listed in the following: A detailed description of development and transmission characteristics can be found in Bauch et al. **[2]**. General information concerning DCF77 can be found in Reference **[3]**. The latest complete modernization of the signal generation electronics has been reported in Reference **[4]**. And finally a detailed description of the PM has been reported by P. Hetzel **[5]**. For publications in the German language one may see Piester et al. **[6]** and references therein.

In this paper DCF77 features described previously in **[2]**, **[4]**, and **[5]** have been compiled, which the authors consider to be of interest for a reader of these Proceedings' papers. In this report we describe briefly the signal generation unit, the signal characteristics, i.e. AM, PM and carrier phase. In conclusion a brief description of the service availability and an outlook are made.

INSTALLATIONS

During Summer 2006, completely new electronics for signal generation of DCF77 were installed and put into routine operation in September the same year **[4]**. In Figure 1 and Figure 2, the current operational control unit is shown as of 2010. The transmitted signal is generated, as in the previous setup architecture, with three independent atomic clocks as inputs to three time code generators, from which one is chosen as the master source and one as the backup. In regular operation, the phases of the carriers of all outputs are kept in mutual agreement within a few tenths of a microsecond. However, in the case of a malfunction, a switch matrix discards the corresponding output or switches all outputs off if there is no coincidence between the two remaining generators in order to prevent a false transmission.

Figure 1. Electronic control unit in 2010. As a detail, one can see the three signal generators with their greenish displays and three cesium frequency standards just above the uninterruptable power supply units on the bottom.

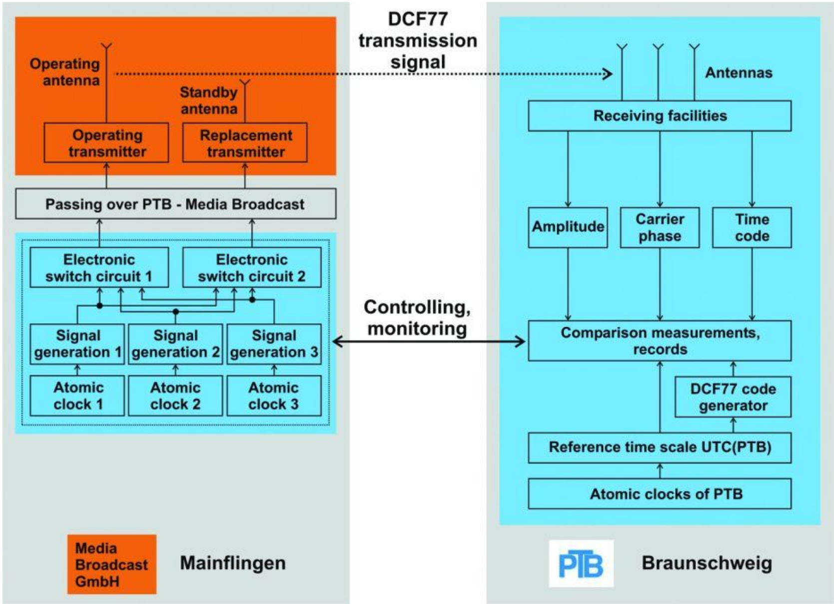

Figure 2. Block diagram of the DCF77 control and transmission facilities in Mainflingen and of the monitoring systems at PTB in Braunschweig.

BROADCASTING PROGRAM

The content of the DCF77 program comprises traceable standard frequency as derived from the carrier phase (CP), AM SI second markers at the beginning of every second and an AM time and date code message. The PM is phase coherent to the beginning of the second and the same time and date information as encoded in the AM is provided. Some characteristics of AM, PM, and CP are addressed in the following sections.

No changes to the signal structure have been introduced recently. As reported before **[7]**, the content of 14 amplitude modulated bits, which are transmitted during the seconds 1 to 14, is no longer provided by PTB (see Figure 4 for the current coding scheme and Reference **[8]** for a detailed description). Under the responsibility of the Federal Office of Civil Protection and Disaster Relief (the German Bundesamt für Bevölkerungsschutz und Katastrophenwarnung, BBK), warnings to the population could in principle be transmitted using these 14 bits. Negotiations are still ongoing and at present no decision has been made as to whether DCF77 will be used for that purpose or not. As a further extension of the information content transmitted by DCF77, weather information has been provided under responsibility of Meteo Time GmbH since November 2006 **[9]**. The same 14 bits are employed in a way that ensures compatibility with the transmission protocols of the warning messages. The Meteo Time service was available on the Swiss low frequency transmitter HBG until the end of 2011 **[10]** when this service was shut down.

AMPLITUDE MODULATION (AM)

The 77.5 kHz carrier of DCF77 is amplitude modulated with second marks. See Figure 3 and Reference **[2]** for details. At the beginning of each second (except for the last second of each minute, which serves as identification for the beginning of the next minute) the amplitude is reduced phase-synchronously with the carrier oscillation for a duration of 0.1 s or 0.2 s to a residual level of 15%. In Figure 3 the falling edge of the envelopes of the carrier oscillation emitted by DCF77 (curve a) at the beginning of a second mark and the associated control signal (curve a′) are shown. The blanking interval of 250 µs in the drive signal causes a faster decay of the antenna circuit, so that the obtained decay rate is practically identical with that which would be obtained for a drive signal completely without residual amplitude. For comparison, the broken line curve b shows which steepness would be obtained if the drive signal was reduced directly to the residual amplitude without a blanking interval (curve b′). The steeper the falling edge, the more exact is the determination of the beginning of the carrier reduction which is defined as the beginning of the second.

The phases of the drive signal (a′ in Figure 3) and of the emitted signals are controlled and, if necessary, corrected now and then with an uncertainty of < 0.01 µs by means of an atomic clock, representing UTC(PTB) – the local realization of Coordinated Universal Time – which is transported from Braunschweig to the transmitter station. For this purpose, the occurrence of the falling edge of the DCF77 time signals are determined at the modulator unit, on a measuring probe between transmitter output and transmitting antenna and in the near field of the transmitting antenna with reference to the signal of the transportable atomic clock. The modulator unit is adjusted in such a way that the emitted reference phase correspond to UTC(PTB).

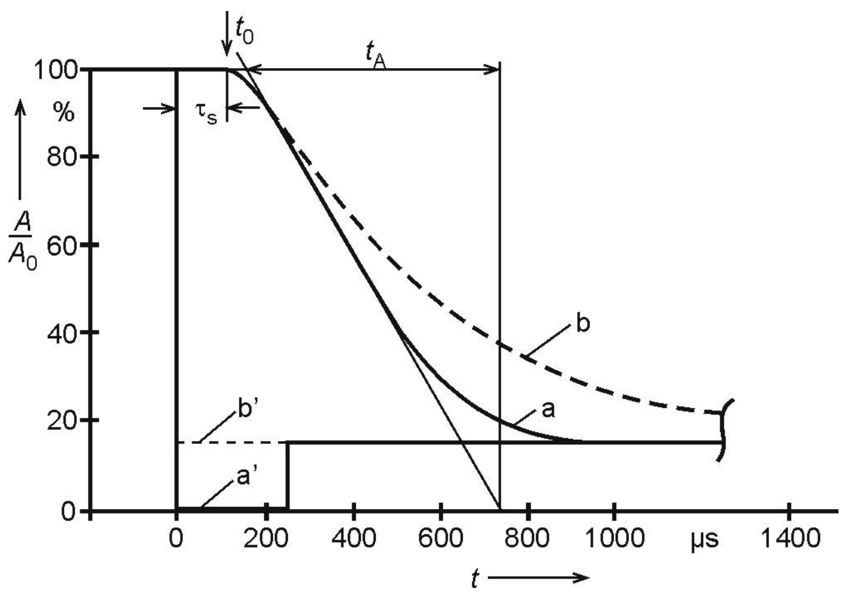

Figure 3. Falling edge of the carrier envelopes emitted by DCF77 at the beginning of a second mark. For details see the text.

The different durations of the second marks serve for the binary encoding of time and date: second marks with a duration of 0.1 s correspond to the binary zero, and marks with a duration of 0.2 s to the binary one. Once during each minute, the numbers of the minute, the hour, the day, the day of the week, the month and the year are transmitted using BCD coding (BCD: Binary Coded Decimal, every digit of a number is encoded separately). From the calendar year, only the unit place and the decimal place are transmitted, i.e., the year 2012 is transmitted only as 12. The emitted code contains the information for the minute that follows. The temporal sequence of the bits and their significance are explained by the encoding scheme shown in Figure 4. For its definition many years ago, PTB acted on the assumption that the code should be compatible with the signal structure used in the years before and that it should be easily decodable with the electronic means available at that time. Before its implementation, the coding technique was discussed with different authorities, scientific institutes and companies. Different coding proposals as to which information should be emitted and which coding type (binary or BCD) should be used were put up for discussion. The wish of the clock industry to transmit – in addition to the time and the date – also the number of the day of the week was, for example, taken into account. In all later amendments and complements of the coded time information or of the signal structure, it was always made sure that the function of DCF77 time service instruments already in use was not affected, in order to provide planning reliability to the users of DCF77 and to the manufacturers of radio-controlled clocks. The code determined in 1973 for the second marks 20 – 58 has not been changed since its introduction. Only the coding scheme has been supplemented by the announcement bits and the time zone bits.

The time zone bits Z1 and Z2 (second mark Nos. 17 and 18) indicate which time system the time information transmitted after second mark 20 refers to. For the emission of Central European Time (CET = UTC+1 h), Z1 has the state "zero" and Z2 has the state "one." When Central European Summer Time (CEST = UTC+2 h) is emitted, this is the other way round.

Announcement bit A1 (No. 16) indicates an imminent change in the time system. Prior to the transition from CET to CEST or back, A1 is emitted for one hour each in the state "one": prior to the transition from CET to CEST (CEST after CET) from 01:00:16 a.m. CET (02:00:16 a.m. CEST) to 01:59:16 a.m. CET (02:59:16 a.m. CEST).

Announcement bit A2 (No. 19) indicates the imminent introduction of a leap second. A2 is also emitted for one hour in state "one" before a leap second is inserted. Before a leap second is inserted on January 1 (July 1), A2 is therefore emitted sixty times from 00:00:19 a.m. CET (01:00:19 a.m. CEST) until 00:59:19 a.m. CET (01:59:19 a.m. CEST) in state "one."

The announcement bits A1 and A2 serve to inform the processors in radio-controlled clocks that use the regularity of time counting for the purpose of fault recognition, about the irregularity in time counting to be expected. Without the evaluation of A1 or A2, the irregularity could be interpreted as an erroneous reception, with the result that the changed time counting would not be used immediately.

The day of the week is coded in accordance with standard ISO 8601 or DIN EN 28601, Monday being day 1 (one) of the week. The three parity check bits P1, P2 and P3 complement the preceding information words (7 bits for the minute, 6 bits for the hour and 22 bits for the date, including the number of the weekday) to an even number of ones. A protection of the code beyond the three parity bits has been dispensed with in view of the regularity of the time information transmitted. The known rules of time counting allow transmission errors to be detected at any time by a comparison of successive time telegrams.

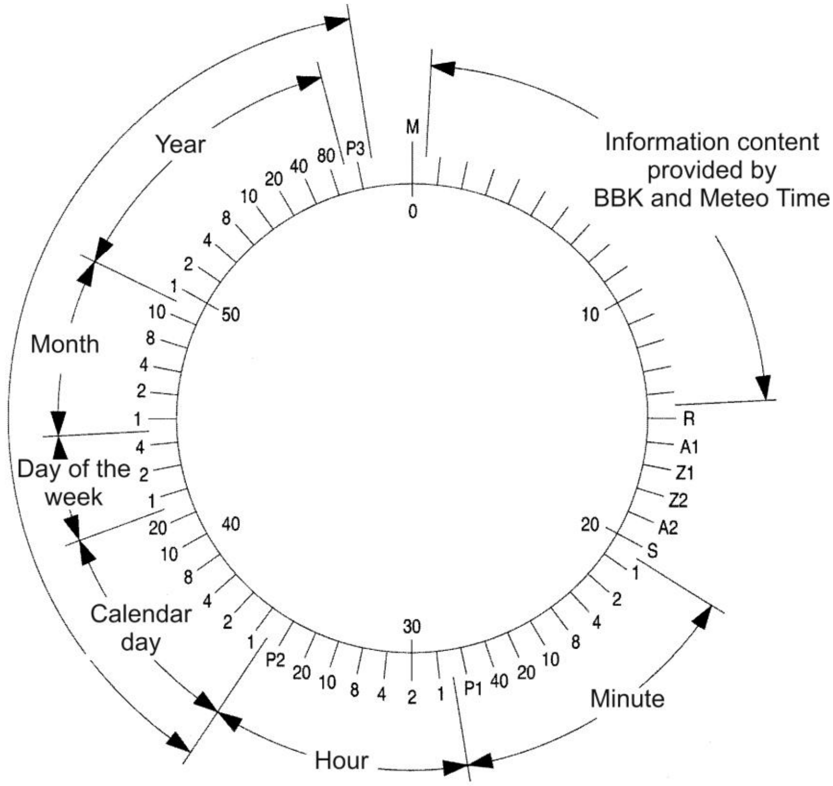

Figure 4. Current coding scheme of the DCF77 time code frame. For a detailed description see References **[5]**, **[2]**, **[8]**, or in the German language **[6]**.

At the suggestion of a federal agency responsible for civil protection, it was investigated in 2003 whether the emission of "time signals" with DCF77 could also be used to transmit warning information, and whether DCF77 could be an element in a warning system of the Federal Government. HKW-Elektronik GmbH was entrusted with the realization and evaluation of a field test in which fictive warning information was emitted with the second marks 1 to 14. The DCF77 control facilities have been extended in such a way that the fictive warning information received in the transmitting station with a satellite terminal could be integrated into the broadcasting program. With approximately 900 radio alarm clocks specifically modified, the alarms received were recorded at different distances from the transmitter and under different receiving conditions. In its final report, HKW demonstrated that the alerting time and the reachability of the different radio receivers were uniformly good in our country. Although it has been demonstrated in this way that the technical possibility of using DCF77 signals for the intended purpose exists, no decision has been taken so far to actually make use of this possibility. At present, the second marks 1 – 14 are, instead, used to transmit weather information provided by the Swiss company MeteoTime GmbH. This does not, however, rule out a future use for population warning. The provision of weather data does not lie in the area of responsibility of PTB, but is contractually regulated by Media Broadcast GmbH. Radio-controlled clocks that have been manufactured without the specific feature of decoding the data contents in bits 1 – 14 will not be affected by the extension of the scope of broadcasting, but they cannot make use of this information either.

At present, the second mark 15 is still being used as a flag to signalize irregularities in the control facilities. The correctness of the emitted time information is, however, also guaranteed in the case of a prolonged bit 15.

PSEUDO-RANDOM PHASE-SHIFT KEYING (PRPSK)

In addition to the amplitude modulation the carrier is phase modulated by a pseudo-random phase-shift keying (PRPSK) **[5] [11]** shifting the phase by $\Delta\varphi = \pm 13°$ around its mean value φ_m. The PRPSK is accomplished according to a pseudo-random binary sequence of maximal length with $2^9 = 512$ states, in a way that $\varphi_m + \Delta\varphi$ and $\varphi_m - \Delta\varphi$ are equally distributed. Therefore the mean value of the carrier phase is not influenced and the stability of the carrier phase is not significantly degraded. Figure 5 shows the course of the amplitude and of the phase of the DCF77 carrier within one second. The carrier phase, the AM second marker and the phase keying are phase synchronous. The duration of one phase chip T_T is 1.55 ms and the full sequence takes 793 ms. For a detailed description of the PRPSK, in particular the generation of the PRPSK sequence, see **[5]** or in the German language **[6]** and **[11]**.

Because of the signal structure of DCF77, the PRPSK is not applied continuously. It is started 0.2 s after the beginning of each second and stops after completion of one cycle. This ensures that the falling edge defined as the beginning of the second remains undisturbed and the noise cycles fall within the range of the 100% amplitude. In Figure 6 the resulting transmitted spectrum is depicted. During a given second, the “normal” pseudo-random noise (PRN) sequence is transmitted in the case of a binary zero of the AM. In the case of a binary one in the AM signal, the PRN sequence is transmitted inverted. That means as with the AM one bit per second is transmitted, and the data content is identical to that in the AM for the seconds 15 to 59 of a minute. Only the minute marker identification is different in the case of the PRPSK modulation: instead of omitting the 59th second marker, 10 inverted PRN sequences are transmitted in the seconds 0 to 9. In seconds 10 to 14 the PRN sequence is not inverted. The carrier, the AM time signals and the noise signals are always phase coherent.

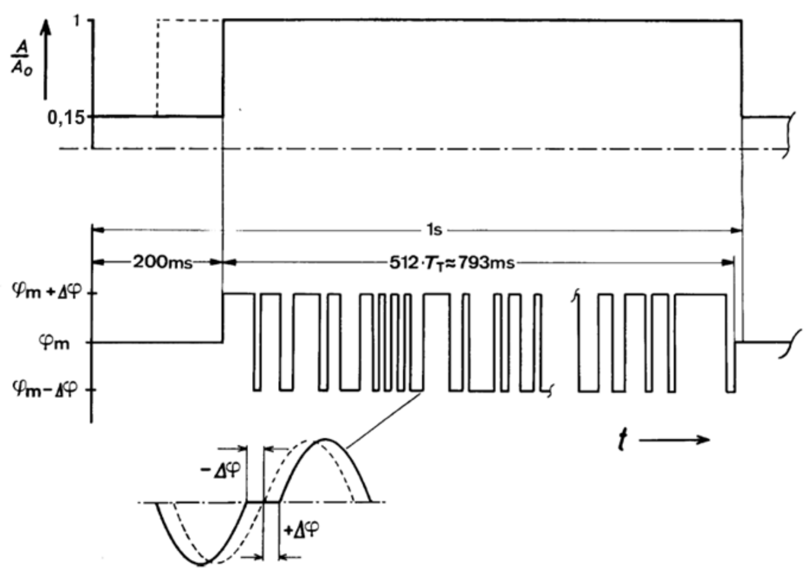

Figure 5. Amplitude and phase of the DCF77 carrier during one second.

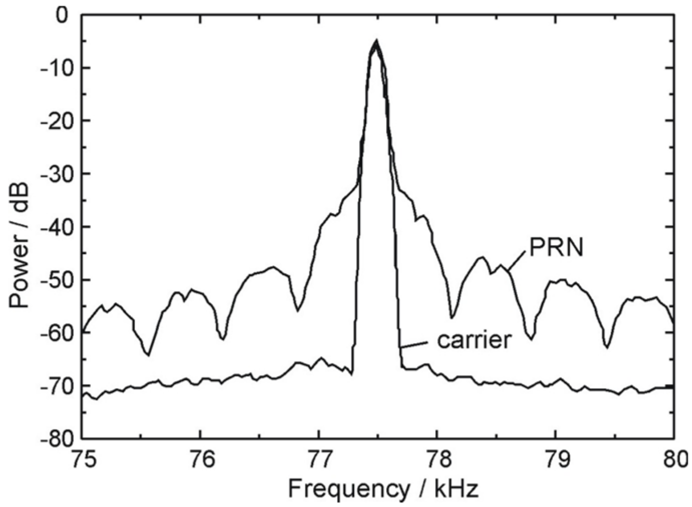

Figure 6. Spectrum of the DCF77 carrier with and without PRPSK modulation measured with 100 Hz resolution bandwidth at the transmitter station.

It is noted that following the example of DCF77 the US plans to introduce a similar concept of PRPSK modulation in their low frequency transmitter WWVB. See **[12]** for details.

CARRIER PHASE

As has already been mentioned, the carrier frequency of DCF77 amounts to 77.5 kHz. It is derived from an atomic clock of PTB, whose output frequency (10 MHz) agrees with an uncertainty $2 \cdot 10^{-13}$ with the nominal value and whose relative daily frequency fluctuations are approximately $5 \cdot 10^{-14}$. When the carrier frequency is used over short measuring times the phase time deviations from the mean value must be taken into account which are due to the pseudo-random phase modulation and by transients caused by the transmitting antenna in the rhythm of the time signals. Over long measuring times, these phase time variations average out and can be disregarded. Compared to that, phase time variations of the emitted carrier and of the phase-coherent modulated time signals at the place of transmission caused by temperature variations and slight detunings of the antenna adaptation are slow. These can amount to up to approximately ± 0.1 µs, related to the output signals of the atomic clock from which they are derived. Averaged over one day, a relative uncertainty of $2 \cdot 10^{-12}$ thus results for the emitted carrier frequency at the place of transmission. By controlling the frequency and the phase time of the DCF77 carriers, the uncertainty for frequency comparisons over very long measuring times can be further reduced. Consequently, frequency comparisons over 100 days are, on average, possible with a relative uncertainty clearly below 10^{-13}. In Figure 7 a long period of hourly data of the DCF77 carrier phase received at PTB in Braunschweig (distance to transmitter: 273 km) and measured against UTC(PTB) are depicted. The corresponding frequency instability is shown in Figure 8.

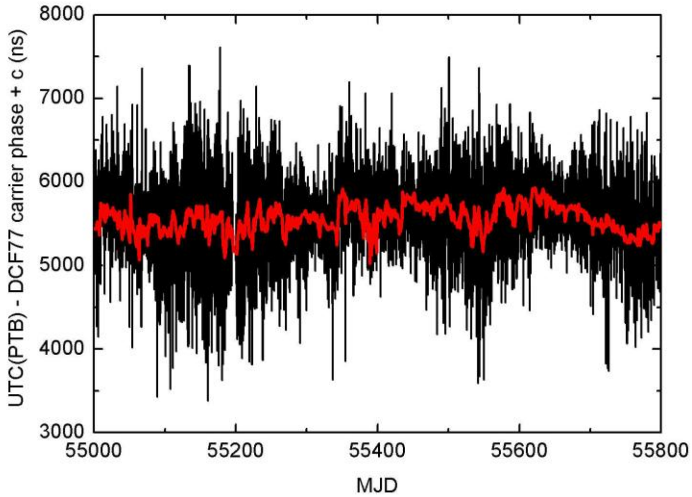

Figure 7. Carrier phase reception of DCF77 in Braunschweig: hourly data (black) and daily ±4-hour-averages around 12:00 UTC (red) over an extended period from MJD 55000 (2009-06-18) to MJD 55800 (2011-08-27).

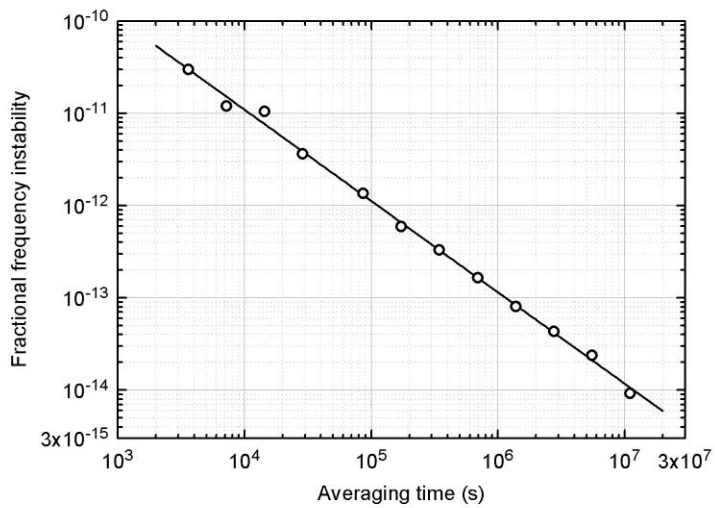

Figure 8. Fractional frequency instability of the DCF77 carrier phase received in Braunschweig. For averaging times from 1 h to 8 h an autumn day has been chosen (2011-10-10) and for averaging times of 1 d and more the daily averages of data shown in Figure 7 have been used.

AVAILABILITY

DCF77 transmits in continuous operation (24 hours). With Media Broadcast GmbH, a temporal availability of the DCF77 transmission of at least 99.7% every year has been contractually agreed upon. Due to the fact that a replacement transmitter and a standby antenna are available, there are no shut-downs for maintenance work at regular intervals. However, short interruptions of up to a few minutes must be expected when switch-over to the backup transmitter and the standby antenna is required in the case of unexpected events or due to maintenance work. Switch-offs with a duration of more than 2 minutes have been observed in the past years with a distribution as shown in Figure 9. The temporal availability over several years is shown in Figure 10. The most frequent cause of interruptions of longer duration was the electric detuning of the antenna resonance circuit by displacements of the antenna in heavy storm ore freezing rain. When the mismatch becomes too large the transmission is interrupted.

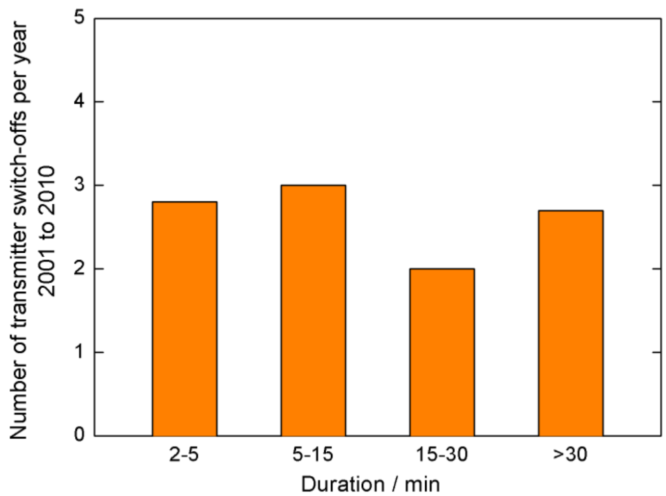

Figure 9. Frequency distribution of the DCF77 transmission interruptions per year from 2001 to 2010.

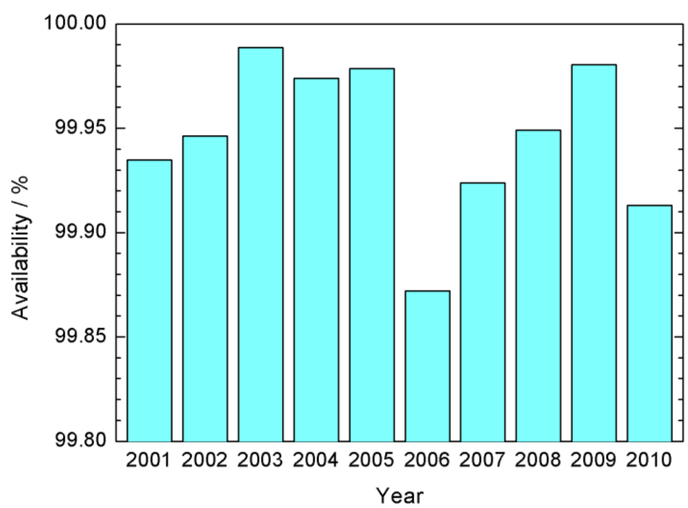

Figure 10. Annual availability, leaving unconsidered switch-offs having a duration of less than 2 minutes.

CONCLUSION AND OUTLOOK

With the longwave transmitter DCF77 controlled by PTB at 77.5 kHz, a reliable time signal and standard frequency transmitter has been available for many years, which can be received in many parts of Europe. Radio-controlled DCF77 clocks can be manufactured at low cost, and millions of them are in use. Today, approximately half of all "large electrical clocks" (table clocks, mounted clocks, wall clocks and alarm clocks) sold in the private sector are radio-controlled clocks. In addition, more than half a million radio-controlled industrial clocks are in use, among them clocks which make use of the pseudo-random phase shift keying of the carrier. Such receivers are implemented in network time servers in computer networks used, e.g. for stock markets which need to make more than 400 transactions per second together with a high resolution of time **[13]**. The carrier frequency of the DCF77 is used to calibrate or to automatically correct standard frequency generators. In traffic, e.g. in railway and air-traffic control, DCF77 plays an important role. Parking meters and traffic lights are synchronized by DCF77. In an ever-increasing number of buildings, heating and ventilation systems are controlled by DCF77, and roller shutters are closed or opened by DCF77. In the telecommunication and energy-supply industries, DCF77 radio-controlled clocks are used to allow time-related tariffs to be correctly billed. Numerous NTP servers feed the time received from DCF77 into computer networks, and all radio and television stations receive the exact time from DCF77. DCF77 thus continues being the most important medium for the dissemination of legal time by PTB.

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