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SERIES J: CABLE NETWORKS AND TRANSMISSION OF TELEVISION, SOUND PROGRAMME AND OTHER MULTIMEDIA SIGNALS

Transport of MPEG-2 signals on packetised networks

Measurement of MPEG-2 transport streams in networks

ITU-T Recommendation J.133

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ITU-T Recommendation J.133

Measurement of MPEG-2 transport streams in networks

Summary

MPEG-2 Transport Streams that are transmitted over any real networks are exposed to certain effects caused by the network components which are not ideally transparent. One of the predominant effects is the acquisition of jitter in relation to the PCR values and their position in the TS. This Recommendation specifies measurements that enable determination of this jitter.

Source

ITU-T Recommendation J.133 was prepared by ITU-T Study Group 9 (2001-2004) and approved under the WTSA Resolution 1 procedure on 29 July 2002.

FOREWORD

The International Telecommunication Union (ITU) is the United Nations specialized agency in the field of telecommunications. The ITU Telecommunication Standardization Sector (ITU-T) is a permanent organ of ITU. ITU-T is responsible for studying technical, operating and tariff questions and issuing Recommendations on them with a view to standardizing telecommunications on a worldwide basis.

The World Telecommunication Standardization Assembly (WTSA), which meets every four years, establishes the topics for study by the ITU-T study groups which, in turn, produce Recommendations on these topics.

The approval of ITU-T Recommendations is covered by the procedure laid down in WTSA Resolution 1.

In some areas of information technology which fall within ITU-T's purview, the necessary standards are prepared on a collaborative basis with ISO and IEC.

NOTE

In this Recommendation, the expression "Administration" is used for conciseness to indicate both a telecommunication administration and a recognized operating agency.

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As of the date of approval of this Recommendation, ITU had not received notice of intellectual property, protected by patents, which may be required to implement this Recommendation. However, implementors are cautioned that this may not represent the latest information and are therefore strongly urged to consult the TSB patent database.

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ITU-T Recommendation J.133

Measurement of MPEG-2 transport streams in networks

1 Scope

A MPEG-2 Transport Stream that is transmitted over any real network is exposed to certain effects caused by the network components which are not ideally transparent. One of the predominant effects is the acquisition of jitter in relation to the PCR values and their position in the TS. The four measurement parameters defined in the following describe the various jitter components which can be differentiated by demarcation frequencies.

2 References

The following ITU-T Recommendations and other references contain provisions which, through reference in this text, constitute provisions of this Recommendation. At the time of publication, the editions indicated were valid. All Recommendations and other references are subject to revision; users of this Recommendation are therefore encouraged to investigate the possibility of applying the most recent edition of the Recommendations and other references listed below. A list of the currently valid ITU-T Recommendations is regularly published. The reference to a document within this Recommendation does not give it, as a stand-alone document, the status of a Recommendation.

2.1 Normative references

[1] ITU-T Recommendation H.222.0 (2000) | ISO/IEC 13818-1: 2000, *Information technology – Generic coding of moving pictures and associated audio information: Systems*.

[2] ETSI TR 101 290 V1.2.1 (2001), *Digital Video Broadcasting (DVB); Measurement guidelines for DVB systems*.

2.2 Informative references

[3] ISO/IEC 13818-9:1996, *Information technology – Generic coding of moving pictures and associated audio information – Part 9: Extension for real time interface for systems decoders*.

3 Abbreviations and acronyms

This Recommendation uses the following abbreviation:

PCR Program Clock Reference

4 System clock and PCR measurements

4.1 Reference model for system clock and PCR measurements

This clause presents a reference model (see Figure 1) for any source of a Transport Stream (TS) concerning the generation of PCR values and delivery delays. It models all the timing effects visible at the TS interface point. It is not intended to represent all the mechanisms by which these timing effects could arise in real systems.

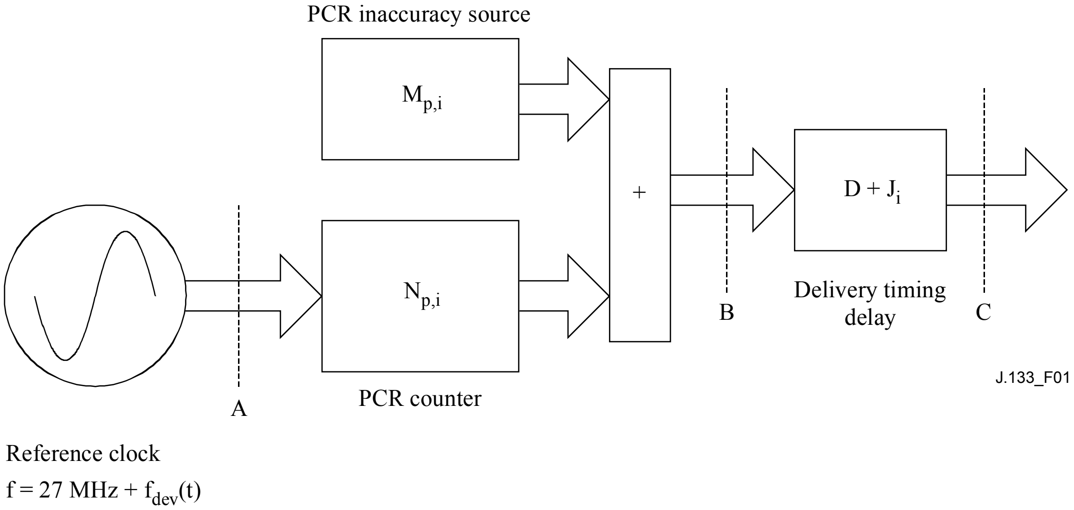


Figure 1/J.133 – Reference model

Reference points are indicated by dashed lines. This is a model of an encoder/multiplexer (up to reference point B) and a physical delivery mechanism or communications network (between reference points B and C). The components of the model to the left of reference point B are specific to a single PCR packet identifier (PID). The components of the model to the right of reference point B relate to the whole Transport Stream. Measuring equipment can usually only access the TS at reference point C.

The model consists of a system clock frequency oscillator with a nominal frequency of 27 MHz, but whose actual frequency deviates from this by a function f_{dev} (p,t). This function depends on the time (t) and is specific to a single PCR PID (p). The "Frequency Offset PCR_FO" measures the value of f_{dev} (p,t). The "Drift Rate PCR_DR" is the rate of change with time of f_{dev} (p,t).

The system clock frequency oscillator drives a PCR counter which generates an idealized PCR count, $N_{p,i.}$ p refers to the specific PCR PID p, and i refers to the bit position in the Transport Stream. To this is added a value from a PCR inaccuracy source, $M_{p,i}$, to create the PCR value seen in the stream, $P_{p,i}$.

The simple relationship between these values is:

$$P_{p,i} = N_{p,i} + M_{p,i} \tag{1}$$

$M_{p,i}$ represents the "Accuracy PCR_AC".

The physical delivery mechanism or communications network beyond point B introduces a variable delay between the departure time T_i and the arrival time U_i of bits:

$$U_i - T_i = D + J_i \tag{2}$$

In the case of a PCR, U_i is the time of arrival of the last bit of the last byte containing the PCR base (see 2.4.3.5 of ITU-T Rec. H.222.0 | ISO/IEC13818-1 [1]). D is a constant representing the mean delay through the communications network. J_i represents the jitter in the network delay and its mean value over all time is defined to be zero. $J_i + M_{p,i}$ is measured as the "Overall Jitter PCR_OJ".

In the common case where the Transport Stream is constant bitrate, at reference point B, the Transport Stream is being transmitted at a constant bitrate R_{nom}. It is important to note that in this reference model this bitrate is accurate and constant; there is no error contribution from varying bitrate. This gives us an additional equation for the departure time of packets:

$$T_i = T_0 + \frac{i}{R_{nom}} \tag{3}$$

T_0 is a constant representing the time of departure of the zeroth bit. Combining equations (2) and (3) we have for the arrival time:

$$U_i = T_0 + \frac{i}{R_{nom}} + D + J_i \tag{4}$$

4.2 Measurement descriptions

The following measurements require a demarcation frequency for delimiting the range of drift rate and jitter frequencies of the timing variations of PCRs and/or TSs.

The demarcation frequency used should be chosen from the Table 1 and indicated with the measurement results.

A description of the derivation of the demarcation frequencies is included in Appendix I.

Table 1/J.133

Profile	Demarcation frequency	Comments
MGF1	10 mHz	This profile is provided to give the total coverage of frequency components included in the timing impairments of PCR-related measurements. This profile provides the most accurate results in accordance with the limits specified in 2.4.2.1 of ITU-T Rec. H.222.0 | ISO/IEC 13818-1. If jitter or drift-rate measurements are found out of specification when using other profiles, it is suggested to use this one for better accuracy.
MGF2	100 mHz	This profile is accounting for intermediate benefits between the profiles MGF1 and MGF3, by giving reasonable measurement response as well as reasonable account for low frequency components of the timing impairments.
MGF3	1 Hz	This profile provides faster measurement response by taking in account only the highest frequency components of the timing impairments. This profile is expected to be sufficient in many applications.
MGF4	Manufacturer-defined	This profile will provide any benefit that the manufacturer may consider as useful when it is designed and implemented in a measurement instrument. The demarcation frequency has to be supplied with the measurement result. Optionally any other data that the manufacturer may consider to be relevant may be supplied. For testing against ISO/IEC 13818-9 (±25 ms jitter limit) a demarcation frequency of 2 mHz is required. A filter for such demarcation may be implemented under this MGF4 profile.

4.3 Program Clock Reference – Frequency Offset (PCR_FO)

Definition

PCR_FO is defined as the difference between the program clock frequency and the nominal clock Frequency (measured against a reference which is neither PCR- nor TS-derived).

The units for the parameter PCR_FO should be in Hz according to:

$$\text{Measured Frequency} - \text{Nominal Frequency}$$

or in ppm expressed as:

$$\frac{\text{Measured Frequency (in Hz)} - \text{Nominal Frequency (in Hz)}}{\text{Nominal Frequency (in MHz)}}$$

Purpose

The original frequency of the clock used in the digital video format before compression (program clock) is transmitted to the final receiver in form of numerical values in the PCR fields. The tolerance as specified by ITU-T Rec. H.222.0 | ISO/IEC 13818-1 [1] is ±810 Hz or ±30 ppm.

Interface

For example, at interface G in Figure I.8.

Method

Refer to Appendix I for a description of a measurement method.

4.4 Program Clock Reference – Drift Rate (PCR_DR)

Definition

PCR_DR is defined as the first derivative of the frequency and is measured on the low frequency components of the difference between the program clock frequency and the nominal clock frequency (measured against a reference which is not PCR derived, neither TS derived).

The format of the parameter PCR_DR should be in mHz/s (@ 27 MHz) or ppm/hour.

Purpose

The measurement is designed to verify that the frequency drift, if any, of the program clock frequency is below the limits set by ITU-T Rec. H.222.0 | ISO/IEC 13818-1 [1]. This limit is effective only for the low frequency components of the variations as indicated by the demarcation frequency described in Appendix I.

The tolerance as specified by ITU-T Rec. H.222.0 | ISO/IEC 13818-1 [1] is ±75 mHz/s @ 27 MHz or ±10 ppm/hour.

Interface

For example, at interface H in Figure I.8.

Method

Refer to Appendix I for a description of a measurement method.

4.5 Program Clock Reference – Overall Jitter (PCR_OJ)

Definition

PCR_OJ is defined as the instantaneous measurement of the high frequency components of the difference between when a PCR should have arrived at a measurement point (based upon previous PCR values, its own value and a reference which is neither PCR- nor TS-derived) and when it did arrive.

The format of the parameter PCR_OJ should be in nanoseconds.

Purpose

The PCR_OJ measurement is designed to account for all cumulative errors affecting the PCR values during program stream generation, multiplexing, transmission, etc. All these effects appear as jitter at the receiver but they are a combination of PCR inaccuracies and jitter in the transmission. This value can be compared against the maximum error specification by ITU-T Rec. H.222.0 | ISO/IEC 13818-1 [1] for PCR Accuracy of ±500 ns only if the jitter in the transmission is assumed to be zero.

Interface

For example, at interface J in Figure I.8.

Method

Refer to Appendix I for a description of a measurement method.

4.6 Program Clock Reference – Accuracy (PCR_AC)

Definition

The accuracy of the PCR values PCR_AC is defined as the difference between the actual PCR value and the value it should have in the TS represented by the byte index for its actual position. This can be calculated for constant bitrate TS; the measurement may NOT produce meaningful results in variable bitrate TS.

The units for the parameter PCR_AC should be in nanoseconds.

Purpose

This measurement is designed to indicate the total error included in the PCR value with respect to its position in the TS.

The tolerance as specified by ITU-T Rec. H.222.0 | ISO/IEC 13818-1 [1] is ±500 ns.

This measurement is considered to be valid for both real time and off-line measurements.

Interface

For example, at interface E in Figure I.6.

Method

Refer to Appendix I for a description of a measurement method.

NOTE – PCR Accuracy is defined by ITU-T Rec. H.222.0 | ISO/IEC 13818-1 [1]: "A tolerance is specified for the PCR values. The PCR tolerance is defined as the maximum inaccuracy allowed received PCRs. This inaccuracy may be due to imprecision in the PCR values or to PCR modification during re-multiplexing. It does not include errors in packet arrival time due to network jitter or other causes".

Appendix I

PCR-related measurements

This appendix provides background information on the concept of PCR-related measurements and the reasoning behind the definition of the parameters. The aim is to gather the information which enables different implementations of PCR-related measurements to show consistent and comparable results for the same Transport Stream.

I.1 Introduction

Recovering the 27 MHz clock at the decoder side of a digital TV transmission system is necessary to re-create the video signal. To allow recovery of the clock, the PCR values are sent within the Transport Stream. It is required that the PCR values are correct at the point of origin and not distorted in the transmission chain to the point of creating problems in the process of decoding the compressed signals.

Measuring the accuracy of the PCR values and the jitter accumulated on them when transmitted in a Transport Stream is necessary to assure the confidence of decodability of such stream.

As jitter and drift rate are important parameters for the overall process, a clear definition is needed for what is understood as PCR jitter and a guidance to its measurement method.

I.2 Limits

From the specifications set in ITU-T Rec. H.222.0 | ISO/IEC 13818-1 [1], it is possible to define a limit mask for the frequency deviation from the nominal 27 MHz.

Frequency offset: the difference between the actual value and the nominal frequency of the clock (27 MHz). The limit is set to ±810 Hz. Converting this value into relative or normalized units results in $810/27 \times 10^6 = 30 \times 10^{-6}$. This means that the frequency of the clock at any moment should be the nominal ±0.003 %, or the nominal ±30 ppm. Rating the limit of the frequency offset as relative has the advantage of obtaining a limit valid for any value of frequency for a reference clock used to synthesize the nominal clock of 27 MHz. For example, the frequency error in Hz of a 270 MHz serial clock derived from the 27 MHz system clock can be divided, or normalized, by 270 MHz to determine if the frequency offset is within 30 ppm.

Frequency rate of change, or **frequency drift rate**: the "speed" at which the frequency of a clock varies with time. In other words it is the first derivative of the frequency with respect to time or the second derivative of phase with respect to time.

The limit is set to 75 millihertz (mHz) per second for the 27 MHz clock. It can be converted into relative limit by dividing by 27 MHz which produces a result of $(75 \times 10^{-3}) / (27 \times 10^6) = 2.777... \times 10^{-9}/\text{s}$.

It means that the maximum rate of change allowed for the clock frequency is ±0.000 000 277 7...%/s of the nominal value, or ±0.00277...ppm/s of the nominal, or ±2.77...ppb/s of the nominal value of the system clock frequency. (Note that a billion is taken here as 10^9, in many countries a billion is represented as 10^{12}).

This result can also be presented as 0.001 %/hour, or as being 10 ppm/h.

$$27\,000\,000 - 810 \le \text{system\_clock\_frequency} \le 27\,000\,000 + 810 \text{ @ } 27 \text{ MHz}$$

$$\text{Frequency tolerance} = \pm 30 \times 10^{-6} \text{ @ } 1 \text{ Hz} \qquad \text{(I-1)}$$

$$\text{Rate of change of system\_clock\_frequency} = 75 \times 10^{-3} \text{ Hz/s @ } 27 \text{ MHz}$$

$$\text{Drift tolerance} = \pm 2.7778 \times 10^{-9}/\text{s @ } 1 \text{ Hz} \qquad \text{(I-2)}$$

$$\text{Phase tolerance} = \pm 500 \times 10^{-9}\ \text{s} \qquad \text{(I-3)}$$

This represents the maximum error of a PCR value with respect to its time position in the Transport Stream. The maximum limit for the phase represented in a PCR value is ±500 ns; this value is an absolute limit at the generation of PCRs and does not include network-induced jitter.

ISO/IEC 13818-9 [3] (Extension for real time interface for systems decoders) specifies in clause 2.5 (Real-Time Interface for Low Jitter Applications) a limit for t-jitter equal to 50 μs.

$$\text{Low jitter applications tolerance} = 25 \times 10^{-6}\ \text{s} \qquad \text{(I-3b)}$$

NOTE – The limits for frequency offset and drift rate are imposed for the system clock as it is represented by the values of the corresponding PCR fields. They include the effects of the system clock and any possible errors in the PCR calculation. The limit of 500 ns is not imposed to the system clock, but to the accuracy representing the PCR values with respect to their position in the Transport Stream. However, the PCR errors are fully equivalent to phase and jitter errors when the PCRs are used at the decoding point to reconstruct the system clock.

I.3 Equations

The waveform of the phase modulation may have any shape that can be analyzed as a composition of sinusoidal waveforms of various amplitudes and phases. Also the clock may be a pulsed signal. In this case the formulas below apply to the fundamental component of such periodic signal.

For example, the equation for a sinusoidal clock with sinusoidal phase modulation can be written as:

$$F_{clk}(t) = A \times \sin[\omega_c t + \phi(t)] = A \times \sin[\omega_c t + \phi_p \times \sin(\omega_m t)]$$

where:

ω_c nominal angular frequency of the program clock, $(\omega_c = 2\pi \times 27\ \text{MHz})$;

$\phi(t)$ phase modulation function;

ϕ_p peak phase deviation in radians;

ω_m phase modulating angular frequency in units of radians/s.

The **instantaneous phase** of the clock has two terms as:

$$\phi i(t) = \omega_c t + \phi(t) = \omega_c t + \phi_p \times \sin(\omega_m t) \qquad \text{(I-4)}$$

The instantaneous angular frequency of the clock is found as the first derivative of the instantaneous phase as:

$$\omega_i(t) = d\phi_i(t)/d\,t = \omega_c + \phi_p \times \omega_m \times \cos(\omega_m t) \qquad \text{(I-5)}$$

where:

ω_i instantaneous angular frequency of the clock, $\omega_i = \phi_i'$, in units of radians/s.

The **frequency rate of change**, or **drift rate**, is given by the first derivative of the angular frequency, or the second derivative of the phase as:

$$r_i(t) = d\omega_i(t)/d\,t = -\phi_p \times \omega_m{}^2 \times \sin(\omega_m t) \qquad \text{(I-6)}$$

where:

r_i instantaneous rate of change of the clock, $r_i = \phi_i''$, in units of radians/s^2.

I.4 Mask

A limit mask can be derived as a group of functions representing the limit specifications.

From the instantaneous phase equation (I-4) it can be seen that the maximum peak value of phase modulation is ϕ_p which can be compared to the limit set by ITU-T Rec. H.222.0 | ISO/IEC 13818-1 [1].

The ***phase equation*** may be found as:

$$\phi_p = \omega_c \times T_{max} = 2\pi \times 27 \text{ MHz} \times 500 \times 10^{-9} \text{seconds} = 84.823 \text{ radians} \tag{I-7}$$

where:

T_{max} maximum time error of clock edge = 500×10^{-9} s

From the instantaneous angular frequency equation (I-5) it can be seen that the maximum peak value of angular frequency offset is given by $\phi_p \times \omega_m$, which can be compared to the limit set by ITU-T Rec. H.222.0 | ISO/IEC 13818-1 [1] of 810 Hz.

The maximum angular frequency deviation from the nominal is:

$$\phi_p \times \omega_m = 2\pi \times 810 \text{ radian/s}$$

By dividing by ω_m, the ***frequency equation*** for peak phase error as a function of modulation frequency may be found as:

$$\phi_p = \frac{2\pi \times 810}{\omega_m} \tag{I-8}$$

From the instantaneous drift rate equation (I-6) it can be seen that the maximum peak value of angular frequency drift rate is $\phi_p \times \omega_m{}^2$, which can be compared to the limit set by ITU-T Rec. H.222.0 | ISO/IEC 13818-1 [1] of 75 mHz/s.

$$\phi_p \times \omega_m{}^2 = 2\pi \times 0.075 \text{ radian/s}^2$$

By dividing by $\omega_m{}^2$, the ***drift rate equation*** for peak phase error as a function of modulation frequency may be found as:

$$\phi_p = 2\pi \times 0.075 / \omega_m{}^2 \tag{I-9}$$

All three equations may be normalized by dividing by 2π × 27 MHz.

The ***phase equation*** becomes:

$$T_{max} = \frac{\phi_p}{2\pi \times 27 \times 10^6} = \frac{84.823}{2\pi \times 27 \times 10^6} = 500 \times 10^{-9} \text{(seconds)} \tag{I-7a}$$

The ***frequency equation*** becomes:

$$Tf(\omega_m) = \frac{\phi_p}{2\pi \times 27 \times 10^6} = \frac{2\pi \times 810}{2\pi \times 27 \times 10^6 \times \omega_m} = \left(\frac{30 \times 10^{-6}}{\omega_m}\right) s \tag{I-8a}$$

The ***drift rate equation*** becomes:

$$Tr(\omega_m) = \frac{\phi_p}{2\pi \times 27 \times 10^6} = \frac{2\pi \times 0.075}{2\pi \times 27 \times 10^6 \times \omega_m{}^2} = \left(\frac{2.7778 \times 10^{-9}}{\omega_m{}^2}\right) s \tag{I-9a}$$

The three equations (I-7a, I-8a and I-9a) can be seen in the graph of Figure I.1.

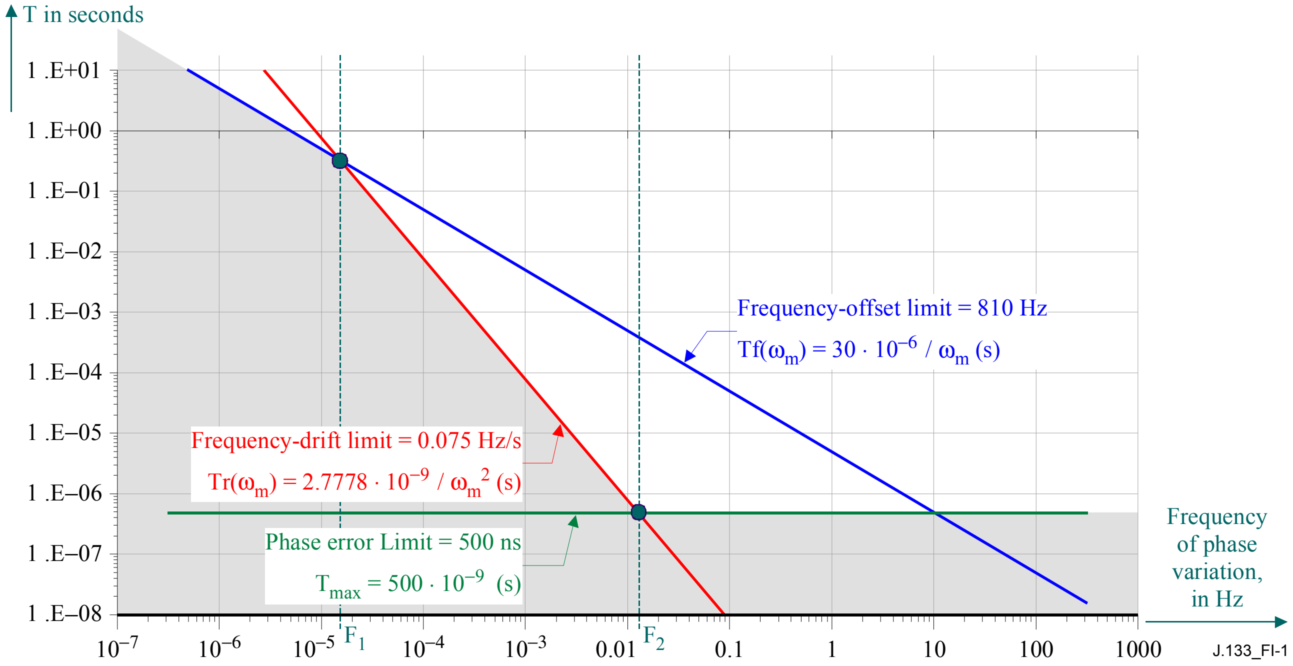


Figure I.1/J.133 – PCR jitter components

I.5 Break frequencies

Values for two break frequencies of Figure I.1.

F1 can be found by re-arranging the equations for frequency and drift rate (I-8 and I-9 respectively) and solving for the value of ω_m that provides the same peak phase error:

$$\phi_p = 2\pi \times 810 / \omega_m \text{ and } \phi_p = 2\pi \times 0.075 / \omega_m{}^2 \text{ radians}$$

$$\omega_m = (2\pi \times 0.075)/(2\pi \times 810) = 9.2592 \times 10^{-5} \text{ radian/s}$$

$$F_1 = \omega_m / 2\pi = 14.736 \times 10^{-6}\,\text{Hz}$$

The break frequency F_1 is extremely low to have any practical use. When the frequency offset is to be measured, there is no need to wait about 5 days to have an averaged result appropriated to the period of such a signal. It is not considered here due to its very long-term significance. It can be seen that the drift limit is enough for practical purposes of jitter analysis.

F_2 can be found by re-arranging and solving the equations of phase and drift rate (I-7 and I-9 respectively) for the value of ω_m that has the same peak phase error:

$$\phi_p = 84.823 \text{ radians and } \phi_p = 2\pi \times 0.075 / \omega_m{}^2 \text{ radians}$$

$$\omega_m = \sqrt{0.4712/84.823} = 0.074535 \text{ radian/s}$$

$$F_2 = 0.074535/2\pi = 0.01186 \text{ Hz}$$

NOTE 1 – The same values may be obtained by using the normalized equations (I-7a), (I-8a) and (I-9a).

This break frequency (F_2 ~ 10 mHz) is recommended as the demarcation frequency for separating the measurements of jitter and drift. It has been defined as filter MGF1 in Table 1.

This value defines the corner frequency to be used in the filters for processing the PCR data. A mask can be drawn from the two equations used to obtain this value (phase equation I-7a and drift equation I-9a).

The mask so defined is represented in Figure I.2.

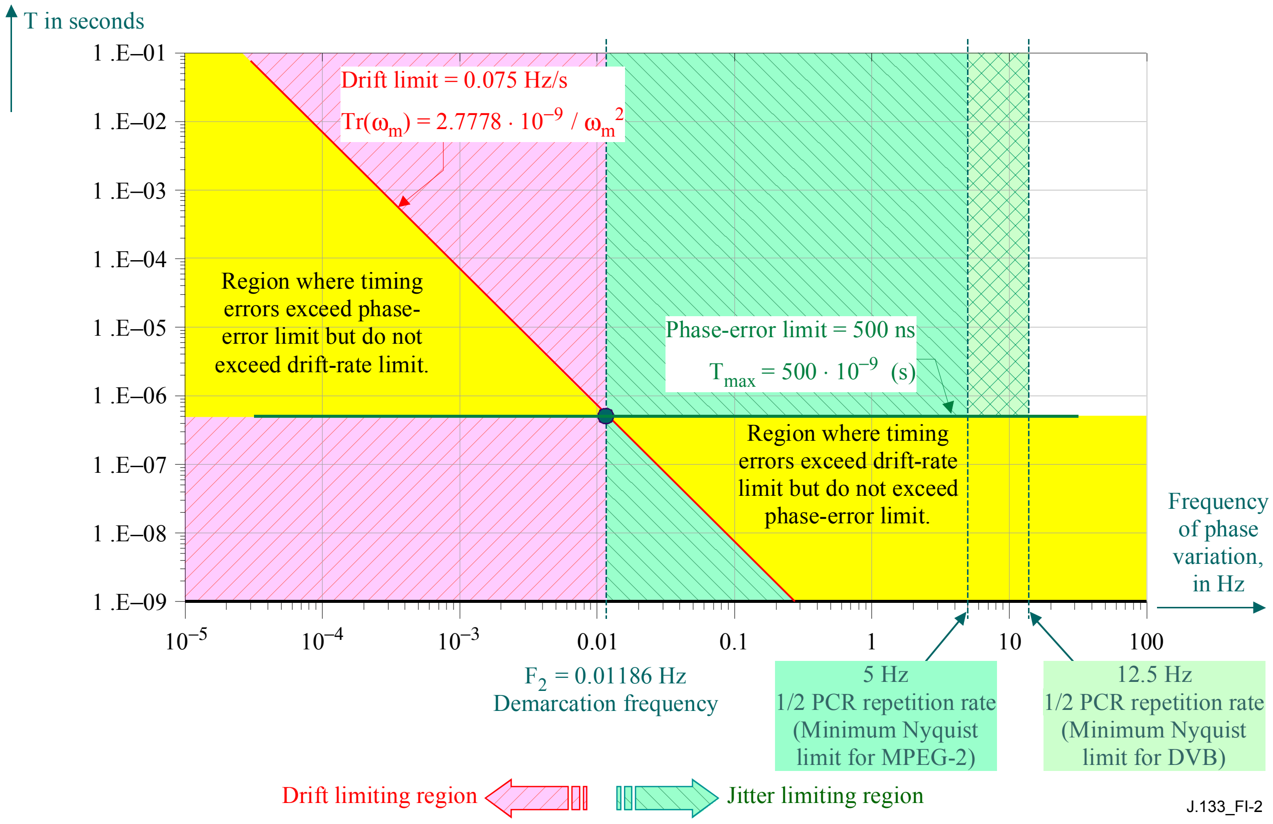


Figure I.2/J.133 – Mask for PCR jitter components

It can be seen that the maximum drift of 75 mHz/s may only be reasonably applied to jitter frequencies lower than the demarcation frequency. Above such frequency it is possible in practice to find drifts much faster than the limit, when real PCR errors are considered.

Above the demarcation frequency, the limit that applies is the absolute 500 ns for any PCR value.

NOTE 2 – For the Low Jitter Applications (ISO/IEC 13818-9 [3]), the ±25 µs limit yields a demarcation frequency of 1.67 mHz, to be used in place of the 10 mHz. This suggests the use of a filter with about 2 mHz break frequency when checking against this limit. This filter has been lumped under MGF4 due to the long time constant involved, which makes it to provide a very slow response for a practical implementation.

I.6 Further implicit limitations

From Figure I.2 it can be seen that a practical limit is also imposed to the ability to measure jitter frequencies above a certain frequency.

For PCR values inserted at the minimum rate of 100 ms as per ITU-T Rec. H.222.0 | ISO/IEC 13818-1 [1], the samples arrive to the measurement instrument at a 10 Hz rate. The Nyquist value (half the sampling rate) is equal to 5 Hz.

For PCR values inserted at the minimum rate of 40 ms as per TR 101 154 the samples arrive to the measurement instrument at a 25 Hz rate. The Nyquist value is equal to 12.5 Hz.

If higher PCR insertion rates are used in any of the above environments, the corresponding Nyquist frequency increases proportionally. This implies that any statistics made by the measurement instrument based in jitter spectral analysis has to measure the actual PCR rate.

Depending on the type of analysis, it is necessary to take in account that the PCR samples do not necessarily arrive at regular intervals. For any practical implementation, the designer may decide what is the preferred way for implementing the filters: digital signal processing (DSP) techniques (infinite impulse response (IIR) or finite impulse response (FIR) filters), with interpolation (linear, sinx/x, etc.) or without interpolation, analogue circuitry or hybrid technology by mixing analogue and numerical analysis, etc.

It is interesting to note, however, that in most practical cases the rate of samples will occur at very high frequencies (1000 times higher) compared to the frequency break points of the proposed filters (MGF1 at 10 mHz). The minimum rate for PCRs is 10 Hz for general MPEG Transport Streams (25 Hz in DVB systems) and at this over-sampled PCR values the transient response shape of filters with bandwidths near 10 mHz are not significantly affected by the non-uniform rate.

I.7 Measurement procedures

It is possible to do jitter measurements fitting the data with a second-order curve (quadratic regression) limited by drift-rate specification (see Figure I.3). **However, this is not necessary if one takes the view of creating separate measurements of jitter and frequency-offset/drift-rate based on the more familiar method of sinusoidal spectral content of the timing variations.**

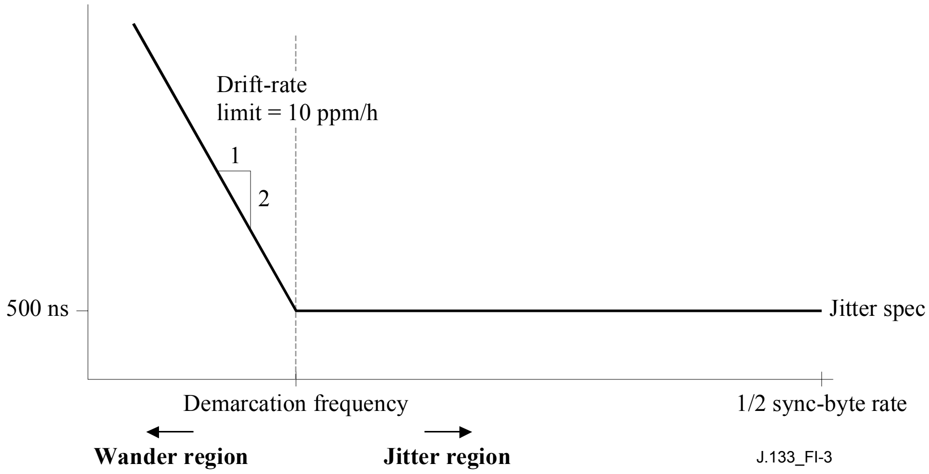


Figure I.3/J.133 – Total spectral mask of timing variations

For jitter spectral components below the demarcation frequency, the peak sinusoidal components of the PCR timing-error can increase proportional to the square of the period of the spectral component without exceeding the drift-rate limit of 10 ppm/h (also, equivalently, 2.8 ppb/s and 75 mHz/s @ 27 MHz). Since the decoder phase-locked loop (PLL) and all subsequent video timing equipment track this error, these components can far exceed the peak limit of 500 ns.

By inverting the specification mask, a spectrally weighted measurement or measurement filter becomes apparent as follows in Figure I.4.

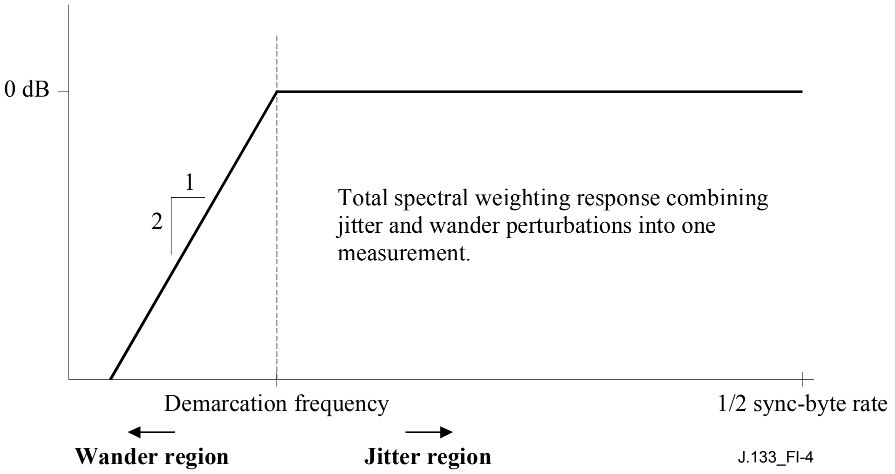


Figure I.4/J.133 – Filter by inverting the spectral mask of timing variations

This can be decomposed into two separate measurements such that the sum of the jitter and drift-rate measured outputs is essentially the same as the original (see Figure I.5).

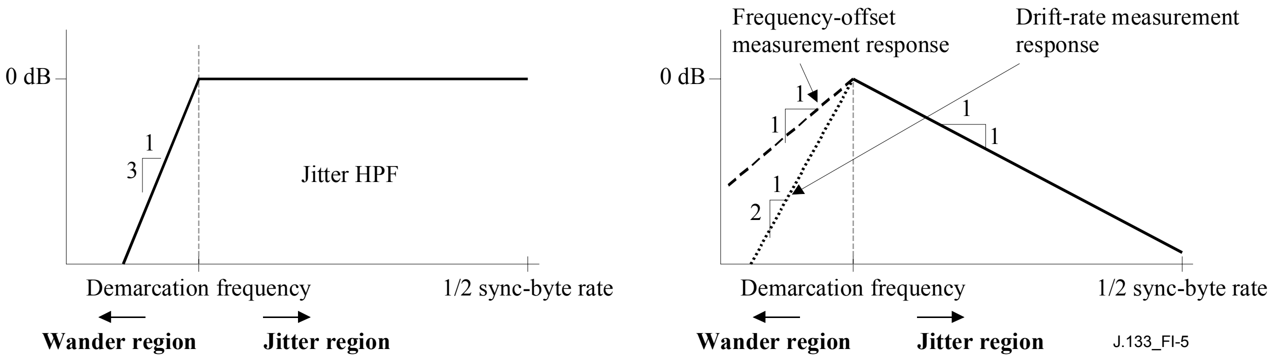


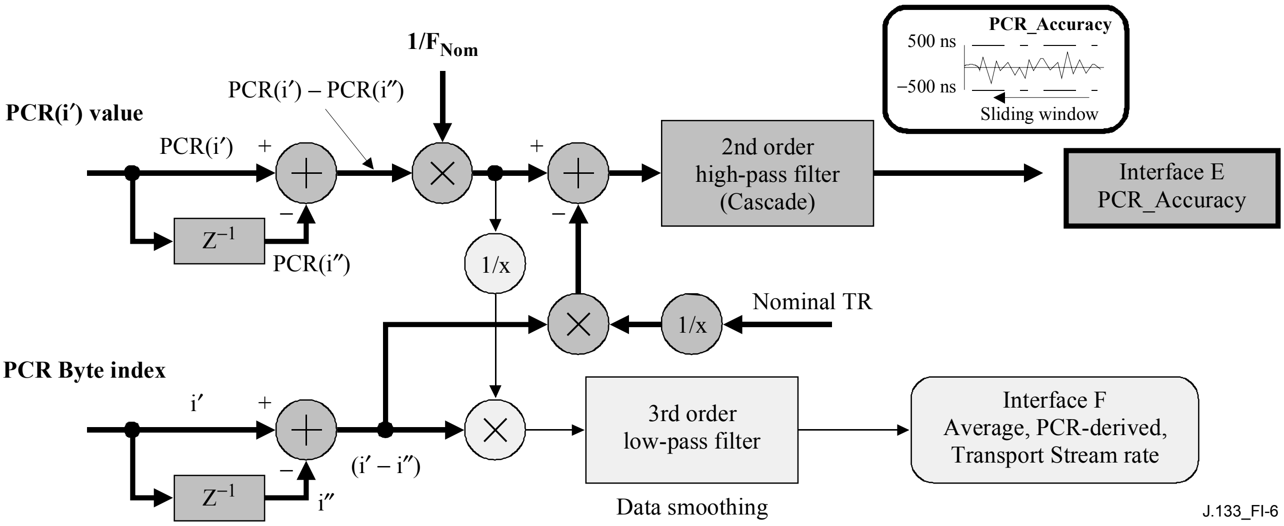
Figure I.5/J.133 – Third-order high-pass filter for jitter and first-order roll-off for drift measurements

Now jitter can be evaluated against given performance limits somewhat independently of the frequency Drift-rate performance limits. Note that in Figure I.5 the jitter high-pass filter (HPF) has a third-order response to reject the drift-rate components from the measurement. Also in Figure I.5 right, the drift-rate measurement response has a first-order roll-off to reject the jitter components from its output. Also shown is the preferred frequency-offset measurement response, which also rejects jitter spectral components. Note (see Figure I.5 right) that below the demarcation frequency, the frequency-offset is a first-derivative slope and the drift-rate is a second-derivative slope.

The timing error need not be directly measured since its time-derivative or frequency-offset contains all that is needed to implement the measurement filters. This means that only two samples to compute the time-delta or first-past-difference of the byte arrival time are needed. This is equivalent to measuring the instantaneous frequency offset rather than the actual time-error of the Transport Stream and greatly simplifies the measurement with no loss in information.

I.7.1 PCR_Accuracy (PCR_AC)

The result of PCR_AC is obtained at interface E of Figure I.6.



PCR(i′)	PCR_base(i′) * 300 + PCR_ext(i′)
PCR Byte index	index of the byte containing the last bit of the immediately following program_clock_reference_base field applicable to the program being decoded.

Figure I.6/J.133 – PCR_Accuracy measurement

The PCR_ACs that affect the PLL clock recovery for a specific program can be measured independently of arrival-time by extracting the change in adjacent PCR values and the number of bytes between PCRs as follows:

$$K(i) = i' - i'', \text{ bytes}, [PCR(i) - PCR(i-1)]/F_{Nom} - K(i)/TR = d(PCR\_AC(i))/dt$$

where:

TR	nominal Transport Stream rate, bytes/s, $F_{Nom} = 27$ MHz;
K(i)	number of bytes between current PCR(i) and previous PCR(i–1).

All high-pass and low-pass filter bandwidths as MGF1, MGF2, MGF3 and MGF4.

Note that this method measures PCR_AC independently of arrival-time. This can only be done for constant bitrate TS. Drift rate and frequency offset are not measured. PCR interval errors are also not measured but can be determined indirectly from K(i)/TR. Also note that PCR_AC is measured above the demarcation frequency to be consistent with those spectral components that contribute to PLL jitter. The drift components of PCR_AC are likely negligible compared to clock drift.

The second-order high-pass filter represents a second-order HPF response to the PCR accuracy due to the first-derivative effect of the first-past-difference calculation of the PCRs shown in the diagram. This is best illustrated as a discrete-time system operating at the average PCR rate in Figure I.7.

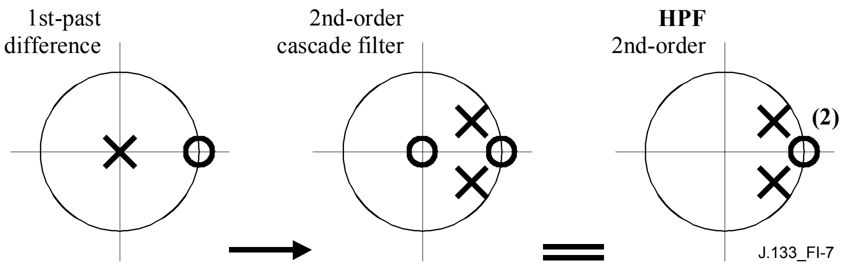


Figure I.7/J.133 – Second-order HPF

In terms of the reference model presented in 4.1, Figure I-6 measures the difference in two PCR inaccuracies Mp,i′ – Mp,I″. A series of these measurements can be processed further to derive the individual PCR inaccuracies Mp,I by assuming that average inaccuracy is zero.

I.7.2 PCR_drift_rate (PCR_DR)

The result of PCR_DR is obtained at interface H of Figure I.8.

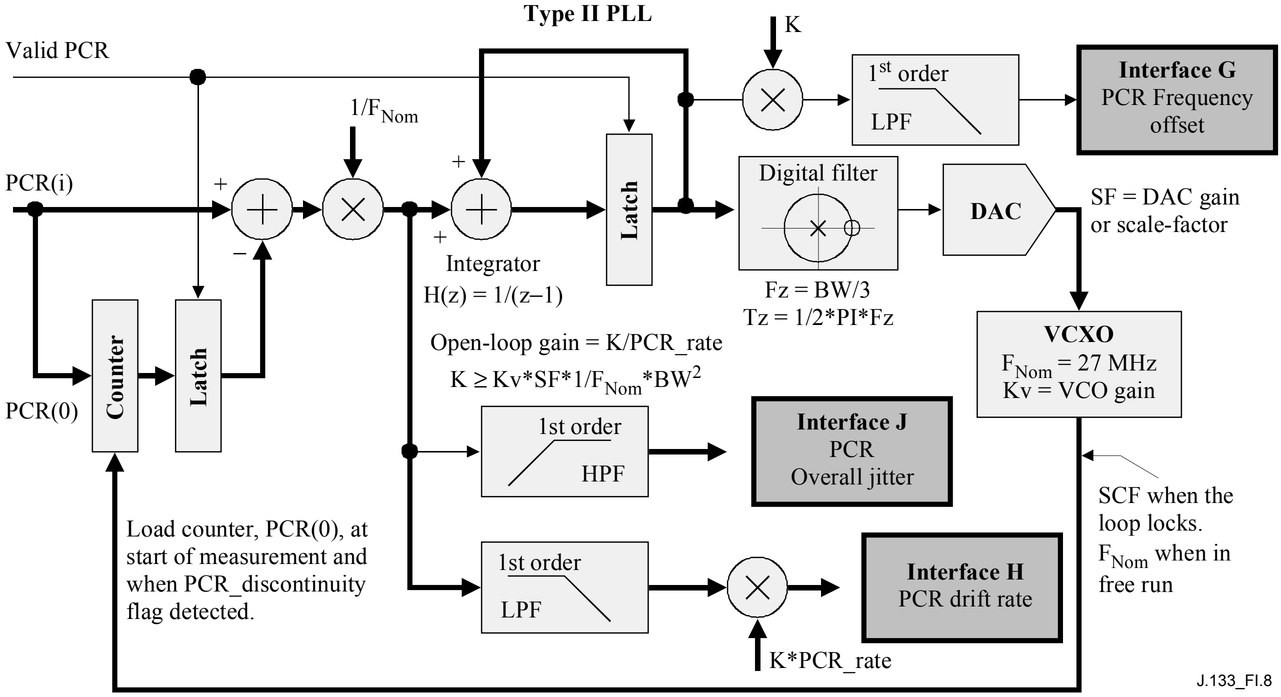


Figure I.8/J.133 – Overall PCR jitter measurement combining the effects of PCR_AC and PCR_arrival_time_jitter

This measurement result is obtained after the combined action of the second-order HPF represented by the loop (before the integrator represented by the adder and latch), followed by the first-order low-pass filter (LPF). This combined action provides the response indicated in Figure I.5 for drift rate.

I.7.3 PCR_frequency_offset (PCR_FO)

The result of PCR_FO is obtained at interface G of Figure I.8.

This measurement is obtained after the combined action of the first-order HPF represented by the loop and the integrator (represented by the adder and latch) followed by the first-order LPF. This combined action provides the response indicated in Figure I.5 for frequency offset.

I.7.4 PCR_overall_jitter measurement

The result of PCR_OJ is obtained at interface J of Figure I.8.

This measurement result is obtained after the combined action of the second-order HPF represented by the loop (before the integrator represented by the adder and latch), followed by the first-order HPF. This combined action provides the response indicated in Figure I.5 for jitter (left drawing).

Overall jitter includes the composite effect of PCR accuracy errors and PCR arrival-time jitter. It is important since this relates directly to the effect on the program-recovered clock jitter and drift. This method should also include a measurement of clock drift-rate and frequency-offset. Therefore, the most practical method is to implement a SCF recovery PLL like the one in the program decoder. By carefully controlling the bandwidth and calibrating the VCXO, it is possible to measure, simultaneously, PCR overall jitter, SCF frequency-offset, and system clock frequency (SCF) drift-rate with the frequency responses described before.

Explanation

Note that the PLL is a Type II control system with two ideal integrators (digital accumulator shown and VCXO). This creates a second-order high-pass closed-loop response at the output of the phase subtraction. Therefore, below the loop bandwidth, the response is proportional to drift-rate and proportional to jitter above the loop bandwidth. It is necessary to add an additional first-order HPF to the jitter measurement to remove the effects of drift-rate. Conversely, it is necessary to add a first-order LPF to the drift-rate output to remove the effects of jitter from that measurement.

NOTE 1 – If the filters are implemented using DSP techniques on the raw data, and since the PCR_rate is the sample rate, the average PCR_rate should be determined by measuring the PCR_interval and filtering the result with a 10 mHz LPF or lower. The value of PCR_rate can be used for those values shown in the figure to effect the selected measurement bandwidth, BW, such that it is independent of PCR_rate.

NOTE 2 – The design shown is a digital/analogue hybrid with a digital-to-analogue (DAC) converter driving the analogue loop filter. For a 14-bit DAC the SF would be 2^{-14}. The voltage-controlled crystal oscillator (VCXO) with gain Kv can be constructed from a sub-system consisting of an oven-controlled crystal oscillator (OCXO) and a frequency-locked loop (FLL) locking a VCXO. This can be used to calibrate the Frequency-offset output to the wanted accuracy if desired. Otherwise, the VCXO can be used alone and its frequency error or offset verified by applying a known, accurate frequency, TS and subtracting the error from subsequent measurements.

NOTE 3 – Alternatively, a free-running OCXO can be used to determine the PCR_interval with known methods and a numerical voltage-controlled oscillator (VCO) can be constructed. With this method a completely digital or software only version can be constructed using the measured PCR_interval and the PCR values. It can be shown that this method can have a bandwidth that is essentially independent of average PCR_rate with the measured jitter values relatively independent of variations in PCR_interval.

Although this method describes a PLL implementation as a hybrid of DSP and analogue signal processing, other methods that yield the same filtered responses are possible.

I.8 Considerations on performing PCR measurements

The measurement and validation of contributions to jitter and drift rate of a program system time clock (STC) carried by its discrete-time samples via PCR values of each program in a TS require certain mathematical analysis of such samples in order to compute the performance limits for direct comparison to those indicated in this Recommendation.

Typical sampled system analysis relies on a regular sampling rate of the data to be analyzed. This is not generally the case of the discrete-time samples carried by PCR values which, per their own nature, depend on criteria and priorities at the multiplexing stage.

ITU-T Rec. H.222.0 | ISO/IEC 13818-1 [1] establishes a maximum interval of 100 ms between consecutive PCR values. The DVB recommends that all DVB compliant systems will transmit the

PCR values with a maximum interval of 40 ms, but all receivers should work properly with intervals as long as 100 ms.

None of the standards forced that the interval, whatever it is, should be constant. This is because in the multiplexing process there is a need for an allowance as to the instant the packet containing the PCR field for a given program is to be inserted into the TS. However, the intention of the designers and operators of multiplexers is to provide such values at the most regular rate as possible.

At the receiver, the regeneration of the 27 MHz of system clock for the program under the decoding process is controlled by a signal that makes use of each of the PCR values corresponding to such program at the time of arrival to introduce corrections when needed. It is assumed that the stability of the clock regenerator is such that the phase does not unduly drift from one PCR value to the next over intervals as long as 100 ms.

However, it is the responsibility of the TS to provide the values of PCR correctly with an error no greater than 500 ns from the instantaneous phase of the system clock. The limit of 500 ns may be exceeded as an accumulated error over many PCR values. However, when the accumulated error spans a sufficiently long duration, it should be considered in terms of its drift contribution and, allowed to exceed the 500 ns limit. What "sufficiently long" means has been derived in I.5 and is represented graphically by the break points of the graph in Figure I.2. For sinusoidal frequencies lower than 12 mHz, the limit is set by the drift rate specification rather than by the 500 ns limit.

If appropriate filters are built into the measurement device to separate the received PCR value spectral components around a jitter vs. drift demarcation frequency, then it is possible to compare the errors received against the appropriate limits indicated in this Recommendation.

Should the design of the measurement device be built as analogue device with hardware filters, then the designer will use the demarcation frequency as a requirement for the design of the filters with independence of the sampling rate at which the PCRs are actually arriving. This demarcation frequency is derived from the limits indicated in this Recommendation and does not depend on sampling rate for the PCR values.

If the design of the filters is done by DSP techniques, the designer must take into account the average sampling rate of the PCR values and adapt the filters to maintain a relatively fixed bandwidth for the measurement. This approach implicitly assumes that the sampling rate (average arrival rate of PCR values) is not only known but is relatively constant.

A good recommendation is to have the value of the coefficients determined adaptively by measuring the actual arrival rate of PCR values. In other words, use an adaptive filter with the variable parameter being the measured PCR rate.

This approach has been tested in practice using very strong frequency modulation for the PCR values rate; the results in the measured jitter and drift do have a very close correlation (within the accuracy limits of the measuring device) to the jitter and drift errors inserted by the test generator into the PCR values under test. Generally, small differences in measurement filter bandwidths do not affect jitter measurement results significantly since the jitter spectral components are most often broad band. In fact, the order of the filter is most important since this determines the filter output sensitivity to out-of-band components, which may have small amplitudes but very high first- and second-time derivatives.

Another consideration to have in account is not related to the verification of stream validity but is related to a debugging tool to find the origin of the jitter should it exist and have certain periodicity or resonant frequencies. This tool shall apply Fourier analysis to the received sampled data.

Again, for this type of analysis to be valid, it is assumed that the sampling rate is known and is regular. Then the sampling rate has to be measured in order to know frequencies analyzed in each frequency bin (the resolution as a function of the number of time domain samples used in the calculation and the relative stability of the sampling rate over the measurement interval).

The problem of the non-uniformity of the sampling rate could be overcome by careful interpolation before the Fourier technique is applied. In general this interpolation is not necessary due to the fact that as a debugging tool, the need is not to know what is the "exact" value of the frequencies and its amplitudes. What is needed is only to obtain an idea on whether the jitter is just random or whether it has some predominant frequencies embedded.

Generally, when a Fourier analysis is done on regularly sampled signals and there is a stable sinusoidal component on the signal, its parameters can be obtained with great accuracy and a clear spectral line could be displayed with such data represented as in a spectrum analyzer. If the sinusoidal component were not stable, then a broad spectral line with lowered amplitude would be expected, broader and lower as greater is the frequency modulation (FM) implicit in such a sinusoid.

If a stable sinusoid is present but the sampling rate is FM modulated, as is the case of PCR arrival rate, then a broad and lower spectral line can be expected, just similar to the previous case described. When a great deal of FM (random or not) is present in the sampling signal, the spectrum becomes broader with less amplitude in each bin. However as a diagnostic tool it may still be valid.

I.9 Choice of filters in PCR measurement

I.9.1 Why is there a choice?

PCR measurement is a difficult task. The PCR values do not occur very often and when they do, they are rather large (42 bits) numbers. The Clock reference is intended to be very stable, and as such a measurement device must have at least the same stability to make a measurement. It is this long-term stability (of the order of a few ppm change in frequency per hour) in a counter which is incrementing very fast (27 MHz), but transmitted infrequently (40 ms or so) which causes the problems.

A "Demarcation" frequency has been defined (Figure I.2) which is able to divide the inaccuracies added to the PCR clock into Drift (low frequency component) and Jitter (high frequency component). It is based on the limits indicated in ITU-T Rec. H.222.0 | ISO/IEC 13818-1 [1] that sets a region below 10 mHz (MGF1) where the drift limit (75 mHz/s) is dominant and a region above 10 mHz (MGF1) where errors are allow to exceed the drift rate but not the phase-error limit (500 ns); that is why MGF1 is the highly recommended demarcation frequency used for accurate compliance to ITU-T Rec. H.222.0 | ISO/IEC 13818-1 [1].

For practical measurements, however, three fixed demarcation frequencies have been specified. MGF1-3 and a user- or manufacturer-defined one is also allowed MGF4. The demarcation frequency **chosen** is a compromise between the desired accuracy of the clock as defined in the MPEG specification, and the practical concerns with performing the measurement.

In order for two measurement devices to give the same results for a given Transport Stream, they must use the **same** demarcation frequency in the measurement. In addition, any secondary effects due to irregular arrival of the PCR samples may be removed so that results may match more closely. The way this is done is beyond the scope of this measurement guideline, but designs should give similar results when, say, a 10-minute stream has PCRs every 20 ms for the first 5 minutes and then 40 ms for the next 5 minutes.

When the filter profiles MGF1 to MGF4 defined in this Recommendation are implemented, there will be deviations between the real response of the filters and the desired response of the ideal filters. This will give some measurement errors between devices. In general, the precision of the filtering is a commercial choice of the equipment manufacturer who is building equipment for a specific market.

The choice

These guidelines are intended to create an environment where similar machines give similar results, and users are able to understand the implications of choosing different measurement parameters. The errors between different devices will vary depending on a number of factors:

1) Are the same demarcation frequencies being used? This is the major factor.

   If different devices use different demarcation frequencies, then they will give different results. This will be a major source of error. A discussion of the nature of the error is given below.

2) Are the demarcation filters of the same order? This is less important.

   If one device uses a second order filter and another uses a fifth order filter, then the nature of the filter response will be quite different. There is likely to be a small difference between measurement devices particularly if significant frequency components of the errors are close to the chosen demarcation frequency.

3) Is the measurement being made near the crossover of the offset/drift/jitter frequencies?

   Near the crossover frequency, the order of the filter and its impulse response are likely to affect the frequency components which are included or rejected from the measurements. This has much less of an affect than the choice of demarcation frequency.

I.9.2 Higher demarcation frequencies

There are several effects of choosing a higher demarcation frequency (e.g. MGF3):

1) Jitter turns into drift or frequency offset.

   A higher demarcation frequency means that frequency component which would have been classed as jitter will now be classed as frequency offset or drift. This has the effect of reducing the magnitude of the overall jitter frequency component. It also makes the system clock look less stable than it actually is.

2) The measurement settles faster.

   The settling time is closely related to 1/frequency. If the frequency is increased by two orders of magnitude, then the settling time may be reduced by two orders of magnitude. There are DSP techniques which can be used to improve settling times, and the use of these is a commercial choice of the equipment vendor.

   As a **rough** rule of thumb, a higher demarcation frequency settles faster but gives a less accurate result. Jitter measurements should appear smaller and drift measurements should appear larger.

I.9.3 Lower demarcation frequencies

There are several effects of choosing a lower demarcation frequency (e.g. MGF1):

1) Separation of drift and jitter into more representative groupings.

   A lower demarcation frequency means that frequency components are more accurately classed as jitter, frequency offset or drift. This has the effect of measuring the frequency components based on assumptions which are closer to the values in the MPEG2 specification.

2) The measurement takes longer to settle.

   The settling time is closely related to 1/frequency. If the frequency is reduced by two orders of magnitude, then the settling time may increase by two orders of magnitude. There are DSP techniques which can be used to improve settling times, and the use of these is a commercial choice of the equipment vendor.

As a **rough** rule of thumb, a lower demarcation frequency settles more slowly but gives a more accurate result. Jitter measurements should appear larger and drift measurements should appear smaller.

The final choice of demarcation frequency rests with the user of the equipment and will come down to a trade-off between speed of measurement and precision of measurement. These guidelines should allow different measurement devices to give comparable results in the heart of the measurement region, some ambiguity at the crossover point and then agreement in the next region.

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