Best Practice Manual

for Digital Audio Authenticity Analysis

ENFSI-FSA-BPM-002

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ENFSI wishes to promote the improvement of mutual trust by encouraging forensic harmonization through the development and use of Best Practice Manuals. Furthermore, ENFSI encourages sharing Best Practice Manuals with the whole Forensic Science Community which also includes non ENFSI Members.
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The text may be translated into other languages as required. The English language version remains the definitive version.

Further information
For further information about this publication, contact the ENFSI Secretariat. Please check the website of ENFSI (www.enfsi.eu) for update information.

BEST PRACTICE MANUAL FOR DIGITAL AUDIO AUTHENTICITY ANALYSIS

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1. AIMS

This Best Practice Manual (BPM) aims to provide a framework for procedures, quality principles, training processes and approaches to the forensic examination. This BPM can be used by Member laboratories of ENFSI, by other forensic science laboratories and by forensics experts to establish and maintain working practices in the field of forensic digital audio authenticity analysis that will deliver reliable results, maximize the quality of the information obtained, and produce robust evidence and unbiased conclusions. The use of consistent methodology and the production of more comparable results will facilitate interchange of data between laboratories.

The term BPM is used to reflect the scientifically accepted practices at the time of creation. The term BPM does not imply that the practices laid out in this manual are the only good practices used in the forensic field. In this series of ENFSI Practice Manuals the term BPM has been maintained for reasons of continuity and recognition.

2. SCOPE

This BPM addresses the forensic authenticity analysis of digital audio recordings. It provides recommendations concerning required resources, available scientifically validated methods and applicability thereof, quality assurance, handling of the recording under analysis, and interpretation guidelines. This document does not describe the methods for evidence gathering from digital media storage or equivalent. It assumes that the forensic principles for evidence handling are followed and addresses all necessary operations starting from when the audio recording is submitted together with an examination request. This BPM does not provide example analysis reports since they may vary considerably according to the laws and to the capabilities of the facility performing the analysis.

3. TERMS AND DEFINITIONS

Audio authenticity analysis – act of providing an assessment about the evidence having characteristics compatible with an authentic digital recording or not.

Audio file format – an organized structure for storing an audio recording in a file.

Authentic digital recording – as applied to audio recordings, a continuous recording made simultaneously with the acoustic events, in a manner fully and completely consistent with the method of recording, stored on a recoverable digital format, and which is free from unexplainable artefacts or discontinuities.

Contextual information – additional information provided about the evidence, specifying the recording conditions and methods, e.g., date, time and place of the recording, type and configuration of the device and software involved, presence of known interruptions (pressing pause button, receiving an incoming call).

Cryptographic hashing functions – publicly known algorithms used to map data of arbitrary size to a single fixed-length sequence of bits, referred to as hash or hash value. These values can be used, e.g., to substantiate the integrity of digital evidence or for comparisons against sets of known values. Hash computation must be efficient, deterministic, unforgeable, and grant low collision probability.

Digital audio recordings – representation of audio signals by means of a set of numerical values, each value representing a discrete time instant.

Electric Network Frequency (ENF) – instantaneous frequency of the electric network, varying smoothly and randomly around the nominal operative value (50Hz in continental Europe).

Metadata – data containing information about a file. As applied to audio recordings, it may store information about, e.g., audio parameters, codecs, dates and times, hardware or software involved.

Wiped storage media – storage media which has been processed to erase any trace left by previous files which have been stored on it, e.g., by overwriting its content with random bits.

4. RESOURCES

4.1 Personnel

Personnel should have received specific forensic training in the field of audio forensics. Examples of appropriate training include:

- Laboratory in-house training;
- Training from a university or equivalent;
- Training from an external certified organization.

Which training types are allowed and recognized may vary according to the specific legislation and may also vary between laboratories.

4.2 Equipment

Suitable equipment is required to perform proper audio analyses:

- Computer and high-quality audio card with audio resolution ranging from 8 kHz — 48 kHz, 16 bit, stereo.
- High quality headphones with full frequency resolution 20 Hz — 22 kHz, high quality loudspeakers are optional but recommended.
- Computer software with the possibility to read and decode audio data including at least the following codecs or formats: AAC, MP3, WMA, WAV/AIFF, OGG, AMR.
- Computer software which allows visualization of the waveform, spectrum and spectrogram of audio.

The choice of equipment is of primary importance: inappropriate equipment may significantly degrade the quality of the forensic analysis. See for example [6] on the effects of peripheral stimuli and equipment used on speech intelligibility in noise.

4.3 Reference Materials

Not applicable.

4.4 Facilities & Environmental Conditions

Minimum requirements:

- Room with controlled noise level for in-house labs.
- Closed-back or noise-cancelling headphones and / or appropriate acoustic treatment to reduce unwanted background noise for mobile labs.

4.5 Risk-based Thinking

See sections **Fehler! Verweisquelle konnte nicht gefunden werden.** and 8.2

4.6 Materials and Reagents

Not applicable.

5. METHODS

5.1 Principles of Audio Authenticity Analysis

Authenticity analysis of digital audio recordings is based on *traces* left within the recording during the recording process, and by other subsequent editing operations.

The first goal of the analysis is to *detect and identify* which of these traces can be retrieved from the audio recording, and to document their properties.

In a second step, the properties of the *retrievable traces* are analysed, to determine if they support or oppose the hypothesis that the recording has been modified.

It is not always obvious whether traces are due to recording or post-processing. A key objective of any authenticity analysis is therefore to determine whether observed features of a piece of audio evidence were introduced by the original recording process or by subsequent actions.

5.1.1 Recording Traces

The majority of traces are left in the recording during the recording process, as depicted in Figure 1.

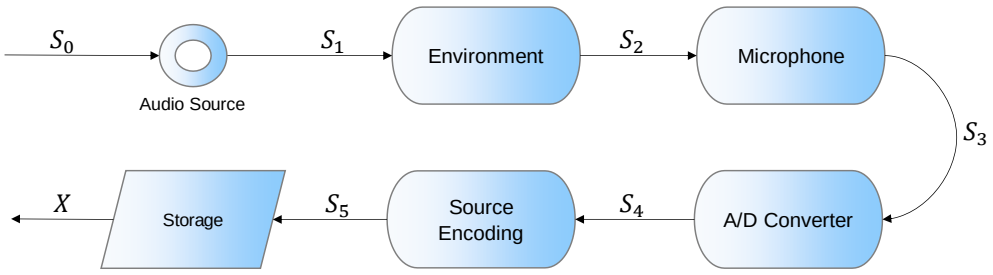

Figure 1: Recording process flow

In a first step, the speaker's thoughts S_0 are converted into the original speech signal.

The speech S_1 is then propagated through the environment. During this acoustic propagation, S_1 can be modified by reverberations and mixed with random, periodic or harmonic environmental noise.

This complex mixture S_2 is then converted to an electrical signal by the microphone (transducer). At this point, the signal is modified by the microphone frequency response, influenced by microphone thermal noise, and may obtain additional spurious traces such as a DC-offset or an electrical network frequency (ENF) component.

The analogue electrical signal S_3 is then converted into its digital representation, according to the specific bit-depth and sampling frequency used by the analogue-to-digital converter.

The digital representation S_4 is then encoded using either a lossy or lossless scheme, thus acquiring encoding artefacts, bitrate, mono or stereo mode, and any other parameter specific to the scheme.

Lastly, the encoded signal S_5 is stored together with any related metadata, on the device storage as the original evidence X.

5.1.2 Traces of Post-processing

A second class of traces may be introduced if the recording is subsequently edited or is subject to other human interventions, e.g.:

- Inter-sample dependencies left by digital resampling of the original content, in which the output contains correlations between neighboring audio samples not compatible with the random nature of the input signal.
- Signs of double encoding, such as the presence of encoding artefacts which are of a higher severity than that which would be expected if the audio had been encoded only once.
- Replicated time intervals, i.e., time intervals in which the content is perfectly identical which does not happen in natural speech recordings. The presence of such replicas is a sign of human post-processing of the initial recording.

The main and most important characteristic of such traces is that they *cannot be attributed to any part of the purported (claimed) recording process*. Hereon, we will refer to this class of traces with the term “traces of post-processing”.

Operations which modify the content of the recording, such as deleting a portion of the file, copy-pasting a time interval coming from the same file, splicing content from a different recording, may also generate *discontinuities* in the recording traces.

Other operations, such as the aforementioned resampling and double encoding, may mask other editing or manipulation signs. Thus, the importance given to the *detection* of traces of post-processing.

5.1.3 Hypothesis Testing

In an ideal world, the aim of an audio authenticity analysis would be to answer the question:

Is the evidence under analysis an authentic recording[1] or not?

However, in practical casework it is not usually appropriate or possible to answer this question with a “yes” or a “no”. Audio authenticity analysis instead consists in *supporting/refuting* a hypothesis that the evidence under analysis is an authentic recording, based on the characteristics of the traces within the recording and the available contextual information.

If we consider the two following alternative propositions:

[1] The definition of authentic recording is provided in section **Fehler! Verweisquelle konnte nicht gefunden werden.**.

- H0: the evidence presents traces supporting the hypothesis that the recording is authentic;
- H1: the evidence presents traces supporting the hypothesis that the recording is not authentic

it should be clear that the goal of authenticity analysis is *not* to state which proposition is the correct one, but to *evaluate* which hypothesis is the more likely, and how strong (or weak) this support for that proposition is. It is possible to have *no support* for either case.

Proposition H1 can be expressed also by means of the following statement, which we can consider the fundamental principle of audio authenticity analysis:

If any recording trace is inconsistent at any point in the file
OR
If unexplainable post-processing traces are present
} The recording is not authentic

The above principle implies that the analysis should not strive for explicit authentication but rather focus on post-processing detection. This implies the following:

1. *Every* detected recording trace – e.g., microphone frequency response, encoding (scheme, bitrate, mono or stereo-mode), ENF, reverberation, DC-offset, bit-depth, metadata – should be checked for inconsistencies within the recording.
2. *Every* detected recording trace should be checked for inconsistencies with any existing reference audio recording, as well as with any contextual information regarding the recording process.
3. *Any* trace that is suspected of being a possible post-processing trace should be thoroughly documented and compared with the provided contextual information.

In the following sections we are going to introduce several forensics methods, all of which are related to the fundamental principle above, and to describe how these methods may be applied. See section 12 for evaluation and interpretation.

5.2 Methods Classification

Methods for audio forensics analysis can be divided in two main classes:

1. *Informed analysis methods*, focused on the detection of inconsistencies between traces left by the recording process and contextual information regarding the recording process of the evidence, possibly with the help of reference recordings.
2. *Blind analysis methods*, relying solely on the content, focused on the detection of inconsistencies of traces left by the recording process within the file, and on the detection of traces that may have been left by editing.

Informed analysis methods can be described in terms of:

a) Which recording trace is addressed;
b) Which contextual information should be used in order to conduct the analysis.

Blind analysis methods may be categorized as follows:

a) Methods addressing the continuity of time-variant traces:
   — Methods verifying the continuity of: speech signal, environmental noise signals, electric network frequency.

b) Methods addressing the invariability of time-invariant traces:
   — Methods verifying the lack of changes of: reverberations, constant background noise, DC-offset, microphone frequency response, microphone thermal noise, bit-depth, cut-off frequency, encoding artefacts and any noises/traces caused by the electronic elements.
c) Methods addressing the invariability of periodic traces:
   — Methods verifying the periodicity of: periodic environmental noise, periodic encoding artefacts.
d) Methods involving the detection of traces of post-processing:
   — Methods detecting: inter-sample dependencies, double encoding traces, replicated time intervals, abnormal distribution of quantization levels.

With this categorization, every method can thus be described in terms of:

a) Which trace is addressed.
b) Which property of the trace is checked.

See

Figure 2 and Figure 3 for examples of both blind and informed analysis methods.

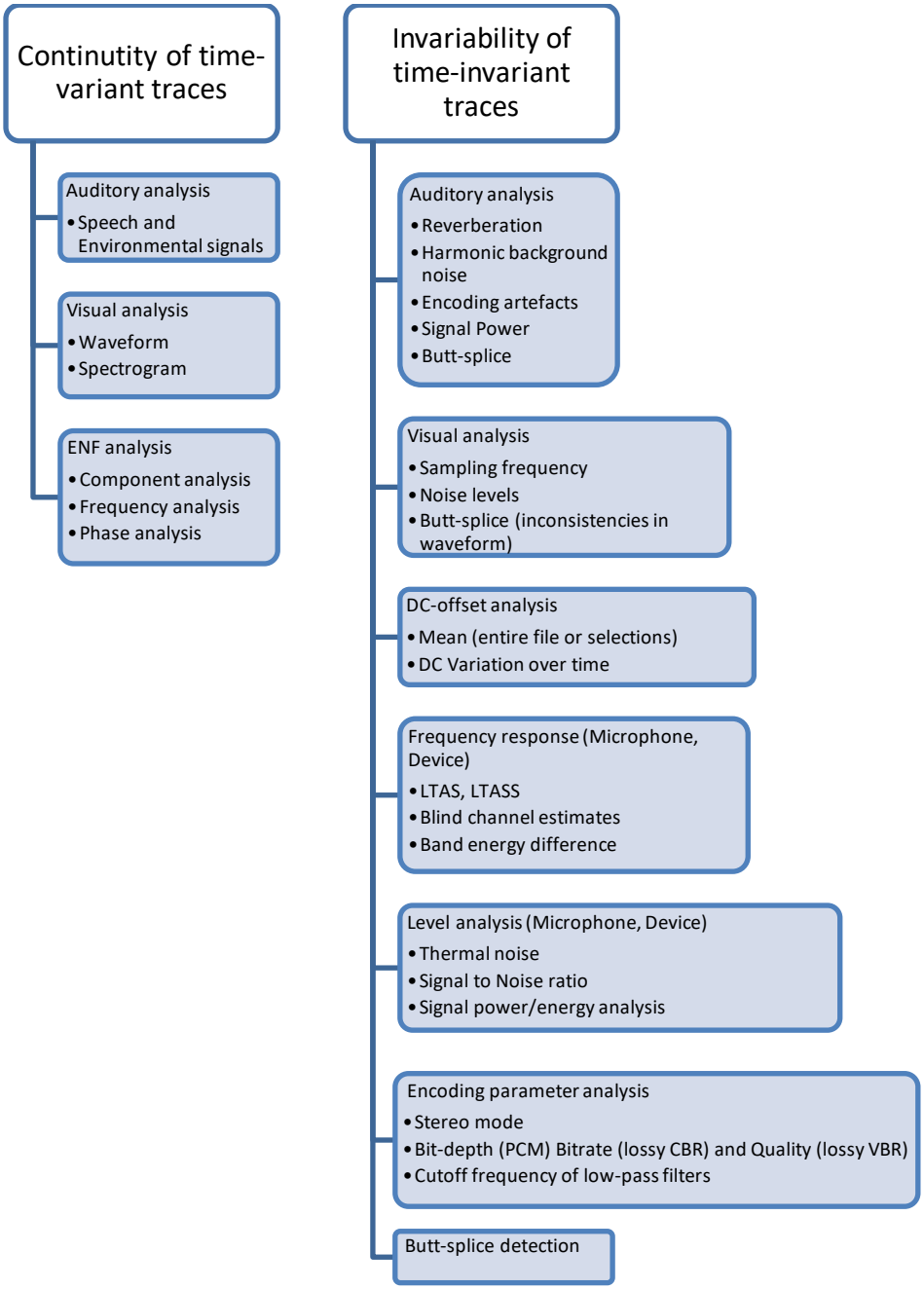

Figure 2: Overview of the available blind and informed analysis methods

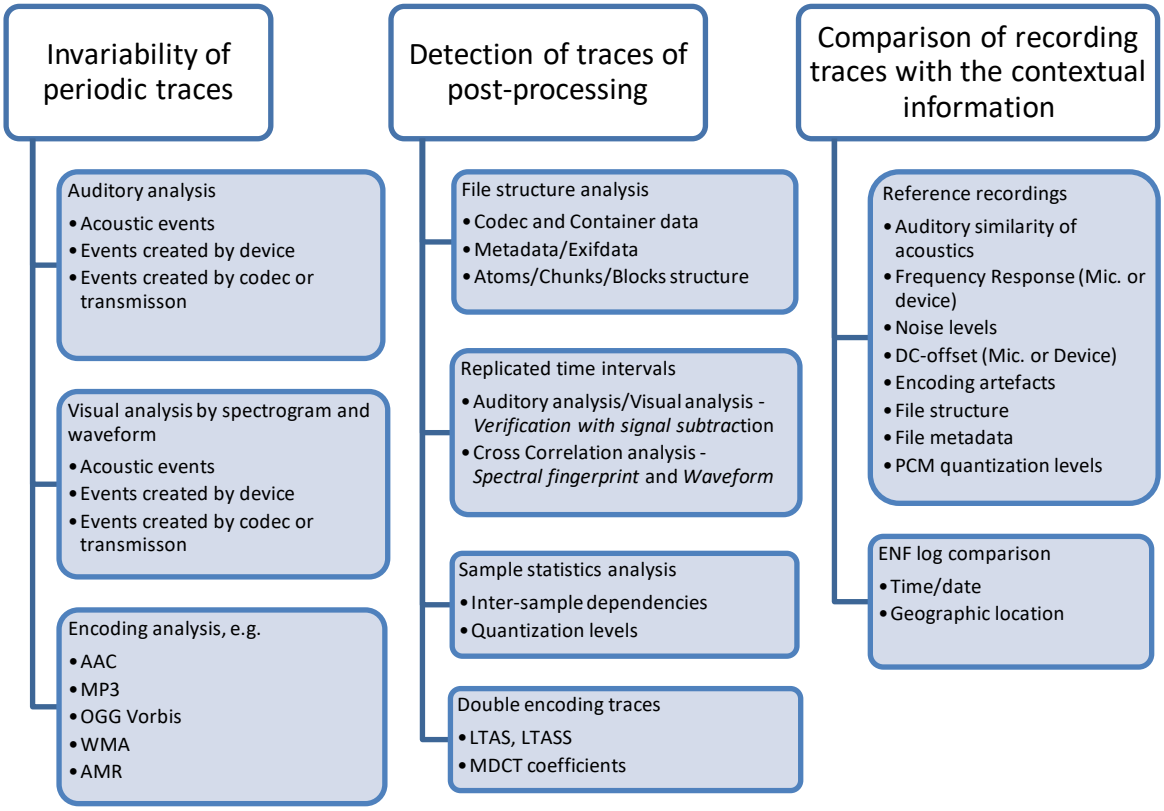

Figure 3: Overview of the available blind and informed analysis methods, continued

5.3 Laboratory and Case Specific Framework

The choice of which methods to adopt is left to each laboratory, according to the available tools, technologies, and knowledge. It is recommended that audio laboratories maintain a chain-of-custody for evidential material whenever possible.

We encourage forensic practitioners to follow peer-reviewed methods, widely accepted by the scientific community, and thoroughly evaluated *within the laboratory*.

Practitioners should bear in mind that some of the technology in the research field may not yet be ready for application in real-life conditions.

The implementation of chosen methods is also dependent on the specifics of the examination:

- "traces should be consistent *within* the recording," with the goal to find out whether there are any unexplained inconsistencies within the audio recording

And / or

- "traces should be consistent *with the contextual information* provided concerning the recording," with the goal to find out whether there are any inconsistencies with the statements provided concerning the evidence.

The latter requires detailed information regarding the contextual aspects and purported provenance of the recording for example: recording device, recording software, any additional

hardware (e.g. headset/headphones); time, location, speakers' identities; known events which may create *expected* artefacts – e.g., phone calls, TV switching channels etc. (see section **Fehler! Verweisquelle konnte nicht gefunden werden.**).

Both can be valid approaches if allowed by the laboratory and juridical system.

5.4 Method descriptions

5.4.1 Continuity of Time-variant Traces

When looking at the continuity of time-variant traces, the focus of the auditory analysis is to listen for inconsistencies in the signal. For example, unnatural fade-in/fade-outs and abrupt changes in a word or in an environmental sound such as a passing car or café ambiance. Visual analysis of waveform and spectrogram can be used to verify and supplement the findings from the auditory analysis. It is beneficial to compare the findings from the auditory and visual analyses with provided contextual information. Apparent inconsistencies can in many cases be explained by this additional contextual information. For example, changes in environmental sounds could be due to opening or closing a window, a door or by changing rooms during a recording. For more details see [7], [8] and regarding the limitations of auditory and visual analyses see [9].

In addition to the intended signal the recording equipment may also capture the Electric Network Frequency (ENF) signal; that is, an alternating current power hum which fluctuates smoothly around its nominal value of 50 or 60 Hz (according to the location in which the recording is made). This may happen due to induction in the microphone itself, the cables involved, or the internal electronics of the recording device. When this happens, the recording contains a series of harmonic tones the fundamental of which is the ENF [45], [46], [47].

Due to the ENF variations being slow and well defined in their magnitudes, deletions or addition of content may create discontinuities in the frequency [48], [49] and / or the phase trajectories [50], [51] of the ENF component extracted from the recording in question. As these discontinuities sometimes also happen on unaltered recordings, due to local impulse noises on the network, discontinuity analysis should be performed together with at least one other analysis – for example, determining whether the ENF matches the purported recording time [52], [53], [54].

When the recording process described in Figure 1 occurs in a single electrical network, then the original digital recording is expected to contain one series of ENF harmonic tones or none. More than one ENF series can indicate that analogue copying of the original signal may have taken place, with the additional ENF trace having been captured during the copying process.

5.4.2 Invariability of Time-invariant Traces

Here the auditory analysis involves listening for:

- Unnatural changes in reverberation;
- Unnatural changes in background sounds;
- Unnatural changes in encoding artefacts;
- Unexpected differences in sound levels including clicks, pops and level changes of sound sources.

The visual analysis involves looking for unexpected changes in spectral characteristics and waveform such as:

- Changes in cut-off frequency (which may have occurred due to recordings with different sample rates being spliced together);
- Changes in noise levels;
- Sudden/abrupt changes in the waveform, e.g., butt-splices;
- Sudden and unexplained changes in signal level.

In original, unaltered recordings, the DC-offset of a device has a well-defined mean and finite standard deviation which can be estimated using the whole recording duration [20], [21], [22]. Intervals in which the local DC-offset is very different to the global one, may have been caused by portions of file having been added by editing. Such occurrences should also be examined by auditory analysis, since DC-offset mismatches may generate audible clicks.

The frequency response of a recording device does not change abruptly. Hence, methods which examine features related to the microphone or device frequency response [38], [39], [40] may be used to identify possible additions of content recorded on a different device, or to make comparisons with test recordings made on a declared device.

Power and level analysis as described in [9] can be used to look for both abrupt changes and more gradual changes in sections in the signals power and level. Such changes may be introduced, e.g., by deletion of material, by changes in the noise-floor happening when different recordings are edited together, but also by drop-outs or sudden changes of the recording conditions.

The encoding parameters of a recording do not change over the file length. For uncompressed WAV files, this implies that the real bit-depth, the PCM coding and mono or stereo mode of the base signal should remain constant throughout the file duration [24], [26]. For compressed (e.g. MP3, AAC) files, the same would be true for the bitrate (in case of CBR), encoding quality (in case of VBR), cut-off frequency of the lowpass filter and mono or stereo mode, which can be recovered from the compressed domain, as well as after decoding the file [27], [28], [29], [30], [31], [32].

Butt-spliced edits or other discontinuities occurring between one sample and the next may be detected in PCM encoded files by examining the 1st or 2nd order differentials of sample values against time [23]. Changes in sample value that are dissimilar to the rate of change of sample values in the immediately surrounding audio may result in an impulse in a plot of the difference signal. If perceptual encoding is applied after editing, such discontinuities are no longer detectable with the method in [23]. It is important to acknowledge that discontinuities are not necessarily caused by editing, so evidence of discontinuities is not evidence of editing.

5.4.3 Invariability of Periodic Traces

The focus of the auditory and visual analyses in this step is to listen and look for sudden changes in traces coming from the transmission, device or background sounds, such as unexpected changes in periodic dropouts created in the signal from transmission or encoding process, or unexpected changes of the rate of a wall clock in the room (or similar) that can be heard in the background of the recording.

Periodic traces from lossy encoding are also embedded in a file. In the case of transform-based codecs such as MP3, AAC, WMA and Ogg Vorbis, this periodicity is reflected by the framing grid offset, which can be estimated and analyzed using the inverse decoding paradigm [33], [34], [35]. In the case of speech codecs using CELP or LPC as AMR-NB, FR, HR, EFR, the residuals obtained by re-encoding the file with the same scheme exhibit a strong periodicity equal to the length of the base block used for LP analysis [36].

5.4.4 Detection of Traces of Post-processing

Analysis of the file structure and metadata of audio files is usually a key component of any digital audio authenticity analysis. These methods are based on the visualization of the file structure in the hexadecimal and ASCII representation using hexadecimal viewing software, and on searching for significant information about a file condition. For example, information from post-processing software may sometimes be seen in the metadata [10], [11], [12], [13], [14], [15], [16], [17], [18], [19].

The presence of time intervals in which the content is perfectly identical to that present in other sections is a strong sign of human post-processing of the initial recording. The occurrence of such intervals, which may correspond, e.g., to single words or short utterances, can be identified via auditory and visual analyses. The presence of a replicated portion may be verified using signal subtraction: if the signal is cancelled out by this process a copy/paste might have been made for that particular part of the signal.

Auditory analysis can also be used as a confirmation tool in order to verify a finding from an automatic method, e.g., copy-move forgery detection methods based on correlation analysis [62] or audio fingerprinting [63].

Digital resampling is a process whereby the sampling frequency of the file is converted from the original value fs_{old} to a new value fs_{new}. The relation between the two frequencies can often be expressed by means of the formula $fs_{new} = (P/Q) \cdot fs_{old}$, with P and Q being coprime. E.g., up-sampling from 16kHz to 24kHz can be written as $24kHz = (3/2) \cdot 16kHz$, and down-sampling from 44.1 kHz to 8kHz can be written as $8kHz = (80/441) \cdot 44.1kHz$.

Whenever digital resampling by a rational factor P/Q is applied to a recording, with P and Q being coprime, re-sampling creates periodic inter-sample dependencies appearing within blocks of Q samples. This periodicity can be identified for uncompressed files both in the case of up-sampling with $P/Q > 1$ [67] and in the case of down-sampling with $P/Q < 1$ [68] even if in this second case the detection accuracy is lower due to the task being more challenging.

A change in amplitude (i.e., digitally applied gain or attenuation) of the audio content may lead to anomalies in the quantization levels used in the recording. The number of quantization levels would be that dictated by the encoder, but their distribution may be affected in a processed recording, resulting in visible gaps and periodicities within the histogram of the quantization levels [24].

Double encoding effects appear whenever a lossy-encoded file is firstly decoded, and then re-encoded using the same or a different format. At the time of writing, only the case of double encoding using the same scheme has been investigated, and successfully applied to both MP3 and AAC. The detection was performed by comparing an artificially simulated single-encoded version of the input file with the actual evidence, to determine the presence of double encoding artefacts [69], [70], [71].

5.4.5 Comparison of Recording Traces with the Contextual Information

Where information regarding the context and purported provenance of an audio recording has been provided, and / or where the equipment allegedly used to make the recording is available for testing, tests may be carried out to assess whether the audio file under examination is consistent with the purported events and equipment.

If the location (i.e., the environment in which the recording took place) is known, then a comparison of the acoustical properties may aid the analysis/investigation. At the time of

writing, no automatic environment classification analysis has been proposed able to cope with real case scenarios, with or without reference recordings.

Methods such as estimating the decay rate (e.g. RT60 parameter) of late reverberations [64] or applying de-reverberation techniques to then build a profile of the reverberant signal [65] are considered to be unreliable at the time of writing **Fehler! Verweisquelle konnte nicht gefunden werden.**.

If a reference recording can be produced in the alleged environment using the alleged recording device and setup (including locations of microphone and acoustic sources), a comparison via critical listening can be carried out.

If the recording device alleged / purported to have made the recording is known, techniques for recording device analysis can be used.

Microphone frequency response analysis may be used in portions of recordings in which the speech signal is predominant, to determine which, among a set of possible microphones / devices, is most likely to have been used to make the recording [38], [39], [40], [41], and / or to provide information regarding the characteristics of the microphone / device used. Similarly, but focusing on nearly-silent portions of the audio recording, *microphone thermal noise analysis* may be used [42], [43], [44].

General frequency content can be assessed by comparing the LTAS and / or LTASS features obtained for the evidence with those obtained for the reference recordings [24], [28]. It should be noted, however, that these features are influenced not only by the frequency response of the microphone / recording device, but also by other factors such as the encoding parameters or the signal content. Hence the recording conditions must be known and documented as far as possible, to avoid errors.

Comparison of *DC-offset* of the evidential recording against that of reference recordings made on the purported recording equipment may also be used [20], [21], [22].

To avoid any analysis bias, the direct comparison of two recordings in terms of microphone traces should be performed only when the recording conditions are similar, e.g., with similar environment, presence or absence of speech, device, approximate signal amplitude and encoding settings. The features used for the comparison must also be obtained using the same analysis settings (e.g., window length, shape, hop-size, type and number of filter-banks) in both the evidence and the reference file. All settings should be thoroughly documented, for reproducibility.

Frequency response and thermal noise analysis may support the hypothesis of a specific recording device being involved or may be used to exclude specific devices from a list of candidates. DC-offset analysis, however, should never be used to support the usage of a specific device, but only to exclude specific devices from a list of candidates [20], [21], [22].

If the purported model of the audio recorder and the recording software and version are known, encoding analysis can be performed.

If the submitted evidence is provided as PCM file, *inverse decoding* can be used to check that there are no unexpected traces of lossy encoding [26], [30], [32], [36]. If the evidence is provided as compressed (e.g., MP3, M4A) file, *statistical encoding analysis* can be used to verify the ‘real’ bitrate derived from the baseline signal [27], [28], [37], in addition to the one declared on the container.

In some cases, recorders may perform lossy encoding to then store the file in an uncompressed format – thus creating “expected” traces of lossy encoding in PCM files stored on the device. Other recorders may store an encoded file using a higher or lower bitrate than the “real” one used during the recording – thus creating “expected” traces of double-encoding in the compressed files stored on the device. It is therefore important, whenever possible, to make test recordings if the purported software / device are known, and to consider the whole range of options and settings available on the purported recording software / device.

If the purported model of the audio recorder and the recording software are known, metadata and file structure analysis can be performed. If the version of the recording software and the recording settings are not known, test recordings with various possible versions and settings may be required.

Given the input evidence, *metadata and file structure analysis* can be performed to identify which metadata are present on the file, and in which order they are present. Metadata can be categorized into functional (necessary for a correct file playback, mostly dependent on the format used for storage), library related (introduced by the specific encoding library) and software related (introduced by the specific software used for creating the file). These three categories should be considered in conjunction with one another, and it is good practice to store expected values for these metadata and file structure in reference databases [12].

Example metadata and file structure analyses can be found for WAV files [10], [13], MP3 files [10], [14], WMA files [10], [15], M4A files [11], [17], and AMR files [16]. Although these publications may be used as reference, it is important to recognize that the consistency in metadata between questioned and reference recordings is insufficient to claim the absence of any modification, since metadata can also be edited as part of the tampering process.

If the purported model of the audio recorder, the recording software and version, as well as the purported recording settings are known, and the submitted file is in uncompressed PCM format, *quantization level analysis* can be performed.

During the A/D conversion stage, the input analogue signal is digitized using a specific hardware related bit-depth. Bit-depths offered by A/D converters do not always match the bit depth of uncompressed files: the ones stored using 16-bit linear PCM may thus contain signals quantized with 11,12,14 bits. This *real* lower bit-depth can be retrieved and compared to the one found for reference files [24].

It is important to recognize that the consistency in quantization levels between questioned and reference recordings is insufficient to claim the absence of any modification, since they can be edited by expert audio engineers as part of the tampering process.

If the purported / alleged location in which the recording was made is known, and the evidence contains an ENF-signal of adequate quality, the nominal frequency (50/60 Hz) of the ENF should match the one used by the electric network in the provided location. A fine-grained localization, however, is not evidentially reliable at the time of writing [55], [56], [57].

If the evidence contains an ENF-signal of adequate quality and length, *ENF temporal pattern matching* can be performed to determine the time of recording.

ENF temporal pattern matching requires a ENF database which has been properly created and maintained [46], [51], [58], [59]. If an adequate database is available, the frequency trajectory of the ENF component extracted from the evidence can be compared to it according

to [45], [46], [47], [51], [60], [61]. Some ENF databases can also be accessed on demand from trusted sources.

To minimize errors, time and frequency resolutions used for extracting the ENF should match the ones used in the database. Harmonics of the fundamental ENF may also be used to estimate the ENF signal trajectory on the evidence recording.

5.5 Remarks

5.5.1 Dealing with Discontinuous Recordings

Some cases may require the analysis of recordings which are known to be discontinuous from the contextual information. This may happen, e.g., whenever a phone call is interrupting a recording made by a mobile phone, or whenever a pause button on a hand-held recorder is pressed by the user.

In these cases, the recording process was not continuous, but the continuity of fragments between *documented or explainable* discontinuities may still be examined. Furthermore, depending on the recording software and equipment, discontinuities (e.g., pauses) may be indicated by specific signal traces and/or metadata in the file under examination. If this is the case, the analysis would proceed as normal, but in addition the aforementioned explainable / documented discontinuities would be tested to ensure that they are consistent with the apparent / declared sequence of events.

5.5.2 Global / Local Analysis Methods

Most methods described in section **Fehler! Verweisquelle konnte nicht gefunden werden.** address signals with a finite specific length, i.e., they are described in terms of an analysis window which may or may not span the whole file length. Whenever this is the case, then the methods can be used for both global and local analysis.

Global analysis, performed on the whole file length, may be used to check the consistency of the detected traces with the contextual information provided on the content. E.g., it may be used to perform a first screening based on the ENF traces being compatible with the recording time/date, or on the consistency of quantization levels with the container bit-depth.

Local analysis, performed on consecutive analysis windows, may be used instead to check the consistency of the detected traces within the recording and / or to detect artefacts supporting a hypothesis of content modification. E.g., the analysis may look for ENF phase discontinuities on silent portions of the file, or whether the distribution of used quantization levels varies through the file duration.

Where applicable minimum requirements for the length of the analysis windows (and sometimes, of the best operative length of such windows) are stated in the previously cited publications. In case of doubts, practitioners are encouraged to contact the authors for clarification, rather than risking misuse of the methods.

6. VALIDATION AND ESTIMATION OF UNCERTAINTY OF MASUREMENT

6.1 Validation

Validation can be done for each one of the implemented measurement methods. It is suggested that as a minimum three conditions should be used for each validation study. The

dataset for validation should always mirror the casework relevant for the laboratory. For example, for the validation of a method for detecting recompression of an audio file, the conditions may be: file with no recompression as baseline, recompression to the same resolution, recompression to a lower resolution and a higher resolution.

For methods based on human perception, i.e., auditory and visual analysis (waveform/spectrogram), it is strongly recommended that at least two examiners conduct independent analyses. The results should be compared and summarized.

6.2 Estimation of Uncertainty of Measurement

Not applicable.

7. QUALITY ASSURANCE

7.1 Proficiency Testing / Collaborative Exercises

It is recommended that laboratories participate in any suitable available proficiency testing or collaborative exercise every three years. If this is not possible it is recommended that interlaboratory exercises are conducted with two or more laboratories every other year.

7.2 Quality Controls

Not applicable.

7.3 Data Collection for Control, Monitoring and Trend Analysis

Not applicable.

7.4 Verification / Peer Review

Not applicable.

8. HANDLING ITEMS

8.1 At the Scene

Not applicable.

8.2 In the Laboratory

Practitioners should always create and work on a working copy of the audio evidence, and not on the original submitted copy. To ensure that an error-free 1:1 copy of the evidence has been obtained, cryptographic hash functions, for example SHA-2 or SHA-3 should be used. Some software needs an uncompressed file format to conduct an analysis. If so, the conversion algorithm used should be validated to ensure the integrity of the audio content is maintained.

If the evidence digital recording system is provided, then a forensic image of the storage content should be created and the analysis run on a copy of the evidence files as stated above. If the evidence digital recording system has removable media, then it should be replaced with a similar one for the creation of test or reference recordings. Access to the evidence storage should be protected by write blockers where it is technically possible to do so.

9. INITIAL ASSESSMENT

During the initial assessment of material and of the inquiry, contextual information as relevant to the case should be sought after, and ideally, should come from the person who purportedly made the recording. For example:

- In what context was the recording made? E.g. outside, covert recording, telemarketing etc.
- Information regarding the equipment (both hardware and software) and its set up is very useful as well as, where possible, access to the equipment itself.
- Do the recording software and device implement algorithms for automatic gain adjustment, low-cut filter or automatic pausing during silence? Were these options active during the recording session?
- Was the recording session interrupted, e.g. by phone calls?
- Did the recording session take place with a static setup, or was the microphone hand-held and moved around the environment?
- At what time/date was the recording made?
- Is it a first generation recording or was it transferred or re-encoded?
- Was the signal processed, e.g., for speech enhancement?

The main purpose of asking these questions is to attain a foundation of information and data which may be supported or refuted through the examinations undertaken. See section **Fehler! Verweisquelle konnte nicht gefunden werden.**.

Furthermore, when relevant, any specific allegations regarding tampering should be provided to the examiner in as much detail as possible by the submitting party.

During the initial assessment the quality and quantity of the questioned recordings should always be assessed, in order to determine which methods can be used in the investigation. For example, if the signal to noise ratio is very low then a particular method for copy/clone detection might not be possible to use.

10. PRIORITISATION AND SEQUENCE OF EXAMINATIONS

Not applicable.

11. RECONSTRUCTION

When possible, reference recordings should be created using reference equipment (same brand, model, firmware and application, file format and settings as stated in the inquiry and data derived from the case). If no reference equipment is available and reference recordings need to be produced on the evidence device, a forensic image of the entire evidence equipment's memory should be taken (where technically possible) before recording the references. *If possible, the production of reference recordings on the evidence equipment should be avoided, unless the equipment records to removable media.* If the evidence equipment uses removable media, the media containing the questioned recordings should be removed and new or wiped media used for the reference recordings.

Practitioners should try to create reference recordings containing audio material similar to that on the questioned recording. For example, if the recording contains equipment handling noise

or wind noise, sounds from a café or traffic, the reference recording should be made with similar sounds where possible. This aids comparison of the recordings.

12. ASSESSMENT OF RESULTS AND INTERPRETATION

It is recommended that the hypotheses addressed should be formulated based on the inquiry by the client and the contextual information given. As stated in section 5 and **Fehler! Verweisquelle konnte nicht gefunden werden.** the main goal is to retrieve, document and analyze all available traces.

All the results collected from the investigation should be taken into consideration and the level of support for each hypothesis should be stated. The latter can be done and presented in many different ways, in tables or plain text etc. The conclusions may be expressed according to a numerical scale and / or a verbal scale.

When formulating the conclusion, it is of utmost importance that the conditions and limitations on which the conclusion is based are stated.

13. PRESENTATION OF RESULTS

Evidence can be presented to the court either orally or in writing. Presentation of evidence should clearly state the results of any evaluation and interpretation of the examination. Written reports should include all the relevant information in a clear, concise, structured and unambiguous manner as required by the relevant legal process. It is strongly recommended to peer review written reports.

Expert-witnesses should resist responding to questions that take them outside their field of expertise unless specifically directed by the court, and even then, a declaration as to the limitations of their expertise should be made.

It is recommended that the questioned audio material should be played back when presenting the evidence to the court. The equipment used for playback should be adapted to the special acoustic conditions of a courtroom (good loudspeakers or headphones).

14. HEALTH AND SAFETY

Not applicable.

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16. AMENDMENTS TO PREVIOUS VERSION

Not applicable.

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