

## Article

# Evaluating Short-Wave Effects in Railway Track Using the Rail Surface Signal

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**Abstract:** Condition assessment and maintenance planning of railway infrastructure is a prerequisite for safe and reliable train operation. As the loads are constantly increasing, condition assessment of the track must also be further developed. Existing methods can describe the condition of the track well in many cases, but they will reach their limits with faster deterioration processes and shorter time windows for inspection and maintenance, both associated with higher loads. This development can only be countered with an increased understanding of the system and the associated better planning of component specific measures. Among others, short-wave effects of the track need to be considered. The aim of this paper is to demonstrate the possibility of describing short-wave effects with an already existing data source. Insulated rail joints, welding joints, switch components, but also rail corrugation of different wavelengths and squat can be detected, evaluated and monitored by a measuring system based on optical distance meters. These assets and wear phenomena form essential parts of track asset management, but still are not described sufficiently by established methods. Although the so-called rail surface measurement system has been installed on the main Austrian measuring car for years, its full potential could not be exploited due to insufficient positioning accuracy. The method presented in this paper intends to change that. This allows for a holistic assessment of track condition when planning maintenance activities.

**Keywords:** railways; asset management; short-wave effects; insulated rail joints; welding joints; switch components; squat; corrugations



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## 1. Introduction

The track quality not only directly affects the safe operation of the train [1] but also its interaction performance with infrastructures [2]. Irregularities of the track lead to an increased force input for both the vehicle and the track itself, are in this way self-reinforcing and therefore increase without appropriate measures. On the infrastructure side, the interactions are determined by the amplitude and the wavelength of the track discontinuity [3]. Effects with short wavelengths can cause rail fractures and are therefore relevant to safety [4]; at the same time, the elimination of the effects is cost-relevant, as Muhamedsalih demonstrates on squats [5]. Noise problems caused by short-wave effects, as discussed by Li [6], can reduce the attractiveness of the railway system for passengers and residents. In addition, according to Chiengson, the increased force effect due to the high-frequency excitation of vehicles leads to increased deterioration processes of the entire track [7].

To make short-wave effects measurable, measurement systems with high-frequency sampling rates have to be used. Historically, measurement systems used by most infrastructure operators evaluate the infrastructure in longer wavelength ranges. The European standard EN 13848-1 covers three wavelength ranges: D1 (3–25 m), D2 (25–70 m) and D3 (70–150 m) [8]. D3 is only relevant for speeds above 250 km/h, while D1 and D2 must be used obligatorily for asset management. The annex of the standard also refers to possible

measurement methods for short-wave effects, primarily by means of axle box accelerations. However, this part of the standard is declared to be purely informative and is not specified as a minimum requirement.

A requirement that comes with the handling of short-wave and thus punctual faults is exact positioning. Since the timely development of a quality parameter must be considered for a meaningful condition assessment, various measurement runs must be positioned to each other in sufficient quality. Historically, location deviations of measurement runs in the meter scale were justifiable, as characteristic values were calculated over a length of 100 m and more [9]. In addition, today the condition of the track geometry of open track is successfully assessed in this way. Even if the longitudinal level itself is used as a quality index [10], positioning accuracies of 25 cm are sufficient, since this parameter is usually not stored in a higher resolution anyway. To evaluate short-wave effects, we need relative positioning accuracies in the centimeter to millimeter scale. The sector's experience in describing short-wave effects with measuring data is relatively low due to these issues of missing precise position. Nevertheless, also today these effects are assessed by different methods.

The most common way of evaluating short-wave effects (the term "short-wave effect" is defined differently in various works. For this paper, the term is used for all effects of the railway track whose characteristics have a wavelength of less than 1 m. This includes any kind of corrugations, squats, welding joints, insulated joints, switch components, rail breaks, skid marks, indentations, break-outs at the running edge and machining errors) is still visual in-track inspection. Due to the high competence of the responsible track staff, visual inspection still delivers the most reliable results. Nevertheless, significant disadvantages of visual inspection occur. Regular route inspections are carried out at walking pace and are therefore very slow, resulting in high costs on the one hand and low frequencies on the other one. As the trend moves towards less available staff, track condition assessment can no longer be carried by track inspections only in the future. In addition, as the number of trains increases, entering the danger zone must be reduced to a minimum.

One very broad investigated method for the evaluation of short-wave effects are axle box accelerations. Li gives an example for the detection of squats [11], and Molodova describes the possibility for evaluating the health condition of insulated rail joints [12]. Axle box accelerators can be applied at very high speeds and still provide high sampling rates. Additional track unavailability can be avoided by mounting the devices on axles of in-service trains or regular measuring cars. Axle box accelerations are a direct consequence of short-wave effects in the wheel–rail contact point. On the other hand, accelerations are not only triggered by rail condition but also by the condition of the wheels. While a wheel that is flat produces periodic peaks that can be handled relatively well, the influence of wheel out-of-roundness and indentations is rather unpredictable. In addition, the speed of the vehicle has an influence on the amplitude of the measurements making it difficult to compare the signal characteristics [13].

High-resolution images of rails are another method for rail defect detection with great potential, but has not yet been successfully implemented beyond trial operations. This procedure needs intelligent image processing algorithms. De Ruvo and Hovad give an overview on the principles of this method [14,15]. Despite a great deal of research, no system has been fully proven in operation yet.

It is also possible to evaluate short-wave effects using lasers. There are different possibilities of laser arrangement and subsequent data processing. The measurement system of the rail surface described in detail in the method section corresponds to one of these designs.

Vidovic could show that it is also possible to use Fibre Optic Sensing for the detection of short-wave defects [16]. In his thesis, Vidovic demonstrated that the system provides information on the condition of insulated rail joints and turnout crossings. Research on distributed acoustic sensing is ongoing.

There are several other concepts conceivable. Papaalias gives an overview on measuring principles like ultrasonic transducers, magnetic induction, eddy current technologies, radiography, long-range ultrasonics and laser ultrasonics [17].

Although all the described methods are fundamentally suitable for the assessment of short-wave effects, they have not been able to establish themselves in practice for a variety of reasons. This is partly due to the fact that the achievable measurement speeds are clearly too low, which makes a network-wide implementation unfeasible. This applies, for example, to many of the methods described by Papaalias. For various technical reasons, fiber optic sensing and image recognition tools are not yet developed far enough to make reliable statements. It is also not expected that all relevant effects can be evaluated with these systems. The same applies to axle box accelerations. These have already been intensively researched and provide reliable results for certain scenarios. However, they do not only react to the effects of the rail, but also to vehicle properties and stiffness changes of the track. A reliable classification of effects only with axle box accelerations is not considered possible, at least not at present. In addition, many of the methods raise the question of the relative and absolute positioning of the data.

Exact positioning of the measurement data is required for all measurement principles. Wang distinguishes absolute positioning errors and relative positioning errors [18]. Since absolute positioning errors describe the deviation between the positioning and the absolute position of a point on the track, they are particularly important for planning maintenance activities. Relative errors, on the other hand, describe the deviation of the positioning between different measurement runs and are relevant for the investigation of time series. For short-wave effects, relative errors are primarily relevant, but the absolute error can also be very important. Additionally, Wang describes a way to significantly decrease the relative positioning errors using big-data fusion and incremental learning [18].

Khosravi also deals with the positioning of track geometry measurements [19], using different alignment methods including cross-correlation function, recursive alignment by fast Fourier transformation, dynamic time warping, correlation optimized warping and a combined method. The combined method has proven to be the most reliable, but also the most complex.

The data sources of the underlying research of this paper are measurement systems of the EM 250, the main track measurement car of OeBB-Infrastruktur AG (Austrian Federal Railways). Fellingner has developed an algorithm allowing for a precise post-positioning of the majority of the measured area with the help of signal characteristics [20]. The rail surface signal dealt with in this paper was not included in the method due to the significantly higher sampling rate and the requirement of an even more precise positioning. Nevertheless, Fellingner's method is adapted to the data format of the measuring car and therefore forms the basis for the method described later on.

## 2. Positioning Method

For the detection and evaluation of short-wave effects, we use the original output of an available measurement system. This data is obtained from the rail surface measurement system, a chord-based system in which three optical distance sensors are mounted in a row. Figure 1 illustrates the basic setup of the laser sensors.

The first and the last laser build a virtual chord. The actual measurement value describes the distance between the rail surface of the middle laser and the chord surface at the same position. The measurement system can be mounted onto vehicles with speeds up to 250 km/h and still returns a data point every 5 mm. The recorded wavelength range is between 0.01 and 1 m. The combination of a sampling rate of 5 mm and the high frequency spectrum of the system makes us confident for possible use cases, as other measurement systems (in Austria) cannot provide this.

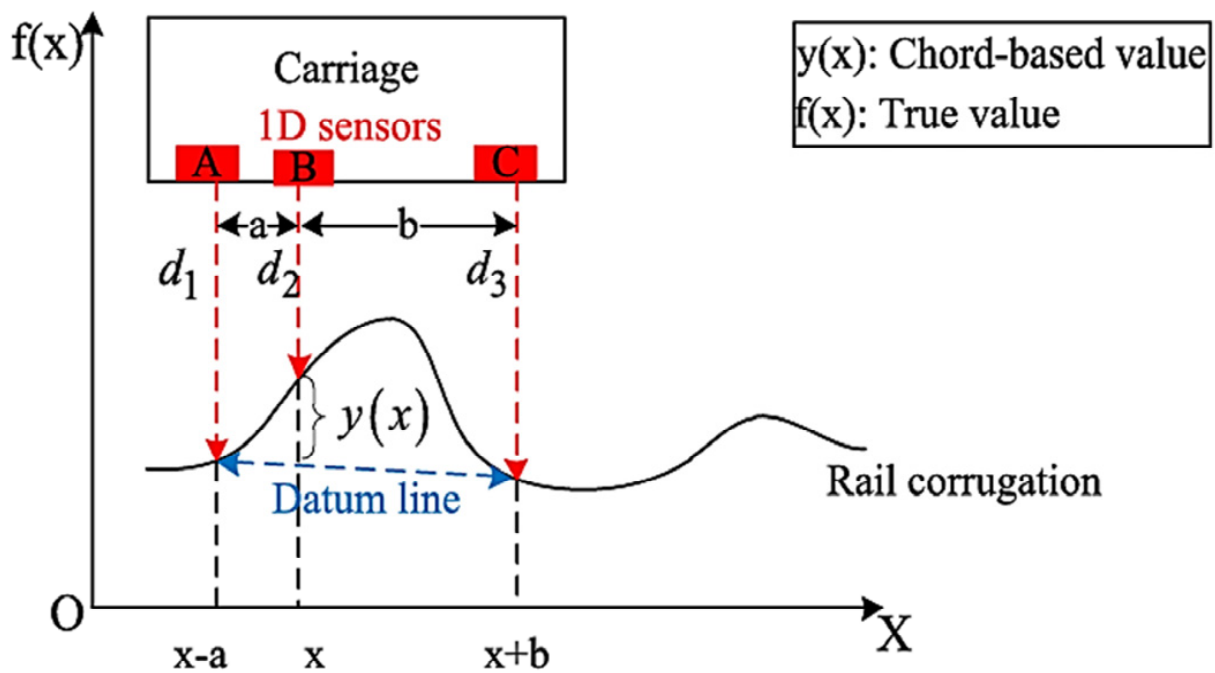
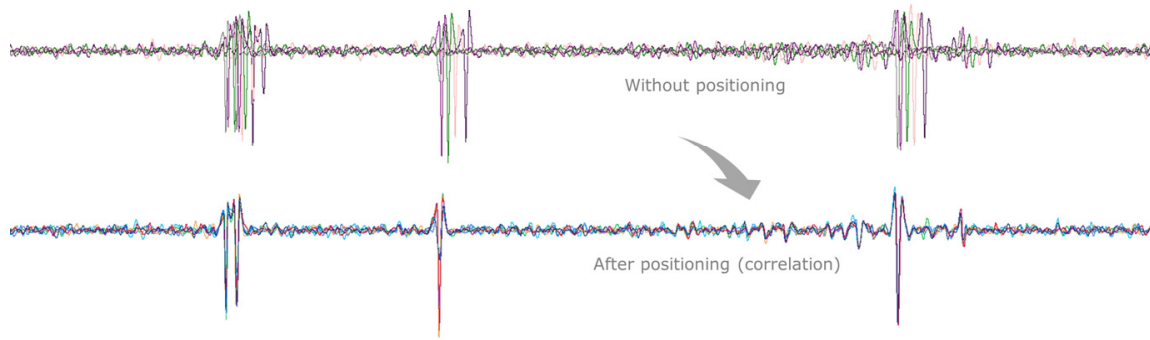


Figure 1. Measurement principle of the rail surface signal [21].

The asymmetrical chord principle with three measuring points leads to very stable measuring results. Whereas a direct measuring method would lead to a lack of accuracy if vehicle movements occur, the chord principle can handle these very well. Linear correlated shifts influence all three outputs in the same way and are thus automatically compensated. Small pitch motions lead to linear correlated but opposite shifts of the first and last laser and therefore do not influence the output of the chord value. The chord measurement system's output-signal reflects the corrugation of the railhead with distorted amplitudes. The amount of distortion depends on the wavelengths of the output signal characteristics and can be extracted from the transfer function of the measuring system. If the actual space curve of the rail corrugation is needed, relatively complicated algorithms have to be used for the recalculation of the space curve. These algorithms can only deliver an approximated space curve and thus a lower data quality. As for many evaluations, it is sufficient to work with chord-values and signal characteristics of chord values; pros and cons of a recalculation of the space curve must be weighed against each other.

Although, the measurement system has been mounted onto the EM250 since 2005 and some modified parameters have been partly in use since then, the original output signal was not investigated up to now. The main reason might be the already mentioned precondition of an exact positioning process. Without re-positioning, the potential of the small sampling rate cannot be exploited.

For re-positioning we use an algorithm shifting signals of different measurement runs synchronously to each other. For this purpose, signal characteristics are used and a synchronicity criterion is defined. We chose the sum of the Euclidean distance as it delivers the most reliable results. To determine the best possible relative position of two measurement runs, the signal of one measurement run is shifted sequentially by a certain distance and the similarity measure to the second run is calculated anew each time. In contrast to Fellingner, the signal is shifted by only 25 mm per iteration. The relative displacement with the smallest summed Euclidean distance is therefore carried out for all measurement runs with synchronous measurements as result. To demonstrate synchronicity, Figure 2 shows input and output of the computing process.



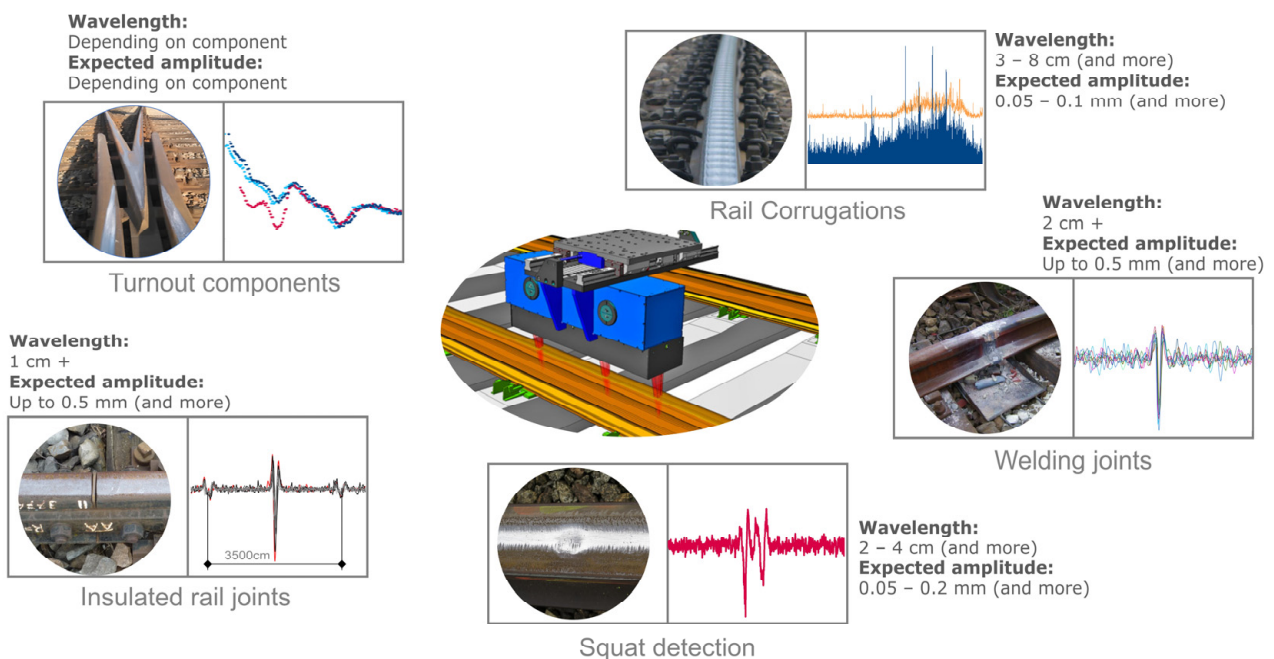
**Figure 2.** Input and output of the positioning algorithm.

The different colors of the signals in Figure 2 reflect different runs of the measuring car. In this case five measurement runs are processed corresponding to about 1.5 years. The lines in the upper half of the figure represent the filtered signal without exact positioning. While the signal characteristics appear to match each other, the different runs are displaced to each other. The lower half of the figure shows the same signals after precise positioning. Here, all signal characteristics match each other.

Although the described method works in principle, it is computationally expensive and time-consuming due to the large amount of data (one data point every 5 mm) and the high number of iterations (to catch outliers, all potential displacements  $\pm 25$  m must be covered leading to 2000 iterations per measurement run). For this reason, a process step is carried out upstream guaranteeing a positioning accuracy of  $\pm 1$  m and reducing the computing time by a multiple.

### 3. Results and Discussion

After providing the necessary data (positioning) quality, we can evaluate the potentials of the measurement system. Different rail phenomena lead to different signal characteristics. Figure 3 shows short-wave phenomena already possible to be identified with the surface signal or derivatives of the signal.



**Figure 3.** Potentials of the rail surface signal [22].

### 3.1. Rail Surface Corrugations

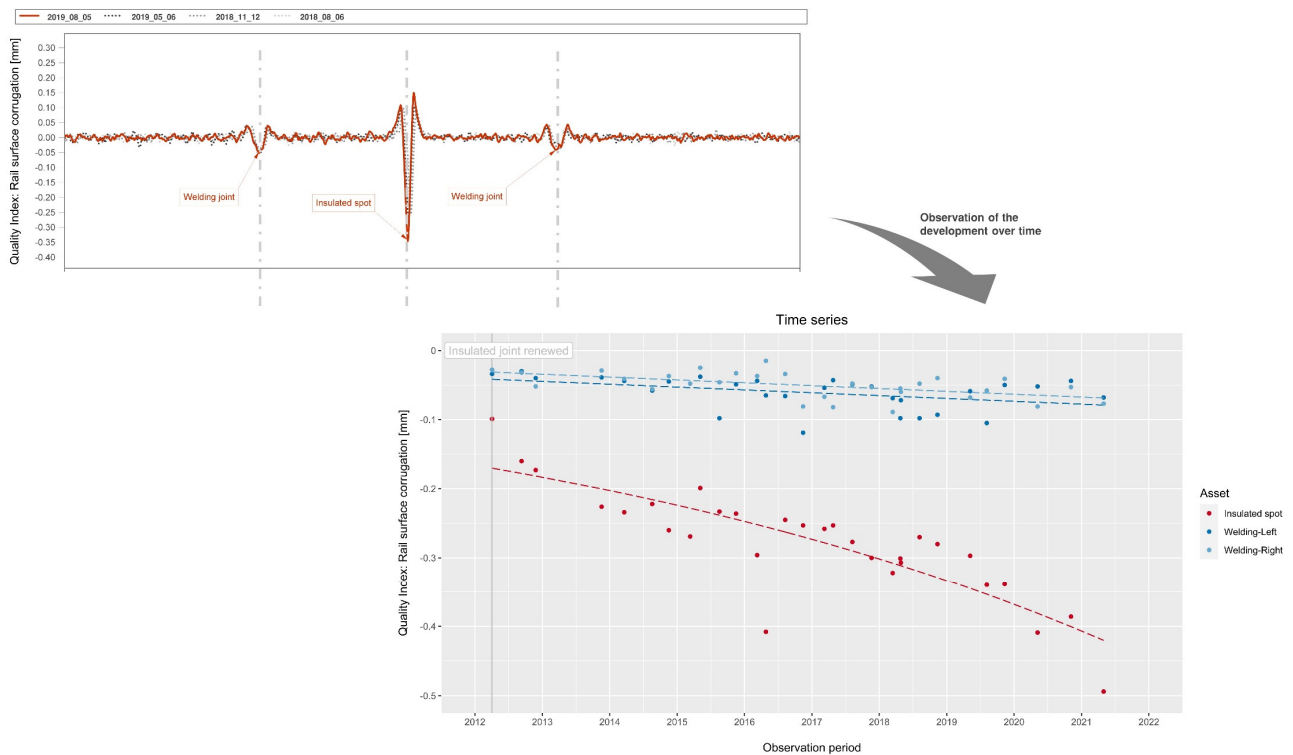
Rail surface corrugations are the original reason for installing this measuring system on the measuring car. In addition to the original measured value, the measuring system also outputs channels with dominant amplitudes and frequencies for detecting corrugations with different corrugation lengths. Corrugations of wavelengths are indicated as a series of intense signal deflections in the channel output for the respective wavelength range.

### 3.2. Turnout Components

In conjunction with other measurement data, it is assumed that the rail surface signal can also contribute to the condition assessment of turnout components. This aspect is part of the FFG project Railways for Future: Resilient Digital Railway Systems to enhance performance. Detailed results will be available in future.

### 3.3. Insulated Rail Joints

Insulated rail joints are still an indispensable part of the infrastructure for many networks. Dividing track into blocks for the train control system, the joints isolate sections of track from each other. However, insulated rail joints form points of inhomogeneity often leading to a poor-quality condition. This is true for the insulating joints as well as for components in the area of the joint. In the rail surface signal, insulated joints appear through three signal deflections being symmetrical in relation to each other. The first and the last deflection represent the welding joints where the factory-made insulated joint is welded into the track. The middle deflection corresponds to the insulated spot. An over-linear deterioration could be observed at the insulating spots examined so far. Figure 4 shows the typical signal characteristics and the temporal quality development of the insulated spot and the adjoining welding joints.



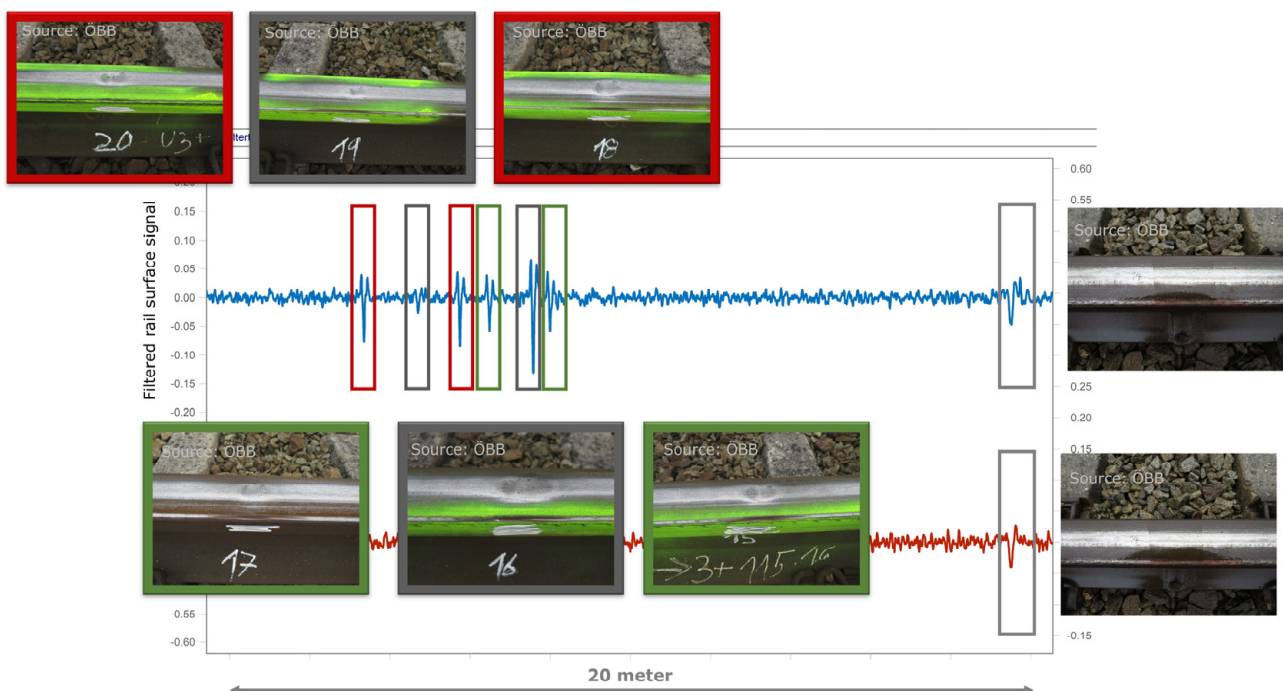
**Figure 4.** The time development of the rail surface signal in response to an insulated rail joint.

The quality index for the time series analysis is the minimum value of the deflections in place of the respective asset. For the area shown, there is neither a maintenance operation documented nor evident in the data. It is noticeable that the quality level of the insulated

rail joint is already significantly worse directly after installation compared to the welding joints, and additionally deteriorates disproportionately over the years. We suspect that this is a manifestation of the self-reinforcing effect already described.

### 3.4. Welding Joints

For most infrastructure operators, continuously welded rails are the state of the art. The welding technology used is technically very advanced, while welding joints nevertheless still form points of inhomogeneity increasing dynamic load-input into the system. Inhomogeneities due to welding joints are clearly visible in the rail surface signal. They show, as demonstrated in Figure 5, a more linear and slower degradation over time compared to the insulating spot. However, a correlation between the different welding processes and the deterioration rate is suspected.



**Figure 5.** A comparison of the signal characteristics of the measurement system with documented squats.

### 3.5. Squats

One type of rolling contact fatigue damage has gained prominence in the recent years in many countries: squats. Untreated squats pose a risk of rail breakage due to vertical cracks. In addition, the typical indentations of the rail surface lead to increased dynamic load inputs into the system. Detected early enough, squats can be removed relatively easily using a common rail surface treatment such as grinding or milling. However, detected too late, the only option is to exchange rails, coming along with both high replacement costs and the extra costs of track unavailability. Squats are recognizable in the measurement signal due to their indentation of the rail surface. Figure 5 shows a part of a section where any kind of rail defects were documented during the visual inspection.

A comparison of the rail surface data with the documented effects shows that the positions largely match. Initial investigations indicate that at least squats of class B (moderate) are detectable. The main issue is a differentiation between squats and other effects of the rail, especially welding joints. We are currently working on methods to ensure this distinction.

For all described potentials the signal characteristics can be assigned to the components and plausible deteriorations over time can be observed. Statistical significance is currently investigated.

#### 4. Conclusions

Not least due to the lack of regulations in railway standards, short-wave effects are not investigated by a uniform and established measurement system. As these effects are indispensable for a holistic description of the system, this paper discusses possible technologies. Current research in this area is driven primarily by axle box acceleration measurements and image recognition tools. However, with the rail surface measuring system another possibility to measure and evaluate short-wave effects is available. The system is based on optical distance lasers that scan the rail surface in the middle of the rail head using chordal methods. Current evaluations show that the measurement system has the potential to evaluate effects such as squats, insulated rail joints, welding joints, switch components and corrugations of different characteristics. The findings are expected to lead to a better holistic understanding of the track system supporting a better planning of maintenance actions.

The reliability of results is the subject of further investigations. Since a sound data base of 15 years of measured recording of the rail surface signal and other parameters such as longitudinal level can be drawn upon, another goal is the evaluation of alternating effects between short-wave effects and the holistic condition of the track.

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