

WHEEL / RAIL NOISE, CORRUGATION and REPROFILING

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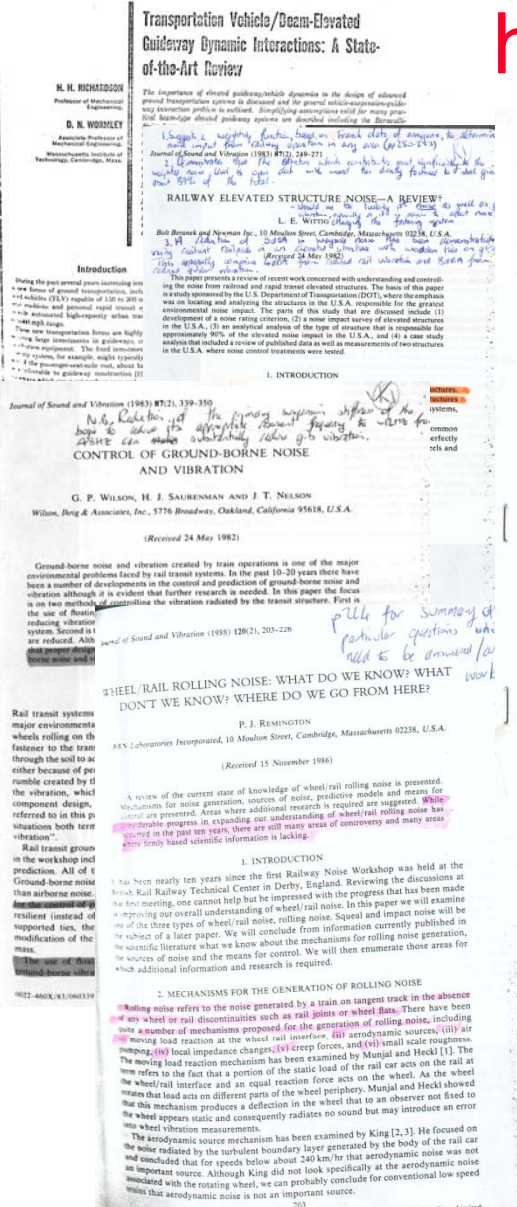
WRI EU seminar, Derby, UK 21-23 October 2015

scope of presentation

- **Wheel/rail noise**
 - historical background
 - types of wheel/rail noise
 - wheel and rail irregularities and noise
- **reprofiling and corrugation development**
 - good and bad practice
- **Standards to control irregularities**
- **Measurements**
 - corrugation, acoustic roughness and long waves (rails)
 - OOR, corrugation, acoustic roughness,.. (wheels)
- **conclusions**

wheel / rail noise: historical background

- 1970s-1980s
 - much work done in North America
 - structure-borne noise was of particular interest
- 1990s to present
 - more work in Europe, less in US
 - standards drafted mainly in Europe
- future
 - China
 - resurgence of interest in US?



Theoretical modelling of wheel-rail noise generation

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The major source of noise from railways, particularly at high speeds, emanates from the wheel-rail region. This wheel-rail rolling noise is generally (a) based on structural vibrations of the wheels and rails, excited from the contact patch and (b) the main excitation is caused by the wheel and rail surface roughness (undulations), which introduce a relative vibration between the wheel and rail.

A linear mathematical model of wheel-rail interaction has been developed which incorporates detailed predictions of the vibration of the wheel, the rail and the contact area. Results of this model give good agreement with experimental results as long as the properties of the wheel, the rail and the contact area are known.

Journal of Sound and Vibration (1993) 161(3), 381-400

WHEEL-RAIL NOISE GENERATION, PART I: INTRODUCTION AND INTERACTION MODEL

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(Received 12 February 1991, and in final form 30 October 1991)

In this, the first of a series of papers on wheel-rail noise generation, a survey of relevant literature is first presented. That noise is generally thought to be wheel and rail structural vibrations excited by a combination of the wheel and rail surface roughness. A detailed model of the noise generation process is then developed, which is based on the excitation by the roughness, which forms a relative displacement input at the wheel-rail interface. While not new in concept, this model is presented in a much more general form than previously, and effective alternative excitation mechanisms are considered.

Journal of Sound and Vibration (1996) 188(1), 149-160

ON THE RELATIONSHIP BETWEEN WHEEL AND RAIL SURFACE ROUGHNESS AND ROLLING NOISE

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(Received in final form 20 November 1995)

Theoretical models linking rolling noise and surface roughness have been available for some 20 years. For even longer, the qualitative link has been acknowledged between the presence of visible corrugation on rail or wheel surfaces and increased noise generation. This roughness, or undulation in the surface profile, has wavelengths of most importance between about 10 and 30 mm, and amplitudes from between about 0.1 µm and 30 µm—greater for severe corrugation. An important open question is relation to roughness excitation is the validity of the assumed linear relation between roughness and noise. In part, the answer to this question depends on the quality and completeness of the roughness measurements. This is illustrated by comparisons of different rail roughness systems. Special care must also be taken with the processing of roughness data before a representative excitation spectrum can be derived. In this paper experimental evidence from a number of sources is presented to confirm the linear relation between roughness and noise, at least for roughness amplitudes which are not too severe. Attention is also given to the validity of the assumption made in the models that the wheel and rail roughness spectra may be added on an equal basis to give the total roughness spectrum.

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1. INTRODUCTION

While theoretical models linking rolling noise and surface roughness have been developed in recent years [1–5], for even longer the qualitative link has been acknowledged between the presence of visible corrugation on the surface of the rail (known as 'rolling rail') or of the wheel ('polygonization') and increased noise generation.

In the theoretical models used for rolling noise [1–5] a linear relation has been assumed between roughness amplitude at a given wavelength λ (in m) and the sound pressure produced at the corresponding frequency f , given by $f = V/\lambda$, where V is the train speed in m/s. Full validation of these models involves complex measurement exercises and has been presented elsewhere [5, 6]. In this paper, the specific question of the linearity of the relationship between roughness and noise, for which many more results are available, will be addressed.

According to the theoretical models, the roughness introduces a relative displacement between the wheel and the rail. This is essentially a physically correct model, although some assumptions have to be made, in particular that the roughness effectively acts at a single point and that the contact patch size and shape (and thereby stiffness) are not influenced by the roughness. By assuming linearity of the excitation mechanism, and also of the Hertzian contact spring, the calculations can be performed in the frequency domain. Clearly, linearity could fail to apply in two extreme situations. The first is that when the

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sources of wheel / rail noise

- Bender, Remington, Galaitsis, Rudd, Ver (BBN, 1976)
 1. rolling noise:
 - wheel and rail “roughness” critical
 2. impact:
 - wheel / rail discontinuities
 - could consider as special case of 1.
 3. squeal:
 - stick/slip: difference in static / dynamic friction critical
 - “tonal” response: excitation of lightly-damped wheel resonances
 - “friction modifier” is an excellent practical control
 - can affect slightly by grinding to improve steering, and thereby reduce “angle of attack”

Here we discuss noise excited by wheel & rail irregularities.

Wavelength ranges of interest

		20m/s (72km/h)	50m/s (180km/h)
audible ground-borne noise	25-250Hz	800-80mm	2000- 200mm
structure-borne noise	100-2000Hz	200-10mm	500-25mm
wheel-rail rolling noise	100-5000Hz	200-4mm	500-10mm

- large range of wavelengths of interest
 - at least 4-500mm just for rolling noise at typical train speeds
 - 4-2000mm for rolling noise and ground-borne noise

model of wheel / rail *rolling* noise generation (DJT, 1991)

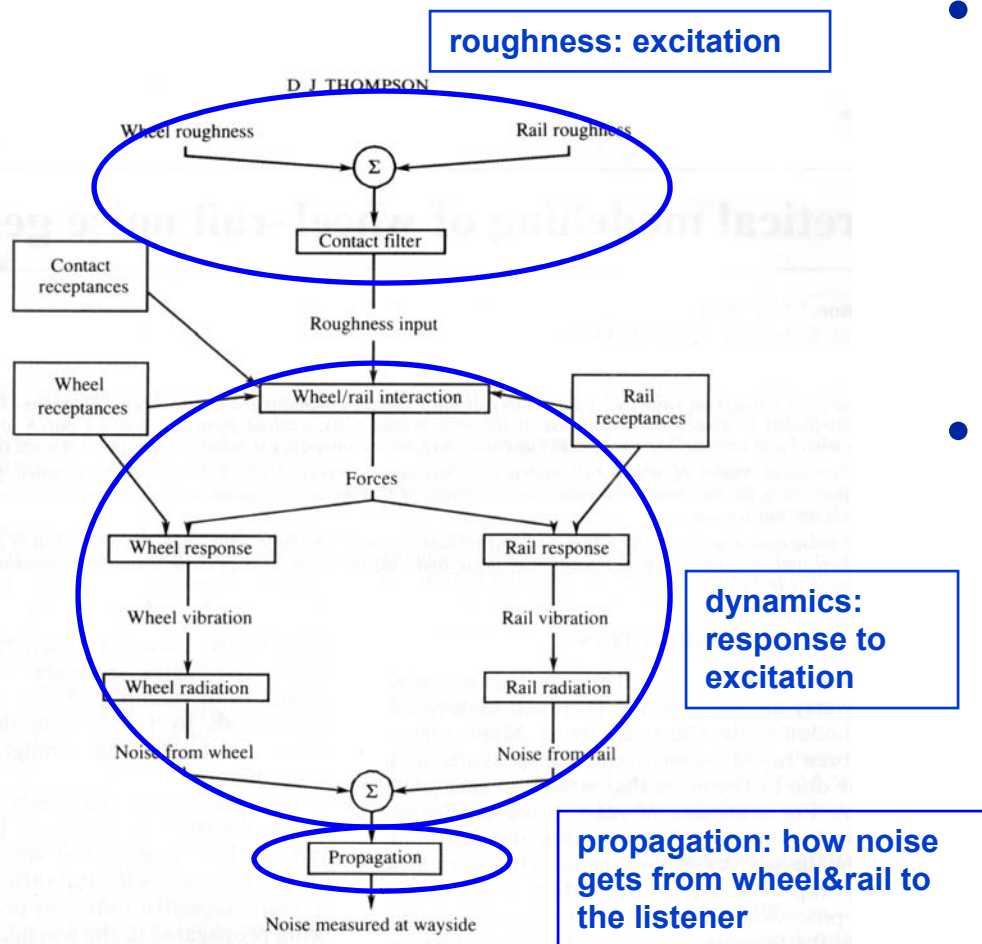
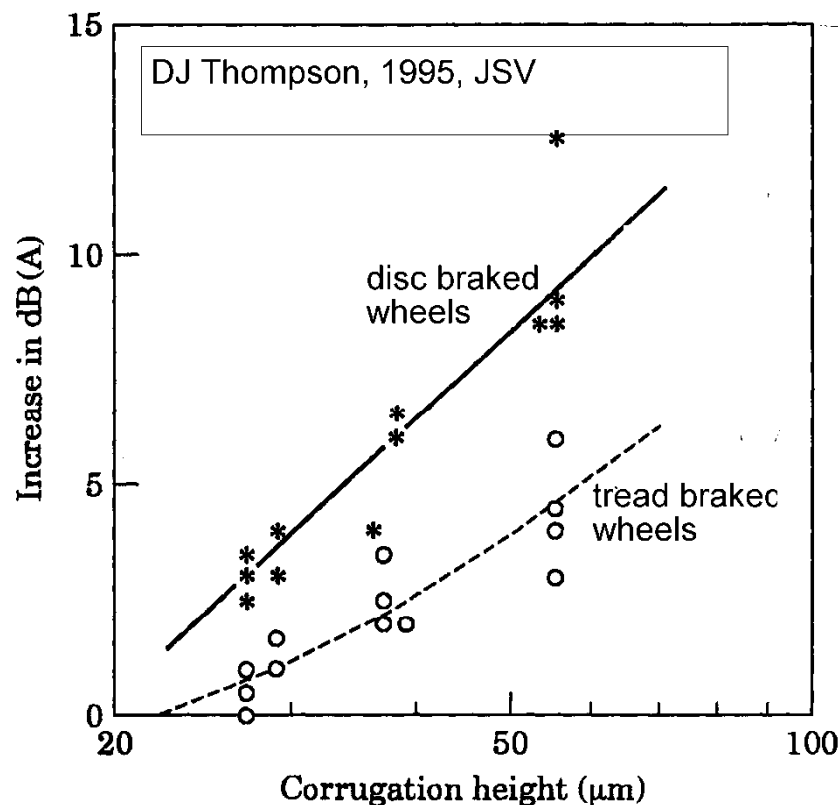


Fig. 1 A framework for wheel-rail noise generation

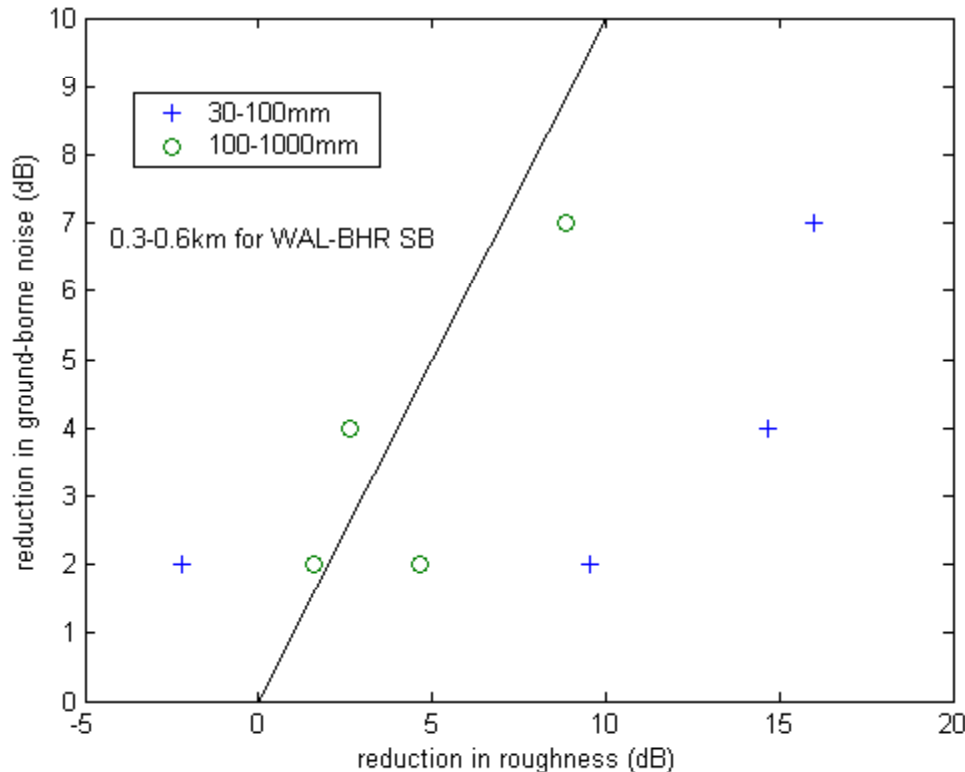
- excitation of dynamic behaviour by wheel/rail “roughness” i.e. irregularities
- control noise by
 - controlling roughness
 - modifying dynamic behaviour
 - affecting propagation

How much do irregularities influence air-borne noise?



- >10dB increase in noise with corrugation (“short” wavelength)
∴ removal of irregularities can reduce noise by >10dB

How much do irregularities influence ground-borne noise?



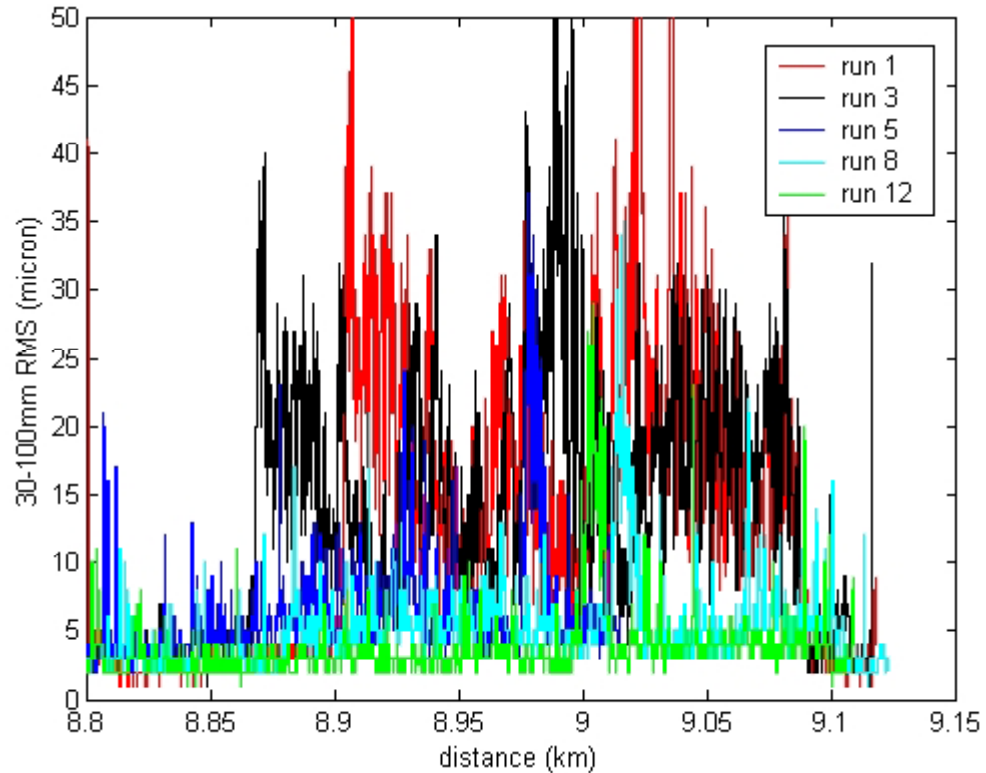
- noise data from 4 sites courtesy of James Shepherd, N&V Engineer, London Underground
- corrugation pre/post grinding from Schweerbau GmbH (CAT)

- in-property noise reduction correlates roughly with reduction in “roughness” in 100-1000mm wavelength range
 - 20-200Hz for 20m/s (50mph)
 - 25-250Hz considered the range for “audible ground-borne noise”
- expect in-vehicle / air-borne noise to correlate better with short wavelength roughness
 - reduction in 30-100mm roughness with grinding is much greater than the reduction in 100-1000mm roughness

rail corrugation and wheel / rail noise: the influence of reprofiling

- rail corrugation is the main cause of excitation of wheel and rail, and therefore of noise
- removal (or prevention) of corrugation is therefore a critically important way of reducing wheel / rail noise
 - prevention:
 - asymmetric profiling to improve curving and reduce corrugation in curves
 - reduce irregularities: “prevention” where discrete irregularities e.g. welds are critical in corrugation initiation
 - reprofiling (mainly grinding) is otherwise a “treatment” of corrugation, albeit one of the most widely used and most effective

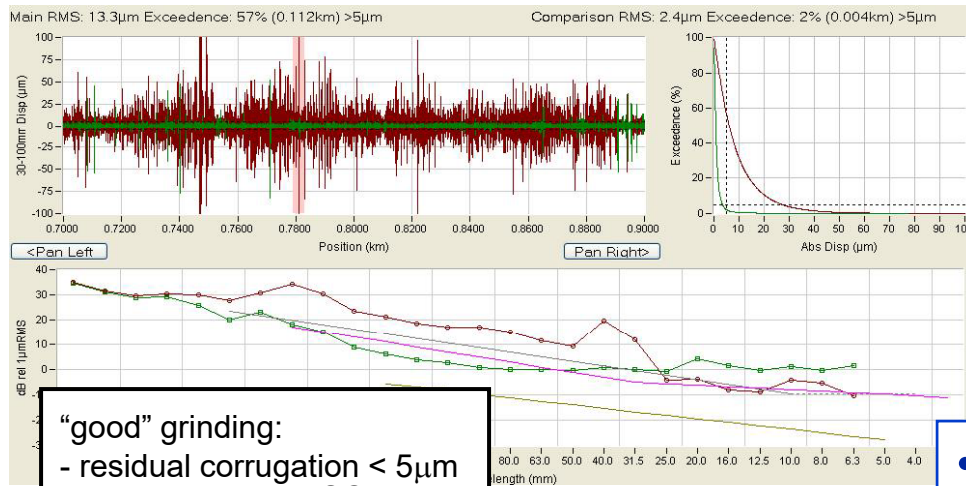
removal of corrugation (metro system)



- reduction in 30-100mm corrugation: 12 passes
 - $> 0.050\text{mm}$ RMS initially
 - $< 0.003\text{mm}$ (0.12 thou) RMS after 12 passes
- measurements (at 1mm interval) *during grinding* using train-based equipment
 - accuracy of microns

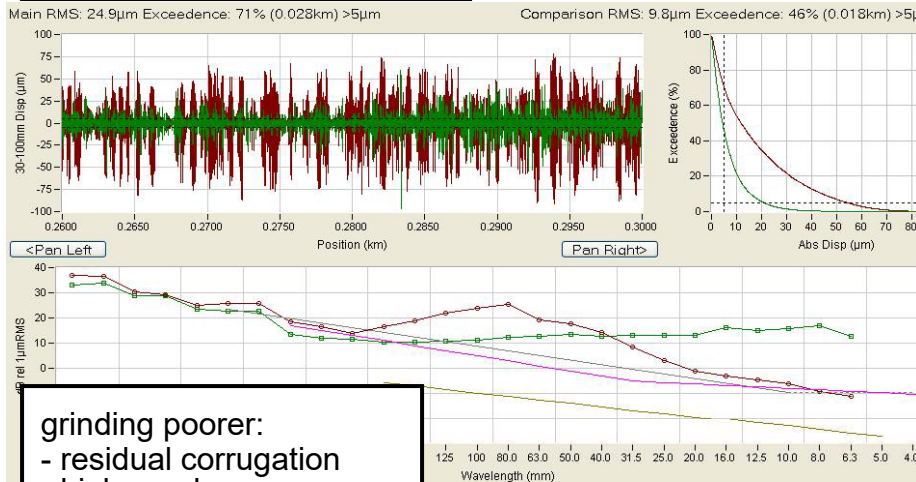
reprofiling

what is possible and what should be avoided?



“good” grinding:

- residual corrugation < 5µm
- spectrum below ISO3095

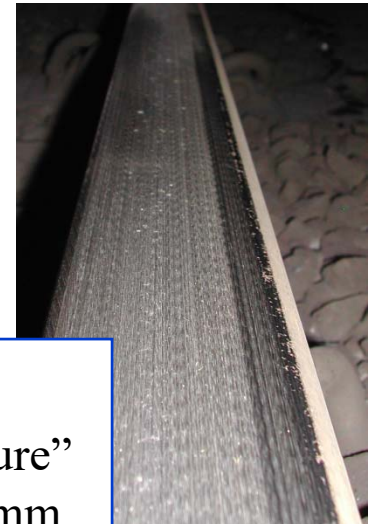
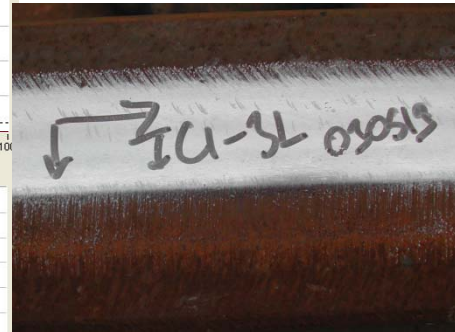


grinding poorer:

- residual corrugation
- high roughness
- spectrum well above ISO3095

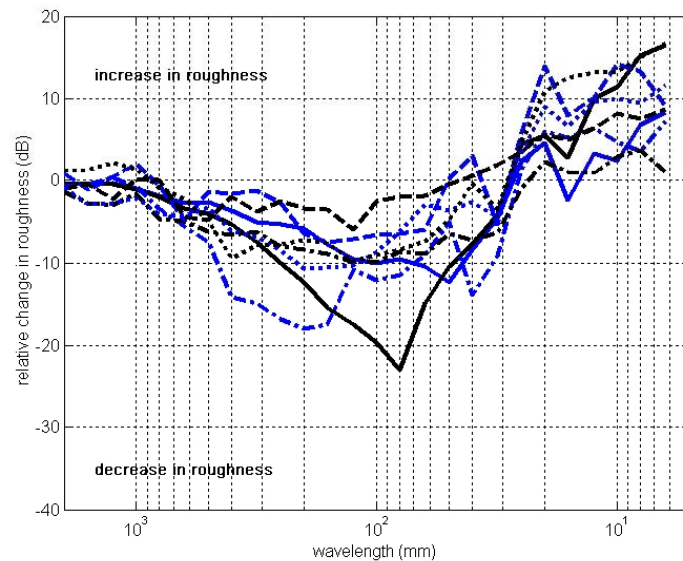
- **minimise**

- “grinding signature” (typically 20-30mm wavelength)
- short wave roughness

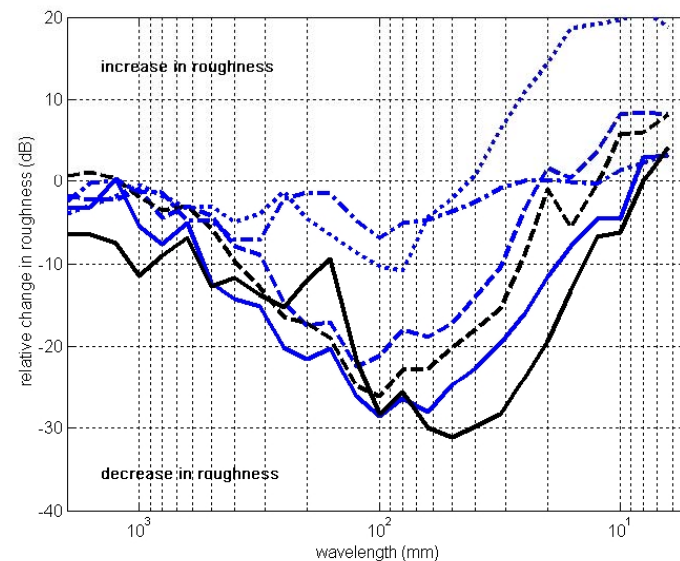


Effect of reprofiling on irregularities

typical

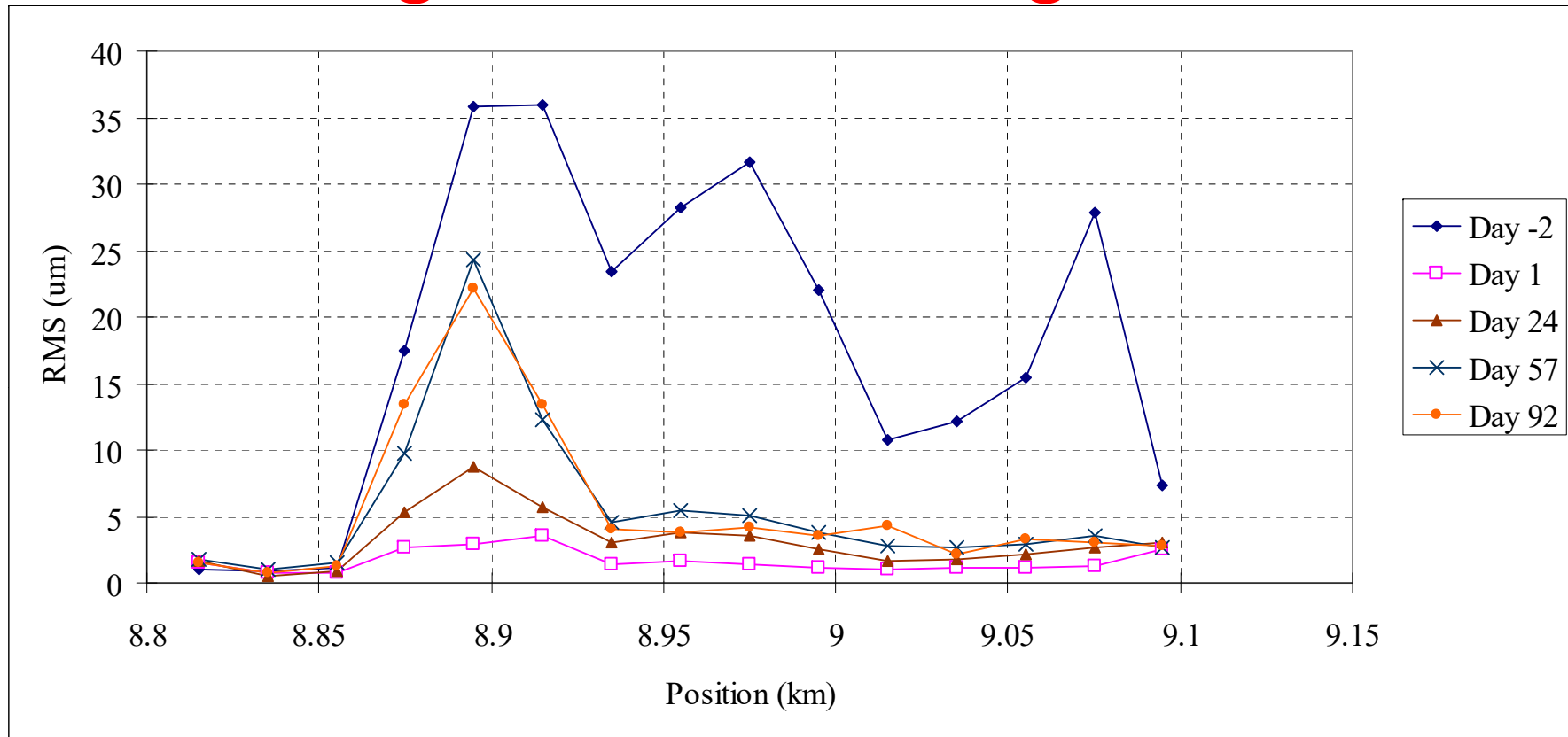


extremes



- Typical reduction in roughness of 10-20dB in mid-wavelength range (30-300mm).
- Increase in roughness for $\lambda < 30\text{mm}$

regrowth of corrugation



- 30-100mm corrugation on metro (measured with CAT)
 - well developed after only 2 months
- note that corrugation develops rapidly from very small residual corrugation ($<4\mu\text{m}$ RMS)

NB This is not typical: very rapid development

EN / ISO standards relevant to reprofiling and irregularities

- EN ISO 3095
 - acoustic type testing of vehicles
- EN 15610: 2009
 - rail roughness measurement
 - now contains the specification for rail roughness measurement that was once in EN ISO 3095
 - forms basis of EN for wheel roughness measurement
- EN 13231-3:2006
 - reprofiling of rails
 - also 2012 version for those with lower standards
- EN 13674-1
 - rail standard

Wavelength ranges considered in Standards

(European and International)

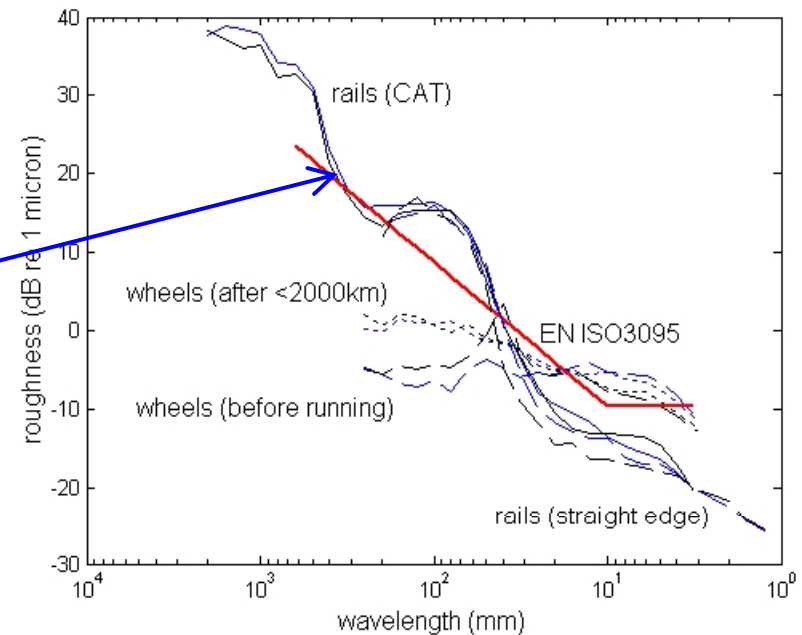
	maximum (mm)	minimum (mm)
EN 15610	250	3.15
EN ISO 3095	630	3.15
EN 13231-3	1000	10

- EN15610 is adequate for w/r rolling noise for low speed traffic (< 20 m/s)
- EN 3095 is adequate for w/r rolling noise for higher speeds (< 50 m/s)
- Only EN 13231-3 approaches sufficiency for ground-borne noise
 - but it is not an acoustic standard

EN ISO 3095:2005 & EN 15610:2009

- EN ISO 3095: acoustic type testing of vehicles

- specifies the limiting roughness spectrum for a site to be used for this purpose
- strictly not a standard for “allowable corrugation”, but is nevertheless useful
 - more demanding than EN13231-3:2006
- similar (lower) levels specified for TSIs in Europe (rules for interworking of trains)



- EN 15610 has the same roughness limit

EN 13231-3:2006

- European standard for reprofiling of rails

Table 1 — Window lengths

Wavelength range (mm)	10 - 30	30 - 100	100 - 300	300 - 1 000
Window length (m)	0,15	0,5	1,5	5

Table 2 — Moving average of RMS amplitude limits

Wavelength range (mm)	10 - 30	30 - 100	100 - 300	300 - 1 000
Limit of moving average of RMS amplitude (mm)	0,004	0,004	0,012	0,040

Table 3 — Moving average of peak-to-peak amplitude limits

Wavelength range (mm)	10 - 30	30 - 100	100 - 300	300 - 1 000
Limit of moving average of peak-to-peak amplitude (mm)	0,010	0,010	0,030	0,100

Table 4 — Acceptance criteria for longitudinal profile expressed in terms of allowable percentages of track exceeding moving average RMS or peak-to-peak amplitude limits

Wavelength range (mm)	10 - 30	30 - 100	100 - 300	300 - 1 000
Class 1	5 %	5 %	5 %	10 %
Class 2	No requirement	10 %	10 %	No requirement

most significant wavelength ranges

- EN 13231-3:2012 has more generous limits for allowable residual irregularities

EN 13674-1:2003

- European rail standard

- vertical flatness of new rails

- Class A

- $\leq 0.3\text{mm}$ over 3m chord

- $\leq 0.2\text{mm}$ over 1m chord

- Class B

- $\leq 0.4\text{mm}$ over 3m chord

- $\leq 0.3\text{mm}$ over 1m chord

- At least 95% of rails to be within limits specified

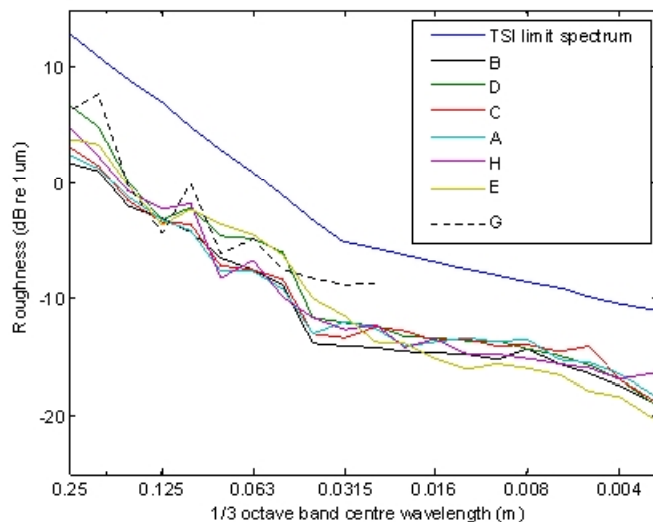
- Remainder to be within 0.1mm of these limits.

These limits are primarily a means of reducing relatively low frequency (<50Hz) dynamic forces (vehicle ride, GBV, ballast degradation)

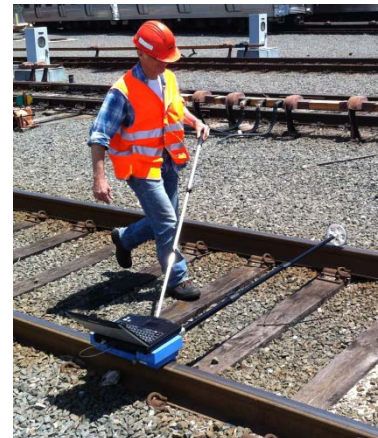
measurement of roughness & corrugation: manual equipment



- straight-edge based equipment
 - simple
 - slow, bulky, limited measuring length (1m increments)
- trolley (CAT)
 - accuracy better than $1\mu\text{m}$
 - useable by one person
 - measure at walking speed (1m/s)
 - can also measure long wavelengths ($>1\text{m}$) and welds



results from
CEN test of
EN15610: CAT
is "H"



vehicle-based equipment



- systems for
 - rail grinders / reprofiling trains
 - hi-rail or similar
 - self-contained trolleys
- measure microns at up to 50km/h



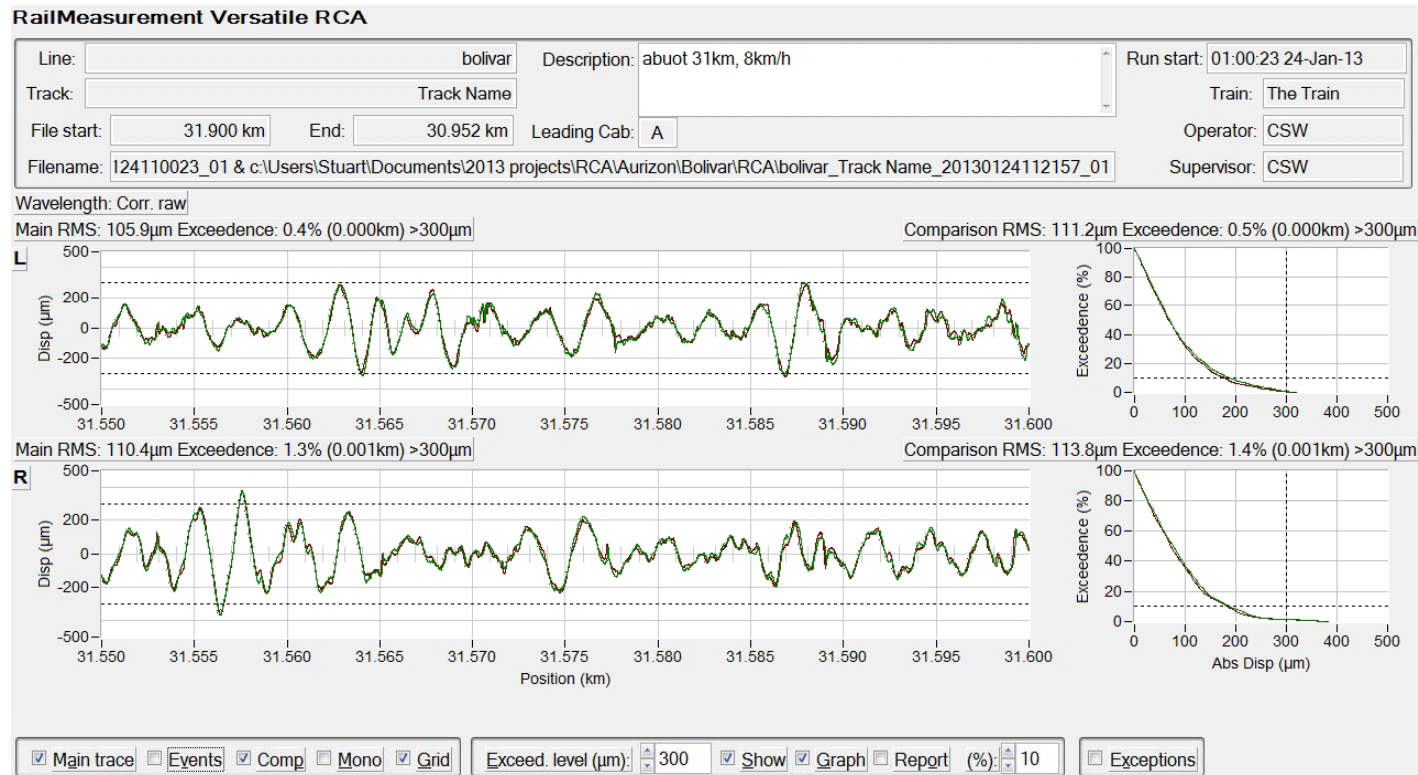
How good is an instrument?

- Can an instrument be “calibrated” or even “validated” for measurements of long wavelength?
- If not, how can we tell whether or not an instrument is “correct”?
- Can we tell how correct it is?

proposal

**If repeatability is better, then
equipment is better.**

an objective and relevant assessment of “repeatability”



- Two measurements with RCA under same conditions over 50m of track.
 - raw displacement “looks” repeatable

Objective assessment of repeatability

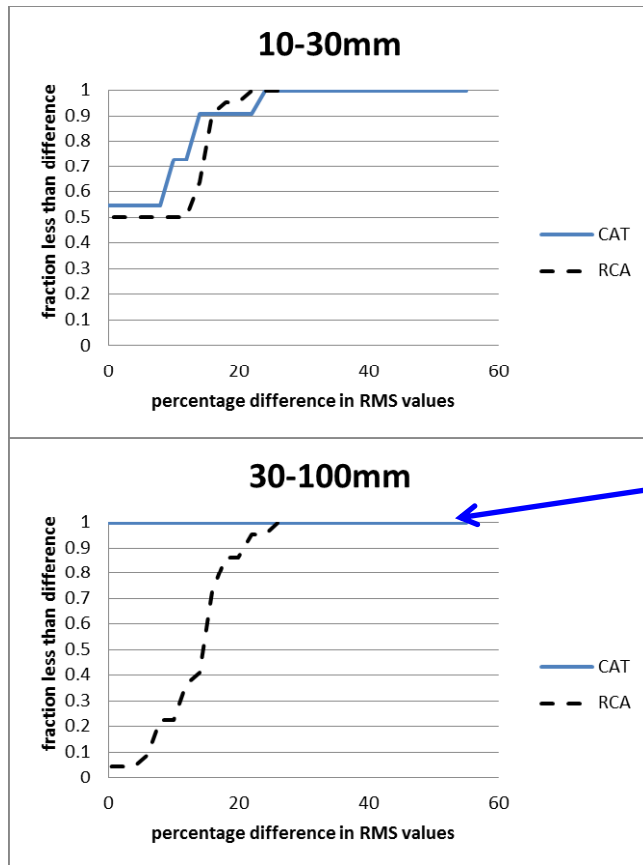
- Percentage difference in measurements

$$y = 2 * |s_A - s_B| * 100 / (s_A + s_B) \%$$

where s_A and s_B are RMS amplitudes of irregularities for runs A and B, which are made under identical conditions e.g. speed, direction,....

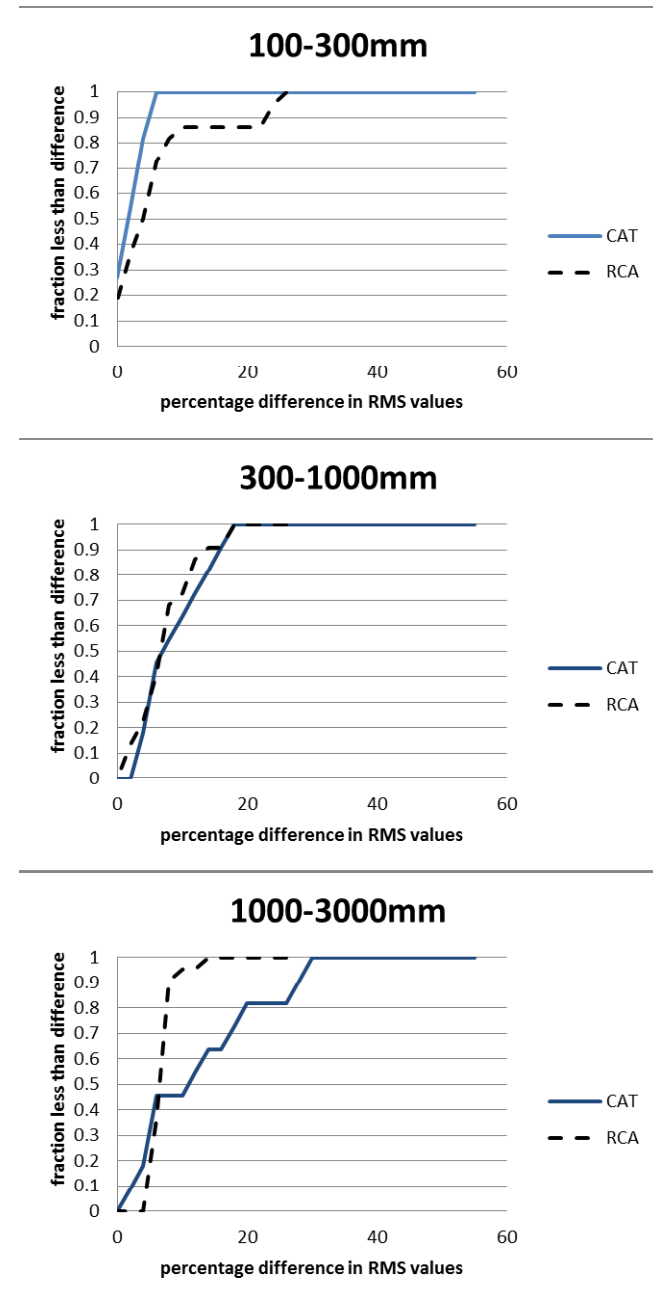
- calculate y for
 - same section of track (10m lengths)
 - different wavelength ranges (10-30mm, 30-100mm,....,1000-3000mm)
- express as fractional exceedences

fractional exceedences

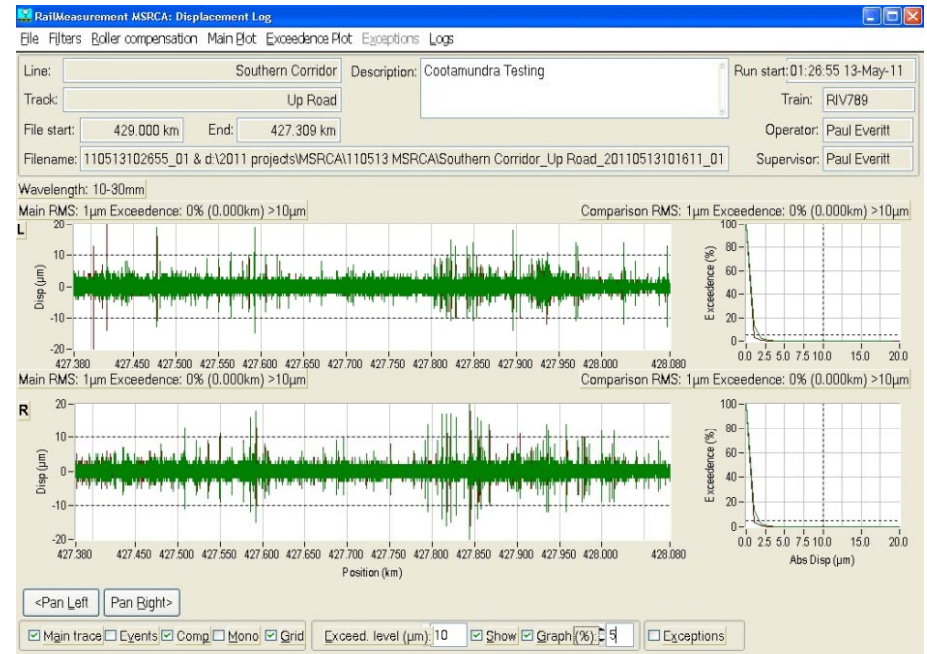
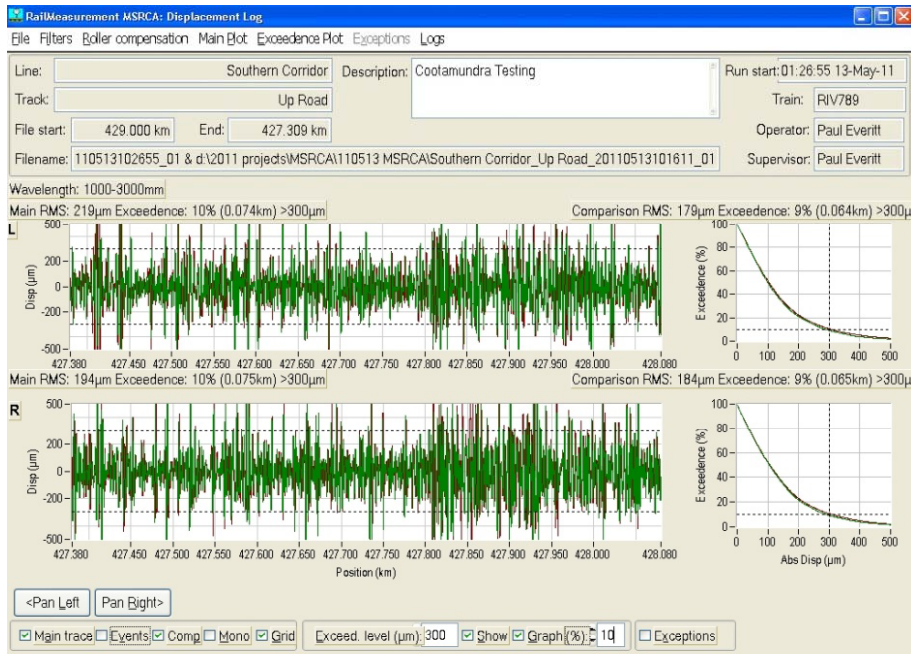


perfect
repeat-
ability of
CAT in 30-
100mm
band

- perfect repeatability corresponds to exceedence of 1.0 for difference of 0% in RMS values

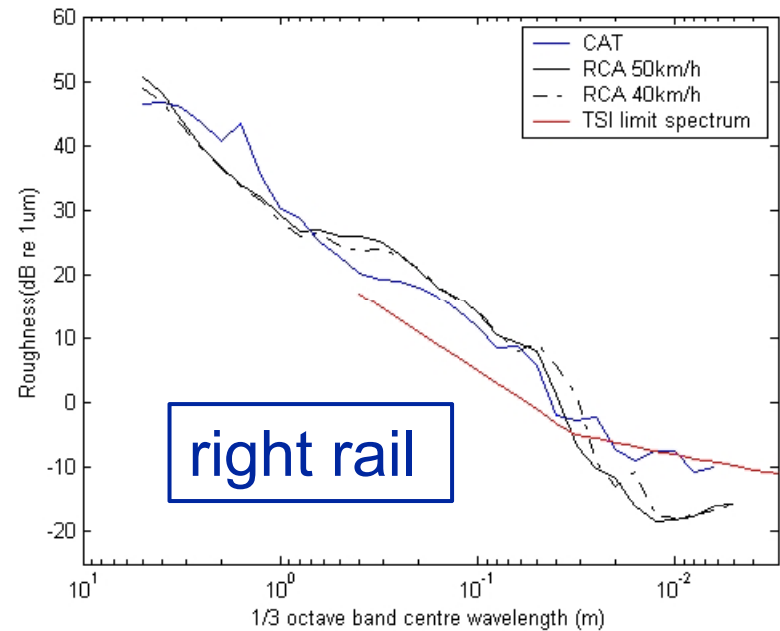
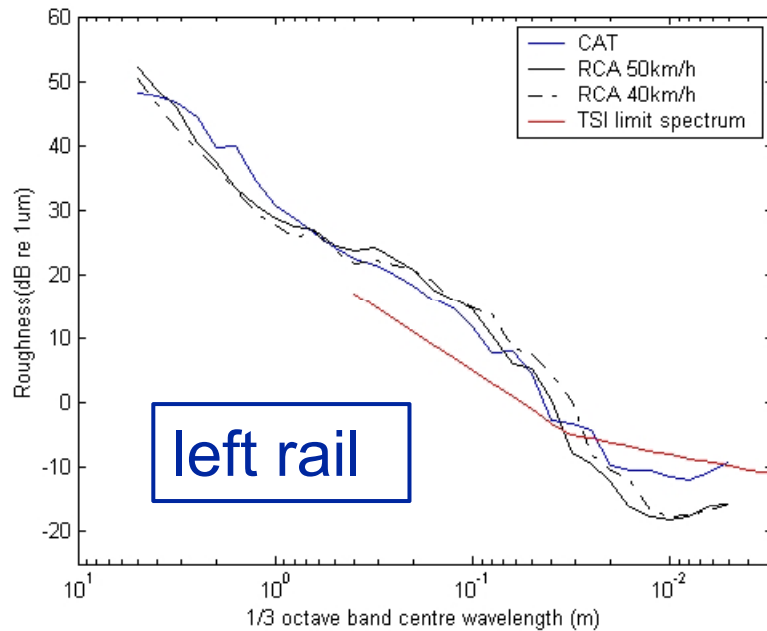


effect of speed on reproducibility

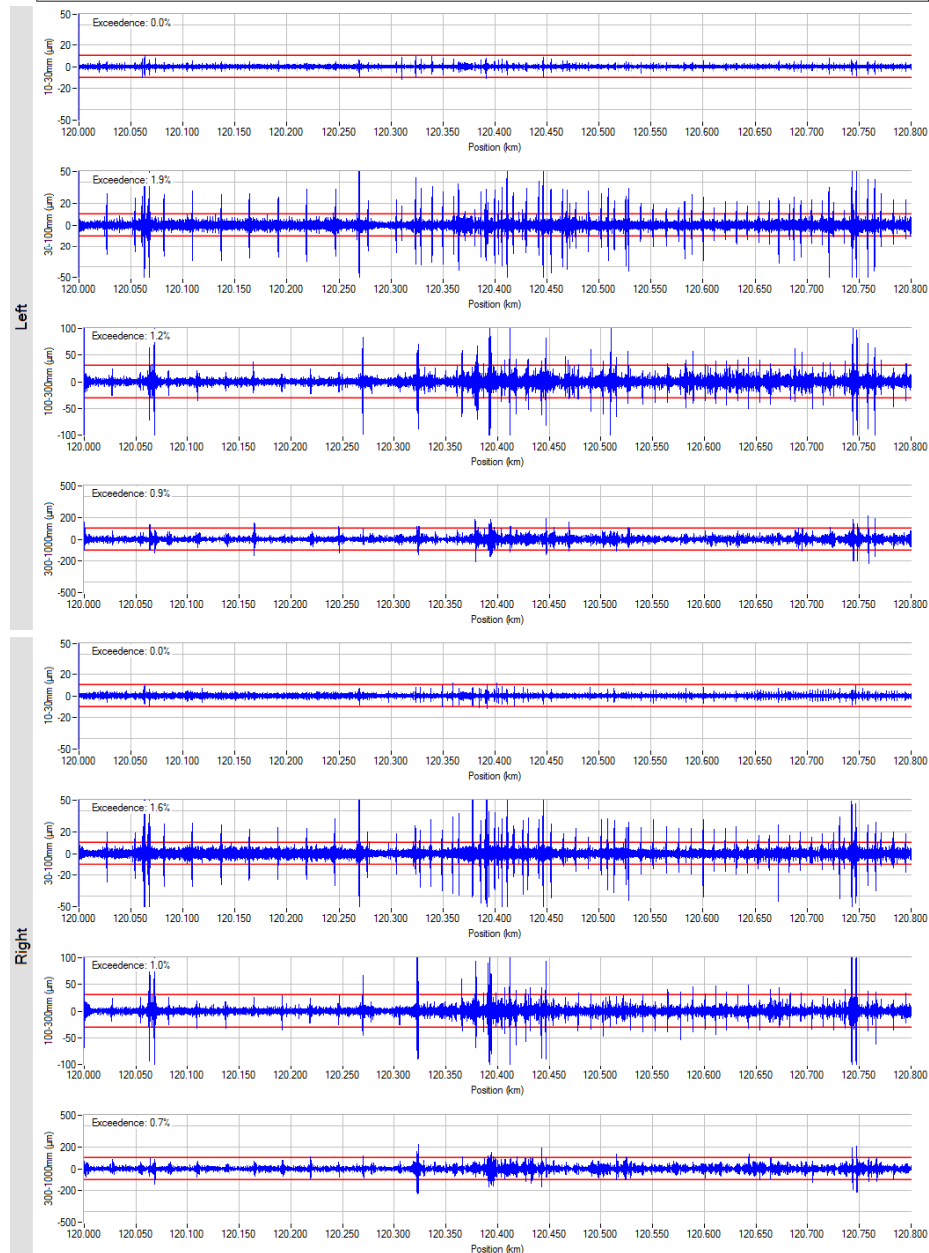


- Measurements at 40km/h and 50km/h over 700m
 - 1000-3000mm (left), full scale +/-0.500mm
 - 10-30mm (right), full scale +/-0.020mm
- can develop objective measures of repeatability and reproducibility

one-third octave spectra (6-5000mm)



- excellent reproducibility of RCA
- good correlation with CAT for $\lambda > 20\text{mm}$
 - short waves slightly underestimated by RCA contact



presentation of corrugation data

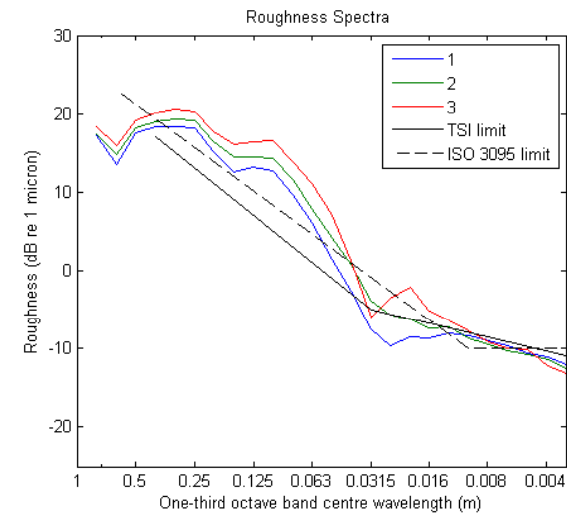
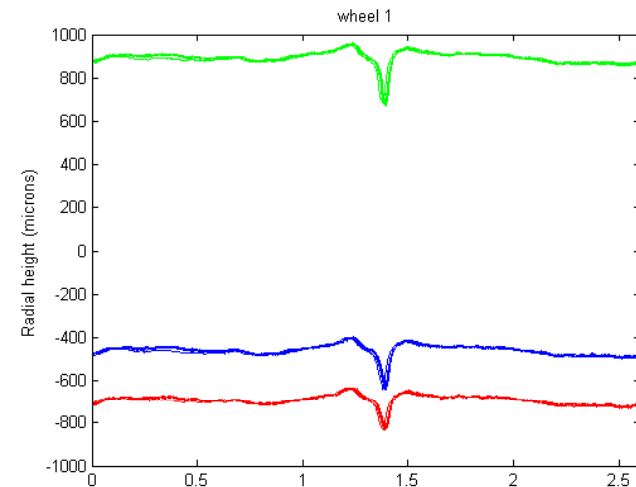
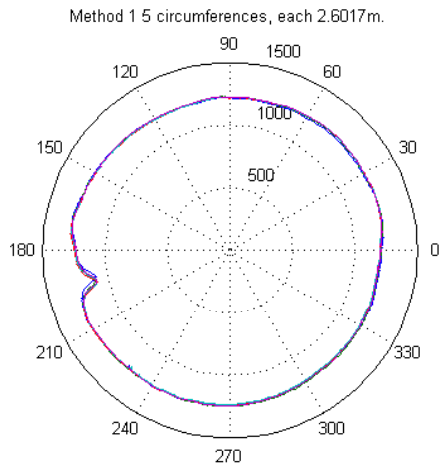
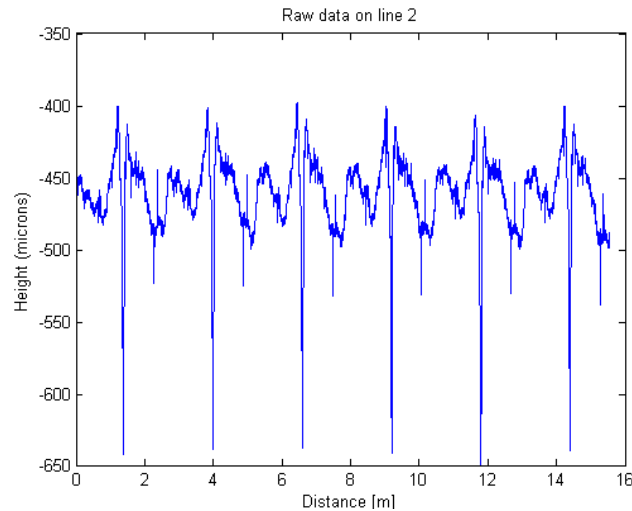
- 4 wavelength ranges, both rails, 500m per page
- percentages noted out of prescribed limits

Wheel irregularities



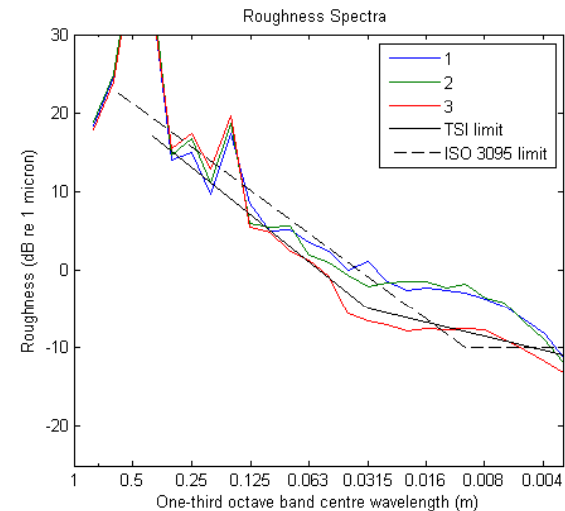
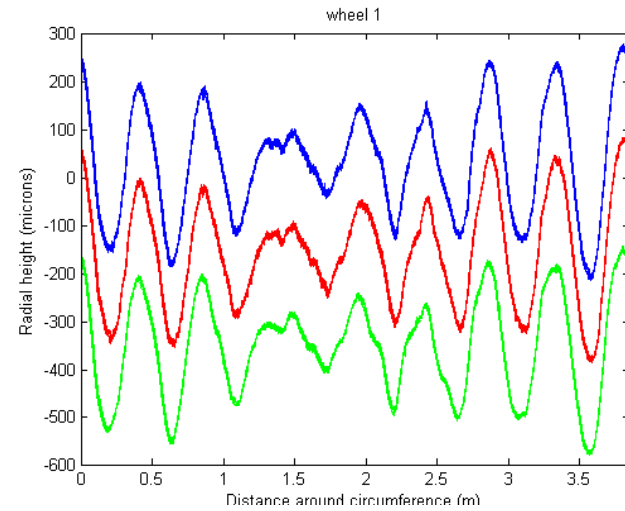
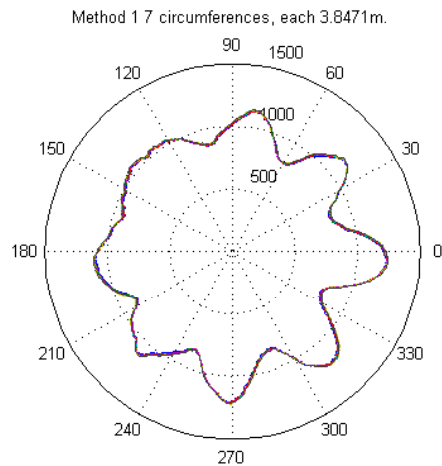
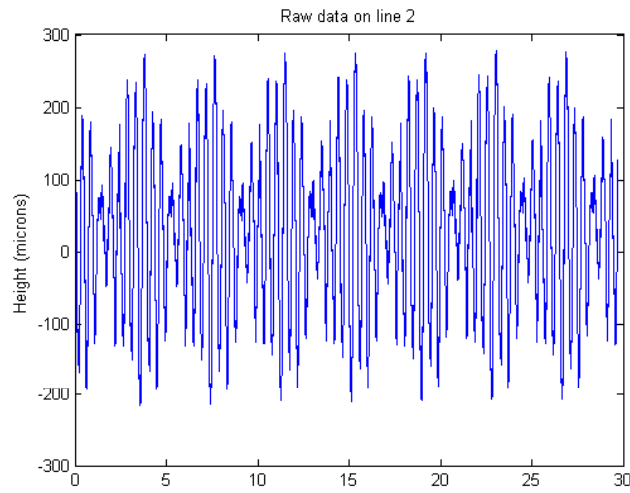
- measurements using RML “TriTops” instrument
 - developed in collaboration with ISVR
 - measures OOR, roughness, general irregularities (flats etc), diameter

wheelflat



- analyses of interest for both acoustics and maintenance

periodic out-of-round (OOR)



- very graphic demonstration of OOR

conclusions (1 of 2)

- hand-held and vehicle-based equipment is available that is sufficiently accurate to measure irregularities that are important for corrugation and reprofiling
 - suitable for wavelengths of at least 10-5000mm
- equipment is also available to measure wheel irregularities
- the level of acoustic roughness on worn wheels is similar to that on worn rails
- the wavelength range considered in Standards is barely sufficient for the full range of wheel/rail noise

conclusions (2 of 2)

- short wavelength irregularities influence air-borne noise, long wavelength irregularities influence ground-borne noise e.g. for 50m/s
 - 10-500mm: rolling noise
 - 200-2000Hz: audible ground-borne noise
- reprofiling (grinding and milling) typically
 - reduces irregularities 30-1000mm, primarily 30-300mm
 - increases roughness $\lambda < 30\text{mm}$
 - has little effect on irregularities $\lambda > 1\text{m}$