Averaging underwater noise levels for environmental assessment of shipping

Nathan D. Merchant[a)] and Philippe Blondel
Department of Physics, University of Bath, Bath, BA2 7AY, United Kingdom
n.d.merchant@bath.ac.uk, p.blondel@bath.ac.uk

D. Tom Dakin and John Dorocicz
Ocean Networks Canada, University of Victoria, Victoria, British Columbia V8W 2Y2, Canada
tdakin@uvic.ca, jdorocic@uvic.ca

Abstract: Rising underwater noise levels from shipping have raised concerns regarding chronic impacts to marine fauna. However, there is a lack of consensus over how to average local shipping noise levels for environmental impact assessment. This paper addresses this issue using 110 days of continuous data recorded in the Strait of Georgia, Canada. Probability densities of $\sim 10^7$ 1-s samples in selected 1/3 octave bands were approximately stationary across one-month subsamples. Median and mode levels varied with averaging time. Mean sound pressure levels averaged in linear space, though susceptible to strong bias from outliers, are most relevant to cumulative impact assessment metrics.

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1. Introduction

Underwater sound pressure levels (SPLs) in areas of local shipping activity are highly variable due to vessel passages, and probability distributions of shipping noise are generally non-Gaussian.[1] Consequently, average SPLs depend on the averaging method employed. Although average SPLs of shipping noise are commonly reported in assessments of acoustic impact on marine life, there is a lack of consensus over which average is most appropriate: examples in the literature include the median,[2] (linear space) mean,[3] and mode.[4]

As environmental policy responds to advances in research into the effects of anthropogenic noise on marine fauna, there is a growing need for scientific consensus and clarity in the reporting of underwater noise assessment metrics. One example is the European Marine Strategy Framework Directive,[5] which aims to describe low-frequency ambient noise trends using average 1/3 octave band levels,[6] the first quantitative policy initiative of its kind. Subsequent work[7] has recommended the use of the (linear) mean SPL for the implementation of this legislation, solely on the basis that it is more robust to variations in averaging time than the median (though no evidence was presented for this assertion). We believe this case highlights the need for an evidence-based examination of this issue.

This paper assesses the case for the above averaging methods as applied to noise from heavy commercial shipping traffic. Data amounting to 110 days of continuous recording were acquired over a 137-day period in the Strait of Georgia, Canada, a major commercial shipping route. The underlying SPL distributions are analyzed at 1-s resolution, and each metric is empirically assessed for varying averaging times and in the presence of outliers. The relative merits of each method are then discussed with

[a)]Author to whom correspondence should be addressed.

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regard to standardization and relevance to the assessment of long-term impacts on marine life.

2. Data acquisition and analysis

Measurements were made from a cabled seafloor observatory in the Strait of Georgia, British Columbia, operated by Ocean Networks Canada (ONC). The observation station is located at 49°02.5309′N, 123°19.0520′W in waters ~170 m deep, on the main shipping route south from the Port of Vancouver. Data were recorded using an Instrument Concepts (Great Village, Nova Scotia, Canada) icListen-LF smart hydrophone system comprising a GeoSpectrum (Dartmouth, Nova Scotia, Canada) M24 hydrophone and integrated electronics to transmit the digitized signal via Ethernet to shore. The instrument was deployed on the VENUS network[8] as part of a technology demonstration run by ONC's Center for Enterprise and Engagement (ONCCEE). An end-to-end calibration of the system was performed by ONCCEE, using a custom-built pistonphone for the range 0.1–100 Hz. For the range 300–1600 Hz, the calibration was carried out using a reference hydrophone on a test rig in the Saanich Inlet at a depth of 100 m in waters ~200 m deep. Both results agreed with the manufacturer's declared sensitivity. Data were sampled at 4 kHz and 24 bits, recording continuously in 5-min segments.

All recordings made between 14 Dec 2011 and 30 April 2012 were downloaded from the VENUS server, and consisted of 31 908 WAV (waveform audio file)-formatted files totaling 107 GB. Due to anomalous metadata (which rendered the files unreadable at the correct sampling frequency) or file length (which would result in inconsistent averaging times in the subsequent analysis), 196 files were discarded. Further data were absent due to downtime during administrative tasks and redactions made by the Royal Canadian Navy, which terminates the data stream intermittently to protect sensitive information. The overall coverage of the time series was 80%.

Data were processed in MATLAB (version 2011b) using custom-written scripts. The power spectral density was calculated in 1-s non-overlapping segments using a Hann window. Two files were produced for each 5-min measurement: one containing 1/3 octave levels maintaining 1-s time resolution and another with the linearly averaged power spectrum (1-Hz resolution) of the entire 5-min file. These were then concatenated to form master files for subsequent analysis. Probability distributions (PDs) of octave-separated 1/3 octave band levels were estimated using the kernel smoothing density estimate function "ksdensity" in MATLAB using 0.1-dB bins.

SPL is the mean squared sound pressure, p_{rms}^2, expressed in decibels

$$\mathrm{SPL} = 10\log_{10}\left(\frac{p_{\mathrm{rms}}^2}{p_{\mathrm{ref}}^2}\right), \tag{1}$$

where p_{ref} is a reference pressure of 1 μPa and SPL has units of dB re 1 $\mu\mathrm{Pa}^2$. Average SPLs were computed using the median, $\mathrm{SPL}_{\mathrm{Md}}$, the mode, $\mathrm{SPL}_{\mathrm{Mo}}$, and the linear-space mean, $\overline{\mathrm{SPL}}_{\mathrm{lin}}$. $\mathrm{SPL}_{\mathrm{Md}}$ was computed in linear space. $\mathrm{SPL}_{\mathrm{Mo}}$ was calculated as the maximum of the PD estimate. For N samples of p_{rms}^2, $\overline{\mathrm{SPL}}_{\mathrm{lin}}$ is given by

$$\overline{\mathrm{SPL}}_{\mathrm{lin}} = 10\log_{10}\left(\frac{\frac{1}{N}\sum_{i=1}^{N} p_{\mathrm{rms},i}^2}{p_{\mathrm{ref}}^2}\right), \tag{2}$$

where $p_{\mathrm{rms},i}^2$ is the ith value of the mean squared pressure. The dB-domain mean, $\overline{\mathrm{SPL}}_{\mathrm{dB}}$, was also included for completeness

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$$\overline{\mathrm{SPL}}_{\mathrm{dB}} = \frac{1}{N}\sum_{i=1}^{N} 10\log_{10}\left(\frac{p_{\mathrm{rms},i}^2}{p_{\mathrm{ref}}^2}\right). \tag{3}$$

To examine the effect of varying averaging time, the temporal resolution of the 1/3 octave spectra was reduced from 1 s using the standard Welch method[9] (i.e., using the mean of each frequency band in linear space) for averaging times of up to $\sim 10^7$ s. To limit the influence of transients in the spectrum, Parks *et al.*[4] proposed an alternative to the Welch method using the median instead of the mean, and subsequently to use the mode of these median values as the average level. This approach was also implemented for comparison to the standard mode. In the discussion below, "integration time" refers to the time over which p_{rms}^2 was calculated (1 s), and "averaging time" is the length of the averaged power spectrum windows (from 1 to $\sim 10^7$ s).

3. Distribution of shipping noise levels

The spectrogram for the analysis period consisted of frequent ship passages with frequency content concentrated in the range 30–500 Hz, and maximal between around 60 and 100 Hz [Fig. 1(a)]. Two discrete spectral components were also apparent: one at 74 Hz and another at 400 Hz. The latter is believed to originate at an industrial terminal near the site, while the former is likely to be system noise from a fan on adjacent equipment at the deployment site. The 1/3 octave bands chosen for analysis did not include these frequencies.

Monthly probability densities were plotted to examine stationarity over the period. The 125-Hz band, representative of the other octave-separated frequencies, is shown in Fig. 2(a). All months exhibited a similar density curve, agreeing more closely at higher SPLs. The greater occurrence of low SPLs in December and January is attributable to periods of exceptionally low shipping noise around December 25–26, January 1–2, and January 15, evident in Fig. 1(a). The peak at 130 dB re 1 μPa^2 in February [Fig. 2(a)] was due to the signature of the CCGS John P. Tully (Canadian Coast Guard Ship on a VENUS maintenance cruise) between February 23 and

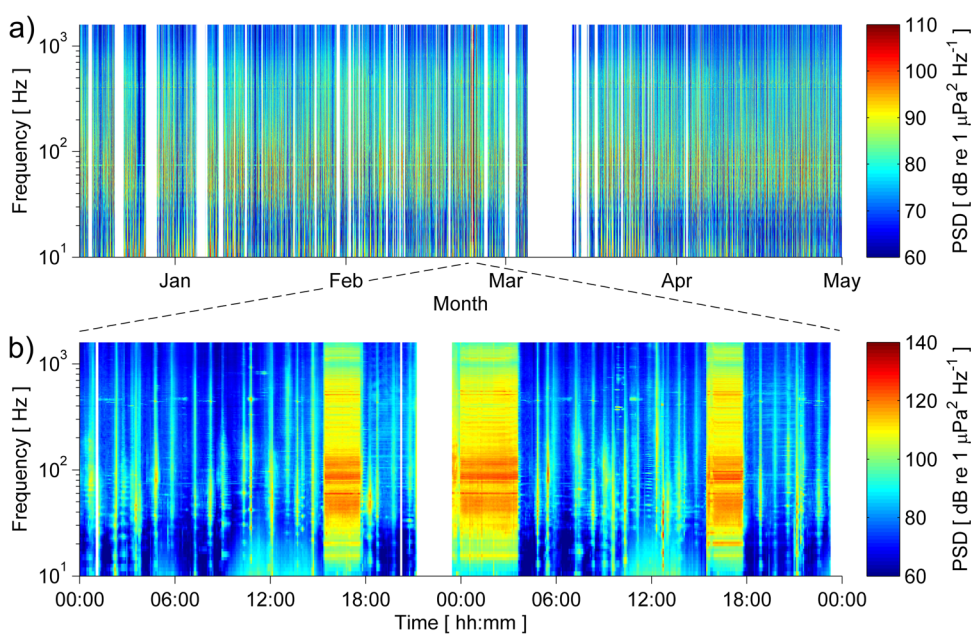

Fig. 1. (Color online) Power spectral densities over the range 10–1600 Hz using 5-min averages. (a) Complete dataset: 14 December 2011 to 30 April 2012. (b) Exceptional ship signature: 23–24 February 2012. Note the difference in dynamic range between (a) and (b).

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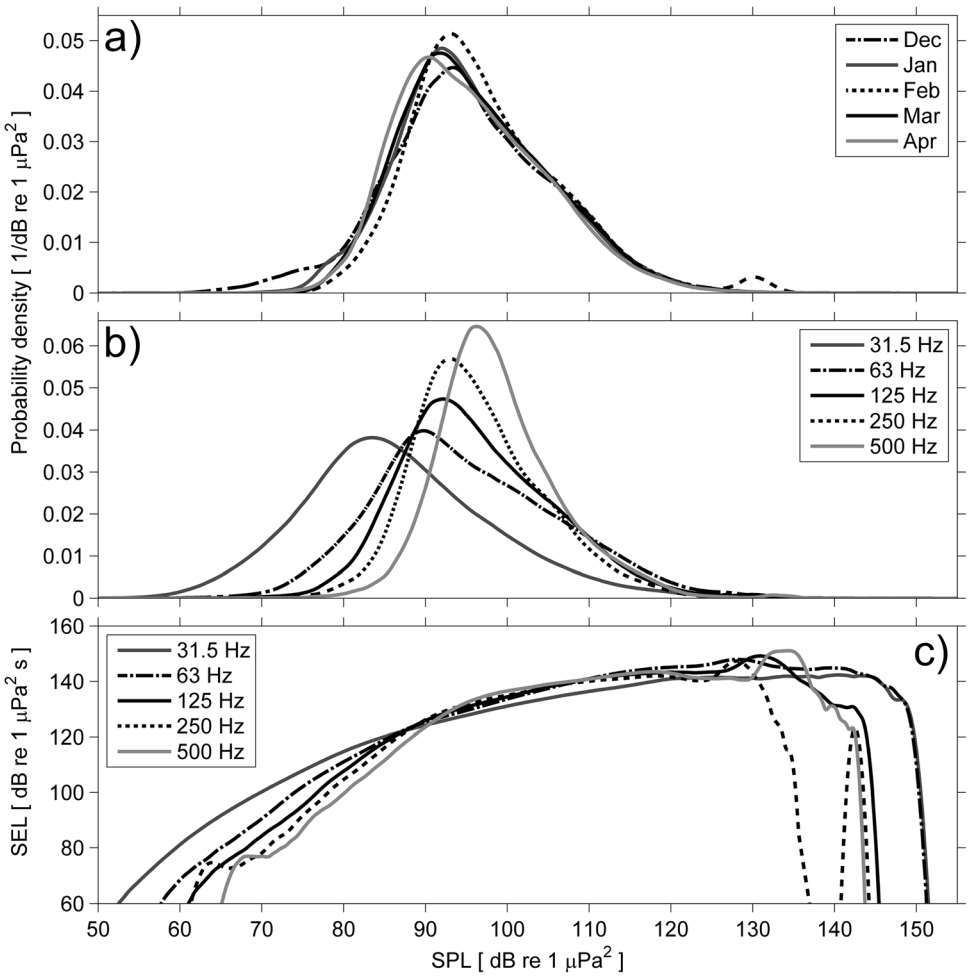

Fig. 2. (a) Estimated PDs for each month in the 125-Hz band. Bin width: 0.1 dB, integration time: 1 s. (b) PDs of octave-separated 1/3 octave bands over observed frequency range of shipping noise. (c) 24-h SEL calculated from PDs in (b).

February 24 [Fig. 1(b)]. Overall, probability densities of octave-separated 1/3 octave bands in the range 30–500 Hz appeared right-skewed [i.e., non-Gaussian; Fig. 2(b)]. The mode increased and variance decreased with increasing frequency across this range. Figure 2(c) shows the distribution of sound exposure level (SEL) over the SPL densities in Fig. 2(b), computed for a period of 24 h. SEL is a cumulative exposure metric defined as the integral of squared instantaneous sound pressure, $p^2(t)$, with respect to time, which can be expressed as a sum of non-overlapping 1-s samples of p^2_{rms}

$$\mathrm{SEL} = 10\log_{10}\left(\frac{\int_0^T p^2(t)dt}{p^2_{\mathrm{ref}}\,s}\right) = 10\log_{10}\left(\frac{\sum_{i=1}^{T} p^2_{\mathrm{rms},i}}{p^2_{\mathrm{ref}}\,s}\right), \tag{4}$$

where T is the exposure period in seconds, s is a reference time of 1 s, and SEL has units of dB re 1 μPa^2 s. The peaks in SEL in the SPL range 125–135 dB re 1 μPa^2 [Fig. 2(c)] were attributable to the ship signature mentioned above.

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4. Approaches to averaging

The case for reporting SPL_{Md}—as advocated, for example, by McQuinn *et al.*[2]—is that it is more representative of SPLs commonly received by marine fauna (since it is generally closer to the peak of the SPL probability distribution than $\overline{SPL}_{lin}$). This argument was extended to its logical conclusion by Parks *et al.*,[4] who reported the most probable level, SPL_{Mo} [using a non-standard method (see Sec. 3)]. While it may often be useful to report the most representative noise level, for the assessment of cumulative, long-term noise exposure, there is a strong case that (frequency-weighted) SEL is a more appropriate metric for marine mammals[10,11] and may be an appropriate metric for fish.[12] SPL_{Md} and SPL_{Mo} are insensitive to SEL, which is largely determined by higher SPLs [Fig. 2(c); see also Merchant *et al.*[13]]. In this regard, $\overline{SPL}_{lin}$ has the advantage of being directly related to SEL

$$SEL = \overline{SPL}_{lin} + 10\log_{10}T, \tag{5}$$

where T is the exposure period in seconds. Furthermore, in aerial acoustics $\overline{SPL}_{lin}$ is already an established metric for traffic noise assessment in the form of the equivalent continuous noise level, L_{eq}, which is A-weighted for human hearing and defined for specified time periods (e.g., 8 h, 24 h).[14]

The downside of the sensitivity of $\overline{SPL}_{lin}$ to higher SPLs is that it is susceptible to upward bias by loud events which may be anomalous or otherwise unrepresentative.[2,4] This phenomenon is clearly demonstrated in Fig. 3(a), where $\overline{SPL}_{lin}$ for February was raised by 5.5 dB due to exceptionally high SPLs from a single vessel for only a few hours. If such biases are detected, potentially subjective judgments have to be made over how representative specific features of the data are for the habitat under consideration. Figure 3(a) also shows that SPL_{Md} was not immune to the influence of the ship signature, though at 0.2 dB its effect was greatly diminished. Any effect on SPL_{Mo} was below the 0.1-dB bin resolution.

Since SPL is itself defined by p^2_{rms}, the aggregate mean, $\overline{SPL}_{lin}$, was unaffected by changes in averaging time [Fig. 3(b)]. As suggested by Van der Graaf *et al.*,[7] SPL_{Md} varied with averaging time, increasing slightly ($\sim$0.5 dB) from 1 to 100 s, and rising more steeply above $\sim$400 s. In general, this variation will depend on the overall distribution of p^2_{rms}. SPL_{Mo} exhibited a sharp step at $\sim 10^3$ s: this resulted from

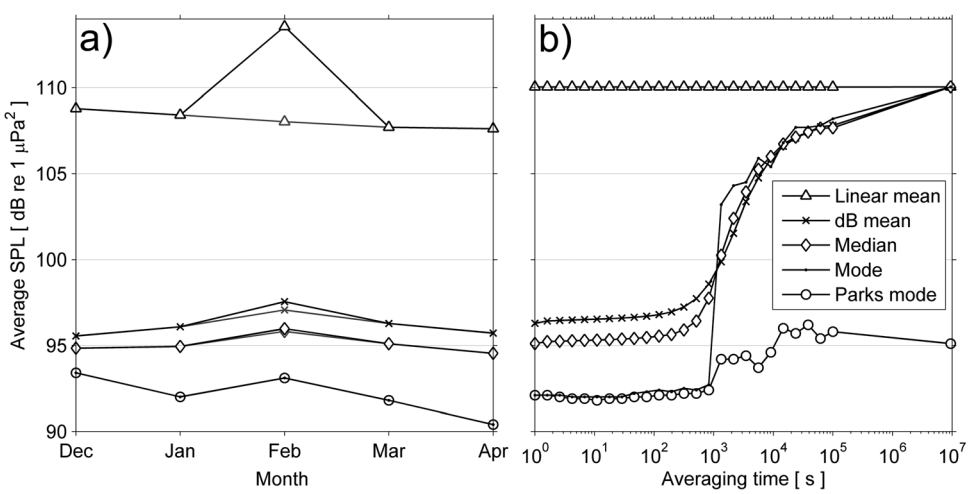

Fig. 3. (a) Average SPLs in 125 Hz band for each month; averages with February ship signature [see Fig. 1(b)] omitted are plotted in gray. Integration time: 1 s. (b) Total average SPL for 125 Hz band vs averaging time. "Parks mode" refers to the averaging method in Ref. 4.

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bimodality in the SPL probability distribution as it progressed from background-dominated short averaging times to longer averaging times dominated by ship passages. These results imply that if SPL_{Md} or SPL_{Mo} are to be used as indicators of shipping noise levels, the averaging time should be standardized and sufficiently short that p^2_{rms} can be considered continuous in each time window.

The alternative SPL_{Mo} proposed by Parks *et al.*[4] varied less with averaging time than SPL_{Mo} [Fig. 3(b)], though the increased variability with increasing averaging time highlights the instability of the mode for small populations. Given the robustness of the mode to outliers [Fig. 3(a)], this approach appears to present a more reliable averaging method for large numbers of samples where it is preferable to compute the most probable SPL, or where extraneous transients bias SPL upward.

Although it may be useful to report more than one averaging metric in shipping noise assessment, we suggest that in circumstances where one value must be chosen, $\overline{SPL}_{lin}$ presents the strongest case, given its relation to SEL, its robustness to varying averaging times, and its established use in aerial acoustics. While it is clear that brief, high-amplitude events can result in misleading bias when computing $\overline{SPL}_{lin}$, if a combination of analyses is employed, as presented here, the influence of such events can be identified, characterized and, if appropriate, removed.

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References and links

[1]P. L. Brockett, M. Hinich, and G. R. Wilson, "Nonlinear and non-Gaussian ocean noise," J. Acoust. Soc. Am. **82**(4), 1386–1394 (1987).

[2]I. H. McQuinn, V. Lesage, D. Carrier, G. Larrivee, Y. Samson, S. Chartrand, R. Michaud, and J. Theriault, "A threatened beluga (*Delphinapterus leucas*) population in the traffic lane: Vessel-generated noise characteristics of the Saguenay-St. Lawrence Marine Park, Canada," J. Acoust. Soc. Am. **130**(6), 3661–3673 (2011).

[3]L. Hatch, C. Clark, R. Merrick, S. Van Parijs, D. Ponirakis, K. Schwehr, M. Thompson, and D. Wiley, "Characterizing the relative contributions of large vessels to total ocean noise fields: A case study using the Gerry E. Studds Stellwagen Bank National Marine Sanctuary," Environ. Manage. (NY) **42**(5), 735–752 (2008).

[4]S. E. Parks, I. Urazghildiiev, and C. W. Clark, "Variability in ambient noise levels and call parameters of North Atlantic right whales in three habitat areas," J. Acoust. Soc. Am. **125**(2), 1230–1239 (2009).

[5]European Commission, "Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008, Establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive)," Off. J. European Union **L164**, 19–40 (2008).

[6]M. L. Tasker, M. Amundin, M. André, A. Hawkins, W. Lang, T. Merck, A. Scholik-Schlomer, J. Teilmann, F. Thomsen, S. Werner, and M. Zakharia, "Marine Strategy Framework Directive—Task Group 11: Report Underwater noise and other forms of energy," Report No. EUR 24341 EN, Joint Research Centre, Office for Official Publications of the European Communities, Luxembourg, 2010.

[7]A. J. Van der Graaf, M. A. Ainslie, M. Andre, K. Brensing, J. Dalen, R. P. A. Dekeleng, S. Robinson, M. L. Tasker, F. Thomsen, and S. Werner, "European Marine Strategy Framework Directive—Good environmental status (MSFD GES): Report of the technical subgroup on underwater noise and other forms of energy," 2012.

[8]VENUS Project, http://venus.uvic.ca/ (last viewed 25 May 2012).

[9]P. Welch, "The use of fast Fourier transform for the estimation of power spectra: A method based on time averaging over short, modified periodograms," IEEE Trans. Audio Electroacoust. **15**(2), 70–73 (1967).

[10]W. T. Ellison, B. L. Southall, C. W. Clark, and A. S. Frankel, "A new context-based approach to assess marine mammal behavioral responses to anthropogenic sounds," Conserv. Biol. **26**(1), 21–28 (2012).

[11]B. L. Southall, A. E. Bowles, W. T. Ellison, J. J. Finneran, R. L. Gentry, C. R. Greene, Jr., D. Kastak, D. R. Ketten, J. H. Miller, P. E. Nachtigall, W. J. Richardson, J. A. Thomas, and P. L. Tyack, "Marine

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mammal noise exposure criteria: Initial scientific recommendations," Aquat. Mamm. **33**(4), 411–521 (2007).
[12]A. N. Popper and M. C. Hastings, "The effects of human-generated sound on fish," Integr. Zool. **4**(1), 43–52 (2009).
[13]N. D. Merchant, M. J. Witt, P. Blondel, B. J. Godley, and G. H. Smith, "Assessing sound exposure from shipping in coastal waters using a single hydrophone and Automatic Identification System (AIS) data," Mar. Pollution Bull. **64**(7), 1320–1329 (2012).
[14]*Handbook of Acoustical Measurements and Noise Control*, 3rd ed., edited by C. M. Harris (McGraw-Hill, New York, 1991).

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