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Think twice before f-numbering

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ABSTRACT

In a 2021 paper, we delved into the details of delay-sum beamforming (DAS) in high-frame-rate ultrasound for medical imaging [1]. We also proposed a simple and fast method of determining an f-number, which is based on the directivity of the transducer elements. In their comment, Martin F. Schiffner and Georg Schmitz argue that we mistakenly link image quality enhancement to the reduction of measurement noise. They disapprove our proposed f-number, claiming it deteriorates the signal-to-noise ratio (SNR). Based on their previous work [2], they also highlight that the f-number should be derived from the grating lobe angles. In this reply, we explain their error in the SNR argument. We also illustrate the potential drawbacks of exclusively relying on grating lobes to establish an f-number with a DAS, suggesting that alternative approaches might be worthy of consideration.

We would like to thank Martin F. Schiffner and Georg Schmitz for their careful reading of our paper [1] and for their detailed comments on our choice of f-number [2]. As a reminder to the reader, we proposed an f-number based on the directivity of the elements. Our f-number is related to the aperture angle-of-view ($=2\alpha$, see Fig. 5 in [1]):

$$f_{\#} = \frac{1}{2\tan(\alpha)}, \text{ with } \alpha = \left\{ \vartheta \in \left[0, \frac{\pi}{2}\right] \middle| \cos\vartheta \operatorname{sinc}\left(\pi \frac{W}{\lambda_c} \sin\vartheta\right) = D_{thresh} \right\} \quad (1)$$

The parameter W stands for the width of one transducer element. The $\cos \operatorname{sinc}$ argument represents the directivity of a piston-like element embedded in an infinite soft baffle [4]. Although directivity is wavelength-dependent, we have chosen to use the central wavelength (λ_c). This simplification has the advantage of allowing delay-and-sum (DAS) in the time domain. In our paper, we showed that the DAS process is reduced to a sparse matrix–vector product, with a DAS matrix that can be computed once, as long as the transmission sequences and the beamforming lattice remain unchanged. During beamforming, the f-number defined by (1) eliminates backscattered signals with directivities below a given threshold D_{thresh} so that they do not contribute to the ultrasound image. In [1], we discarded directivities below -3dB based on the quality of B-mode and vector Doppler images (i.e. $D_{thresh} = 0.71$).

Our f-number does not consider grating lobes and is therefore not dependent on the pitch. On the other hand, Schiffner and Schmitz (S&S) introduced an f-number that aims to mitigate artifacts induced by grating lobes [3]. Taking advantage of a frequency-domain DAS, they designed a frequency-dependent f-number for better results. In their comment published in this issue of Ultrasonics, the authors claimed that 1) our f-number worsens the signal-to-noise ratio, 2) the f-number should be determined based on the directivity of the element and the angles of the grating lobes. In this short reply, we show that:

(1) Contrary to what they assert, our f-number improves the signal-to-noise ratio.
(2) The conclusion that the f-number should be calculated on the sole basis of the grating lobes should be taken with caution.

1 SNR improvement

S&S calculated the beamforming gain (G) in signal-to-noise ratio (see Eq. (2) in their comment) that results from f-numbering. This gain is nil for a full-aperture beamforming, i.e. when the f-number is zero. Using this equation, they identified optimal f-numbers that maximize G (thick green line in Fig. 1b of their comment). Additionally, they computed the gain G provided by the f-number that we proposed (Eq. (1) in this reply), with $D_{thresh} = 0.71$ (i.e. a -3dB-threshold). They referred to our f-number model as S3, where the number 3 stands for -3dB. Because the gain G given by S3 is smaller than the maximal gain, S&S concluded that S3 degrades the SNR (see blue and green curves in Fig. 1a). However, it is worth noting that S3 provides a gain range of 24 down to 7 for a

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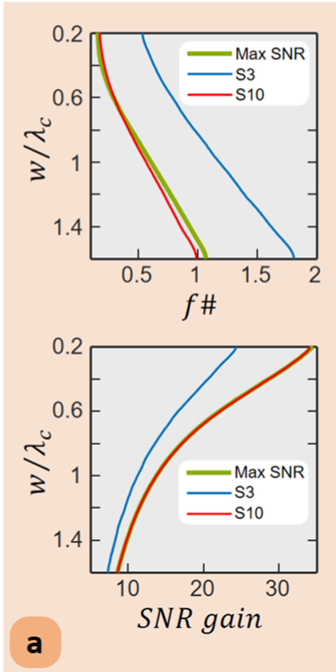

Fig. 1a. Top: f-number ($f\#$) as determined by Eq. (1) with $D_{thresh} = 0.71$ (S3, blue curve) and $D_{thresh} = 0.32$ (S10, red curve). The green curve shows the f-numbers that provide the maximum beamforming SNR. Bottom: SNR gain, as calculated by Schiffner and Schmitz in their comment, for S3 et S10. The green curve shows the gains for maximum SNR. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

normalized width (W/λ_c) in $[0.2, 1.6]$. As all of these gain values are greater than 1, one can thus rightfully assert that S3 improves SNR. In our paper, we proposed using a −3dB threshold. The DASMTX function in the open-source MUST MATLAB toolbox can be freely modified by users [5]. An interested user would find that a −10 dB threshold ($D_{thresh} = 0.32$) gives the f-numbers that maximize the beamforming SNR gain, as shown in Fig. 1a (S10, red vs. green curves). Based on these observations, we consider that S&S's claim that "the f-number suggested by Perrot *et al.* worsens signal-to-noise ratio" is incorrect.

2 No grating lobe, yet artifacts remain

S&S suggested calculating a frequency-dependent f-number to mitigate artifacts due to grating lobes [3]. Grating lobes occur when the pitch, i.e. the distance between the centers of two elements of a linear probe, is greater than half the wavelength. The pattern of the grating lobes also depends on the directivity of the elements and, therefore, on their width. According to S&S's method, the f-number can be set to zero if there is no grating lobe, which occurs when the pitch is less than half the minimum wavelength. To mimic this condition, we used SIMUS [6] to simulate an idealized linear transducer with a pitch smaller to $\lambda_c/4$: center frequency = 7.6 MHz, pitch = 50 µm, element width = 0.27 mm, number of elements = 763, no apodization. Note that such a configuration provides a negative kerf width; this transducer is 100% theoretical. We also mimicked its real counterpart: pitch = 300 µm, number of elements = 128. We simulated a carotid ultrasound image and a PSF. We beamformed the I/Q signals with a delay-and-sum from the MUST toolbox [5] using both full-aperture, i.e. f-number = 0, and Eq. (1) with $D_{thresh} = 0.71$, which gave an f-number of 2.1. For comparison, we also beamformed the I/Q signals using the Fourier-domain method and f-number proposed by S&S [3]. The size of the beamforming grid was 300 × 400. S&S's code necessitates selecting multiple parameters. To avoid any selection bias on our part, we choose the parameters suggested in Figs. 3 and 5 of their article [3]: $\chi_0 = 45^{\circ}, F_{ub} = 3, \delta = 10^{\circ}$,

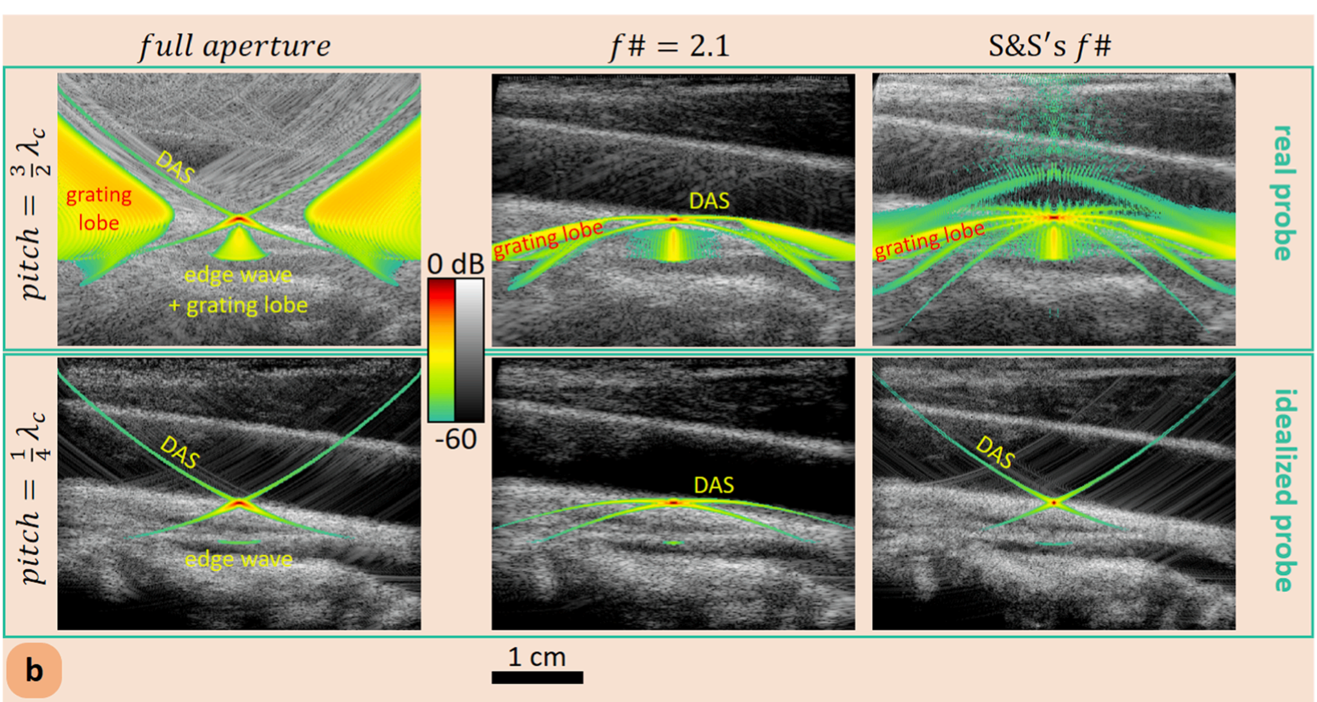

Fig. 1b. PSF overlaid on a simulated carotid artery with a real normal-pitch (top row) and idealized small-pitch (bottom row) probe. The I/Q signals were DASed with a full aperture (left column), our directivity-based f-number (center), and Schiffner and Schmitz' (S&S) f-number (right column). For the S&S's configuration, we used the parameters that are listed in [3]: $\chi_0 = 45^{\circ}, F_{ub} = 3, \delta = 10^{\circ}$. W: element width, λ_c: center wavelength, $f\#$: f-number.

with a 100% bandwidth.

On a personal computer's CPU, our beamformer took 0.7 (normal probe) and 4.1 (idealized probe) seconds, while S&S's beamformer was 600 to 900 times slower (680 and 3560 s). The grating lobes severely degraded the ultrasound image with the real probe when a full aperture was used during beamforming (Fig. 1b, top left). Artifacts also included PSF tails induced by the DAS method and those created by the waves transmitted by the edge elements. The 2.1 *f*-number significantly reduced artifacts (Fig. 1b, top center). However, the negative effects of the grating lobes were still visible. S&S's frequency-dependent *f*-number did not reduce artifacts (Fig. 1b, top right) with the chosen parameters. As expected, the idealized probe had no grating lobes. In this condition, S&S propose to use a full aperture (*f*-number = 0). Artifacts were visible in the image after DAS beamforming (Fig. 1b, bottom right), despite the absence of grating lobes, while most of these were eliminated with the S3 method (Fig. 1b, bottom center). These artifacts were linked to the PSF tails of high-reflection backscattering, and can be largely eliminated by using steered plane waves and coherent compounding.

In summary, our *f*-number, calculated based on the directivity of the elements, improves SNR during DAS beamforming. As Schiffner and Schmitz rightly pointed out, it partially mitigates grating lobes collaterally. It also decreases the tails of the point spread function (PSF) and the edge-wave artifacts. These changes occur because using an *f*-number, whatever the means of its calculation, involves summation around the apex of I/Q hyperbolas rather than over the entire hyperbola. Of course, reducing these artifacts comes with a trade-off, namely a decrease in lateral resolution. We were unable to produce images of higher quality with S&S's beamformer. The S&S beamformer depends on four input parameters, all of which can be set at the user's discretion. In addition, it is time-consuming, which makes it difficult to apply recursive approaches to select the hyperparameters that may tend toward optimal image quality.

To conclude, it should be stressed that beamforming artifacts can arise from multiple factors, leading to several proposed *f*-numbers in the literature. We have opted for a straightforward *f*-number [1], which typically produces satisfactory B-mode or Doppler images. In contrast, Schiffner and Schmitz have introduced a more advanced, yet time-consuming and user-dependent, method [3]. Nevertheless, as briefly highlighted in this response, no *f*-number can guarantee 100% satisfaction. The user needs to recognize this and select the *f*-number method that best aligns with her expectations. The selection of *f*-number represents only one of many steps toward achieving excellent image quality.

CRediT authorship contribution statement

Damien Garcia: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Mohamed Tamraoui:** Data curation, Investigation, Methodology, Software, Validation, Visualization. **François Varray:** Software, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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