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Reproducibility, Verification, and Validation of Experiments on the Marschner-Lobb Test Signal

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Abstract

The Marschner-Lobb (ML) test signal has been used for two decades to evaluate the visual quality of different volumetric reconstruction schemes. Previously, the reproduction of these experiments was very simple, as the ML signal was used to evaluate only compact filters applied on the traditional Cartesian lattice. As the Cartesian lattice is separable, it is easy to implement these filters as separable tensor-product extensions of well-known 1D filter kernels. Recently, however, non-separable reconstruction filters have received increased attention that are much more difficult to implement than the traditional tensor-product filters. Even if these are piecewise polynomial filters, the space partitions of the polynomial pieces are geometrically rather complicated. Therefore, the reproduction of the ML experiments is getting more and more difficult. Recently, we reproduced a previously published ML experiment for comparing Cartesian Cubic (CC), Body-Centered Cubic (BCC), and Face-Centered Cubic (FCC) lattices in terms of prealiasing. We recognized that the previously applied settings were biased and gave an undue advantage to the FCC-sampled ML representation. This result clearly shows that reproducibility, verification, and validation of the ML experiments is of crucial importance as the ML signal is the most frequently used benchmark for demonstrating the superiority of a reconstruction scheme or volume representations on non-Cartesian lattices.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Picture/Image Generation—Display algorithms I.4.10 [Image Processing and Computer Vision]: Image representation—Volumetric

1. Introduction

The analytically defined ML signal [ML94] is the most popular benchmark for evaluating the visual quality of volumetric reconstruction schemes. Although its spectrum is not band-limited in a strict theoretical sense, above a "practical band limit" its energy is minimal. On the other hand, a significant portion of the spectrum is located right below this limit. Therefore, a proper reconstruction of the test signal is a challenging task if it is sampled near the practical Nyquist limit. The ML experiments nicely show many important properties of a given filter such as smoothing and postaliasing effects, ringing effect, or the preferred directions in case of an anisotropic reconstruction. However, as the reconstruction techniques became more and more complicated, the reproduction of the ML experiments also became more difficult. The reproduction of the images in the classical paper of Marschner and Lobb [ML94] would take just a couple of days for a talented student as it requires just elementary knowledge on ray casting and convolution filtering. In contrast, to reproduce ML experiments for comparing CC, BCC, and FCC lattices took us several weeks, as it required deep background knowledge on non-Cartesian lattices and non-separable box splines. Overall, the trend is that the time just for reproducing the previous results is dramatically increasing. Therefore, as the reconstruction techniques become more complex, more attention has to be paid on reproducibility.

2. Reproduction of Lanczos Filtering on BCC and FCC Lattices

For our experiments [VCG12, VCRG14], we used very large Lanczos kernels to reconstruct the ML signal from its CC,

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BCC, and FCC representations. The Lanczos filter is easy to use on the CC lattice, but its adaptation to the non-separable BCC and FCC lattices is much more difficult to implement. Ye and Entezari [YE12] precisely derived the closed form formulas for the BCC and FCC Lanczos filters in a comprehensible way, which significantly helped the reproduction of their experiments. However, as they used relatively compact kernels, they did not focus on an efficient addressing of the neighboring voxels that are covered by the filter kernel. In our work, this was important as we used much larger kernels. Our goal was to minimize the bias in comparing the CC, BCC, and FCC lattices. Therefore, we tried to very accurately approximate the ideal low-pass filter on each lattice by using large Lanczos kernels. Nevertheless, in the future, we plan to extend our framework by more practical filters, such as box splines [Ent07] and Voronoi splines [Mir12]. After this extension, we would like to make our implementation freely available.

3. Verification of the Implementation

We used two verifications to ensure that our implementation is correct. We applied the Lanczos filtering on a low-resolution volume that contained only one impulse in the middle. In this case, the reconstruction should produce the impulse response of the Lanczos filtering. We checked elementary requirements for a correct implementation. For example, the obtained impulse response has to be symmetric and has to ensure zero crossings at the neighboring lattice points. We checked this for cross-sections of different angles. Concerning the ML reconstructions we analyzed from which direction the aliasing artifacts appear first if we gradually decrease the sampling density. These directions have to be exactly the same as the directions towards the nearest aliasing spectra in the frequency domain. As shown in Figures 4 and 5 of our comparative study [VCRG14], our implementation fulfils this requirement.

4. Validation of the ML Experiments for Comparing CC, BCC, and FCC Lattices

To the best of our knowledge, we were the first to analyze the validity of the ML experiments for comparing CC, BCC, and FCC representations [VCG12, VCRG14]. Note that the higher sampling efficiency of the BCC and FCC lattices has been derived from the assumption that the spectrum is not just band-limited but also isotropic [PM62, TMG01]. We recognized that the ML signal, in fact, does not meet this assumption as its spectrum is disc-shaped. However, we also showed that the sampling lattices can be rotated such that the prealiasing effect is maximized on each lattice. This yields a fair basis for comparisons. Recently, our experiments inspired us to analyze the hypothesis that the FCC lattice is superior over the BCC lattice for sampling isotropically band-limited signals below the Nyquist limit [EMBM06, Ent07, Ent09, Mir12]. This hypothesis was explained by the fact that the dual BCC lattice is an optimal sphere-covering lattice [CSB87], therefore it ensures the packing of the spherical spectrum with minimal overlap in the frequency domain. Let us try to reconstruct a spherical spectrum of a fixed radius R and, consistently to the sphere-covering problem, we assume that the replicas of the spectrum optimally cover the entire frequency space. In this case, R has to be the radius of the circumscribing spheres of the Voronoi cells (see Figure 1). This condition directly determines the densities of the dual lattices in the frequency domain: $F_{BCC}(R) = \frac{\sqrt{5}^3}{32R^3}$, $F_{FCC}(R) = \frac{1}{2R^3}$. Consequently, the densities of the corresponding sampling lattices in the spatial domain are the reciprocals: $S_{BCC}(R) = 2R^3$, $S_{FCC}(R) = \frac{32R^3}{\sqrt{5}^3} \approx 2.862R^3$. Thus, the FCC sampling achieves a reduced overlap between the replicas of the spectrum by a 43.1% higher sampling density. However, the fact that, increasing the density of a certain sampling lattice decreases the prealiasing effect, follows from sampling theory. Therefore, the fact that a denser FCC sampling causes lower prealiasing than a sparser BCC sampling does not prove the superiority of the FCC lattice.

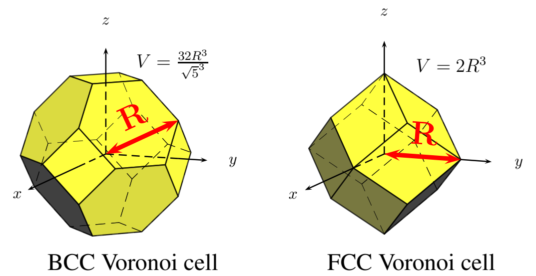

Figure 1: *The Voronoi cells of the BCC and FCC lattices. R denotes the radius of the circumscribing spheres.*

5. Conclusion

In this paper, we have shown an example that nicely demonstrates the importance of reproducibility, verification, and validation. After having ML experiments for comparing CC, BCC, and FCC lattices reproduced, we recognized that the original settings were biased, and gave an undue advantage to the FCC lattice. Inspired by our experiments, we thoroughly investigated a hypothesis on the optimality of the FCC lattice for sampling isotropically band-limited signals below the Nyquist limit. Although we did not falsify this hypothesis, we have shown that the optimality of the dual BCC lattice for sphere covering is not sufficient for validating it.

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