ADAPTIVE FILTERS FOR PIECEWISE SMOOTH SPECTRAL DATA

EITAN TADMOR AND JARED TANNER

Abstract. We introduce a new class of exponentially accurate filters for processing piecewise smooth spectral data. Our study is based on careful error decompositions, focusing on a rather precise balance between physical space localization and the usual moments condition. Exponential convergence is recovered by optimizing the order of the filter as an *adaptive* function of both the projection order, and the distance to the nearest discontinuity. Combined with the automated edge detection methods, e.g., [GeTa02], adaptive filters provide a robust, computationally efficient, black box procedure for the exponentially accurate reconstruction of a piecewise smooth function from its spectral information.

To David Gottlieb, on his 60^{th} birthday, with friendship and appreciation

1. Introduction

The Fourier projection of a 2π-periodic function, $S_N f(\cdot)$, enjoys the well known spectral convergence rate, that is, the convergence rate is as rapid as the *global* smoothness of $f(\cdot)$ permits. Specifically, if $f(\cdot)$ has s bounded derivatives then $|S_N f(x) - f(x)| \leq Const\|f\|_{C^s} \cdot N^{1-s}$. This interplay between global smoothness and spectral convergence is reflected in the dual Fourier space through the rapidly decaying Fourier coefficients $|\widehat{f}(k)| \leq 2\pi\|f\|_{C^s}|k|^{-s}$. On the other hand, spectral projections of piecewise smooth functions suffer from the well known Gibbs' phenomena, where the uniform convergence of $S_N f(x)$ is lost in the neighborhood of discontinuities and the *global* convergence rate of $S_N f(x)$ deteriorates to first order. These related phenomena are manifestations of unacceptably slowly decaying Fourier coefficients.

Two interchangeable processes are available for recovering the rapid convergence in the piecewise smooth case. These are mollification, carried out in the physical space and filtering, carried out in the Fourier space. Filtering accelerates convergence when premultiplying the Fourier coefficients $\widehat{f}(k)$ by a rapidly decreasing function $\sigma(\cdot)$, resulting in modified coefficients, $\widehat{f}(k)\sigma(|k|/N)$, with a greatly accelerated decay rate as $|k| \uparrow N$. This accelerated decay in the dual space corresponds to a smoothly localized mollification in the physical space. In [TT02] we showed how to parameterize an optimal mollifier in order to gain the exponential convergence for piecewise analytic f's. The key ingredient in our approach was *adaptivity*, where the optimal mollifier is adapted to the maximal region of local smoothness. Here we continue the same line of thought by introducing *adaptive filters*, which allow the same optimal recovery of piecewise smooth functions from their Fourier coefficients. In particular, piecewise analytic functions are recovered with exponential accuracy. A brief overview follows.

We consider a family of general filters $\sigma(\cdot)$ which are characterized by two main properties. First, we seek the rapid decay of $\sigma_k := \sigma(|k|/N)$ which is tied to a regular, compactly supported multiplier $\sigma \in C_0^q[-1,1]$. Being compactly supported, such filters are restricted to N-Fourier expansions,

$$S_N^\sigma f(x) := \sum_{|k|\leq N} \sigma\left(\frac{|k|}{N}\right)\widehat{f}(k)e^{ikx}. \tag{1.1}$$

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The operation of such filters in Fourier space corresponds to mollification in physical space, expressed in terms of the associated mollifier, $\Phi^\sigma(y) := 1/2\pi \sum_{|k|\le N} \sigma(|k|/N)e^{iky}$,

$$S_N^\sigma f(x) \equiv f \star \Phi^\sigma(x) = \frac{1}{2\pi}\int_{-\pi}^{\pi} \Phi^\sigma(y) f(x-y)dy \qquad \Phi^\sigma(y) := \frac{1}{2\pi}\sum_{|k|\le N} \sigma\left(\frac{|k|}{N}\right)e^{iky}. \tag{1.2}$$

Second, such filters are required to satisfy the usual moments condition, e.g. [MMO78, Va91]

$$\int_{-\pi}^{\pi} y^n \Phi^\sigma(y) = \delta_{n0}, \qquad n = 0, 1, \dots, p-1 < q. \tag{1.3}$$

The first requirement of C_0^q-smoothness is responsible for localization — the essential part of the associated mollifier, Φ^σ is supported near the origin, consult (2.5) below. The second property drives the accuracy of the filter, by annihilating an increasing number of its moments.
The rich subject of filters include the classical filters of finite order accuracy where finite $p \le q$ dictate a fixed convergence of polynomial order, $\mathcal{O}(N^{-p})$, consult [Va91]. By letting $q \uparrow \infty$ one obtains a $C_0^\infty[-1,1]$-filter, that is, an infinitely differentiable compactly supported filter σ, which respects (1.3) for increasing orders p. Majda et. al., [MMO78] employed such filters to postprocess piecewise solutions with propagating singularities and achieve spectral convergence in the sense of having a convergence rate faster than any fixed order. Vandeven, [Va91], constructs spectrally accurate filters by relating the order of the filter, (q, p), to the increasing order of the projection, $q = q(N), p = p(N)$. An alternative approach for spectral accuracy employs highly oscillatory mollifiers which are activated in physical space. In [GoTa85], Gottlieb and Tadmor constructed such (properly dilated) mollifiers of the form $\Phi(y) = \rho(y)D_p(y)$, where $D_p(\cdot)$ stands for the usual Dirichlet kernel of degree $p \sim \sqrt{N}$ and ρ is a standard $C_0^\infty[-1,1]$ cut-off function normalized such that $\rho(0) = 1$.
The different filters and mollifiers advocated in these works enable to reconstruct the underlying piecewise smooth data from its given spectral content. Spectral accuracy is achieved in smooth regions as long as they are bounded away from discontinuities, but the error deteriorates in the neighborhood of such discontinuities due to spurious oscillations. The latter difficulty was addressed by Gottlieb, Shu and collaborators, by invoking Gegenbauer expansions which are driven by a judicious choice of a localizer $(1-y^2)^\lambda$ which are appended to the Dirichlet kernel $D_p(y)$, consult [GoSh98] and the references therein. Their approach allows for high resolution *uniformly up to* the discontinuities, but its precise (p, λ)-parameterization as a function of N has a rather sensitive f-dependence which impact the overall robustness of the Gegenbauer reconstruction, e.g., [Bo05]. In [TT02] we have introduced an alternative approach where the accuracy is *adapted* according to the maximal region of local smoothness. Specifically, we have shown how the Gottlieb-Tadmor mollifiers are optimized when their order is chosen *adaptively* as $p \sim Nd(x)$. Here $d(x)$ is distance between the location x to its nearest discontinuity, $d(x) = distance(x, sinsuppf(\cdot))$; the distance function $d(x)$ could be recovered from the Fourier coefficients by edge detection, e.g., [GeTa00],[GeTa02]. The resulting adaptive mollifiers lead to exponentially accurate, numerically robust mollifiers of order $exp(-\alpha(\kappa N d(x))^{1/\alpha})$ with $\alpha > 1$ dictated by the detailed C_0^∞-regularity of ρ; specifically, $\alpha > 1$ reflects the Gevrey regularity of ρ (for Gevrey regularity and the similar class of ultramodulation spaces we refer to e.g., [Jo] and [PT02], respectively). The key ingredient in our adaptive approach is giving up the *exact* moments condition; instead, (1.3) is satisfied modulo these exponentially-negligible errors, replacing the exact (1.3) with the requirement

$$\sigma^{(n)}(0) = \delta_{n0}, \qquad n = 0, 1, \dots, p-1 < q. \tag{1.4}$$

The precise relation between (1.4) and (1.3) is quantified in theorem 2.2 below. We note that it is rather simple to construct admissible filters satisfying the last requirement for an *arbitrary* p; a prototype example is given by the $C_0^\infty[-1,1]$-filters

$$\sigma_p(\xi) = \begin{cases} exp\left(\dfrac{\xi^p}{\xi^2 - 1}\right), & |\xi| < 1 \\ 0 & |\xi| \geq 1. \end{cases} \tag{1.5}$$

The purpose of this paper is to construct a new class of exponentially accurate *adaptive filters*. As before, the key issue is the parameterization of their order, p. Here we develop the rigorous study for the optimal parameterization for such filters. We advocate adaptive filters in the sense that their order, $p = p(N, d(x))$, depends on both — the order of the projection, N, and the distance function $d(x)$. Summarized in theorem 2.1 below, our main result states that the optimal adaptive filter is determined to be of order $p(N) \sim (Nd(x))^{1/\alpha}$ with $\alpha > 1$ reflecting the Gevrey regularity of σ. While achieving exponential accuracy away from discontinuities, the new filters are adapted so as to prevent spurious oscillations *throughout* the computational domain, including discontinuous neighborhoods. We mention here the adaptive filters introduced by Boyd in [Bo96]. Boyd's procedure was based on the acceleration summability by the so called Euler lag averaging; the acceleration was limited, however, since the resulting piecewise constant filters of order $p \sim Nd(x)$ were consistently larger than the optimal order and they exhibit slower convergence than the non-adaptive order of [MMO78].
Our current discussion on adaptive filters follows a similar approach for the adaptive Gottlieb-Tadmor mollifiers constructed in [TT02], $\rho(y)D_p(y)$, where the precise Gevrey regularity of the ρ allows us to obtain tight error bounds which in turn reveal the optimal adaptive parameterization, $p = p(N, d(x))$. New tight error bounds are outlined in §2 and are confirmed by numerical simulations in §3.

2. Adaptive order filters

In this section we show how the regularity and moments properties of the filter σ are translated into precise statements of localization and accuracy of the associated mollifier $\Phi^\sigma(x)$. We begin by decomposing the filtering error $f(\cdot) - S_N^\sigma f(\cdot) = f - f * \Phi^\sigma$ into the two terms

$$\begin{aligned} f(x) - f * \Phi^\sigma(x) \quad &= \quad \int_{-\pi}^{\pi} \Phi^\sigma(y)[f(x) - f(x-y)] \cdot [1 - \chi(y)]dy + \\ &\quad + \int_{-\pi}^{\pi} \Phi^\sigma(y)[f(x) - f(x-y)]\chi(y)dy =: \mathcal{I}_1 + \mathcal{I}_2. \end{aligned} \tag{2.1}$$

Here, $\chi(\cdot) = \chi_x(\cdot)$ is a auxiliary cut-off function adapted to the smoothness region of f. To this end we let $d(x)$ denote the distance between x and its nearest discontinuity so that the y-function $f(x) - f(x-y)$ remains smooth for the largest symmetric interval, $|y| \leq d(x)$. We then set $\chi(y) \equiv \chi_x(y) := \rho(y/d(x))$ where ρ is a standard C_0^∞ cut-off function,

$$\chi(y) \equiv \chi_x(y) := \rho\Big(\frac{y}{d(x)}\Big) \qquad \rho(y) = \begin{cases} \equiv 1, & |y| \leq 1/2 \\ \equiv 0, & |y| \geq 1. \end{cases}$$

We observe that the dilated cut-off function $\chi_x(y) = \rho(y/d(x))$ enforces the support of the first integrand on the right of (2.1) to be bounded $d(x)/2$-away from x while the second term is supported in the $d(x)$-neighborhood of x. To simplify matters, we assume that ρ is adapted to the same C_0^∞ regularity of σ.

We turn to estimate the first error term on the right of (2.1) which measures the essential localization of the mollifier. To this end, we use the following aliasing formula, expressing our N-degree mollifier, $\Phi^\sigma(y)$ in terms of the equally sampled inverse Fourier transform, $\varphi^\sigma(y) := \int \sigma(\xi)e^{iy\xi}d\xi$([1]),

$$\Phi^\sigma(y) \equiv \frac{N}{2\pi}\sum_{n=-\infty}^{\infty}\varphi^\sigma((N(y+2\pi n)), \quad \Phi^\sigma(y) = \frac{1}{2\pi}\sum_{|k|\le N}\sigma\left(\frac{|k|}{N}\right)e^{iky} \tag{2.2}$$

The usual Fourier decay rate estimates then yields,

$$\begin{aligned}|\Phi^\sigma(y)| &\le \frac{N}{2\pi}\sum_{n=-\infty}^{\infty}|\varphi^\sigma(N(y+2\pi n))| \le N^{1-p}\|\sigma\|_{C^p}\sum_{n=-\infty}^{\infty}|y+2\pi n|^{-p}\\ &< Const\cdot N\|\sigma\|_{C^p}(N|y|)^{-p}, \quad \forall p, \quad y\in[-\pi,\pi].\end{aligned} \tag{2.3}$$

We observe that the first integrand on the right of (2.1) is supported across the possible discontinuities of $f(x)-f(x-\cdot)$. Lack of smoothness excludes the possibility of high-oscillatory cancelations. Instead we now seek a tight upper bound on the decay of the associated mollifier, Φ^σ for $|y|\ge d(x)/2$. To this we need to quantify the C^∞-regularity of our filter σ. We focus on σ's which have *Gevrey regularity* of order α, denoted G_α below; in our case, $\sigma=\sigma_p$ in (1.5) belong to G_2, namely, there exist constants, $M=M_\sigma$ and $\eta=\eta_\sigma>0$ (independent of p) such that

$$\|\sigma_p\|_{C^p}\le M_\sigma(p!)^\alpha\eta_\sigma^{-p}, \quad \alpha=2, \quad \sigma_p(\xi)=\begin{cases} exp\left(\dfrac{\xi^p}{\xi^2-1}\right), & |\xi|<1\\ 0 & |\xi|\ge 1.\end{cases} \tag{2.4}$$

Details are outlined to lemma 2.1 below. Incorporating the above growth rate into the localization estimate (2.3) yields

$$|\Phi^\sigma(y)|\le Const.M_\sigma(p!)^2\Big(\frac{1}{\eta_\sigma N|y|}\Big)^p,$$

which is minimized at $p=p_{min}:=(\eta\cdot Nd(x))^{1/2}$. This shows that with this choice of adaptive p, the mollifier associated with our σ-filter, Φ^σ is essentially localized in the neighborhood of x, as it admits an exponential decay

$$|\Phi^{\sigma_p}(y)|\le Const_\sigma\cdot Ne^{-(\eta_\sigma N|y|)^{1/2}}. \tag{2.5}$$

Here and below η is a positive constant which may differ among the different estimates. In particular, since $[1-\chi_x(y)]$ and hence the first integrand on the right of (2.1) are supported at $|y|\ge d(x)/2$, the exponential bound follows

$$|\mathcal{I}_1|\le Const_{\sigma,f}\cdot Ne^{-(\eta_\sigma Nd(x))^{1/2}} \tag{2.6}$$

We turn to the second error term, $\mathcal{I}_2=\int\Phi^\sigma(y)[f(x)-f(x-y)]\chi_x(y)dy$. Traditionally, such a term is upper bounded by $(d(x))^p\|f\|_{C^p[x-d(x),x+d(x)]}/p!$ through Taylor expanding $f(x-y)$ about $y=0$ and by invoking the moments condition (1.3). This bound is useful for a vanishing neighborhood,

[1]The result follows, for example, by sampling the Fourier transform $\sigma(\xi)=1/2\pi\int\varphi^\sigma(y)e^{-iy\xi}dy$,

$$\begin{aligned}\sigma\left(\frac{|k|}{N}\right) &= \frac{N}{2\pi}\int\varphi^\sigma(Ny)e^{-iNy\frac{|k|}{N}}dy\\ &= \frac{N}{2\pi}\sum_{n=-\infty}^{\infty}\int_{-\pi}^{\pi}\varphi^\sigma(N(y+2\pi n))e^{-i|k|y}dy = \frac{N}{2\pi}\int_{-\pi}^{\pi}\left(\sum_{n=-\infty}^{\infty}\varphi^\sigma(N(y+2\pi n))\right)e^{-i|k|y}dy,\end{aligned}$$

and comparing with the discrete inverse Fourier transform, $\sigma(|k|/N)=\int\Phi^\sigma(y)e^{-i|k|y}dy$

$d(x) \ll 1$, while suffering by increasing the contribution of the first term on the right of (2.1), as reflected through its upper-bound (2.6). We therfore let $d(x)$ be as large as possible so we cannot argue by localization. Instead, this portion of the error decreases due to *cancelation* of oscillations by increasing the order p of Φ^{σ_p}. To this end we write

$$(2.7) \qquad \mathcal{I}_2 = \int_{-\pi}^{\pi} \Phi^{\sigma_p}(y)g(y)dy \equiv \sum_{|k|\leq N} \sigma\left(\frac{|k|}{N}\right)\widehat{g}(k), \quad g(y) = g_x(y) := [f(x) - f(x-y)]\chi_x(y),$$

and we turn to estimate the Fourier coefficients on the right. By our assumption, $f(x) - f(x-y)$ remains analytic for $|y| \leq d(x)$ and hence $g_x(y) = [f(x) - f(x-y)]\chi(y)$ is C^∞. We quantify the C^∞-regularity of $\chi_x(\cdot)$ in terms of the same Gevrey regularity of order $\alpha = 2$ that σ has, so that $\|\chi_x\|_{C^p} \leq M(p!)^2(\eta_\rho d(x))^{-p}$. Thanks to the analyticity of $f(x) - f(x-y)$, it follows that if $\rho(\cdot)$ and hence $\chi_x(\cdot)$ belong to Gevrey class G_α, so does $g_x(y) = [f(x) - f(x-y)]\chi_x(y)$, and hence

$$\|g_x(y)\|_{C^p} \leq M\frac{(p!)^\alpha}{(d(x)\eta)^p}, \qquad |y| < d(x).$$

The constants $M = M_{\rho,\eta}$ and $\eta = \eta_{\rho,f}$ capture the detailed Gevrey and analyticity properties of $\rho(y)$ and $f(x-y)$ for $|y| < d(x)$; the order p is arbitrary. The Fourier coefficients $\widehat{g}(k)$ in (2.7) do not exceed

$$|\widehat{g}(k)| \leq Const.\|g_x(y)\|_{C^p}|k|^{-p} \leq Const.M\frac{(p!)^2}{(\eta|k|d(x))^p}, \quad \eta = \eta_{\rho,f}.$$

For $\sigma(|k|/N)$, we distinguish between the low modes, $|k| \leq N/2$ and the high modes $N/2 < |k| \leq N$, setting

$$\begin{aligned} \mathcal{I}_{21} \quad &:= \quad \sum_{|k|\leq N/2} \left[\sigma_p\left(\frac{|k|}{N}\right) - 1\right]\widehat{g}(k) \\ \mathcal{I}_{22} \quad &:= \quad \sum_{N/2<|k|\leq N} \left[\sigma_p\left(\frac{|k|}{N}\right) - 1\right]\widehat{g}(k) \end{aligned}$$

Since $g(y) = [f(\cdot) - f(\cdot - y)]\chi(y)$ vanishes at $y = 0$ we have $\sum \widehat{g}(k) = g(0) = 0$ and hence $\mathcal{I}_2 = \mathcal{I}_{21} + \mathcal{I}_{22} + \mathcal{I}_{23}$ where $\mathcal{I}_{23} := -\sum_{|k|>N}\widehat{g}(k)$. For the first term we use a Taylor expansion around the origin: the accuracy assumption (1.4) yields

$$\left|\sigma_p\left(\frac{|k|}{N}\right) - 1\right| \leq \frac{1}{p!}\|\sigma\|_{C^p([-\frac{1}{2},\frac{1}{2}])}\left(\frac{|k|}{N}\right)^p, \quad |k| \leq \frac{N}{2}.$$

Restricted to the $[-1/2, 1/2]$ interval, σ retains an analytic bound $\|\sigma\|_{C^p} \leq Const.p!\eta_\sigma^{-p}$, and hence $\mathcal{I}_{21}$ does not exceed

$$\begin{aligned} |\mathcal{I}_{21}| \quad &:= \quad \Big|\sum_{|k|\leq N/2}\left[\sigma_p\left(\frac{|k|}{N}\right) - 1\right]\widehat{g}(k)\Big| \leq \frac{1}{p!}\|\sigma\|_{C^p([-\frac{1}{2},\frac{1}{2}])}\sum_{|k|\leq N/2}\left(\frac{|k|}{N}\right)^p\frac{(p!)^2}{(\eta_{\rho,f}|k|d(x))^p} \\ (2.8) \qquad &\leq \quad Const.N(p!)^2\frac{1}{(\eta N d(x))^p}, \quad \eta = \eta_\sigma\eta_{\rho,f}. \end{aligned}$$

For the high modes, $\widehat{g}_x(k)$ are sufficiently small so that the simple bound of $|\sigma_p(|k|/N)| \leq 1$ will do for $\mathcal{I}_{22}$,

(2.9)
$$|\mathcal{I}_{22}| := \Big| \sum_{N/2<|k|\le N} \left[\sigma_p\left(\frac{|k|}{N}\right) - 1\right]\widehat{g}(k)\Big| \le \Big| \sum_{N/2<|k|\le N} \frac{(p!)^2}{(\eta_\sigma |k| d(x))^p}\Big| \le Const.N(p!)^2 \frac{1}{(\eta_\sigma N d(x)/2)^p}.$$

Similarly, $\mathcal{I}_{23}$ does not exceed

$$|\mathcal{I}_{23}| := \Big| \sum_{|k|>N} \widehat{g}(k)\Big| \le (p!)^2 \sum_{|k|>N} \frac{1}{(\eta_\sigma |k| d(x))^p} \le Const.N(p!)^2 \frac{1}{(\eta_\sigma N d(x))^p}. \tag{2.10}$$

We combine the last three bounds to conclude

$$|\mathcal{I}_2| \le Const.N(p!)^2 \frac{1}{(\eta N d(x))^p}, \quad \eta = \min(\eta_\sigma \eta_{\rho,f}, \eta_\sigma/2, \eta_{\rho,f})$$

which is minimized at the same value as before, $p = p_{min} := (\eta \cdot Nd(x))^{1/2}$, so that

$$|\mathcal{I}_2| \le Const \cdot N e^{-(\eta N d(x))^{1/2}} \tag{2.11}$$

Finally, we recall the assumed regularity of ρ is in fact dictated by that of σ and hence the various bounds, $\eta = \eta_{\sigma,f}$. We summarize by stating

Theorem 2.1. *Given the Fourier projection $S_N f$ of a piecewise analytic function $f(\cdot)$, we consider a $C_0^\infty[-1,1]$ filter $\sigma(\xi)$,*

$$S_N^\sigma f(x) = \sum_{|k|\le N} \sigma\left(\frac{|k|}{N}\right) \widehat{f}_k e^{ikx}.$$

Assume that σ has G_α-regularity and that it is accurate of order p in the sense of satisfying the moments condition

$$\sigma^{(n)}(0) = \delta_{n0}, \quad n = 0, 1, \ldots, p-1. \tag{2.12}$$

We set the adaptive order $p(x) := (\eta \cdot Nd(x))^{1/\alpha}$ depending the distance function $d(x) = dist(x, sinsupp f(\cdot))$. The resulting adaptive *filter, $S_N^\sigma f$, recovers the pointvalues $f(x)$ with the following exponential accuracy*

$$|f(x) - S_N^\sigma f(x)| \le Const \cdot N e^{-\alpha(\eta \cdot N d(x))^{1/\alpha}}. \tag{2.13}$$

The constant $\eta = \eta_{\sigma,f}$ is dictated by the specific Gevrey and piecewise-analyticity properties of σ and f.

We close this section with the promised statements on the exponential error bound (2.4).

Lemma 2.1. *Consider the p order filter* $\sigma_p(\xi) = \begin{cases} exp\left(\dfrac{\xi^p}{\xi^2-1}\right), & |\xi| < 1 \\ 0 & |\xi| \ge 1. \end{cases}$ *Then there exist constants η such that*

$$\|\sigma_p\|_{C^p} \le Const.(p!)^2 \eta^{-p}, \tag{2.14}$$
$$\|\sigma_p\|_{C^p([-\frac{1}{2},\frac{1}{2}])} \le Const.p!\eta^{-p}. \tag{2.15}$$

To verify (2.14) we first note that $\sigma_p^{(s)}$ is a collection of polynomial terms which premultiply the exponential in the variable $\xi^p/(\xi^2-1)$. Each derivative of σ_p doubles the number of such terms; thus, by successive application of Leibniz's rule, $\sigma_p^{(s)}$ consists of 2^s α-terms, each of which is of the form

$$C_\alpha \prod_{\alpha_j} \Big(\frac{\xi^p}{\xi^2-1}\Big)^{(\alpha_j)} exp\Big(\frac{\xi^p}{\xi^2-1}\Big), \quad |\alpha| = \sum_j \alpha_j = s. \tag{2.16}$$

Here, the C_α's are constant integers with $|C_\alpha| \leq \eta_1^{-s}$ for some fixed $\eta_1 > 0$. We consider the prototype term $T_{p,s} := \big(\frac{\xi^p}{\xi^2-1}\big)^{(s)} exp\Big(\frac{\xi^p}{\xi^2-1}\Big)$, corresponding to $\alpha = (0, 0, \ldots, s)$,

$$\begin{aligned} T_{p,s} &= \Big(\frac{\xi^p}{\xi^2-1}\Big)^{(s)} exp\Big(\frac{\xi^p}{\xi^2-1}\Big) \\ &= \sum_{k=0}^{s} \begin{pmatrix} s \\ k \end{pmatrix} \frac{p!}{(p-s+k)!} \xi^{p-s+k} \frac{k!}{(\xi^2-1)^{k+1}} exp\Big(\frac{\xi^p}{\xi^2-1}\Big) + \text{ lower order terms }. \end{aligned} \tag{2.17}$$

Here, by 'lower order terms' we refer to the singular behavior of $(\xi^2-1)^{-j}, j \leq k$ near $\xi = \pm 1$, which weaker then the leading term $(\xi^2-1)^{-k+1}$. To control the amplitude of $T_{p,s}$ we let $a(\xi) := (\xi^2-1)$ and note that the expression $|a(\xi)|^{-k} exp(\alpha a(\xi) + \beta/a(\xi))$ is maximized at $\xi = \xi_{max}$ such that $a(\xi_{max}) \sim -\beta/k$, yielding

$$|T_{p,s}| \leq Const. \sum_{k=0}^{s} \begin{pmatrix} s \\ k \end{pmatrix} \frac{p!}{(p-s+k)!} k! k^k e^{-k} < Const. p! \sum_{k=0}^{s} \begin{pmatrix} s \\ k \end{pmatrix} k! \leq Const. 2^s p! s!.$$

The other 2^s terms in (2.16) admit similar bounds and the resulting $T_{p,p}$ bound yields (2.14) with $\eta = 4\eta_1$. To prove (2.15), we restrict attention to a subinterval which is bounded away from ± 1, so that the ξ-dependent terms in (2.17) remain uniformly bounded, $(\xi^2-1)^{-j} exp\big(\xi^p/(\xi^2-1)\big) \leq \eta_2^{-k}, j \leq k+1$, and we are left the desired upper bound

$$|T_{p,p}| \leq Const. \sum_{k=0}^{p} \begin{pmatrix} p \\ k \end{pmatrix} \frac{p!}{k!} k! \eta_2^{-k} < Const. 2^p p! (\eta_2)^{-p},$$

and (2.15) follows with $\eta = 4\eta_1\eta_2$. ■

The intricate part in the construction of such highly-accurate filters or mollifiers is the further requirement for their localization (in physical space) or smoothness (in Fourier space). One cannot increase the order p arbitrarily without steepening Φ^σ, or equivalently, without losing smoothness of σ. The solution taken here was to satisfy the moments condition *approximately*, modulo exponentially negligible errors while retaining the desired smoothness properties. We note that our optimal adaptive filter is essentially localized in the physical space in the sense that the associated mollifier Φ^σ is exponentially small for $|y| \gg 1/N$, (2.5), see figure 2.1. In contrast, the adaptive mollifiers constructed in [TT02], $\rho(y/d(x))D_p(y/d(x))/d(x)$, were compactly supported in physical space (adapted to the smoothness neighborhood of x) and only essentially localized in the dual Fourier space. The precise result is quantified in the following.

Theorem 2.2. *Consider the even filter σ with Gevrey regularity G_α satisfying the p-order accuracy condition (1.4), with $p \sim N^{1/\alpha}$. Then the associated mollifier, Φ^σ satisfies the moments condition (1.3) modulo an exponentially negligible error,*

$$\int_{y=-\pi}^{\pi} y^n \Phi^\sigma(y) dy = \delta_{n0} + Const. e^{-(\eta N)^{1/\alpha}}, \quad n \leq Const. N^{1/\alpha}$$

For proof, we appeal to (2.2)

$$\int_{y=-\pi}^{\pi} y^n \Phi^\sigma(y)dy = \frac{N}{2\pi}\int_{y=-\pi}^{\pi} y^n\varphi^\sigma(Ny)dy + \frac{N}{2\pi}\sum_{n\neq 0}\int_{y=-\pi}^{\pi} y^n\varphi^\sigma(N(y+2\pi n))dy =: \mathcal{I}_1 + \mathcal{I}_2.$$

For the first term on the right we have

$$\mathcal{I}_1 = \frac{N}{2\pi}\int_{y=-\infty}^{\infty} y^n\varphi^\sigma(Ny)dy - \frac{N}{2\pi}\int_{|y|\geq\pi} y^n\varphi^\sigma(Ny)dy =: \mathcal{I}_{11} + \mathcal{I}_{12}.$$

We now have $\mathcal{I}_{11} = (-iN)^n\sigma^{(n)}(0) = \delta_{n0}$ by (1.4), where the usual decay rate $|\varphi^\sigma(y)| \leq Const.\|\sigma\|_{C^s}\cdot |y|^{-s}$ yields

$$|\mathcal{I}_{12}| \leq Const.\frac{N^{1-s}}{2\pi}\|\sigma\|_{C^s}\int_{\pi}^{\infty} y^{n-s}dy \leq Const.(\eta N)^{1-s}(s!)^\alpha, \quad n \leq s-2.$$

The remainder amounts to a similarly exponentially small term

$$|\mathcal{I}_2| \leq Const.\frac{N^{1-s}}{2\pi}\|\sigma\|_{C^s}\int_{y=-\pi}^{\pi} |y|^n\frac{1}{(2\pi-|y|)^s}dy \leq Const.(\eta N)^{1-s}(s!)^\alpha, \quad n \leq s$$

which is minimized at $s \sim (\eta N)^{1/\alpha}$ and the lemma follows. ■

We note in passing that the last theorem could be used as a starting point for an alternative proof of the main result stated in theorem 2.1.

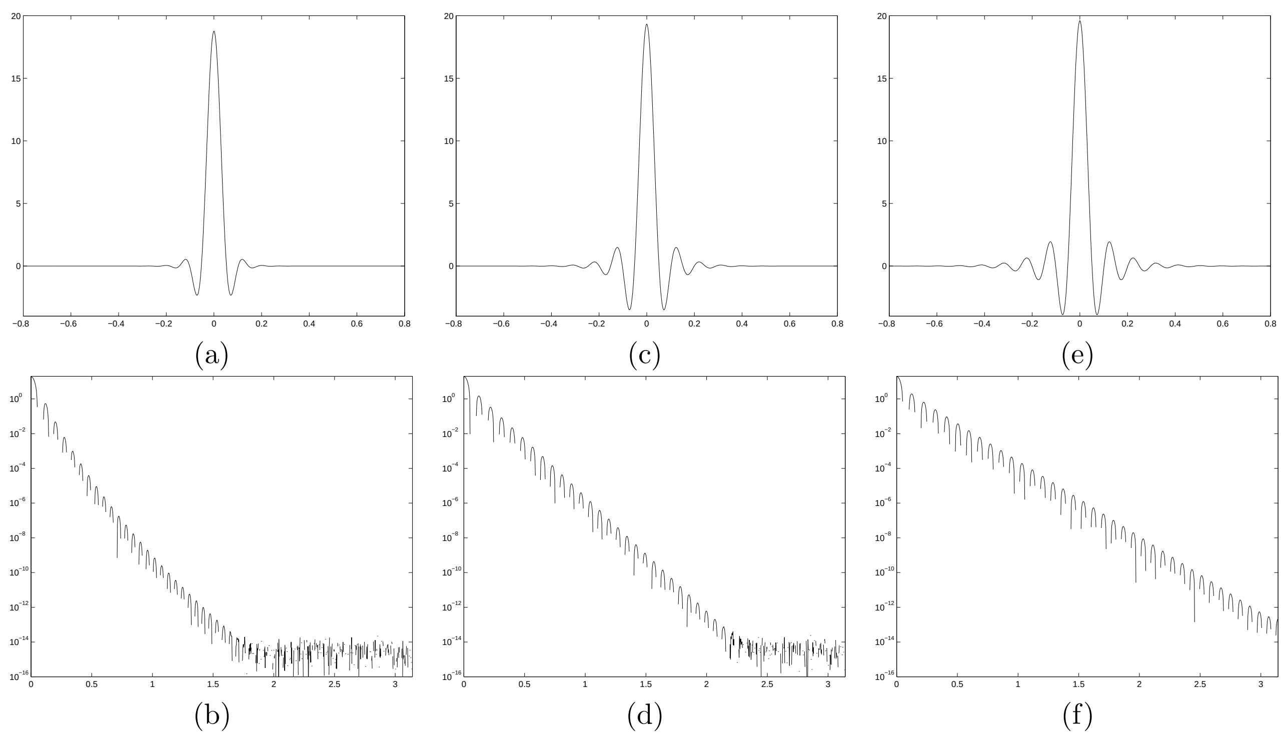


Figure 2.1: The mollifier (top) and its semi-log plot (bottom) with the mollifier defined from the filter (3.1) used in the numerical experiments, with $N = 128$ and filter orders $p = 4, 8$, and 12 in (a-b), (c-d), and (e-f) respectively.

3. Numerical Experiments

For the following examples we utilize the filter

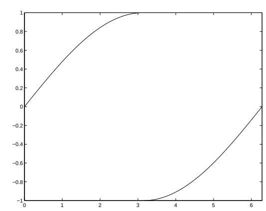
$$\sigma_p(\xi) = \begin{cases} \exp\left(\frac{c_p \xi^p}{\xi^2-1}\right) & |\xi| < 1 \\ 0 & |\xi| \geq 1 \end{cases} \tag{3.1}$$

which has Gevrey regularity of order $\alpha = 2$. Its advocated order is then optimized at the adaptive order, $p = p(x) = \sqrt{\kappa N d(x)}$. For a given filter, the free constant c_p should be selected to enhance the immediate localization of $\Phi^\sigma(\cdot)$ by minimizing $\|\sigma\|_{C^1}$. The value of such an optimal c_p does not permit a closed form expression; an approximate condition used in the numerical examples below is $\sigma^{(2)}(1/2) = 0$, resulting in

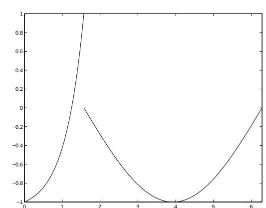
$$c_p := 2^p \frac{3}{4} \cdot \frac{9p^2 + 3p + 14}{9p^2 + 12p + 4}.$$

To allow direct comparison between our adaptive filters and the adaptive mollifiers advocated in [TT02], we concern ourselves with the two prototypes of piecewise analytic functions, $f_1(x)$ and $f_2(x)$ given below.

$$f_1(x) = \begin{cases} \sin(x/2) & x \in [0, \pi) \\ -\sin(x/2) & x \in [\pi, 2\pi) \end{cases} \tag{3.2}$$



$$f_2(x) = \begin{cases} (2e^{2x} - 1 - e^{\pi})/(e^{\pi} - 1) & x \in [0, \pi/2) \\ -\sin(2x/3 - \pi/3) & x \in [\pi/2, 2\pi) \end{cases} \tag{3.3}$$



The first function, $f_1(\cdot)$, possesses a mild regularity constant and a single discontinuity at $x = \pi$; consequently $d(x) = |x - \pi|$ for $x \in [0, 2\pi]$. The second function, $f_2(\cdot)$, was constructed as a more challenging test problem with a large gradient to the left of the discontinuity at $x = \pi/2$. Moreover, lacking periodicity $f_2(\cdot)$ feels three discontinuities per period;

$$d(x) = min(|x|, |x - \pi/2|, |x - 2\pi|) \quad x \in [0, 2\pi].$$

For both functions the exact Fourier coefficients, $\{\widehat{f}(k)\}_{k \leq N}$, are given and then filtered to recover the intermediate pointvalues $\frac{\pi}{N}(\nu - \frac{1}{2})$ for $\nu = 1, 2, \ldots 2N$. Graphs (a)-(d), use fixed order filters, verifying the well known fact that higher order filters gives superior convergence away from discontinuities and lower order filters near discontinuities. Graphs (e)-(f) illustrate the superior convergence for the adaptive filter described in theorem 2.1, computed with adaptive order $p = p(x) = \max(2, \frac{1}{2}(Nd(x))^{1/2})$. We note in passing that the same filter order is used for both $f_1(\cdot)$ and $f_2(\cdot)$, ignoring the different analyticity properties of f_1 and f_2 (reflected by different analyticity constants η_f), and achieving exponential accuracy in both instances. Results of the adaptive filter are contrasted with the spectrally accurate filter of Vandeven, [Va91], where the variables order, $p = N^\gamma$ remains uniform throughout the computational domain.

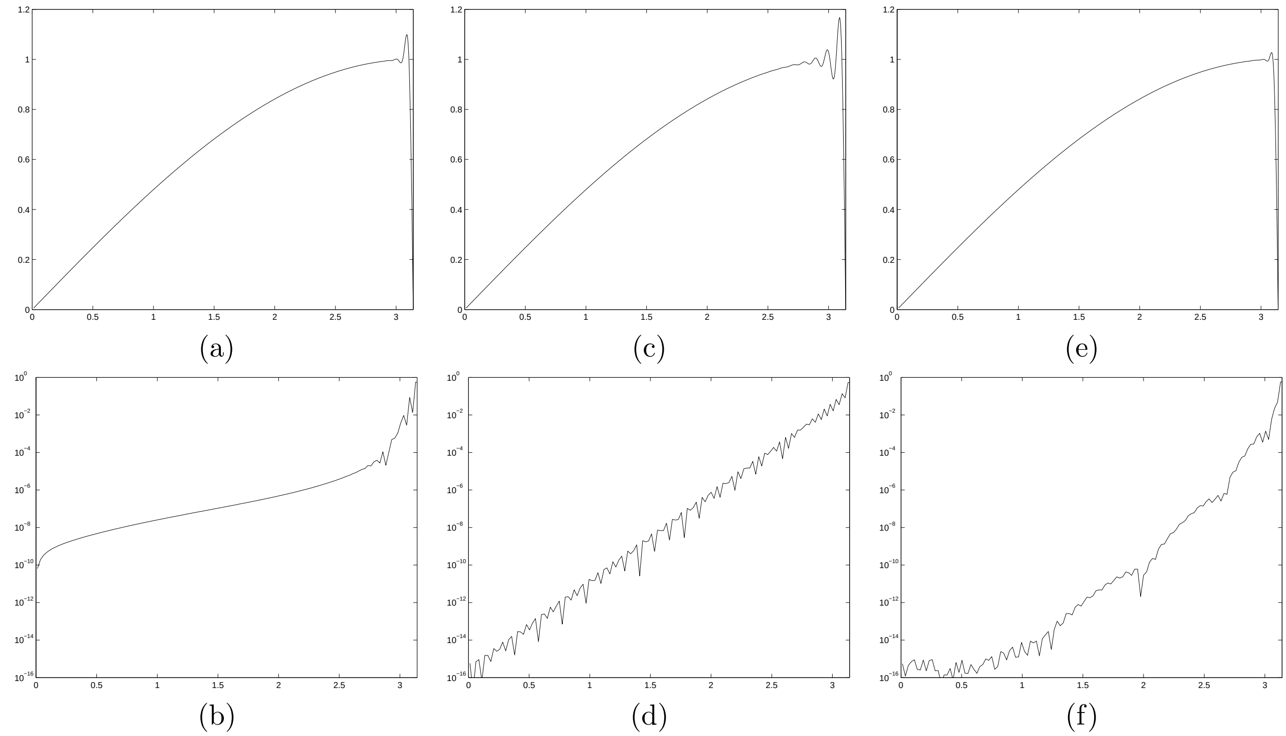


Figure 3.1: Recovery of $f_1(x)$ (top) and the approximation error (bottom) from their $N = 128$-mode spectral projections. The filter (3.1) was of orders $N^{1/4}$ (a)-(b), $N^{1/2}$ (c)-(d), and $\max(2, \frac{1}{2}(Nd(x))^{1/2})$

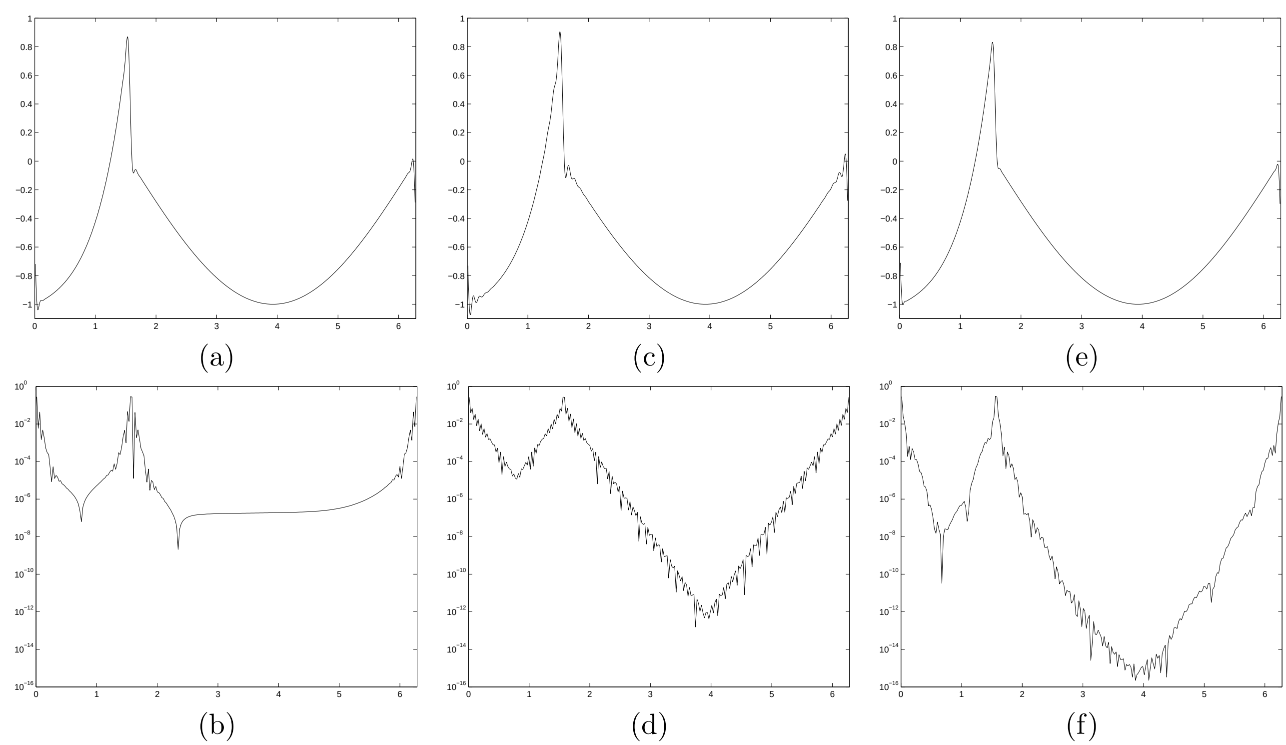


Figure 3.2: Recovery of $f_2(x)$ (top) and the approximation error (bottom) from their $N = 128$-mode spectral projections. The filter (3.1) was of orders $N^{1/4}$ (a)-(b), $N^{1/2}$ (c)-(d), and $\max(2, \frac{1}{2}(Nd(x))^{1/2})$ (e)-(f).

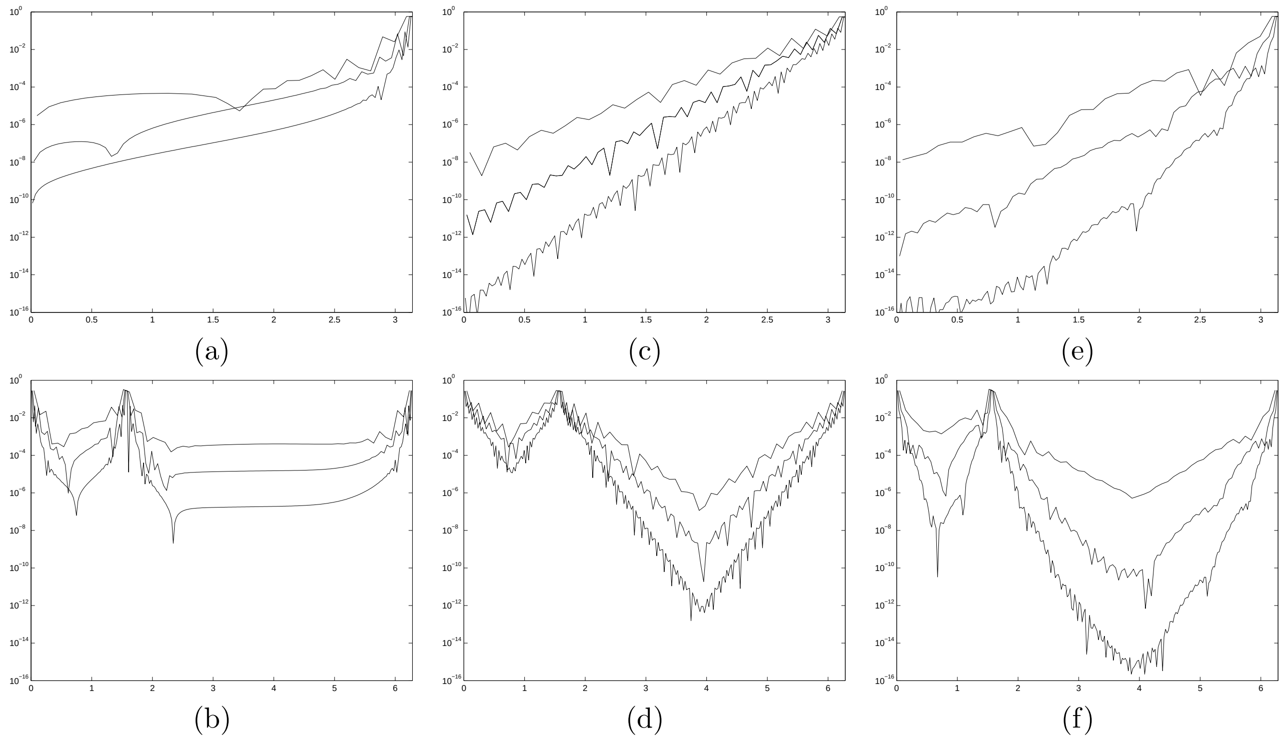


Figure 3.3: Error plots for the recovery of $f_1(x)$ (top) and $f_2(x)$ (bottom) from their $N = 32, 64, \text{and} 128$ mode spectral projections. The filter (3.1) was of orders $N^{1/4}$ (a)-(b), $N^{1/2}$ (c)-(d), and $\max(2, \frac{1}{2}(Nd(x))^{1/2})$ (e)-(f).

4. Summary

The analysis presented here quantitatively resolves the classical methodology that for improved accuracy low order filters should be used near discontinuities and high order filters away. The optimal adaptive filters presented here retain the traditional robustness associated with low order filtering, yet achieve a significant increase in accuracy with minimal increase to computational cost. Combined with the automated edge detection methods, [GeTa00], adaptive order filtering is a *black box* procedure for the exponentially accurate reconstruction of a piecewise smooth function from its spectral information.

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