Lectures 3/4. High Frequency Boundary Element Methods

Simon Chandler-Wilde

University of Reading, UK

www.reading.ac.uk/~sms03snc

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This afternoon's focus

Background. The number of degrees of freedom in a conventional BEM needs to increase as the wave number k increases.

- In the BEM context, can we avoid this by using clever basis functions, e.g. solutions of the Helmholtz equation or solutions of the Helmholtz equation multiplied by standard basis functions?
- Does it help if we know enough about the high frequency behaviour of the solution? (What is this behaviour?)
- By doing this, is a solver achievable with $O(1)$ cost in the limit as $k \to \infty$?

In fact, can we achieve

'prescribed error tolerances within fixed computational times for scattering problems of arbitrarily high frequency'

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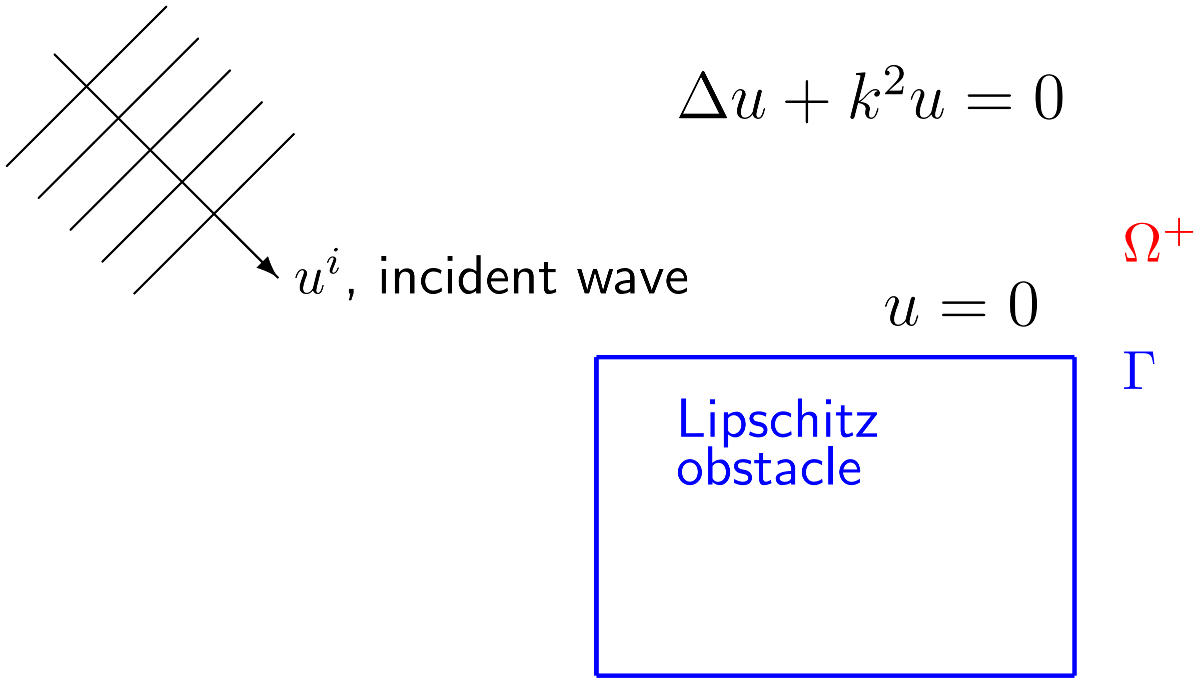
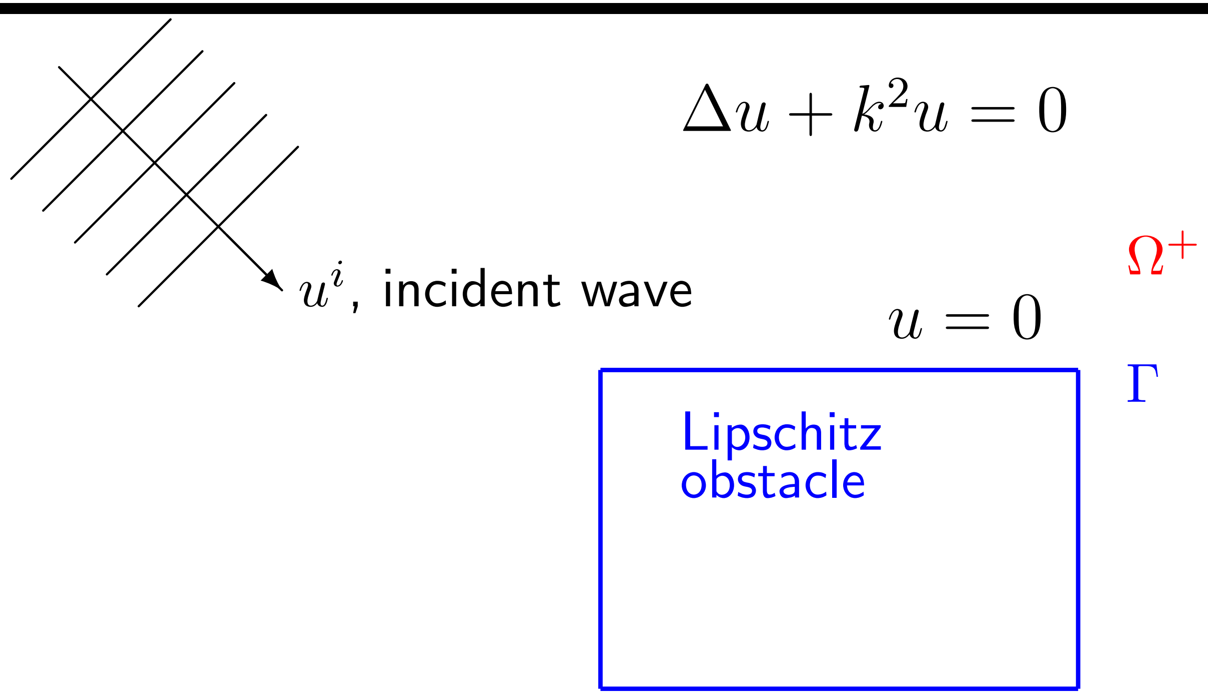
The answer will be:

- for some 2D problems, definitely yes, or at least something very close to this
- for general 3D problems maybe not, but some significant improvement on conventional methods may be possible, and this is a promising research area

The Scattering Problem



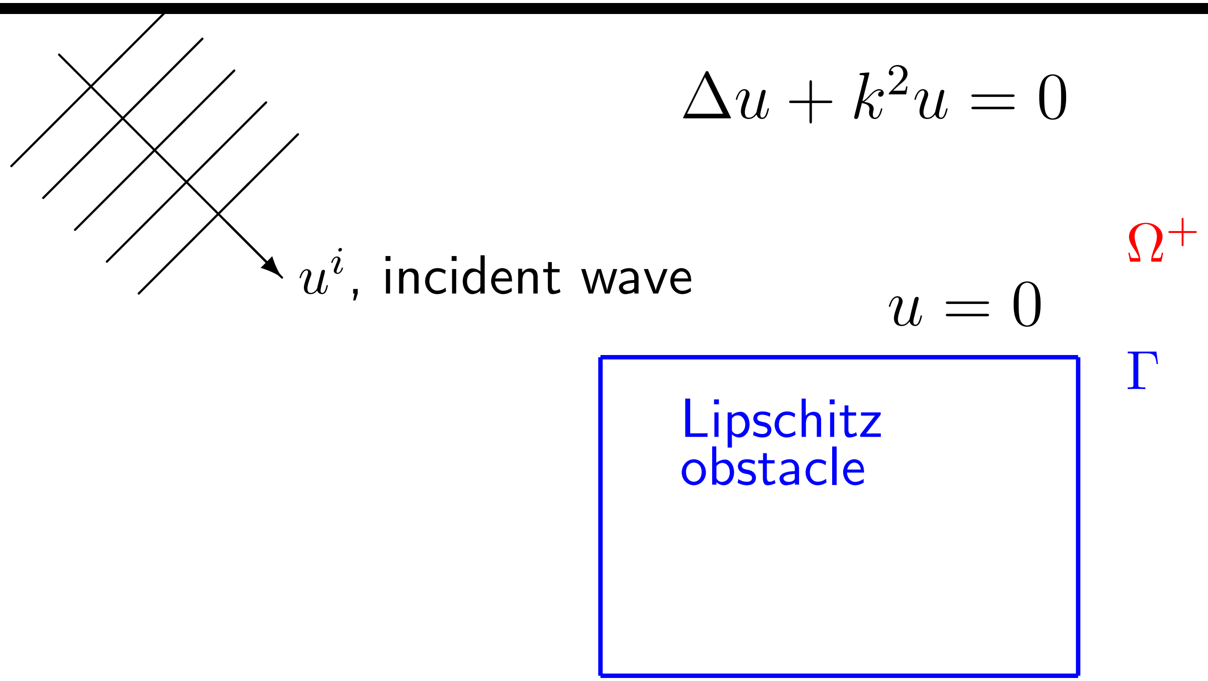


Green's representation theorem:

$$u(x) = u^i(x) - \int_\Gamma G(x,y)\frac{\partial u}{\partial n}(y)ds(y), \quad x \in \Omega^+,$$

where

$$G(x,y) := \tfrac{\mathrm{i}}{4}H_0^{(1)}(k|x-y|) \text{ (2D)}, \qquad := \frac{1}{4\pi}\frac{\mathrm{e}^{\mathrm{i}k|x-y|}}{|x-y|} \text{ (3D)}.$$

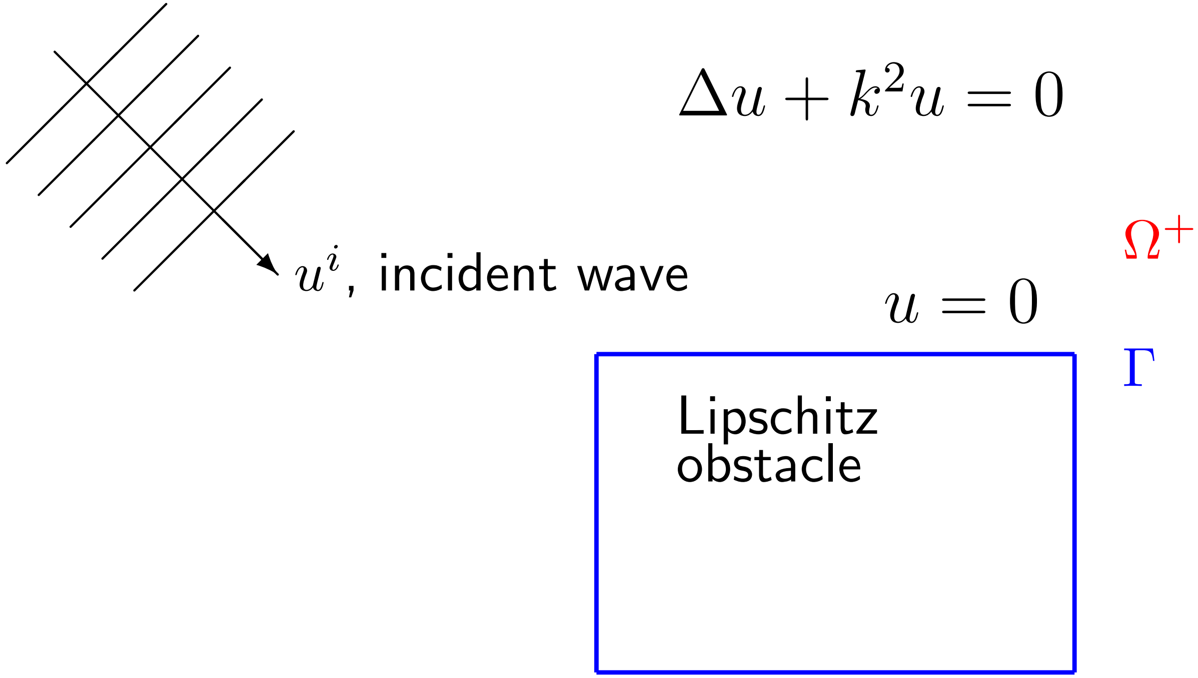


Taking a linear combination of Dirichlet and Neumann traces of the previous equation (see my Lecture 2), we get the BIE

$$\frac{1}{2}\frac{\partial u}{\partial n}(x) + \int_\Gamma \left(\frac{\partial G(x,y)}{\partial n(x)} + \mathrm{i}\eta G(x,y) \right) \frac{\partial u}{\partial n}(y) ds(y) = f(x), \quad x \in \Gamma,$$

where

$$f(x) := \frac{\partial u^i}{\partial n}(x) + \mathrm{i}\eta u^i(x).$$



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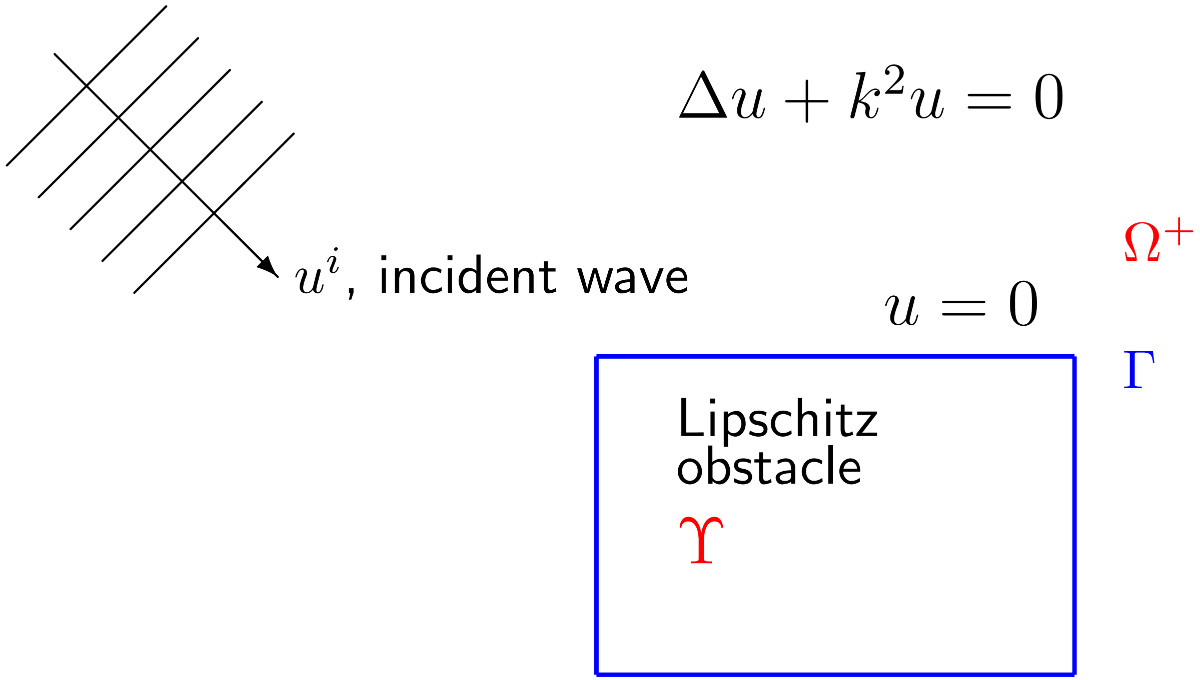
Theorem 3.1 (see Lecture 2, p. 33) If $\eta \in \mathbb{R}$, $\eta \neq 0$, then this integral equation is uniquely solvable in $L^2(\Gamma)$.



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Theorem 3.1 (see Lecture 2, p. 33) If $\eta \in \mathbb{R}$, $\eta \neq 0$, then this integral equation is uniquely solvable in $L^2(\Gamma)$. In fact (see Lecture 2), if Υ is **starlike** and $\eta = k$ then the inverse operator is bounded independently of k.

$$\frac{1}{2}\frac{\partial u}{\partial n}(x) + \int_\Gamma \left(\frac{\partial G(x,y)}{\partial n(x)} + \mathrm{i}\eta G(x,y) \right) \frac{\partial u}{\partial n}(y) ds(y) = f(x), \quad x \in \Gamma.$$

Conventional BEM (see Ralf's notes): Approximate $\partial u/\partial n$ by a piecewise polynomial, i.e.

$$\frac{\partial u}{\partial n}(x) \approx \sum_{j=1}^{N} a_j \mathbf{b}_j(x),$$

where $\mathbf{b}_1(x), \ldots, \mathbf{b}_N(x)$ are the piecewise polynomial basis functions (more precisely, if the boundary is curved, these functions are the images of conventional FEM basis functions under a mapping from a reference element in $\mathbb{R}^{d-1}$ to Γ).

$$\frac{1}{2}\frac{\partial u}{\partial n}(x) + \int_\Gamma \left(\frac{\partial G(x,y)}{\partial n(x)} + \mathrm{i}\eta G(x,y) \right) \frac{\partial u}{\partial n}(y) ds(y) = f(x), \quad x \in \Gamma.$$

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Applying a **Galerkin method** (Ralf's notes) or a **collocation method** (which means: stick the approximation into the integral equation and force the integral equation to hold at N carefully chosen points – the **collocation points**) we get a linear system to solve with N degrees of freedom, namely the unknown values of a_1, ..., a_N.

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Conventional BEM: Apply a Galerkin method, approximating $\partial u/\partial n$ by a piecewise polynomial of degree P, leading to a linear system to solve with N degrees of freedom. **Problem:** N of order of $(kL)^{d-1}$, where L is a linear dimension, and cost is $O(N^2)$ to compute full matrix and apply iterative solver.

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Conventional BEM: Apply a Galerkin method, approximating $\partial u/\partial n$ by a piecewise polynomial of some degree p, leading to a linear system to solve with N degrees of freedom. **Problem:** N of order of kL^{d-1}, where L is linear dimension, and cost is $O(N^2)$ to compute full matrix and apply iterative solver. ... or close to $O(N)$ if a fast multipole method (see Ralf's notes) is used.

This is **fantastic** but still infeasible as $kL \to \infty$.

Alternative: Reduce N by using new basis functions, namely oscillatory basis functions which can represent the solution well. Specifically, let's try an approximation of the form

$$\frac{\partial u}{\partial n}(x) \approx \sum_{i=1}^{M} \sum_{j=1}^{N_i} a_{ij} \mathrm{e}^{\mathrm{i}k g_i(x)} \mathbf{b}_{ij}(x),$$

with $a_{ij} \in \mathbb{C}$ the unknown coefficients,

$g_1(x), \ldots, g_M(x)$ known **phase functions**,

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Moreover, let's have a total #dof $N = \sum_{i=1}^{M} N_i$ much less than in the conventional BEM, maybe even $N = O(1)$ as $k \to \infty$, the **'high frequency $O(1)$ algorithm'** holy grail.

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All the implementations I will describe have $g_i(x) = x \cdot \hat{d}_i$, for some unit vector $\hat{d}_i$, so

$$\mathrm{e}^{\mathrm{i}k g_i(x)} = \exp(\mathrm{i}k x \cdot \hat{d}_i)$$

is a **plane wave** travelling in direction $\hat{d}_i$.
Cf. Markus's hugely relevant lectures for the same idea in the FEM context.

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$$\frac{\partial u}{\partial n}(x) \approx \sum_{i=1}^{M} \sum_{j=1}^{N_i} a_{ij} \mathrm{e}^{\mathrm{i}kg_i(x)} \mathbf{b}_{ij}(x),$$

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The Plan: let's have a total #dof $N = \sum_{i=1}^{M} N_i$ which is $N = O(1)$ as $k \to \infty$, and then we will have achieved the **'high frequency $O(1)$ CPU time algorithm'** holy grail.

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No! Unfortunately, $N = O(1) \not\Rightarrow$ CPU time $= O(1)$.

The Snag: our N^2 matrix entries are highly oscillatory integrals

E.g. if the integral equation is

$$\int_\Gamma G(x,y)\frac{\partial u}{\partial n}(y)ds(y) = f(x), \quad x \in \Gamma,$$

and we use a collocation method, collocating at points x_ℓ, $\ell = 1, \ldots, N$, then the matrix entries have the form

$$\int_{\Gamma_{ij}} G(x_\ell, y)\exp(\mathrm{i}kg_i(y))\mathbf{b}_{ij}(y)\,ds(y)$$

where Γ_{ij} is the support of b_{ij}.

If $N = O(1)$ then, where $h = \max_{ij}\mathrm{diam}(\Gamma_{ij})$, necessarily $kh = 2\pi h/\lambda \to \infty$ as $k \to \infty$.

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and we use a collocation method, collocating at points x_ℓ, $\ell = 1, \ldots, N$, then the matrix entries have the form (in 3D)

$$\int_{\Gamma_{ij}} \frac{1}{4\pi|x_\ell - y|} \exp[\mathrm{i}k(|x_\ell - y| + g_i(y))]\mathbf{b}_{ij}(y)\, ds(y)$$

where Γ_{ij} is the support of b_{ij}.

The integrand is increasingly oscillatory as $k \to \infty$ but at least we **know what this oscillation is**.

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and we use a **Galerkin method**, then the matrix entries have the form (in 3D)

$$\int_{\Gamma_{ij}}\int_{\Gamma_{mn}} \frac{1}{4\pi|x-y|}\exp[\mathrm{i}k(|x-y|+g_i(y)-g_m(x))]\mathbf{b}_{ij}(y)\mathbf{b}_{mn}(x)\,ds(y)ds(x).$$

Each entry is a 4-dimensional, increasingly oscillatory integral as $k \to \infty$.

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Recent research on evaluation of oscillatory integrals is developing tools to attack these problems. See Iserles et al. [15, 16], Bruno et al. [3], Huybrechs et al. [13], Ganesh et al. [12].

How are people choosing $\hat{d}_i$ and b_{ij}??

$$\frac{\partial u}{\partial n}(x) \approx \sum_{i=1}^{M} \sum_{j=1}^{N_i} a_{ij} \exp(\mathrm{i}kx \cdot \hat{d}_i)\mathbf{b}_{ij}(x),$$

with $a_{ij} \in \mathbb{C}$ the unknown coefficients,
$\hat{d}_1, \ldots, \hat{d}_N$ distinct unit vectors,
$\mathrm{b}_{ij}(x)$ **conventional BEM basis functions**.

Approach 1. M large.

Approach 2. $M = 1$.

Approach 3. M small, directions $\hat{d}_i$ carefully chosen to match high frequency solution behaviour.

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with $\hat{d}_1, \ldots, \hat{d}_N$ distinct unit vectors and $\mathbf{b}_{ij}(x)$ conventional BEM basis functions.

Approach 1. Fix $N_i = N^*$ so $N = MN^*$, use conventional, fixed degree boundary elements on a (usually uniform) mesh, and have M largish (e.g. 18 in 2D, 200 in 3D) and the directions $\hat{d}_i$ uniformly spread, e.g., in 2D ($d = 2$),

$\hat{d}_i = (\cos(2\pi i/N^*), \sin(2\pi i/N^*))$, $i = 1, \ldots, N^*$.

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This is very successful (numerical results in 2D, 3D, for acoustic/elastic waves and Neumann/impedance b.c.s, convex, non-convex scatterers), reducing number of degrees of freedom per wavelength from e.g. 6-10 to close to 2. However N still increases proportional to kL. There are also severe conditioning problems (the basis is almost linearly dependent). See de La Bourdonnaye et al. [8, 9], Perrey-Debain et al. [23, 24, 22, 25].

Some similarities to conventional high order (p large) BEMs (?)

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with $\hat{d}_1, \ldots, \hat{d}_N$ distinct unit vectors and $\mathbf{b}_{ij}(x)$ conventional BEM basis functions.

Approach 2. $M = 1$.

How are people choosing $\hat{d}_i$ and $\mathbf{b}_{ij}$??

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with $\mathbf{b}_j(x)$ conventional BEM basis functions.

Approach 2. $M = 1$, with $\hat{d}$ the direction of the incident plane wave.

How are people choosing $\hat{d}_i$ and b_{ij}??

$$\frac{\partial u}{\partial n}(x) \approx \exp(\mathrm{i}kx \cdot \hat{d}) \sum_{j=1}^{N^*} a_j \mathbf{b}_j(x),$$

with $\mathbf{b}_j(x)$ conventional BEM basis functions.

Approach 2. $M = 1$, with $\hat{d}$ the direction of the incident plane wave. In other words, we remove some of the oscillation by **factoring out the oscillation of the incident wave**. A slight variant on this is to write

$$\frac{\partial u}{\partial n}(y) = \frac{\partial u^i}{\partial n}(y) \times \mu(y)$$

and then approximate μ by a conventional BEM.

Approach 2. We remove some of the oscillation by **factoring out the oscillation of the incident wave**, e.g.

$$\frac{\partial u}{\partial n}(y) = \frac{\partial u^i}{\partial n}(y) \times \mu(y) \quad (*)$$

and then approximate μ by a conventional BEM.

For **smooth convex obstacles** this should work well: equation $(*)$ holds with $F(y) \approx 2$ on the illuminated side and $F(y) \approx 0$ in the shadow zone (this is the high frequency **Kirchhoff** or **physical optics** approximation).

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This is an old idea, but has seen sophisticated analysis, algorithmic ideas, and numerical analysis applied in recent years, see Zhou et al. [1], Darrigrand [7], Bruno et al. [3, 4], Dominguez et al. [10], Ecevit [11], Huybrechs and Vanderwalle [14].

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To understand how algorithms in this class work we have to look at the solution to scattering by smooth convex obstacles - in fact let us digress and look at high frequency asymptotics more generally.

The Geometrical Theory of Diffraction – see Keller et al. [18, 17]

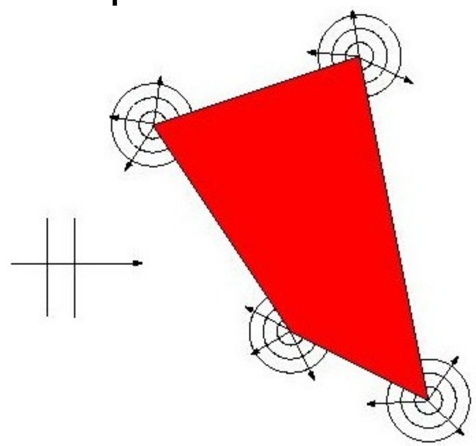
A partly heuristic, semi-rigorous theory, whose principles are:

- At high frequency a ray model is appropriate
- The paths of rays are determined by Fermat's principle, i.e. rays take the quickest route
- Phase of the field on a ray is determined by distance along the ray, i.e. $u(x) = |u(x)|\mathrm{e}^{\mathrm{i}ks}$, s distance along ray
- Localization: interaction with obstacles depends only on the geometry local to the point where the ray hits the obstacle, and so can be determined by solving **canonical scattering problems**

Two Examples. If obstacle has corners then rays are reflected from sides but also diffracted from corners. Each diffracted ray (in 2D) has the form:

$$u^{diff}(x) = u^i(x_c) D(\theta, \theta_0) \frac{e^{ikr}}{\sqrt{r}}$$

where x_c is the corner, (r, θ) are polar coordinates of x relative to the corner (i.e. of $x - x_c$), θ_0 is the angle of incidence and $D(\theta, \theta_0)$ is a diffraction coefficient which depends on the local geometry.



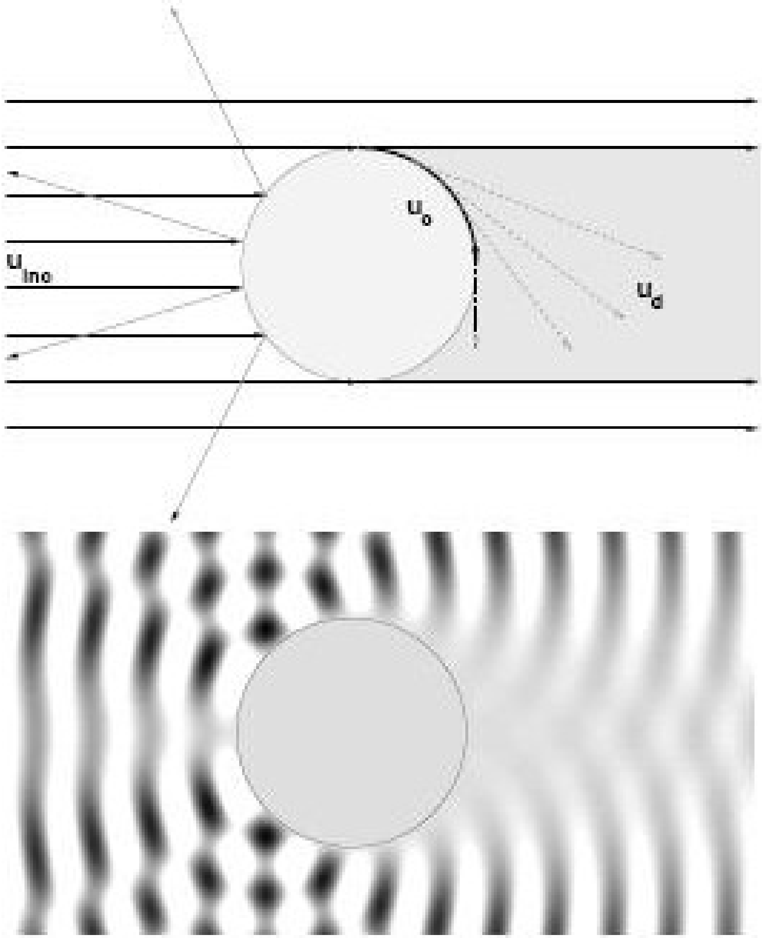


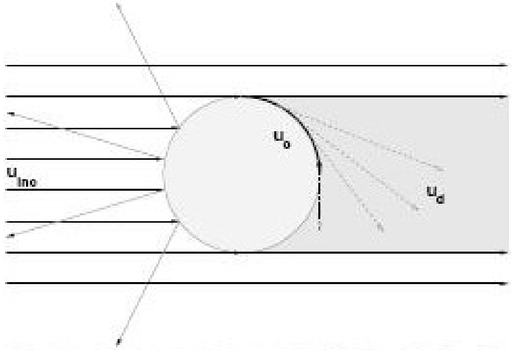
Figure 1: If obstacle is smooth then reflected and creeping rays are generated (graphic from [21]).

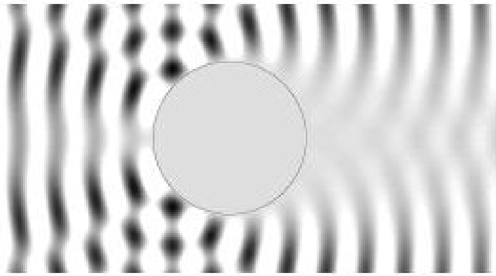
Exact and/or rigorous High Frequency Asymptotics??

There exist very powerful formal methods for generating high frequency asymptotics, e.g. the method of matched asymptotic expansions [17].

Exact solutions are known for simple geometries, mainly 2D, which are a strong guide to general behaviour.

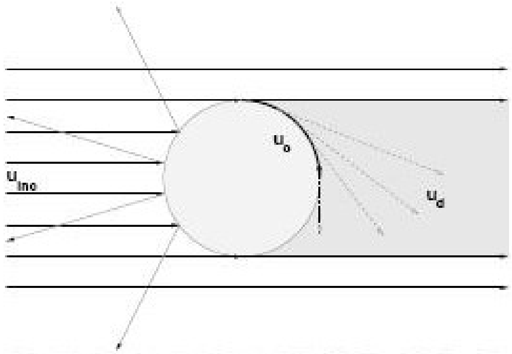
A little exact, rigorous asymptotics is known for general scatterers. E.g. scattering by a smooth, convex, positive curvature obstacle in 2D/3D (Melrose and Taylor [20]).

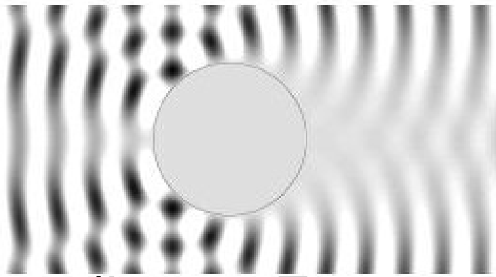




Rigorous asymptotics [20] predicts on Γ:

- Kirchhoff approximation works on illuminated side, i.e. $\dfrac{\partial u}{\partial n} \approx 2\dfrac{\partial u^i}{\partial n}$ (for $u = 0$)



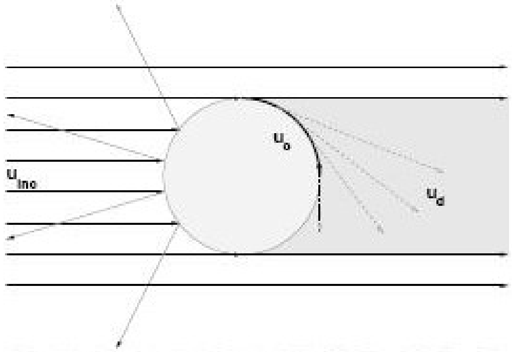


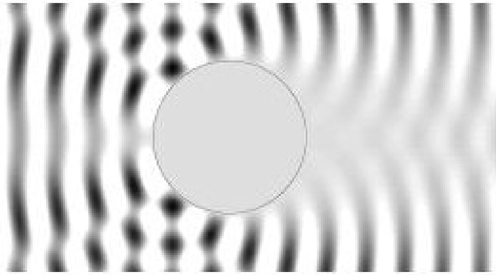
Rigorous asymptotics [20] predicts on Γ:

- on the shadow side there are two creeping rays, the normal derivative of each creeping ray field having the form

$$\frac{\partial u^{creep}}{\partial n}(x) = A\exp(\mathrm{i}(ks - C_0 F(s)k^{1/3}s))\exp(-C_1 F(s)k^{1/3}s),$$

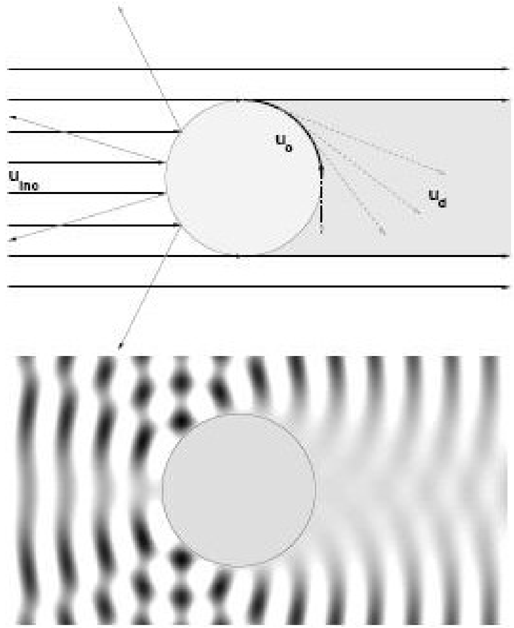
  where C_0 and C_1 are known positive constants, s is arc-length, and $c_1 s \leq F(s) \leq c_2 s$





Rigorous asymptotics [20] predicts on Γ:

- something complicated happens in the so-called **transition zones**, or **Fock-Leontovich** zones, around the tangency points (the North and South poles), in intervals of length $\approx R^{2/3}k^{-1/3}$ around the tangency points, where R is the radius of curvature at the tangency point. (Complicated, but smooth on the length scale $R^{2/3}k^{-1/3}$.)



Rigorous asymptotics [20] predicts on Γ:

- For further details see Melrose and Taylor [20] (which is incomprehensible to me), or see Dominguez, Graham, Smyshlyaev [10] (but I don't understand how they get their Theorem 5.1 from [20]).

Approach 2. We remove some of the oscillation by **factoring out the oscillation of the incident wave**, e.g.

$$\frac{\partial u}{\partial n}(y) = \frac{\partial u^i}{\partial n}(y) \times \mu(y) \quad (*)$$

and then approximate μ by a conventional BEM.

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The research splits into two groups:

Group 1. Use a quasi-uniform mesh BEM to approximate μ, see Zhou et al. [1], where it is shown that the error is

$$N^{-p} + (k^{1/3}/N)^{p+1}$$

in 2D, using polynomial degree p BEMs, and see Darrigrand [7] for impressive 3D implementations (including for an aircraft wing).

Approach 2. We remove some of the oscillation by **factoring out the oscillation of the incident wave**, e.g.

$$\frac{\partial u}{\partial n}(y) = \frac{\partial u^i}{\partial n}(y) \times \mu(y) \qquad (*)$$

and then approximate μ by a conventional BEM.

Group 2 (2D only). Ignore the deep shadow zone (where field is zero), use a standard spectral approximation on the illuminated side, and then a refined mesh or spectral approximation in the transition zones of width $k^{-1/3}$. See Bruno et al. [3, 4], Ecevit [11] for impressive numerical results which suggest $N = O(1)$ works, and Dominguez et al. [10] ditto, plus rigorous numerical analysis which shows $N = O(k^{1/9+\epsilon})$ works. Bruno et al. [3] deals with the oscillatory integral problem, though the details and justification are a little hazy. Another implementation, which focuses on the oscillatory integrals, and achieves a small, **sparse** matrix is Huybrechs and Vanderwalle [13].

How are people choosing $\hat{d}_i$ and b_{ij}??

$$\frac{\partial u}{\partial n}(x) \approx \sum_{i=1}^{M} \sum_{j=1}^{N_i} a_{ij} \exp(\mathrm{i}kx \cdot \hat{d}_i) \mathbf{b}_{ij}(x),$$

with $a_{ij} \in \mathbb{C}$ the unknown coefficients,
$\hat{d}_1, \ldots, \hat{d}_N$ distinct unit vectors,
$\mathrm{b}_{ij}(x)$ **conventional BEM basis functions**.

Approach 3 (2D so far). M small, directions $\hat{d}_i$ carefully chosen on the basis of the geometrical theory of diffraction to match high frequency solution behaviour. E.g. Bruno et al. [3] suggest how this might work for a (not too) non-convex obstacle (but have since adopted a slightly different, multiple scattering approach for scattering by a few, convex obstacles ([4], and see Ecevit [11]).

How are people choosing $\hat{d}_i$ and b_{ij}??

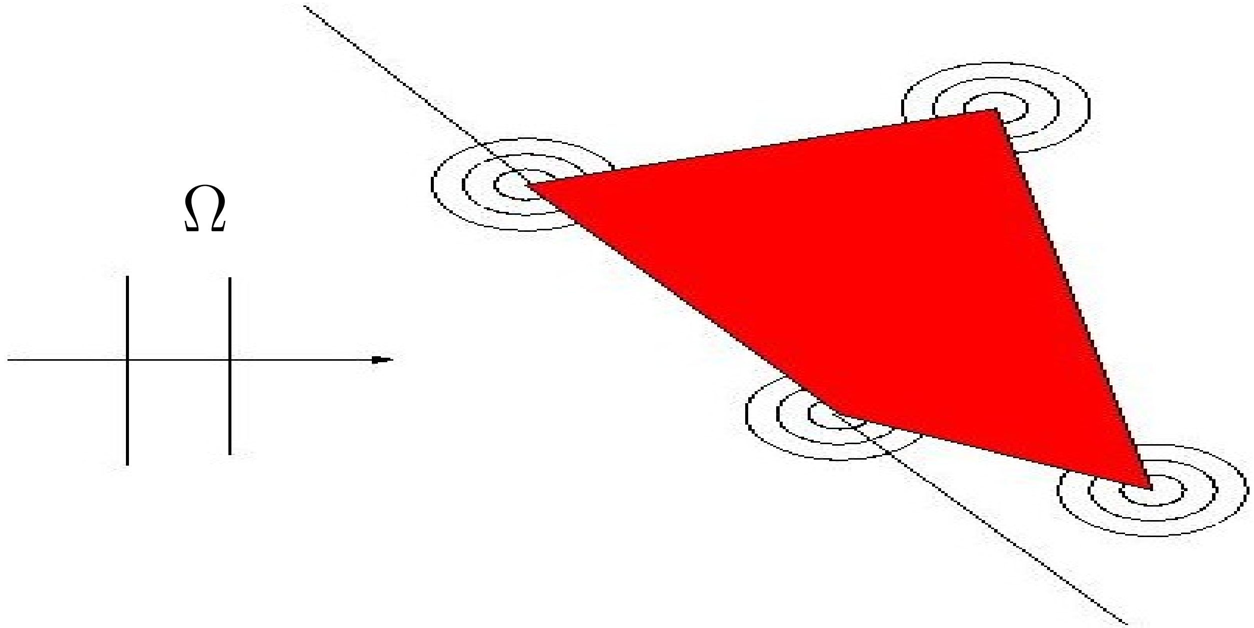
$$\frac{\partial u}{\partial n}(x) \approx \sum_{i=1}^{M} \sum_{j=1}^{N_i} a_{ij} \exp(\mathrm{i}kx \cdot \hat{d}_i) \mathbf{b}_{ij}(x),$$

with $a_{ij} \in \mathbb{C}$ the unknown coefficients,
$\hat{d}_1(x), \ldots, \hat{d}_N(x)$ distinct unit vectors,
$\mathbf{b}_{ij}(x)$ **conventional BEM basis functions**.

Approach 3 (2D). M small, directions $\hat{d}_i$ carefully chosen on the basis of the geometrical theory of diffraction to match high frequency solution behaviour. With Langdon, I have implemented and analysed a method in this vein for scattering by two specific scattering problems [6, 19, 2, 5], the second scattering by convex polygons.

A Simple Technique for Understanding Solution Behaviour for the Convex Polygon

Rigorous, high frequency asymptotics.

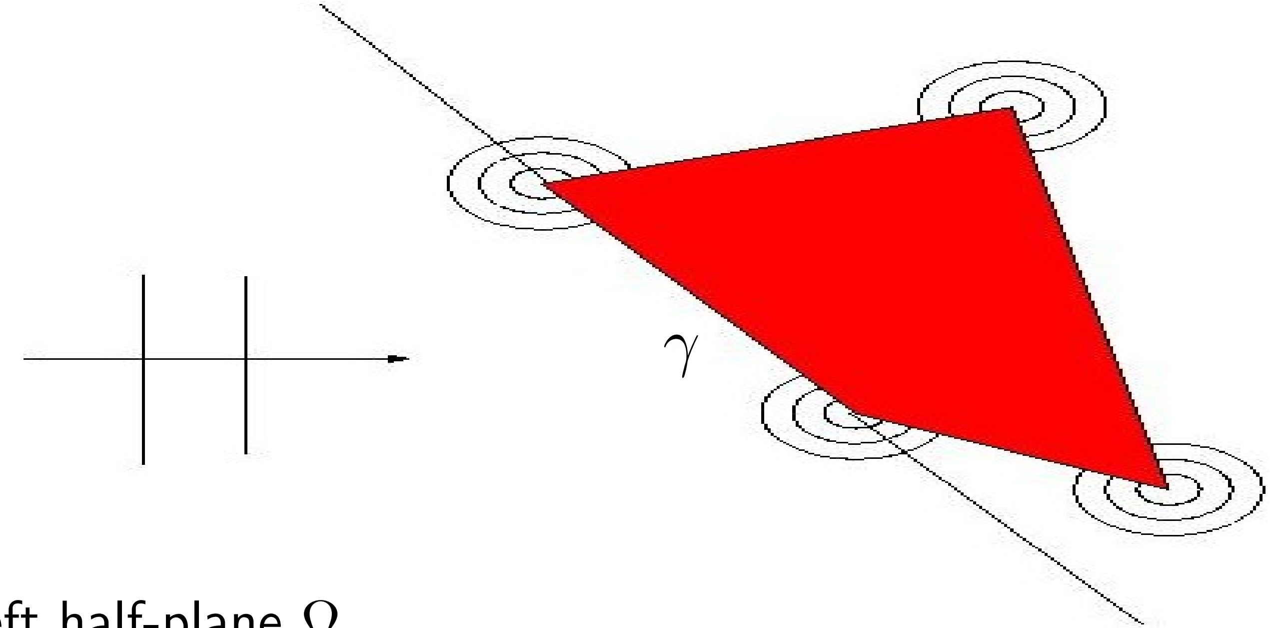


Let

$$G_D(x,y) := G(x,y) - G(x,y')$$

be the Dirichlet Green function for the left half-plane Ω. By Green's representation theorem,

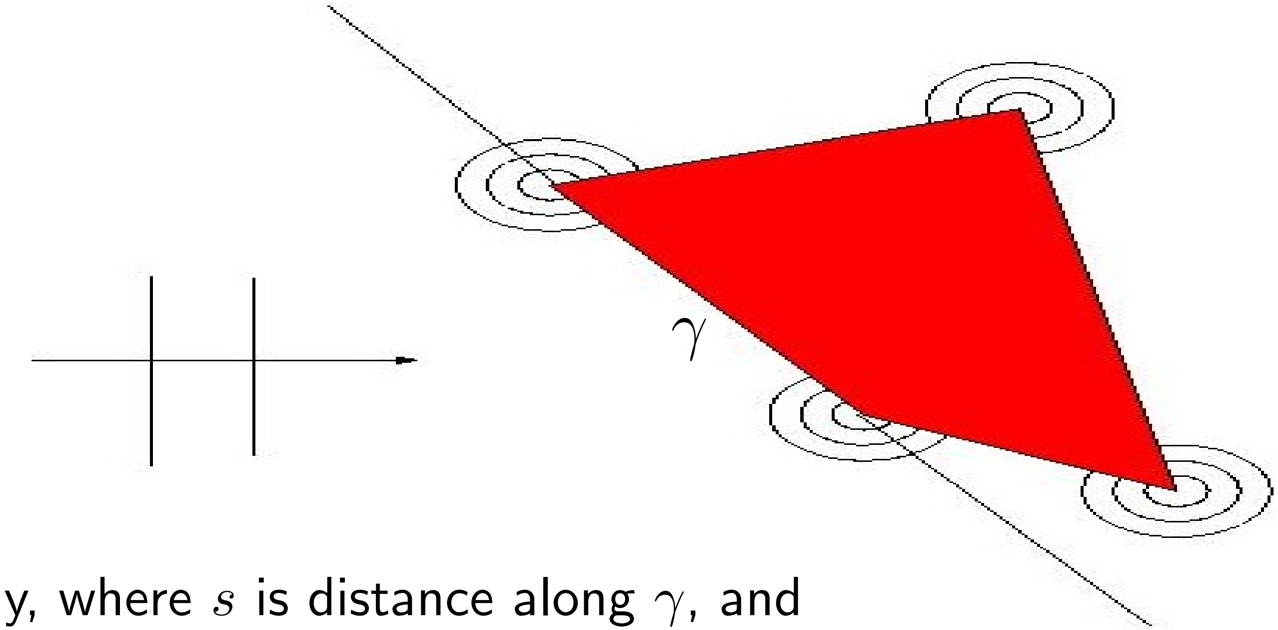
$$u(x) = u^i(x) + u^r(x) + \int_{\partial\Omega\setminus\Gamma} \frac{\partial G_D(x,y)}{\partial n(y)} u(y) ds(y), \quad x \in \Omega,$$



In the left half-plane Ω,

$$u(x) \quad = \quad u^i(x) + u^r(x) + \int_{\partial\Omega\backslash\Gamma} \frac{\partial G_D(x,y)}{\partial n(y)} u(y) ds(y)$$

$$\Rightarrow \frac{\partial u}{\partial n}(x) = 2\frac{\partial u^i}{\partial n}(x) + 2\int_{\partial\Omega\backslash\Gamma} \frac{\partial^2 G(x,y)}{\partial n(x)\partial n(y)} u(y) ds(y), \quad x \in \gamma = \partial\Omega \cap \Gamma.$$



Explicitly, where s is distance along γ, and
$\phi(s)$ and $\psi(s)$ are $k^{-1}\partial u/\partial n$ and u, at distance s along γ,

$$\phi(s) \quad = \quad P.O. + \frac{\mathrm{i}}{2}\left[\mathrm{e}^{\mathrm{i}ks}v_+(s) + \mathrm{e}^{-\mathrm{i}ks}v_-(s)\right]$$

where

$$v_+(s) := k\int_{-\infty}^{0} F\big(k(s-s_0)\big)\mathrm{e}^{-\mathrm{i}ks_0}\psi(s_0)ds_0.$$

and $F(z) := \mathrm{e}^{-\mathrm{i}z}H_1^{(1)}(z)/z$

$$\phi(s) \quad = \quad P.O. + \frac{\mathrm{i}}{2}\left[\mathrm{e}^{\mathrm{i}ks}v_+(s) + \mathrm{e}^{-\mathrm{i}ks}v_-(s)\right]$$

where

$$v_+(s) := k\int_{-\infty}^{0} F\big(k(s-s_0)\big)\mathrm{e}^{-\mathrm{i}ks_0}\psi(s_0)ds_0.$$

Now $F(z) := \mathrm{e}^{-\mathrm{i}z}H_1^{(1)}(z)/z$ which is non-oscillatory, in that

$$F^{(n)}(z) = O(z^{-3/2-n}) \text{ as } z \to \infty.$$

$$\phi(s) \quad = \quad P.O. + \frac{\mathrm{i}}{2}\left[\mathrm{e}^{\mathrm{i}ks}v_+(s) + \mathrm{e}^{-\mathrm{i}ks}v_-(s)\right]$$

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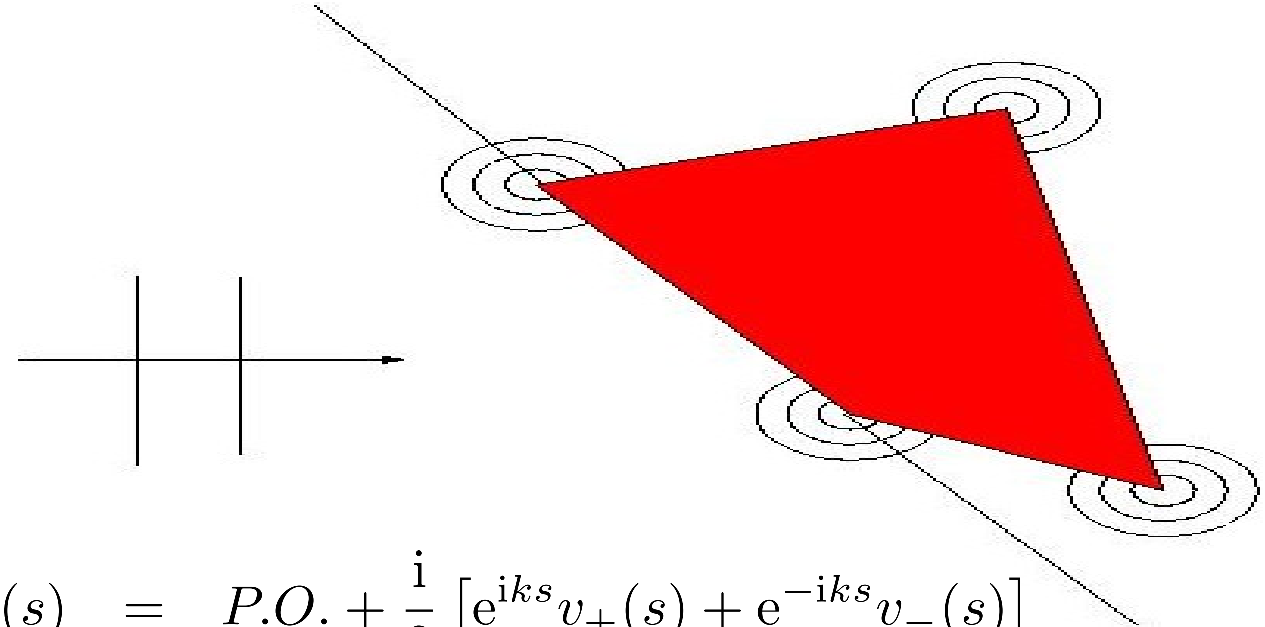
$$F^{(n)}(z) = O(z^{-3/2-n}) \text{ as } z \to \infty.$$

$$\Rightarrow v_+^{(n)}(s) = O(k^n(ks)^{-1/2-n}) \text{ as } ks \to \infty.$$



$$\phi(s) \quad = \quad P.O. + \frac{\mathrm{i}}{2}\left[\mathrm{e}^{\mathrm{i}ks}v_+(s) + \mathrm{e}^{-\mathrm{i}ks}v_-(s)\right]$$

where

$$k^{-n}|v_+^{(n)}(s)| = O\left((ks)^{-1/2-n}\right) \text{ as } ks \to \infty$$

and (by separation of variables local to the corner),

$$k^{-n}|v_+^{(n)}(s)| = O\left((ks)^{-\alpha-n}\right) \text{ as } ks \to 0,$$

where $\alpha < 1/2$ depends on the corner angle.

A Numerical Scheme for the Convex Polygon Which Uses this Precise Understanding of Solution Behaviour

$$\phi(s) \quad = \quad P.O. + \frac{\mathrm{i}}{2}\left[\mathrm{e}^{\mathrm{i}ks}v_+(s) + \mathrm{e}^{-\mathrm{i}ks}v_-(s)\right]$$

where

$$k^{-n}|v_+^{(n)}(s)| = \begin{cases} O\left((ks)^{-1/2-n}\right) & \text{as } ks \to \infty \\ O\left((ks)^{-\alpha-n}\right) & \text{as } ks \to 0, \end{cases}$$

where $\alpha < 1/2$ depends on the corner angle.

Thus approximate

$$\phi(s) \quad \approx \quad P.O. + \frac{\mathrm{i}}{2}\left[\mathrm{e}^{\mathrm{i}ks}V_+(s) + \mathrm{e}^{-\mathrm{i}ks}V_-(s)\right],$$

where V_+ and V_- are piecewise polynomials on graded meshes, i.e. linear combinations of standard boundary element basis functions.

Thus approximate

$$\phi(s) \quad \approx \quad P.O. + \frac{\mathrm{i}}{2}\left[\mathrm{e}^{\mathrm{i}ks}V_{+}(s) + \mathrm{e}^{-\mathrm{i}ks}V_{-}(s)\right],$$

where V_{+} and V_{-} are piecewise polynomials on graded meshes.

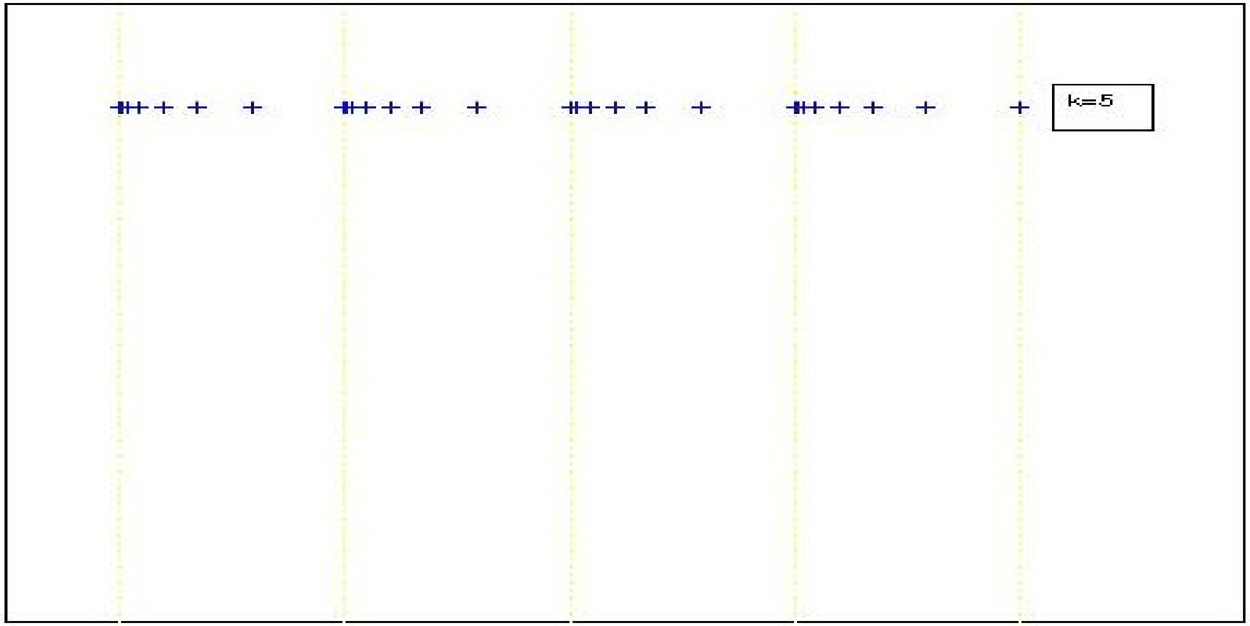


Figure 2: Scattering by a square

Thus approximate

$$\phi(s) \quad \approx \quad P.O. + \frac{\mathrm{i}}{2}\left[\mathrm{e}^{\mathrm{i}ks}V_+(s) + \mathrm{e}^{-\mathrm{i}ks}V_-(s)\right],$$

where V_+ and V_- are piecewise polynomials on graded meshes.

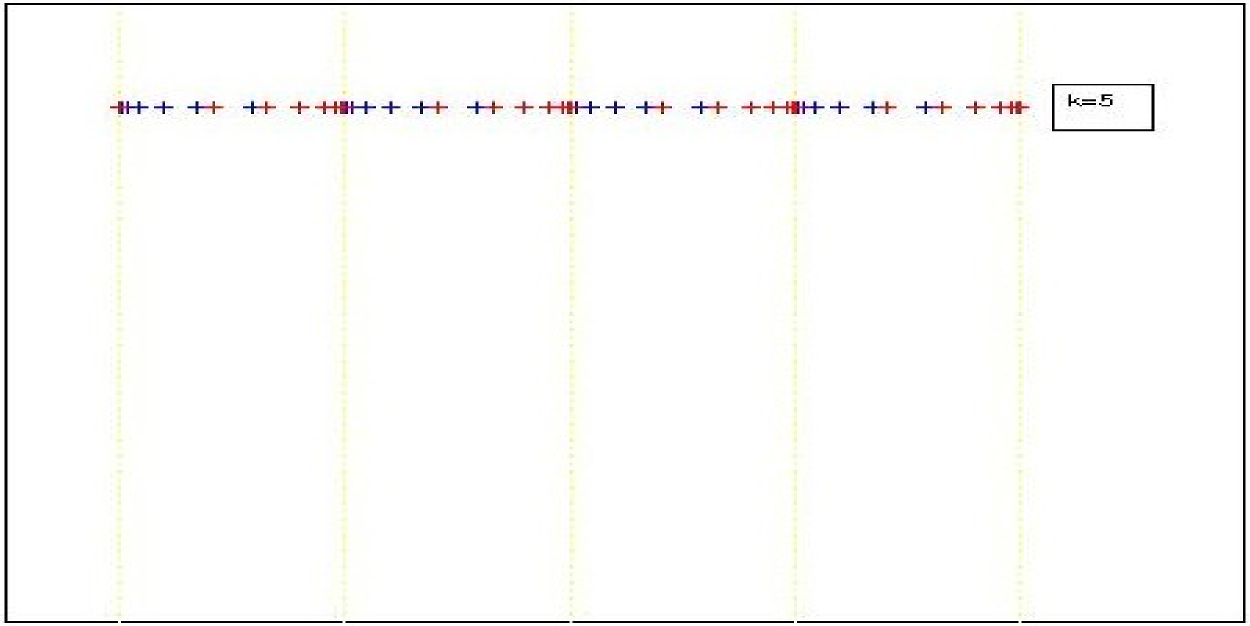


Figure 3: Scattering by a square

Thus approximate

$$\phi(s) \quad \approx \quad P.O. + \frac{\mathrm{i}}{2}\left[\mathrm{e}^{\mathrm{i}ks}V_+(s) + \mathrm{e}^{-\mathrm{i}ks}V_-(s)\right],$$

where V_+ and V_- are piecewise polynomials on graded meshes.

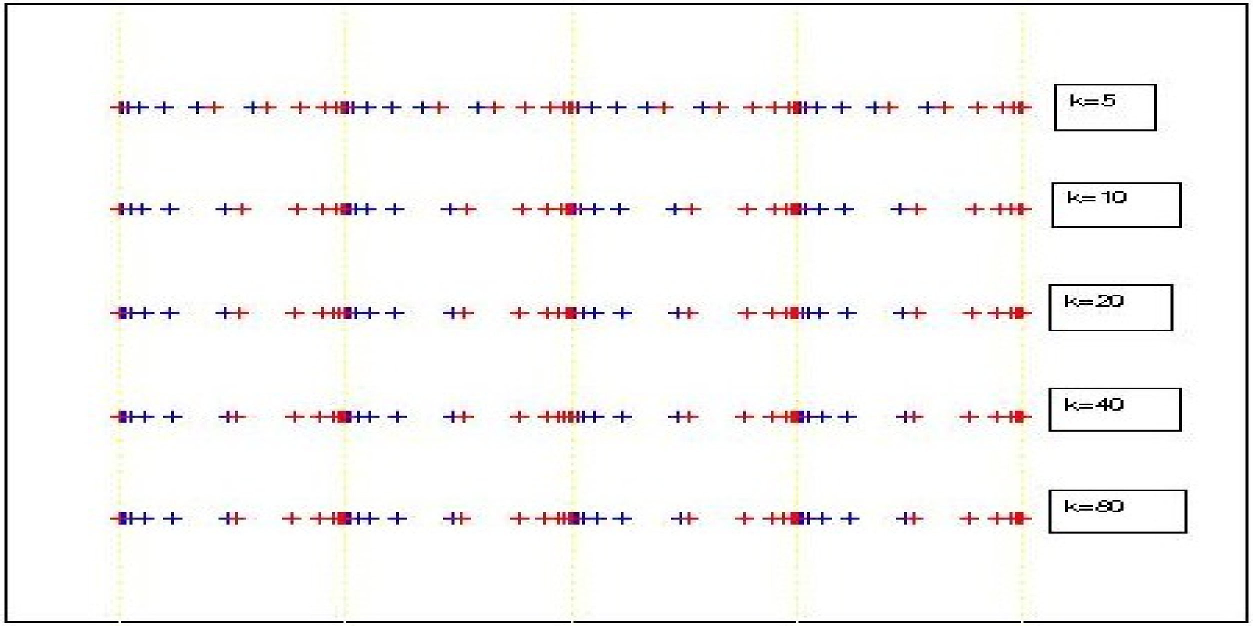


Figure 4: Scattering by a square

Thus approximate

$$\phi(s) \quad \approx \quad P.O. + \frac{\mathrm{i}}{2}\left[\mathrm{e}^{\mathrm{i}ks}V_+(s) + \mathrm{e}^{-\mathrm{i}ks}V_-(s)\right],$$

where V_+ and V_- are piecewise polynomials on graded meshes.

Theorem Where ϕ_N is the best L_2 approximation from the approximation space, n is the number of sides, N the number of degrees of freedom, p the polynomial degree, and L the total arc-length,

$$k^{1/2}||\phi - \phi_N||_2 \leq C \sup_{x\in D} |u(x)| \frac{[n(1+\log(kL/n))]^{p+3/2}}{N^{p+1}},$$

where C depends (only) on the corner angles and p.

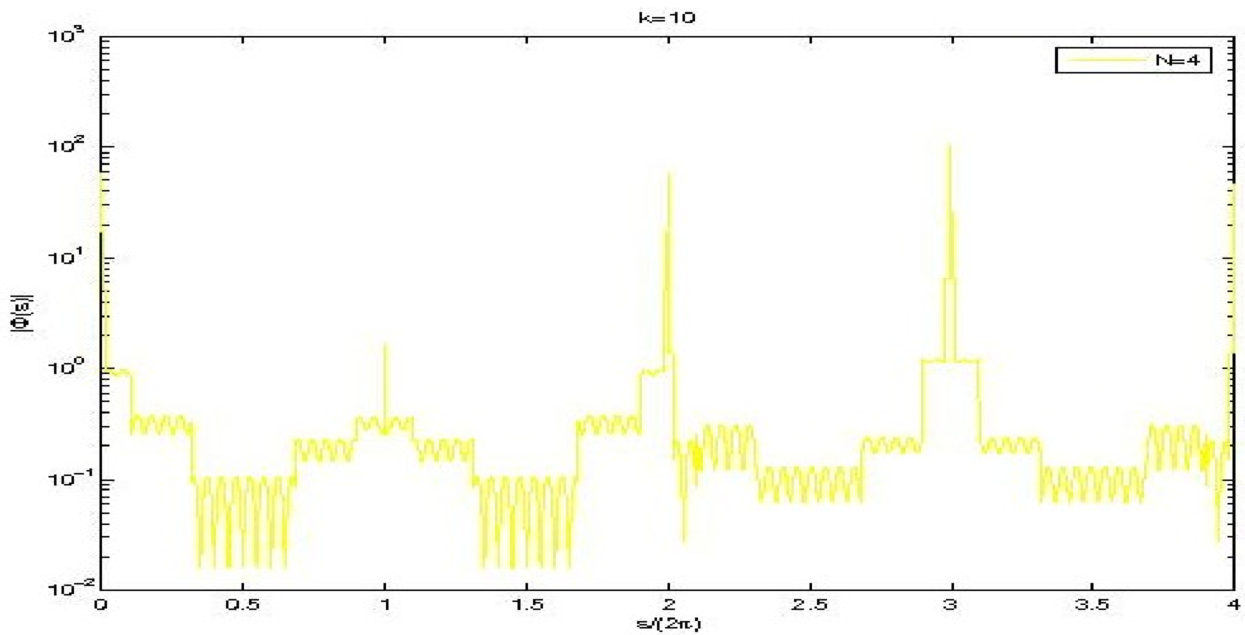
Numerical results

scattering by a square, $k = 5$

scattering by a square, $k = 10$

Numerical results (scattering by a square)

Solution minus P.O. approximation;



Numerical results (scattering by a square)

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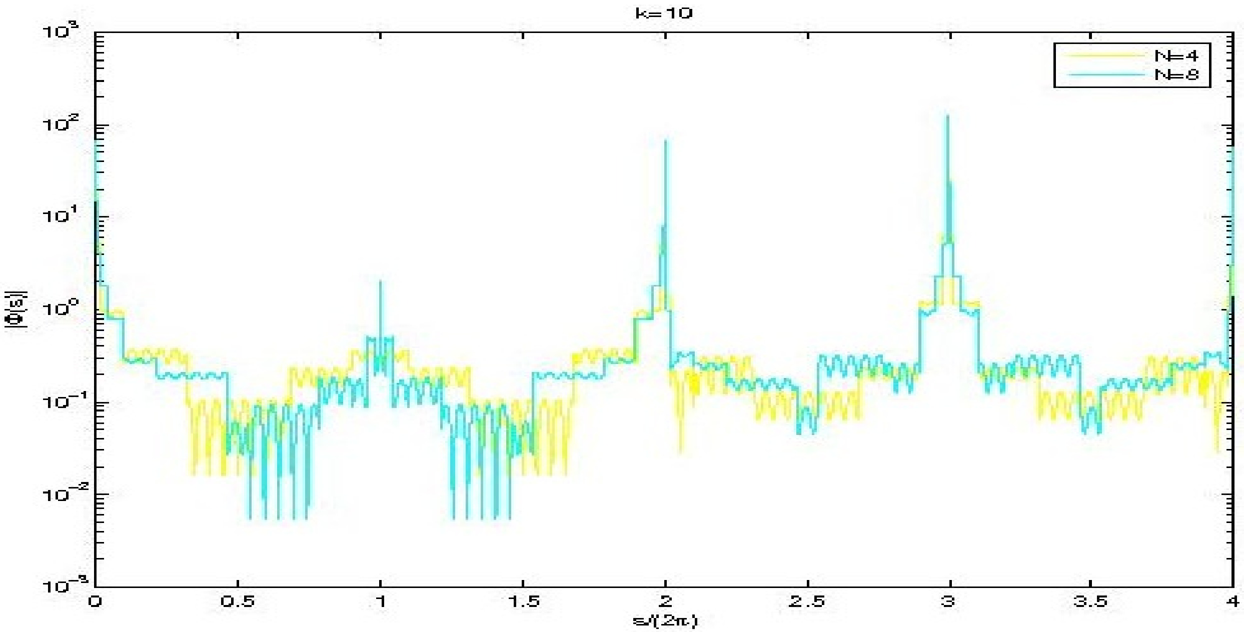
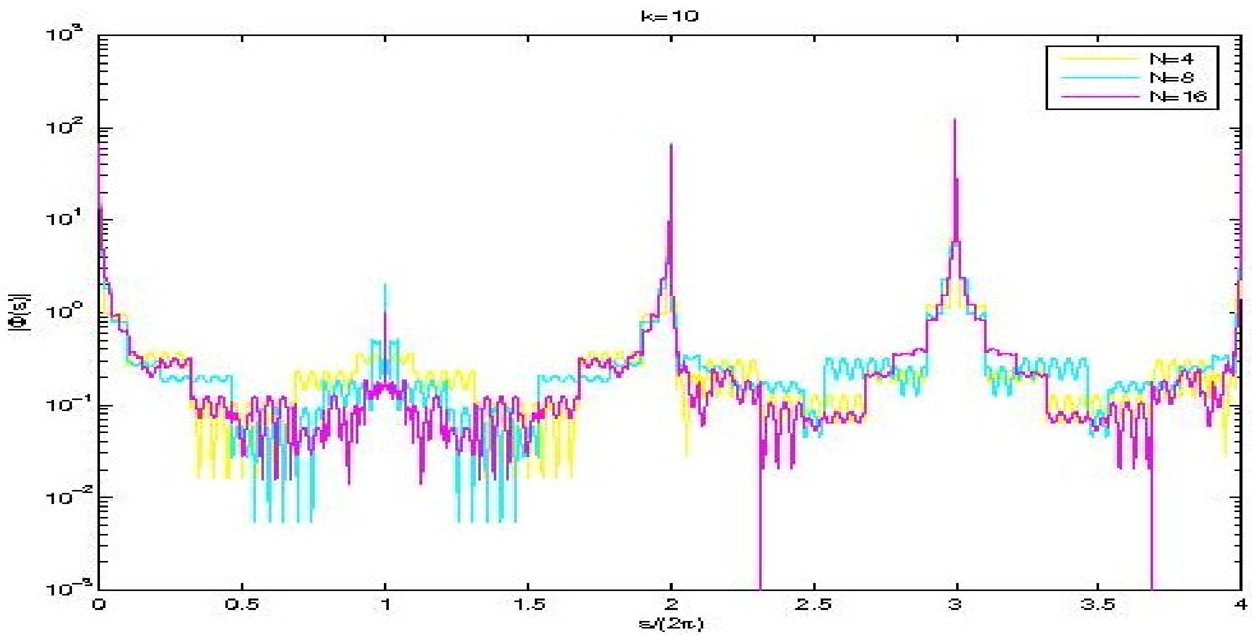


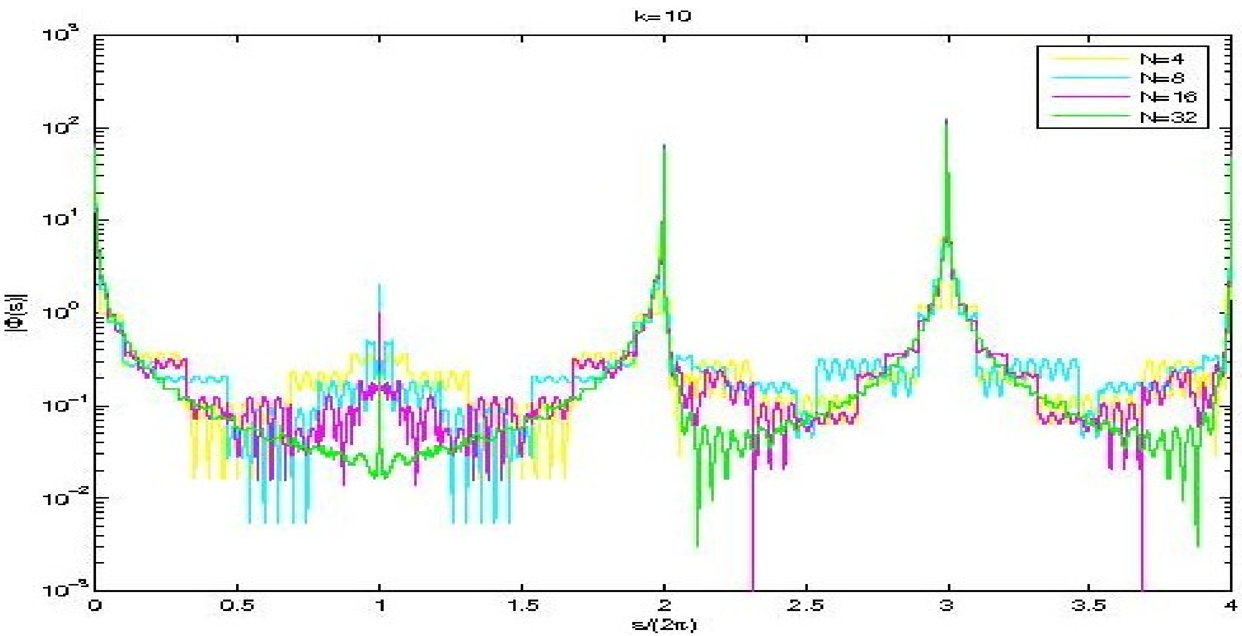
Numerical results (scattering by a square)

Solution minus P.O. approximation;



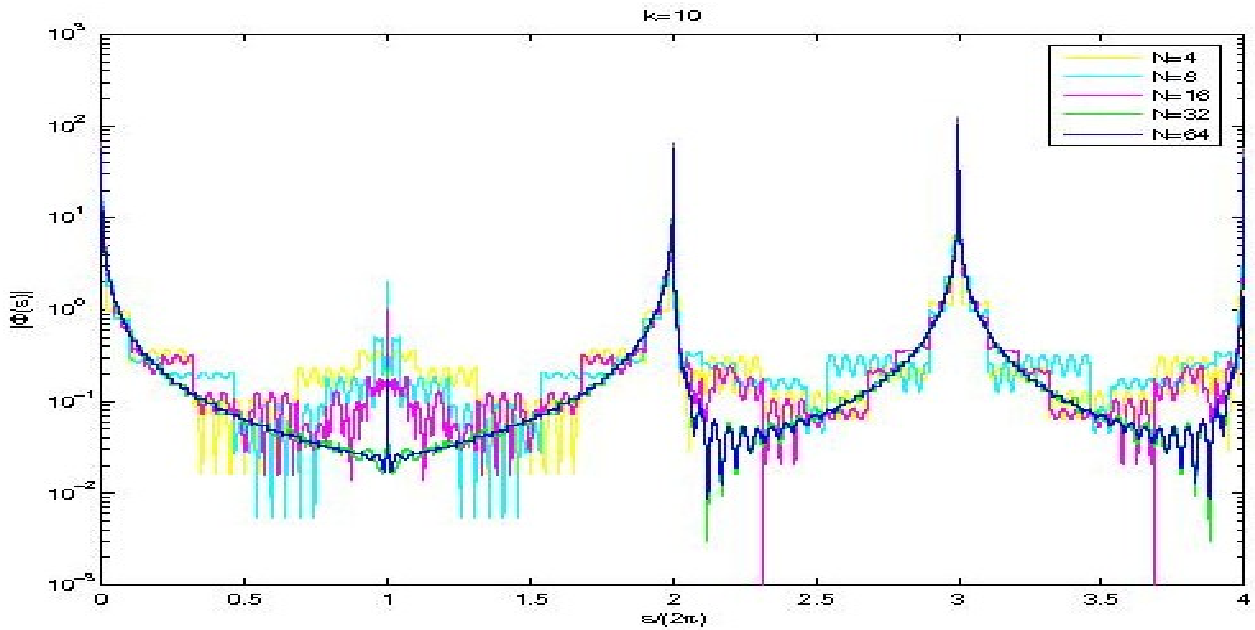
Numerical results (scattering by a square)

Solution minus P.O. approximation;



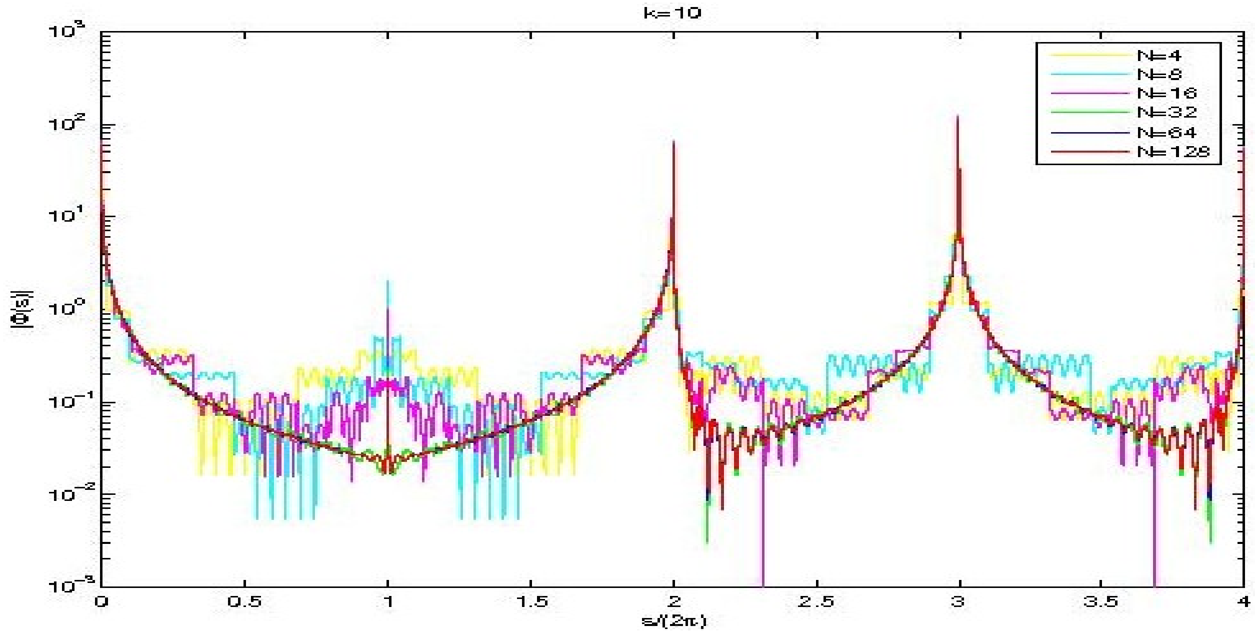
Numerical results (scattering by a square)

Solution minus P.O. approximation;



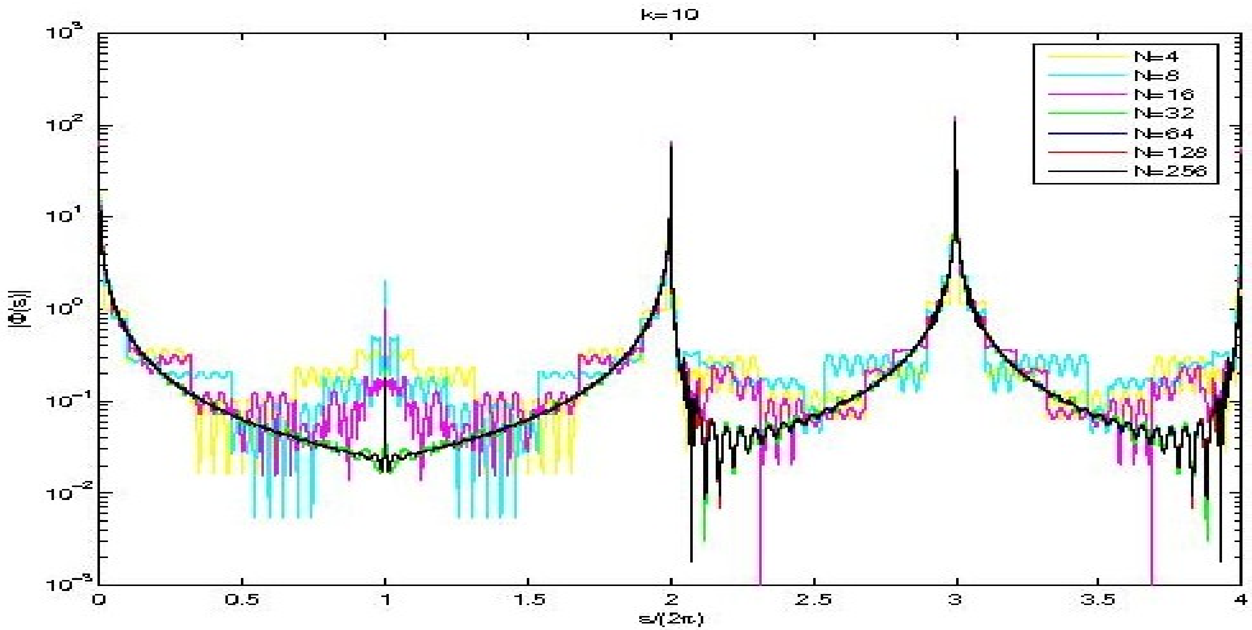
Numerical results (scattering by a square)

Solution minus P.O. approximation;



Numerical results (scattering by a square)

Solution minus P.O. approximation;



Numerical results (scattering by a square)

"Exact" solution minus P.O. approximation, $k = 20$;

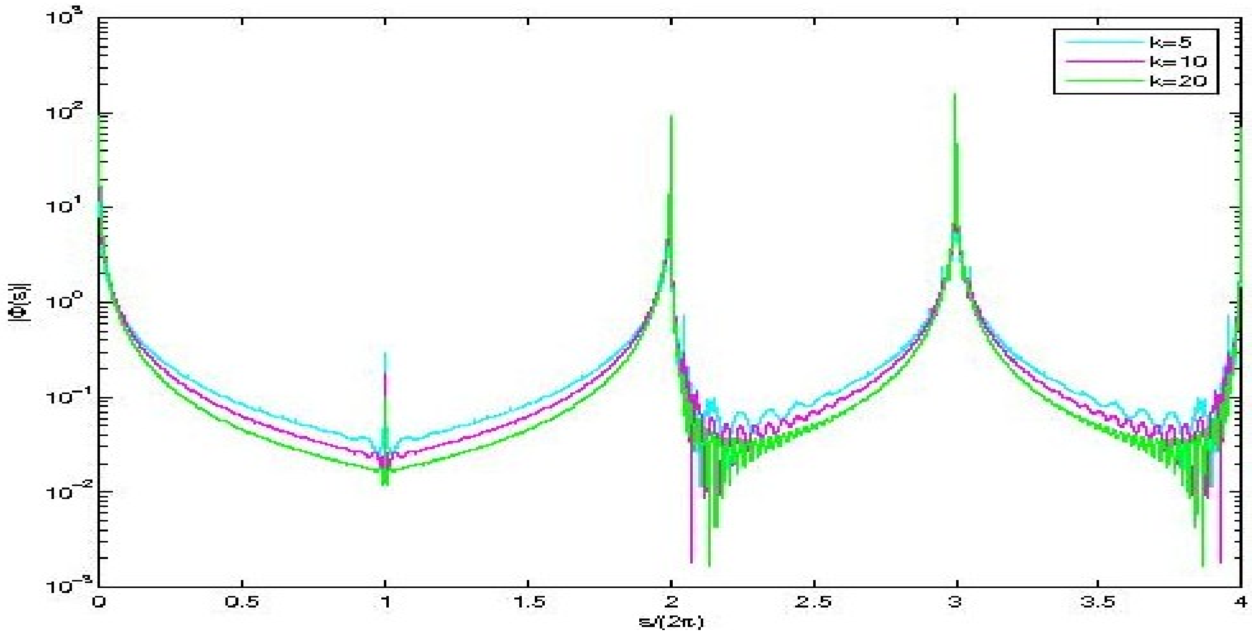


Table 1: Relative errors, $k = 10$

k	N (#dof)	$\|\phi - \phi_N\|_2 / \|\phi\|_2$	EOC
10	24	$1.1187\times10^{+0}$	1.5
	48	4.0499×10^{-1}	0.7
	88	2.5348×10^{-1}	0.9
	176	1.3979×10^{-1}	1.3
	360	5.5216×10^{-2}	0.9
	712	3.0358×10^{-2}	

Table 2: Relative errors, $k = 160$

k	N (#dof)	$\|\phi - \phi_N\|_2 / \|\phi\|_2$	EOC
160	32	$1.0350 \times 10^{+0}$	1.3
	56	4.2389×10^{-1}	0.5
	120	3.0406×10^{-1}	0.6
	240	2.0471×10^{-1}	1.5
	472	7.3763×10^{-2}	1.0
	944	3.6983×10^{-2}	

What we are actually computing . . .

The difference between the exact solution and the leading order physical optics/Kirchhoff approximation;

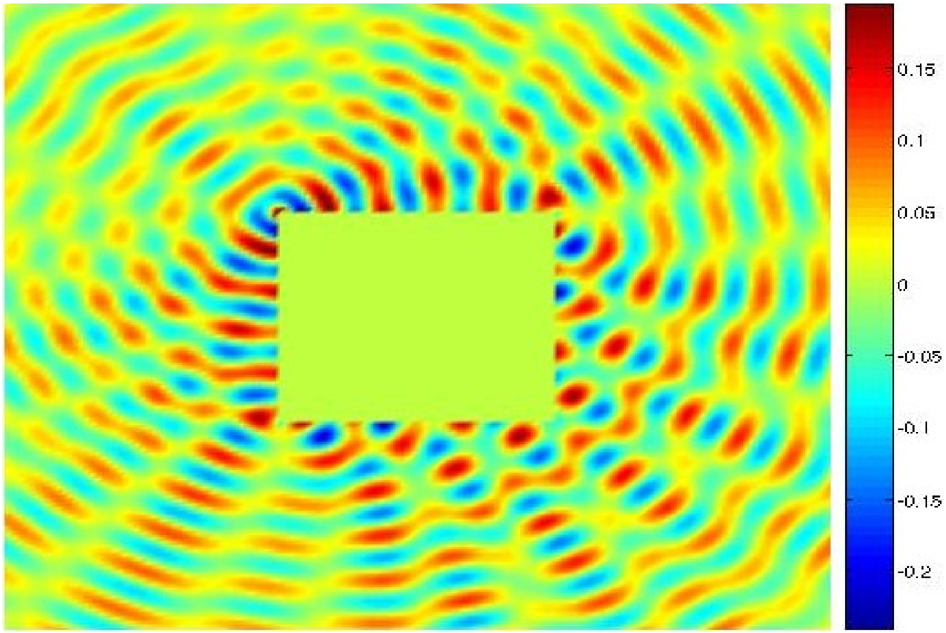


Figure 5: square, $k = 5$

What we are actually computing . . .

The difference between the exact solution and the leading order physical optics/Kirchhoff approximation;

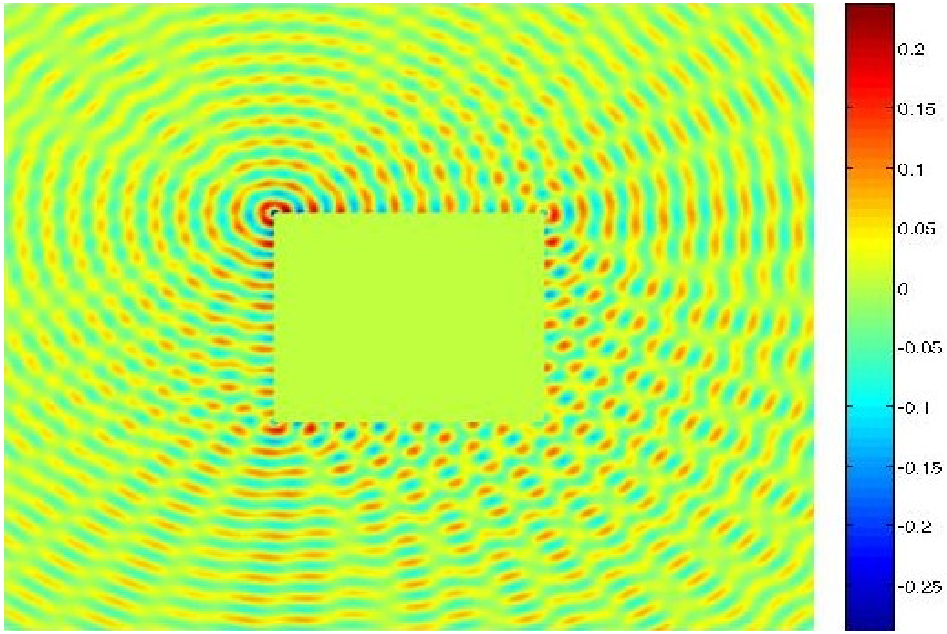


Figure 6: square, $k = 10$

What we are actually computing . . .

The difference between the exact solution and the leading order physical optics/Kirchhoff approximation;

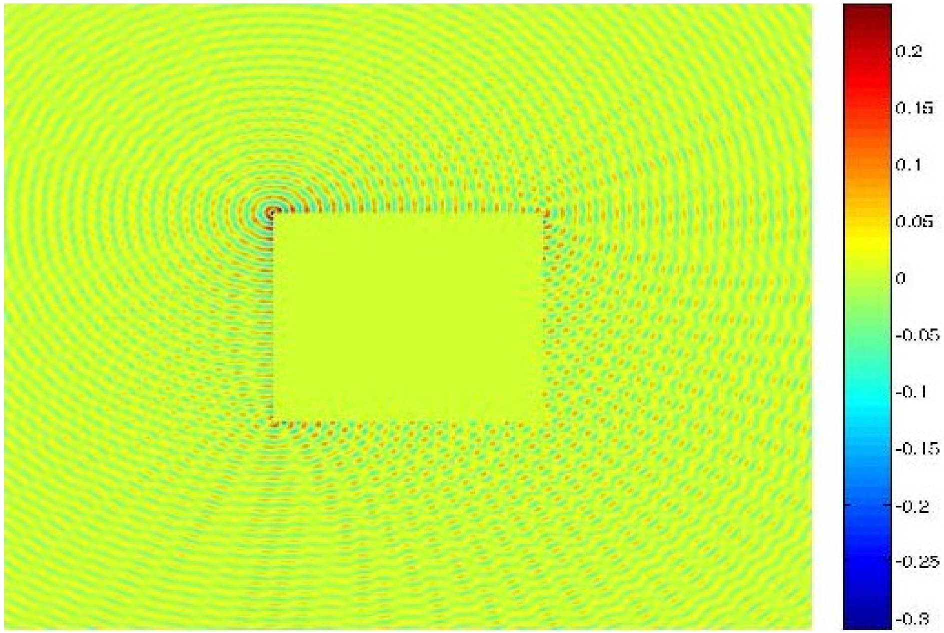


Figure 7: square, $k = 20$

What we are actually computing . . .

The difference between the exact solution and the leading order physical optics/Kirchhoff approximation;

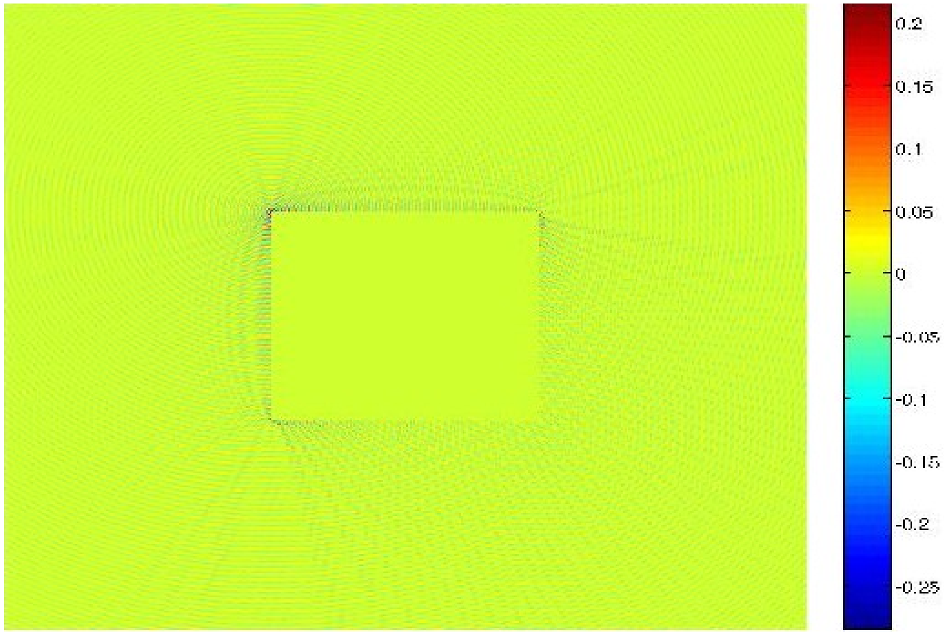


Figure 8: square, $k = 40$

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